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TRAVAUX

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Introduction

The International Association of Geodesy (IAG) is publishing its reports regularly since 1923 (Tome 1). They were called "Travaux de la Section de Géodésie de l'Union Géodésique et Géophysique Internationale" in the first years. According to the renaming of the IUGG Sections as Associations, the name was changed in 1938 to "Travaux de l'Association de Géodésie". They are published on occasion of the IUGG General Assemblies, which were held every three years until 1963, and since then every four years. These volumes serve as a comprehensive documentation of the work carried out during the past period of three or four years, respectively. The reports were published until 1995 (Volume 30) as printed volumes only, and since 1999 (Volume 31) in digital form as CD and/or in the Internet.

Since 2001, there are also midterm reports published on occasion of the IAG Scientific Assemblies in between the General Assemblies. Usually they are presented before the Assembly to the IAG Executive Committee (EC) and are discussed in the EC meetings in order to receive and give advices for the future work. The present Volume 40 contains the midterm reports of all IAG components for the period 2015 to 2017 and is presented at the IAG-IASPEI Scientific Assembly in Kobe, Japan, July 30 to August 4, 2017.

The editors thank all the authors for their work. A feedback of the readers is welcome. The digital versions of this volume as well as the previous ones since 1995 may be found in the IAG Office homepage (http://iag.dgfi.tum.de). Printed versions are available on request.

Hermann Drewes
IAG Secretary General

Franz Kuglitsch
Assistant Secretary

Commission 1 – Reference Frames

http://iag.geo.tuwien.ac.at/c1/

President: Geoffrey Blewitt (USA)
Vice President: Johannes Böhm (Austria)

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Overview

Commission 1 activities have been dealing with the theoretical aspects of how best to define reference systems, and how such reference systems can be used for practical and scientific applications. The reader is referred to the Geodesists Handbook 2016 for further details on the objectives of Commission 1 and its components. Commission 1 has been closely interacting with other IAG components including Commissions, ICCT, Services, and GGOS, where reference system aspects are of concern. Much of this interaction is facilitated by Joint Study Groups and Joint Working Groups of Commission 1. This mid-term report summarizes the work performed during 2015-2017 by the various components of Commission 1, including the Sub-commissions and their Working Groups, and Joint Working Groups who have their primary affiliation with Commission 1.

In addition to the work performed by the components of Commission 1, the following summarizes activities in 2015-2017 that were performed on behalf of the entire Commission:

- A web site for Commission 1 was established at http://iag.geo.tuwien.ac.at/c1/.
- The terms of reference and structure of Commission 1, and membership/descriptions of its components were detailed in our contribution to the Geodesists Handbook 2016.

- The Steering Committee of Commission 1 had its first annual meeting in Vienna, Austria, April 2016. The second annual meeting will be held in Kobe, Japan, August 2017.
- Commission 1 leadership convened an IAG Symposium to be held at the IAG-IASPEI Joint Assembly to be held in Kobe, Japan, July-August 2017.
- Considering that Commission 1 is defined to be identical with Sub-commission B2 of COSPAR, steps have been taken to reinvigorate this connection by planning to hold the next quadrennial symposium of Commission 1 (Reference Frames for Applications in Geosciences, "REFAG") to be held at the COSPAR 42nd General Assembly in Pasadena, California, USA, July 14-22, 2018. The REFAG 2018 Program Committee includes Geoffrey Blewitt (USA), Johannes Böhm (Austria), Zuheir Altamimi (France), and Urs Hugentobler (Germany).
- Commission 1 was represented at the IAG Executive Committees in 2015 (San Francisco, USA), 2016 (Potsdam, Germany) and 2017 (Vienna, Austria), during which progress reports were presented.
- Commission 1 was represented at the IAG Strategic Planning Meeting in Potsdam, Germany, 2016.

The following pages now provide reports for all IAG components that are primarily affiliated with Commission 1 and its Sub-commissions.

Sub-commission 1.1: Coordination of Space Techniques

Chair: *Urs Hugentobler (Germany)*

Overview

Sub-commission 1.1 focusses on the coordination of research related to the geodetic space techniques with emphasis on co-location aspects at fundamental geodetic observatories as well as on co-location targets in space, considering common parameters such as coordinates, troposphere parameters, and clock parameters.

The GGOS Working Group "Performance Simulations and Architectural Trade-Offs (PLATO)" was installed in 2013. In the IAG structure 2015-2019 PLATO acts as an IAG Joint Working Group in IAG Sub-Commission 1.1 in order to establish a link for the study and assessment of co-locations in space as a very relevant topic in the context of coordination of space geodetic techniques. In 2016 PLATO was converted into a "Standing Committee" in the GGOS framework in order to allow studies on a time frame extending the usual duration of working groups.

In addition to a large variety of SLR, LLR and VLBI simulations covering different aspects related to the design of ground- and space-based architecture of measurement systems, to improved analysis methods, and to observation scenarios and their impact on TRF accuracy and stability, PLATO members contributed important simulation results for the proposal for the E-GRASP/Eratosthenes mission proposal in reply of ESA's Earth Explorer-9 call prepared under the lead of Richard Biancale.

Working Group 1.1.1 on co-location using clocks and new sensors was set up. A position paper was prepared focusing on the relevance of precise time and frequency distribution at fundamental stations and corresponding closure measurements as a method to monitor local ties. A meeting is planned addressing the next generation geodetic stations and metrology concept. Activities of the ESA Topical Team on Geodesy, Clocks and Time Transfer exploit synergies with the IAG WG 1.1.1.

Terms of Reference

Space techniques play a fundamental role for the realization and dissemination of highly accurate and long term stable terrestrial and celestial reference frames as well as for accurate monitoring of the Earth orientation parameters linking the two fundamental frames. The current space geodetic techniques contributing to ITRF and ICRF, i.e., Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) have particular strengths and technique-specific weaknesses.

Strengths of the techniques are exploited by combining them making use of fundamental sites co-locating more than one technique. Sub-commission 1.1 focusses on the coordination of research related to the geodetic space techniques with emphasis on co-location aspects at fundamental geodetic observatories as well as on co-location targets in space, considering common parameters such as coordinates of stations and satellites, troposphere parameters, and clock parameters.

Working Groups of Sub-commission 1.1:

WG 1.1.1: Co-location using Clocks and New Sensors

Chair: *Ulrich Schreiber (Germany)*

Members
- *Sten Bergstrand (Sweden)*
- *Srinivas Bettadpur (USA)*
- *Rüdiger Haas (Sweden)*
- *Younghee Kwak (Germany)*
- *David McCormick (USA)*
- *Markku Poutanen (Finnland)*
- *Ivan Prochazka (Czech Republic)*

Activities and publications during the period 2015-2017

The establishment of accurate local ties of different space geodetic techniques at fundamental geodetic observatories poses a long-standing problem. While geometric ties can be determined at sub-millimeter-level, the relation to physical phase centers of the instruments and temporal stability of such offsets are usually known with significantly lower precision. This working group evaluates novel ways for inter-technique cross-calibration at geodetic sites using existing and new sensors and technologies, such as highly accurate time and frequency transfer, ultra-stable clocks, and co-location targets. The activities of the working group are closely related to JWG 2.1 on Relativistic Geodesy. A corresponding coordination meeting took place in Hannover, Germany, on April 12, 2017.

1. Position Paper

A position paper addressing the main topics of the working group was formulated stimulating the discussions among the WG members. The position paper addresses the issue of local ties at geodetic observatories and highlights a concept allowing to access the physical phase center of SLR as well as VLBI and other space geodetic instruments through closure measurements of travel times. The concept involves precise time distribution of timing signals between the instruments and a common calibration target through compensated optical fibers.

Figure 1.1.1 shows the concept of a demonstrator that is developed at the Geodetic Observatory in Wettzell allowing to cross-calibrate the reference points of several VLBI telescopes. A precisely time-tagged signal is broadcast by a reference target and received by the radio telescopes through standard receive channels. The signal is registered with respect to a reference signal (p-cal and formatter) with precisely known time relation to the broadcast signal. The concept thus allows to precisely relate the geometric free space travel distance from the reference target to instrument reference point through time closure measurements.

The highlighted concept is currently built up at the Geodetic Observatory Wettzell in the framework of the research unit FOR 1503 funded by the German Science Foundation (DFG).Similar concepts and performance and implementation issues for the other space geodetic techniques are discussed in the context of the working group.

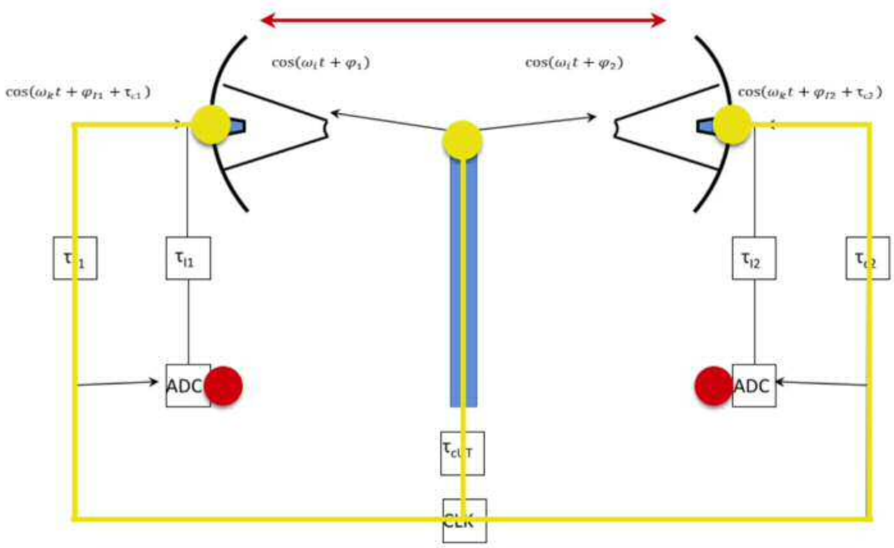

Fig 1.1.1: Concept for precise cross-calibration of the reference points of VLBI telescopes through time closure measurements.

2. Meeting on Next Generation Geodetic Stations and Metrology

A workshop on Next Generation Geodetic Stations and Metrology is planned by Srinivas Bettadpur at Center for Space Research at University of Texas at Austin for late summer 2017. Background is the operation of the McDonald Geodetic Observatory as a multi-technique geodetic observatory within the NSAS's Next Generation Space Geodesy Network. The goal of the workshop is to develop a list of areas of attention and research that bear the potential for leading to an idealized geodetic observatory supporting the needs of a future terrestrial reference frame.

The effort attempts to reassess the available knowledge from the viewpoint of metrology science and its implementation with the needs defined by the next generation reference frame. Topics of discussion are in particular the contribution of distribution of precise time and frequency between the different systems at an observatory, concepts of inter-system survey ties at ppm-level, contribution of gravity measurements, and requirements for characterization of the environment.

3. ESA Topical Team on Geodesy, Clocks and Time Transfer

In the framework of the ESA Topical Team on Geodesy, Clocks and Time Transfer a workshop is in planning focussing on distribution of precise time between geodetic observatories using space techniques. The topical team is chaired by Ulli Schreiber and receives funding from ESA for the organization of workshops. It consists of an international group of experts and coordinates the activities of different research groups working on topics related to clocks and time transfer for geodetic applications, activities that are relevant in the context of the tasks of IAG WG 1.1.1. The topical team identifies scientific problems and relevant new technologies and organizes topical workshops. A main focus is the exploitation of the Atomic Clock Ensemble in Space (ACES) that will be launched in 2018 to the International Space Station.

JWG 1.1.2: Performance Simulations and Architectural Trade-Offs (PLATO)

Chair: *Daniela Thaller (Germany)*
Vice Chair: *Benjamin Männel (Germany)*

Members

- *AIUB (Astronomical Institute, University of Bern, Switzerland)*
- *BKG (Bundesamt für Kartographie und Geodäsie, Germany)*
- *CNES (Centre National d'Etudes Spatiales, France)*
- *DGFI-TUM (Deutsches Geodätisches Forschungsinstitut, TU München, Germany)*
- *ETH Zürich, Switzerland*
- *GFZ (GeoForschungsZentrum Potsdam, Germany)*
- *GRGS (Group de Recherche de Géodésie Spatial, France)*
- *GSFC (Goddard Space Flight Center, USA)*
- *IfE (Institut für Erdmessung, University of Hannover, Germany)*
- *IGN (Institut National de l'Information Géographique en Forestièr, France)*
- *JCET (Joint Center for Earth Systems Technology, USA)*
- *JPL (Jet Propulsion Laboratory, USA)*
- *NMA (Norwegian Mapping Authority)*
- *TU Berlin, Germany*
- *TU München, Germany*
- *TU Wien, Austria*

Activities and publications during the period 2015-2017

The terrestrial reference frame (TRF) is the foundation for virtually all space-based and ground-based Earth observations. Positions of objects are determined within an underlying TRF and the accuracy with which objects can be positioned ultimately depends on the accuracy of the reference frame. In order to meet the anticipated future needs of science and society GGOS has determined that the accuracy and stability of the ITRF needs to be better than 1mm and 0.1mm/y, respectively. The current ITRF is at least an order of magnitude less accurate and stable than these goals. Further improvements of the ITRF are thought to be achieved by:
- Developing next generation space-geodetic stations with improved technology and system performance;
- Improving the ground network configuration in view of global coverage and co-locations;
- Improving the number and accuracy of surveys between co-located stations;
- Deploying, improving and optimizing space-based co-locations.

This joint working group aids these activities and helps to evaluate the impact on the accuracy and stability of future ITRFs. To this purpose a variety of aspects related to design of ground- and space-based architectures of measurement systems and their impact on TRF accuracy and stability are investigated. WG members develop improved analysis methods using all existing data and co-locations and carry out extensive simulations for future improvements and optimization of ground network, space segment and observation scenarios.

Organization

At the meeting of the GGOS Bureau of Networks and Observations during the EGU General Assembly in April 2016 it was decided that PLATO will be a "Standing Committee" in the GGOS framework in order to allow studies on a time frame extending the usual duration of working groups. In the IAG structure 2015-2019 PLATO acts also as an IAG Joint Working Group in IAG Sub-Commission 1.1 in order to establish a link for the study and assessment of co-locations in space as a very relevant topic in the context of coordination of space geodetic techniques. This report overlaps with the corresponding Traveaux report for the GGOS Bureau of Networks and Observations.

In June 2016 Richard Gross (JPL) who co-chaired PLATO since 2013 handed over the co-chair to Benjamin Männel (GFZ).

Members of PLATO are informed about ongoing and planned activities with a newsletter.

1. Meetings

In regular meetings WG members report about the progress of the work related to PLATO including performed and planned studies, results from simulations and analysis of real data and the results of the groups are compared:

- Thursday, April 16, 2015, at TU Vienna during the EGU General Assembly
- Thursday, April 21, 2016, at TU Vienna during the EGU General Assembly
- Thursday, April 27, 2017, at TU Vienna during the EGU General Assembly

2. Achievements

Several members were successful in acquiring funding for simulation studies (DGFI-TUM, AIUB, TU Vienna, GFZ). Several geodetic software packages have been augmented by the capability to carry out realistic simulation scenarios (VieVS, DOGS, Bernese, Geodyn). The following sections give information on achievements related to specific areas.

SLR Simulations

Simulations for improved global SLR station networks were carried out. Simulations for an SLR station in Antarctica (Syowa, co-located with VLBI) showed the benefit for geocenter parameter determination. Simulations for improved SLR tracking of GNSS satellites started.

LLR Simulations

Simulations related to more LLR data assuming millimeter ranging accuracies (up to three future single-prism reflectors on the moon and two additional LLR sites on the southern hemisphere) were carried out. The effect on the lunar reflector coordinates, the mass of the Earth-Moon system and two relativistic parameters (temporal variation of the gravitational constant and equivalence principle) were studied. Especially, the measurements to the new type of reflectors would lead to an improved accuracy of the estimated parameters up to a factor of 6 over a decade of new measurements.

VLBI Simulations

Simulations (and analysis of data as far as available) for new VGOS telescopes employing next generation broadband VLBI technology, showed that the GGOS requirements of 1 mm accuracy and 0.1 mm/year stability will likely be fulfilled for the reference frame. Simulations and analysis of VLBI tracking data of GNSS satellites and the Chinese APOD cube-satellite (i.e. using co-locations in space) were carried out using the Australian VLBI antennas for several sessions during 2016.

Local Ties

The impact of the Local ties on the reference frame products was studied regarding different stochastic models of the LT, selection of the LT, and the impact of systematically wrong LT. It was shown that the LT standard deviations of 1 mm or better lead to the best datum realization of an SLR+VLBI-TRF. Simulating wrong LT indicate Wettzell, Badary and AGGO as important LT sites in the SLR and VLBI combination.

E-GRASP/Eratosthenes

PLATO members were actively participating in the preparation of the E-GRASP/Eratosthenes proposal lead by Richard Biancale. The proposal was submitted in 2016 in response of the ESA Earth Explorer-9 call. After good scientific assessment by ESA a revised version of the proposal was submitted to the 2017 EE9 call. The satellite mission proposed co-locates all fundamental space-based geodetic instruments, including GNSS and DORIS receivers, laser retro-reflectors, and a VLBI transmitter on the same satellite platform on a highly eccentric orbit with particular attention on the time and space metrology on board.

A variety of simulations were performed by PLATO members both for discriminating the best orbital scenario according to many geometric/technical/physical criteria and for assessing the expected performances on the TRF according to GGOS goals.

3. Future Plans

Future plans include the examination of trade-off options for station deployment and closure, technology upgrades, impact of site ties, etc. Simulation studies related to ground infrastructure are planned to assess the impact on reference frame products of network configuration, system performance, technique and technology mix, co-location conditions, site ties while simulation studies related to space infrastructure are planned to assess impact on reference frame products of: co-location in space, space ties, and available satellites.

Work to project future network capability over the next 5 and 10 year periods using projected network configuration in new system implementation will be performed. Improved analysis methods for reference frame products by including all existing data and available co-locations will be developed and analysis campaign with exchanged simulated observations.

A status reports will be given at the IAG Scientific Assembly (July 2017), GGOS days (October 2017) and REFAG Meeting (autumn 2018). Annual meetings are foreseen in conjunction with the EGU General Assemblies.

4. Conferences

PLATO is present at the main geodetic conferences. Presentation were given at the IGS Workshop in Sydney in Feb. 2017, IVS General Meeting in Johannesburg in March 2016, the EGU General Assembly in Vienna in April 2015 and April 2016, the IUGG General Assembly in July 2015, the ILRS Workshop in Potsdam in October 2016, at the AGU Fall Meeting in San Francisco in December 2016.

A presentation is planned at the upcoming IAG Scientific Assembly July, 30 - August 4, 2017 in Kobe, Japan with title “The GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO)” highlighting results of ongoing studies and giving first recommendations.

5. Publications

Ampatzidis D, König R, Glaser S, Schuh H (2016), The Assessment of the Temporal Evolution of Space Geodetic Terrestrial Reference Frames, IAG Symposia Series, DOI 10.1007/1345_2016_251

Glaser S, Ampatzidis D, König R, Nilsson T, Heinkelmann R, Flechner F, Schuh H (2016), Simulation of VLBI Observations to Determine a Global TRF for GGOS, IAG Symposia Series, DOI 10.1007/1345_2016_256

Glaser S, König R, Ampatzidis D, Nilsson T, Heinkelmann R, Flechner F, Schuh H (2017), A Global Terrestrial Reference Frame from simulated VLBI and SLR data in view of GGOS, Journal of Geodesy, DOI 10.1007/s00190-017-1021-2

Plank L, Hellerschmied A, McCallum J, Böhm J, Lovell J (2017), VLBI observations of GNSS satellites: from scheduling to analysis. J Geod, Springer, doi: 10.1007/s00190-016-0992-8

Schuh H, König R, Ampatzidis D, Glaser S, Flechtner F, Heinkelmann R, Nilsson T (2016), GGOS-SIM – Simulation of the Reference Frame for the Global Geodetic Observing System, IAG Symposia Series, DOI 10.1007/1345_2015_217

Sub-commission 1.2: Global Reference Frames

Chair: *X. Collilieux (France)*

Overview

Sub-commission 1.2 focuses its activity on the definition and realization of the terrestrial reference system (TRS). Since 2016, it includes the link to world height system (WHS). It studies fundamental questions and more practical aspects that can improve current terrestrial reference frame (TRF) determinations.

Numerous activities are actually realized in other IAG-related structures, namely:
- Sub-commission 1.3 on "Regional reference frames", including EUREF, SIRGAS…
- International Earth Rotation and Reference Systems Service (IERS)
- Other relevant IAG services (IGS, ILRS, IVS, IDS)
- IAG Global Geodetic Observing System (GGOS)
- Inter-Commission Committee on Theory.

We therefore encourage the reader to refer to their individual reports.

At first, this report highlights recent work with respect to the relativistic modelling of reference frames. Then, it presents the ITRF2014, the latest realization of the International Terrestrial Reference System (ITRS), which is published by the International Earth Rotation and Reference Systems Service (IERS) and represents the state of the art of current TRS realizations. It provides coordinates of a set of points at the Earth and delivered in a self-consistent Terrestrial Reference Frame with their variance-covariance information. Those are computed for more than 35 years of observations from the four space geodetic techniques, namely: DORIS, GNSS, SLR and VLBI. The report also presents the work of the IERS combination centres which conduct researches on Terrestrial Reference Frame determination. Whereas vertical coordinate reference systems were realized at the continental scale up to now, work is underway to realize a world height system. This activity is summarized in this report. Such a realization should be interoperable and consistent with the current geometric determination of the Terrestrial Reference System. Recent research on local ties and space ties, with a special highlight on the E-GRASP/Eratosthenes mission proposal are then summarized. Finally, ongoing work on ISO standardization and conventions is summarized.

WG 1.2.1 "Offset Detection in Geodetic Coordinate Time series" of sub-commission 1.2 that was created in 2015 (Drewes et al., 2015) will not be continued in 2017-2019. It is ended due to lack of activity.

Summary of the Sub-commission's activities during the period 2015-2017

Contributors to this report:

- *Z. Altamimi*
- *R. Biancale*
- *C. Boucher*
- *X. Collilieux (president)*
- *P. Delva*
- *L. Sanchez*
- *M. Seitz*
- *D. Thaller*
- *S. Williams*

Relativistic modelling

Relativistic reference frames are based on a network of clocks in space linked with time transfer technologies. Such realized frames are entirely decoupled from ground fixed stations and could be used to reference any point on the Earth's surface.

Recent work by Kostić et al. (2015) is worth reporting here. They have presented a new method for implementing a relativistic positioning system with a GNSS. The spacetime metric is described with a perturbed Schwarzschild metric, while the dynamics is completely solved using a first order perturbation approach, including perturbations due to Earth multipoles (up to the 6th), the Moon, the Sun, Venus, Jupiter, solid tide, ocean tide, and Kerr rotation effect. The authors find that positioning in this perturbed spacetime is highly accurate and time efficient already with standard numerical procedures and laptop.

Within IAG, relativistic modelling is investigated in JWG 2.3 "Relativistic Geodesy: First Steps Towards a New Geodetic Technique". See their report for more details.

ITRS Center and ITRF2014

Overview

The main activities of the ITRS Centre during the period 2015-2017 include the maintenance of the ITRF network, database and website. The full report is available in the report of the ITRS centre in the IERS section of the travaux. Main points are summarized in the following.

Activities and publications during the period 2015-2017

The main activities of the ITRS Centre related to research analysis during this period include:

- The ITRS Product Centre collects all new surveys operated by either Institut National de l'Information Géographique et Forestière (IGN) or the hosting agencies of ITRF co-location sites. At the occasion of the ITRF2014 analysis, several new local tie SINEX files and corresponding reports were submitted to the ITRS Centre. These new survey results were made available via the ITRF website after the release of the ITRF2014.
- The operational entity of the ITRS Centre at the IGN Survey department has prepared a document describing the IGN current practice of local survey that could help surveyors who do not know how to proceed and are not used with mm precision. The document is in its final stage and will be published in a dedicated IERS Technical Note.

Publication of ITRF2014:

- During the preparation of ITRF2014, various tests and combined coordinate sets have been processed by IERS combination centers (see below).
- The final ITRF2014 solution was published in January 2016, with a dedicated website: <http://itrf.ign.fr/ITRF_solutions/2014/>.
- A full ITRF2014 article was published in Journal of Geophysical Research (Altamimi et al., 2016).
- The ITRF2014 is available for download at the dedicated website: <http://itrf.ign.fr/ITRF_solutions/2014/>.

The ITRF2014 is an improved realization of the International Terrestrial Reference System (ITRS) and is demonstrated to be of higher quality than the past ITRF versions. It involves two main innovations dealing with the modelling of station non-linear motions, namely seasonal (annual and semi-annual) signals present in the time series of station positions and post-seismic deformations for 124 sites that were subject to major earthquakes. In order to illustrate the performance of the modelling of the non-linear station motions, figure 1.2.1 shows, as an example, the trajectory of Tsukuba (Japan) site after the Tohoku earthquake, where GNSS and VLBI instruments are co-located. The Post-Seismic Deformation parametric model fitted to the GPS data was then applied to the VLBI time series. Figure 1.2.1 illustrates the de-trended residuals of both stations, after removing the linear velocity and annual and semi-annual signals.

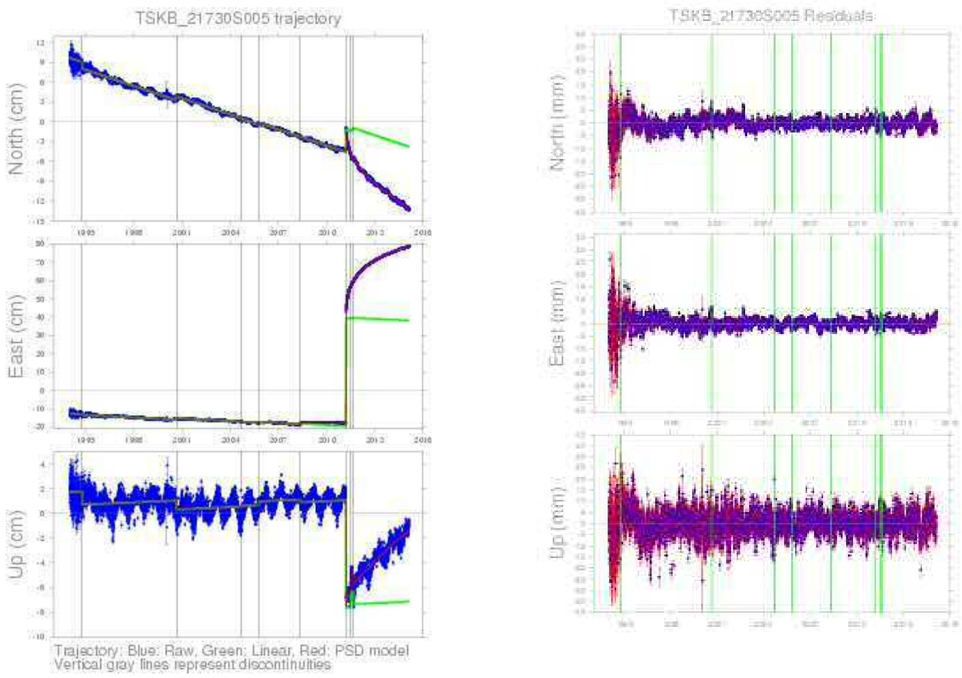

Fig. 1.2.1 Left: Site trajectory of Tsukuba (Japan), GNSS. Right: De-trended residuals of Tsukuba (Japan), GNSS

IERS Combination Center

The report of the IERS components can be found in the IAG report. Relevant components of the report are summarized in this document since they are related to Terrestrial Reference Frame computation strategy that is a field of research.

IERS Combination Center: DGFI

Deutsches Geodätisches Forschungsinstitut - Technische Universität München (DGFI-TUM) is acting as one of the ITRS Combination Centers within the IERS since 2001.

DGFI-TUM's latest realization of the ITRS is the DTRF2014. The DTRF2014 is an independent realization of the ITRS based on the same input data as the realizations ITRF2014 and JTRF2014 (see section IERS combination center: JPL). While the ITRF2014 is based on the combination of solutions, the DTRF2014 is computed by the combination of normal equations. DTRF2014 is the first ITRS realization corrected for non-tidal atmospheric and hydrological loading. However, all information to reconstruct the real station positions at each observation epoch is delivered. DTRF2014 is available for download at <http://www.dgfi.tum.de/en/science-data-products/dtrf2014/>. In addition to this work, the impact of the combination of station coordinates on the ICRS realization was object of new research.

IERS Combination Center: IGN

The members of the IGN Combination Center, often in cooperation with other scientists, conduct research and developments activities relating to the ITRF in particular and reference frames in general. R&D activities include ITRF accuracy evaluation, mean sea level, loading effects, combination strategies, and maintenance and update of CATREF software. Main contributions are report below:

- Specific new developments were achieved and validated in preparation for the ITRF2014: CATREF software was enhanced and upgraded to include periodic terms of the station position time series, such as in particular annual, semi-annual terms for all techniques and draconitic signals for satellite techniques, especially GNSS.
- Other developments were also finalized and validated, such as modelling of post-seismic deformations for sites affected by major Earthquakes, as well as an improved strategy for the detection of discontinuities in the technique station position time series.
- First and early results of the ITRF2014 input data analysis were presented at various conferences in 2015.
- A preliminary ITRF2014 solution called ITRF2014P was generated and submitted on September 09, 2015 to the Technique Centers of the four techniques for evaluation. A certain number of feedbacks were then received and all concerns were answered and taken into account for the final ITRF2014 solution.

IERS Combination Center: JPL

Jet Propulsion Laboratory (JPL) has developed a new methodology to provide Terrestrial Reference Frames at a weekly basis (Wu et al., 2015). It is based on a Kalman smoother that estimate time series of station positions and EOPs of the geodetic stations from the four space geodetic techniques. It allows modelling station position as stochastic processes and thus to model more complex ground displacement types.

Based on ITRF2014 input data, JPL has processed its combined terrestrial Reference Frame called JTRF2014. It is based on time series of station positions series of 972 stations instead of station positions and velocities as provided in ITRF2014. Research has been conducted to:

- Weight individual technique data
- Estimate station position stochastic process properties
- Detect discontinuities

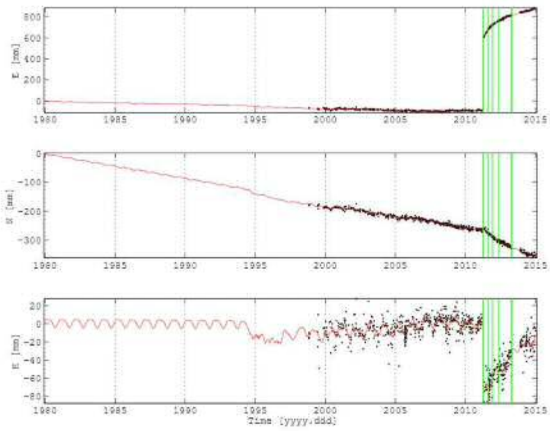

Fig. 1.2.2 (from Gross et al. 2015) Observed (black dots) and Kalman-smoothed, interpolated, and extrapolated (red line) position of the VLBI station at Tsukuba, Japan. The vertical green lines indicate the epochs of discontinuities in the observed position of the station. The east, north, and height (or up) component of the station's position are shown in the top, middle, and bottom panels, respectively.

Link to gravity

The JWG 0.1.2 "Strategy for the Realization of the International Height Reference System (IHRS)" is working on specifying the International Height Reference System. The working group has first focused on the selection criteria for the reference stations of the network. Among them, reference stations should be co-located with current ITRF and regional reference frame stations and tide gauges. The determination process of the potential at those sites is under discussion and a first list of stations proposed. More details can be found in the JWG 0.1.2 report.

Local ties

At co-location sites where several technique instruments are operating, the relative positions of the instrument reference points need to be known. They are called local tie vectors. Those are indispensable datasets for deriving and validating a Terrestrial Reference Frame. It is fundamental to support research for local tie determination to reach a 1-mm accuracy monitoring of the local tie vectors. Communication on the best practices for determining local tie vectors is also of the outmost importance since the determination of a local tie vector is an expensive task. As mentioned above in the ITRS center report, a new IERS technical note is being published to report the procedures that have been defined at IGN France for surveying co-location sites. The research activity related to the derivation of local tie vectors is summarized in the JWG 1.1 Joint Working Group on "Site Survey and co-location" report.

Space ties

Up to now, Terrestrial Reference Frames are computed from separate technique coordinate sets and terrestrial local ties. However, the position of satellites that carry several positioning sensors (laser reflectors, GNSS antenna, DORIS antenna) can be determining by a simultaneous computation using all available data. In this case, the relative positions of the instruments on board of the satellites (determined using measurement or known a priori) plays the role of a space tie in a Terrestrial Reference Frame processing at the observation level.
This issue is discussed in the JWG 1.1.3 named "Performance Simulations and Architectural Trade-Offs (PLATO)". During the two first years, the working group has conducted several studies based on simulated data to show the impact of including VLBI measurements on satellites, the effect for an improved SLR tracking to GNSS satellites and the interest of improving the SLR tracking network configuration. Please refer to the report of the working group for more details and references.

E-GRASP/Eratosthenes mission

The IAG sub-commission 1.2 is in favor of a dedicated satellite mission that would carry all space geodetic techniques in order to improve the determination of the Terrestrial Reference Frame. Thus, the IAG sub-commission 1.2 supports the E-GRASP/Eratosthenes (European-Geodetic Reference Antenna in Space, hereafter named E-GRASP) mission proposal. This proposal aims at realizing the terrestrial reference system with an accuracy of 1 mm and a long-term stability of 0.1 mm/yr.
The satellite platform is to be considered as a dynamic space geodetic observatory that carries all these geodetic instruments. It aims at being well-calibrated. In this way, one can determine all the instrumental biases inherent to the different observing techniques simultaneously. All of these instruments will be referenced to one another on a single orbiting platform through a unique and very precise clock such a mini-Passive Hydrogen Maser (mPHM). Moreover, a laser

detector allows for a high precision synchronization of the on-board mPHM with ground clocks through very short laser ranging pulses. The mPHM will be monitored using a time transfer by laser link (T2L2) from ground stations to that on-board detector. The payload will incorporate a new version of the T2L2 instrument (previously flown on Jason-2), which will provide users with a common view, time transfer technique, accurate at intercontinental scales. An electrostatic micro-accelerometer will be incorporated 1) to guarantee high precision orbit determination and mitigating the errors mapping into the modeling of non-conservative forces, 2) to allow in orbit center of mass determination. Another role of this accelerometer will be to serve as a position reference for the geodetic instruments on the platform in order to determine the correction of angular motion between each instrument.
A mission duration of 5 years is expected with a possible extension. The orbit choice for the platform is tending towards a quite eccentric orbit, that aims to maximize observability by the various instruments and that offers perspectives for secondary mission objectives, for instance determining relativistic parameters in fundamental physics.

ISO standardization

The standardization activity related to Terrestrial Reference Frames is studied in the GGOS Working Group "ITRS Standards for ISO TC 211", see the report of GGOS “Bureau of Products and Standards”. The group is presently working on a draft of the ISO TC211/19161-1 standard (presently version 1 5).

Link to conventions

The new Terrestrial Reference Frame features will be integrated into the IERS conventions during the next two years 2017-2019.

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Sub-commission 1.3: Regional Reference Frames

Chair: *Carine Bruyninx (Belgium)*

Overview

Sub-commission 1.3 contains six regional Sub-Commissions (SC)
- Sub-Commission 1.3a: Europe
- Sub-Commission 1.3b: South and Central America
- Sub-Commission 1.3c: North America
- Sub-Commission 1.3d: Africa
- Sub-Commission 1.3e: Asia-Pacific
- Sub-Commission 1.3f: Antarctica

and one Working Group (WG) "Time-dependent transformations between reference frames".

This mid-term report gathers the contributions of the above regional sub-commissions and WG for the period 2015-2017. As stated in the Terms of Reference, IAG Sub-commission SC1.3 deals with the definitions and realizations of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF). It offers a home for service-like activities addressing theoretical and technical key common issues of interest to regional organizations.

In addition to the specific objectives of each regional Sub-commission, the main objectives of SC1.3 as a whole are to:
- Coordinate the activities of the regional Sub-commissions focusing on exchange of data, competences and results;
- Promote operation of permanent GNSS stations, in connection with IGS whenever appropriate, as the basis for the long-term maintenance of regional reference frames;
- Promote open access to the GNSS data from permanent GNSS stations used for the maintenance of regional reference frames and scientific applications;
- Develop specifications for the definition and realization of regional reference frames, including the vertical component with a special consideration of gravity and other data;
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations;
- Encourage and assist countries, within each regional Sub-commission, to re-define and modernize their national geodetic systems, compatible with the ITRF;
- Support the initiatives of the GGRF (Global Geodetic Reference Frame) WG of the UN-GGIM (United Nations Initiative on Global Geospatial Information Management).

The reports of all regional sub-commissions and the WG are presented hereafter.

Sub-commission 1.3a: Europe (EUREF)

Chair: Markku Poutanen (Finland)

Introduction and structure

The long-term objective of EUREF, as defined in its Terms of Reference is "the definition, realization and maintenance of the European Reference Systems, in close cooperation with the pertinent IAG components (Services, Commissions, and Inter-Commission projects) as well as EuroGeographics". For more information, see http://www.euref.eu.

The results and recommendations issued by the EUREF sub-commission support the use of the European Reference Systems in all scientific and practical activities related to precise geo-referencing and navigation, Earth sciences research and multi-disciplinary applications. EUREF applies the most accurate and reliable terrestrial and space-borne geodetic techniques available, and develops the necessary scientific principles and methodology. Its activities are focused on a continuous innovation and on evolving user needs, as well as on the maintenance of an active network of people and organizations, and may be summarized as follows:

- Maintenance of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) and upgrade of the respective realizations;
- Refining the EUREF Permanent Network (EPN) in close cooperation with the International GNSS Service (IGS);
- Improvement of the European Vertical Reference System (EVRS);
- Contribution to the IAG Project GGOS (Global Geodetic Observing System) using the installed infrastructures managed by the EUREF members.

These activities are reported and discussed at the meetings of the EUREF Technical Working Group (TWG), which take place three times a year, and the annual EUREF Symposia, an event that occurs every year since 1990. The EUREF symposia have an attendance of about 100-120 participants from more than 30 European countries and other continents, representing Universities, Research Centers, and NMCAs (National Mapping and Cadaster Agencies). EuroGeographics (the consortium of the European NMCAs) supports the organization of the EUREF Symposia, reflecting the importance of EUREF for practical purposes.
The latest EUREF symposia took place in Leipzig, Germany (2015), San Sebastian, Spain (2016) and Wroclaw, Poland (2017).

TWG Members

- *E. Brockmann (Switzerland)*
- *C. Bruyninx (Belgium)*
- *R. Dach (Switzerland)*
- *J. Dousa (Czech Republic)*
- *R. Fernandes (Portugal)*
- *H. Habrich (Germany)*
- *Kenyeres (TWG chair)*
- *M. Lidberg (Sweden)*
- *T. Liwosz (Poland)*
- *M. Poutanen (Finland, EUREF chair, ex-officio)*
- *R. Pacione (Italy)*
- *G. Stangl (Austria)*
- *W. Söhne (Germany, EUREF secretary, ex-officio)*

Z. Altamimi (France), *A. Caporali (Italy)*, *J. Ihde (Germany)* and *J. Torres (Portugal)* are regularly participating to the TWG meetings as honorary members.
A. Araszkiewicz (Poland) and *C. Völksen (Germany)* are regularly participating to the TWG meetings as invited guest and Working Group chair, resp.

Activities during the period 2015-2017

Most of the activities covering the European GNSS Network (EPN) are reported on an annual basis in the Technical Reports of the International GNSS Service (IGS). In addition to the overview and summary given here, see Bruyninx et al. (2015) and Bruyninx et al. (2016) for more details.

EUREF Permanent GNSS Network (EPN) – Tracking Network, Network Coordination, EPN Central Bureau

Over the last two years, the number of permanent GNSS tracking stations in Europe belonging to the European Permanent Network (EPN) was growing from 265 by mid-2015 to 318 by mid-2017 (see Fig. 1.3a.1). The number of sites recording GLONASS data simultaneously to GPS data was significantly increasing from 70 % by mid-2015 to 90 % by mid-2017. One focus was on the upgrade of the EPN towards a multi-GNSS network. By mid-2017, 142 stations (45 %) are recording Galileo data. Moreover, 96 stations and 8 stations are recording the BeiDou constellation and the QZSS, resp.

In November 2016, the EPN CB launched a completely revised version of the web portal. The navigation was rearranged; the portfolio was streamlined to remove old and no longer used items. Moreover, the access was made more flexible to be used also with modern equipment like, e.g., smartphones and tablets.

The EUREF Regional Data Centre (RDC) and the Analysis Centre (AC) at OLG in Austria are going to be shut down in 2017. Therefore, in 2016 the Austrian colleagues started to build up a new RDC and a new AC at BEV in parallel to the existing structure.

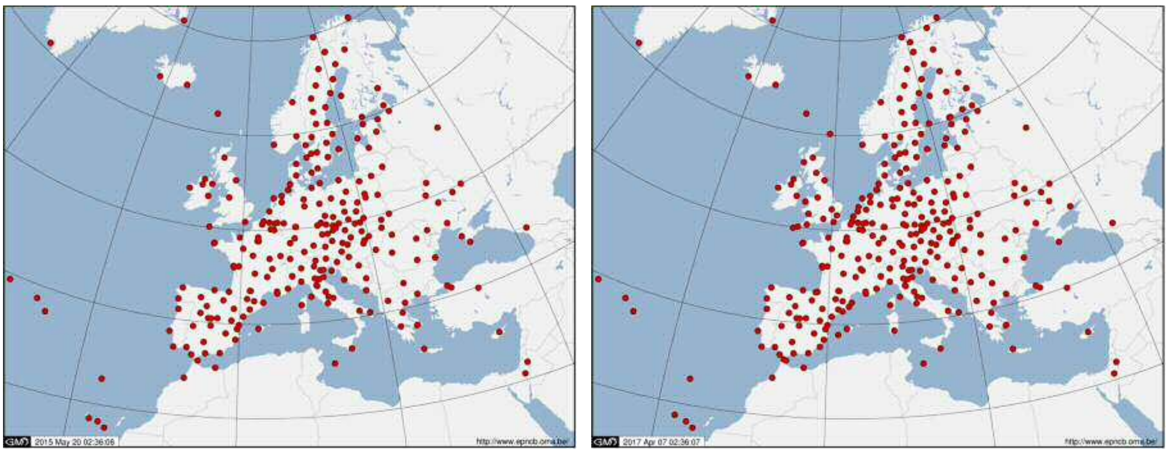

Figure 1.3a.1: EUREF Permanent GNSS Network (EPN), status May 2015 (left) and April 2017.

During the period, the first EPN stations started providing real-time data in RTCM 3.2 format. In addition to GPS and GLONASS, most of the streams contain Galileo, BeiDou, QZSS and SBAS. The monitoring of the three EUREF broadcasters at the EPN CB was extended. In addition to the RTCM 2 and 3.1 format, also the RTCM 3.2 data stream content is now verified against the proposed content of the sourcetable.

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EUREF Working Groups – Multi-GNSS WG, Deformation Modelling WG, EPN Densification WG, Reprocessing WG

Thanks to the effort of the Multi-GNSS WG and the EPN CB, the number of stations submitting RINEX 3 files to the EPN was increasing to more than 1/3. In addition, the use of long RINEX filenames increased significantly. In 2016, the first EPN Analysis Center (LPT, Swisstopo) started processing Galileo and BeiDou data in addition to GPS and GLONASS on a routine basis.

The EPN densification project is combining weekly SINEX solutions provided by European countries for their dense national active GNSS networks with the weekly EPN SINEX solutions, resulting in a cumulative position and velocity solution for more than 3000 stations.

The second reprocessing of the EPN, Repro-2, was finalized in 2016. Covering the period 1996 to 2014, five analysis centers (ACs) were contributing. Three ACs processed the complete EPN using three different software packages (BSW 5.2, GAMIT 10.5 and GIPSY 6.2), two ACs processed large subnetworks with BSW5.2. The Analysis Centre and the Troposphere Coordinators respectively carried out the combinations. The combination results for coordinates as well as for troposphere parameters are the basis for the new accumulated EPN solutions.

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European Vertical Reference System (EVRS)

The last realization of the European Vertical Reference System (EVRS) has been released 2008 under the name EVRF2007. At the EUREF symposium June 2008 in Brussels, Resolution No. 3 was approved proposing to the European Commission the adoption of the EVRF2007 as the mandatory vertical reference for pan-European geo-information. EVRF2007 is based on the measurements of the Unified European Leveling Network (UELN). The datum is realized by 13 datum points distributed evenly over the stable part of Europe. The measurements have been reduced to the common epoch 2000 by applying corrections for the glacial isostatic adjustment (land uplift) in Fenno-Scandinavia, which are provided by the Nordic Geodetic Commission (NKG) under the name NKG2005LU.

In the meantime, UELN is continuously enhanced using additional or updated levelling data submitted by different countries (Fig. 1.3a.2). Since 2015, the network parts of Germany and Switzerland have been replaced by new measured leveling data. Also in 2015, the French scientific zero-order leveling network NIREF has been integrated in the UELN. NIREF was observed between 1983 and 2014 and is much more precise than IGN69 data, but not dense enough to replace completely these old data in UELN. Therefore, both networks were combined. Because of a known bias in the North-South direction, the data of IGN69 were introduced with lower weights than NIREF data. The including of NIREF data in UELN allowed the first time to integrate the height difference between France and UK that had been measured through the Channel tunnel in 1994. Using the NIREF data and the tunnel measurement the computed UELN height in Dover (UK) changed by 140 mm.

In 2016, Estonia delivered new leveling data in a very high precision. Furthermore, UELN has been expanded by Belarus, which provided 1st order leveling data at the first time.
For the next time a new data set of Italy is expected. Moreover, the enlargement of the UELN by the network of Ukraine is planned.

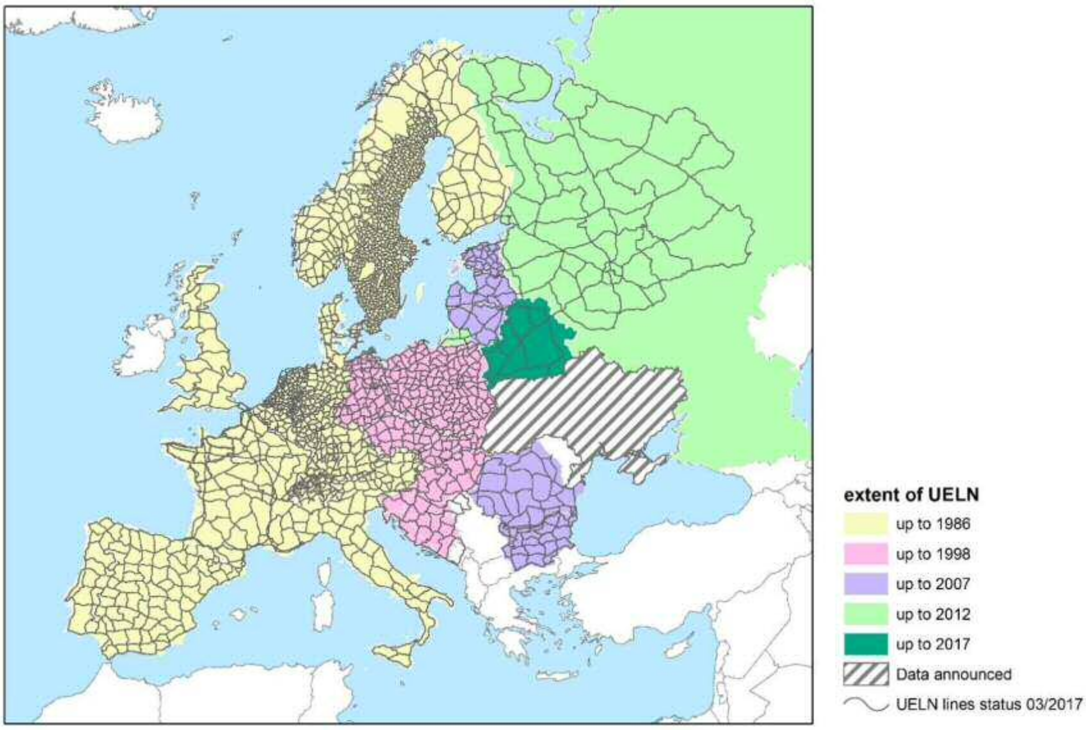

Figure 1.3a.2: Expansion of the Unified European Leveling Network (UELN)

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Revision of EUREF terms of reference

During 2015 and 2016, the EUREF Terms of Reference (ToR) have been updated, discussed in EUREF 2015 and 2016 symposia, as well as during the TWG meetings. The ToR have been adopted in the EUREF 2017 symposium in Wroclaw.

Outreach and capacity building

EUREF organized the following meetings

EUREF Technical Working Group (TWG) meetings:

- March, 23-24, 2015, in Warsaw, Poland, hosted by MUT (Military Technical University)
- June, 1-2, 2015, in Leipzig, Germany, hosted by BKG (Federal Agency for Cartography and Geodesy)
- October, 13, 2015, in Bern, Switzerland, hosted by AIUB (Astronomical Institute of the University of Bern)
- Feb, 29 - March, 1, 2016, in Lisbon, Portugal, hosted by IPMA (Instituto Português do Mar e Atmosfera)
- May, 23, 2016, in San Sebastian, Spain, hosted by ARANZADI (Sociedad de Ciencias Aranzadi)
- October, 20-21, 2016, in Vienna, Austria, hosted by BEV (Bundesamt für Eich- und Vermessungswesen)

EUREF Annual Symposia:

- June, 3-5, 2015, in Leipzig, Germany (approx. 110 participants from 33 countries)
- May, 25-27, 2016, in San Sebastian, Spain (approx. 95 participants from 28 countries, see Fig. 1.3a.3)
- May 15-17, 2017, in Wroclaw, Poland (approx. 100 participants)

EUREF Analysis Workshop:

- October, 14-15, 2015, in Bern, Switzerland, AIUB (Astronomical Institute of the University of Bern)

EUREF Tutorials:

- June, 2, 2015, in Leipzig, Germany (approx. 65 participants)
- May, 24, 2016, in San Sebastian, Spain (approx. 60 participants)
- May, 16, 2017, in Wroclaw, Poland (approx. 45 participants)

Figure 1.3a.3: Participants of the EUREF 2016 Symposium in San Sebastian, Spain

EUREF also cooperated with other organizations. The TWG members Z. Altamimi and M. Poutanen are participating on the work of UN GGRF, a permanent UN sub-committee on geodesy. The writing team is creating the working plan, based on the roadmap accepted in 2016, and the UN General Assembly resolution in 2015 on sustainable global geodetic reference frame. M. Poutanen is chairing the UN-GGIM: Europe special expert group “GRF-Europe”.

The European Plate Observing System (EPOS) is going to approach the end of the Implementation Phase. EUREF’s activities, e.g. the EPN and the combined solutions, are identified to be part of Work Package 10 “GNSS Data and Products” and, therefore, EUREF has been engaged in the preparation of the Operational Phase, which should start in 2019.

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Sub-Commission 1.3b: South and Central America (SIRGAS)

Chair: *William Martinez (Colombia)*
Vice-chair: *Virginia Mackern (Argentina)*

Introduction and structure

SIRGAS is the Geocentric Reference System for the Americas. Its definition corresponds to the International Terrestrial Reference System (ITRS) and it is realized by a regional densification of the International Terrestrial Reference Frame (ITRF). SIRGAS includes the definition and realization of a vertical reference system, based on ellipsoidal heights as geometrical component and geopotential numbers (referred to a global conventional W_0 value) as physical component.

SIRGAS is a member of the Sub-Commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of the IAG (International Association of Geodesy) and corresponds to a Working Group of the Cartography Commission of the PAIGH (Pan-American Institute for Geography and History). The administrative issues are managed by a Executive Committee, which depends on the Directing Council, main body of the organization. The official policies and recommendations of SIRGAS are approved and given by the Directing Council. Since this Council is composed by one representative of each member country, one of IAG and one of PAIGH, it is also in charge of communicating the SIRGAS recommendations to the national bodies responsible for the local geodetic reference systems. The scientific and technical activities are coordinated by the Working Groups in close cooperation with the Scientific Council and the representatives of IAG and PAIGH.

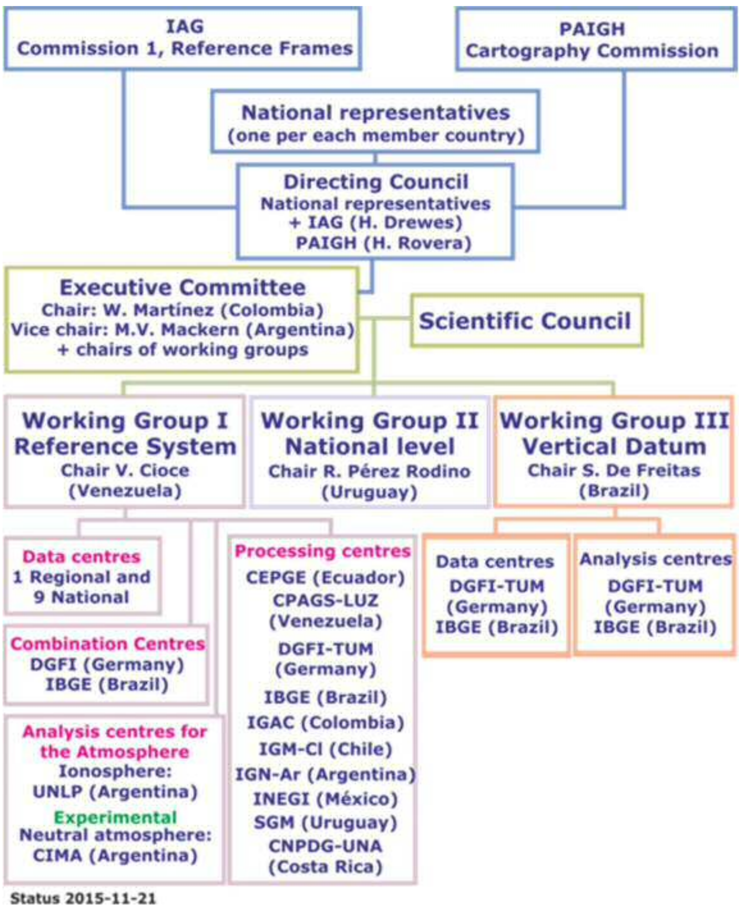

Figure 1.3b.1: SIRGAS structure

Members

Executive committee

- *William Alberto Martínez Díaz, President (Colombia)*
- *María Virginia Mackern Oberti, Vicepresident (Argentina)*
- *Víctor Cioce, SIRGAS-WI Chair (Venezuela)*
- *Roberto Pérez Rodino, SIRGAS-WGII Chair (Uruguay)*
- *Silvio Rogerio Correia De Freitas, SIRGAS-WGIII Chair (Brazil)*

Directing Council

- *Hermann Drewes, Representative of IAG*
- *Hector Carlos Rovera Di Landro, Representative of PAIGH*
- *Andres F. Zakrajsek; Juan Francisco Moirano (Argentina)*
- *Arturo Echalar Rivera; Mario Sandoval Nava (Bolivia)*
- *Luiz Paulo Souto Fortes; Sonia Maria Alves Costa (Brazil)*
- *Cristian Iturriaga Sáez; Hector Parra Bravo (Chile)*
- *Jose Ricardo Guevara Lima; Francisco Javier Mora Torres (Colombia)*
- *Max Lobo Hernández; Álvaro Álvarez Calderón (Costa Rica)*
- *Jose Gustavo Rodríguez Mejía; Eugenio Leopoldo Taveras Polanco (Dominican Republic)*
- *Carlos Manuel Estrella Paredes; Guillermo Freire (Ecuador)*
- *Carlos Enrique Figueroa; Wilfredo Amaya Zelaya (El Salvador)*
- *Óscar Cruz Ramos; Fernando Oroxan Sandoval (Guatemala)*
- *Rene Duesbury; Hilton Cheong (Guyana)*
- *Bruno Garayt; Alain Harmel (French Guyana)*
- *Luis Alberto Cruz (Honduras)*
- *Raúl Ángel Gómez Moreno (Mexico)*
- *Wilmer Medrano Silva; Ramón Aviles Aburto (Nicaragua)*
- *Israel Sánchez; Javier Cornejo (Panama)*
- *Sindulfo Miguel Colman; Joel Roque Trinidad (Paraguay)*
- *Jesus Vargas Martínez; Julio Sáenz Acuña (Peru)*
- *Norbertino Suárez; Jose Maria Pampillón (Uruguay)*
- *Jose Napoleón Hernández; Melvin Jesús Hoyer Romero (Venezuela)*

Activities during the period 2015-2017

Most important activities

The number of continuously operating GNSS stations included in the SIRGAS-CON network (see Figure 1.3b.2) is composed by 396 active stations of which 83 belong to the IGS global network, 299 have GPS + GLONASS capability, 46 measure on GPS + GLONASS + Galileo and 15 GPS + GLONASS + Galileo + BeiDou.

The SIRGAS-N national networks are computed by nine SIRGAS Local Processing Centers. These processing centers deliver loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. All Analysis Centers follow unified standards for the computation of the loosely constrained solutions.

The support of the countries interested on adopting SIRGAS as their official reference frame continued. At this moment, 19 countries in the region have already adopted SIRGAS as the official reference frame for Geodesy and Cartography. More than 50 institutions from 19 countries, including the national mapping agencies of Latin America, are committed to SIRGAS in a voluntary partnership.

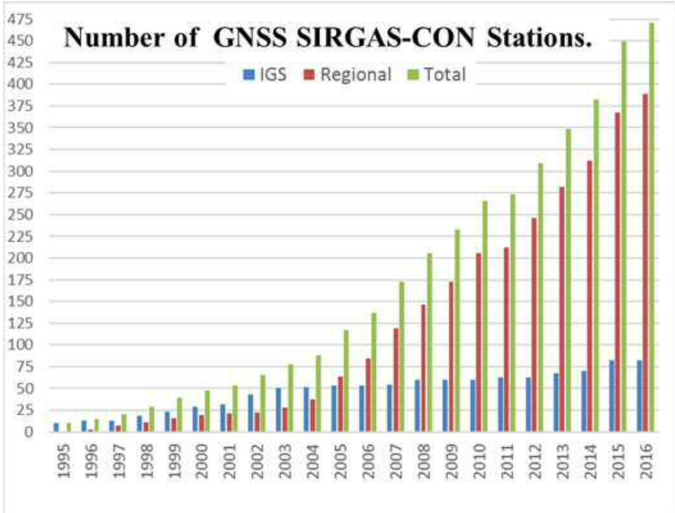

Figure 1.3b.2: Number of GNSS SIRGAS-CON stations

SIRGAS continues its consolidation as the continental reference frame and as the basic layer of spatial data infrastructures national and regional levels.

The SIRGAS-Real Time project advances successfully: Its objectives were achieved and its support to the countries is integrated into the WGII (SIRGAS at the national level).

WGI and WGII recognize the need to adjust the measurement intervals of the permanent stations to 1 second in order to provide more appropriate data for seismological and atmospheric phenomena.

An effort has been made by the countries in the use of SIRGAS products and their infrastructure in the study of seismic and atmospheric activity in the region. Particularly with works related or based on the velocity model VES2015.

SIRGAS continues promoting the activities related to the vertical datum (WGIII) in Central America and invites them to link their permanent stations and to undertake future processing centers in the context of SIRGAS.

Once again, SIRGAS is involved into the most important activities of geodesy through the selection of key national stations and in the future complementary measurements for the materialization of the IHRS in the region, which has been entrusted to the National Representatives and Institutions.

SIRGAS is active in the United Nations GGRF Sub-Committee and will continue participating in the corresponding working groups.

With the SIRGAS 2016 events, progress is made in the implementation of the Join Action Plan signed with PAIGH, UN-GGIM: Americas and GEoSUR for the advance of the regional spatial data infrastructure.

Outreach and capacity building

During the period 2015-2017, SIRGAS organized the following meetings:

- Third WGIII Workshop on processing and adjustment of gravimetric and levelling data corresponding to the national vertical networks. Curitiba, Brazil, May 18-22, 2015. The workshop included five nine-hour sessions with theoretical classes and practical exercises. It was attended by 29 participants from Argentina, Bolivia, Brazil, Chile, Costa Rica, Ecuador, Panama, Peru and Uruguay.
- The Symposium SIRGAS2015 took place in Santo Domingo, Dominican Republic, November 18 to 20, 2015. In the days prior to the Symposium (November 16 and 17), a new edition of the SIRGAS School on Reference Systems was held. Both events were hosted by the Universidad Nacional Pedro Henríquez Ureña (UNPHU). They were supported by the

project "Monitoring crustal deformation and the ionosphere by GPS in the Caribbean" granted by the IUGG in agreement with the International Association of Seismology and Physics of the Earth's Interior (IASPEI), the IAG, and the International Association of Geomagnetism and Aeronomy (IAGA). The Symposium was attended by 148 participants from the same 19 countries. In 54 oral presentations and 15 posters, the following topics were presented: SIRGAS advances and new challenges, maintenance and new perspectives for the continental reference frame, national reference frames, geodetic estimation of geophysical parameters, height systems, gravimetry and geoid, geodetic analysis of the Earth's crust deformation, and practical applications and use of reference frames.

Figure 1.3b.2: Attendees of the Symposium SIRGAS2015

- The SIRGAS School 2015 was attended by 60 participants from 19 countries: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Germany, Guatemala, Haiti, Honduras, Mexico, Monserrat (UK), Panama, Puerto Rico (USA), Uruguay, USA, and Venezuela. The subject of the school concentrated on strengthening the basic concepts needed for the appropriate generation and use of fundamental geodetic and geophysical data in the Caribbean Region, especially for studying, understanding and modelling deformations of the Earth's surface and features of the ionosphere and its influence on navigation systems used for civil aviation.
- The Symposium SIRGAS2016 was held in Quito, Ecuador, between November 16-18, hosted by the Instituto Geográfico Militar of Ecuador, and supported by the IAG and the Pan American Institute of Geography and History (PAIGH). The Symposium was attended by 217 participants, from 14 countries (Germany, Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, United States, Mexico, Panama, Dominican Republic, Uruguay and Venezuela). Fifty-six oral and twelve poster presentations were discussed. Main topics were: maintenance of the continental reference frame (3 presentations); detection and evaluation of geodynamic effects on the reference frame (9 presentations); reports of the analysis and combination centers (5 presentations); studies of the neutral atmosphere (5 presentations); progress in the implementation and maintenance of national frameworks (14 presentations); SIRGAS in real time (6 presentations); aspects of the practical application of SIRGAS products (3 presentations); height systems (11 presentations); gravimetry and geoid (8 presentations) and various reports (4 presentations).
- The SIRGAS Workshop 2016 had as a main objective the unification of the National Vertical Networks in the region of SIRGAS, by means of the processing and adjustments with a view to the realization of continental adjustment based on geopotential numbers. 45 representatives from 10 countries, responsible for the national vertical networks, attended the Workshop: Argentina, Brazil, Chile, Colombia, Costa Rica, Ecuador, Panama, Peru, Dominican Republic and Uruguay).

Figure 1.3b.3: Attendees of the SIRGAS Workshop 2016

SIRGAS participated to the following international conferences in 2015-2016

- European Geosciences Union, General Assembly 2015 (EGU 2015). Vienna, Austria, April 15, 2015.
- International Union of Geodesy and Geophysics, General Assembly 2015 (IUGG2015), Prague, Czech Republic. June 22 - July 2, 2015.
- Fifth Session of the United Nations Committee of Experts on Global Geospatial Information Management. New York, USA. August 3, 2015.
- A glimpse at geodetic activities in Latin America. L.P.S. Fortes. IN: GGOS Days 2016, Cambridge, MA., USA. October 24 - 27, 2016.
- UN-GGIM: Global Geodetic Reference Frame (GGRF) for Sustainable Development. W. Martínez.En: XXII Semana ICG 2016, Universidad Distrital Francisco José de Caldas. Bogotá, Colombia. Octubre 24, 2016.
- Incorporation of the Caribbean to the Geocentric Reference System for the Americas SIRGAS. W. Martínez, M.V. Mackern, V. Cioce, R. Rodino, S.R. De Freitas. In: UN-GGIM: Americas Third Session. Mexico City, Mexico. October 5, 2016.
- Plan de acción conjunto 2016-2020 para acelerar el desarrollo de la infraestructura de datos espaciales de las Américas. W. Martínez. In: UN-GGIM: Americas Third Session. Mexico City, Mexico. October 5, 2016.
- Marco Estadístico Geoespacial de las Américas: MEGA (Mapa Integrado de las Américas con información estadística sobre población). W. Martínez. En: Conferencia estadística de las Américas de la CEPAL. XV reunión del Comité Ejecutivo. Santiago de Chile, Chile. June 14-16, 2016. Boletín informativo No. 21 28.
- Sistema de Referencia Geocéntrico para las Américas, Plan de Acción Conjunto 2016 -2020. W. Martínez. En: Perspectivas de la Integración de la Información Geoespacial y Estadística a Nivel Global, Regional y Local, Ministerio de Benes Nacionales de Chile. Santiago de Chile, Chile. June 15, 2016.
- El Sistema de Referencia Geocéntrico para las Américas (SIRGAS). C. Brunini, L. Sánchez, H. Drewes, W. Martínez, M.V. Mackern. En: XIV Congreso Internacional de Topografía, Catastro, Geodesia y Geomática. San José, Costa Rica. Septembre 22-24, 2016.
- El Marco de Referencia Geodésico Global (GGRF). C. Brunini. En: Jornada Sobre la Calidad de la Información Geoespacial. La Plata, Argentina. Septembre 19, 2016.

The SIRGAS Symposium and workshop 2017 will be held in Mendoza, Argentina in November 2017. The event will be organized by the Universidad Nacional de Cuyo and the Universidad Juan Agustín Maza.

Sub-Commission 1.3c: North America (NAREF)

Co-Chairs: Michael Craymer (Canada), Dan Roman (USA)

Introduction and structure

The objective of this sub-commission is to provide international focus and cooperation for issues involving the horizontal, vertical, and three-dimensional geodetic control networks of North America, including Central America, the Caribbean and Greenland (Denmark).

The regional sub-commission is co-chaired by representatives from the Canadian Geodetic Survey and the U.S. National Geodetic Survey, currently Dr. Michael Craymer and Dr. Dan Roman, respectively. Dr. Roman replaced Dr. Neil Weston as the U.S. co-chair in 2015.

The Sub-Commission is currently composed of three working groups:
- SC1.3c-WG1: North American Reference Frame (NAREF)
- SC1.3c-WG2: Plate-Fixed North American Reference Frame
- SC1.3c-WG3: Reference Frame Transformations

The following summarizes the activities of each working group. For more information and publications related to these working groups, see the regional Sub-Commission web site at http://www.naref.org/.

Members

SC1.3c: Regional Sub-Commission for North America
- *Michael Craymer (Canada)*
- *Guido Alejandro Gonzalez Franco (Mexico)*
- *Finn Bo Madsen (Denmark)*
- *Dan Roman (USA)*

SC1.3c-WG1: North American Reference Frame Densification (NAREF) Working Group
- *Yehuda Bock (USA)*
- *Kevin Choi (USA)*
- *Michael Craymer (Canada)*
- *Herb Dragert (Canada)*
- *Peng Fang (USA)*
- *Remi Ferland (Canada)*
- *Guido Alejandro Gonzalez Franco (Mexico)*
- *Jake Griffiths (USA)*
- *Tom Herring (USA)*
- *Finn Bo Madsen (Denmark)*
- *Mike Piraszewski (Canada)*

SC1.3c-WG2: Plate-Fixed North American Reference Frame Working Group
- *Geoff Blewitt (USA)*
- *Michael Craymer (Canada)*
- *Remi Ferland (Canada)*
- *Jake Griffiths (USA)*
- *Steve Hilla (USA)*
- *Dan Roman (USA)*
- *Dru Smith (USA)*

SC1.3c-WG3: Reference Frame Transformations in North America Working Group
- *Kevin Choi (USA)*
- *Michael Craymer (Canada)*
- *Remi Ferland (Canada)*
- *Dan Roman (USA)*
- *Tomas Soler (USA)*

Activities during the period 2015-2017

SC1.3c-WG1: North American Reference Frame (NAREF)

The objective of this working group is to densify the ITRF and IGS global networks in the North American region by organizing the computation of weekly coordinate solutions and associated accuracy information for continuously operating GPS stations that are not part of the current IGS global network. A meeting of the working group was held in 2015 during the AGU Fall Meetings in San Francisco.

Originally, the regional densification of the ITRF and IGS network consisted of weekly combinations of several different regional weekly solutions across the entire North American continent using different GPS processing software. However, no weekly combinations have been generated since GPS week 1583 due to the large number of stations. Since that time, Canada and Mexico have continued to generate and submit weekly solutions for their own regions while the U.S. ceased their weekly solutions after GPS week 1631.

In 2016, Canada completed the reprocessing in IGb08 of all of their weekly solutions since 2000 using the Bernese GNSS Software v5.2 and following the IGS repro2 guidelines. Because no combined IGS repro2 orbits where available at the time, these repro2 solutions used CODE repro2 products instead. The solutions include nearly 200 federal and provincial public GNSS tracking stations across Canada as well as over 250 high accuracy campaign station and nearly 600 U.S. CORS in the northern conterminous U.S., eastern Alaska and GNet stations in Greenland (see Fig. 1.3c.1). The U.S. has begun their own repro2 reprocessing in 2017 using IGS repro2 products while Mexico currently has no plans to reprocess.

Canada has also completed the combination of their repro2 weekly solutions into a multi-year cumulative solution that is updated monthly using currently weekly solutions (see Figure 1.3c.1). These cumulative solutions include the estimation of coordinates, velocities, annual and semi-annual seasonal terms, exponential terms for post-seismic modelling, together with coordinate and velocity discontinuities. The U.S. plans a similar combination after the completion of their repro2 reprocessing.

Canada is currently investigating including commercial RTK networks in their cumulative solutions to densify sparse regions of the public networks.

In addition to public GNSS tracking stations, Canada has been computing weekly coordinate solutions and monthly updated cumulative solutions for nearly 700 Canadian commercial RTK base stations in support of compliance agreements between the federal government and commercial RTK service providers. Canada is presently investigating the suitability of these RTK stations to densify sparse regions of the high accuracy public network for improved modelling of crustal dynamics.

Finally, plans are underway in both Canada and the U.S. to move to IGS14.

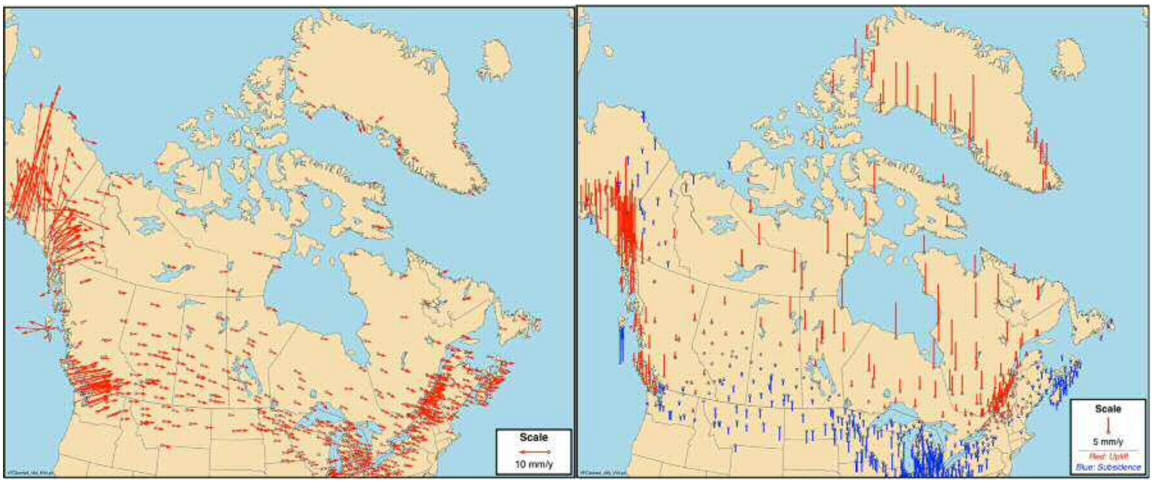

Figure 1.3c.1: Horizontal (left) and vertical (right) velocities from Canadian multiyear cumulative solution transformed to NAD83 using weekly solutions to GPS week 1929. Vertical velocity vectors in red represent uplift while those in blue represent subsidence.

SC1.3c-WG2: Plate-Fixed North American Reference Frame

The objective of this working group is to establish a high-accuracy, geocentric reference frame, including velocity models, procedures and transformations, tied to the stable part of the North American tectonic plate which would replace the existing, non-geocentric North American Datum of 1983 (NAD83) reference system and serve the broad scientific and geomatics communities by providing a consistent, mm-accuracy, stable reference with which scientific and geomatics results (e.g., positioning in tectonically active areas) can be produced and compared. In addition, similar plate-fixed reference frames will be established for U.S. states and territories on other tectonic plates in the Caribbean and Pacific regions.

Although the best realization of a geocentric reference frame at the time it was introduced in 1986, it is now well known that NAD83 is offset from the actual geocentre (and thus ITRF) by about 2 meters. It is also well known that the NNR-NUVEL-1A plate motion model, used to keep NAD83 aligned with the North American tectonic plate, is biased by about 2 mm/yr. These problems make NAD83 incompatible with modern geocentric reference frames used internationally and by all GNSS positioning systems. Consequently, there is a need to replace NAD83 with a high accuracy geocentric reference frame that is compatible with ITRS/ITRF.

The U.S. has been making plans to replace both NAD83 in 2022 along with the replacement of its NAVD88 vertical datum with one based on a geoid. Although there are presently no plans in Canada to replace its NAD83(CSRS), the Canadian Geodetic Survey will make coordinates and velocities available in the new reference frame along with transformation from/to NAD83.

There have been on-going discussions between Canada and the U.S. on the various options for defining regional geocentric reference frames. It has been agreed that the new reference frame will be aligned exactly with the latest realization of ITRF at an adopted reference epoch and keep aligned to the tectonic plate through an estimated Euler pole rotation. Discussion are underway on the selection of a set of reference frame stations representing stable North America and the estimation of the motion of the North American tectonic plate.

In the meantime, the U.S. is installing a new high-level network of 10-20 highly stable GNSS tracking stations across the country that will be contributed to the IGS. Unlike most of the other CORS network in the U.S., these sites will be owned and operated by the U.S. National Geodetic Survey and built and operated to IGS standards. Referred to as Foundation CORS, this network will provide a more stable foundation for the new reference frame in the U.S.

Attempts will be made to co-locate these GNSS stations with other techniques in order to create true GGOS stations. The first of these sites was installed in Miami is late 2014.

Active promotion of the new reference frames and vertical datum in the U.S. is presently underway. There have been informative discussions with the public during three Federal Geospatial Summits organized by the U.S. National Geodetic Survey in 2010, 2015 and 2017. A fourth is planned for 2020. During the last Summit in April 2017, the following names for new reference frames were announced:

- North American Terrestrial Reference Frame of 2022 (NATRF2022)
- Caribbean Terrestrial Reference Frame of 2022 (CTRF2022)
- Mariana Terrestrial Reference Frame of 2022 (MTRF2022)
- Pacific Terrestrial Reference Frame of 2022 (PTRF2022)

A special session on the scientific and practical challenges of replacing NAD83 was also held at the AGU 2016 Fall Meeting in San Francisco.

SC1.3c-WG3: Reference frame transformations in North America

The objective of this working group is to determine consistent relationships between international, regional and national reference frames in North America, to maintain (update) these relationships as needed, and to provide tools for implementing these relationships.

This work primarily involves maintaining the officially adopted relationship between ITRF and NAD83 in Canada and the U.S. The NAD83 reference frame was re-defined in 1998 as a 7-parameter Helmert transformation from ITRF96 at epoch 1997.0. Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental time-dependent transformations between ITRF versions as published by the IERS. The NAD83-ITRF transformation was most recently updated to ITRF2014 in January 2017 just prior to adoption of ITRF2014 by the IGS. The updated transformation has been implemented in transformation software at the Canadian Geodetic Survey and U.S. National Geodetic Survey.

To enable the propagation of coordinates between the various epochs adopted by different jurisdictions in Canada and the U.S., a new velocity model and transformation software was developed by Snay et al. (2016) for North America. The model integrates velocity fields from various sources to provide North American coverage. The resulting interpolation grid of velocities has been implemented in TRANS4D, an update to the HTDP software that models and predicts horizontal motion for the U.S.

More recently, Canada has developed its own unique velocity model that incorporates a GIA model to better model vertical crustal motions in the central and northern regions where GNSS stations are sparse (Robin et al, 2016). The model uses the latest Canadian cumulative solution discussed in SC1.3c-WG1 together with a blending of the ICE-6G and LAUR16 GIA models. The blended GIA model was effectively distorted to fit the GPS velocities thereby providing a more reliable velocity interpolation grid for GIA areas with sparse GNSS coverage. Figure 1.3c.2 illustrates the resulting vertical velocity grid in the IGb08 reference frame.

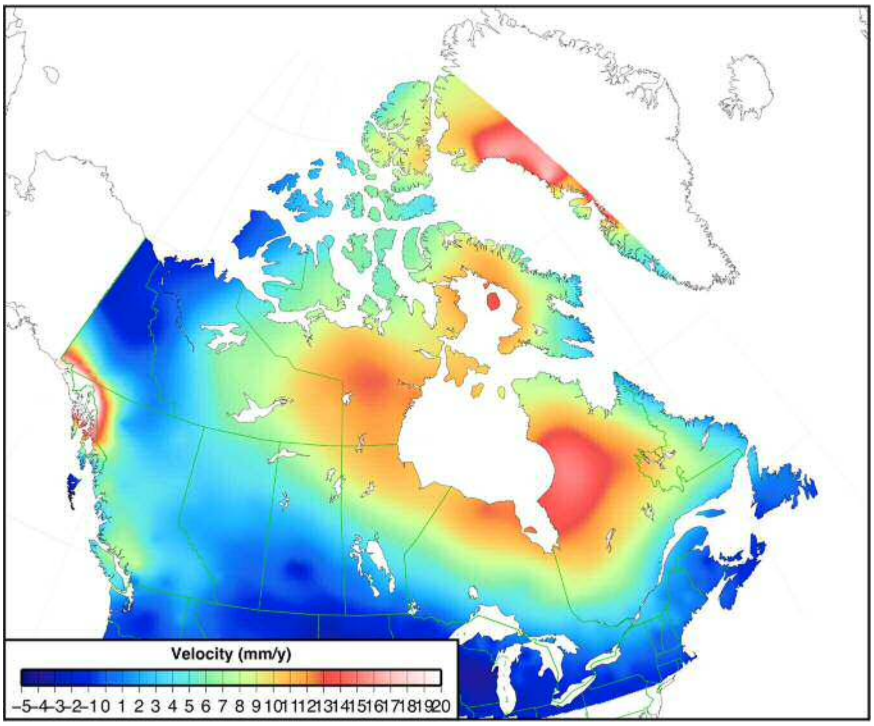

Figure 1.3c.2: Canadian vertical velocity model in IGb08 obtained from an integration of GNSS velocities with a GIA model.

Other activities

Commercial real-time kinematic (RTK) services and their networks of base stations have grown over the years. They are effectively providing access to the NAD83 reference frame for many users. Because these networks are not always integrated into the same realization of NAD83, Canada began a program of validating the NAD83(CSRS) coordinates of these services to ensure they are properly integrated into the NAD83(CSRS) reference frame. The Canadian Geodetic Survey is now providing monthly coordinate and velocity solutions for 6 of the largest commercial RTK services in Canada; a total of more than 800 stations (see Fig. 1.3c.3). Compliance agreements have signed with the three largest services where they have committed to using coordinates for their base stations that are generated in a consistent way by CGS. This ensures those RTK services are integrated into the latest realization of NAD83(CSRS). The U.S. National Geodetic Survey is also working towards a similar program to validate their commercial RTK services.

NAREF is also looking to foster closer cooperation and collaboration with SIRGAS. To this end, the U.S. will be participating in future SIRGAS meetings.

References

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Snay, R.A., J.T. Freymueller, M.R. Craymer, C.F. Pearson, and J. Saleh (2016). Modeling 3-D crustal velocities in the United States and Canada. Journal of Geophysical Research – Solid Earth, Volume 121, doi:10.1002/2016JB012884.

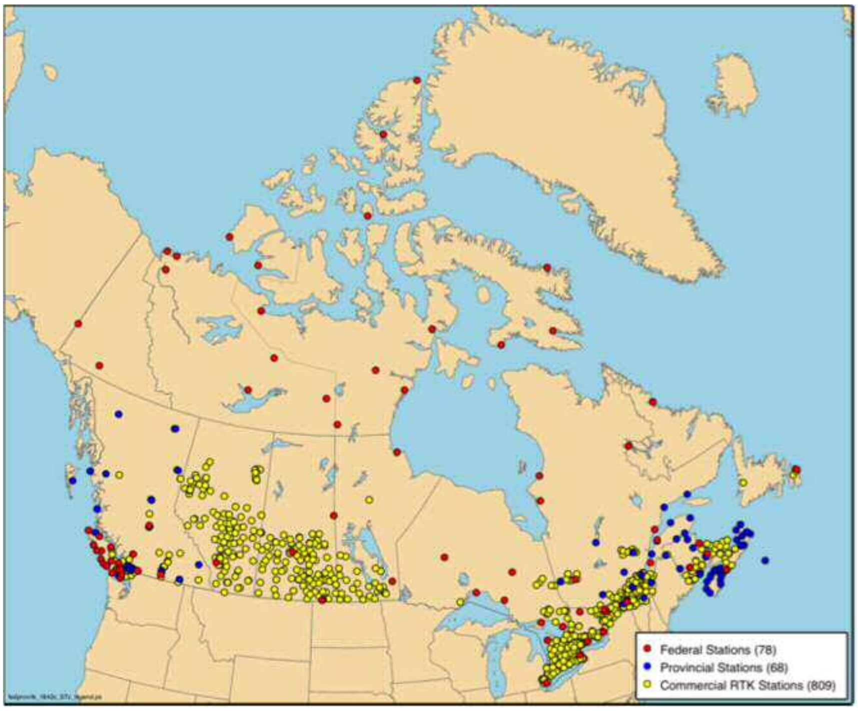

Figure 1.3c.3: Distribution of the six largest commercial RTK networks in Canada (yellow dots) in relation to public federal and provincial networks of permanent GNSS stations.

Sub-Commission 1.3d: Africa

Chair: *Elifuraha Saria (Tanzania)*

Introduction

The African Geodetic Reference Frame (AFREF) is a unified geodetic reference frame for Africa proposed to be the fundamental basis for the national and regional three-dimensional (3D) reference networks. AFREF is intended to be consistent and homogeneous with the current International Terrestrial Reference Frame (ITRF) to make it easier to coordinate planning and development activities within the 54 countries in Africa and across national boundaries.

Since the Windhoek declaration in December 2002, AFREF project is under the initiative of United Nations Economic Commission for Africa (UNECA) Committee on Development Information (CODI). It was agreed that the AFREF projects to be coordinated at sub-regional levels by the sub-regional representative and the overall continental level management, coordination and implementation to be organised by AFREF steering committee. Until now the secretariat of the committee is hosted at Regional Centre for Mapping of Resources for Development (RCMRD).

This report elucidates the progress of Sub-Commission (SC) 1.3d Africa related to IAG activities and action plans as they are stipulated in the SC1.3 objectives. Members of the Sub-Commission (SC) 1.3d are all 54 Africa nations.

Activities and publications during the period 2015-2017

Data and GNSS Station

As it has been explained in earlier reports, most of stations installed in Africa is a contribution from scientific groups working in Africa, African Institutions as well as individual countries modernizing their reference frame. Although these installations may be for other purposes, they also contribute indirectly or directly to the activities of AFREF.

Since its establishment in 2009, the AFREF Operational Data Centre (ODC – ftp afrefdata.org) is still archiving data from the permanent GNSS stations in Africa. Considerable number of stations in Africa are in places with no internet connection. These stations require a budget to visit and download data and send to the ODC. There are also other portals that support archiving AFREF data which are maintained by different organisations, for example

- ftp data-out.unavco.org, → Mostly CORS stations that are contributed by United states organisations
- ftp garner.ucsd.edu and ftp cddis.gsfc.nasa.gov → Mostly some IGS and other CORS station operating in Africa
- ftp geoid.hartrao.ac.za – Mostly IGS, TRIGNET and other CORS stations operating in and outside Africa
- www.station-gps.cea.com.eg → Only for Egypt station especially (ALX2)

The progress in increasing number of GNSS station, has been positive since its establishment. Since the start of 2017 the available stations are ranging between 65 - 70. The map below shows the current distribution of stations that contribute to AFREF.

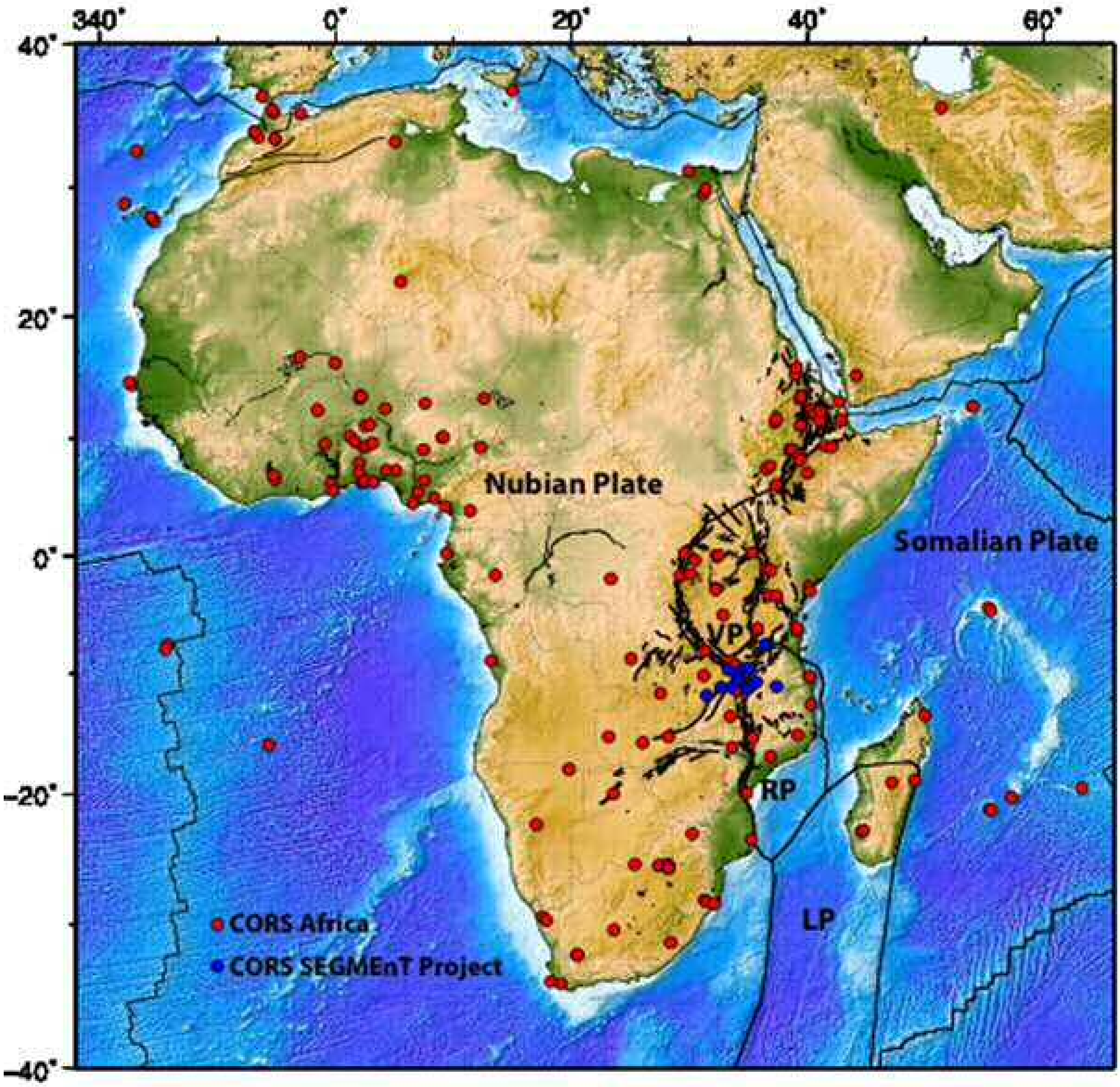

Figure 1.3d.1: CORS operating in Africa, some of the station are not operational however their data are still being utilized. The lack of freely available CORS data in the area from Angola through Central Africa, Sudan and Sahara and North African countries is of concern. For Angola, data are there but are not shared.

AFREF Static Solution and Optimal Site Location

As it was published on GIM article under the former AFREF chair in 2014, four Analysis centres (HartRAO in South Africa, SEGAL (UBI/IDL) in Portugal, Directorate of Surveys & Mapping in Tanzania, Ardhi University in Tanzania.) from Africa or with Africa affiliate processed GPS data for GPS Week 1717 (DOY 340 – 346). The results were computed from the selected 50 Continuously Operating Reference GNSS Stations (CORS) in Africa. The solution from the four analysis centres were combined using CATREF software at the Institut Géographique National (IGN), France. The results show a good agreement between the solution and the final cumulative solution with WRMS of 3 mm, 3mm and ~7 mm in X, Y and Z respectively. The estimated coordinate solution is published in the AFREF ODC.

On the other hand, more studies on AFREF have been conducted about the optimal location for AFREF sites. The recent paper on optimal location for AFREF sites was carried out by one of our Analysis Center HartRAO in South Africa (Muzondo et al., 2015).

AFREF Velocity Solution,

AFREF velocity solution is the next step after publishing the static solution. The aim is to compute velocity solution from all GNSS and DORIS sites around Africa. The approach will be the same to the static solution, however the duration will be from 1996 to 2017. This year the AFREF steering committee will have a meeting in Nairobi in September, there we will come up with a call for a solution from each analysis centre. We expect to write to all analysis centres and we may ask IGN France to do the combination, or we may do the combination in one of the analysis centres. Five analysis centres are identified

i. Ardhi University – Weekly Solution 1996 – 2017 – 22 Years
ii. HartRAO – Weekly Solution 1996 – 2017 – 22 Years
iii. CANARIES – Weekly Solution 2000 – 2017 – 17 Years
iv. Univ. of Luxemburg / Ethiopia – Will contribute via (ADDISU / Elias / Yelebe)
v. SEGAL - Rui

Together with the velocity solution, AFREF expect to publish the AFREF tectonic model, which will be the output from the Velocity solution, however some GNSS episodic sites may be included.

Establishment of Africa Geodetic Commission (AGC)

African geodesists and geophysicists have been operating without having an organ to manage, monitor and disseminate their views. It has been a culture for African geodesists and geophysicists to meet in other meetings that are organised by other organs. Given the development in technology on geodetic instrumentation and software as well as the increase in number for Africa to study geodesy it is time now to establish a union of Africa Surveyors.
Through some discussion between Africa Geodesists, Dr. Joseph Dodo from Nigeria was selected to organise and come up with the first draft. The Draft will be discussed in our AFREF meeting in Nairobi in September 2017.

Challenges

AFREF has been slow to move forward since its inception, due to lack of funding for training and meeting amongst African geodesists as well as computational facilities among African institutions. Spatial distribution of geodetic infrastructure to archive the AFREF goal of 500 – 1000 kilometres proximity is still very poor and may need attention. This has been contributed by many factors although one of the factors may be related to funding, ignorance or challenges depending on the politic in individual countries as well as some countries in Africa not sharing their data. However larger number of young African geodesist is growing and attention is well nurtured to make AFREF successful.

In spite of this slow progress, some geodetic sites are still being installed and archive at the AFREF ODC. In 2017/2018 the African geodesy commission (AGC) will be established and through this, the standards and procedure for AFREF velocity computations will be set, thank you to the great support from UNECA.

Progress has been made with the establishment of the ODC and the computation of a set of static co-ordinates for over 50 stations based on the ITRF, thus creating a uniform reference frame for Africa. The coverage of CORS across Africa and the co-ordination of activities, such as the installation of references stations in close proximity to one another, remains problematic and needs attention. As with any project of this magnitude, obtaining funding and political buy-in from national leaders is a challenge.

Acknowledgements

We acknowledge and thank all organizations and individuals for their efforts towards AFREF initiatives, in particular UNECA, IAG, IGA and all governmental initiative. This includes all organisations and governmental agencies that make their data openly available for AFREF computations. This includes the Nigerian GNSS Reference Network (NIGNET), Ethiopian Mapping Agency (EMA), the Regional Centre for Mapping of Resources for Development (RCMRD), the TRIGNET in South Africa, the Tanzania Geodetic Reference Frame (TAREF), AfricaArray (via UNAVCO archive). Other includes individual projects particularly AMMA project in Benin, SEGMENT project in Tanzania, Malawi and Zambia as well as initiatives from SEGAL Portugal for installation in Mozambique.

We thank officer-in-charge of the Geoinformation Systems Section at UNECA Mr. Andre Nonguierma for supporting AFREF initiative, particularly financial support for the AFREF steering committee meeting.

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Wonnacott, R., 2005. AFREF: Background and Progress towards a Unified Reference System for Africa. Proceedings of International Federation of Surveyors (FIG) Working Week, Cairo, Egypt.

Sub-Commission 1.3e: Asia-Pacific

Chair: *John Dawson (Australia)*

Introduction and structure

The objective of sub-commission 1.3e is to improve the regional cooperation that supports the realization and densification of the International Terrestrial Reference frame (ITRF). Its work is carried out in close collaboration with the Geodetic Reference Framework for Sustainable Development Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP).

The specific objectives of the Sub-commission 1.3e are:

- The densification of the ITRF and promotion of its use in the Asia Pacific region;
- To encourage the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
- To develop a better understanding of crustal motion in the region;
- To promote the collocation of different measurement techniques, such as GPS, VLBI, SLR, DORIS and tide gauges, and the maintenance of precise local geodetic ties at these sites; and
- To outreach to developing countries through symposia, workshops, training courses, and technology transfer activities.

Members

- *John Dawson (Australia)*
- *Yamin Dang (China)*
- *Dr. Farokh Tavakoli (Iran)*
- *Mr. Basara Miyahara (Japan)*
- *Yi Sang Oh (Republic of Korea)*
- *Azhari bin Mohamed (Malaysia)*
- *Enkhtuya Sodnom (Mongolia)*
- *Mr. Graeme Blick (New Zealand)*

National mapping agencies of the Asia-Pacific region,
see http://www.un-ggim-ap.org/abountunggimap/mc/201602/t20160224_97787.shtml

Activities during the period 2015-2017

APREF

Efforts to improve access to the ITRF have continued through the Asia Pacific Reference Frame (APREF) initiative. APREF incorporates GNSS data from a CORS network of approximately 620 stations, contributed by 28 countries in the Asia Pacific. Data are routinely processed by four Analysis Centers and made available publically. In 2016, an additional GNSS CORS site from Thailand commenced contributing data to the APREF GNSS network. Preparations are also underway to reprocess the APREF data archive using the IGS14 reference frame.

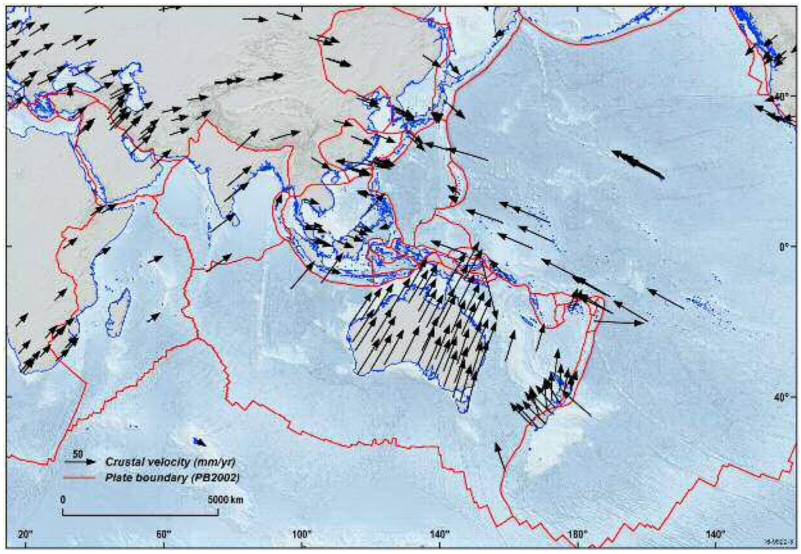


Figure 1.3e.1: The velocity field of the Asia-Pacific Reference Frame (APREF)

Table 1. APREF products.

APREF Product	Available From
Daily RINEX Files	ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/data/daily/
Station Logs	ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/logs/
Weekly SINEX files	ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/solutions/apref/
Coordinate Time Series	http://192.104.43.25/status/solutions/analysis.html

United Nations Global Geodetic Reference Frame

Sub-Commission 1.3e made a significant contribution towards the development of the UN-GGIM Global Geodetic Reference Frame Roadmap document prior to the Sixth Session of UN-GGIM at the UN Headquarters, New York.

Asia Pacific Regional Geodetic Project

The working group has continued to support the annual Asia Pacific Regional Geodetic Project (APRGP), which is a week-long GNSS campaign throughout the region (see Fig. 1.3e.2). Campaigns were undertaken in 2015 and 2016. A campaign is planned for 2017.

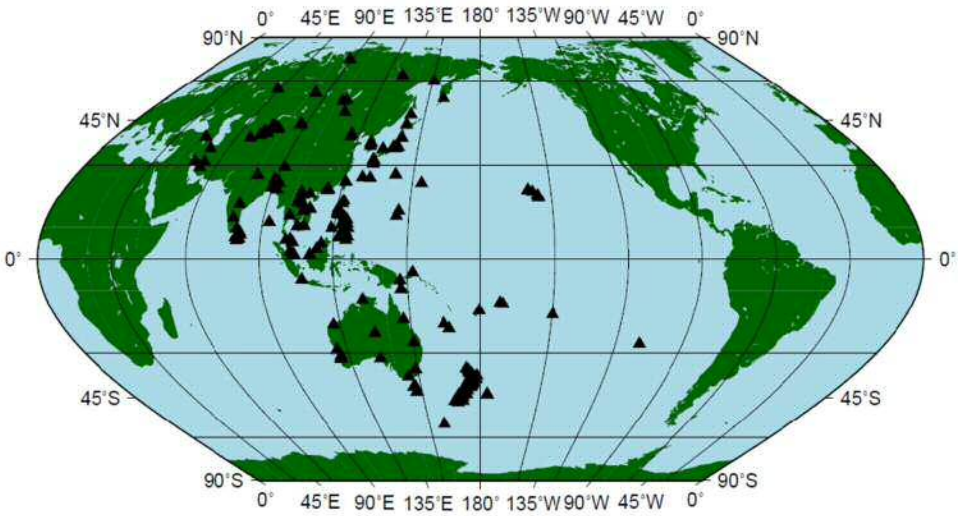


Figure 1.3e.2: Participating stations of the APRGP 2015 GNSS campaign.

Outreach and capacity building

Efforts to build capacity in the region have included:

- A UN-GGIM-AP, FIG, IAG, ICG and NZIS Technical Seminar on Reference Frame in Practice: Reference Frames, Datum Unification and Kinematics was held in Christchurch, New Zealand, 1-2 May 2016. A summary of the meeting can be downloaded from https://www.fig.net/news/news_2016/2016_05_rfip_comm5/RFIP_Report_nic_donnelly.pdf
- A joint IAG, UN-GGIM-AP, FIG and JUPEM forum on Geospatial and GNSS CORS Infrastructure was undertaken 16 – 17 October 2016, Kuala Lumpur – Malaysia. The forum compromised of 6 sessions, and 22 presentations. The forum hosted by JUPEM (Department of Survey and Mapping, Malaysia) had over 150 delegates from 21 countries. Over the 2 days, the forum attracted over 100 participants each day and these attendees actively engaged and contributed to the program. To review and access all presentations listed in the following sessions, please navigate to FIG Asia Pacific Capacity Development Network website for the appropriate links:
  http://www.fig.net/organisation/networks/capacity_development/asia_pacific/index.asp
- A joint technical seminar of IAG, UN-GGIM-AP, FIG, IAG, Japan Federation of Surveyors, International Committee for GNSS (IGC), Geospatial Information Authority of Japan (GSI) has been planned. The Seminar will be held 29-30 July 2017 before the IAG-IASPEI 2017 in Kobe, Japan. The programme will focus on geodetic reference frames and crustal deformation. The planned programme includes theory, ITRF, APREF, UN Initiatives, monitoring and modelling of crustal deformation, case studies and software dealing geodetic adjustment.

Figure 1.3e.3: Geospatial and GNSS CORS Infrastructure and Systems – this forum was held at the Park Royal, Kuala Lumpur, Malaysia on the 16 - 17 October, and comprised of 6 sessions, 22 presentations and attracted over 150 registrants

Publications

Hu, G. 2015. Report on the Analysis of the Asia Pacific Regional Geodetic Project (APRGP) GPS Campaign 2014. Record 2015/15. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2015.015

Hu, G. 2016. Report on the Analysis of the Asia Pacific Regional Geodetic Project (APRGP) GPS Campaign 2015. Record 2016/20. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2016.020

Sub-Commission 1.3f: Antarctica

Chair: Martin Horwath (Germany)

Introduction and Structure

SC 1.3f deals with the densification of the ITRF in Antarctica and the application of geodetic GNSS measurements in geodynamics, geophysics, glaciology and further fields (cf. Figure 1.3.f.1 for an example of vertical crustal deformation studies). For this, the SC 1.3f promotes and supports all activities to realize geodetic GNSS measurements on bedrock sites in Antarctica. A close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR) Expert Group "Geodetic Infrastructure in Antarctica" (GIANT). Antarctica is a special case since it does not fall under control of any state but is subject to the Antarctic treaty that ensures freedom of research.

Members

The membership is identical with that of SCAR GIANT (see www.scar.org). In that way, cooperation and coordination can be best pursued since all nations are represented that are active with respect to geodetic GNSS in Antarctica.

Activities and publications during the period 2015-2017

UN GGIM

The group supported the endorsement of the UN resolution on *A Global Geodetic Reference Frame for Sustainable Development*, which was finally approved on 18 February 2015 (see also unggrf.org).

Geodetic GNSS database

In close linkage with SCAR a database on geodetic GNSS in Antarctica (SCAR GNSS Database) is being maintained at TU Dresden. This is an ongoing activity (see https://data1.geo.tu-dresden.de/scar).

GIANT-REGAIN

At the SCAR Meeting 2016 in Kuala Lumpur an initiative was launched, chaired by Matt King (Australia) and Mirko Scheinert (Germany) named "Geodynamics in Antarctica based on Reprocessing GNSS Data Initiative" (GIANT-REGAIN). This initiative aims to provide a consistent solution of coordinates and coordinate changes for a large set of GNSS bedrock stations in Antarctica for further applications in geodesy, geophysics, geodynamics (especially studies on glacial-isostatic adjustment). It is anticipated that first results of this initiative will be published in 2017.

Outreach and capacity building

Related to SC 1.3f, a business meeting of SCAR GIANT was organized at the SCAR Meeting 2016 in Kuala Lumpur.
SC 1.3f participated to related meetings and conferences, especially to the International Symposium on Antarctic Earth Sciences, Goa 2015, and in the SCAR Open Science Conference, Kuala Lumpur 2016.

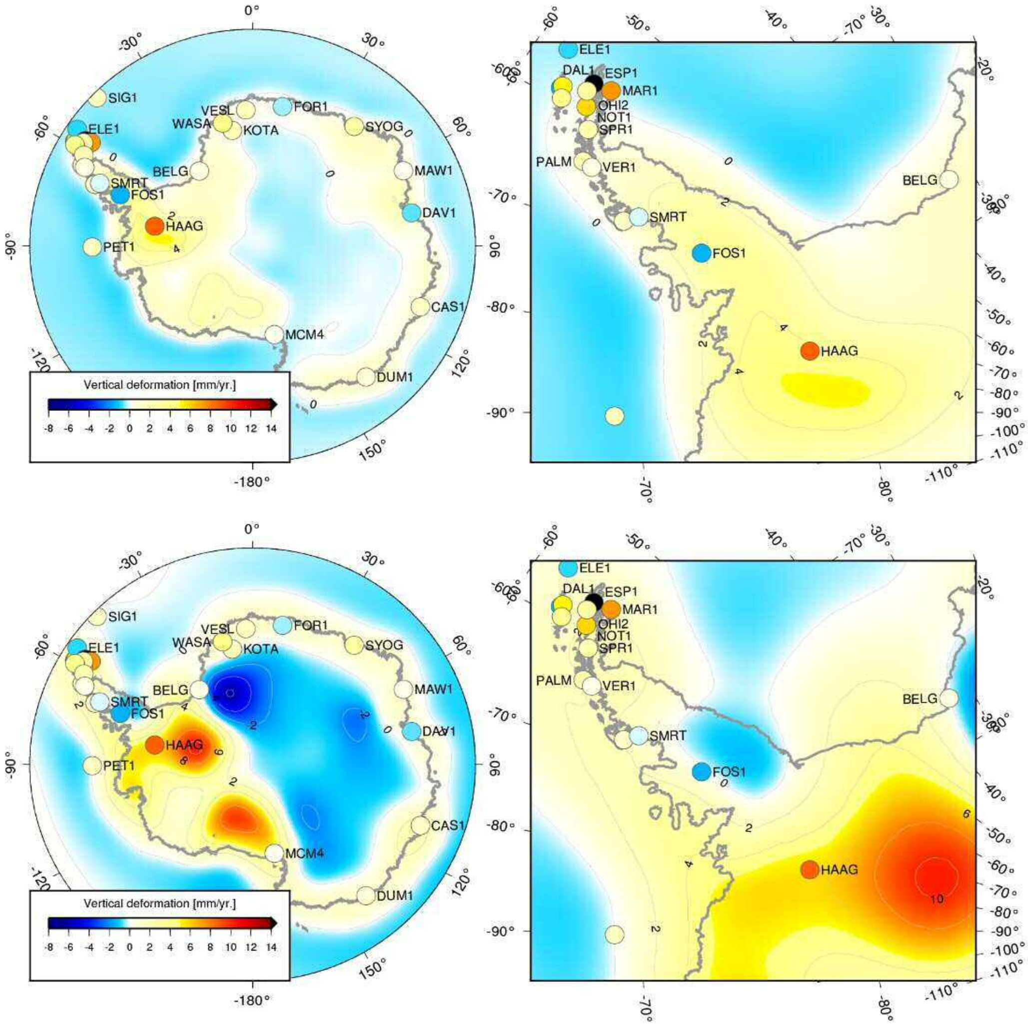


Figure 1.3.f.1: Vertical deformation rates from GNSS (color-coded points) vs. GIA predictions (model IJ05R2 (Ivins et al. 2013) [top], W12a (Whitehouse et al. 2012) [bottom]) (adapted from Rülke et al., 2016).

Publications

King, M., P. Whitehouse, W. van der Wal (2016): Incomplete separability of Antarctic plate rotation from glacial isostatic adjustment deformation within geodetic observations, Geophys. J. Int., 204, 324-330, doi: 10.1093/gji/ggv461

King, M. and Santamaria-Gomez, A. (2016): Ongoing deformation of Antarctica following recent Great Earthquakes, Geophys. Res. Lett., 43, doi: 10.1002/2016GL067773.

Rülke, A., R. Dietrich, A. Capra, E. Dong Chen, J. Cisak, T. Eiken, A. Fox, L. D. Hothem, G. Johnston, E. C. Malaimani, A. J. Matveev, G. Milinevsky, H.-W. Schenke, K. Shibuya, L. E. Sjöberg, A. Zakrajsek, M. Fritsche, A. Groh, C. Knöfel, M. Scheinert (2016): The Antarctic regional GPS network densification - status and results. In: Rizos, C. and Willis, P. (eds.) IAG Symposia series 143, Springer (Proc. IAG General Assembly, Potsdam 2013), doi: 10.1007/1345_2015_79.

Wolstencroft, M., M. King, P. Whitehouse, M. Bentley, G. Nield, E. King, M. McMillan, A. Shepherd, V. Barletta, A. Bordoni, R. Riva, O. Didova, B. Gunter (2015): Uplift rates from a new high-density GPS network in Palmer Land indicate significant late Holocene ice loss in the southwestern Weddell Sea, Geophys. J. Int., 203, 737-754, doi: 10.1093/gji/ggv327.

Working Groups of Sub-commission 1.3:

WG 1.3.1: Time-Dependent Transformations Between Reference Frames

Chair: *Richard Stanaway (Australia)*

Introduction and structure

The main aim of the WG is to focus research in deformation modelling into the rapidly emerging field of regional reference frames used in applied geodesy, particularly positioning and GIS. Deformation models and other time-dependent transformation models provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for land surveying and mapping.

The WG will integrate the findings of IAG WG 1.3.1 "Integration of dense velocity fields in the ITRF" (2011-2015), the EUREF WG on Deformation Models and other current research into developing a global deformation and transformation model schema that can be used to support realization of regional and local reference frames from ITRF to support GIS and positioning technologies. This will require development of a standardized time-dependent transformation model format that can be accessed from international registries of geodetic parameters such as those hosted by ISO/TC 211 and EPSG (European Petroleum Survey Group).

WG 1.3.1 is working closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames). WG members comprise of a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying and GIS.

Members

- *Richard Stanaway (Australia)*
- *Hasanuddin Abidin (Indonesia)*
- *Sonia Alves (Brazil)*
- *Graeme Blick (New Zealand)*
- *Miltiadis Chatzinikos (Greece)*
- *Chris Crook (New Zealand)*
- *Paul Denys (New Zealand)*
- *Nic Donnelly (New Zealand)*
- *Rui Fernandes (Portugal)*
- *Yasushi Harada (Japan)*
- *Kevin Kelly (USA)*
- *Juliette Legrand (Belgium)*
- *Daphné Lercier (France)*
- *Martin Lidberg (Sweden)*
- *Rob McCaffrey (USA)*
- *Christopher Pearson (New Zealand)*
- *Craig Roberts (Australia)*
- *Laura Sánchez (Germany)*
- *Yoshiyuki Tanaka (Japan)*
- *Norman Teferle (Luxembourg)*

Activities and publications during the period 2015-2017

There has been a major impetus for national and regional datum modernization since 2015 with many countries implementing or considering time-dependent reference frames. The impetus has been driven by increasing adoption of precise GNSS positioning, especially at the mass-market level, precision GIS and the United Nations 2015 resolution in support of a Global Geodetic Reference Frame.

One of the main aims of WG 1.3.1 is to develop a framework for standardization of time-dependent reference frame transformations. At present, the 14-parameter model is widely used (e.g. for transformations between different realizations of ITRF, ETRF, GDA and NAD83). Plate motion models (PMM) can also be used to describe the kinematics of the stable portion (rigid) of a tectonic plate or microplate. The rotation rate parameters of the 14-parameter transformation model can be adapted from a PMM (rotation rates of the Cartesian axes). The 14-parameter and PMM approach, however, does not adequately deal with intraplate, plate boundary, co-seismic and post-seismic deformation. Models of these forms of deformation are essential for higher precision transformations and there is a rapidly growing requirement to develop international standards to for deformation model formats and application (e.g. IOGP/EPSG and ISO/TC 211). Presently, different jurisdictions in tectonically active regions have different approaches to handle these types of deformation. The lack of a standardized approach for time-dependent transformations is leading to a potentially unmanageable scenario where every jurisdiction has a different schema. This is an undesirable situation for developers of positioning and GIS software and it is also an impediment for many developing countries with limited budgets to modernize their geodetic datum in the absence of a standardized template or schema. Trimble (Lercier et al., 2016) and ESRI are compiling an inventory of models and formats to support standardization and their findings will be included in the WG final report in 2019.

WG 1.3.1 is currently reviewing the different approaches currently in use globally with a view to developing a standardized schema or model translation capability for time-dependent reference frame transformations. This report will provide a summary of this research to date.

North America

An updated crustal motion model has been developed (Snay et al., 2016; Fig. 1.3.1.1) to support applied geodesy in the USA and Canada with the development of TRANS4D software, which will supersede the HTDP software currently being used for time-dependent transformations. The new model now includes uncertainties of estimated velocities and vertical velocities.

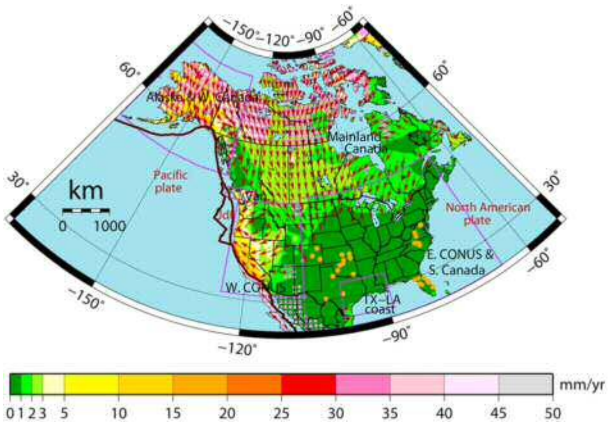


Figure 1.3.1.1: Velocities with respect to the stable North American plate (NA12 reference frame). Contour colours indicate velocity magnitude, and dark red arrows indicate velocity direction when the velocity magnitude exceeds 1 mm/yr. Orange dots represent the 30 GPS sites whose velocities were employed to define the NA12 reference frame (from Snay et al., 2016).

South America

The present SIRGAS Velocity Model (VEMOS2015; Sánchez and Drewes, 2016; see Fig. 1.3.1.2) was inferred from GNSS (GPS+GLONASS) measurements gained after the strong earthquakes occurred in 2010 in Chile and Mexico (Sánchez et al., 2013; 2016). It is based on a multi-year velocity solution for a network of 456 continuously operating GNSS stations comprising a five years period from March 14, 2010 to April 11, 2015. VEMOS2015 was computed using the least square collocation (LSC) approach with empirically determined covariance functions. It covers the region from 55°S, 110°W to 32°N, 35°W with a spatial resolution of 1° x 1°. The average prediction uncertainty is ±0.6 mm/a in the north-south direction and ±1.2 mm/a in the east-west direction. The maximum is ±9 mm/a in the Maule deformation zone (Chile) while the minimum values of about ±0.1 mm/a occur in the stable eastern part of the South American plate.

The main purpose of VEMOS2015 is to allow the translation of station positions through time. However, this model is only valid for the time period 2010-2015. For the translation of station positions before the 2010 earthquakes, the model VEMOS2009 (Drewes and Heidbach, 2012) should be used. Although VEMOS2015 includes GNSS observations over five years, some regions were affected by further earthquakes and their effects are not included in VEMOS2015 yet. Consequently, it is necessary to update this model regularly. In forthcoming activities, we shall improve the distribution of the continuously operating GNSS stations, especially along the boundaries between the different tectonic features. In the analysis of the station position time series, we want to consider possible surface loading and local effects to improve the reliability of the estimated velocities. Finally, we plan also to perform detailed studies about the temporal-spatial evolution of the deformation field.
VEMOS2015 is available at https://doi.pangaea.de/10.1594/PANGAEA.863132.

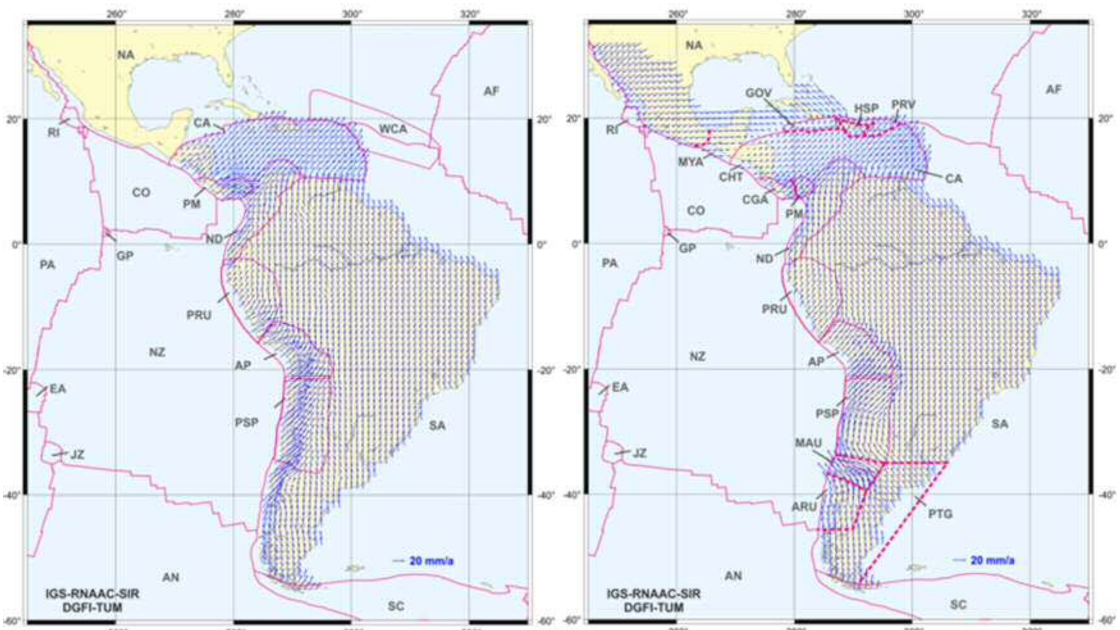


Figure 1.3.1.2: VEMOS2009 (left) referred to the ITRF2005 (Drewes and Heidbach 2012), and VEMOS2015 (right) referred to IGb08 (Sánchez and Drewes 2016), taken from www.sirgas.org.

Scandinavia

A new land uplift model NKG2016LU has been developed by the NKG (Nordic Geodetic Commission (Fig. 1.3.1.3). The use of land uplift models enables precise transformations between national realizations of ETRS89 and different realizations of ITRF at the few mm level.

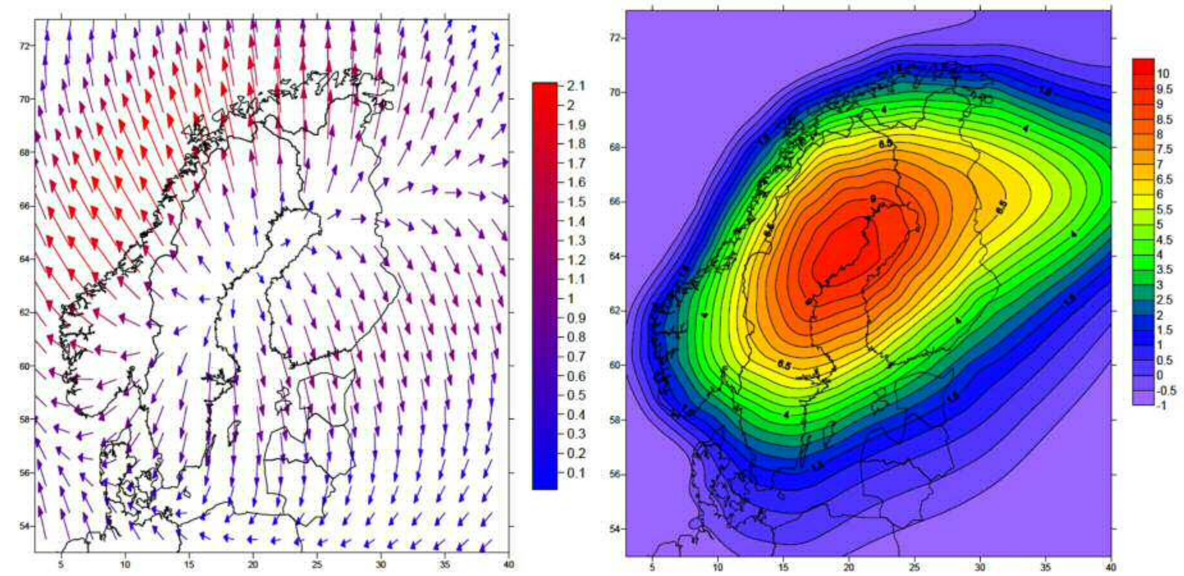


Figure 1.3.1.3: The NKG_RF03vel velocity model. Reference for the horizontal velocity field (left) is “stable Eurasia” as defined by the ITRF2000 Euler pole for Eurasia. The vertical uplift rates are “absolute” values relative the earth centre of mass. Units: mm/year (from Lidberg et al., 2017).

Indonesia

The Geospatial Agency of Indonesia has launched a new geocentric datum named the Indonesian Geospatial Reference System 2013 (IGRS 2013) (Susilo et al., 2016, Fig. 1.3.1.4). This new datum is a semi-dynamic datum in nature realized by ITRF2008, with a reference epoch of 1 January 2012 (2012.0). A deformation (velocity) model is used to transform coordinates from an observation epoch to or from this reference epoch. For its initial implementation, the model considers an initial deformation model setting based on 4 tectonic plates, 7 tectonic blocks, and 126 earthquakes. At present, the velocity model of IGRS 2013 is mainly realized using repeat GPS observations on the passive geodetic control network and CORS, covering the period from 1993 to 2014. These GPS data are managed by the Geospatial Agency of Indonesia (BIG), Land Agency of Indonesia (BPN), and the Sumatran GPS Array (SUGAR). The GPS data has been reprocessed and analyzed using the GAMIT/GLOBK 10.5 processing software suite. The derived velocities field shows the spatial variation of velocity direction and magnitude, which represents various plates or blocks tectonic motion in Indonesia region. This analysis has been used for the development of the IGRS 2013 deformation model.

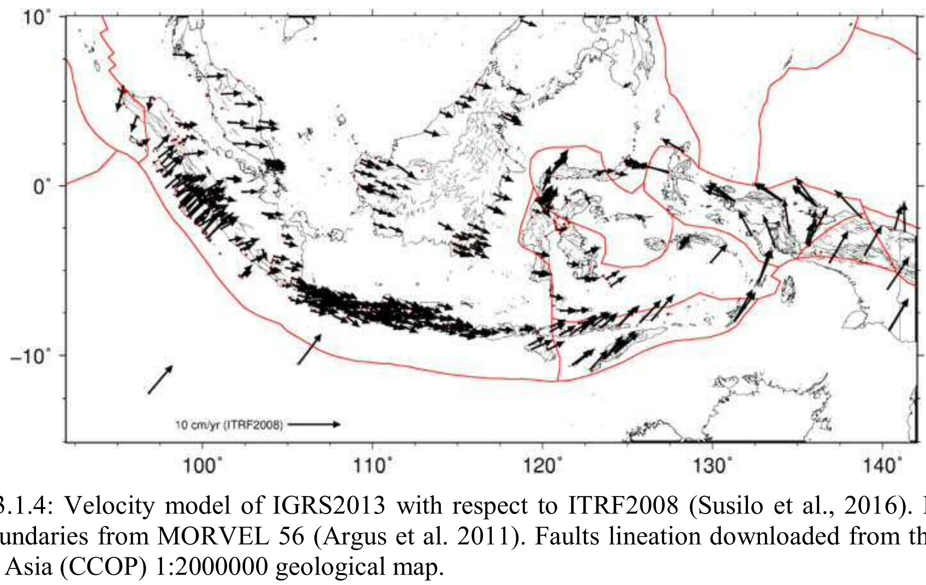
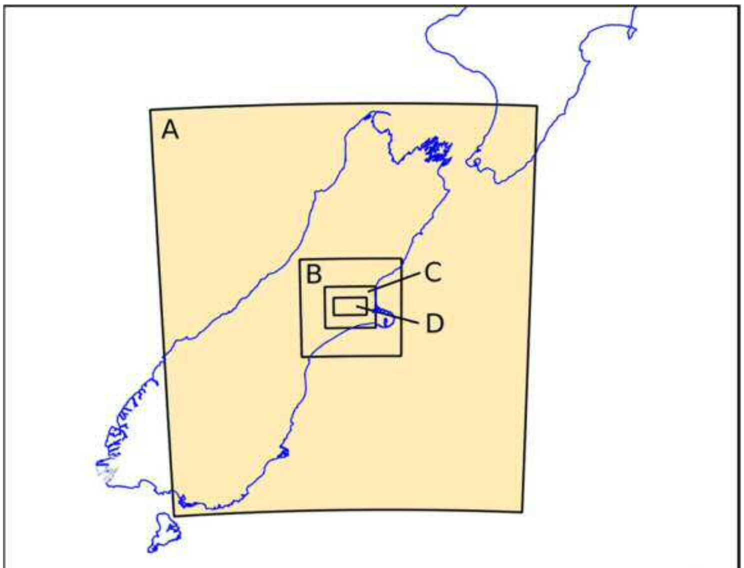


Figure 1.3.1.4: Velocity model of IGRS2013 with respect to ITRF2008 (Susilo et al., 2016). Red line is blocks boundaries from MORVEL 56 (Argus et al. 2011). Faults lineation downloaded from the East and Southeast Asia (CCOP) 1:2000000 geological map.

New Zealand

The New Zealand Geodetic Datum 2000 (NZGD2000) Deformation Model has been updated based on improved site velocities estimated from GPS observations made on both the passive geodetic network and active CORS network between 1996 and 2011 (Crook et al., 2016). Earthquake patch models of coseismic displacement have also been incorporated for a number of significant earthquakes that have occurred in New Zealand (Fig. 1.3.1.5). The NZGD2000 deformation model velocity field is published on a rectilinear 0.1° grid of ellipsoidal coordinates in comma separated variable (csv) format. The current model can be downloaded at: http://apps.linz.govt.nz/ftp/geodetic/nzgd2000_deformation_20160701_full.zip



Grid	No Lon	No Lat	Size Lon (deg)	Size Lat (deg)
A	52	54	0.15	0.125
B	50	59	0.075	0.0625
C	84	118	0.0375	0.03125
D	141	306	0.01875	0.015625

Figure 1.3.1.5: Multi-resolution grid for 2010 Darfield earthquake.

Australia

Australia will be implementing GDA2020 in 2017 which will be a realization of ITRF2014 projected to epoch 2020.0. GDA2020 will supersede GDA94 but will still be a plate-fixed reference frame. An intraplate deformation model is being developed for Australia and the format and implementation is expected to be based on the New Zealand approach.

Japan

The Japanese Geodetic Datum 2000 (JGD2000) has been updated following the very significant coseismic and postseismic deformation arising from the 2011 Tohoku earthquake sequence (Fig. 1.3.1.6). From 2014, JGD2000 has been re-realized by the 1318 station GEONET CORS network.

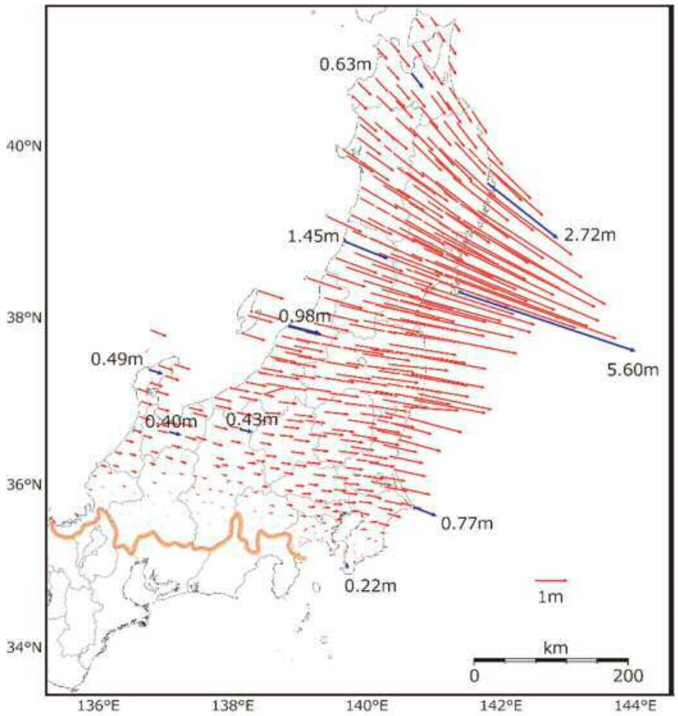


Figure 1.3.1.6: JGD2000 coordinate changes arising from the 2011 Tohoku earthquake sequence

Nepal

Following the April 25, 2015 Mw7.8 Gorkha earthquake, a new semi-dynamic datum is being developed for Nepal incorporating a secular site velocity model based on ITRF2014 (Fig. 1.3.1.7) and co-seismic deformation model to enable pre earthquake spatial data to be transformed and visualized in ITRF2014 (Pearson et al., 2016).

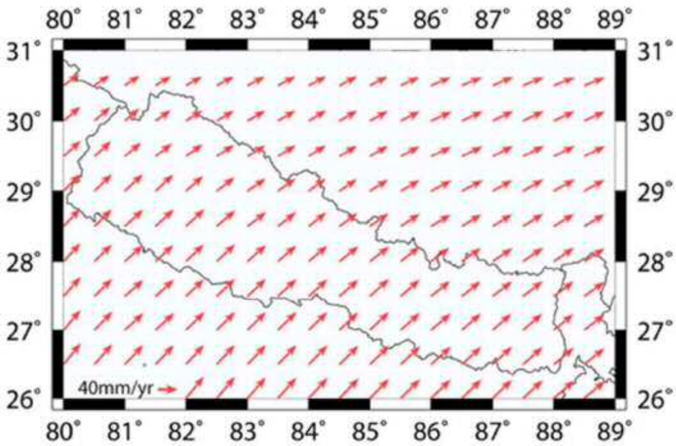


Figure 1.3.1.7: Velocity grid for Nepal and surrounding parts of India and China

Outreach and capacity building

The main WG meeting and workshop during the period was the Technical Seminar on Reference Frames in Practice held in Christchurch, New Zealand, 1-2 May 2016 (see Figure 1.3.1.8). Ten members of WG 1.3.1 attended and made presentations. The workshop was organized by FIG Commission 5, in conjunction with the International Association of Geodesy (IAG), the International Committee on GNSS (ICG), the United Nations Initiative for Global Geospatial Information Management for Asia-Pacific (UN-GGIM-AP) and the New Zealand

Institute of Surveyors (NZIS). The main focus of the workshop was deformation modelling and datum unification with an emphasis on the tectonically active Asia-Pacific region. Many countries in the region have complex challenges maintaining local reference frames in the face of rapid tectonic deformation. Country case studies were presented for Australia, Fiji, Japan, Nepal, New Zealand, Philippines, Poland and the USA. Reports and presentations are available at http://www.fig.net/fig2016/commission5.htm. A special thanks to WG member Nic Donnelly for organizing such an informative and useful workshop.

The next WG meeting is planned for the IAG-IASPEI Joint Scientific Assembly to be held between 30 July and 4 August 2017 in Kobe, Japan. Preceding this will be another Reference Frame in Practice workshop, which will be attended by many members of the WG. Looking ahead, future meetings and activities will coincide with REFAG 2018 (IAG Commission 1) and the IUGG in Montreal in 2019. A final WG report and recommendation will be completed in early 2019.

Figure 1.3.1.8: Technical Seminar on Reference Frames in Practice held in Christchurch, New Zealand, 1-2 May 2016.

Outlook for 2017 - 2019

The WG will complete a review of time-dependent transformation approaches currently used by different jurisdictions with particular regard to model formats and application with positioning and GIS software. A recommendation for an international standard will be made based on an assessment of the approaches currently in use. An international deformation model service similar in structure to the International service for the Geoid may also be proposed.

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Crook, C., Donnelly, N., Beavan, J. and Pearson, C. (2016). From geophysics to geodetic datum: updating the NZGD2000 deformation model, New Zealand Journal of Geology and Geophysics Vol. 59, Iss. 1

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Sub-commission 1.4: Interaction of Celestial and Terrestrial Reference Frames

Chair: *Zinovy Malkin (Russia)*

Structure

Working Group 1.4.1: Consistent realization of ITRF, ICRF, and EOP
Working Group 1.4.2: Impact of geophysical and astronomical modeling on reference frames and their consistency
Working Group 1.4.3: Improving VLBI-based ICRF and link to the Gaia-based CRF (GCRF)

Overview

International terrestrial and celestial reference frames, ITRF and ICRF, respectively, as well as the tie between them expressed by the Earth Orientation parameters (EOP) are key products of geodesy and astrometry. The requirements to all the components of this triad grow steadily and the mm/μas level of accuracy is the current goal of the astronomic and geodetic community.

The current computation procedures for ITRF and ICRF are based on multi-stage processing of observations made with several space geodetic techniques: VLBI, SLR, GNSS, and DORIS. Not all of them provide equal contributions to the final products. The latest ITRF realizations have been derived from combination of normal equations obtained from all four techniques, whereas the ICRF is a result of a single global VLBI solution. The latter is tied to the ITRF using an arbitrary set of reference stations. However, VLBI relies on the ITRF origin provided by satellite techniques and shares responsibility with SLR for the ITRF scale. Finally, all the techniques contribute to positions and velocities of the ITRF stations.

This situation causes complicated mutual impact of ITRF and ICRF, which should be carefully investigated in order to improve the accuracy of both reference systems and the consistency between each other and EOP. The subject becomes more and more complicated when moving to millimeter accuracy in all components of this fundamental triad. Consequently, we face systematic errors involving the connection between the ICRF and ITRF realizations, which cannot be fixed by datum correction during the current solution.

There are several issues currently preventing the realization of the terrestrial and celestial reference systems (TRF and CRF, respectively) at the mm/μas level of accuracy:

- Insufficient number and non-optimal distribution of active and stable stations (VLBI and SLR in the first place) and radio sources.
- Technological (precision) limitations of existing techniques.
- Incompleteness of the theory and models.
- Not fully understood and agreed-upon details of the processing strategy.

These issues are the subject of research of the IAG SC 1.4. All the three IAG SC 1.4 working groups are working in close cooperation with each other, in particular, because there is clear interaction among their topics. To provide this, it was decided that each WG chair becomes a member of two other working groups, and the SC chair is a member of all the three groups.

Past meetings

IAG SC 1.4 Meeting on 25 April 2017 in Vienna during the EGU 2017
A meeting of IAG Sub-Commission 1.4 was held on 25 April 2017 at the Vienna University of Technology. Since it was scheduled as splinter meeting during the General Assembly of the European Geophysical Union (EGU) in Vienna, in total 12 participants could join. Six presentations were given at the meeting. After introduction of the SC chair, three presentations

from each WG summarized the group activity during past two years. Finally, two contributed presentations were given, devoted to more detailed consideration of the topics discussed at the meeting. During and after the presentation, the meeting participants took part in active discussion on the most "hot" topics such as the nature and sources of the systematic errors in the current CRF realizations and impact of the analysis options, in particular accounting for the galactic aberration in the future.

Other related meetings
Several other meetings with active participation of the SC 1.4 members were held in 2016 and 2017, where the scientific problems related to the IAG SC 1.4 topics were discussed:
- 9th IVS General Meeting, Johannesburg, South Africa;
- ICRF-3 Working Group Meeting, 17-18 October 2016, Haystack, USA;
- 23rd EVGA Working Meeting, Gothenburg, Sweden.

The next regular IAG SC 1.4 meeting is planned during the week of EGU 2019, April 7-12 in Vienna. An intermediate meeting in 2018 is under discussion.

Working Groups of Sub-commission 1.4:

WG 1.4.1: Consistent Realization of ITRF, ICRF, and EOP

Chair: *Manuela Seitz (Germany)*

Members
- *Claudio Abbondanza (USA)*
- *Sabine Bachmann (Germany)*
- *Richard Gross (USA)*
- *Robert Heinkelmann (Germany)*
- *Chris Jacobs (USA)*
- *Hana Krásná (Austria)*
- *Sébastien Lambert (France)*
- *Karine Le Bail (USA)*
- *Daniel MacMillan (USA)*
- *Zinovy Malkin (Russia)*
- *David Mayer (Austria)*
- *Benedikt Soja (USA)*

Activities and publications during the period 2015-2017

General aspects

Many applications in the geosciences, astrometry and navigation require consistency of the terrestrial and the celestial reference frame and the Earth Orientation Parameters. But ITRS, ICRS and EOP are not realized fully consistently today (Fig. 1.4.1). In addition, the realizations of the reference systems do not take full advantage of the high precision of the space geodetic techniques due to (i) modeling deficiencies in single technique analysis and (ii) inhomogeneity w.r.t. modeling and parameterization between the techniques.
The WG 1.4.1 aims to develop and investigate the methods to generate consistent TRF-CRF-EOP solutions based on optimal modeling, analysis and combination strategies and to assess the quality of the results. The focal points of the WG are:
(1) Investigation of the impact of different analysis options and combination strategies on the consistency of TRF, CRF, and EOP derived from a joint analysis of space geodesy observations.
(2) Investigation of the consistency of the current ICRF and ITRF versions and IERS EOP C04 series.
(3) Investigation of the consistency of VLBI-only (IVS) CRF, TRF, and EOP series with the ITRF, ICRF, and C04 EOP series.
(4) Study of effects of geodetic datum realization on VLBI-derived CRF.
(5) Study of optimal use of the space-collocated techniques for the improvement of the consistency of TRF, CRF, and EOP.

Consistency of current ITRF solutions and EOP

In 2015/2016, three new realizations of the ITRS are computed and released by the ITRS Combination Centers DGFI-TUM, IGN and JPL. The IGN solution, the ITRF2014, is computed from a combination of the VLBI, SLR, GNSS and DORIS solutions. In the ITRF2014 solution, non-linear station motions are approximated by estimating annual and semi-annual signals. The realization performed by DGFI-TUM, the DTRF2014, is based on the combination of normal equations of the space-geodetic techniques. In DTRF2014, computation non-linear station motions caused by hydrologic and atmospheric loading are reduced. The loading signals are considered by model values based on the hydrology model GLDAS and the atmospheric model NCEP, respectively. The time series of model values are derived and provided by Tonie van Dam. JPL computes an ITRS realization, the JTRF2014, by applying a Kalman filter approach. The resulting station position time series approximate the non-linear station motions very well.

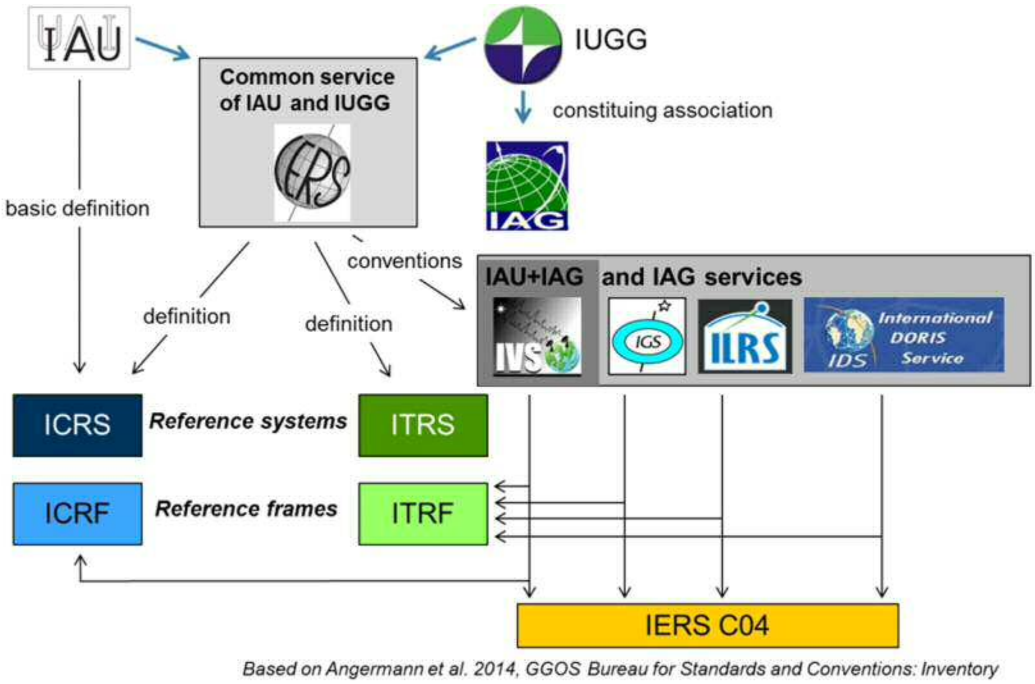

Fig.1.4.1: Infrastructure of ITRS and ICRS realization. Today ITRS and ICRS are realized independently by different Combination/Product Centres and based on different observation data.

In order to investigate the consistency of the current ITRS realizations, the GFZ group computes EOP series and global CRF solutions by fixing the station coordinates to the previous ITRS realization ITRF2008 and the new realizations ITRF2014, DTRF2014 and JTRF2014. The individual EOP series obtained from a session-wise analysis are compared using the series based on the ITRF2014 coordinates as a reference. The EOP series obtained by fixing the station coordinates to DTRF2014 show the smallest differences. The difference series of the terrestrial pole coordinate series show small drifts in the very early years of VLBI observation and a slightly increased scatter in 2013/2014. The WRMS values are 0.004 mas and 0.002 mas for x- and y-pole, respectively. For UT1 and nutation no systematic occur. The WRMS values are 0.10 µs for UT1 and 0.09 and 0.11 nas for X- and Y-pole, respectively. The EOP series computed by fixing ITRF2008 coordinates show a larger scatter compared to the ITRF2014 based series than the DTRF2014 based series. This can be related to the fact that ITRF20014 and DTRF2014 are computed from the same input data. The scatter of the ITRF2008 based series increases strongly after 2008 when coordinates are extrapolated. For the JTRF2014 based EOP series a larger scatter than for DTRF2014 series was obtained which might be a result of the different approximation of station motions. But also, systematic effects are identified which can be related to the handling of seismic events.

In a second step, global CRF solutions are computed by again fixing the station positions and velocities to the three reference frames and by fixing also the EOP. The CRF solutions obtained from fixing ITRF2014 and DTRF2014, respectively, agree very well. The WRMS values are 2.06 µas and 9.67 µas for RA*cos(DE) and DE, respectively. Only small systematics in declination and declination rate are found. For JTRF2014 the differences are larger, in particular for sources in the high southern declinations. For ITRF2008 also larger differences are obtained which can be explained by the 6 more years of data used for the 2014 realizations.

Realization of ITRS and ICRS from VLBI data

VLBI is the only space-geodetic technique, which observes extra galactic objects and thus allows for a consistent realization of TRF, CRF and the EOP. Therefore, it is very important to investigate the impact of different VLBI analysis options on the resulting TRF and CRF. In the period 2015-2017, three analysis options were investigated: the reduction of non-linear station motions, an improved modeling of tropospheric a priori parameters and the effect of combining different VLBI solutions on the stability of source positions.

In the ITRS realizations ITRF2014, DTRF2014 and JTRF2014 for the first time, non-linear station motions are considered. TU Vienna investigated the impact of non-linear station motions in VLBI-based TRF-CRF-EOP solutions on source positions and EOP. The results indicate that the seasonal signals do not propagate into the orientation of celestial reference frame but they can cause significant position changes for radio sources observed non-evenly over the year. On the other hand, it was found that the harmonic signals in station horizontal coordinates propagate directly into the ERP by several tens of microarcseconds.

VLBI solutions depend on the quality of the a priori values of tropospheric parameters as these parameters are slightly constrained in the VLBI solutions. Therefore, TU Vienna tested different types of a priori modeling (see report of WG 1.4.2). It was found, that the different modeling options lead to significant differences in the declination biases, which occurs around 30°S.

BKG performs the combination of different VLBI solutions routinely in its function as IVS Combination Centre. Up to now, station positions and EOP were combined on a routine basis. In order to investigate the benefit of a combination of source positions for the CRF, BKG includes source positions in the combination process. The results look very promising. The WRMS of session-wise estimated source positions were improved by the combination as shown in Fig. 1.4.2. Figure 1.4.3 displays the homogeneity of position residuals of all contribution solutions w.r.t. ICRF-2 exemplarily for one R1 session. The impact of the combination of sources on the TRF was found to be not significant.

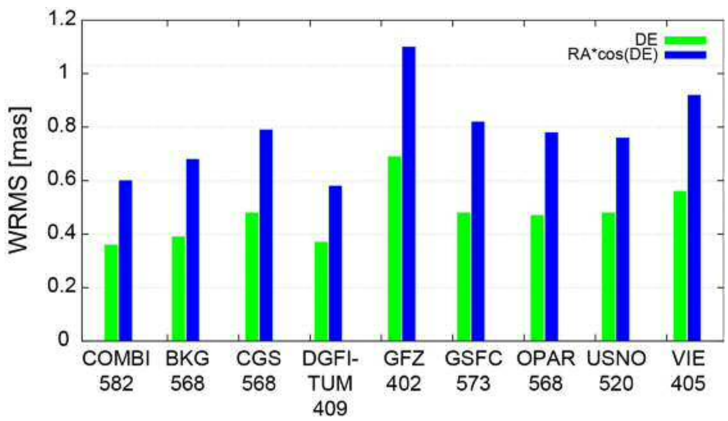

Fig.1.4.2 WRMS over all sources for individual and combined solutions. Only sources with ten sessions and a time span of more than 2 years were considered. The number of sources is given below the name of the analysis center (AC).

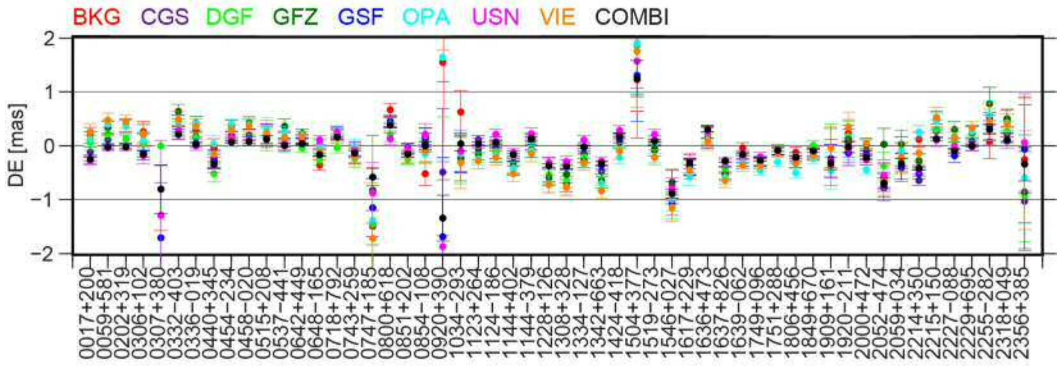

Fig.1.4.3 Source position residuals w.r.t. ICRF2 for individual and combined solution for session 14MAY27XA (R1637).

Two further VLBI analysis options are investigated by WG 1.4.2: the spline parameterization for special handling sources that allows to include these sources in the NNR conditions and the minimization of source structure effects on the CRF.

Consistent realization of ITRS and ICRS

Two groups are working on the consistent realization of ITRS and ICRS, namely JPL and DGFI-TUM.

In the recent years, JPL developed a Kalman filter approach (KALREF) for the realization of the ITRS and became an ITRS Combination Centre. JPL provided the solution JTRF2014 in the framework of the ITRS realization. For this purpose, JPL improved their TRF solution by using GRACE data and loading models to include statistics of regional ground deformation in the Kalman filter's stochastic model of process. In a second step, the Kalman filter approach was extended to compute also CRF solutions. Therefore, radio source coordinates were modeled as random walk processes and a source-based process noise model was developed. The special handling of sources featuring measurable motions, benefit most from this time series approach.

In a last step, both Kalman filter setups will be coalesced by extending the software KALREF to include radio source positions and nutation parameters.

At DGFI-TUM, consistent realizations of ITRS and ICRS were performed by combining the space geodetic techniques on normal equation level. For the most recent solution, VLBI and SLR normal equations from DGFI-TUM and the routinely provided normal equations of the IGS Analysis Centre CODE were combined, covering the time span from January 2005 – December 2015. The parameters that were included in the combination are shown in Tab.1.

	GNSS	SLR	VLBI	Combi.
station coord. & vel.	X	X	X	X
source coord.			X	X
terrestrial x-/y-pole	X	X	X	X
UT1-UTC (LOD)	(X)	(X)	X	X
celestial X-/Y-pole			X	X

Table 1.4.1: Parameters included in the combination performed for a consistent realization of ITRS and ICRS at DGFI-TUM.

The local ties play an important role for the combination of the terrestrial networks. In order to investigate their impact on the CRF, test solutions introducing all local ties were computed. Using appropriate weights for the local ties, standard deviations of source positions decreased due to the combination. It was found, that for sources that were observed at least 3 times and thus have smaller standard deviations in the VLBI only solution, the effect is smaller by at least a factor of 10 as compared with sources that were less often observed.

Further studies by DGFI-TUM will concentrate on the impact of the EOP combination and of the modeling of seasonal signals of station positions on the CRF. In addition, the improvement reached by VCS-II sessions will be studied. DGFI-TUM is also involved in the ICRF-3 working group activity, and will investigate the impact of a common realization of ITRS and ICRS on the ICRF-3.

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Working Group 1.4.2: Impact of Geophysical and Astronomical Modeling on Reference Frames and Their Consistency

Chair: *Daniel MacMillan (USA)*

Members

- *Robert Heinkelmann (Germany)*
- *Hana Krásná (Austria)*
- *Sébastien Lambert (France)*
- *Zinovy Malkin (Russia)*
- *David Mayer (Austria)*
- *Lucia McCallum (Plank) (Australia)*
- *Tobias Nilsson (Germany)*
- *Manuela Seitz (Germany)*
- *Stanislav Shabala (Australia)*

Working Group 1.4.2 deals with the modeling of geophysical and astronomical effects, and how they affect the consistent determination of the terrestrial and celestial reference frames. The work of the group generally falls into the following categories: (1) analysis and solution parametrization, (2) external models, and (3) internal inconsistencies within the VLBI technique. Over the last two years, there have been several presentations and published papers on these topics including troposphere modeling, source position estimation, and galactic aberration estimation. Several of the group members (D. MacMillan, S. Lambert, H. Krásná, and Z. Malkin) are also in the IVS Aberration Working Group, which has been working on a recommendation for a galactic aberration model for VLBI analysis and for use in the ICRF3 solution.

Karbon et al. (2016) addressed the issue of systematic variation of radio source positions and its effect on the TRF and EOP in VLBI solutions. They employed an efficient automated recursive spline fitting procedure to determine spline parameters for each source. The spline parametrizations are then applied as a priori models for each source (see Fig. 1.4.2.1). This allows sources with significant systematic variation, e.g., the ICRF2 "special handling" sources, to be included in the CRF NNR condition. In the ICRF2 solution, these sources were excluded from global estimation and were estimated as local session parameters, thereby weakening their contribution to estimated CRF. Depending on the distribution of sources in the NNR condition, this spline procedure expands the number of datum sources by 114-146% for 1980-1990 and 27-46% for 1990-2013. Benefits of this parametrization are an improvement in nutation precision with respect to the IAU 2006/2000 precession model of 10-12% and a reduction in position series precision of up to 2.5-4 mm for high latitude sites (likely due to sources at high declination), e.g., Ny-Ålesund, but less than 0.05 mm for other sites.

Plank et al. (2016) investigated the effect of source structure on the CRF. In simulations, they applied 2-component source models and determined the resulting shift in source position estimates. For sources with structure index of 2 or 3, these shifts tend to be aligned with the source jet direction. Based on this result, they investigated a method of source position estimation that tries to minimize the effect of source structure by estimating the component in the direction of the jet for each 24-hr observing session and the component perpendicular to the jet as a global parameter. In simulations using observing schedules for the operational R1/R4 sessions, the median effect of structure is reduced for sources with structure indices 2-3. It remains to try the method with observed data.

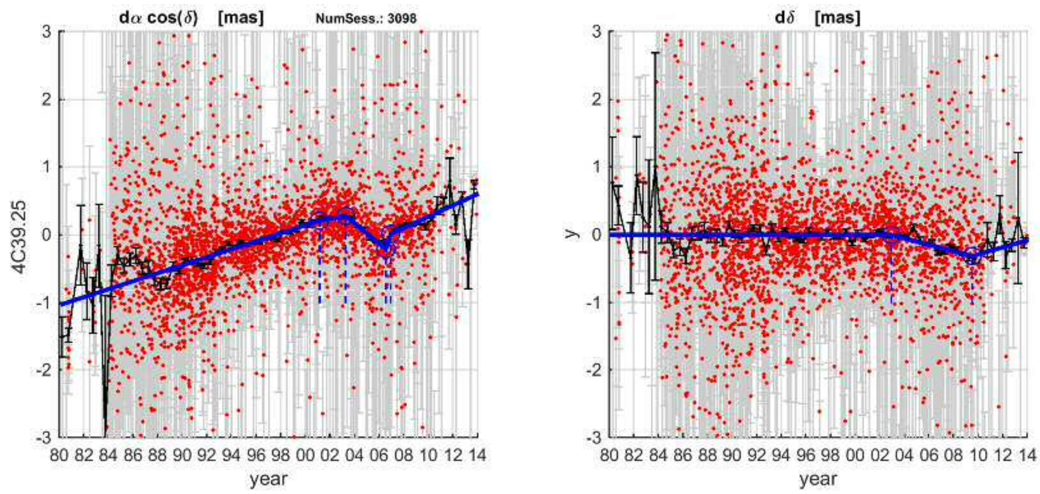

Fig. 1.4.2.1: Session-wise estimates of the radio source 4C39.25 position right ascension and declination (red points, semi-annual means (black curve), and the spline fits (blue curve) to the estimates (Karbon et al. 2016)

Krásná and Titov (2017) have investigated an alternative method of estimating galactic acceleration (secular aberration drift). They estimate for each source a global scale parameter relative to the a priori terrestrial reference frame. Considering the RA and DEC dependencies of the scale parameter, it turns out that the galactic acceleration vector (GA) can be derived from the scale parameter estimates for each source. Krásná and Titov then investigate the dependence of GA on the minimum number of observations required for a source to be included in the estimation. They obtained the same results with VieVS and with OCCAM software. Several estimates of the galactic aberration amplitude were then compared: 1) All VLBI data 1979-2016, standard estimation, 6.1 ± 0.2 µas/year; 2) VLBI R1/R4/NEOS/CONT sessions 1993-2016, standard estimation, 5.4 ± 0.4 µas/year; and 3) All VLBI data 1979-2016 where the number of observing sessions/source, scale parameter method, observations/source > 50, 5.2 ± 0.2 µas/year.

Ma C. et al. (2016) discusses different issues that need to be addressed in the development of ICRF3. The site observation data distribution has improved significantly so that southern hemisphere sites contribute 40% of all observations compared with 10-20% from 1995 to 2009. The average source position noise (uncertainty computed by decimation test) have improved since ICRF2 (2009) from (52 µas, 62 µas) to (32 µas, 43 µas). One of the significant systematic effects that has been found in recent global CRF solutions is that there is a systematic bias in declination that peaks at about 0.1 mas at 30ºS between current solutions using all data through 2016 and ICRF2 positions that were based on data from 1980 to 2009. This bias disappears if the Australian AUSCOPE network data observed during the period since ICRF2 is removed from analysis solutions. It is not clear whether the addition of the southern hemisphere stations has improved the observing geometry for southern declination sources relative to the source geometry available for ICRF2 or whether some AUSCOPE station errors cause the bias. Tests indicate that troposphere delay modeling does not cause the systematic.

Mayer et al. (2017) investigated the effect of different troposphere modeling options on the CRF declination bias of current solutions relative to ICRF2. They did not find any option that removed the bias, but there was a significant variation between options of up to 60 µas in the bias versus declination. Figure 1.4.2.2 shows the declination bias (smoothed over declination) for 1) standard wet zenith and gradient parameter estimation, 2) troposphere ray-traced delays applied without gradient estimation, 3) ray-traced delays applied with gradient estimation, 4) standard solution with elevation weighting, 5) standard solution using DAO gradient as *a priori* but with constraints, and 6) standard solution with DAO gradients with gradient constraints.

The difference in declination bias between the standard solution (1) and the solutions (2 and 3) that used ray-traced delays yields a declination bias that peaks at about 60 µas at about 30ºS. The rms variability of this difference is significantly greater if gradients are not estimated in the ray-traced delay solution.

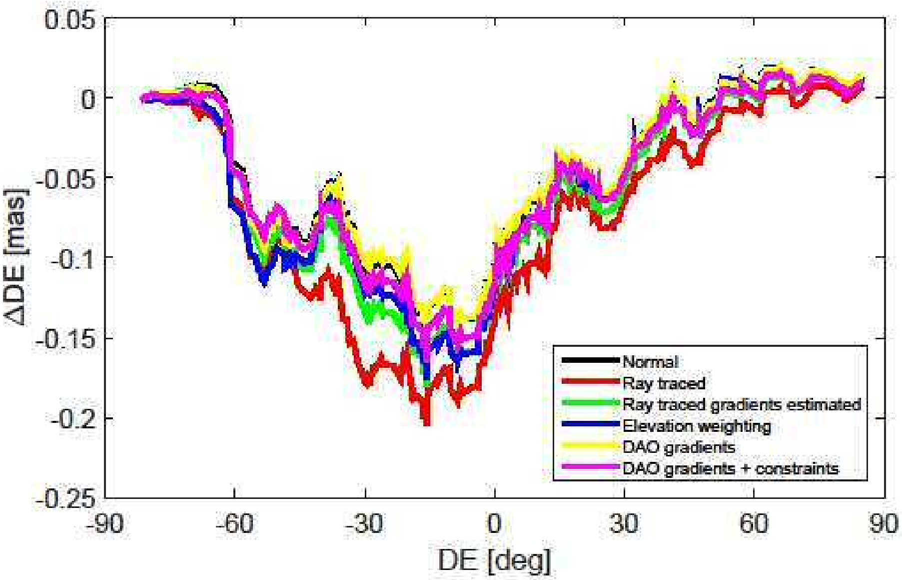

Fig. 1.4.2.2: Difference between declinations from each solution and ICRF2 declinations.

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WG 1.4.3: Improving VLBI-based ICRF and link to the Gaia-based CRF (GCRF)

Chair: *Sébastien Lambert (France)*

Members
- *Maria Karbon (Germany)*
- *Daniel MacMillan (USA)*
- *Zinovy Malkin (Russia)*
- *Francois Mignard (France)*
- *Jacques Roland (France)*
- *Manuela Seitz (Germany)*
- *Stanislav Shabala (Australia)*

The WG 1.4.3 was formed mid-2016 with the membership including François Mignard (specialist of astrometry, Co-PI of the ESA Gaia mission) from Observatoire de la Côte d'Azur, France, Jacques Roland (specialist of active galactic nuclei) from Institut d'Astrophysique de Paris, France, Maria Karbon (specialist of VLBI) from GFZ, Potsdam, Germany, and Stanislav Shabala (specialist of AGN) from University of Tasmania, Australia, as well as the chairs of SC 1.4, WG 1.4.1, and WG 1.4.2.

The year 2016 was the year of the Gaia Data Release 1 (in which the WG 1.4.3 Chair is involved as a member of the Gaia DPAC CU 9 validation group). DR1 constitutes a great step in the field of high precision astrometry because it offers, for the first time, a CRF of an accuracy similar to VLBI but realized independently, although at different wavelengths (Mignard et al. 2016, Arenou et al. 2017). The DR1 axes were shown to agree with the ICRF axes to within a few hundreds of microseconds of arc. The next release is scheduled for mid-2018 with an improved accuracy. The comparison of VLBI and Gaia should therefore help in improving both techniques by detecting their respective defects. It should also bring some indirect benefit to geodesy following that everything improving the CRF is good for VLBI and therefore good for Earth rotation and TRF measurements.

Mid-2016, the IAU ICRF3 WG launched a first round of comparisons of prototype CRF solutions. Both those solutions and recent, publicly available, VLBI solutions (e.g., from GSFC or USNO) revealed at least two important points:
- Most of the VLBI catalogs provide non-Gaussian correlated errors that limit the accuracy of the estimates to some tens of microseconds of arc (Fig. 1.4.3.1). This noise arises likely from unmodeled or mismodeled correlated station-dependent parameters (in other words, the modeling of the troposphere and clock behavior should be improved).
- VLBI catalogs present pronounced zonal errors increasing as the declination decreases to southern values. The reason(s) of this systematic is not clear at this time although there are some evidences in the network geometry and/or a calibration defect on some antennas in Australia. This problem is being addressed within the ICRF3 WG. If solved, it will be a great step forward a more accurate, ground-based, quasi-inertial reference frame compared to the ICRF2. If not solved, these zonal errors will constitute one of the striking difference with Gaia that, owing to the scanning law, does not show such errors (Fig. 1.4.7).

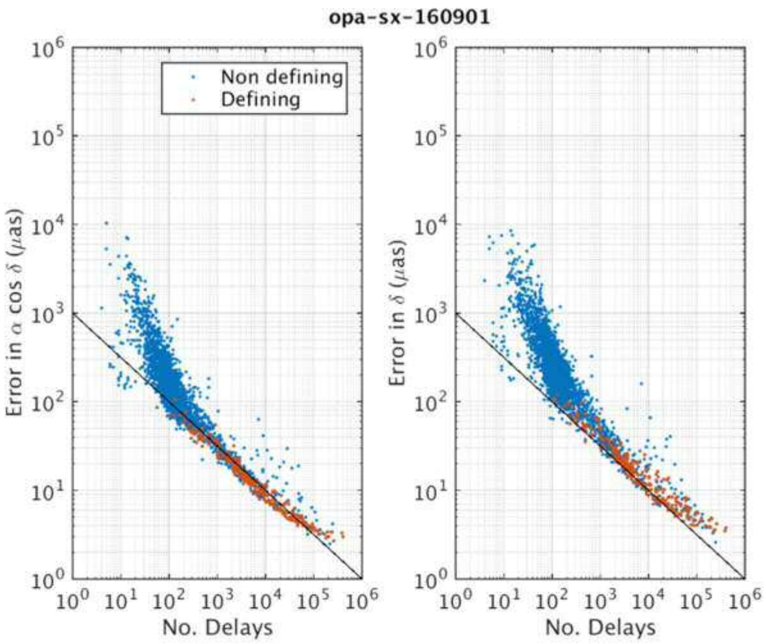

Fig. 1.4.3.1: The standard error on radio source positions as a function of the number of delays from a global analysis of the full VLBI observational database since 1979 with Calc/Solve at Paris Observatory. The main feature of these figures is the fact that the standard errors do not decrease as the number of observations increases, as expected for a Gaussian-noise.

Questions on how the geodetic products (e.g., Earth orientation parameters and TRF) are impacted by the above-mentioned problems and how a modified VLBI analysis strategy could improve them have not been addressed yet within the WG 1.4.3. A side question would be whether the Gaia catalog could be used to `clean' the systematics of the VLBI CRF, although the difference between radio and optical position (typically of the order of 0.2 mas) will impose some limitation.

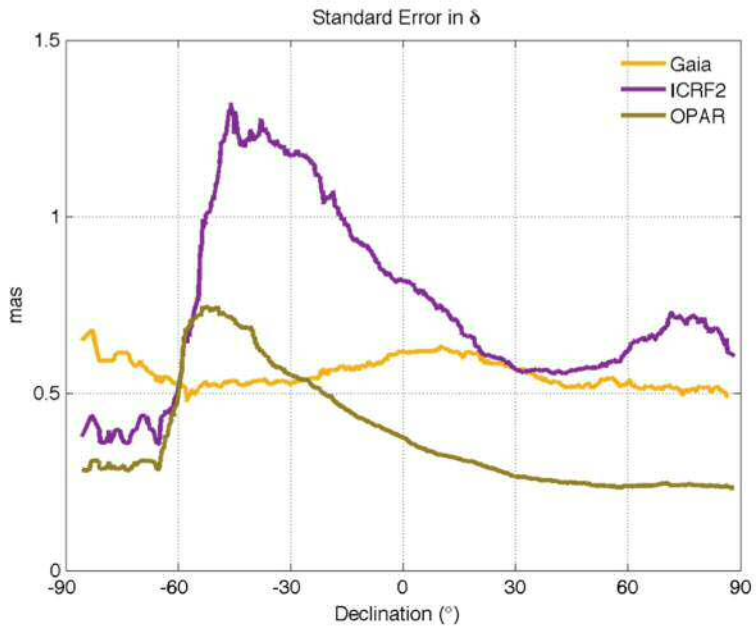

Fig. 1.4.3.2: The smoothed standard error in declination versus the declination as given in (violet) the ICRF2, (yellow) the Gaia DR1 catalog restricted to quasars, and (green) a global analysis of the full VLBI observational database since 1979 with Calc/Solve at Paris Observatory. The main feature of this plot is the fact that (i)

both ICRF2 and OPAR show an increase of the error at Southern declination (although less prominent for OPAR), and (ii) the absence of such a behavior for Gaia. Note that the lack of sources close to the South Pole makes the curves irrelevant at south of 60 degrees.

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Mignard, F., Klioner, S., Lindegren, L. et al. 2016, Gaia data release 1: reference frame and optical properties of ICRF sources, Astron. Astrophys. 595, 5

Commission 1 Joint Working Group 1.1: Site Survey and Co-Location

Chair: *Sten Bergstrand (Sweden)*
Vice Chair: *John Dawson (Australia)*

Ex officio members

- *Erricos C. Pavlis, ILRS (USA)*
- *Jerome Saunier, IDS (France)*
- *Jim Long, NASA SGP (USA)*
- *Ralf Schmid, IGS (Germany)*
- *Rüdiger Haas, IVS (Sweden)*
- *Xavier Collilieux, IGN Surveying entity (France)*

Members

https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html

Activities and publications during the period 2015-2017

The activities have been directed towards a common terminology in space geodesy in order to facilitate exchange of data between services. This has improved surveying practices for DORIS with a local tie uncertainty between observation and topocentric measurements now estimated to be of order 3 mm. Specially adapted programs have been developed to monitor the geometric reference points of VLBI telescopes with terrestrial total stations during observation schemes. Internal VLBI telescope deformations have also been shown to contribute significantly to position uncertainties, and further development in this field is expected. The Onsala-Metsähovi baseline was observed between the IGS and IVS stations at the sites, simultaneously with terrestrial and GNSS measurements of the local ties; processing has been delayed. Different GNSS antenna calibration methods exhibit results that prohibit the determination of local ties to the desired level; an issue which touches the scope of the WG but requires a broader approach.

Appleby G., Behrend D., Bergstrand S., Donovan H., Emerson C., Esper J., Hase H., Long J., Ma C., McCormick D., Noll C., Pavlis E., Ferrage P., Pearlman M. (Lead), Saunier J., Stowers D., Wetzel S. (2015), GGOS Requirements for Core Sites (Rev. 2) https://cddis.nasa.gov/docs/2015/SiteRecDoc_Rev2_20151101.pdf

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Saunier J. (2016), Assessment of the DORIS network monumentation, Advances in Space Research 58 (12), 2725-2741. doi:10.1016/j.asr.2016.02.026.

Commission 1 Joint Working Group 1.2: Modelling Environmental Loading Effects for Reference Frame Realizations

Chair (2015-2017): *T. Van Dam (Luxembourg), new vice chair (2017-2019)*
Vice Chair (2015-2017): *A. Mémin (France), new chair (2017-2019)*

Members

- *Zuheir Altamimi (France)*
- *Johannes Böhm (Austria)*
- *Jean-Paul Boy (France)*
- *Xavier Collilieux (France)*
- *Robert Dill (Germany)*
- *Pascal Gegout (France)*
- *Matt King (Australia)*
- *Anthony Mémin(France)*
- *Laurent Métivier(France)*
- *Gerard Petit(France)*
- *Jim Ray (USA)*
- *Leonid Vitushkin*
- *Xiaoping Wu (USA)*

Activities and publications during the period 2015-2017

The activity of the working group has been focused on the impact of loading deformation in GNSS time series. Several loading models have been used and compared. Loading corrections have been applied a posteriori and at the observation level. Results have been presented during a splinter meeting organized on Wednesday 26th April, 2017 at the EGU General Assembly. The meeting came to the following recommendations for 2017 – 2019:

- Extend investigation of loading effects to other geodetic techniques (VLBI, SLR) and perform an homogeneous analysis with all the techniques
- Check and clearly display the strategy regarding loading effects adopted by each analysis centre
- An up to date list of references should be displayed on the working group website
- This working group should be continued
- A workshop is suggested for 2018 to discuss points that have not been discuss during the splinter meeting (loading and geocenter motion, current and future approaches in modelling loading effects, recommendations to IERS)

It is also proposed, given the new external responsibilities T. van Dam has, that A. Mémin takes the lead of the JWG 1.2, T. van Dam will be co-chair.

Commission 1 Joint Working Group 1.3: Troposphere ties (joint with Sub-Commission 4.3)

Chair: *Robert Heinkelmann (Germany)*
Vice Chair: *Jan Douša (Czech Republic)*

Members

- *Kyriakos Balidakis (Greece)*
- *Elmar Brockmann (Switzerland)*
- *Sebastian Halsig (Germany)*
- *Younghee Kwak (South Korea)*
- *Gregor Möller (Germany)*
- *Angelyn W. Moore (USA)*
- *Tobias Nilsson (Sweden)*
- *Rosa Pacione (Italy)*
- *Tzvetan Simeonov (Bulgaria)*
- *Krzysztof Sośnica (Poland)*
- *Peter Steigenberger (Germany)*
- *Kamil Teke (Turkey)*
- *Daniela Thaller (Germany)*
- *Xiaoya Wang (China)*
- *Pascal Willis (France)*
- *Florian Zus (Austria)*

Activities and publications during the period 2015-2017

The new working group was established in 2015. The terms of reference and objectives were drafted, discussed and approved. The working group chair gave the first presentation about the working group objectives at the IAG Commission 4 Meeting at the Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland, on 5th of September 2016, see http://www.igig.up.wroc.pl/IAG2016/?page=2. The first regular Working Group Meeting was held on the 26th of April 2017 aside the EGU General Assembly at Vienna University of Technology, Vienna, Austria.

During past years, Geodetic Observatory Pecny (GOP) has developed a powerful database, GOP-TropDB (Gyori and Dousa, 2017), for the intra-/inter-technique comparisons for tropospheric parameters stemming from data analyses of space geodetic techniques. The database was completed with a web-gui service for interactive exploration of site/pair metadata and comparison statistics. It is under construction within the IGS Tropospheric WG (Hackman et al, 2016).

The current database is ready to accommodate tropospheric path delays in zenith and horizontal gradients estimated using data of GNSS, VLBI and DORIS, Numerical Weather Model (NWM) re-analysis and radiosondes at least. For inter-technique comparisons of nearby stations, tropospheric parameters usually refer to different locations and thus require vertical, time-dependent correction between site reference altitudes. We developed and assessed several models for calculating tropospheric ties/corrections and vertical scaling with support of different parametrization, vertical approximations and different meteorological data.

The tropospheric ties are optimally separated into two components - zenith dry and wet delays - and we thus focused on developing new model particularly for the wet scaling (Dousa and Elias, 2014). Different strategies for both wet and dry scaling were evaluated in the scenario using numerical weather data fields only, i.e. by approximating NWM differences in vertical profile by using new models for parameter scaling. Additionally, the impact of tropospheric ties was assessed in a comparison of GNSS and radiosonde tropospheric parameters and it will be finally evaluated by applying tropospheric ties specifically for GNSS and VLBI intra/inter-technique site collocations.

The online service has been developed for calculating tropospheric parameters from NWM reanalysis which can be directly used for several scenarios of calculating tropospheric ties. The web is currently available at http://www.pecny.cz/Joomla25/index.php/gop-tropdb/tropo-model-service and it is under preparation to become a part of the IGS Tropospheric WG web-pages (http://www.igs.org).

swisstopo is since years active in generating information which allow to extract tie information. With the enhancement from GPS to GPS/GLO in 2008, 9 from 30 site antennas and receivers were not switched to the new technology: parallel to the continued GPS-only station double stations were build. Furthermore, local tie measurement linked these double stations on a precision of a millimeter (baselines of some 10 meters).

In May 2015, all permanent stations (with the exception of the old GPS-only stations) were enhanced to GPS/GLO/GAL/BDS and a data flow based on RINEX3 was established in summer 2015. Since summer 2016 the complete processing chain is switched to Multi-GNSS using a special development version of the Bernese Software and using CODES MGEX orbit products. The tie information is extremely helpful, because the antennas were "only" calibrated on GPS/GLO.

Routinely, so-called inter system transformation parameters are calculated on a daily basis, showing the differences of coordinates and troposphere parameters between GPS and the satellite systems GLO/GAL/BDS. Troposphere biases are extremely sensitive to analysis models (especially the antenna PCVs for receiver and satellite antennas). These parameters are made available online. Example ZIM2:
http://pnac.swisstopo.admin.ch/pages/en/qsumzim2.html#TRA_LONG

Local refraction effects in space geodetic techniques are normally investigated by small scale GNSS networks. However, with the new pair of radio telescopes at the Geodetic Observatory Wettzell in Germany, the Institute of Geodesy and Geoinformation, University of Bonn, is now able to carry out similar investigations with geodetic VLBI observations, which are affected by the same refraction phenomena. The main objective is to analyse systematic effects between the tropospheric parameters in space and time. In a further step, this scenario is augmented by a local GNSS network set up on the Wettzell area in order to investigate the systematics between different measurement techniques.

The Vienna University of Technology contribution to JWG 1.3 aims at improving the understanding of systematic effects in tropospheric delay modelling between various satellite techniques. First action is related to the modelling of hydrostatic effects.

Comparisons between in-situ measurements of pressure and global HRES weather model data (as provided by ECMWF) reveal in general high accuracy in pressure within 0.5 +/- 1 hPa. Slightly worse agreement was found between in-situ data and regional weather model data (60% larger standard deviation). However, independent from the pressure sources high consistency can only be guaranteed if comparable data processing methods are applied. In particular, vertical interpolation methods and distance dependent pressure variations are further investigated and compared at co-located sites.

Further activity is related to the modelling of wet delays. The GNSS tomography technique allows for estimation of accurate wet refractivity fields in the lower atmosphere. By vertical integration or ray-tracing through these fields, accurate tropospheric wet delays can be derived.

Introduced into the parameter estimation process of various space-geodetic techniques their impact on the station coordinates is analysed. Therefore, the wet delays are either treated as a priori information or as replacement of the tropospheric parameters.

ASI/CGS is going to contribute to objective 1 through VLBI and GNSS inter-technique comparison of atmospheric parameters at the eight European co-located sites. These sites are associated with the European Reference Frame (EUREF) and the European part of the International VLBI Service for Geodesy and Astrometry (IVS), called European VLBI group for Geodesy and Astrometry (EVGA). We plan to compute long-term time series of the differences between the EPN-Repro2 (Pacione et al. 2017) for the period 1996-2014 completed with the EPN operational products afterwards and the EVGA combined solutions.

The German Space Operations Center (GSOC) of the German Aerospace Center (DLR) performs precise orbit and clock determination for satellites of the global and regional navigation systems GPS, GLONASS, Galileo, BeiDou, and QZSS on a routine basis. A global network of about 150 stations is processed with the NAPEOS software to solve for station coordinates, troposphere and Earth rotation parameters, receiver and satellite clocks as well as satellite orbit parameters. DLR/GSOC provides normal equations obtained from the multi-GNSS analysis in SINEX format including station coordinates, troposphere, and Earth rotation parameters for analysis and combination studies of the joint working group.

In last year Shanghai Astronomical Observatory, Chinese Academy of Sciences, studied the possibility of common tropospheric parameters as another ‘local ties’ of TRF. The work mainly includes the following:

1) We compared the tropospheric parameters obtained by different techniques at co-located sites and found the VLBI tropospheric zenith delay is approximately consistent with that of GNSS. But there exists a big constant term and a long period (about 1 year) term in the tropospheric zenith delay difference between SLR and GNSS.
2) We compared the mapping function used in SLR (FCULa mapping function) and GNSS (GMF) at all co-located sites, we found the difference is very small.
3) Compared with the strategy used in GNSS, our SLR orbit determination didn’t consider estimating the ZTD parameters. So, we change our software to estimate the ZTD parameters in SLR. The results show that there are big differences between the dry zenith delay models of SLR and GNSS. We analyzed the difference and found that it is almost approximately a scaling factor between the two kinds of dry zenith delays. The factor is equal 1.061392746364195.
4) Then we compare the wet delays obtain by SLR and GNSS. And there was still a big offset exiting in SLR and GNSS zenith wet delay because the radio wavelength technique is more sensitive to water vapor in troposphere than optical wavelength technique. The SLR zenith wet delay is very small.
5) Next step, we decide to consider the effect of the horizontal gradients of atmosphere on tropospheric delay in SLR, which is described by G. C. Hulley (2007). We will adopt the parameterization used in GNSS to our SLR data processing, then estimate the horizontal gradient parameters and , finally compare them with GNSS. We will continue to find the rules of the ZTD offsets between SLR and GNSS which is of great help to apply tropospheric ties for a combination of the space geodetic techniques.

At GFZ Potsdam we installed a service which provides Numerical Weather Model (NWM) based tropospheric parameters valid for radio frequencies. The station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~800 GNSS stations. Recently we updated our ray-trace algorithm (Zus et. al 2014) in order to derive tropospheric parameters valid for optical frequencies. Therefore, station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~100 SLR stations as well. The tropospheric parameters are derived from short range forecasts and are

available with no latency. The underlying NWM is the NCEP Global Forecast System (0.5 deg resolution, 31 pressure levels). The epochs 0, 6, 12 and 18UTC are based on 6h forecasts whereas the epochs 3, 9, 15, 21UTC are based on 9h forecasts. The data and a short description (how to use) are available at ftp://ftp.gfz-potsdam.de/pub/home/kg/zusflo/TRO/.
Currently we do not fully exploit the information from NWMs. For example, we use model level (or pressure level) fields but we do not take into account the near surface fields. Within this working group we will update our algorithms to extract the near surface pressure, temperature and humidity. We will derive the corresponding lapse rates which can then be used as tropospheric ties.

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Commission 2 – Gravity Field

http://alpha.fesg.tu-muenchen.de/IAG-C2/

President: Roland Pail (Germany)
Vice President: Shuanggen Jin (China)

Structure

Sub-Commission 2.1:	Gravimetry and Gravity Networks
Sub-Commission 2.2:	Methodology for Geoid and Physical Height Systems
Sub-Commission 2.3:	Satellite Gravity Missions
Sub-Commission 2.4:	Regional Geoid Determination
Sub-Commission 2.4a:	Gravity and Geoid in Europe
Sub-Commission 2.4b:	Gravity and Geoid in South America
Sub-Commission 2.4c:	Gravity and Geoid in North and Central America
Sub-Commission 2.4d:	Gravity and Geoid in Africa
Sub-Commission 2.4e:	Gravity and Geoid in Asia-Pacific
Sub-Commission 2.4f:	Gravity and Geoid in Antarctica
Sub-Commission 2.5:	Satellite Altimetry
Sub-Commission 2.6:	Gravity and Mass Transport in the Earth System
Study Group 2.1.1:	Techniques and metrology in terrestrial (land, marine, airborne) gravimetry
Joint Working Group 2.1:	Relativistic Geodesy: Towards a new geodetic technique
Joint Working Group 2.2:	Validation of combined gravity model EGM2020
Joint Working Group 2.1.1:	Establishment of a global absolute gravity reference system
Joint Working Group 2.2.1:	Integration and validation of local geoid estimates
Joint Working Group 2.2.2:	The 1 cm geoid experiment
Joint Working Group 2.6.1:	Geodetic observations for climate model evaluation
Working Group 2.6.1:	Potential field modelling with petrophysical support

Overview

This report presents the activities of the entities of Commission 2 for the reporting period 2015-2017. As shown above, Commission 2 consists of 6 sub-commissions (SC), whereby SC 2.4 is composed of 6 regional sub-commissions, and several Working Groups, Joint Working Groups and Study Groups. Most of these entities were very active and made significant progress in their specifically stated objectives and program of activities. The corresponding reports can be found below, and the main achievements are summarized in the end of this overview section.

Activities during the reporting period 2015-2017

Commission 2 fostered and significantly supported main tasks and objectives of the present IAG period, such as the realization of an International Height Reference System (IHRS; cf. IAG 2015 resolution no. 1), the establishment of a Global Absolute Gravity Reference System (GAGRS; cf. IAG 2015 resolution no. 2), and the realization of a Global Geodetic Reference System (GGRS; following UN Resolution 69/9, and IUGG 2015 resolution no. 3). Based on IUGG 2015 resolution no. 2, commission 2 was also very active in advocating future gravity field mission, by means of supporting the mission proposal *Earth System Mass Transport*

Mission² (e.motion²) in response to the ESA Earth Explorer 9 (EE9) call, and by increasing the visibility towards EU/Copernicus by co-organizing the high-impact event "Observing water transport from space – a vision for the evolution of Copernicus" (31 Mai 2017, Brussels).

Commission 2 also very actively contributed to GGOS-related activities. A keynote presentation at the GGOS Days 2016 on the role of gravity field products in the context of the Global Geodetic Observing System was given, with special emphasis on height unification and integration of gravity/height into a modern GGRF concept (following the corresponding IAG position paper), and an invited paper was presented in the respective GGOS session at EGU2016, Vienna.

Commission 2 also performed several consulting activities, e.g., regarding a recommendation on the future mission operation of Jason-2 as geodetic mission, and for several entities of GGOS, such as the Satellite Mission Standing Committee as part of the Bureau of Networks and Observations, the Bureau of Products and Standards, and the GGOS Committee on the Establishment of the GGRF.

Commission 2 was involved in the organization of several scientific conferences and workshops, as well as sessions at EGU and AGU. More details on this issue will be provided in the following section.

Conferences and Meetings

Gravity, Geoid and Height Systems (GGHS) 2016, Thessaloniki, Greece

The official Commission 2 symposium was held between September 19-23, 2016, in Thessaloniki, Greece, at the premises of the Aristotle University of Thessaloniki (Figure 1). It was the first Joint Commission 2 and IGFS Symposium co-organized with GGOS Focus Area 1 "Unified Height System". GGHS2016 was composed by 6 sessions spanning the entire 5 days of the program. For GGHS2016, 211 abstracts have been received, out of which 94 have been scheduled as oral presentations and 117 as posters. 204 participants from 36 countries participated in the conference. It should be particularly emphasized that this symposium was able to attract also the young generation of scientists, since 35% of the total number of participants were either MSc Students or PhD candidates. Related papers will be published as a special volume of the IAG Symposia Series, which is currently in preparation.

Figure 1 GGHS 2016, Thessaloniki, Greece

In addition to the scientific part, GGHS2016 has also hosted a number of splinter meetings, where vibrant exchange of ideas took place. The following splinter meetings have been organized:

- IAG Commission 2 Steering Committee meeting
- IGFS meeting
- JWG 0.1: Strategy for the Realization of the International Height Reference System (IHRS)
- GGOS Committee on Satellite Missions
- GGOS Committee on Establishment of the Global Geodetic Reference frame
- SC 2.1: Gravimetry and Gravity Networks
- SC 2.2: Methodology for Geoid and Height Determination
- SC 2.3: Satellite Gravity Missions
- JSG 0.11: Multi-resolutional aspects of potential field theory
- GEOMEDII Project Meeting

IAG/IASPEI General Assembly 2018, Kobe, Japan
Commission 2 was also deeply involved in the preparation of the scientific program of the IAG/IASPEI General Assembly 2018, Kobe, Japan. The organization of the two main gravity-related sessions have been coordinated by the president ("Static gravity field") and vice-president ("Temporal gravity field") of Commission 2, and it also supported the preparation of several joint and union sessions.

Further theme-specific events
During the reporting period 2015-2017, commission 2 also initiated, fostered and supported several theme-specific conferences, meetings and workshops, which are presented in detail in the following individual reports of the respective entities of Commission 2.

Activities of the Sub-Commissions

SC 2.1 Gravimetry and Gravity Networks

SC 2.1 together with its associated JWG 2.1.1 and SG 2.1.1 concentrated on the realization of the IAG Resolution no. 2 for the establishment of a global absolution gravity reference system, and on the realization of a Consultative Committee on Mass and Related Quantities (CCM-IAG strategy). The SC 2.1 activities also focussed on the investigation and further development of the instrumentation and methods of absolute and relative gravity measurements, showing notable developments in many parts of the world. SC 2.1 also organized the fourth IAG Symposium "Terrestrial gravimetry – Static and mobile measurements", which was held in April 2016 in St. Petersburg, with 123 participants from 18 countries.

SC 2.2 Methodology for Geoid and Physical Height Systems

SC 2.2 contributed significantly to the realization of the IHRS, and provided active support to the respective JWG 0.1.2, addressing open issues such as agreed standards for geoid computation, and fostering further scientific development related to geoid determination and physical height systems. Another important activity was the initiation of JWG 2.2.2, aiming at the development and validation of geoid determination methodology by benchmarking various region geoid determination approaches. Another topic of interest is how to merge and validate local and regional geoid models, which is performed by JW 2.2.1.

SC 2.3 Satellite Gravity missions

The main activities of SC 2.3 include the promotion of scientific investigations regarding current and future gravity field missions. A new combination service for time-variable field solutions, with the purpose to provide unique and user-friendly gravity products to a wider user community, was developed in the frame of the Horizon 2020 Framework Program of the European Commission, and shall become an integral component of the IGFS infrastructure in the future. In order to increase the visibility towards EU/Copernicus and to emphasize the importance of sustained observation of gravity field changes reflecting mass transport processes in the Earth system, SC 2.3 was deeply involved in the organization of two EU events held in Brussels. Additionally, SC 2.3 contributed to the recommendations of the ESA Geodetic Missions Workshop 2017 in Banff, Canada.

SC 2.4 Regional Geoid Determination

SC 2.4 coordinates the activities of the 6 regional sub-commissions on gravity and geoid determination and supports the organization of conferences, workshops and schools. Highlights of the reporting period are a complete re-computation of the European quasi-geoid (EGG2015) based on the newest version of global GOCE models, the generation of a new South American geoid model, and a regional geoid for the whole continent of Africa. Another focus was the modernization of the US National Spatial Reference System. In almost all regions the data coverage could be improved. As an example, the first Antarctic-wide gravity anomaly dataset was published. Albeit the continuous progress, many activities still suffer from restrictions regarding data access, and also from the fact that the willingness to contribute to international (IAG) activities and data exchange is very low in several regions of the world.

SC 2.5 Satellite Altimetry

The main activities of SC 2.5 include algorithm development for processing of both conventional and new satellite altimetry missions, and the use of improved satellite altimeter data and products in various applications, such as the improvement of global marine gravity field models. SC 2.4 also focussed on the investigation of sea level, sea level change and especially sea level extremes, also connecting the results with the understanding of its causes. Special emphasis was also given to retracking solutions and calibration/validation methods to improve the performance of altimetry especially in coastal regions and for inland water applications. Additionally, SC 2.4 provided consultancy for the recommendation on the Jason-2 geodetic mission issue to the committee of the Jason-2 Steering Group, targeting with a densified Jason-2 ground track for a better resolution of gravity anomalies with narrow east-west content.

SC 2.6 Gravity and Mass Transport in Earth System

SC 2.6 was mainly active via its two (joint) working groups, JWG 2.6.1 “Geodetic observations for climate model evaluation”, and WG 2.6.1 “Potential field modelling with petrophysical support”. Together with JWG 2.6.1, a workshop on “Satellite Geodesy for Climate Studies”, to be held on September 19-21, 2017, in Bonn, has been organized, with the goal to bring together geodetic experts and climate modellers, and thus to foster the use of geodetic products for climate studies.

Activities of Study Groups

There is one SG (SG 2.1.1) reporting to Commission 2 via SC 2.1, and Commission 2 is involved in eight JSGs as a partner, but none of these reports directly to Commission 2. Their reports can be found in the ICCT section (7 JSGs), and the Commission 3 section (1 JSG).

Activities of Working Groups

One WG and six JWGs are reporting to Commission 2. Their reports can be found in the corresponding chapters. Two out of these 6 JWGs (JWG 2.1, JWG 2.2) are attached directly to Commission 2, the four others to the SCs 2.1, 2.2 and 2.6, respectively. Two JWGs (JWG 2.2, JWG 2.2.2) have been established only recently and therefore are not included in the Geodesist's Handbook 2016. Commission is involved in another JWG on the realization of the IHRS, which is reporting to GGOS.

Sub-commission 2.1: Gravimetry and Gravity Network

Chair: *Leonid F. Vitushkin (Russia)*
Vice Chair: *Akito Araya (Japan)*

Overview

In the period 2015-2017 Sub-Commission 2.1 with its Joint Working Group JWG 2.1.1 and Study Group SG 2.1.1 was concentrated on the realization of the IAG Resolution No. 2 for the establishment of a global absolute gravity reference system (GAGRS) (http://www.iugg.org/assemblies/2015prague/2015_Prague_Comptes_Rendus_Part1.pdf, page 69) and on the realization of common Consultative Committee on Mass and Related Quantities (CCM) – IAG Strategy for metrology in absolute gravimetry.

The Sub-commission activities strongly focused on the investigations of the instrumentation and methods of the absolute and relative terrestrial gravity measurements, on the support and development of the gravity networks as well as on the development of new GAGRS.

The development of measurement techniques for gravimetry and the development of the gravity networks are interrelated. The growing number of absolute gravimeters (AG) changes the strategy in the measurement and formation of gravity networks.

Symposiums, the meetings of JWG and WG dedicated to the topics of ToR of SC2.1 were organized in the current period.

Common work of Sub-commission and CCM on the establishment of traceability to SI units (Realization of CCM-IAG Strategy)

The significant aspect of the Sub-commission is the attention to the confidence in gravity measurements provided by close cooperation of Sub-commission JWG and WG with the metrological community presented by the Working group on gravimetry (WGG) of the Consultative committee on mass and related quantities (CCM). CCM WGG, Regional metrology organizations in cooperation with SC2.1 continue the organization of the comparison of absolute gravimeters. The regional comparison of EURAMET (European Association of National Metrology Institutes) was organized [Metrologia, 2017, 54, Tech. Suppl., 07012] was organized with the participation of 4 National metrology institutes and 13 geodetic and geophysical institutes at the new campus of the University of Luxembourg in Belval in November 2015. The comparisons of AGs extended over North America and Asia. The comparison in North America organized by the CCM and SIM (Inter-American Metrology System) at the Table Mountain Observatory (Boulder, Colorado, USA) in 2016. Currently the 10th international comparison of AGs under auspices of the CCM is under the preparation in the Changping Campus of the National institute of metrology (NIM) of China and planned for October 2017.

It is of importance that the gravimetry sites for the comparisons can be used as the absolute gravity reference stations of the GAGRS because of high precision of the values of free-fall acceleration at these stations obtained in the comparisons. The CCM-IAG Strategy provides the possibility of calibration of AGs by means of the national primary measurement standards of acceleration unit in gravimetry (i.e. in the measurement of free-fall acceleration). For example, such a calibration of the AG FGL was performed by the primary measurement standard in gravimetry of Russian Federation and the national calibration certificate was issued. The calibrations of AGs against of national measurement standards in gravimetry allow to provide the traceability of AGs to SI units. With a growing number of AGs the calibrations will make possible to confirm the metrological characteristics of AGs without the participation in the CCM and RMO comparisons of AGs which are not always suitable because of transportation problem, time table and other problems.

The IV-th IAG Symposium "Terrestrial gravimetry. Static and mobile measurements. TG-SMM-2016"

The Sub-commission organized the IV-th IAG Symposium "Terrestrial gravimetry. Static and mobile measurements. TG-SMM-2016" in St Petersburg, Russian Federation on 12-15 April 2016. The slogan of the symposium was "Advancing gravimetry for geophysics and geodesy". The International Scientific Committee chaired by Vladimir G. Peshekhonov (Russia) and Urs Marti (Switzerland) consisted of the members from 12 countries. The symposium was held at the State Research Center of Russian Federation Concern CSRI "Elektropribor" from 12 to 15 April 2016. According to the field of the activities of Sub-commission 2.1 the TG_SMM-2016 consisted of four thematic sessions:

- Terrestrial, shipboard and airborne gravimetry.
- Absolute gravimetry.
- Relative gravimetry, gravity networks and applications of gravimetry.
- Cold atom and superconducting gravimetry, gravitational experiments.

The proceedings of the symposium included 43 papers. 58 presentations have been included in the program. 123 participants from 18 countries – Argentina, Austria, Brazil, China, Czech Republic, Denmark, Finland, France, Germany, Italy, Japan, Kazakhstan, Norway, Russia, Sweden, Switzerland, Ukraine, USA attended the symposium.
Together with the presentations on the development of the absolute and relative gravimeters based on "familiar" physical principles and mechanisms (springs, macroscopic test objects, etc.) the quantum principles and atomic test objects (the clouds of cold atoms) used for the design of new gravity measuring instruments were a major idea of many other talks.

Regional activities in gravimetry

South America (reported by Silvia Alicia Miranda)

Superconducting Gravimetry: In July 2015 the Argentine-German Geodetic Observatory (AGGO) was inaugurated (Figure 2). It is set up in La Plata city (Buenos Aires, Argentina) and it is unique in its type in South America. AGGO is a joint project between the National Scientific and Technical Research Council of Argentina (CONICET) and the BKG. The Observatory has new measurement instrumentation that will be part of the global infrastructure for the observation of the Earth. A superconducting gravimeter SG038 is one of the instruments installed in AGGO, currently the unique of its kind in Latin America and the Caribbean. SG038 data, under the name of La Plata Station, are available through the database of the International Geodynamics and Earth Tide Service (IGETS).

Figure 2 AGGO geodetic observatory (left) and the superconducting gravimeter SG038 (right).

Gravimetry and Gravity networks: During 2015 and early 2016 considerable effort was made by the National Geographic Institute of Argentina (IGN) members on measuring, processing and publishing data belonging to new gravity control networks in Argentina:

- Absolute gravity control network (acronym in Spanish is RAGA): it is composed of 36 points measured from 2014 to 2017 using two Micro-g LaCoste A10 AGs (see http://www.ign.gob.ar/content/tipos-de-redes). This is a project of IGN in close cooperation with the Argentine National Universities of La Plata, Rosario and San Juan, the University of San Pablo and the Institut de recherche pour le développement (IRD).
- First order gravity network (RPO-Ar): 30 gravity monumented point stations were measured. This network consists of 229 points mostly matching monumented stations of the Argentine levelling network. The standard deviations of the adjusted gravity values are lower than 0,04 mGal.
- Second order gravity control network (RSO-Ar): 10 new point stations. RSO-AR consists of approximately 14,000 points coinciding with monumented stations of the high precision levelling network. The historical field notebooks were digitized, reprocessed and then fixed to RPO-Ar network.
- Third order gravity network in Argentina (RTO-Ar): 633 new point stations. RTO-AR is composed of about 6,000 points belonging to precision levelling lines and stations without monumentation.

First National Workshop of AGGO: The workshop was successfully held in the city of La Plata (Argentina) from April 14 to 16 2016 with more than 80 participants. It was organized with the assistance of CONICET and RAPEAS (Argentine Network to the Study of the Upper Atmosphere). A total of 24 oral presentations were given with the main goals of exchange information, discuss ideas and establish plans of work oriented to the use of the AGGO data and products.

Europe (reported by Przemyslaw Dykowski)

- *Austria:* Regular annual AG determinations are carried out on 9 stations across the country. All determinations are co-located with EPN stations with addition to other locations.
- *Czech Republic:* Currently 427 gravity stations are considered as the gravity control system. This is based upon 17 AG stations that in years 2016 – 2017 will be re-measured with the recently acquired FG5X-251 gravimeter from the Pecny Observatory. Pecny observatory also takes part in the EPOS project also in terms of gravimetry.
- *Finland:* The First Order Gravity Network of Finland, FOGN, was re-measured with the A10-020 in 2009-2010. During the measurement campaigns the measurements were controlled by visiting FG5-sites every 1-2 times/week. The FGI maintains the national measurement standard of the acceleration unit in the measurement of free-fall acceleration (AG FG5X-221). There are the comparison facilities at the Metsähovi observatory. At the observatory the old superconducting gravimeter SG-T020 stopped working in autumn 2016. The new superconducting gravimeter iOSG022 was installed in the end of 2016 and is now working well and producing high-quality data. The iGrav013 is also registering at Metsähovi since spring 2016.
- *Germany:* Since 2005 in the frame work of updating the gravimetric gravity control, 499 AG stations have been established with A10 absolute gravimeters by the BKG (A10-002, A10-012 and A10-032). Also 64 AG stations measured with FG5 gravimeters are established and measured. No new instrumental purchase or development was identified.
- *Ireland/Northern Ireland:* Expresses strong interest in establishing a new gravity network possibly based on AG techniques. A joint collaboration for both countries is planned on the whole Ireland island. As to this time there was no serious gravity network works in Ireland since IGSN71 establishment. Also there is no known gravimeter (of any kind) on the Island.

- *Lithuania:* Large scale works are planned (relative surveys on nearly 700 stations) in the next years in order to update the gravity network reference level. Idea is to have 2 stations per 1 km^2. Works are planned to be performed mainly by Scintrex CG-5 gravimeters.
- *Norway:* In 2016 an A10 absolute gravimeter have been purchased by the NMA of Ireland. A plan to re-measure the Norway gravity control is planned in 2017-2019, mainly focused on the coastal areas. Firstly the A10 gravimeter was used for measurements in Ny-Alesund in a newly established geodynamical observatory. Also for the Ny-Alesund location an iGrav superconducting gravimeter is planned to be installed in 2017-2018 season.
- *Poland:* The iGrav-027 gravimeter is operating smoothly with full one year of operation behind it. Currently no surveys related to the gravity control maintenance are planned. As of beginning of the 2017 EPOS-PL project started in Poland. Within the framework of the project regular A10-020 absolute gravimeter campaigns are planned in the Silesian region on active mining areas. Absolute determinations will serve as reference for extensive relative gravimeter surveys. Relative surveys will be performed with Scintrex CG5 and CG6(to be purchased early 2018). This will form a hybrid gravimetric survey (AG and RG) carried out at least two times per year. Additionally within the project three gPhoneX gravimeters will be purchased (also early 2018) and installed on mining areas for gravity variation monitoring. Borowa Gora Observatory is suitable for AG comparisons with 3-4 points that could be measured at the same time. Currently one internal comparison with FG5-230 is planned on annual basis. Other teams are much welcome to participate. The next such comparison is planned in September of 2017.
- *Spain:* Measurement on the Spanish Absolute Gravity Network (REGA) are carried out since 2001 with A10 and FG5 gravimeters, 44 and 32 stations respectively. Additional new measurement were carried out in the recent years on the Canary Islands (1x FG5 and 49 A10 stations) and Balearic Islands (3x A10 stations).
- *Turkey:* In 2016 Turkey began a very big project for the complete renovation of the national gravity control (to be finished in 2020). The whole project estimated at 5 millions Euro assumes the new measurements of the whole country with A10 and FG5 gravimeters (as reference stations) and densification surveys with Scintrex CG5 gravimeters. Within the project new A10 and FG5 gravimeters were purchased as well as 8 Scintrex CG5 gravimeters.

Japan and Asia-Pacific (reported by Akito Araya)

Absolute gravimetry: TAG-1 is an AG developed at ERI (Araya et al., 2014). It includes a silent-drop mechanism for a free-fall mirror and a built-in accelerometer for the correction of seismic disturbances. Accuracy of TAG-1 is evaluated from the comparative observation with FG5's carried out in April, 2016 at the Ishioka Geodetic Observing Station, GSI of Japan. TAG-1 was operated with a frequency stabilized fiber laser at 1550nm on a trial basis to evaluate a potential to construct a network with a number of absolute gravimeters for monitoring volcanic activity. (Araya et al., 2017). In relation to the development of a compact AG, a short-distance rise-and-fall launch system for an AG is developed. The current system can throw up a mirror with 3 mm in height using a piezo-electric actuator, and its recoil reduction mechanism counteracts the vibration using a counter mass. Earth tides were successfully observed with the system (Sakai et al, 2016), and a test observation was carried out near an active volcano. Absolute gravity measurement campaigns were conducted in New Zealand in 2015-2016. In January and March 2016, the measurements using an FG5 #210 (of Kyoto University) were conducted. The measurements in North Island were made at two existing points (the Warkworth Radio Astronomy Observatory and Wellington A) and at one newly established point in Wairakei Research Centre, Taupo. The gravity measurements in South Island were made at five existing AG points of Godly Head, Mt John, University of Otago, Helipad and Bealey Hotel. To complement the AG measurements, relative measurements have been conducted in 2017, using LaCoste Romberg G-meters (#680 and #805) for most AG points and spare points as gravity connections. For planning the AG measurements in the area of 2016 Kaikoura earthquake (Mw 7.8), test measurements were carried out at a few points where huge uplifts have been observed. (Fukuda et al., 2017).

Relative gravimetry: Superconducting gravimeter observation at Ishigakijima, Japan was launched in 2012 with the purpose of detecting potential signals associated with slow slip events. To date, distinguishing slow slip signals from surface water disturbances has not been successful, because interactions between the ocean and the underground water make it difficult to model their effects on gravity. Detailed analysis taking into account the interactions between the ocean, underground water and atmosphere, and their effects on gravity was performed. (Imanishi et al., 2016). Continuous gravity data, using a Scintrex CG-3M relative gravimeter, at Arimura Observatory, Sakurajima Volcano (Kagoshima Prefecture, Japan) have been obtained to monitor volcanic activity. The gravimeter was first installed in May 2010, and it also records the tilt values of the gravimeter, which are utilized to correct the apparent gravity changes due to the tilt. Significant tilt changes associated with the volcanic event on 15 August 2015 can be identified clearly. (Kazama et al., 2016). Continuous gravimetric observations have been made with three successive generations of superconducting gravimeter (SG) over 20 years at Syowa Station (39.6E, 69.0S), Dronning Maud Land (DML), East Antarctica. Non-tidal gravity variations derived from the OSG#058 data showed significant correlation with the accumulated snow depth observed at Syowa Station. The relation between the heavy snowfall in DML and the weakening of Chandler Wobble, which were observed with OSG#058, was discussed. (Aoyama et al., 2016). Performance evaluations for a SG (iGrav #003) and a spring gravimeter (gPhone #136) were conducted at the Mizusawa VLBI Observatory of the National Astronomical Observatory of Japan in comparison with a SG TT #70. Calibration of iGrav #003 had been carried out by colocation with an AG FG5, and that of gPhone #136 was provided by the manufacturer. Colocation observation showed that amplitudes and phases of each major tidal constituent mutually agreed well. iGrav and gPhone will be deployed for monitoring volcanic activity. (Miura et al., 2017)

An *underwater gravity measurement system* using an autonomous underwater vehicle (AUV) has been developed to search for sub seafloor density signatures associated with massive ore deposits. A model calculation showed a gravity anomaly > 0.1 mGal and a gravity gradient anomaly > 10 E are expected from a survey ~50 m above a typical seafloor deposit. The system comprises a gravimeter and a gravity gradiometer mounted in AUV (Urashima, JAMSTEC) which has stable navigation performance and enough space to install both of the gravimeter and the gravity gradiometer. Operation of the system was successful for several observations in the sea, and sub seafloor gravity anomaly was estimated (Shinohara et al., 2015; Araya et al., 2015).

A portable *laser-interferometric gravity gradiometer* for volcanological studies has been developed. The gravity gradiometer measures differential accelerations between two test masses that are in free fall at different heights. Because its principle of operation is based on the differential measurements, measured values are insensitive to the motions of observation points. The laboratory test showed that its resolution of measuring vertical gravity gradients was about a few μGal/m in two seconds measurements. The prototype was moved to the Aso Volcanological Laboratory (AVL) of the Kyoto University in July 2012. Since then, its further development, to be used at an observatory in a volcanic area, has been carried out at the AVL, and trial measurements at the Sakurajima Volcanological Laboratory of the Kyoto University (Kyushu, Japa) were performed. (Shiomi et al., 2015)

An *airborne gravity gradiometry survey* was conducted by the Japan Oil, Gas and Metals National Corporation (JOGMEC) in the Kuju volcano and surrounding area, Oita prefecture, Japan. The density structure modeling was conducted using gravity data and the six components (Gxx, Gxy, Gxz, Gyy, Gyz, and Gzz) of airborne gravity gradiometry data. The high-density (2400 –2550 kg/m3) areas were estimated below the middle and late Pleistocene volcanoes in the shouthern part of the study area at a depth of 0 to 2000 m below sea level. These high-density areas correspond to the distributions of the older Hohi volcanic rocks. (Nishijima and Yanai, 2016)

Geopotential measurements with an uncertainty of 5 cm were demonstrated by determining the height difference of master and slave optical lattice clocks separated by 15 km. A subharmonic of the master clock laser is delivered through a telecom fiber to synchronously operate the distant clocks. Taken over half a year, 11 measurements determine the fractional frequency difference between the two clocks to be $1{,}652.9(5.9)\times10^{-18}$, consistent with an independent measurement by levelling and gravimetry. (Takano et al., 2016)

Gravity networks: Geospatial Information Authority of Japan (GSI) established a new gravity standardization network of Japan, named the Japan Gravity Standardization Net. 2013 (JGSN2013), from the latest AG and relative land gravity measurements covering the whole country. The accuracy of JGSN2013 is evaluated around 10 μGal in standard deviation from the residuals of network adjustment and the leave-one-out cross validation, and this means that the JGSN2013 achieves more accurate gravity standard than the former gravity standard, the Japan Gravity Standardization Net. 1975 (JGSN75), by an order of magnitude. (Miyazaki, 2016). GSI of Japan constructed a gravity measurement facility for domestic comparison of AGs at the Ishioka Geodetic Observing Station, GSI of Japan. The granite test bench in the facility is firmly coupled to the support layer with concrete piles and is isolated from the building in order to reduce the effect of ground vibration. It is designed to set up six AGs simultaneously on each point that has precise coordinates determined by GNSS and leveling before the construction. Since the Ishioka station also has the VLBI facility, the distributed hydrogen maser's signal can be used to minimize clock errors between AGs. (Kato et al., 2017).

Conclusions on the currents state of measurement techniques in gravimetry and on the development of gravity networks

Recently there is a growing number of absolute gravimeters and absolute determinations of free-fall acceleration. There is a progress in the elaboration of absolute gravimeters including that based on a cold atom gravimetry are under the development. Several reports inform on the renovation of gravity networks and on the establishment of new gravity networks over the world. New gravity measurement techniques as gravity gradiometers and the techniques of geopotential measurements based on the precise quantum (cold atoms, cold ions) clocks are under the development. The number of gravimetry sites with collocated AG, superconducting gravimeter and terrestrial GNSS stations increases. Despite of increasing role of absolute AG measurements in the gravimetry survey the role of relative gravimeters is still significant.

Nevertheless, some remarks should be made. The realization of the CCM-IAG strategy in metrology for absolute gravimetry is not completed and it does not cover all the geodetic services and it is not implemented to all geodetic projects related to gravity measurements. There are only a few cases of calibration of absolute gravimeters. Not all the gravimetry teams participate in the comparisons of AGs or calibrate their AGs. There is a progress in the improvement of AGs as the increased repeatability in the measurements free-fall measurements with a cold atom gravimetry and in the improvement of laser interferometric absolute gravimeters. However, there are still the needs for further investigations of the sources of the instrumental systematic uncertainties in the measurements using the AGs.

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Study Groups of Sub-commission 2.1:

SG 2.1.1: Techniques and metrology in terrestrial (land, marine, airborne) gravimetry

Chair: *Derek van Westrum (USA)*
Vice Chair: *Christoph Förste (Germany)*

Members
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- *Vladimir Schkolnik (Germany)*
- *Sergiy Svitlov (Ukraine)*
- *Ludger Timmen (Germany)*
- *Michel Van Camp (Belgium)*

Activities and publications during the period 2015-2017

Strapdown airborne gravimetry
As an alternative to classical, platform-stabilized spring-gravimeters, strapdown inertial measurement units (IMU's) can be applied for kinematic gravimetry. IMU's offer many operational advantages, as low power- and space consumption and an autonomous operation during the flights. Strapdown gravimetry also supports the determination of 3-D gravity (i.e., including the deflection of the vertical).

With the focus of *geoid determination*, in the reporting period 2015-2017 the Chair of Physical and Satellite Geodesy (PSG) at TU Darmstadt took part in the following campaigns:
- 2014 and 2015: Two offshore-campaigns in the South Chinese Sea (Malaysia)
- 2015: Northwest Mozambique and Malawi
- 2015/2016: Antarctica: The *PolarGap* campaign

These campaigns were carried out in cooperation with the Technical University of Denmark (DTU Space). For all these campaigns, PSG's iMAR RQH-1003 strapdown IMU was flown side-by-side with a classical LaCoste and Romberg S-type sea/air gravimeter, allowing a direct comparison of the two sensors. It could be shown, that mainly thermal drifts of the Honeywell QA-2000 quartz accelerometers prevent the IMU from a gravity determination at the milli-Gal level in the longer wavelenths (hours). The main research focus since 2014 was the design and evaluation of IMU calibration schemes, which are able to circumvent such drifts (Becker 2016, Becker et al. 2015a). This research was very successful: The cross-over precision could be reduced from several mGal down to 0.9 – 1.1 mGal for the four non-polar campaigns, thereby showing similar or even superior results compared to the LCR S-type gravimeter (Becker 2016, Becker et al. 2016). For the PolarGap campaign, the stand-alone IMU gravity reached a precision of 1.8 mGal after applying the correction. It is still an open question what was the limiting factor compared to the campaigns at lower latitudes, e.g. the stronger temperature changes, or the lower GNSS satellite elevation (leading to a significantly larger VDOP). For all of the abovementioned campaigns, it could be shown that the iMAR sensor was barely sensitive to even strong turbulence, being another important operational advantage compared to the classical systems: This can be cost-saving in production-oriented campaigns, as less lines (or even no lines!) need to be repeated any more due to strong turbulence.

With the focus on *3-D (vector) gravity determination*, in cooperation with the US-American National Geodetic Survey (NGS), PSG's iMAR RQH-1003 sensor was flown side-by-side with a TAGS airborne gravimeter in the scope of the GRAV-D project in October 2016 out of Amarillo, Texas (17 flights). The goal of this measurement was again to assess to potential of strapdown airborne gravity, in particular with respect to the potentially higher spatial resolution, and the higher robustness against turbulence. Three additional flight lines near Alamosa, Colorado were flown: For these lines, highly accurate ground reference measurements of 3-D gravity (absolute gravity value and deflection of the vertical, DoV) will become available in 2017/2018. Based on this ground-truth comparison, the potential of using the iMAR RQH sensor for the determination of the DoV shall be investigated. In addition to PSG's iMAR RQH sensor, a Honeywell IMU with comparable inertial sensors has been a part of NGS' general aircraft instrumentation for the GRAV-D flights for many years. In the scope of this cooperation, it shall also be investigated, if the existing Honeywell IMU of all the GRAV-D flights can be used at least for an augmentation of the TAGS gravity results, in particular during turbulent parts of the flights.

Regarding *geology and geophysics applications*, in the Antarctic summer 2016/2017, PSG cooperated with British Antarctic Survey (BAS) in the scope of the Filchner Ice Shelf System project. For a total of 24 flights, the iMAR RQH sensor was the only gravity sensor on board the survey aircraft. Since the main focus of these survey flights was set on radar measurements for geophysical mapping and research, the flights had to be performed in drape-flying-mode, i.e. the aircraft altitude *above ground* was approximately maintained at a constant level. Such flights can be difficult for the classical spring-based gravity sensors, as strong gravity changes arising from altitude changes above sea level may exceed the sensor range for short-term gravity variations. There is no such limitation for the strapdown systems. The processing of this data is still in progress; first results however already indicate, that the drape-flying does not reduce the achievable accuracy of the strapdown gravity results. A cross-over precision of approximately 1.7 mGal could already be achieved, which is however again significantly lower compared to the non-polar campaigns listed above. It is again unclear if the precision is mainly limited by the VDOP in the standard PPP-processing that we use. More research on the determination of GNSS accelerations is planned for 2017.

Upcoming Projects: In May 2017, PSG will host a strapdown airborne gravimetry *comparison* campaign. A total of approx. 20 flights hours out of Griesheim (close to Darmstadt) will be flown above a geologically interesting region in the south of Hesse. A dense network of ground gravity points is available in this region, allowing a systematical evaluation of the gravity results. The main goals of this campaign are (1) the side-by-side comparison of five tactical- and navigation-grade IMU's, (2) a systematical investigation of strapdown gravimetry for geology/geophysics in drape-flying mode, (3) the comparison of DoV measurements from aircraft and car against a ground truth reference, and (4) an investigation of in-flight accelerometer bias determination using flight manoeuvres (Becker et al. 2015b). It is intended to establish this region of approx. 10 x 30 kilometres internationally as a testbed for airborne gravimetry, and strapdown airborne gravimetry in particular. For this purpose, a publication of any available ground-truth and airborne gravity data is intended.

Marine gravimetry

The Finnish Geodetic Institute (FGI) is participating in the FAMOS- project 'Finalising Surveys for the Baltic Motorways of the Seas' (www.famosproject.eu). The project is a cooperation between 15 hydrographic and geodetic organizations of 7 Baltic Sea countries and it is co-funded by the European Union Connecting Europe Facility. In Activity 2 of the project marine gravity surveys are carried out in different parts of the Baltic Sea. A paper was published on the marine gravity survey that took place in 2015 in the Bothnian Sea on a Finnish vessel:

In July, the PSG will take part in a shipborne survey in cooperation with BKG and GFZ, investigating the potentials and challenges of strapdown *shipborne* gravimetry, in particular with respect to the sensor stability over very long periods (several days). It is intended to use and evaluate a simple thermal stabilization system.

Absolute and relative gravity measurements

The FGI is doing repeated FG5X *absolute gravity* measurements in Finland for land uplift studies and monitoring. This year also FG5X absolute gravity measurements in Lithuania and Estonia will be done. The FGI will participate in the ICAG2017 that will take place in China in autumn. The Finnish Academy funded project GRAVLASER -'Improved absolute gravity measurements in the Antarctic' aims to deepen the knowledge of cryosphere-lithosphere interaction in Antarctica and to improve current and future scenarios of the Antarctic ice sheet contribution to global sea level rise. The project involves, among other things, measurements of absolute gravity change with the FG5X absolute gravimeter and development of novel laser scanning methods.

The iOSG022 *superconducting gravimeter* was successfully installed at the Metsähovi observatory and is now working well and producing high-quality data. In addition FGI obtained the iGrav013 portable superconducting gravimeter. For now it is operating in Metsähovi alongside the iOSG022.

New technologies

Atom sensor/gravimeter developments: There are currently about 10 institutes in the world and two companies (MUQUANS and AOSENSE) developing such systems, but most are still under improvements in terms of accuracy and compactness (example: some sensors now use atom chips [see Abend PRL117 2016]). There are also some studies into the development of gradiometers, and space programs (or studies) to use gradiometer in space (ESA, CNES, NASA). SYRTE is developing a new sensor, a demonstrator for space (https://syrte.obspm.fr/spip/science/iaci/projets/gradio/), Humboldt Univ. Berlin is adapting its atom gravimeter to launch two clouds, Lens (Firenze) has developed one few years ago, and in China (Wuhan) they are using their gravimeter to make a gradiometer to Also, the MIGA project, under development, which ultimate goal is to detect gravitational waves with atom gradiometer, will have interest for geoscience (https://arxiv.org/pdf/1703.02490.pdf). About the CAG, the accuracy is still 43 nm/s^2, sensitivity is 57nm/ s^2 in 1s of measurement and 0.6nm/ s^2 in 1/2 day. Current effort is now aimed at reducing the uncertainty to 10 or below 10nm/s^2. It measured gravity continuously last month for the LNE Kibble balance (previously watt balance) to measure the Planck constant linked to kilogram to participate to the new redefinition of the kilogram.

The preparation for the "*Very long baseline atom interferometer*" (VLBAI, 10 m atomic fountain) at the Hannover Institute for Technology (HITec) of the Leibniz Universität Hannover has progressed so far that the implementation of the VLBAI in the HITec building can start in autumn of this year. The long-term geodetic objective is to perform stationary absolute measurements of gravity and its derivatives with resolutions exceeding the presently available possibilities of classical instruments by several orders of magnitude. In the future, this VLBAI fountain as an instrument with "higher order accuracy" should take a central role for the definition of gravimetric reference networks in central Europe and the gravimetric datum definition. It will serve for verification of transportable absolute meters w.r.t. their long-term stability. For more information go to https://www.geoq.uni-hannover.de/a02.html, and https://www.iqo.uni-hannover.de/vlbai.html.

At the Geodetic observatory Pecný (VUGTK), it is tried to distinguish between the most critical components of error sources for FG5/FG5X gravimeters together with improvements in optics and electronics. By such a way we would like to contribute on the accuracy improvement of gravimeters based on *laser interferometry*.

TAGS7 Gravimeter on "Optionally Piloted" Aircraft as a UAV test: In March of 2017, the National Geodetic Survey (NGS) began its first operational survey using the Aurora Centaur Optionally Piloted Aircraft for its Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project. The survey operated for about a month, collecting data primarily over western North Carolina and eastern Tennessee. The data from this survey are expected to be released to the public in the summer of 2017. In the future, it is envisioned that operating such aircraft autonomously will reduce costs, increase efficiency, especially in difficult to reach areas.

Geopotential survey of NIST Optical Clock Laboratories, Summer 2015: NGS has established six new bench marks in and around various atomic clock laboratories at the NIST-Boulder, Colorado campus. Classical leveling (<1mm local, relative accuracy, and ~2cm "global" accuracy) and absolute gravity measurements were used to determine heights, gravity values, and geopotential differences between the bench marks. The geopotential differences can be used directly – and immediately – to calculate the expected frequency shifts between the laboratories. After the GRAV-D airborne campaign is complete in 2022, NGS will define a new vertical datum for the United States. At that point it will be easy to provide geopotential numbers referenced to the geoid, accurate to the ~2 cm level. As continent-scale networks of linked optical clocks become feasible, these absolute geopotential values will be critical for direct clock comparisons. (ftp://ftp.library.noaa.gov/noaa_documents.lib/NOS/NGS/TM_NOS_NGS/TM_NOS_NGS_73_2016.pdf)

Regional gravity networks: new gravity reference in Mexico 2016

Within a joint project of the Instituto Nacional de Metrología en Méxicol (CENAM), the Gottfried Wilhelm Leibniz Universität Hannover (LUH), and the Centro de Geociencias, Universidad Nacional Autónoma de México (UNAM), the measurement of nine first order gravity stations employing the reference FG5X-220 free-fall absolute gravity meter of the LUH was completed. The field campaign took place from February 22th to March 14th of 2016, exactly 20 years after the last absolute gravity campaign was completed in Mexico. The measuring campaign started in the National Laboratory of micro-Gravimetry (LNG), with a mutual comparison between the LUH´s FG5X-220 and the CENAM´s FG5X-252, at the beginning and end of the field campaign, the later worked out as base station. Besides a successful instrumental comparison, we increased the existing network of gravity stations, four of which had been measured 20 years ago by NOAA in a tectonically active region of Mexico known as the Jalisco Block (JB).

Figure 3 Collaboration with metrology community: Gravity field measuring and modelling for optical clock comparisons

A coordinated program of clock comparisons has been carried out within the EMRP-funded project "International Timescales with Optical Clocks" (ITOC, 2013-2016), aiming at a validation of the uncertainty budgets of the new optical clocks with regard to an optical redefinition of the SI second. As optical clocks are now targeting a relative accuracy of 10^{-18}, corresponding to a sensitivity of about 0.1 m^2/s^2 in terms of the geopotential or 0.01 m in height, precise knowledge of the gravity potential is required at the respective clock sites. Alternatively, optical clocks may also be employed for deriving the gravity potential (denoted as "chronometric levelling" or "relativistic geodesy") and hence offer completely new options for geodetic height determination. The ITOC project involves clock sites at the national metrological institutes (NMIs) in France (OBSPARIS, LNE-SYRTE), Germany (PTB), Italy (INRIM), the United Kingdom (NPL), and an underground laboratory in France near the Italian border (LSM, Laboratoire Souterrain de Modane). Absolute and relative gravity observations were carried out by the gravimetry group of LUH around the clock sites and then used to compute an updated quasigeoid model.

Gravity applications

The gravity program at the United States Geological Survey (USGS) Arizona Water Science Center has become the "Southwest Gravity Program", as expanding into adjoining states. The primary product is network-adjusted relative- and absolute-gravity measurements of gravity change over time, as related to *hydrologic processes*. To facilitate rapid data analysis and network adjustment, GSadjust software has been developed, based on the PyGrav software (Hector and Hinderer, 2016), but with additional GUI elements for drift correction and network adjustment. Current projects are in Albuquerque and Las Cruces, NM; Tucson, Prescott, and northwestern AZ; and Imperial Valley, CA. A website with software (both in-house and external), references, and a bibliography has been developed (http://go.usa.gov/xqBnQ). Efforts to publish data to the web (including integration with AGrav database) are ongoing.

Geoid Slope Validation Survey in Southern Colorado, Summer 2017

NGS will conduct its third and final Geoid Slope Validation Survey in the mountains of southern Colorado in the summer of 2017. This multi-technique project will consist of classic leveling, long-session GPS, astro-geodetic deflection of the vertical observations, absolute gravity measurements, and vertical gravity gradient determinations at over 200 bench marks, spaced at about 1.5 km east to west along highway US 160. The purpose will be to compare geoid shape accuracies of various models, as well as quantify the contribution of the airborne gravity data acquired as part of the GRAV-D project. At each site, an A10 will be used to determine the absolute gravity value, and a new Scintrex CG-6 will be used to measure quadratic gradient. Initial results from the project are expected to be reported in early 2018.

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Joint Working Groups of Sub-commission 2.1:

JWG 2.1.1: Establishment of a global absolute gravity reference system

Chair: *Hartmut Wziontek (Germany)*
Vice Chair: *Sylvain Bonvalot (France)*

Members
- *Jonas Ågren (Sweden)*
- *Henri Baumann (Switzerland)*
- *Mirjam Bilker Koivula (Finland)*
- *Jean-Paul Boy (France)*
- *Nicholas Dando (Australia)*
- *Reinhard Falk (Germany)*
- *Olivier Francis (Luxemburg)*
- *Domenico Iacovone (Italy)*
- *Jan Krynski (Poland)*
- *Jacques Liard (Canada)*
- *Urs Marti (Switzerland)*
- *Vojtech Palinkas (Czech Republic)*
- *Diethardt Ruess (Austria)*
- *Victoria Smith (UK)*
- *Ludger Timmen (Germany)*
- *Michel van Camp (Belgium)*
- *Derek van Westrum (USA)*
- *Leonid Vitushkin (Russia)*
- *Shuqing Wu (China)*

Activities and publications during the period 2015-2017

Comparisons of Absolute Gravimeters

The Joint Working group on the Establishment of a global absolute gravity reference system was established in February 2016 to prepare the necessary steps to realize IAG resolution No. 2 of 2015 for the establishment of a global absolute gravity reference system. It was first presented at the meeting of the CCM Working Group on Gravimetry at the Royal Observatory of Belgium in Brussels, 23rd to 24th February, 2016. As the comparison of AGs is an essential part of the system, the focus was on links between key comparisons on an international level and additional regional comparisons, propagating the deviations from the comparison reference value. This subject was further elaborated with a poster presentation at the AGU Fall Meeting, San Francisco, 2016. Exemplarily, different options for a reprocessing of comparison results were presented with the aim to establish links between the results of several comparisons and to prove the temporal stability and finally trace back to the level of regional comparisons.

The International Database AGrav

The International Database on Absolute Gravity Measurements will serve as an inventory for the absolute gravity reference system (Figure 4). An extension of the database scheme to store comparison results was presented at the IAG symposium on Terrestrial gravimetry 12-15 April 2016, Saint Petersburg, Russia and published in the proceedings. A first impression on the realization of these updates were presented at the International Symposium on Gravity, Geoid and Height Systems (GGHS) 2016, Sept 19-23, 2016 Thessaloniki, Greece, and further progress at the EGU General Assembly 2017 in Vienna, Austria where a prototype was presented as live application.

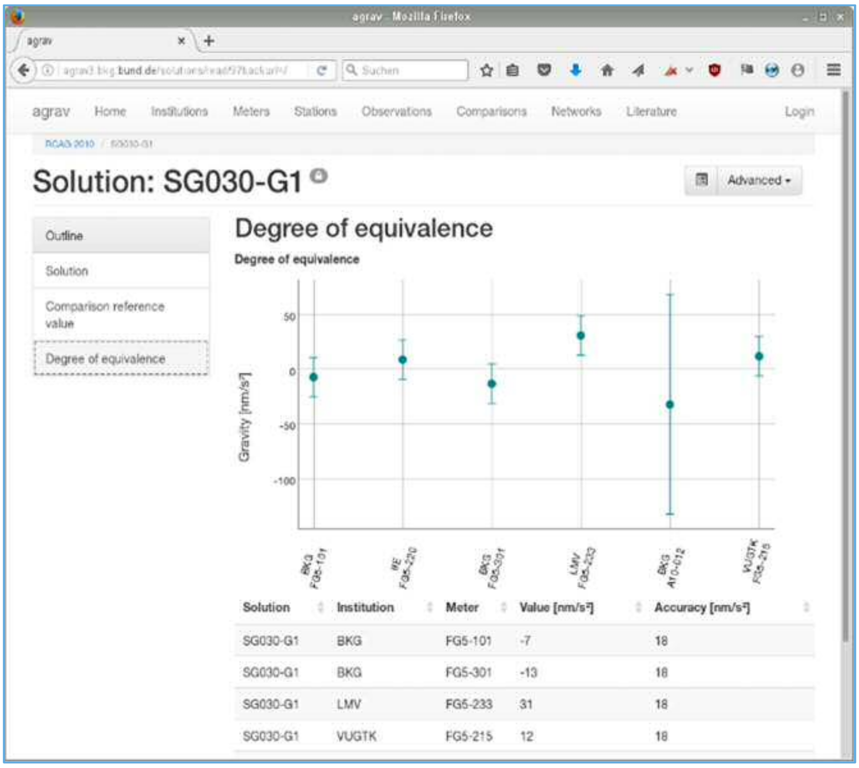

Figure 4 Presentation of the results from the Regional Comparison of Absolute Gravimeters at Wettzell, 2010 in the AGrav database. The degree of equivalence of the participating AGs relative to the reference function obtained from the superconducting gravimeter SG030 is shown.

Meetings of JWG 2.1.1

First meetings at the GGHS on 20.9.2016 in Thessaloniki, Greece.

The objectives of the joint working group (JWG) and possible work packages were presented. The role of repeated international comparisons of absolute gravimeters under guidance of CIPM and regional metrology organizations (RMO) was emphasized, which will ensure a homogenous and traceable absolute gravity reference. Reference stations with repeated absolute gravity measurements and preferably continuous recording of temporal gravity changes will provide the basic infrastructure. The transfer of the results of the international comparisons to other AGs will be realized at these stations, but needs distributed observations of different instruments. It was discussed that standard models for the processing of gravity observations must be defined or updated, in cooperation with the GGOS Bureau of Standards and Conventions. The following work packages were proposed:

- Selection of reference stations, update of station surveys from 2011,
- Homogenous processing of observations, update of the IAGBN standards 1992,
- AG Comparisons: Further cooperation with CCM-WGG, definition of unique processing rules including the treatment of systematic effects,
- Assessment of the stability of the comparison reference value over time,
- Discussion of the role of non-NMI/DI instruments in regional and/or additional comparisons,
- Evaluation of IGSN 71 stations and recommendation for the further use and / or re-observation,
- Availability of the new system for applications in geodesy and geophysics.

The response of the questionnaires of 2011 to the international community with AG and SG instruments was recapped and was proposed to be updated. For further discussion, a board at the forum of the AGrav database is proposed: http://agrav.bkg.bund.de/forum/

Second meeting on 27.04.2017 at the EGU General Assembly in Vienna, Austria.

The main objectives of the realization of the Global Absolute Gravity Reference System (GAGRS) were highlighted:
1. The need for accurate and long term stable reference provided by a primary network of reference stations where gravity is monitored with absolute gravimeters. Such primary network is already a central part of the resolution 2 (2015) and should also contribute to the infrastructure of GGOS Core sites.
2. The need for secondary network of gravity stations which ensures accessibility of the system by a global set of sites, compatible with the above defined reference level, to any user. The aim of this secondary network is to identify and make accessible the largest number of absolute gravity values observed worldwide from field surveys of laboratory measurements to provide absolute reference to any purpose (relative gravity surveys, calibration lines, etc.). This secondary network must be considered as well in order to establish a replacement for IGSN 71.

Along with these objectives two important aspects were also discussed: (i) the role of international or regional comparisons of absolute gravimeters (corner cube or cold-atom instruments) for ensuring the accuracy level and the long term stability of the GAGRS following the best standards of metrology and (ii) the standard models and corrections recommended for the gravity data reduction in order to improve the overall homogeneity and consistency of the absolute gravity observations worldwide.

Finally, the role of the BGI/BKG global absolute gravity database (AGrav) with increasing functionalities aimed at improving the traceability to SI units and visibility of absolute measurements performed by the national institutions has been also pointed out as an efficient tool for the realization of the GAGRS.

Primary network of reference stations

A reference station should ideally provide an absolute gravity value at any time at the microgal level with an historical record of the local gravity changes and of the gravity measurement instrumentation in use. The gravity value should be obtained from repeated absolute gravity measurements with an accuracy at the microgal level with instruments that are linked to international comparisons of gravity meters. The reference station should then allow a comparison with another gravimeter at any time.

Temporal gravity variations should be monitored continuously by a superconducting gravimeter (SG), or in future, by an absolute cold atom gravimeter. Stations with repeated (conventional) absolute gravity measurements should be considered as well, e.g. station Matera/Italy, where FG5 observations are carried out on a weekly basis and which was discussed in particular. A recommendation on the minimum number of observations per year should at least cover seasonal variations, which would require e.g. 6 observations per year. Further, there is no need to maintain or occupy a reference station permanently, if easy access is granted. Complementary to the gravity observations, monitoring of height changes from GNSS measurements at the reference station would be necessary.

Reference stations with colocated gravity and geometric measurement instrumentation where several space geodetic measurements are performed (e.g. GNSS, VLBI, SLR…) might correspond to GGOS core sites. GGOS core sites should be linked to the GAGRS by continuous monitoring of gravity changes and repeated absolute gravity observations.

The data from all reference stations should be documented in the AGrav database.

To define a global set of reference stations, it is proposed to re-evaluate the positive response and update the results of the survey of 2011, addressed to the absolute gravity community and the Global Geodynamics Project (GGP, today IGETS). At this time, 36 stations were proposed. Some of these stations should also correspond to GGOS core sites.

International or regional comparisons stations

A comparison site is a reference station which provides extended facilities to allow the comparison of several absolute gravimeters. Monitoring of temporal gravity changes during the comparison is mandatory.

Secondary network : Infrastructure for an absolute gravity reference network

To replace IGSN71, an infrastructure must be established. It was a consensus among the participants, that it is not feasible and not necessary to comprehensively re-observe or evaluate the IGSN 71 network. As IGSN71 has served as a reference for a large number of relative gravity surveys, such evaluation may be very important for e.g. regional purposes, but is best performed by the pertinent national institutions.
Instead, new infrastructure based on absolute gravity observations performed worldwide by national institutions should be set up. It was recommended that all gravimeters take part in comparisons to ensure the best compatibility with the absolute gravity system and traceability to SI units. Absolute gravity stations should be divided into different levels depending on the uncertainty of the gravity observations, reaching from the field-level (e.g. A10 surveys) to the lab-level (FG5-type instruments).
National agencies should be encouraged to establish compatible first order networks, if necessary in international cooperation with institutions operating absolute gravimeters.
Generally all relevant data should centrally archived and documented in the AGrav database, which is currently extended and updated with a new web application. The data should be accessible to any user.

Standard models and corrections

Current practice on the correction of time variable gravity effects was discussed. A set of standard correction models should be proposed for less experienced users. In particular, for ocean tide loading, most recent models like FES 2014 should be used, the coefficients can be obtained from the ocean tide loading providers of M.S. Bos and H.-G. Scherneck. It was noted that this would result in an inconsistency with the current IERS conventions which recommends FES2004.
A homogenization of gravity corrections in post processing is only possible, if at least set-, better drop-files are provided and archived in the AGrav database. It should checked, if such functionality could be implemented into AGrav and if the users accepting to contribute these data.

Further activities of JWG 2.1.1

Recently, a first order gravity network in Mexico was newly established. For the latter, nine gravity stations employing the reference FG5X-220 free-fall absolute gravity meter of Leibniz Universität Hannover (LUH), Germany were measured from February 22th to March 14th of 2016 within a joint project of the Instituto Nacional de Metrología en Méxicol (CENAM) and Universidad Nacional Autónoma de México (UNAM).

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Sub-commission 2.2: Methodology for Geoid and Physical Height Systems

Chair: *Jonas Ågren (Sweden)*
Vice Chair: *Artu Ellmann (Estonia)*

Overview

The IAG Sub-Commission 2.2 (SC 2.2) promotes and supports scientific research related to methodological questions in geoid determination and physical height systems, both from the theoretical and practical perspectives, concentrating particularly on methodological questions contributing to the realisation of the International Height Reference System (IHRS) with the required sub-centimetre accuracy. SC 2.2 is the only SC of Commission 2 that deals with physical height systems. It differs from SC 2.4 “Regional geoid determination“ (and its subcomponents) in that it concentrates on methodological questions for geoid determination in the context of the realisation of physical height systems, particularly on the now on-going realisation of IHRS (Sanchez et al. 2016; Ihde et al. 2017).

A first SC 2.2 constituting splinter meeting was organized at the 1st Joint Commission 2 and IGFS International Symposium on Gravity, Geoid and Height Systems 2016 in Thessaloniki, Greece.

An important activity has been to start up the Joint Working Group 2.2.2 (JWG 2.2.2), “The 1-cm Geoid experiment”, together with the International Service for the Geoid (ISG) and the Inter-commission Committee on Theory (ICCT). This working group primarily aims at developing geoid determination methodology by benchmarking different regional geoid determination methods (developed by different groups or so-called “schools”) through computations on a few common tests datasets; cf. the JWG 2.2.2 report below.

Another on-going activity is the active support the Joint Working Group 0.1.2 on the “Strategy for the Realisation of the International Height Reference System (IHRS)”. Important questions here are to investigate and agree on standards for geoid computation for the realisation of IHRS. Another issue is how to merge and validate existing local (or regional) geoid models. This is the main topic of the Joint Working Group 2.2.1 “Integration and validation of local geoid estimates”.

The members of the Sub-commission are deeply involved in most aspects of the development of geoid determination methods and the realisation of physical height systems. The SC has been active in arranging scientific conferences, most notably the GGHS2016 conference in Thessaloniki and the upcoming IAG-IASPEI Joint Scientific Assembly in Kobe, Japan, July 30-August 4, 2017.

SC 2.2 It will continue its work in the period 2017-2019 by promoting and supporting scientific development related to geoid determination and physical height systems. This will for instance be made by organizing meetings and conferences and by establishing new study groups or working groups, if needed.

Below the contribution of SC 2.2 to the realisation of IHRS is first elaborated on more closely. This followed by the midterm reports of JWG 2.2.1 and JWG 2.2.2. It should be pointed out that the latter working group (“The 1-cm Geoid Experiment”) was approved very recently by the IAG Executive Committee. This report is consequently very brief.

Contributions to the realisation of the IHRS

A global height reference frame with high accuracy and stability is fundamental to determine the global changes of the Earth. A major step towards the goal of a globally unified height frame was taken by the IAG resolution (No. 1) for the definition and realisation of an International

Height Reference System (IHRS), which was officially adopted at the IUGG 2015 meeting in Prague (Drewes et al. 2016; Sanchez et al. 2016; Ihde et al. 2017). Much work is now being made to realize the IHRS, which will result in the first International Height Reference Frame (IHRF). The realisation will primarily be achieved by geometric satellite methods (like GNSS, SLR and VLBI) in combination with gravimetrically determined geopotential values (e.g. Ihde et al. 2017). The latter can be derived using a Global Geopotential Model (GGM) originating from the dedicated satellite gravity missions, complemented with terrestrial gravity, satellite altimetry and other information to reduce the omission error. In case highest accuracy is to be reached, regional geoid determination is an integral part of the realisation of the IHRS (*regional* here means combining the GGM with *regional* terrestrial gravity other data, like a DEM). It is the intention that IHRS will be realized using a global network of reference stations in a similar way as ITRS is realised by ITRF. The realisation of IHRS (which is the main goal of JWG 0.1.2) will be specified in a document similar to the IERS conventions in the three-dimensional case (ITRS/ITRF).

An important question for SC 2.2 is to what extent geoid (or geopotential) determination for realisation of IHRS can (or should) be *standardised*. It is for instance proposed in Ihde et al. (2017) that a certain long wavelength satellite-only GGM be singled out as a matter of convention, which is then to be modified using regional/local gravity data, satellite altimetry and other data (like a topographic and bathymetric models). This is an example of what could be standardised, but also other aspects need to be specified. This is work in progress for JWG 0.1.2, which involves direct contribution of SC 2.2. One problem in this context concerns the above-mentioned fact that several regional geoid determination methods (and software) are available, which to some extent give different numerical results (e.g. Ågren et al. 2016). Different groups (or schools) tend to prefer their own method, which might be an obstacle to standardisation. It is important to ascertain the magnitude of the disagreements between the methods, which will give a more realistic picture of the achievable accuracy. As mentioned above, benchmarking of various geoid determination methods is the main purpose of the new JWG 2.2.2, which thus contributes directly to the realisation of IHRS.

It is the ultimate goal that the determined potential values at the IHRF stations shall be determined with an accuracy of 10^{-2} m^2s^{-2} (Ihde et al. 2017), which corresponds to 1 mm in the geoid height or height anomaly. IAG thus aims for extremely high accuracy in the long run. It will be a major challenge to determine the potential with anywhere near this accuracy. In order to reach the sub-centimetre geoid, both theoretical and data improvements are required. The theoretical framework for sub-centimetre accuracy are dealt with by the IAG JSG 0.15 "Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre", but it should be emphasized that gravity data (and other types of data) also need to be updated to reach the goal. Recommendations regarding how to update the gravity data around the IHRF stations will be much needed in the future. Today the gravity data situation around the world is very diverse (cf. Sanchez and Sideris 2017). This is complicated by the fact that many of the gravity datasets are classified, or are available only for some groups under special permissions, etc. Even in the parts of the world with good gravity data, the above mentioned goal is far away in for instance the methodologically most demanding mountain areas.

To illustrate the challenge to compute a sub-centimetre geoid model in such a difficult area, a few results are presented from the Nordic NKG2015 geoid modelling project (Ågren et al. 2016). A particularly demanding area is southern Norway, with extremely rough topography and high mountains intersected by deep fjords. Comparatively good gravity data are available on land. In many of the fjords, however, gravity has been missing for a long time, at the same time as sufficiently dense bathymetry has been unavailable (or classified). Recently, however, new marine gravity data were observed in a number of the largest fjords. These new observations were included for the computation of the NKG2015 quasigeoid model, but were neither available for the combined GGM EIGEN-6C4 with maximum degree 2190 (Förste et al. 2015) nor for the updated European regional EGG2015 model (Denker 2015). The relative quasigeoid difference (after subtraction of the mean) between NKG2015 and EIGEN-6C4 are presented in Figure 5, while difference between NKG2015 and EGG2015 can be found in Figure 6. Statistics for the GNSS/levelling residuals after a 1-parameter fit/transformation are given in Table 1.

Table 1 Statistics for the GNSS/levelling residuals after a 1-parameter fit/transformation in Southern Norway. Consistent permanent tide systems and postglacial land uplift epochs. Unit: meter.

Model	#	Min	Max	Mean	StdDev
NKG2015	583	-0.129	0.080	0.000	0.027
EIGEN-6C4	583	-0.219	0.119	0.000	0.054
EGG2015	583	-0.142	0.084	0.000	0.041

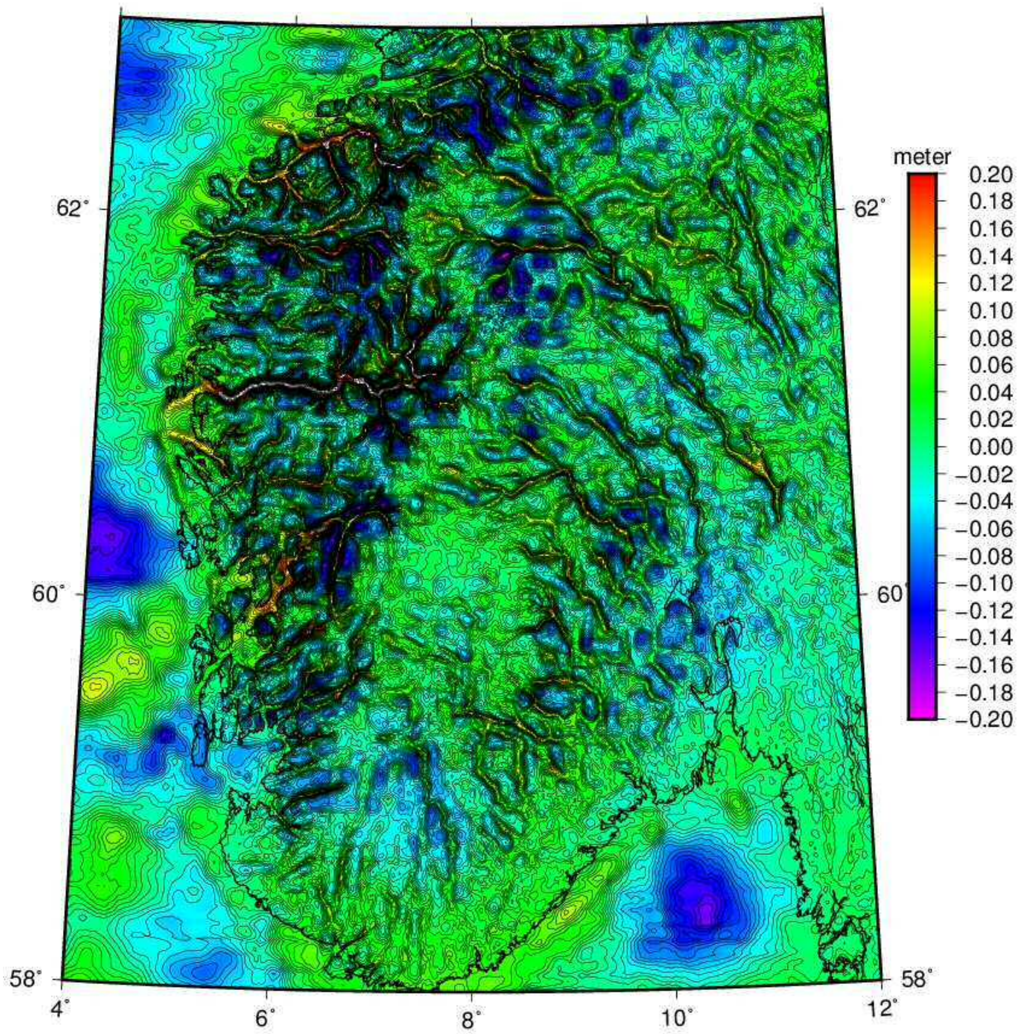

Figure 5 Height anomaly difference between EIGEN-6C4 with maximum degree 2190 (Förste et al. 2014) and NKG2015 in southern Norway. The mean has been subtracted. The same permanent tide system is used for both models. The contour interval is 1 cm. Note the frequent sign changes for the discrepancies over adjacent areas.

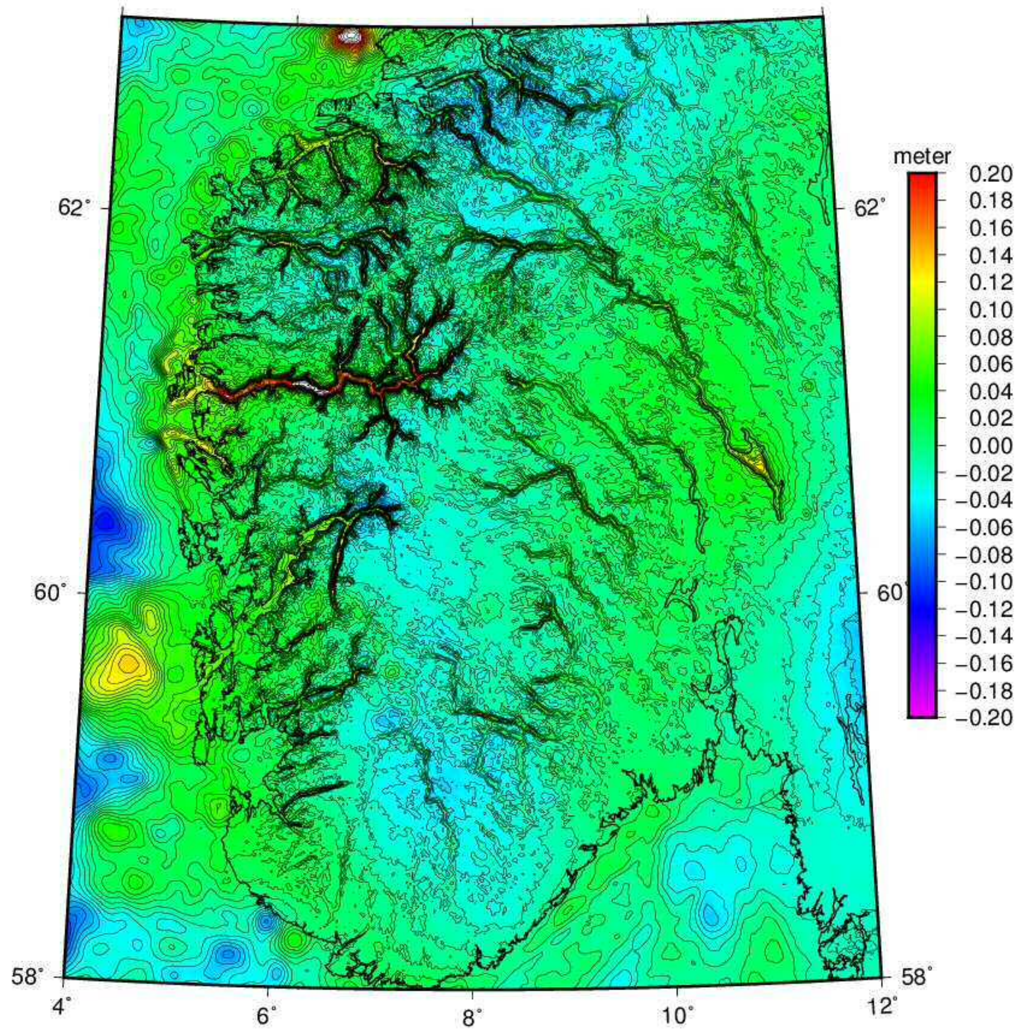

Figure 6 Height anomaly difference between the European EGG2015 (Denker 2015) and NKG2015 in southern Norway. The mean has been subtracted. The same permanent tide system is used for both models. The contour interval is 1 cm.

The above results illustrate the challenge to compute a sub-centimetre geoid in a rough area. It is clear that the omission error is the major limitation for the combined EIGEN-6C4 GGM. Since it is very large, it is difficult to see the effect of the missing fjord data. The omission error is, on the other hand, not a problem for the regional EGG2015 model. In this case the large effect of missing fjord data becomes more visible. Most (but not all) of these fjord differences are due to that the new fjord marine gravity data were used for NKG2015 only. Besides these two factors (omission error and missing fjord data), there are still unexplained discrepancies between the models, which most likely depend on methodological differences (the methods differs significantly). It should be pointed out that it is difficult to separate what depends on the method and what on data. The above results are presented mainly as a future challenge for the realisation of IHRS and for SC 2.2.

Also other parts of the realisation of IHRS concern SC 2.2, for instance vertical datum unification and the role of traditional precise levelling. An important reference regarding vertical datum unification is Sanchez and Sideris (2017), which focus particularly on the unification of the South American height systems.

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Drewes H., Kuglitsch F., Adam J., Rozsa, S., 2016. The Geodesist's Handbook 2016, J. Geod., 90(10), 981–982.

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Joint Working Groups of Sub-commission 2.2:

JWG 2.2.1: Integration and validation of local geoid estimates

Chair: *Mirko Reguzzoni (Italy)*
Vice Chair: *George Vergos (Greece)*

Members
- *G. Sona (Italy)*
- *R. Barzaghi (Italy)*
- *F. Barthelmes (Germany)*
- *M.F. Lalancette (France)*
- *T. Basic (Croatia)*
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- *N. Kuhtreiber (Austria)*
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- *W. Featherstone (Australia)*
- *Jianliang Huang (Canada)*
- *Cheinway Hwang (Taiwan)*
- *Shuanggen Jin (China)*
- *G. Guimaraes (Brazil)*

Activities and publications during the period 2015-2017

During the period 2015-2017, the activities performed in the framework of the JWG 2.2.1 were mainly devoted to data collection and to the establishment of a methodology for merging local geoid solutions. These activities were mainly performed by the International Service for the Geoid (ISG) and, once preliminary results have been computed, the plan is to open a discussion about it within the working group and then involve all the members in the validation procedure.

Data collection

For the purposes of the working group activities it was crucial to have a large dataset of gravimetric geoid models available at ISG. This is because the activities mainly consist in merging such models, removing biases and other systematic effects by exploiting some information coming from satellite-only global gravity models. This required a first activity to collect local geoid models on a worldwide scale. Currently, the ISG archive is composed as reported in Table 2 and Table 3 (last update of the statistics was on 1st April 2017). 124 out of 156 models are classified as gravimetric. This collection included the activities of contacting authors, asking for model publication at ISG, converting the models into a unique ASCII format and publishing dedicated webpages in the ISG website (containing a short model description, a model figure, bibliographic references, the contact person, etc.).

Table 2 Number of models per continent in the ISG archive

Europe	59
North America	36
Africa	17
Asia	15
Oceania	13
South America	9
Antarctica	4
Arctic	3
Total	156

Table 3 Number of models per policy-rule in the ISG archive

Public	112
On-Demand	18
Private	26
Total	156

Methodology

The proposed unification strategy consists of first estimating biases and systematic effects by a least-squares adjustment of the local geoid residuals with respect to a satellite-only model, and then correcting the remaining geoid distortions along the national borders by least squares collocation. The advantage of this approach is that the resulting unified geoid includes both the low frequencies of the satellite-only geoid model and the high frequencies of the local ones. The latter are expected to be more accurate in the definition of the equipotential than those coming from a "terrestrial" global geopotential model combined with the residual terrain effect. Moreover, this procedure allows for a fast update of the unified model when a new geoid is available.

The procedure, which should be as automatized as possible, can be summarized in the following steps:

- Acquisition of the local geoid/quasigeoid model from the ISG archive.
- Detection of the national borders and extraction of a subset of uniformly distributed points.
- Evaluation of the point elevations from a Shuttle Radar Topography Mission (SRTM) at each selected knot of the geoid/quasigeoid model.
- Synthesis of the geoid/quasigeoid from a satellite-only model from the International Center for Global Gravity Field Models (ICGEM) archive.
- Synthesis of the geoid/quasigeoid for degrees higher than 200 from EGM2008 or EIGEN6C4 (activity to be verified if it is necessary).
- Computation of Residual Terrain Correction (RTC) on elevation residuals with respect to a properly averaged Digital Terrain Model (DTM).
- Computation of geoid/quasigeoid residuals by subtracting the global model contributions and the residual terrain correction from the original ISG model.
- Empirical modelling of the error covariance matrix of the geoid/quasigeoid residuals, also considering the available information on the satellite-only global model error covariances.
- Estimation of a bias and other systematic effects $S(\varphi,\lambda)$ by least-squares adjustment, according to the general formula (Heiskanen and Moritz, 1967):

  $$S(\varphi,\lambda) = a_1 + a_2\cos\varphi\cos\lambda + a_3\cos\varphi\sin\lambda + a_4\sin\varphi$$

  or to an approximate one, such as:

  $$\widetilde{S}(\varphi,\lambda) = b_1 + b_2(\varphi-\varphi_0) + b_3\cos\varphi(\lambda-\lambda_0)$$

  to be iteratively applied by revising the empirical error covariance modelling.

- Application of the estimated biases and systematic effects to all the considered local models.
- Merging of neighboring country models by stochastic interpolation (e.g. collocation).
- Production of a new file in ISG format containing the merged geoid/quasigeoid model.

This procedure is currently under test and refinement. In the sequel some results regarding the Italian quasigeoid model ITALGEO05 (gravimetric solution) are reported; see Figure 7 to Figure 15 and Table 4. Once the procedure is fixed, it will be applied to some European neighbor quasigeoid models (we plan to consider Spain, France, Switzerland, Italy, Greece, etc.) and the result will be compared with the existing continental model EGG2008, which is available at ISG too. The guess is that, if the used gravity data were not preliminary reduced by biases, the EGG2008 model could be more affected by distortions due to the presence of different national reference systems.

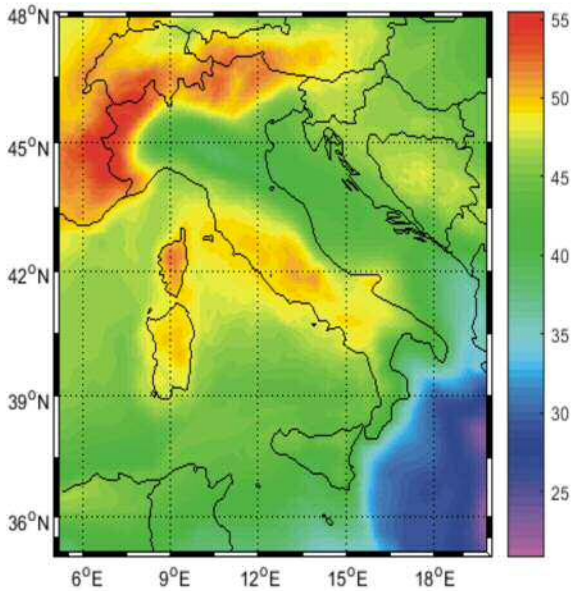

Figure 7 ITALGEO05 quasigeoid model (units in m); this model is in the ISG archive but is not publicly available from the ISG website.

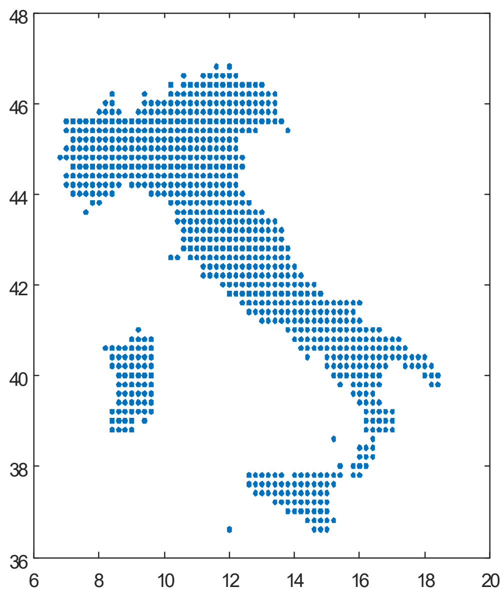

Figure 8 The selected 835 points among the ITALGEO05 grid, inside the Italian borders; these points will be used for estimating a bias and other systematic effects.

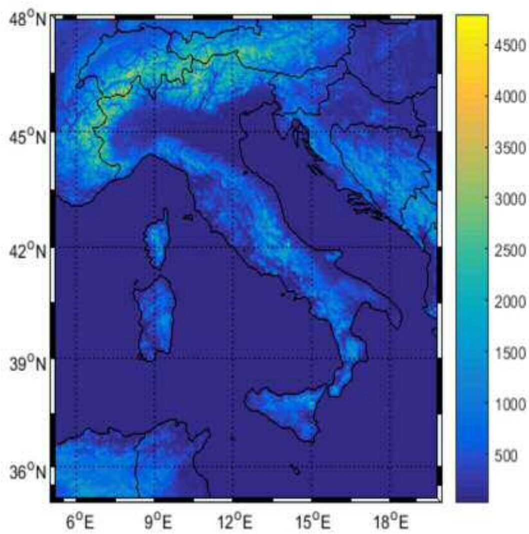

Figure 9 Italian DTM as derived from SRTM (units in m).

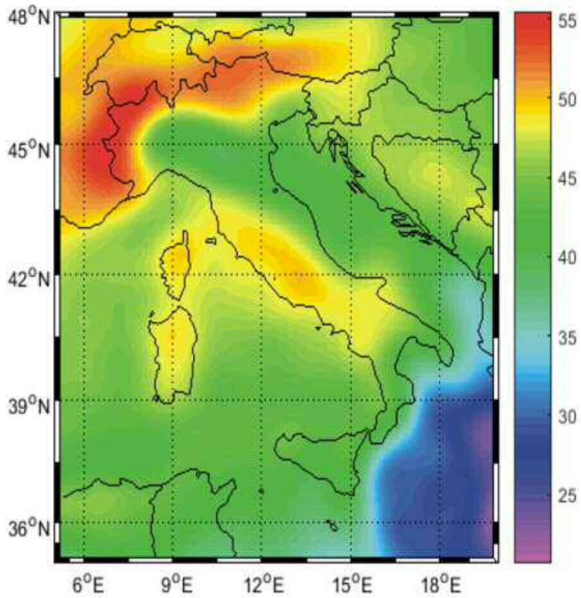

Figure 10 Synthesis of the Italian quasigeoid from GOCO-05S satellite only model up to degree and order 280 (units in m).

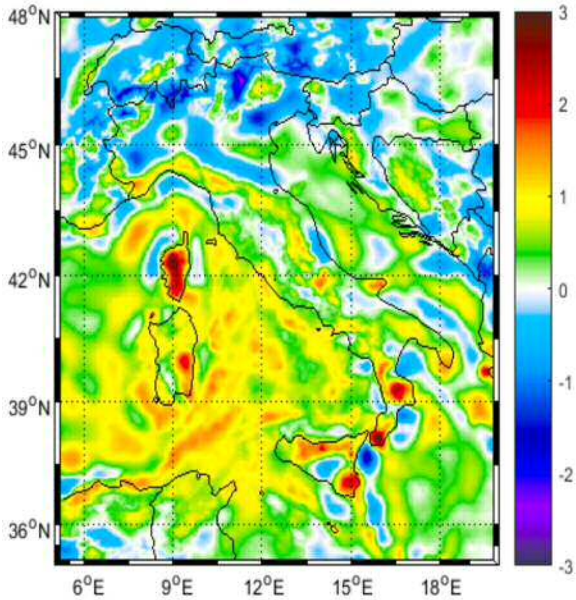

Figure 11 Residuals between ITALGEO05 and GOCO-05S up to degree and order 280 (units in m).

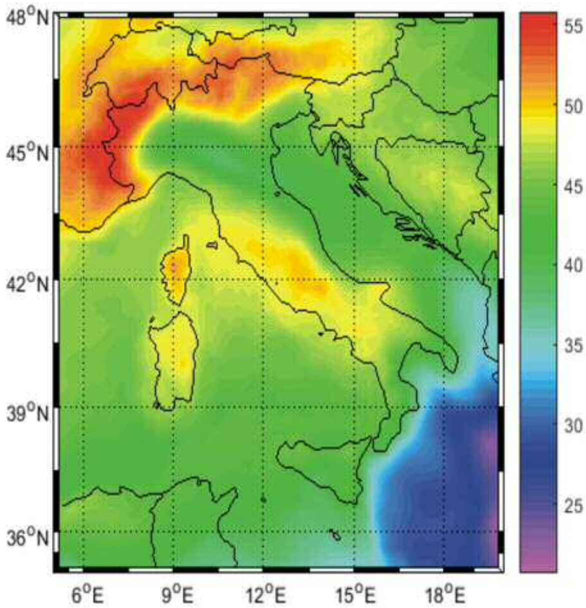

Figure 12 Synthesis of the Italian quasigeoid from GOCO-05S up to degree and order 280, and EGM2008 above degree 280, with a smooth transition down to degree 210 (units in m). This additional information should not degrade the bias estimate (see e.g. Gatti et al., 2013; Gerlach and Rummel, 2013), but could be useful to further reduce the residuals between global and local models. Its use is still under consideration.

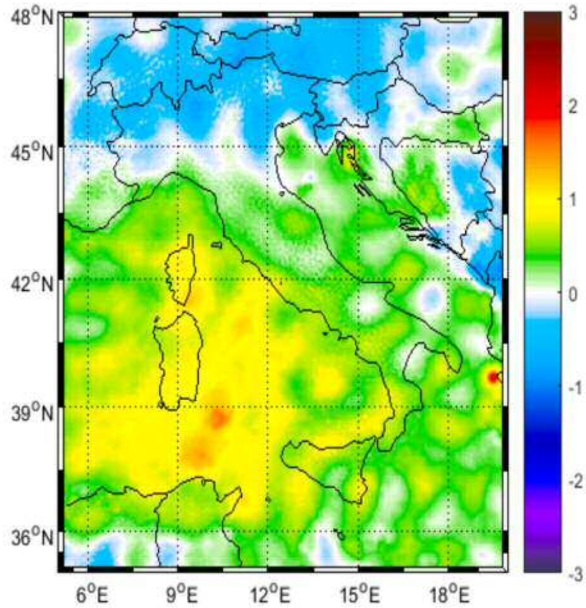

Figure 13 Residuals between ITALGEO05 and GOCO-05S up to degree 280 complemented with EGM2008 up to degree 2190 (units in m).

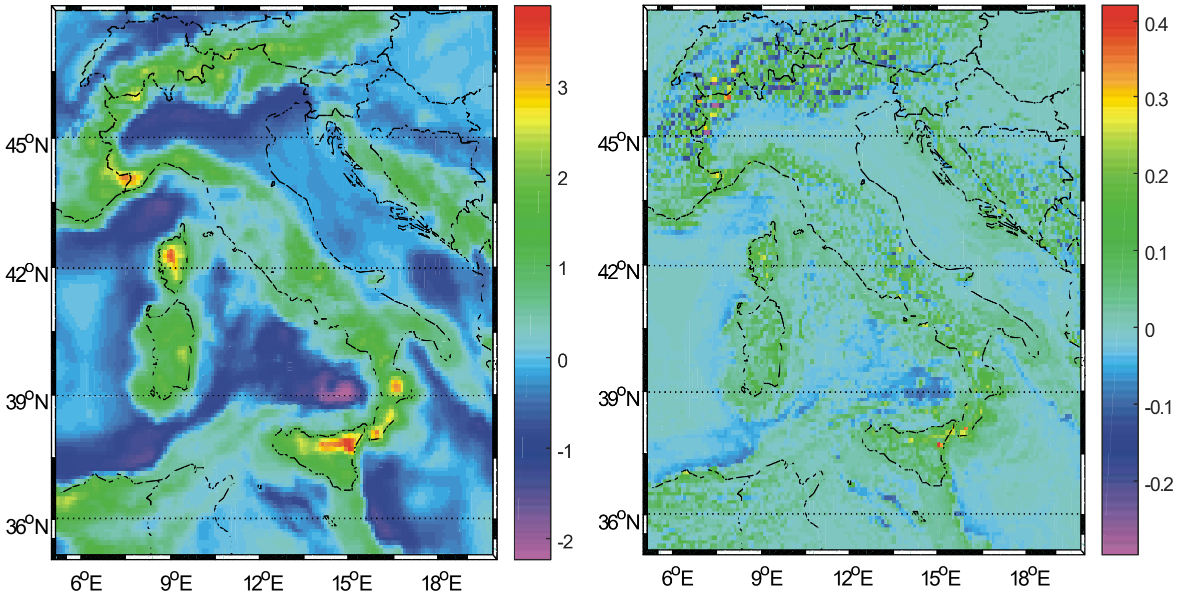

Figure 14 Residual Terrain Correction (RTC) on elevation with respect to an averaged DTM (units in m). On the left, SRTM is averaged over windows of 30'×30', which is compatible with the subtraction of a satellite-only global model from the local quasigeoid. On the right, SRTM is averaged over windows of 5'×5', which is compatible with the subtraction of EGM2008 too. The use of RTC to further reduce the local data in the bias estimation still requires tuning activities.

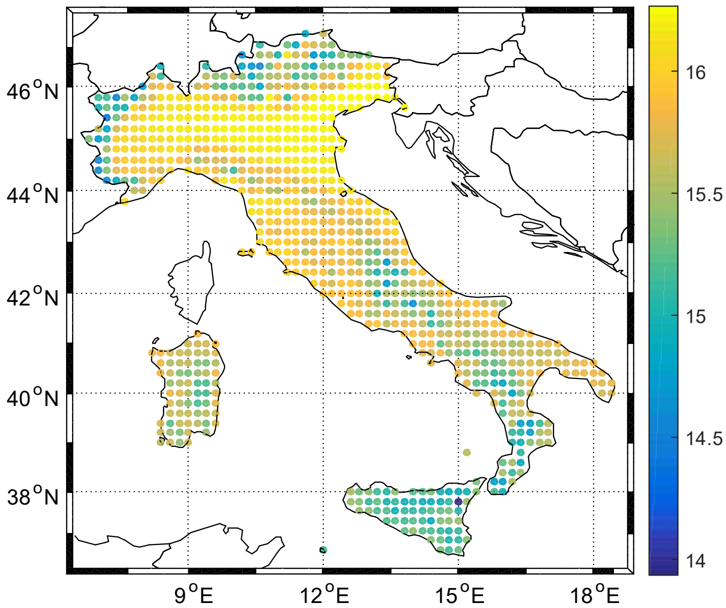

Figure 15 Error variance obtained by propagation from the block-diagonal error covariance matrix of the GOCO-05S coefficients, taking also into account the point elevation (units in cm).

Table 4 Estimated bias and systematic effects of ITALGEO05 (units in m) when using a stochastic model coming from the GOCO-05S error covariance matrix plus a global omission error covariance matrix from EGM2008 degree variances plus a diagonal covariance matrix for the local quasigeoid model error (standard deviation of 5 cm). This stochastic modelling will be improved by an empirical one and the least-squares estimation will be applied iteratively. As already stated, the use of EGM2008 to complement the satellite-only model, as well as a proper RTC, will be investigated.

$\hat{b}_1 = 0.451$	$\hat{\sigma}_{b_1} = 0.039$
$\hat{b}_2 = -7.524$	$\hat{\sigma}_{b_2} = 0.717$
$\hat{b}_3 = -0.832$	$\hat{\sigma}_{b_3} = 0.129$

The same procedure has been applied also to the quasigeoid models of France (QGF98) and Corsica (QGC02A), obtaining the results in Table 5 and Table 6. An analysis on the statistical significance of the estimated parameters will be performed in the future. Finally, the residuals of ITALGEO05, QGF98 and QGC02A with respect of GOCO-05S are shown before and after the trending procedure in Figure 16 and Figure 17.

Table 5 Estimated bias and systematic effects of QGF98 (units in m)

$\hat{b}_1 = -0.884$	$\hat{\sigma}_{b_1} = 0.045$
$\hat{b}_2 = -3.410$	$\hat{\sigma}_{b_2} = 1.133$
$\hat{b}_3 = -4.338$	$\hat{\sigma}_{b_3} = 0.063$

Table 6 Estimated bias and systematic effects of QGC02A (units in m)

$\hat{b}_1 = 1.180$	$\hat{\sigma}_{b_1} = 0.090$
$\hat{b}_2 = 17.429$	$\hat{\sigma}_{b_2} = 10.308$
$\hat{b}_3 = -48.778$	$\hat{\sigma}_{b_3} = 13.402$

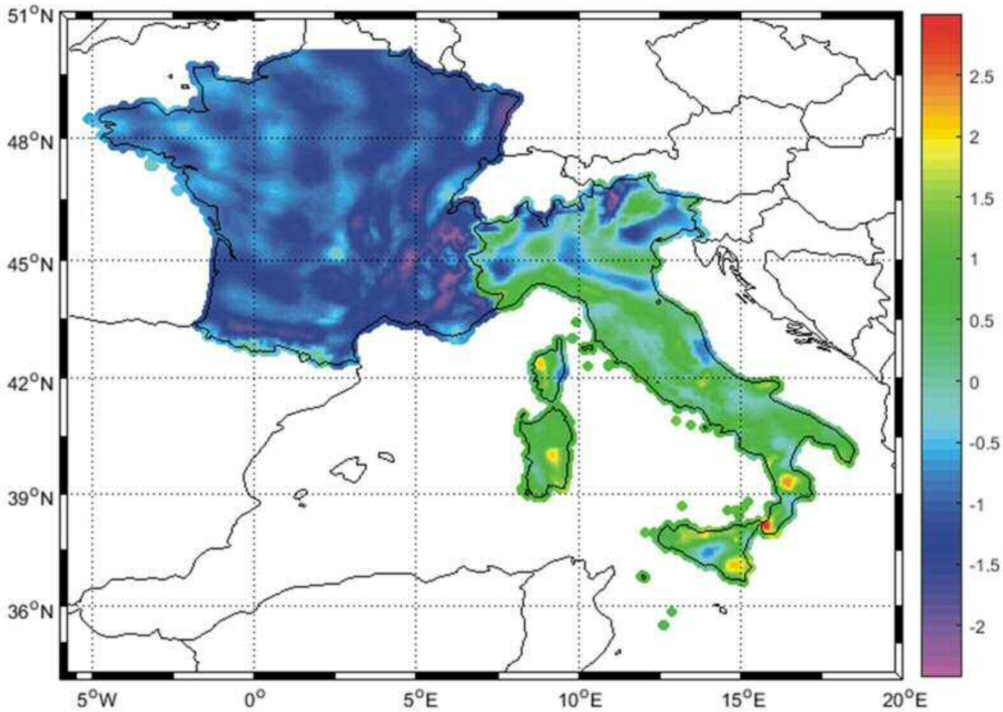

Figure 16 Residuals of ITALGEO05, QGF98 and QGC02A with respect of GOCO-05S before the trending procedure, i.e. as they are stored in the ISG archive (units in m). At the French-Italian border, discontinuities in the quasigeoid residuals are quite evident.

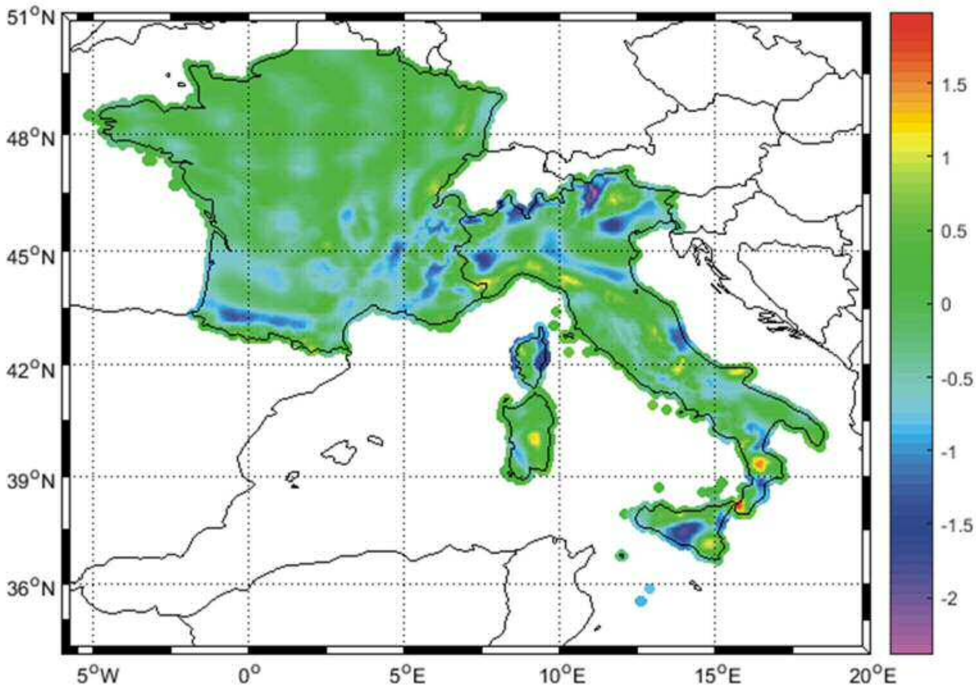

Figure 17 Residuals of ITALGEO05, QGF98 and QGC02A with respect of GOCO-05S after the trending procedure (units in m). At the French-Italian border, discontinuities in the quasigeoid residuals are significantly reduced. A further interpolation to refine the quasigeoid merging will be implemented in the future.

Other related activities

Although based on sparse GPS/levelling data, instead of gridded geoid/quasigeoid national models, similar activities have been performed for the height datum unification of continental Italy with Sicily and Sardinia (Barzaghi et al., 2015) and continental Spain with Balearic and Canary Islands (Reguzzoni et al., 2017). These preliminary studies were useful to better tune the proposed procedure in the framework of the JWG 2.2.1.

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JWG 2.2.2: The 1 cm geoid experiment

Chair: *Yan Ming Wang (USA)*
Vice Chair: *Rene Forsberg (Denmark)*

Members

- *Agren Jonas (Sweden)*
- *Ahlgren Kevin (USA)*
- *Avalos David (Mexico)*
- *Dalyot Sagi (Israel)*
- *Denker Heiner (Germany)*
- *Ellmann Artu (Estonia)*
- *Erol Bihter (Tukey)*
- *Grigoriadis Vasilios (Greece)*
- *Holmes Simon (USA)*
- *Huang Jianliang (Canada)*
- *Hwang Cheinway (Taiwan)*
- *Jiang Tao (China)*
- *Kingdon Robert William (Canada)*
- *Li Xiaopeng (USA.)*
- *Pangastuti Dyah (Indonesia)*
- *Sarid Hezi (Israel)*
- *Veronneau Marc (Canada) Name (Country)*

Activities and publications during the period 2015-2017

The 1 cm Geoid Experiment working group (WG) was proposed in the summer of 2016. It was approved by the IAG Executive Committee in April 2017. The WG has a direct link to the joint study group JSG0.15: Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy. Therefore, the WG is working closely with JSG0.15 in all aspects through careful coordination.

Since the JWG 2.2.2 was approved just a few weeks before the deadline of the midterm report, the planned activities have not yet started. The Terms of Reference with planned activities are therefore presented instead of a report below. This is also needed as the working group is not listed in the Geodesist's Handbook 2016 (Drewes et al. 2016).

Terms of Reference of JWG 2.2.2

Since H. Moritz proposed a 1-cm geoid at the turn of the century, efforts have been made to reach this goal. A highly accurate geoid not only benefits science, but also has a very practical application for the definition of national and world height systems in the GNSS era. Today, geoid models derived from satellite gravity missions such as GRACE and GOCE are determined with cm-accuracy to a spatial resolution of about 100 km. To achieve cm-accuracy at one km spatial resolutions, airborne and terrestrial gravity data are still necessary.

In the geodetic community, there are a few schools of geoid computation methods based on different philosophies and theories. While they all aim to achieve a cm geoid model, numerical differences exist because each method deals differently not only with gravity data and topography, but also with errors in satellite models, terrestrial and airborne data. It is of scientific interest to know how well these methods agree numerically, and to know at the same time, at what accuracy can the geoid be modeled.

The objective of this WG is to compute the local geoid by using the best data available in a few selected areas where highly accurate independent data sets exist for validation purposes. For instance, the National Geodetic survey has been conducting GPS/leveling, gravity, deflection of vertical and airborne gravity over three traverses about 320 km in length in a flat, a moderate and rough topography area. Other such data sets exist, e.g., in South Korea and Taiwan.

The Geoid Experiment Working Group (WG) is meant to coordinate international cooperation on geoid computation by combining satellite gravity models and terrestrial/airborne gravity data in a few selected areas to work towards a 1-cm accuracy goal. Lessons learned from this exciting study will be greatly important for future geoid modeling in the geodetic community.

This WG has a direct link to the joint study group JSG0.15 under ICCT. The WG will work closely with JSG0.15 in all aspects through careful coordination.

WG activities

- Provide common gravity and elevation data sets to the WG members
- Set standard for the geoid models (tidal system, W0 value, the reference ellipsoid, satellite gravity models)
- Complete geoid computation and validation
- Organize workshop and conference sessions
- Report activities to SC2.2, ISG and ICCT

Sub-commission 2.3: Satellite Gravity Missions

Chair: *Adrian Jäggi (Switzerland)*
Vice Chair: *Frank Flechtner (Germany)*

Overview

Sub-commission 2.3 promotes scientific investigations concerning dedicated satellite gravity field missions CHAMP, GRACE, GOCE, and the future GRACE Follow-On mission, the development of alternative methods and new approaches for global gravity field processing also including complementary gravity field data types, as well as interfacing to user communities and relevant organizations. The sub-commission is accompanied by a steering committee consisting of the members Srinivas Bettadpur, Sean Bruinsma, Thomas Gruber, Roland Pail, Torsten Mayer-Gürr, Ulrich Meyer, Cheinway Hwan, Shuanggen Jin, Federica Migliaccio, and Gerhard Heinzel. At its first splinter meeting at the International Symposium on Gravity, Geoid and Height Systems (GGHS) 2016 the steering committee was further enlarged by Annette Eicker and Carmen Böning. The members of the steering committee cover all relevant aspects from the generation, analysis and use of static and temporal global gravity field models dedicated gravity field missions, the combination of different data types, and the study of future mission concepts. Based on discussions at the GGHS splinter meeting and among the steering committee members, the focus of SC 2.3 was put in the first term on the following activities:

A new service to provide time-variable field solutions

The chair and vice chair of SC 2.3 are leading the activities of the European Gravity Service for Improved Emergency Management (EGSIEM), a project of the Horizon 2020 Framework Program for Research and Innovation of the European Commission aiming to unify the knowledge of the GRACE/GRACE-FO community to pave the way for a long awaited standardisation of time-variable gravity-derived products and to explore new and innovative approaches for gravity-based flood and drought forecasting. To achieve these objectives, different prototype services are currently being established in the frame of the EGSIEM project. A proposal has been submitted by SC 2.3 to the IAG Executive Board to continue one of the EGSIEM prototype services, the so-called Scientific Combination Service, beyond the EGSIEM project under the umbrella of the IAG's International Gravity Field Service (IGFS). The new service shall be called International Combination Service for Time-variable Gravity Fields (COST-G) and shall deliver consolidated time-variable global gravity models by combining solutions from several individual analysis centers (ACs, see Figure 18). The contributing ACs shall base their analyses on different methods but apply agreed-upon consistent processing standards to deliver consistent time-variable gravity field models, e.g. from GRACE or GRACE-FO in the near future. A draft version of the COST-G terms of references (ToR) has been discussed at the IAG Executive Board meeting during the EGU General Assembly 2017 in Vienna, Austria. The final version of the COST-G ToR shall be adopted at the IAG Executive Board meeting during the IAG Scientific Assembly 2017 in Kobe, Japan.

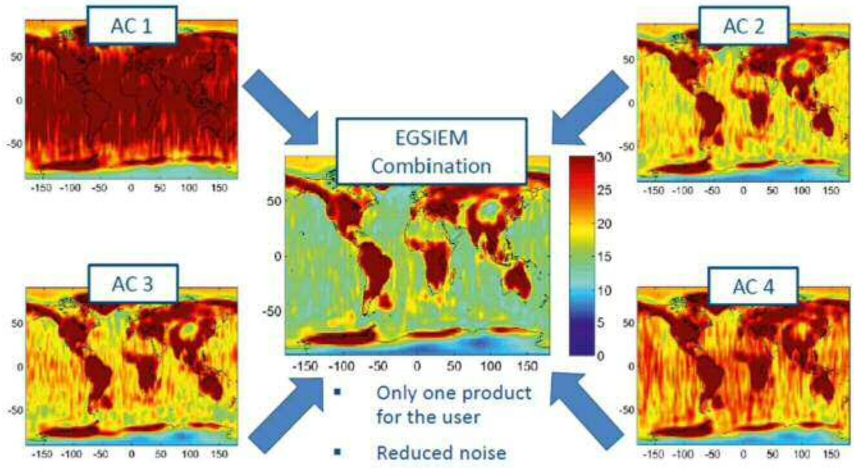

Figure 18: Principle of the COST-G service to generate one consolidated time-variable gravity field product for the user community as a combination of several solutions produced at different analysis centers (ACs).

Recommendations of the Geodetic Missions Workshop 2017 in Banff, Canada

Members of the of the steering committee of SC2.3 were actively involved in the formulation of recommendations from the Geodetic Missions Workshop 2017 in Banff, Canada, towards the ESA directorate of Earth observation. In view of the fact that presently no operational gravity mission is planned and recognizing the need for better water management, disaster preparedness as well as climatological time series and considering the increasing lack of ground-based and up-to-date observations, a sustained gravity observation space infrastructure with higher spatial and temporal resolutions and reduced latency in comparison to present demonstrator missions was recommended to be implemented as a future Sentinel mission of the European Copernicus Programme.

Increase the visibility towards Copernicus

In order to promote the needs of the gravity field community towards the European Copernicus Programme, several lobby events have been organized in Brussels. A first so-called tea time event was organized on March 2, 2017 at the Helmholtz Office in Brussels with the support of GFZ's EU project office and the Swiss Contact Office for European Research, Innovation and Education (SwissCore) to inform representatives of the European Commission on achievements of satellite gravimetry and future perspectives (see agenda in Figure 19). A second and larger event, entitled "Observing water transport from space – a vision for the evolution of Copernicus", was organized by GFZ's EU project office on May 31, 2017 at the Radisson Red Hotel in Brussels to inform representatives of ESA and the European Commission that gravity missions are now ready to be integrated in the European space infrastructure and that continuous gravity measurements are essential for numerous crucial questions regarding changes and dynamic processes in land, freshwater hydrology, cryosphere, ocean, atmosphere and solid Earth (see agenda in Figure 20). Besides teaser talks given at both events by Annette Eicker and Carmen Böning, the distribution of flyers and position papers, the president of Commission 2, Roland Pail, additionally informed at the second event on the science and user needs for a sustained observation of global mass transport from space as they were established by more than 80 international experts under the umbrella of the International Union of Geodesy and Geophysics (IUGG).

HELMHOLTZ | GEMEINSCHAFT

GFZ Helmholtz Centre POTSDAM

SwissCore Contact Office for European Research Innovation and Education

Tea Time Event on March 2nd, 2017

at
Helmholtz Brussels Office,

6th Floor, 98 Rue du Trone, 1000 Brussels

14.00 – 15.30

Programme

Welcome Message

Annika Thies, Helmholtz Bureau Brussels

Introduction: GRACE and Gravity

Frank Flechtner, GFZ, Helmholtz-Zentrum Potsdam

Space approaches to future gravity measurements

Annette Eicker, HafenCity University, Hamburg

Our changing view on the Earth:
New perspectives and chances through GRACE-FO

Carmen Boening, NASA Jet Propulsion Laboratory (JPL), Pasadena

Discussion

Wrap-up & Conclusion

Adrian Jaeggi, AIUB Inst. of Astronomy, Bern University

Reservez s.v.p. angela.richter@helmholtz.de

Figure 19: Agenda of the first lobby event organized in Brussels.

HELMHOLTZ ASSOCIATION

GFZ Helmholtz Centre POTSDAM

IAG Commission 2 "Gravity Field"

AGENDA

Observing water transport from space – a vision for the evolution of Copernicus

Wednesday 31 May 2017 – 18:00 CET

Venue: Radisson RED, Rue d'Idalie 35 (Gare Luxembourg) 1050 Brussels, Belgium

Contact point: GFZ Project Bureau, e-mail: gpb@gfz-potsdam.de
Tel.: +49-331-288-1035, Fax: +49-331-288-1034

17:30	Door open – Registration and Gathering	
18:00	Welcome	**Frank Flechtner,** *IAG, GFZ*
18:05	Introduction to Water Transport Monitoring from Space	**Frank Flechtner,** *IAG, GFZ*
	Application of GRACE Mass Transport Data for Monitoring of Water Resources	**Annette Eicker** *HafenCity University Hamburg*
	Our changing view on Earth: New perspectives and chances through GRACE, GRACE-FO, and beyond	**Carmen Böning** *NASA/JPL*
	User requirements and concepts for future mass transport monitoring	**Roland Pail** *IAG, TU Munich*
19.05	Discussion, followed by Closing Remarks	
19:45	**Networking - Reception**	
20.30	**End of Event**	

Figure 20: Agenda of the second lobby event organized in Brussels.

Sub-commission 2.4: Regional Geoid Determination

Chair: *Maria Cristina Pacino (Argentina)*
Vice Chair: *Hussein Abd-Elmotaal (Egypt)*

Overview

The main purpose of Sub-Commission 2.4 is to initiate and coordinate the activities of the regional gravity and geoid sub-commissions.
Currently there are 6 of them:

- SC 2.4a: Gravity and Geoid in Europe (chair H. Denker, Germany)
- SC 2.4b: Gravity and Geoid in South America (chair M.C. Pacino, Argentina)
- SC 2.4c: Gravity and Geoid in North and Central America (chair Marc Véronneau, Canada)
- SC 2.4d: Gravity and Geoid in Africa (chair H. Abd-Elmotaal, Egypt)
- SC 2.4e: Gravity and Geoid in the Asia-Pacific (chair Jay Hyoun Kwon, Korea)
- SC 2.4f: Gravity and Geoid in Antarctica (chair M. Scheinert, Germany)

These regional SC nominally cover the whole world with the exception of a larger region in the Middle East. But it is clear that not all countries which are listed as a member of a regional SC, are actively participating in international projects or data exchange agreements. This is especially true for some countries in Central America, the Caribbean, Africa and Asia.

Short summary of the activities of the regional SCs

SC 2.4a: European Gravity and Geoid

A complete re-computation of the European quasigeoid (EGG2015) based on a 5th generation GOCE geopotential model was presented at the 26th IUGG General Assembly in Prague, Czech Republic, 2015 (Denker 2015). The new model was evaluated by different national and European GPS and levelling data sets, where emphasis was put on the effect of the data updates and the modeling refinements.

SC 2.4b: Gravity and Geoid in South America

A big effort was carried out by many different organizations in the last few years to improve the gravity data coverage all over South America. As a result approximately 947.953 stations gravity data are available for geoid determination.

A new South America geoid model has been computed on a 5' x 5' grid, by the remove-compute-restore technique using 947,953 point gravity data (free-air gravity anomalies), the SAM3s_v2 DTM for the computation of terrain correction and other topographic and atmospheric effects.

SC 2.4c: Gravity and Geoid in North and Central America

The activities of the sub-commission 2.4c (Gravity and Geoid in North and Central America) is principally focus around the modernisation of the US National Spatial Reference System (NSRS) under the leadership of NOAA’s National Geodetic Survey (NGS). Besides, a new regional gravimetric geoid model was determined for Mexico, Central America and the Caribbean.

SC 2.4d: Gravity and Geoid in Africa

Several geoid models have been developed for some African countries. In 2015, Abd-Elmotaal et al. have computed a first model for the regional geoid for the whole continent of Africa. The IAG sub-commission on the gravity and geoid in Africa suffers from the lack of data (gravity, GNSS/levelling …). Great support of IAG is needed in collecting the required data sets.

SC 2.4e: Gravity and Geoid in the Asia-Pacific

The activity of SC 2.4e was rather low in the reporting period 2015-2017. It focussed on activities in Korea and Taiwan, where additional gravity observations and improved geoid modelling were performed. In Taiwan, absolute gravity changes were interpreted by geodynamic processes, and in Korea a calibration site for relative gravimeters has been established.

SC 2.4f: Gravity and Geoid in Antarctica (AntGG)

As a highlight the publication of the first Antarctic-wide gravity anomaly dataset has to be mentioned (Scheinert et al., 2016). It was given general attention as can be seen by an EOS article (Stanley, 2016). The dataset is publically available via the PANGAEA database. However, this first gravity dataset release is far from comprising a complete coverage over Antarctica. Therefore, further updates are planned when new data will have been acquired.

Sub-commission 2.4a: Gravity and Geoid in Europe

Chair: Heiner Denker (Germany)

Overview

The topic of regional geoid determination was handled from 2003 – 2011 within Commission 2 Projects, and since 2011 the responsibility for this task is within Sub-Commission 2.4, which is further sub-divided according to different regions of the world, such as Sub-Commission SC 2.4a "Gravity and Geoid in Europe". The primary objective of SC 2.4a is the development of improved regional gravity field models (especially geoid/quasigeoid) for Europe, which can be used for applications in geodesy, oceanography, geophysics and engineering. SC 2.4a has cooperated with national delegates from nearly all European countries, whereby existing contacts have been continued and extended.

European quasigeoid model (EGG2015)

A complete re-computation of the European quasigeoid (EGG2015) based on a 5th generation GOCE geopotential model was presented at the 26th IUGG General Assembly in Prague, Czech Republic, 2015 (Denker 2015). The new model was evaluated by different national and European GPS and levelling data sets, where emphasis was put on the effect of the data updates and the modeling refinements. Furthermore, applications of the quasigeoid model, such as vertical datum connections and the delivery of ground truth data for high-precision optical clock comparisons, were investigated. In this context, the EGG2015 model also served for deriving gravity potential estimates and the associated relativistic redshift corrections for optical clock comparisons (Denker et al. 2016). For instance, such a comparison of optical clocks was carried out between Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, and Systèmes de Référence Temps-Espace (LNE-SYRTE) in Paris, representing the first optical frequency comparison across national borders; the fully independent clocks agreed with an unrivalled fractional uncertainty of $5 \times 10\text{-}^{17}$, which corresponds to a height uncertainty of about 0.5 m (Lisdat et al. 2016). Further clock comparisons are expected soon, aiming at a performance level of 10^{-18}, which corresponds to a height uncertainty of about 1 cm. Hence, the optical clocks may offer in the near future completely new options to independently observe and verify geopotential differences over large distances, with the perspective to overcome some of the limitations inherent in the classical geodetic approaches. For example, clocks could be used to interconnect tide gauges on different coasts without direct connection and help to unify various national height networks, even in remote areas.

Terrestrial gravity and terrain data base

Besides the work related to the optical clocks, the terrestrial gravity and terrain data base was continuously updated, with significant updates performed for Germany and Bulgaria. This lead to another European gravimetric quasigeoid computation in 2016 (EGG2016), which was then employed for the development of a new official German quasigeoid model GCG2016 (German Combined QuasiGeoid 2016) on the basis of gravimetric and GNSS/levelling data; this work was done in cooperation with Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt am Main, Germany (for further details see BKG 2016). In addition to this, regional gravity field modelling based on point masses (Lin et al. 2015, 2016) and the computation of topographic and atmospheric effects with tesseroids was investigated (Lin and Denker 2016).

References

BKG (2016) Quasigeoid GCG2016. https://www.bkg.bund.de/DE/Produkte-und-Services/Shop-und-Downloads/Digitale-Geodaten/Quasigeoid/quasigeoid.html

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Lin, M., Denker, H. (2016) Comparison of various methods for modeling gravitational effects of the topography. First Joint Comm. 2 and IGFS Meeting, Internat. Symp. on Gravity, Geoid and Height Systems 2016, GGHS2016, Thessaloniki, Greece, 19 – 23 Sept. 2016 (Poster)

Lin, M., Denker, H., Müller, J. (2015) Regional gravity field modeling using a two-step point mass method: results from IAG JSG0.3 test data. XXVI General Assembly of the International Union of Geodesy and Geophysics (IUGG), Earth and Environmental Sciences for Future Generations, Prague, Czech Republic, 22 June – 02 July 2015, Abstract G02p-412 (Poster)

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Lisdat, C., Grosche, G., Quintin, N., Shi, C., Raupach, S.M.F., Grebing, C., Nicolodi, D., Stefani, F., Al-Masoudi, A., Dörscher, S., Häfner, S., Robyr, J.-L., Chiodo, N., Bilicki, S., Bookjans, E., Koczwara, A., Koke, S., Kuhl, A., Wiotte, F., Meynadier, F., Camisard, E., Abgrall, M., Lours, M., Legero, T., Schnatz, H., Sterr, U., Denker, H., Chardonnet, C., Le Coq, Y., Santarelli, G., Amy-Klein, A., Le Targat, R., Lodewyck, J., Lopez, O., Pottie, P.-E. (2016) A clock network for geodesy and fundamental science. Nature Communications 7, Article number: 12443. doi:10.1038/ncomms12443

Sub-commission 2.4b: Gravity and Geoid in South America

Chair: Maria Cristina Pacino (Argentina)
Vice Chair: Denizar Blitzkow (Brazil)

Overview

This report intends to cover most of the activities in South America related to gravity field determination. It is not complete certainly due to the many activities going on by different organizations, universities and research institutes.

Improvements of gravity data bases

A big effort was carried out by many different organizations in the last few years to improve the gravity data coverage all over South America. As a result approximately 947.953 stations gravity data are available for geoid determination. Figure 21 shows the new and old gravity data. The new gravity observations have been carried out with LaCoste&Romberg and/or CG5 gravity meters. GPS double frequency receivers have been used to derive the geodetic coordinates of the stations. The orthometric height for the recent surveys was derived from geodetic height using EGM2008 restricted to degree and order 150.

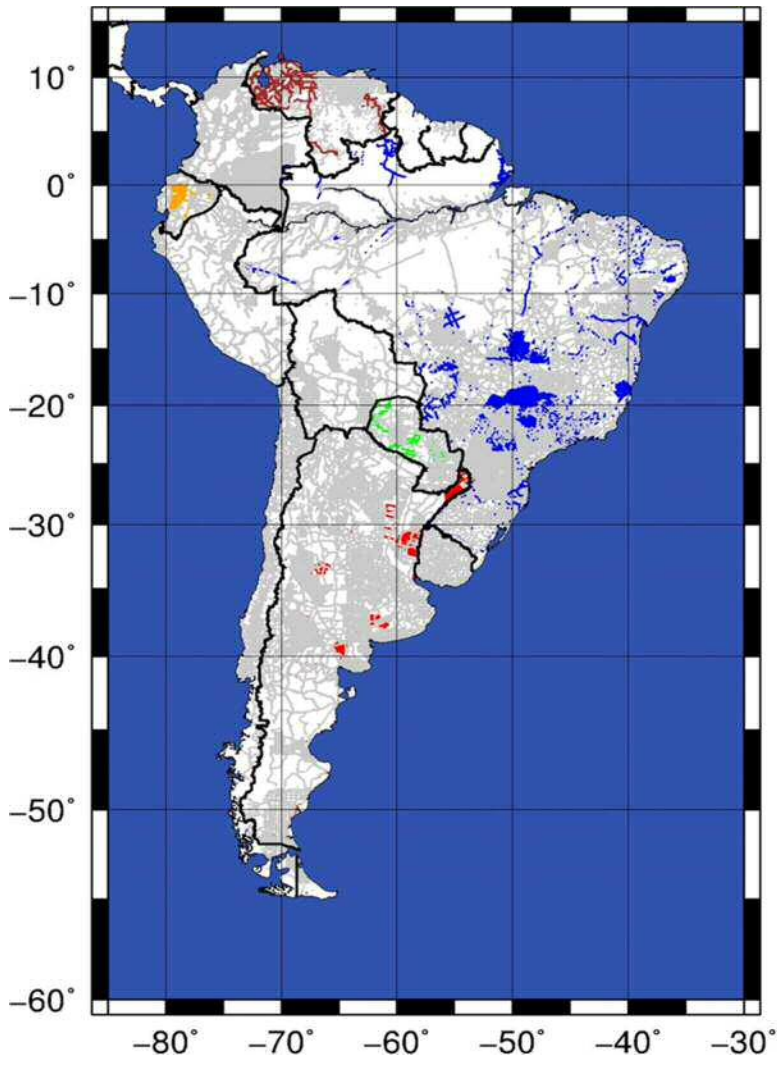

Figure 21 South America gravity data

Argentina

The last four years, 1070 new gravity stations have been measured in Corrientes and Missiones provinces in Argentina (green and red points in Figure 22, respectively).

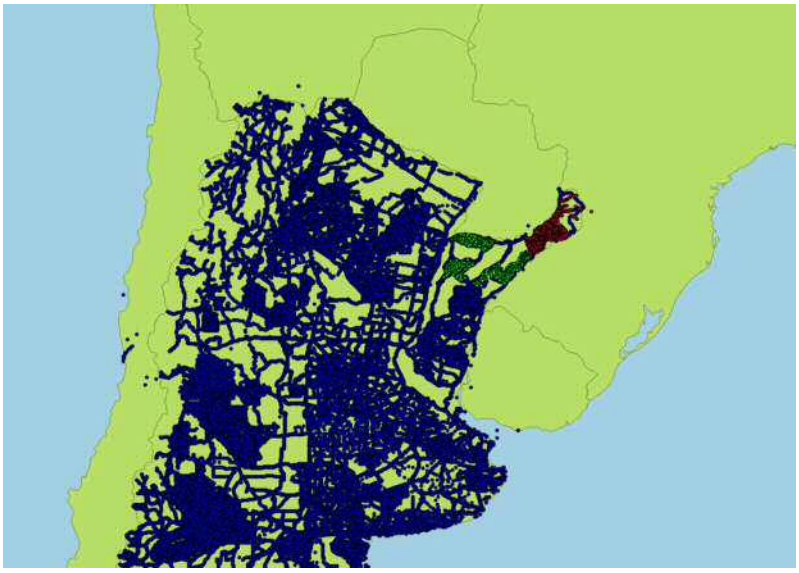

Figure 22 Gravity data in Argentina.

Brazil

In the last five years, IBGE (CGED), Polytechnic School of the University of São Paulo, Laboratory of Surveying and Geodesy (EPUSP-LTG), SAGS project (GETECH/NGA) and the Thematic Project (FAPESP, Brazilian research foundation) a total of 18.186 new gravity stations have been measured (Figure 23 and Figure 24).

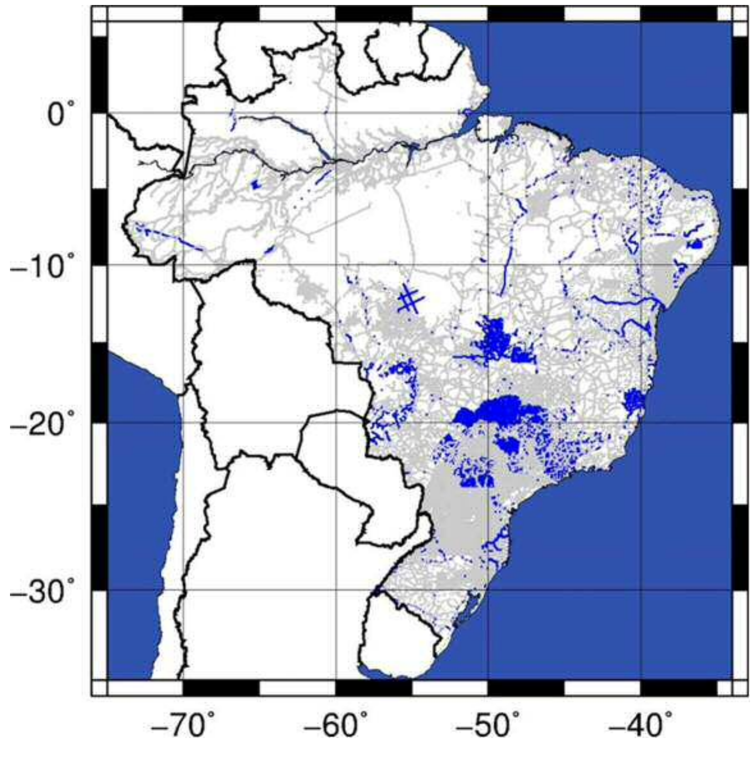

Figure 23 Brazil new gravity data.

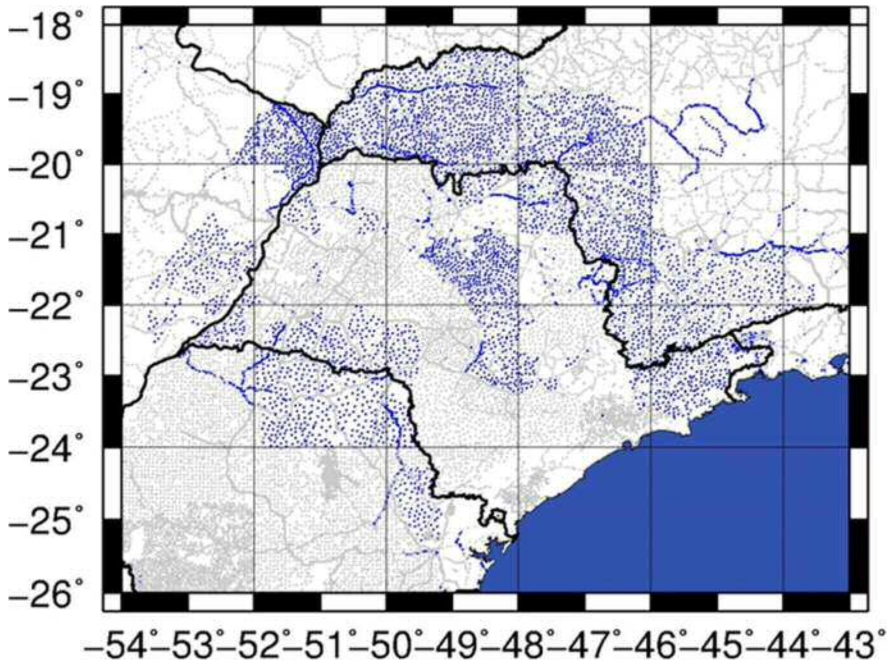

Figure 24 Thematic Project and EPUSP-LTG survey.

Ecuador

From 2013 up to 2016, gravimetric surveys in Ecuador obtained 1194 new points. SAGS gravity data were surveyed by IGM, IBGE and EPUSP. The gravity values of the densification surveys were connected to the existing FGN (Fundamental Gravity Network) in the country. Figure 25 shows the surveys of the 2013, 2014, 2015, and 2016 with pink, green, yellow and red points, respectively.

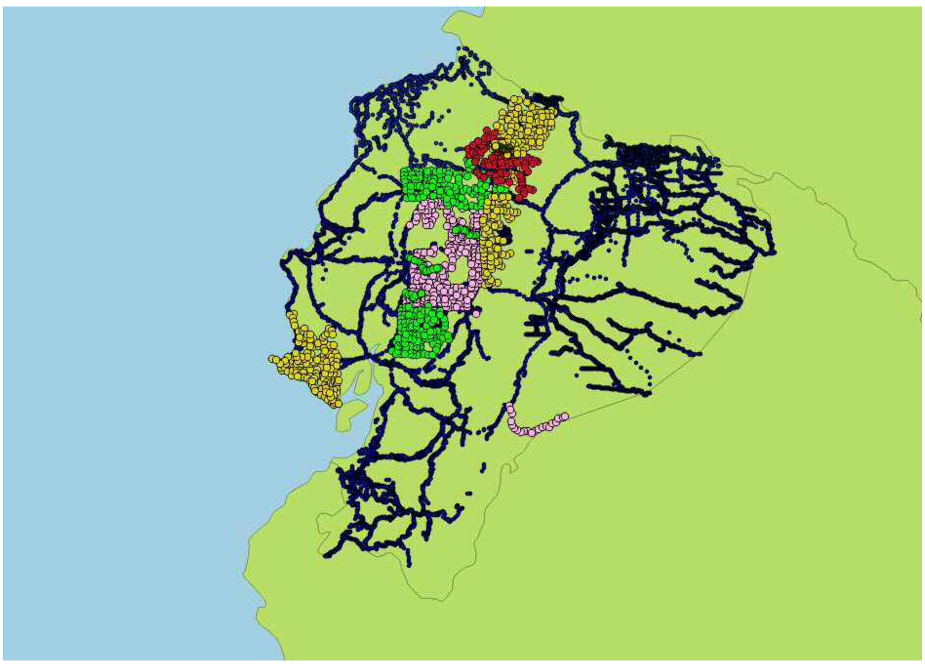

Figure 25 Ecuador surveys.

Venezuela

A total of 591 new gravity stations have been recently measured. They were observed by *Instituto Geográfico Venezuelano Simon Bolivar* (IGVSB), IBGE and EPUSP, densification network on roads (brown, pink and green points in Figure 26) and rivers in the South (orange and yellow points in Figure 26) in Venezuela.

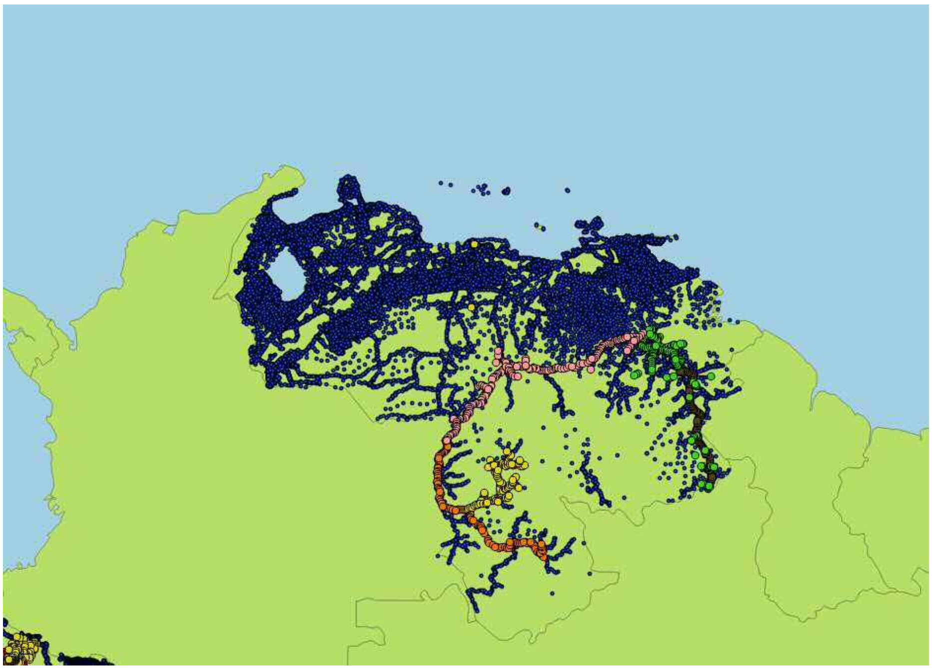

Figure 26 Gravity survey in Venezuela.

Earth tide model

University of São Paulo, supported by a few organizations, is involved in a project for Earth Tide model for Brazil. The idea is to occupy a sequence of 13 stations around the country for one year in each station. The cities planned for occupation are: Cananeia, Valinhos, São Paulo, Presidente Prudente, Porto Velho, already observed, Manaus and Brasilia, under observation at the moment; the cities in regions northeast (Fortaleza and Salvador), midwest (Cuiabá and Campo Grande) and south (Curitiba and Santa Maria) to be observed in the future. For this purpose two gPhone gravity meters are available. Figure 27 shows the distribution of the stations.

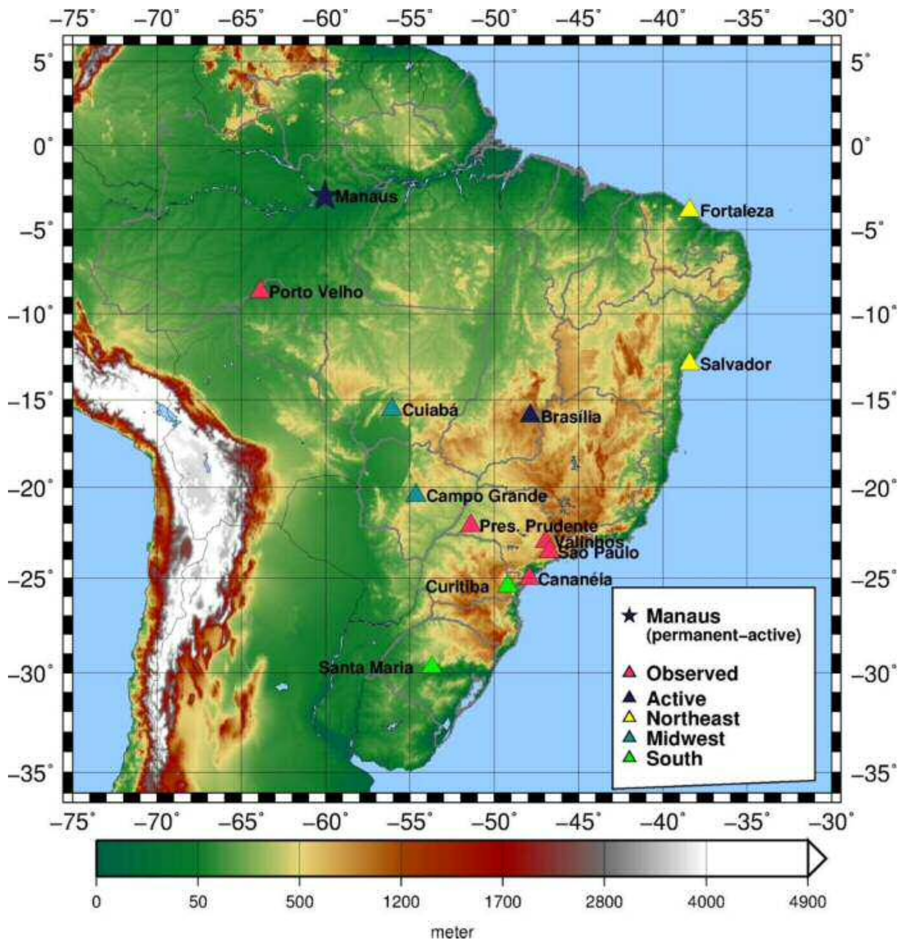

Figure 27 Distribution of sites to be observed for Earth tides.

Absolute gravity network

The Institute of Geography and Cartography of the State of São Paulo owns a gravity meter A-10 under the responsibility of the University of São Paulo (Figure 28). The gravity meter is involved in various activities in São Paulo and in Brazil, out of Argentina, Venezuela and Ecuador. Figure 29 shows the establishment of new (blue point) and reoccupied (red points) absolute stations in São Paulo State. From north to south of Brazil a set of absolute stations have also been established (Figure 30). The idea is to establish an absolute gravity network in Brazil and in South America.

Figure 28 Absolute gravity meter A10-32.

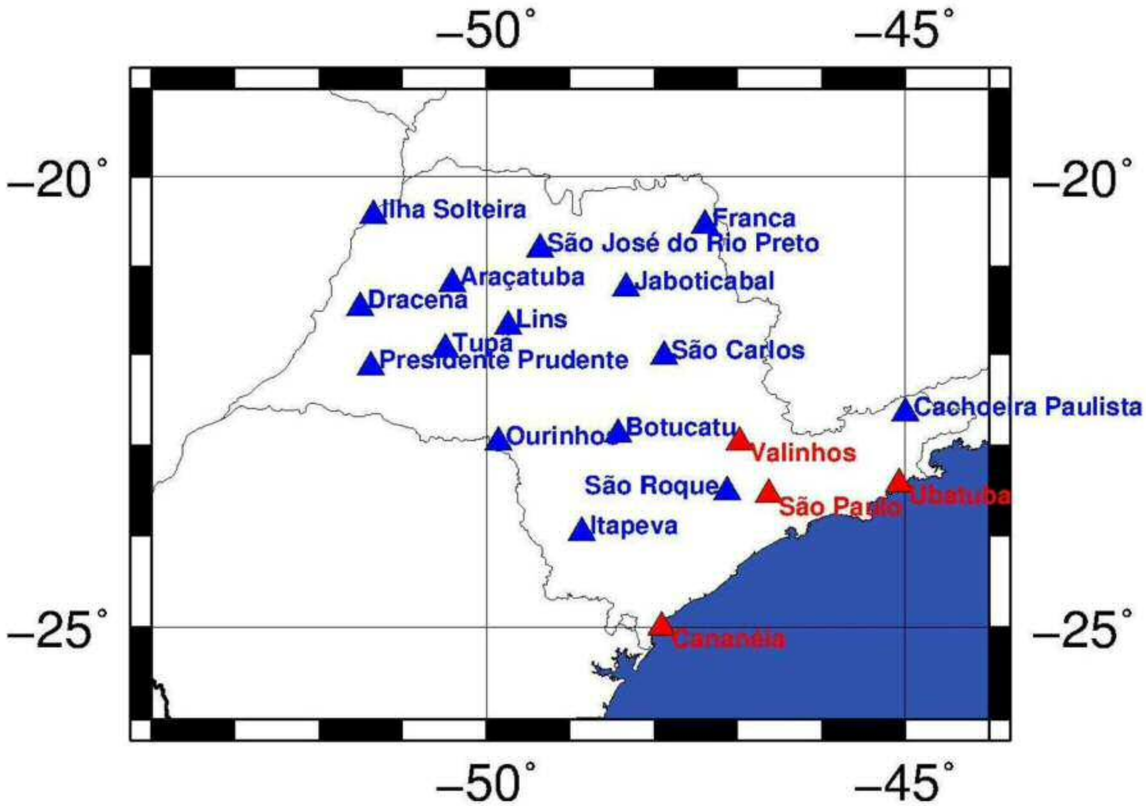

Figure 29 Absolute gravimetric stations in São Paulo State.

Figure 30: Absolute gravity stations in Brazil.

South America geoid model (GEOID2015)

The new South America geoid model has been computed on a 5' x 5' grid, by the remove-compute-restore technique using 947,953 point gravity data (free-air gravity anomalies), the SAM3s_v2 DTM for the computation of terrain correction and other topographic and atmospheric effects. The mean free-air gravity anomaly (FA) in a 5' grid over continent was derived from the complete BA (FA over the ocean obtained from satellite altimetry model DTU10). The short wavelength component was estimated with FFT technique using the modified Stokes integral through spheroidal Molodenskii-Meissl kernel modification. The reference field used was EIGEN-6C4 up to degree and order 200. The computed points are in a grid of 5' x 5' covering the area from 56.9583333° S to 14.9583333° N in latitude, and from 94.9583333° W to 30.0416667° W in longitude. The geoidal heights are referred to WGS84 (Figure 11). The model is available in ISG site (http://www.isgeoid.polimi.it/).

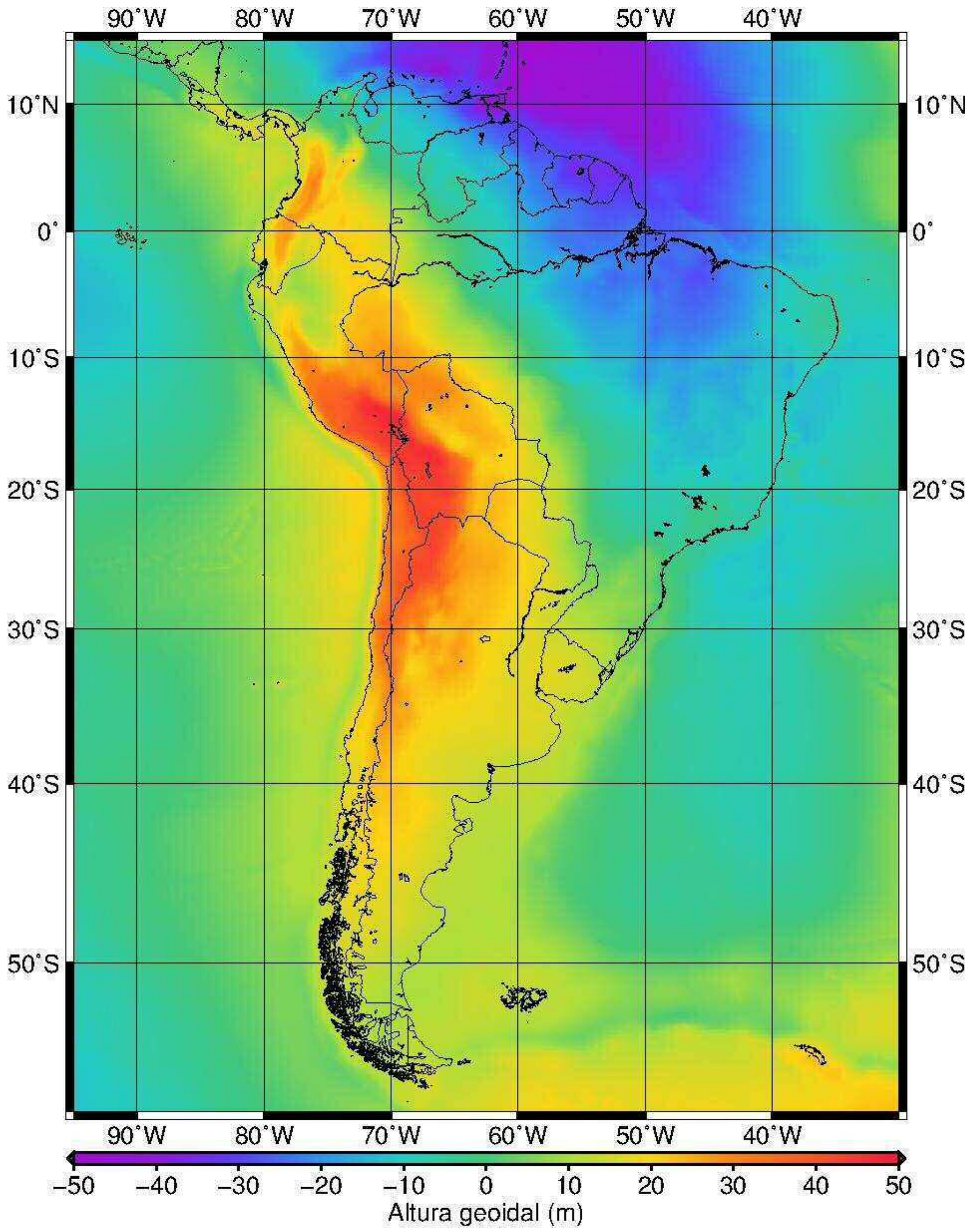

Figure 31 The new South American geoid model GEOID2015.

Sub-commission 2.4c: Gravity and Geoid in North and Central America

Chair: *Marc Véronneau (Canada)*
Vice Chair: *David Avalos (Mexico)*

Overview

The activities of the sub-commission 2.4c (Gravity and Geoid in North and Central America) is principally focus around the modernisation of the US National Spatial Reference System (NSRS) under the leadership of NOAA's National Geodetic Survey (NGS). This modernisation, to be released in 2022, includes not only the update of the NAVD 88 height reference system to a geoid-based height reference system (to be called NAPGD2022), but also the replacement of the NAD 83 (NSRS) geometric reference frame by a North American plate-fixed geocentric frame aligned with an IGS solution (to be called NATRF2022). Naturally, the sub-commission 2.4c contributes to the vertical component of the modernisation. (https://www.ngs.noaa.gov/datums/newdatums/)

As Canada already adopted a geoid-realised height reference system back in 2013 (Véronneau and Huang, 2016), one of the activities of the SC 2.4c is to assure the alignment of the North American-Pacific Geopotential Datum of 2022 (NAPGD2022) with the Canadian Geodetic Vertical Datum of 2013 (CGVD2013). Already, US NGS and the Canadian Geodetic Survey agreed on a common equipotential surface (W_0 = 62,6366,856.0 m^2s^{-2}); however, other parameters and concepts remain to be discussed in order to maintain a common height reference frame over the years. Even though Mexico's INEGI and geodetic agencies for the Caribbean and Central America are not ready in adopting a geoid-based datum for their respective countries, they agreed informally in 2014 in using the same definition adopted at NGS and CGS. It is currently the same value as adopted in the IERS convention.

In order to assure good communication within the sub-commission 2.4c in the development of a geoid model for North America, Central America and the Caribbean, INEGI, NGS and CGS are holding monthly teleconferences since late 2015. NGS is hosting the teleconferences. At the same time, INEGI is taking a leadership role for communication with Central America and several Caribbean countries.

International Height Reference System

In 2015, the IAG introduced a resolution for the International Height Reference System (IHRS) and selected W_0 = 62,636,853.4 m^2s^{-2} (mean tide), which differs by 2.6 m^2s^{-2} with the valued agreed (tide free) between NGS and CGS in 2012. The IHRS datum is higher than the North American datum by about 26 cm. At mid-continent, the North American definition of the vertical datum has the mean sea level of the Atlantic Ocean near Halifax about 38 cm below the datum while the mean sea level of the Pacific Ocean near Vancouver about 17 cm above the datum.

INEGI, NGS and CGS contributed sites and terrestrial gravity data at these sites (50-km radius) for the IHRF reference stations.

In addition, NGS is coordinating geoid work with SIRGAS (sub-commission for South America).

Mexico, Central America and Caribbean

Under INEGI's leadership, a new regional gravimetric geoid model (Avalos et al., 2016) was determined for Mexico, Central America and the Caribbean (GGM-CA-2015; W_0 = 62,636,856 m^2s^{-2}). The realization of this model represents enhanced technical geodetic capabilities for eight national geographic institutions in the region: Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, Mexico and the Dominican Republic. This activity was supported primarily by the Pan-American Institute of Geography and History (PAIGH), but as well by NGS, University of New Brunswick and the Mexican Agency for International Development and Cooperation (AMEXCID). Representatives from CGS and NGS travelled for geoid workshops at INEGI in Aguascalientes, Mexico at different occasions.

Geospatial Summit

US NGS organized successful Geospatial Summits in 2015 and 2017 to provide information to their clients about the planned modernisation of National Spatial Reference System. These summits provide an opportunity to NGS to share updates and discuss the progress in their activities. In addition, they allow NGS to receive feedback and collect requirements from their stakeholder across the federal, public and privates sectors. CGS attended the two summits. (https://www.ngs.noaa.gov/geospatial-summit/index.shtml)

IGLD (2020)

With the modernisation of the height reference systems in the USA and Canada, it also implicates impact to the International Great Lakes Datum of 1985 (IGLD (1985)). This vertical datum used for the management of the Great Lakes and the St-Lawrence Seaway was determined from the national adjustment of the North American levelling network (NAVD 88). However, the height are dynamic (H^d) and include hydraulic correctors to assure each lake is level. Members of the sub-communication 2.4c participate to the twice-yearly meetings of the Coordinating Committee to provide expertise in developing the new IGLD (2020), which will be based on NAPGD2022. Heights for the new IGLD (2020) will remain dynamic with hydraulic correctors. Though, the hydraulic correctors should be smaller in magnitude than for the current IGLD (1985).

CGS and NGS studied together quality of the geoid models over the Great Lakes using altimetry data and GNSS measurements at water gauges. Furthermore, the analysis demonstrated the usefulness of the airborne gravity data from the GRAV-D project in improving the geoid model, in particular over Lake Michigan where the shipboard gravity data are problematic. Results demonstrate that a 1.5 cm precision is achievable (Li et al., 2016).

GRAV-D project

The GRAV-D project is progressing well (https://www.ngs.noaa.gov/GRAV-D/). As of the end of March 2017, the project was 59% completed (see Figure 32). Several blocks over Alaska, along the coasts and over the Great Lakes are publically available. In addition, nine blocks are currently being process and NGS is in the process of collecting data from nine more blocks.

As a highlight, GRAV-D successfully completed the first full airborne gravity survey on an optionally piloted aircraft, the Centaur operated by Aurora Flight Sciences. The survey was conducted out of North Carolina from mid-March to mid-April 2017 and collected high quality gravity data over the Appalachian Mountains.

NGS is releasing annually new gravimetric geoid models that incorporate new satellite gravity models (GRACE/GOCE), airborne gravity data under the GRAV-D project and all available terrestrial gravity data. NGS developed these models under the x series (https://beta.ngs.noaa.gov/GEOID/xGEOID/). For each new model, a similar model is calculated without using the GRAV-D data to study the contribution coming from the GRAV-D project. GRAV-D data are integrated to the geoid model by spherical harmonic expansion.

These models are validated against Geoid Slope Validation Surveys of 2011 and 2014 in Texas and Iowa, respectively. These surveys incorporate multi-techniques on a 325-km baseline: absolute gravity, relative gravity, GNSS, levelling and digital-camera deflections of the vertical. Wang (2016) includes analysis of the Iowa line (high plateau going through the mid-continent gravity high).

In 2016, CGS started experimenting with GRAV-D following a different approach, which consists in embedding them, with the proper frequency, to the terrestrial gravity data. Thus, it incorporates the GRAV-D data to the geoid model by the Stokes integration with a modified kernel. This work is still under development.

Finally, NGS hosted a successful five-day airborne gravimetry workshop for Geodesy Summer School in May 2016 in Silver Spring, MD. The session touches many topics: theory, collection, processing, instrumentation, etc. Renowned experts gave the lectures. The school was well attended with participants from USA, Canada and Europe.

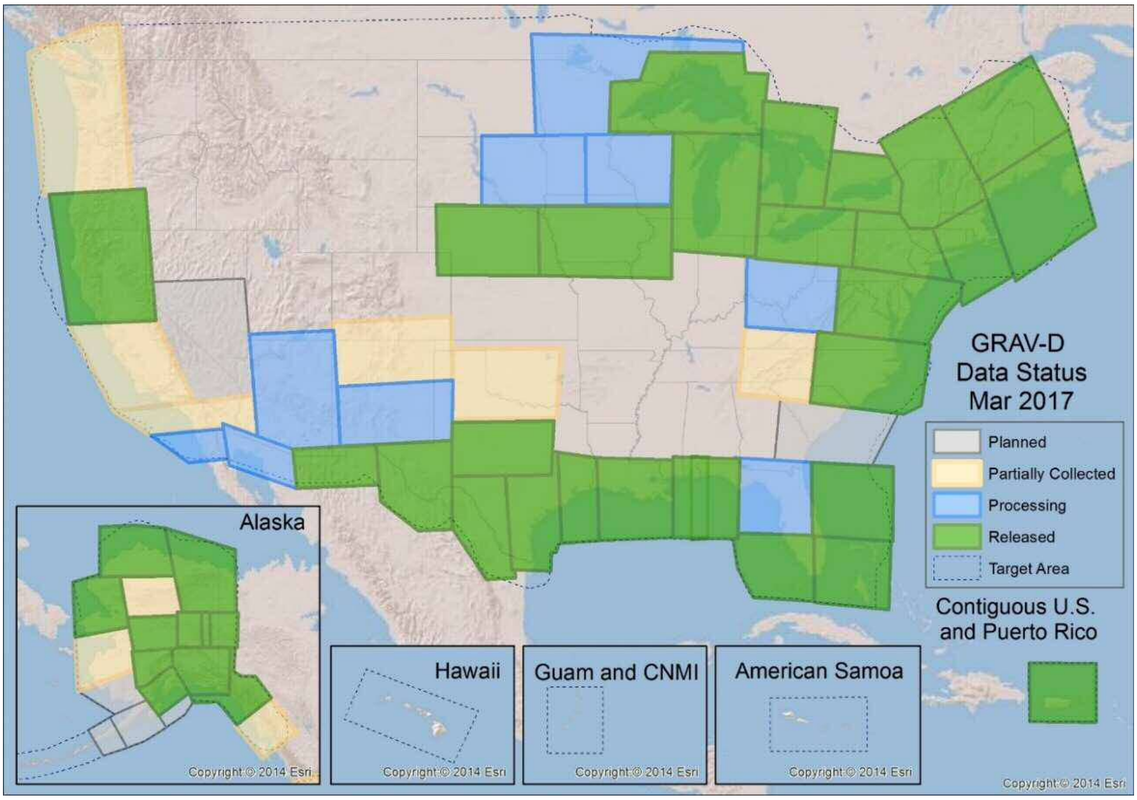

Figure 32 GRAV-D project.

Absolute gravity

NGS hosted the North American Comparison of Absolute Gravimeters in 2016 (NACAG16) at TMGO, near Boulder CO. NACAG16 included the participation of 14 institutions from nine countries across North America (Canada, Mexico, USA), Europe (Germany, Italy, Luxembourg, Russia) and South America (Brazil). The USA had four FG5 (NIST, NGS, Micro-g, NGA), Canada had two FG5 (NRC, CGS) and Mexico had one FG5 (CENAM). Results from NACAG16 are presented in a report available from NGS (Newell et al., 2016).

CGS finalized the realization of its Canadian Absolute Gravity Network. The 64 gravity sites are collocated with continuously-tracking GNSS stations or GNSS stations forming the Canadian Base network (force-centering concrete pillars anchored to the bedrock observed every ~five years). In addition, CGS maintains additional absolute sites for Geosciences (e.g., groundwater, GIA, seismic study). These sites are not only used for gravity standard in Canada, but also as a ground-infrastructure for the determination of g-dot and the relation between g-dot and h-dot for geoid monitoring as a validation approach for GRACE. (http://webapp.geod.nrcan.gc.ca/geod/data-donnees/cgsn-rncg.php?locale=en)

INEGI is working towards the establishment of the first Mexican absolute gravity network. They are working closely with the NGS to finalize an agreement of cooperation. They expect to obtain a set of 16 new stations in the near future, aiming to improve the general accuracy of the relative gravity network.

Relative gravity

INEGI is resuming the fieldwork of relative gravity data collection across Mexico. This activity falls under the project called National Gravity Densification, intended to produce a gravity dataset with a coverage as continuous and homogeneous as possible. The main goal is to achieve a minimum of five observations per cell of 5’x5’ across Mexico. The estimated progress is 65%. In El Salvador, the National Records Center of the National Institute of Geography (IGN/CNR), has produced 1,111 new observations of relative gravity and is expecting to continue this activity in collaboration with NGS.

As part of the realization of a unique geoid model for North America, NGS and CGS received a set of 9 million gravity points across North America from the US National Geospatial-Intelligence Agency (NGA). In addition, INEGI provided a gravity dataset of some 91,000 points across Mexico to NGS and CGS. The next activity is to clean these new datasets with respect to data already existing in the databases at CGS, NGS and INEGI and to build a unique dataset that the three agencies can used to develop geoid models. This would eliminate the discrepancies observed between the different geoid models due to inconsistent datasets. The same process will be done for the Digital Elevation models.

Geoid Monitoring

NGS put in place a team to focus on geoid monitoring allowing study variability of the geoid in time using space technique (GRACE/GRACE-FO) and ground technique in support to the modernisation of the NSRS.

CGS is processing monthly GRACE solutions available from different agencies (GFZ, CRS, and JPL) to linear trend from the effect of Glacial Isostatic Adjustment and glacier melting. In addition, CGS is investigating monthly variation of the geoid due to hydrological cycle.

Miscellaneous

- CGS assessed GRACE and GOCE Release 5 Global Geopotential Models over Canada (Huang and Véronneau, 2015).
- NGS and CGS, with contribution from UofC and China’s mapping office, wrote the Section of Local Geoid Determination in the Encyclopedia of geodesy (Wang et al., 2016).
- CGS is investigating glaciers effect on the geoid (Huang et al., in preparation).

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Sub-commission 2.4d: Gravity and Geoid in Africa

Chair: *Hussein Abd-Elmotaal (Egypt)*

Overview

The African Gravity and Geoid sub-commission (AGG) belongs to the Commission 2 of the International Association of Geodesy (IAG). The main goal of the African Gravity and Geoid sub-commission is to determine the most complete and precise geoid model for Africa that can be obtained from the available data sets. Secondary goals are to foster cooperation between African geodesists and to provide high-level training in geoid computation to African geodesists.

Creation of Detailed DTM's

Abdalla and Elmahal (2016) employed local levelling data to assess the global digital elevation model from Shuttle Radar Topography Mission (SRTM3) over Khartoum State area in Sudan. A linear convolution low-pass Gaussian filter has been employed to reduce noise inherited in the DEMs. The systematic errors in the differences between the DEM-based and levelling heights are removed by using third order polynomial model.

Abd-Elmotaal et al. (2016b) have computed the most detailed 3" × 3" DTM for Africa to date using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). The ASTER-GDEM model, which is available only on land, has been smoothed from its original 1" × 1" resolution to the used 3" × 3" resolution using the block average operator technique employing special characteristics at coastal boarders. The 30" × 30" SRTM30+ has been used, after being interpolated to 3" × 3" grid size, to fill-in the missing sea regions of the ASTER-GDEM model. The created 3" × 3" DTM (see Figure 33) has an accuracy of 25 m and 4 m on land and sea, respectively.

Local Geoid Determination in Africa

Abdalla and Green (2016) have utilized the Fast Fourier Transform and the Least-squares modification of Stokes formula to determine a gravimetric geoid model over Khartoum state in Sudan. The FFT and LSM solutions were evaluated against EGM08 and the local GPS-levelling data. Both comparisons reveal that the LSM solution is more consistent in terms of systematic errors and it is highly correlated with EGM08, the mean values of the geoid differences with respect to EGM08 and GPS-levelling data is found to be 0.14 m and 0.11 m, respectively.

Godah and Krynski (2015a) have computed a new gravimetric geoid model for Sudan using the least-squares collocation and a GOCE-based GGM. The computed geoid for Sudan has a precision of about 30 cm.

Sjöberg et al. (2015) have computed gravimetric geoid for Uganda using the least- squares modification of Stokes formula with additive corrections and the GOCE model TIM_R5 filled with surface gravity anomalies extracted from the World Gravity Map 2012. Using 10 GNSS/levelling data points distributed over Uganda, the RMS fit of the gravimetric geoid model before and after a 4-parameter fit is 11 cm and 7 cm, respectively.

Kühtreiber and Abd-Elmotaal (2015) have proposed an alternative geoid fitting technique that employs the least-squares collocation technique aiming to use the minimum number of GNSS/levelling stations in the geoid fitting process based on minimum range and standard deviation criteria, leaving the rest of the GNSS/levelling stations for the use of the external check of the geoid quality. Abd-Elmotaal et al. (2015a) studied the comparison among three methods on the best combination of the gravity field wavelengths in the geoid determination in Egypt. Abd-Elmotaal (2015a) has computed a geoid model for Egypt using the best estimated response of the earth's crust due to the topographic loads. In 2017, the most precise geoid for Egypt to date has been computed by Abd-Elmotaal implementing Moho depths and optimal geoid fitting approach. The external accuracy of that geoid attains 16 cm.

Establishing Gravity Databases

Abd-Elmotaal et al. (2015b) have established the first gravity database for Africa (AFRGDB_V1.0). The AFRGDB_V1.0 has been established employing a weighted least-squares prediction technique. As the used data set suffers from very large gaps, especially on land, and in order not to let the solution be free on those gaps, an underlying grid has been used to fill in these gaps with a resolution of 30' × 30'. This underlying grid has been created using a high-degree tailored geopotential model for Africa employing similar technique as that developed in (Abd-Elmotaal et al, 2015c).

Abd-Elmotaal et al. (2016e) have evaluated the AFRGDB_V1.0 gravity database for Africa using a new gravity data set, consisting of around 34,000 stations, that has been made available by the Bureau Gravimétrique International (BGI). Most of the points of the new data set are located on the large gaps of the data set used to establish the AFRGDB_V1.0 gravity database. This enables an external check of the AFRGDB_V1.0 gravity database at those new data points. The results show that the AFRGDB_V1.0 has an internal precision of about 9 mgal and external accuracy of about 16 mgal.

Abd-Elmotaal and Kühtreiber (2016) have studied the effect of the curvature parameter on the least-squares prediction within poor data coverage and developed a powerful technique to optimally fit the empirical covariance function. Abd-Elmotaal and Kühtreiber (2017) have proposed an optimum gravity interpolation technique for large data gaps to be used for creating the next version of the gravity database for Africa.

Regional Geoid Determination for Africa

In 2015, Abd-Elmotaal et al. have computed a first model for the regional geoid for the whole continent of Africa (cf. Figure 34). This geoid model has utilized the AFRGDB_V1.0 gravity database of Africa (Abd-Elmotaal et al., 2015b).

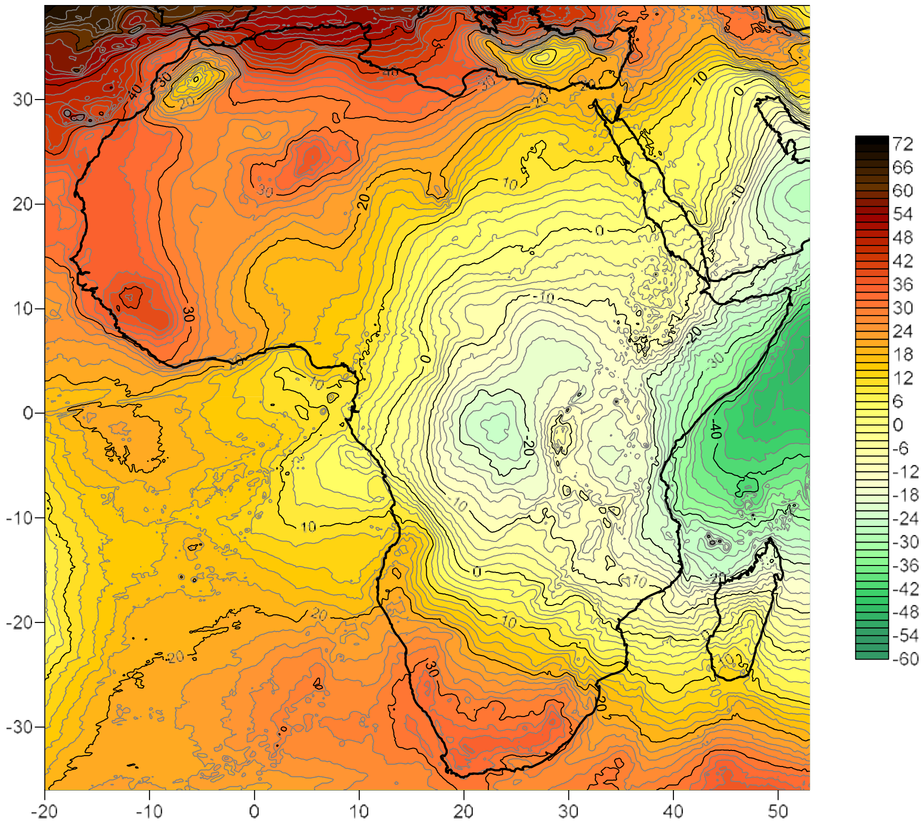

Figure 34 The African geoid model AFRgeo2015 (after Abd-Elmotaal et al., 2015d).

Important Complementary Studies in Africa

Godah and Krynski (2015b) carried out a comparative study of GGMs based on one year GOCE observations with the EGM08 and terrestrial data over the area of Sudan. The results reveal that geoid heights and free-air gravity anomalies obtained from the GOCE-based GGMs agree with the corresponding ones from the EGM08 truncated to d/o 200 with standard deviation of 18–20 cm, and 3.4–4.2 mgal, respectively. Their agreement with the terrestrial free-air gravity anomalies and the GNSS/levelling geoid heights, in terms of standard deviation is about 5.5 mgal, and about 50 cm, respectively. Abd-Elmotaal (2015b) performed an assessment study of the GOCE models over Africa. This study showed that the DIR-R5 solution of GOCE gives the best results for Africa.

Abd-Elmotaal et al. (2016a, 2016c) have studied the effect of Victoria and Nasser Lakes on the gravity reduction and on the geoid determination. These studies reveal that these lakes (especially Victoria Lake) have significant effect on both the gravity reduction and the geoid determination. Consequently their effect should be taken into account in precise geoid determination.

Abd-Elmotaal and Ashry (2016) studied the effect of the digital height model resolution on the gravity reduction and geoid determination for Egypt. The results showed that using very fine DHM with a very coarse DHM will take long CPU time and give worst results. This study reveals that the best combination with minimum required CPU time is 3" × 3" with 30" × 30". Accordingly, there is no need for going to 1" × 1" DHM for Africa as 3" × 3" can save CPU time and efforts and gives good results.

Abd-Elmotaal and Hassan (2016, 2017) have proposed a GRACE-like model that can be efficiently used to estimate the total water storage. These studies showed that the proposed algorithm gives comparable results to those of GRACE without stripes. Abd-Elmotaal et al. (2016d) have estimated the underground water in Africa using GRACE and hydrological models. This study gives reasonably acceptable results for the underground water in Africa.

Future Activities

A new gravity database for Africa (AFRGDB_V2.0) is under construction employing all available data sets up-to-date and makes use of the recently available precise satellite-only earth models of COCE. It will be presented during the forthcoming IAG-IASPEI Scientific Assembly, Kobe, Japan, July 30 – August 4, 2017 by Abd-Elmotaal et al. An improved geoid model for Africa will then be computed utilizing the AFRGDB_V2.0 gravity database.

Ulotu is going to use the CRUST 1.0 and LITHO 1.0 models to compute better reduced gravity anomalies and geoid for Tanzania.

Problems and Request

The IAG sub-commission on the gravity and geoid in Africa suffers from the lack of data (gravity, GNSS/levelling …). The great support of IAG is needed in collecting the required data sets. It can hardly be all done on a private basis. Physical meetings of the members of the sub-commission would help in solving the problems and would definitely contribute to the quality of its outputs. IAG is thus kindly invited to support that action.

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Sub-commission 2.4e: Gravity and Geoid in Asia-Pacific

Chair: *Jay Hyoun Kwon (Korea)*
Vice Chair: *Cheinway Hwang (Taiwan)*

Overview

In the period of 2015-2017, not much activities related to the gravity and geoid are reported in Asia-Pacific area. Korea continuously measures the gravity on top of mountains to upgrade the geoids, and Taiwan also renew the geoid. In terms of research, the geodynamic processes are related to the changes in absolute gravity in Taiwan, while Korea established a calibration site for the relative gravimeter to find out the characteristics of the relative gravimeter with respect to the height and distance differences between the sites. Taiwan agrees to share absolute gravity data as well as the new grid of geoid. Korea is establishing the criteria for the gravity data sharing mainly in terms of resolution and precision.

Gravity and Related Data

The National Geographic Information Institute (NGII) of Korea measured the gravity at triangulation points, which are mostly located at top of mountains, to upgrade the local geoid model. Gravity at a total of 960 triangulation points were measured from 2015-2016. Furthermore, the gravity at 1,160 unified control points are being measured in 2017. As the previous heights of the triangulation points were not accurate enough for the geoid construction, NGII has a plan to measure the height of the triangulation point using VRS from September 2017. NGII is also considering the gravity data sharing via IGB and the level of the precision and resolution for data sharing will be determined soon.

In Taiwan, the absolute gravity values at 24 sites have been continuously measured to study the geodynamic processes (Figure 35). Around Taiwan, gravity data from land, airborne and shipborne gravity measurements has been compiled, augmented with altimeter gravity at sea. The study on the new geoid grid and the geodynamic processes are described in the sections below.

Quasi/Geoid Control

The Korean NGII will initiate the project for re-processing all the gravity data with updated heights of the triangulation points at the end of 2017. The re-processed data as well as the newly measured gravity data will be used to upgrade the geoid. In this project, the accuracy and reliability of the gravimetric geoid will be intensively tested to adopt the gravimetric geoid as the vertical reference surface instead of the hybrid geoid. The mid- and long-term plan for the height system for Korea is underway in which the strategy for the unification of the height system with neighboring country is designed.

Recently Taiwan constructed new 1'×1' grids of free-air and Bouguer gravity anomalies around Taiwan with well-defined error estimates (Hwang et al., 2014). Three sets of relative land gravity measurements are network-adjusted and outlier-edited, yielding accuracies of 0.03-0.09 mGal. Three airborne gravity sets are collected at altitudes 5156 and 1620 m with accuracies of 2.57-2.79 mGal. Seven offshore shipborne gravity campaigns around Taiwan and its offshore islands yield shallow-water gravity values with 0.88-2.35 mGal accuracies. All data points are with GPS-derived geodetic coordinates at cm-dm accuracies, which can be used for precise gravity reductions and computing gravity disturbances. The various datasets are combined by the band-limited least-squares collocation in a one-step procedure. In the eastern mountainous (or offshore) region, Bouguer anomalies and density contrasts without considering the oceanic (or land) topographic contribution are underestimated. The new grids (Figure 36) show unprecedented tectonic features that can revise earlier results, and can be used in a broad range of applications.

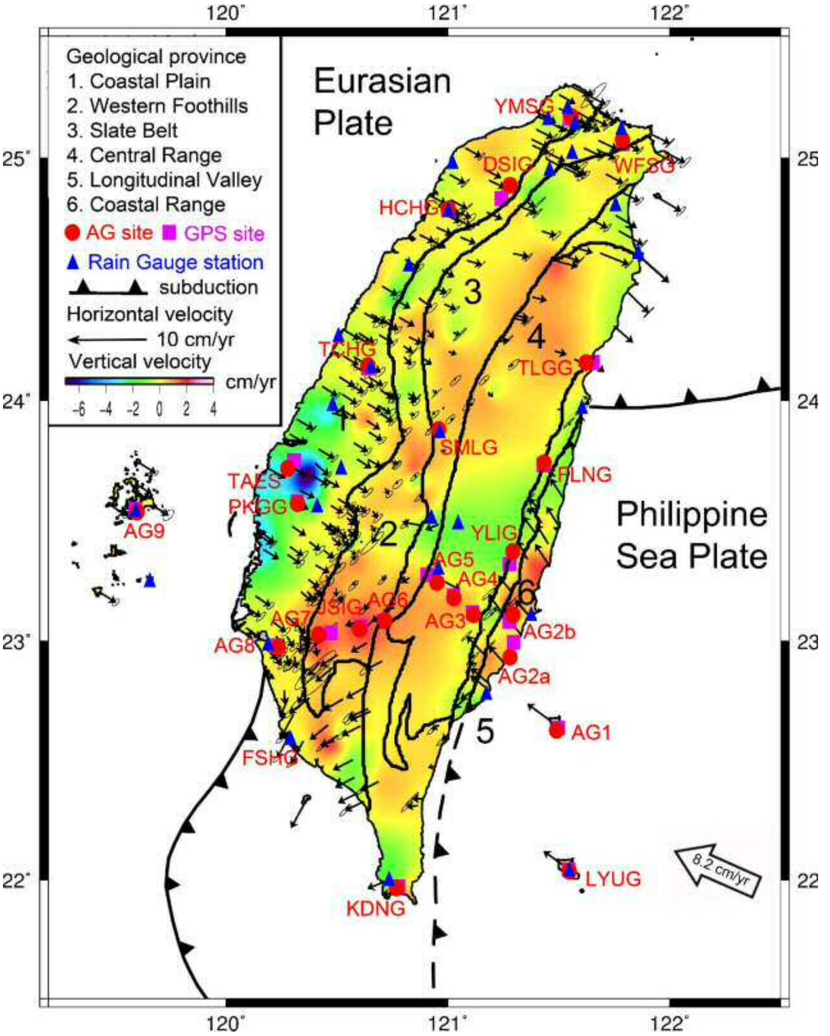

Figure 35 Distributions of 24 absolute gravity (AG) sites (circles), along with their nearest GPS sites (squares), over six geological settings of Taiwan. Also shown are the GPS-derived horizontal rates (arrows, with error ellipses) at 317 sites. The vertical displacement rates from GPS are interpolated into an areal rate (color-shaded) to show the pattern of uplift (positive rate) and subsidence (negative rate) across Taiwan. The mean horizontal displacement rate of the Philippine Sea Plate relative to the Eurasian Plate is 8.2 cm/yr (Ching et al., 2011).

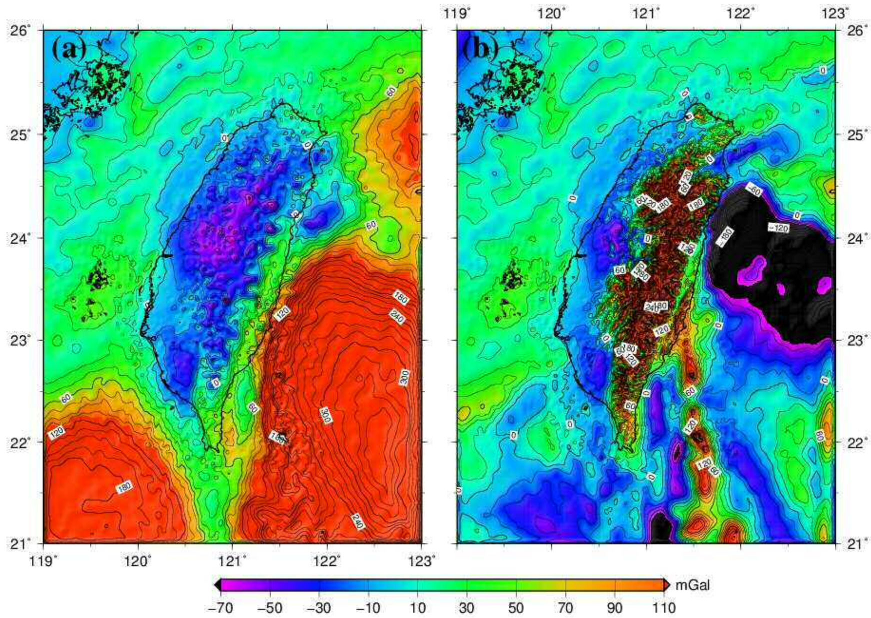

Figure 36 (left) new Bouguer gravity anomalies in Taiwan, (right) free-air gravity anomalies

Education & Research

Based on the gravity measurements, the height system of Korea will be changed to the Helmert orthometric height from normal-orthometric height. A study on the feasibility and evaluating the difference between the two height systems was carried out and presented at FIG meeting in 2016. In addition, a calibration site for the relative gravimeter was constructed in Korea to evaluate the data quality from relative gravimeter. It was found that the uncertainty of the relative gravimeter are induced by the height difference and distance between measuring points. The study deducted an empirical correction equation for the relative gravimeter with parameter of the height difference. The effect of the distance between the measuring points will be investigated in next year.

In the study of the geodynamic processes in Taiwan, gravity changes of non-geodynamic origins are modeled to obtain residual gravity values of geodynamic origins, which cannot be fully explained by GPS-derived vertical displacements. In a preliminary study (Kao et al., 2017), such gravity changes were associated with deposited debris, earthquake, volcanism and Moho deepening using absolute gravity changes over 2004-2016. Gravity changes of up to 53.37 and 23.38 μGal near two Rivers in Taiwan are caused by typhoon Morakot, leading to estimated volumes of 6.0×10^5 m^3 and 3.6×10^5 m^3 in deposited debris. This shows gravimetry can be used in erosion study.

The observed co-seismic gravity change near the epicenter of the M6.9 Pingtung earthquake (December 26, 2006) is 3.12 ± 0.99 μGal, consistent with a dislocation-based gravity change at the μGal level, thereby supplying a gravity constraint on the modeled fault parameters. The AG record at the Tatun Volcano Group is the longest, but large temporal gravity effects here have led to a current gravity signal-to-noise ratio of less than one, which cannot convince a sinking magma chamber, but supply an error bound for gravity detections of long-term or transient magma movements. The gravity values at Ludao and Lanyu decline steadily at the rates of -2.20 μGal/yr and -0.50 μGal/yr, typical magma states over extinct volcanoes. The gravity change rate at an uplifting site in central Taiwan and three subsiding sites in eastern Taiwan are negative, and are potentially caused by Moho deepening at a rate of -3.34 cm/yr.

Taiwan will continue to collect absolute gravity data to investigate these phenomena and will share such data with geodesists interested in this study.

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Sub-commission 2.4f: Gravity and Geoid in Antarctica

Chair: *Mirko Scheinert (Germany)*

Overview

The Sub-Commission is dedicated to the determination of the gravity field in Antarctica. In terms of observations, mainly airborne but also terrestrial campaigns have been and are being carried out to complement and to densify satellite data. Because of the region and its special conditions the collaboration extends beyond the field of geodesy – the cooperation is truly interdisciplinary, especially incorporating experts from the fields of geophysics and glaciology.

Antarctic gravity data

During the last period of (2015 – 2017) further progress has been made to include new data and to open access to already existing data. Here, especially the PolarGap campaign, an international effort of Denmark, the UK and Norway, led by R. Forsberg (DTU Space) has to be mentioned. Results were presented, among others, at the IUGG General Assembly in Prague in 2015, and the SCAR Meeting and Open Science Conference in Kuala Lumpur in 2016.

As a highlight the publication of the first Antarctic-wide gravity anomaly dataset has to be mentioned (Scheinert et al., 2016). It was given general attention as can be seen by an EOS article (Stanley, 2016). The dataset is publically available via the PANGAEA database.

However, this first gravity dataset release is far from comprising a complete coverage over Antarctica. Therefore, further updates are planned when new data will have been acquired.

A close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR), where the geodesy group (SCAR Standing Scientific Group on Geosciences (SSG-GS), Expert Group on Geospatial Information and Geodesy (GIANT Geodetic Infrastructure in Antarctica)). Its program was renewed at the bi-annual SCAR meeting in Kuala Lumpur, 2016. M. Scheinert co-chairs GIANT as well as chairs the GIANT project “Gravity Field”.

Special workshop

Dedicated to the goals of AntGG an International Workshop “Airborne Geodesy and Geophysics with Focus on Polar Applications” was held in Dresden, Germany, 19–21 April 2017. Besides by the IAG it was supported by the German Research Foundation (DFG), the Scientific Committee on Antarctic Research (SCAR) and the German Society for Polar Research (DGP). The workshop was the third in a series of thematic workshops on airborne techniques in polar geosciences. Following respective workshops in Dresden (Germany) in 2009 and in Potsdam (Germany) in 2012, this time we welcomed about 40 participants from six countries (Germany, United Kingdom, USA, China, Norway, Denmark). During six oral sessions, one poster session – accompanied by a small technology display – and a concluding panel discussion, the participants discussed the present status and future prospects of geoscientific airborne surveying in the polar regions. A workshop summary for publication in EOS is in preparation.

Future plans and activities

Future activities are well defined following the “Terms of Reference”. Since any Antarctic activity call for a long-term preparation the main points to be focused on do not change. New surveys will be promoted, nevertheless, due to the huge logistic efforts of Antarctic surveys, coordination is organized well in advance and on a broad international basis. Within AntGG, the discussion on methods and rules of data exchange is in progress and has to be followed on. Compilations of metadata and databases have to cover certain aspects of gravity surveys in Antarctica (large-scale airborne surveys, ground-based relative gravimetry, absolute gravimetry at coastal stations). The main goal to deliver a grid of terrestrial gravity data is being fulfilled (see above). Updates of this dataset are anticipated, once considerable new data is available.

With regard to new gravity surveys in Antarctica, aerogravimetry provides the most powerful tool to survey larger areas. In this context, airborne gravimetry forms a core observation technique within an ensemble of aerogeophysical instrumentation. Further airborne missions may help not only to fill in the polar data gap in its proper sense, but also all remaining gaps over Antarctica. Thereby, it could be of great value to adopt long-range aircraft capable to fly under Antarctic conditions. Respective efforts are underway e.g. in the US or in Germany. In this respect, the chair of AntGG is acting as PI of a German project to utilize the German research aircraft HALO for an Antarctic airborne geodetic-geophysical survey (ANTHALO). In 2012 HALO could already successfully be utilized for a survey over Italy and adjacent seas to demonstrate the feasibility of aerogravimetry aboard HALO (e.g. Barzaghi et al., 2016).

Selected conferences with participation of AntGG members

- IUGG General Assembly, Prague, 23 June – 01 July, 2015.
- XII International Symposium on Antarctic Earth Sciences, Goa, 13-17 July, 2015.
- ESA Living Planet Symposium, Prague, 9-13 May 2016.
- SCAR Open Science Conference, Kuala Lumpur, 22-26 August 2016.
- 1st Joint Commission 2 and IGFS Meeting, Thessaloniki, 19-23 September 2016.
- AGU Fall Meetings (2015, 2016) and EGU General Assemblies (2016, 2017).
- International Workshop "Airborne Geodesy and Geophysics with Focus on Polar Applications", Dresden, 19-21 April 2017.

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Sub-commission 2.5: Satellite Altimetry

Chair: *Xiaoli Deng (Australia)*
Vice Chair: *C.K. Shum (USA)*

Overview

Activities over the period 2015-2017 include the algorithm development and applications of both conventional (e.g. TOPEX/Poseidon, Jason-1, Jason-2 etc.) and new (e.g., CryoSat-2, SARAL Altika, HY-2A and Sentinel-3A) satellite altimetry missions. The sub-commission has also recently submitted a recommendation on the Jason-2 geodetic mission (GM) issue to the committee of the Jason-2 joint steering group. It is believed that the dense Jason-2 GM ground tracks in the Jason-2 inclination will give better resolution of gravity anomalies with narrow east-west extent, and fill holes in coverage left by the other altimetry missions.

Improvement in global marine gravity field from new altimetry data

We continued improving the accuracy of the global marine gravity field using new radar altimeter data from CryoSat-2 and now SARAL AltiKa (Figure 37). One of the main benefits of an improved gravity field is the ability to resolve new structures on the ocean floor (Matthews et al., 2016). The investigation had three main components: (1) develop waveform retracking algorithms and computer codes for these new satellite altimeter data sets that are optimal for gravity field recovery (Zhang and Sandwell, 2016), (2) develop global gravity grids at 1 minute resolution using the new altimeter data, and (3) continue to develop global bathymetry grids at 1 minute, 30 arc second and 15 arc second resolutions.

Much of the gravity field improvement was due to new satellite altimeter data collected by CryoSat-2 and Jason-1. In addition, we have refined the existing tide models resulting in improved performance in coastal areas. Currently 7 years (84 months) of data are available from CryoSat-2 and the satellite has enough consumables to operate beyond 2020. More important, another radar altimeter called SARAL AltiKa altimeter has begun a non-repeat orbit phase starting in July 2016 (Figure 37). AltiKa has a new Ka-band instrument with a factor of 2 better range precision than all previous altimeters (Table 7 from Zhang and Sandwell, 2016). If it continues in this non-repeat orbit for another 6 months, this will result in an additional accuracy improvement of perhaps 1.5 times and three years of operation will result in another factor of 2 improvement in the marine gravity field.

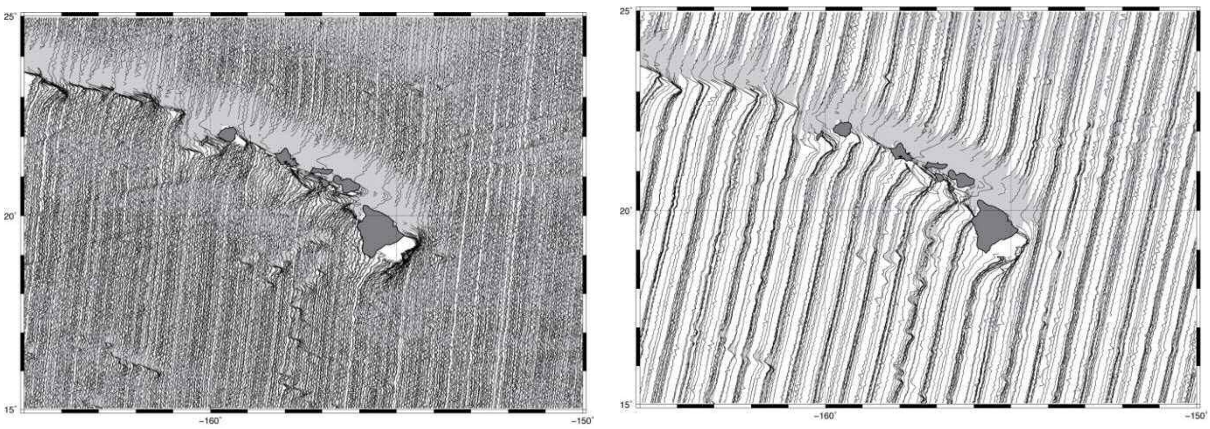

Figure 37 Along track sea surface slope profiles from CryoSat-2 (66 of the 84 mo. available today) and AltiKa (7 of the 10 mo. available today) around Hawaii. Both satellites are healthy and still continue collecting data. AltiKa profiles are two times more precise than all previous altimeters (Table 7).

Table 7. Altimeter noise at 20 Hz

altimeter	Noise* (mm)
Geosat	57.0
ERS-1	61.8
Envisat	51.8
Jason-1	46.4
CryoSat-LRM	42.7
CryoSat-SAR	49.7
AltiKa	**20.5**

*Standard deviation of altimeter waveforms with respect to the 1 Hz average (Zhang and Sandwell, 2016).

Regionally, Hsiao et al. (2016) determined the gravity field of the South China Sea (SCS) using sea surface heights from satellite altimeters Geosat/GM, ERS-1/GM, Jason-1/GM and Cryosat-2. The modelled gravity anomalies show a 6 mGal RMS discrepancy with shipborne measurements in shallow waters. An altimeter-only bathymetric model is then derived from this new gravity grid by the gravity-geological method that uses the latest global and regional models of the ocean depth and marine gravity as a priori knowledge. The new bathymetry model has an accuracy up to 100 m based on validation against multi-beam depth measurements, outperforming current SCS bathymetric models. Optical images from IKONOS-2, QuickBird-2, GeoEye-1, WorldView-1-2 and -3, are rectified and digitized to derive the zero (coastline) and 20-m depth contours (reef lines) around 44 atolls, which are integrated with the altimeter-only depths, giving significantly improved accuracies and spatial resolutions in modelled depths. The improvement percentages of coastlines by the satellite imagery range from 50% to 97% at 41 of the 44 atolls. The web site is available for free access to the optical and depth images, and the depth and gravity grids.

Sea levels and sea level extremes

Sea level changes have been investigate using radar altimeter data from the conventional low resolution mode (LRM), Delay Doppler Altimetry (DDA), and Synthetic Aperture Radar (SAR) mode. One of major benefits of DDA is the higher resolution, which opens new possibilities in the coastal zone at a few km from coast (Fenoglio-Marc et al., 2015). Our investigation had four main components: (1) assess improvement gained by using DDA altimetry methodology with respect to best in-house reprocessed conventional altimetry (CA), (2) investigate sea level change and understand each component, (3) investigate mean dynamic topography at the coast from satellite and in-situ data, and (4) investigate sea level extremes.

Assessing advantages and limitation of DDA with respect to CA. For this scope, improved re-tracking methods dedicated to the coastal zone have been used, which includes the parametric sub-waveform re-tracker TALES, similar to the ALES retracker (Passaro et al., 2015) and the Spatio Temporal Altimetry Retracker (STAR) in Roscher et al. (2015). In this way a comparison between the two modes near coast is possible. The results have shown that the superiority of the DDA mode, as its finer resolution and higher Signal to Noise Ratio (S/N) of the CryoSat-2 data, allows the radar altimeter getting closer to shore. Several studies have shown the improvements in precision and accuracy (Fenoglio-Marc et al., 2015, Passaro et al., 2016, Dinardo et al., submitted). Land contamination starts at 2 km from coast in DDA mode and at 4 km in pseudo-CA. In the critical band 0-2 km from the coast, the impact of land contamination is lower in DDA than that in pseudo-CA/PLRM, as the median curve in SAR is closer to zero than in PLRM median curve (Figure 38). Further study, in the ESA project SCOOP, will characterise the performance of the Sentinel-3 DDA product generated by the currently specified processing baseline and then to test, implement and evaluate improved retrieval methods.

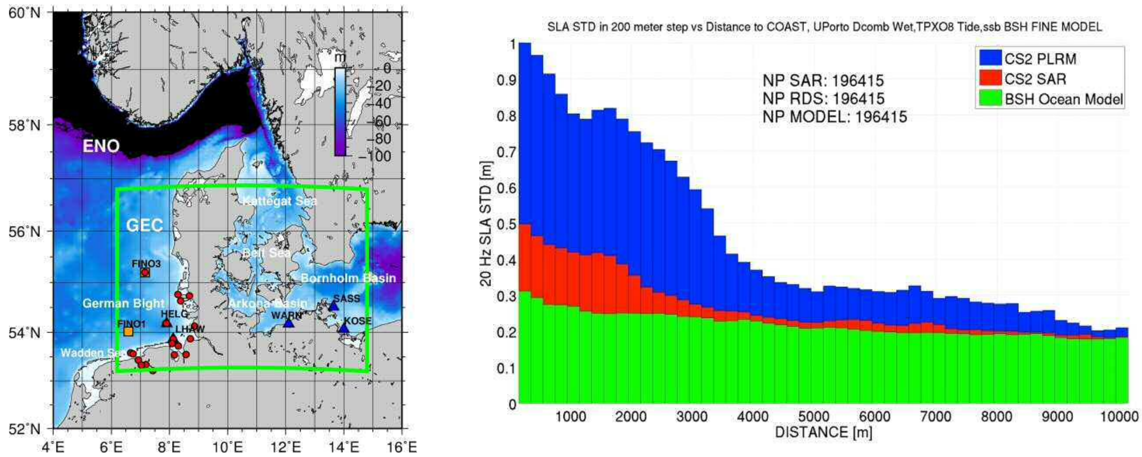

Figure 38. The GEC Region along the German coast (left). Standard variation of sea level anomalies in 200 bins of distance to coast for ocean model (green), SAR (red) and PLRM/TALES (blue) (right) in region GEC.

Addressing the sea level change and the understanding its causes. Today, the period 2002-2017 is the longest time span where space-based measurements from altimetry, GRACE and ARGO are simultaneously available for sea level, mass and steric observations.

Figure 39 shows basin averages for sea level and its components derived combining geodetic and model data. Although the combination of the first attempt provides valuable constraints on volumetric versus mass driven sea surface height changes, these data are rarely assimilated into ocean simulations and reanalysis runs. We have contributed to the regional assessment of the quality of sea level products, verifying their mission-long regional sea level trends and characterizing their error (Ablain et al., 2017). GRACE data have been used to assess mass changes. Regional ocean simulations and re-analysis have been considered. The evaluation of ocean model simulations and reanalysis using geodetic data is challenging, particularly in semi-closed ocean basins, due to the assumptions made in the ocean models and to the limitation of satellite-based data in coastal zone. Our analysis in the Mediterranean Sea Basin averages show that the sea level of both simulations and re-analysis fails to reproduce the observed long-term variability of sea level. The halosteric component is far to be correctly computed by the model runs. The thermo-steric component is finally the more accurate proxy for the long-term sea level changes, at least in basins where the steric-component is a large part of sea level change. Finally we show that the sum of model sea level and thermo-steric sea level has the highest correlation with the total sea level measured by satellite altimetry (Figure 40). Moreover, the synergy between altimeter data and model simulations is promising to overcome the errors of mass balances.

In the frame of the regional assessment of a new Altimeter Sea Level Record (Reprocessed ESA Essential Climate Variable SLCCI), we have investigated the agreement between vertical land motion (VLM) and the difference in trends between altimetry and selected tide gauges along the German coasts (Figure 41). We found that GPS-derived VLM and the trend of the altimeter and tide gauge differences depart by about 1 mm/yr, which is within the uncertainty of the trends, and which is large compared to the GPS rates. We also noticed that the agreement improves (correlation, standard deviation and difference of trends) when SLCCI data instead of the AVISO data are used. This indicates a higher quality of the SLCCI data compared to other altimeter products (Figure 3). The work is supported by the Climate Change Initiative Project (SLCCI/ESA).

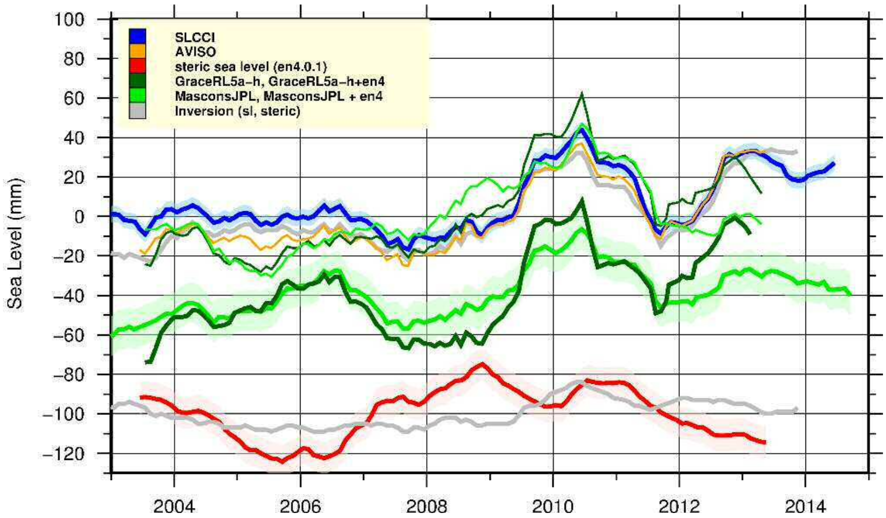

Figure 39. Mediterranean Sea: Smoothed time-series of observed and computed sea level, as well as its steric and mass components. Components are from GRACE RL05a corrected for land hydrology (dark green), JPL mascon solution (light green), temperature and salinity profiles (red) and from the inversion method (green). All monthly time-series have been de-seasonalized and smoothed by a running average with lag of 12 months.

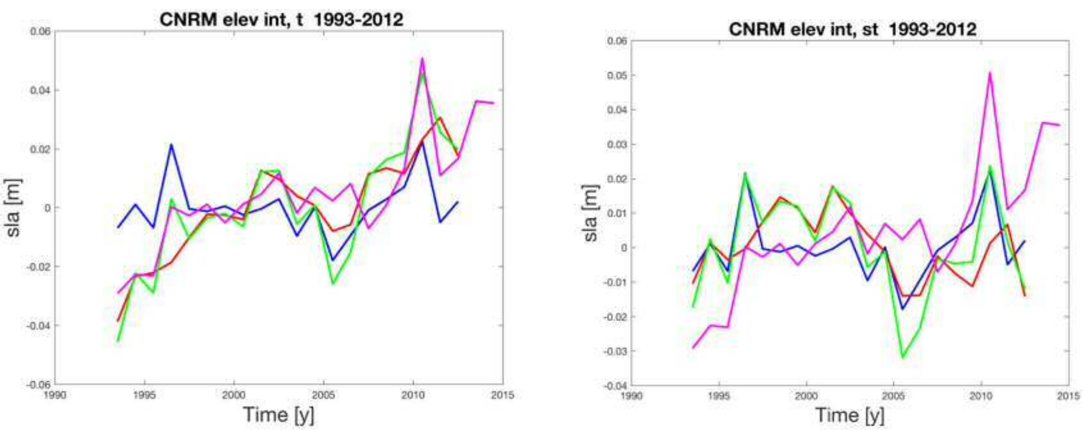

Figure 40. CNRM model for the Mediterranean Sea: Sea surface height (green) from elevation plus thermos-steric (left) and plus steric (right). Is compared to sea level from CCI grids (violet), thermo-steric (red) and elevation (blue)

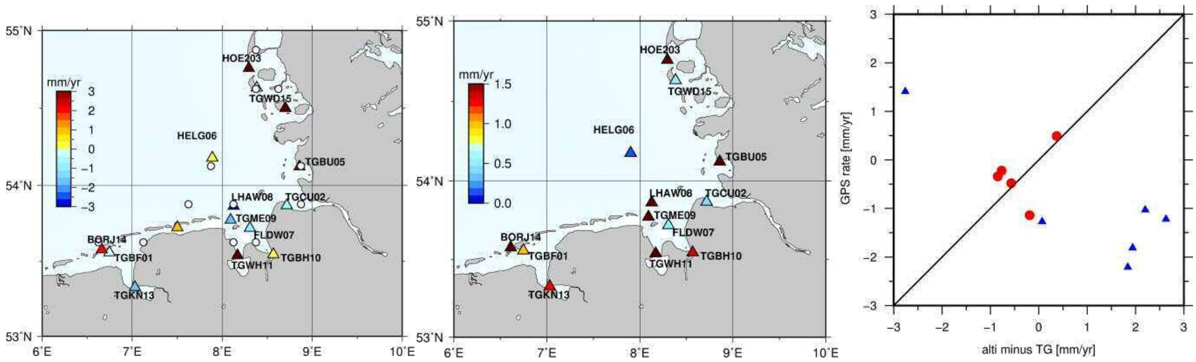

Figure 41. Left: Vertical Land Motion from altimetry minus tide gauge stations with location of both tide gauge (triangle) and altimeter point selected (circle). Centre: absolute value of the difference of VLM from the two methods. Right: Scatterplot of VLM with stations with differences smaller than 1 mm/yr in red.

Similarly to the Mediterranean Sea study, we have analyzed basin average sea level change and its components in the Bay of Bengal (Kusche et al., 2016). SAR and PLRM SAR and TALES provide improved coastal sea surface heights. This leads to both improved coastal sea surface heights and inversion results, especially at regional scales (Figure 42).

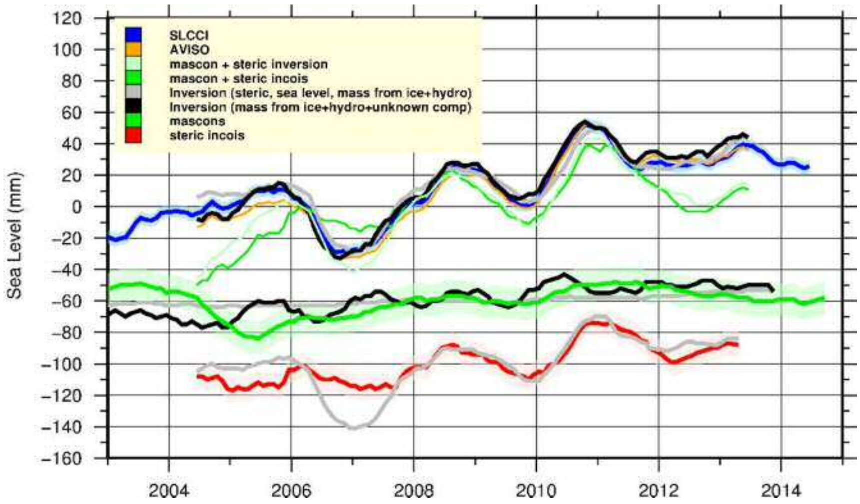

Figure 42. Bay of Bengal: Smoothed time-series of observed and computed sea level, as well as its steric and mass components. Mass components are from GRACE RL05a corrected for land hydrology (black), JPL mascon solution(green), temperature and salinity profiles and from the inversion method. All monthy time-series have been de-seasonalized and the smoothed by a running average with lag of 12 months.

Further work is planed: (1) investigate the residual signals and corresponding physical processes, (2) extend and improve the IGG Jason/GRACE joint inversion method (Rietbroek et al., 2016), (3) incorporate Cryosat-2 data in DDA and pseudo-DDA mode in the coastal zone database.

Mean dynamic topography from altimetry. This study combines several elements: (1) propose and develop an approach to estimate a consistent DT at tide gauges, coastal areas, and open ocean, (2) validate the approach in well-surveyed areas where DT can be determined at tide gauges, (3) connect measurements of a global set of tide gauges and investigate trends, and (4) evaluate the improvement in mean dynamic topography and difference in trends by using the Delay Doppler altimeter data near coast (Figure 43). The work is still ongoing (ESA Project GOCE++Dycot).

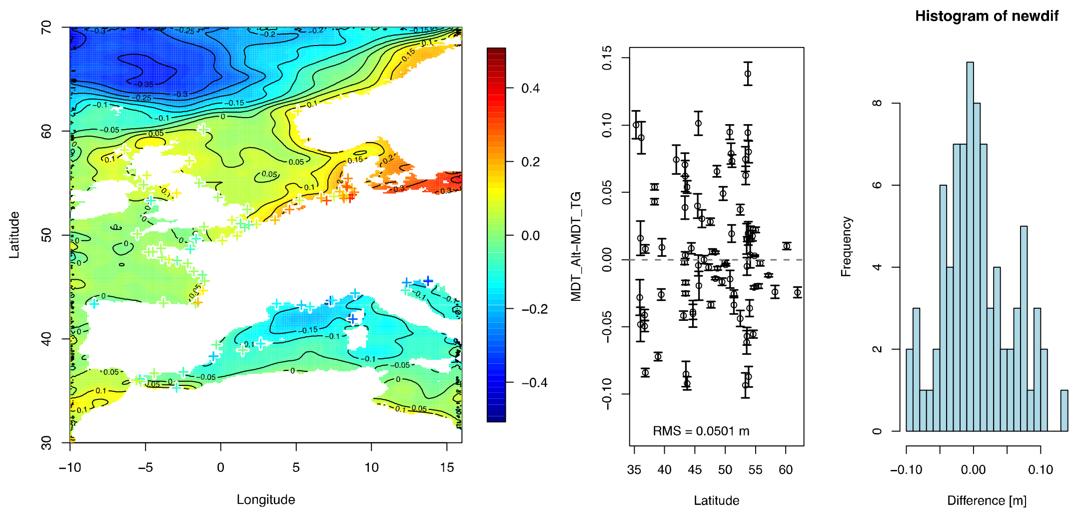

Figure 43. North-Eastern Atlantic. Mean Dynamic Topography from geodetic method in ocean and at the tide gauge (left), differences (middle) and histogram of differences (right).

In addition, Chang et al. (2016) combined multiple mission satellite altimetry along-track sea surface heights (SSHs), the Gravity field and steady-state Ocean Circulation Explorer (GOCE) time-wise solution generated geoid model, and in situ hydrographic data, to estimate global surface and subsurface absolute geostrophic currents over the period 1996-2011. They used the profile approach to process satellite altimetry data, mitigating the negative impact of omission errors resulting from the spatial resolution discrepancies between the truncated GOCE geoid model and SSHs, on the estimation of the absolute dynamic topography (ADT), which was then combined with the relative dynamic topography derived from in situ hydrographic profiles to estimate near global mesoscale geostrophic current velocities at different depth layers. Results were validated by in situ moored current meter observations from the Tropical Atmosphere Ocean/TRIangle Trans-Ocean buoy Network (TAO/TRITON) and the Prediction and Research Moored Array in the Atlantic (PIRATA), showing the outperformance of profile approach over the conventional pointwise approach in determination of geostrophic currents.

Sea level extremes from altimetry. A major climate hazard is coastal flooding induced by extreme water level events along low-lying, highly populated coastlines due to presently and continuously rising sea levels (Stewart and Deng, 2015). Staneva et al. (2016) addressed the impact of wind, waves, tidal forcing and baroclinicity on the sea level of the German Bight during extreme storm events. The improved skill resulting from the new developments justifies further use of the coupled-wave and three-dimensional circulation models in coastal flooding predictions.

At the Australia coast, 20 years of data from multi-missions of satellite altimetry (e.g., Topex, Jason-1, Jason-2) were integrated with 14 tide-gauge data to provide consistent sea levels (Deng et al., 2016; and Gharineiat and Deng, 2016). Moreover, Gharineiat and Deng (2016) used a state-of-the-art approach of the Multi-Adaptive Regression Splines (MARS) to consider nonlinear sea-level components along the northern coast of Australia. The result comparison of the MARS with the multiple-regression shows an improved sea level prediction, as MARS can explain 62% of sea level variance while multiple-regression only accounts for 44% of variance. The predicted sea levels during six tropical cyclones are validated against sea level observations at three independent tide-gauge sites. The comparison results show a strong correlation (~99%) between modelled and observed sea levels, suggesting that the MARS can be used for efficiently monitoring sea level extremes.

Retracking, calibrating and validating of altimetry data

We continued research into optimize the satellite altimetric sea levels from multiple retracking solutions near the coast. Kuo et al. (2016) improved Envisat altimetric measurements in Taiwan coastal oceans by developing a waveform retracking system. Research by Idris et al. (2017) investigated the validation strategy for the retracked altimetry data. They compared Jason-1 altimetry retracked sea levels with the high frequency (HF) radar velocity in the Great Barrier Reef, Australia. The comparison between both datasets is not direct because the altimetry derives only the geostrophic component, while the HF radar velocity includes information on both geostrophic and ageostrophic components, such as tides and winds. The comparison of altimetry and HF radar data is performed based on the parameter of surface velocity inferred from both datasets. The results show that 48% (10 out of 21 cases) of data have high (≥ 0.5) spatial correlation, while the mean spatial correlation for all 21 cases is 0.43 (Figure 44). This value is within the range (0.42 to 0.5) observed by other studies.

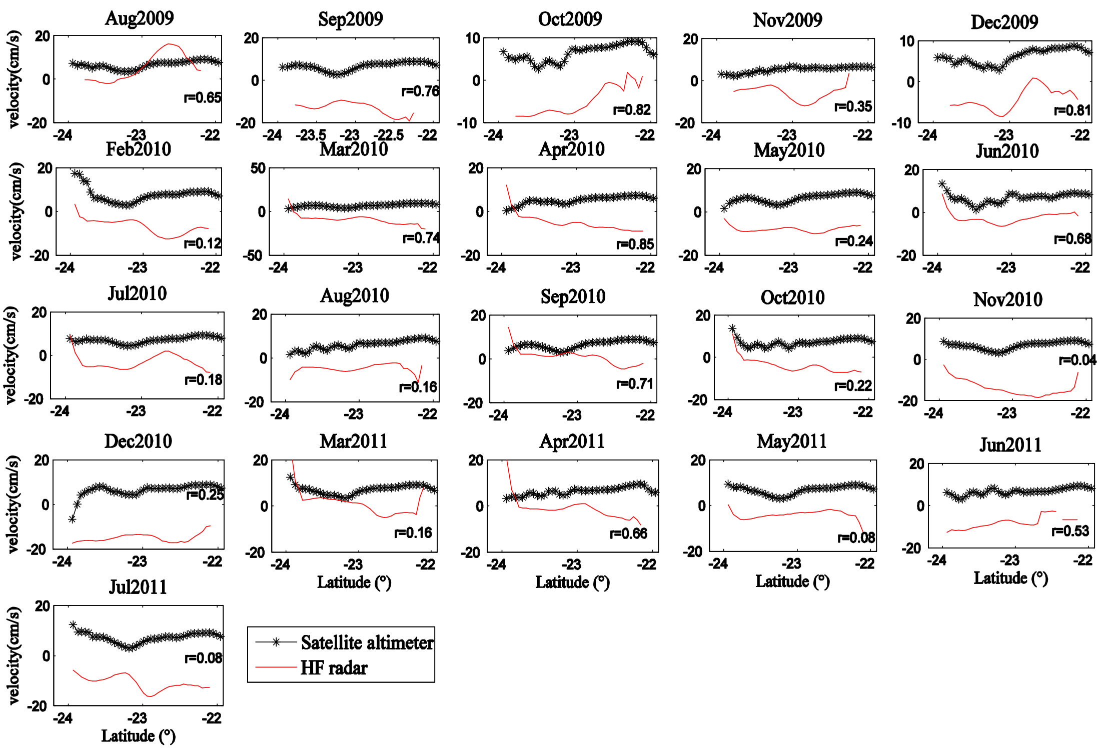

Figure 44. The monthly HF and altimeter geostrophic velocity normal to the satellite track from 2009 to 2011. The altimeter geostrophic velocities are filtered with a cut-off wavelength of 56 km. The latitude between −24 and −23 deg is situated on the continental shelf with the latitude −24 deg being the closest point to the coastline, while the latitude greater than −23 deg is situated on the continental shelf break (Idris et al. 2017).

Since the launch of China's first altimetry and scatterometry satellite, Haiyang-2A (HY-2A), various validation studies of HY-2A radar altimetry using preliminary data products have been conducted. The HY-2A Geophysical Data Record (GDR) IGGA product has so far been generated. Bao et al. (2015) presented the first comprehensive assessment of HY-2A's altimeter data quality and the altimetry system performance through calibrating and cross-calibrating the HY-2A GDR_IGGA product. Jason-2 altimeter observations were used for the cross calibration of the HY-2A altimeter over the oceans between ±60º latitude bounds. The statistical results from single- and dual-satellite altimeter crossover analysis demonstrated that HY-2A fulfils its mission requirements. An averaged bias of -0.21 cm with respect to Jason-2 and a standard deviation of 6.98 cm from dual-satellite crossover analysis were found. It was concluded that the performance of HY-2A altimetry is similar to Jason-2 based on a detailed analysis of the paper.

Monitoring vertical land motion from altimetry

Members in Taiwan have used altimetry to monitor the land motion. Hwang et al. (2016) used multi-mission radar altimetry with an approximately 23 year data-span to quantify land subsidence in cropland areas. Subsidence rates from TOPEX/Poseidon, JASON-1, ENVISAT, and JASON-2 during 1992-2015 show time-varying trends with respect to displacement over time in California's San Joaquin Valley and central Taiwan, possibly related to changes in land use, climatic conditions (drought) and regulatory measures affecting groundwater use. Near Hanford, California, subsidence rates reach 18 cm/yr with a cumulative subsidence of 206 cm, which potentially could adversely affect operations of the planned California High-Speed Rail. The maximum subsidence rate in central Taiwan is 8 cm/yr. Radar altimetry also reveals time-varying subsidence in the North China Plain consistent with the declines of groundwater storage and existing water infrastructure detected by the Gravity Recovery and Climate Experiment (GRACE) satellites, with rates reaching 20 cm/yr and cumulative subsidence as much as 155 cm.

Kuo et al. (2015) successfully used satellite altimetry, including Topex/Poseidon and Jason-2, retrieved by novel retrackers to monitor vertical land motions in Southwestern Taiwan. Modified threshold and improved subwaveform threshold retrackers were used in the study to improve the accuracy of altimetric land surface heights (LSHs). The results indicate that the vertical motion rates derived from both retrackers coincide with those calculated by 1843 precise levelling points, with a correlation coefficient of 0.96 and mean differences of 0.43 and 0.52 cm/yr (standard deviations: 0.61 and 0.69 cm/yr).

Improved inland water levels from SAR and conventional altimetry

Villadsen et al. (2016) developed several new methods for obtaining stable inland water levels from CryoSat-2 SAR altimetry, including the Multiple Waveform Persistent Peak (MWaPP) retracker and a method combining the physical and empirical retrackers. Using a physical SAR waveform retracker over inland water has not been attempted before but shows great promise in this study. It has found that the new empirical MWaPP retracker is easy to implement, computationally efficient, and gives a height estimate for even the most contaminated waveforms over inland waters.

Marshall and Deng (2016) developed a robust and automated method based on image analysis of multispectral and Advanced Synthetic Aperture Radar (ASAR) imagery for the selection of altimetry waveforms over inundated zones is presented. The advantage of the method is that the waveform footprint can be automatically assessed for inundation extent as well as level of vegetation cover, with waveforms that meet threshold levels being flagged for further retracking and water surface elevation determination (Figure 45).

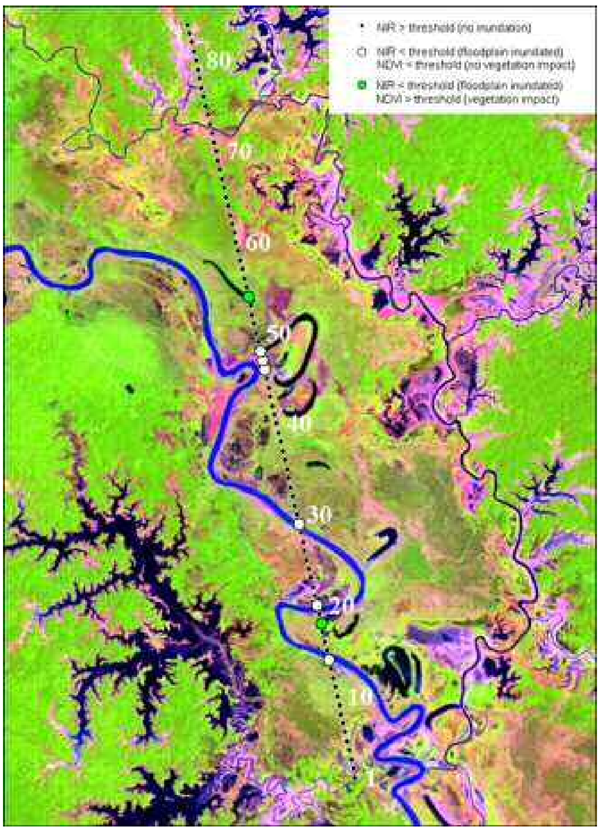

Figure 45. Landsat ETM7 (bands 5, 4, 3) on 28th October 2002, waveforms located over inundated zones overlapping Envisat RA-2 18Hz waveforms pass 0677, cycle 10. White dots over water body are automatically selected (Marshall and Deng, 2016).

In addition, in order to investigate the climate implication, Hwang et al. (2016) investigated the multi-decadal monitoring of lake level changes in the Qinghai-Tibet Plateau, China, by using TOPEX/Poseidon-family altimeters. Su et al. (2016) improved processing algorithms for Envisat altimetry ice sheet elevation change data using the repeat-track analysis. Rateb et al. (2017) estimated spherical harmonics (SH) errors and scale factors for African hydrological regimes. Then, terrestrial water storage (TWS) in Africa was determined based on Slepian localization and compared with JPL-mascon and SH solutions. The TWS trends in the lower Nile and Sahara at −1.08 and −6.92 Gt/year, respectively, are higher than those previously reported.

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Sub-commission 2.6: Gravity and Mass Transport in the Earth System

Chair: *Jürgen Kusche (Germany)*
Vice Chair: *Isabelle Panet (France)*

Overview

The Sub-commission's activities during the period 2015-2017 are mainly via its (joint) working groups.

Joint Working Groups of Sub-commission 2.6:

JWG 2.6.1: Geodetic observations for climate model evaluation

Chair: *Annette Eicker (Germany)*

Members

- *Carmen Böning (USA)*
- *Marie-Estelle Demory (UK)*
- *Albert van Dijk (Australia)*
- *Henryk Dobslaw (Germany)*
- *Wei Feng (China)*
- *Vincent Humphrey (Switzerland)*
- *Harald Kunstmann (Germany)*
- *J.T. Reager (USA)*
- *Rosa Pacione (Italy)*
- *Anne Springer (Germany)*
- *Paul Tregoning (Australia)*

Activities and publications during the period 2015-2017:

Organization of the workshop "Satellite Geodesy for Climate Studies"

The main focus of the working group in the first part of the IAG term has been the organization of a workshop on "Satellite Geodesy for Climate Studies" to be held on September 19-21, 2017, in Bonn, Germany (http://geodesy-for-climate.org/; Figure 46). The workshop is a joint initiative of SC 2.6 (Gravity and Mass Transport in the Earth System) and the working groups JWG 2.6.1 (Geodetic Observations for Climate Model Evaluation) and JWG 4.3.8 (GNSS Tropospheric Products for Climate). With this workshop we aim at bringing together geodetic data specialists and climate modelers with the goal of strengthening the use of geodetic data in the climate community.

The rationale of the workshop is as follows: The growing record of space-gravimetric and -geodetic data (GRACE, GNSS, radar altimetry, InSAR, VLBI, …) provides a new view on Essential Climate Variables such as terrestrial water storage and continental ice-mass changes, steric and barystatic sea level variability, sea ice coverage, tropospheric water vapor variations, and others. These observational data sets have the strong advantage to be homogeneous around the globe, and independent from any other data commonly used to validate climate models. Geodetic time series start to reveal a complex picture of low-frequency natural climate variability, long-term climate change and other anthropogenic modifications in geodetic data. It is still difficult to evaluate decadal variability from geodetic data alone, but in combination with other observations or reanalyses they provide excellent tools for climate model evaluations. The workshop will be organized in four sessions, with working group members serving as convenors and keynote speakers:

- *Session A: What is required for validating climate models using geodetic data?* (Convenors: Carmen Böning, Marie-Estelle)
- *Session B: Long and consistent geodetic time series* (Convenors: Wei Feng, Shin-Chan Han)
- *Session C: Climate modelling and observable variables* (Convenors: J.T. Reager, Albert van Dijk)
- *Session D: Prospects of future missions and constellations* (Convenors: Bert Wouters, Henryk Dobslaw)

At the time of writing, 46 abstracts for oral contributions have been submitted, and 17 for poster contributions.

Current activities of the working group focus around inviting further international experts as keynote speakers, setting up the workshop program, and the local organization of venue, catering, social program etc.

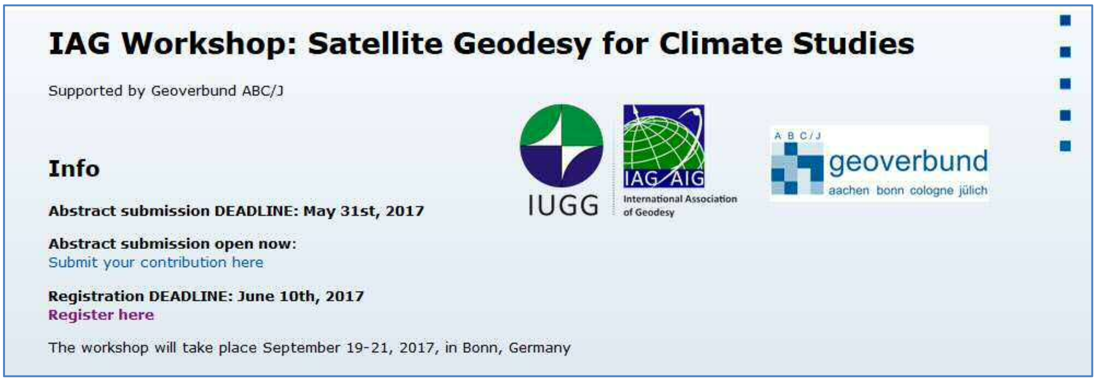

Figure 46 Screenshot of the workshop webpage

Splinter meetings

Splinter meetings of the working group members took place at the IAG GGHS meeting in Thessaloniki (September 2016) and at the EGU General Assembly (April 2017). The topic of the splinter in September was a discussion about efforts to promote satellite gravity related topics towards the European Union with the future goal of establishing satellite gravimetry within the Copernicus program. Following this discussion in Thessaloniki, two representatives of the working group (C. Böning and A. Eicker) joint the organization team for two lobby events that took place in Brussels with members of the European Commission (March 2017 and May 2017) and acted as speakers at both of these events. The second splinter meeting in Vienna in April was dedicated to the planning of the workshop "Satellite Geodesy for Climate Studies".

Joint publications (planned)

As a result of the workshop to take place in September 2017 we are currently planning to set up a special issue in an international journal on the workshop (and working group) topic of using satellite geodesy for climate studies. Furthermore, the main conclusions obtained from the workshop and a future roadmap for strengthening the use of geodetic data in the climate community shall be formulated in terms of a white paper to be composed by the workshop organizers.

Working Groups of Sub-commission 2.6:

WG 2.6.1: Potential field modelling with petrophysical support

Chair: *Carla Braitenberg (Italy)*

Members
- *Jon Kirby (Australia)*
- *Juanggen Jin (China)*
- *Erik Ivins (USA)*
- *Xiapoping Wu (USA)*
- *Valeria Barbosa, (Brazil)*
- *Leonardo Uieda (Brazil)*
- *Orlando Alvarez (Argentina)*
- *Jörg Ebbing, (Germany)*
- *Holger Steffen (Sweden)*
- *Sabine Schmidt (Germany)*
- *Rezene Mahatsente (USA)*
- *Daniele Sampietro, (Italy)*
- *Christian Hirt (Germany)*

Activities and publications during the period 2015-2017

The activity in this first term was to prepare the material for a public homepage in which a repository of relevant publications and software would be present that is useful especially for researchers beginning to work on the subject of integrating potential field modelling with the physical properties of the rocks at the in situ conditions and using the constraining data on rock composition that are available from petrologic investigations. Another physical constraint comes from the isostatic equilibrization and the dynamic mass changes desumable from observed GNSS movements. These themes are defined in the term of reference of the working group, which aims at developing and promoting methods and software that are needed for a full understanding of the Earth static and variable gravity and gradient field. The homepage will be published at end of July 2017 and shall be used as a platform for sharing research material. Up to now the activities among members of the group relied on email-correspondence and -cooperation. One workshop is planned before the end of the term, in which the researcher confident in potential field methods should be advised how to include the physical modelling of the lithosphere, including isostatic considerations, present tectonic movements and rock properties. The petrophysical modelling must include assumptions or models of depth variation of temperature and pressure and the crust and mantle composition. An overview of the constraining data from the geological literature essential to the solution of the problem, shall be given.

Commission 2 Joint Working Group 2.1: Relativistic Geodesy: Towards a new geodetic technique

Chair: *Jakob Flury (Germany)*
Vice Chair: *Gerard Petit (France)*

Members
- *Geoff Blewitt (US)*
- *Claude Boucher (France)*
- *Pascale Defraigne (Belgium)*
- *Pacome Delva (France)*
- *Gesine Grosche (Germany)*
- *Claus Lämmerzahl (Germany)*
- *Christian Lisdat (Germany)*
- *Jürgen Müller (Germany)*
- *Pavel Novak (Czech Republic)*
- *Paul Eric Pottie (France)*
- *Bijunath Patla (US)*
- *Nikos Pavlis (US)*
- *Piet Schmidt (Germany)*
- *Pieter Visser (The Netherlands)*
- *Marie-Francoise Lequentrec-Lalancette (France)*
- *Elena Mazurova (Russia)*
- *Sergei Kopeikin (US)*
- *Chris Hughes (UK)*
- *Davide Calonico (Italy)*

Activities during the period 2015-2017

JWG 2.1 is fostering the international exchange on concepts and methods in relativistic geodesy. Topics include the development and use of networks of optical atomic clocks as well as satellite and space methods. The expertise of the group members covers space geodesy, reference frames, physical geodesy, oceanography, time and frequency metrology, and relativistic geodesy. Due to the interdisciplinary background of the group members, attempts for organizing a kick-off as a splinter meeting at a conference were not successful in 2016. Therefore, the group came together for a 2-day workshop on May 15-16, 2017, at Leibniz Universität Hannover, Germany.

The topics of the workshop included:
- theoretical developments on relativistic geoid, potential field modelling, and relativistic geodesy,
- perspectives for resolving dm-scale uncertainties of tide gauges and potential reference for geodetic and oceanographic applications (Figure 47),
- perspectives for using time as a geodetic observable,
- practical issues such as the understanding of the reference to the geoid in the definition of Terrestrial Time (TT),
- new studies on GNSS time and frequency transfer,
- remote frequency transfer and clock comparisons using optical fiber networks,
- current developments in European optical fiber networks (Figure 48),

- the work of the Consultative Committee for Time and Frequency (CCTF) on primary and secondary frequency standards (Figure 49).

The full agenda with participants and the presentation slides are available at https://www.geoq.uni-hannover.de. Minutes of the workshop are being finalized.

The next steps will include to start a joint working document to collect and update activities and topics on the field of the group. The next workshop is envisaged to be held in Paris in 2018 (tbc).

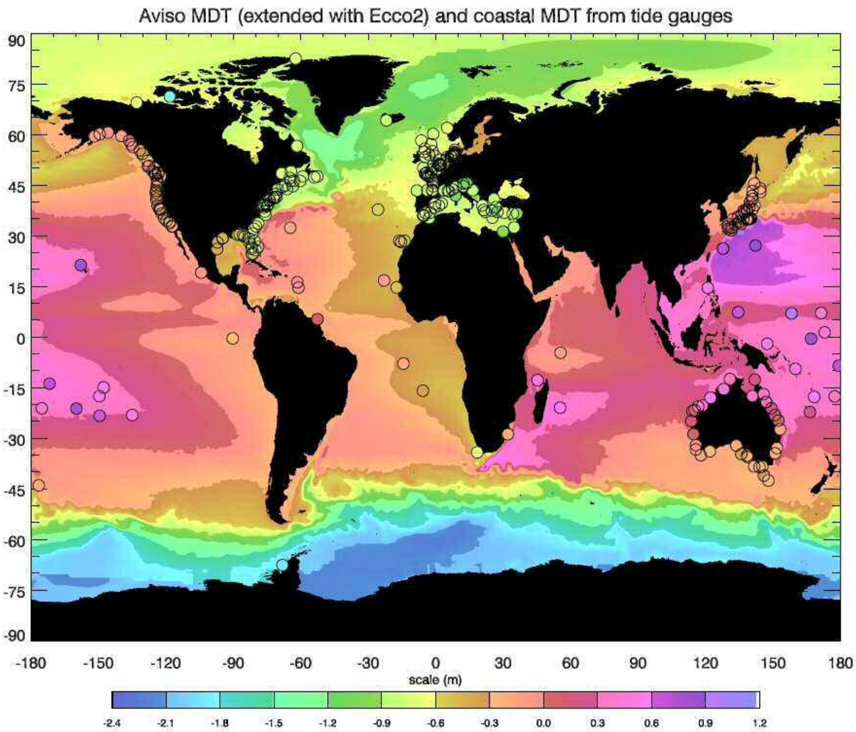

Figure 47 Contour plot: Aviso mean dynamic topography (MDT), extended with Ecco2 ocean model; circles: coastal MDT in tide gauges equipped with GPS, referred to Eigen-6c4 geoid. Source: C. Hughes

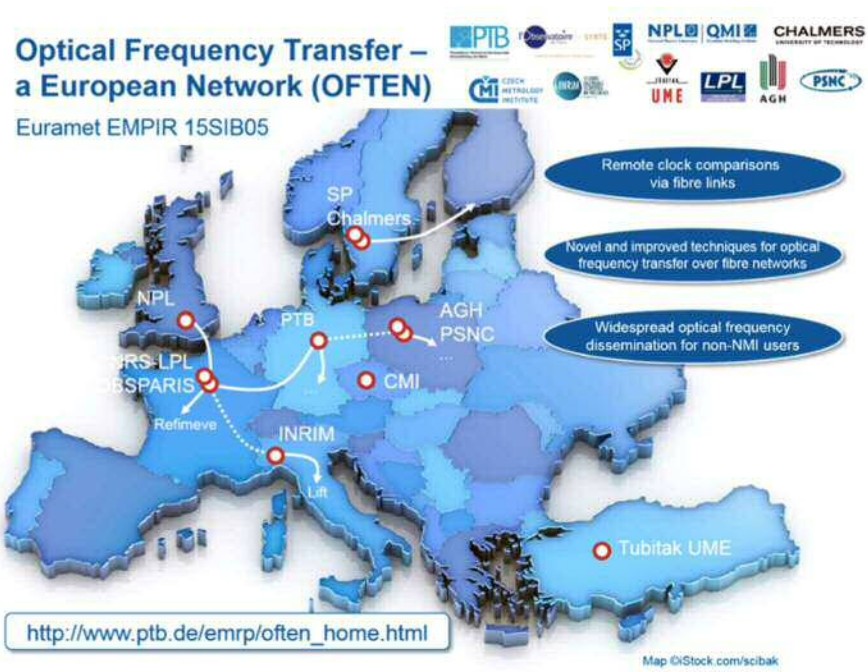

Figure 48 Optical frequency transfer links investigated in the project OFTEN. Source: PTB

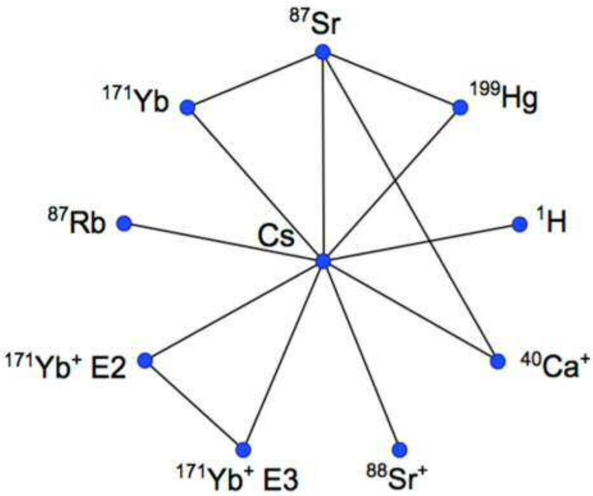

Figure 49 (from Margolis and Gill, 2016) New frequency ratio measurements considered by the Frequency Standards Working Group (WGFS) of the CCTF in September 2015. Most were absolute frequency measurements, i.e. frequency ratios involving the caesium primary standard, but four optical frequency ratios had also been measured directly (in one case by two independent groups).

Selected references

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Margolis HS, Gill P (2016) Determination of optimized frequency and frequency ratio values from over-determined sets of clock comparison data. In Journal of Physics: Conference Series Vol. 723, No. 1, p. 012060. IOP Publishing.

Müller J, Dirkx D, Kopeikin SM, Lion G, Panet I, Petit G, Visser PN (2017) High Performance Clocks and Gravity Field Determination. arXiv preprint arXiv:1702.06761. 2017 Feb 22.

Petit G, Defraigne P (2016) The performance of GPS time and frequency transfer: comment on 'A detailed comparison of two continuous GPS carrier-phase time transfer techniques'. Metrologia 53(3):1003.

Commission 2 Joint Working Group 2.2: Validation of combined gravity model EGM2020

Chair: Srinivas Bettadpur (USA)

Activities during the period 2015-2017

JWG 2.2 is currently being set up, the list of members is not yet finalized. The terms of reference, objectives and program of activities has been adopted during the IAG EC meeting on 28 April 2017. The JWG will start its activity after the availability of the first preliminary versions of EGM2020, to be expected by autumn 2017.

Terms of Reference

The National Geospatial-Intelligence Agency (NGA), in conjunction with its U.S. and international partners, has begun to work on the next Earth Gravitational Model. The final version of the new 'Earth Gravitational Model 2020' (EGM2020) has an expected public release date of 2020. EGM2020 will be essentially an ellipsoidal harmonic model up to degree (n) and order (m) 2159, but will be released as a spherical harmonic model to degree 2190 and order 2159. EGM2020 will benefit from new data sources and procedures. Updated satellite gravity information from the GOCE and GRACE mission, will better support the lower harmonics, globally. Multiple new acquisitions (terrestrial, airborne and ship borne) of gravimetric data over specific geographical areas, will provide improved global coverage and resolution over the land, as well as for coastal and some ocean areas. NGA and partners are evaluating different approaches for optimally combining the new GOCE/GRACE satellite gravity models with the terrestrial data. These include the latest methods employing a full covariance adjustment. NGA is also working to assess systematically the quality of its entire gravimetry database, towards correcting biases and other egregious errors where possible, and generating improved error models that will inform the final combination with the latest satellite gravity models. A first preliminary version is expected to be available already by 2017, which shall be validated and successively improved until the generation of the final EGM2020 model.

Objectives

The main objective of this working group is to validate EGM2020 and preliminary versions of it, to identify potential deficiencies and propose model improvements in different regions of the world. For this independent external validation, a full arsenal of validation methods and external independent data sources shall be applied. This includes validation against GPS/levelling observations, regional data bases of gravity field functionals, other global and regional gravity field models, orbit tests to assess mainly the long wavelengths of the field as well as the spectral transition from satellite to terrestrial data, assessment in the frame of mean dynamic ocean topography computations, correlation analysis with topographic potential and isostatic potential models, etc. Potential deficiencies in the preliminary versions of the model shall be identified, in order to improve the model until its final release in 2020. Additionally, the plausibility and consistency of the uncertainty estimates (variance-covariance information) provided together with the model shall be assessed.

Commission 3 – Earth Rotation and Geodynamics

http://www.rcep.dpri.kyoto-u.ac.jp/iag-commission3/Commission_3.htm

President: Manabu Hashimoto (Japan)
Vice President: Cheng-Li Huang (China)

Structure

Sub-commission 3.1:	Earth Tides and Geodynamics
Sub-commission 3.2:	Crustal Deformation
Sub-commission 3.3:	Earth Rotation and Geophysical Fluids
Sub-commission 3.4:	Cryosphere Deformation
Sub-commission 3.5:	Tectonics and Earthquake Geodesy
Joint Study Group 3.1:	Intercomparison of Gravity and Height Change
Joint Working Group 3.1:	Theory of Earth Rotation and Validation
Joint Working Group 3.2:	Constraining Vertical Land Motion of Tide Gauges

Overview

Geodynamics is the science that studies how the Earth moves and deforms in response to forces acting on the Earth, whether they derive from outside or inside of our planet. This includes the entire range of phenomena associated with Earth rotation and Earth orientation such as polar motion, Universal Time or length of day, precession and nutation, the observation and understanding of which are critical to the transformation between terrestrial and celestial reference frames. It also includes tidal processes such as solid Earth and ocean loading tides, and crust and mantle deformation associated with tectonic motions and isostatic adjustment etc.

During the last few decades, many geophysicists have come to use geodynamics in a more restricted sense to address processes such as plate tectonics and postglacial rebound that are dominantly endogenic in nature. Because the Earth as a mechanical system responds to both endogenic and exogenic forces, and because these responses are sometimes coupled, Commission 3 studies the entire range of physical processes associated with the motion and the deformation of the solid Earth. The purpose of Commission 3 is to promote, disseminate, and, where appropriate, to help coordinate research in this broad arena.

Commission 3 fosters and encourages research in the areas of its sub-entities by facilitating the exchange of information and organizing Symposia, either independently or at major conferences in geodesy or geophysics. Some events will focus narrowly on the interests of the sub-commissions and other entities listed above, and others will have a broader commission-wide focus.

Summary of the Commission's activities during the period 2015-2017

Commission 3 members were active to hold several meetings, where they served as chairpersons of LOC or keynote speakers, and convene sessions in international conferences. In total, 6 meetings and 16 sessions or splinter meetings convened by Commission 3 members in international conferences. 3 books were published by Commission 3 members.

Commission 3 will convene a session G04 "Earth Rotation and Geodynamics" in coming IAG-IASPEI 2017 held in Kobe, Japan, July 31 - August 4, 2017. 29 papers ware submitted, which will be presented in 4 oral sessions and 1 poster session. The commission will have a splinter meeting during IAG-IASPEI to discuss future activities.

Commission 3 will be active in the next two years. Some sub-commissions will schedule several meetings and a couple of proceedings of past meetings are now under revision.

Meetings

Geodesy, Astronomy and Geophysics in Earth Rotation (GAGER2016) - A Joint IAU/IAG/IERS Symposium, Cheng-Li Huang, Chairperson of LOC, 19/7/2016 - 23/7/2016, Wuhan, China.

Publications (by President and Vice-president)

Fukahata, Y., and M. Hashimoto, Simultaneous estimation of the dip angles and slip distribution on the faults of the 2016 Kumamoto earthquake through a weak nonlinear inversion of InSAR data, Earth Planets Space, 68, 2016.

Hashimoto, M., Ground deformation in the Kyoto and Osaka area during recent 19 years detected with InSAR, "International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH)", IAG Symposia Series, 145, 155-164, 2016.

Hashimoto M. (Ed.), International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH), IAG Symposia Series, 145, 168 pp., 2017.

Lindsey, E., R. Natsuaki, X. Xu, M. Shimada, M. Hashimoto, D. Melgar, and D. Sandwell, Line-of-sight displacement from ALOS-2 interferometry: Mw 7.9 Gorkha earthquake and Mw 7.3 aftershock, Geophys. Res. Lett., 42, 2015.

Presentations (by President and Vice-President)

Fukahata Y., and M. Hashimoto, Simultaneous estimation of the dip angle and slip distribution on the two active faults of the 2016 Kumamoto earthquake, JpGU-AGU2017, SSS08-08, Chiba, Japan. May 2017.

Chung R., K.-E. Ching, M. Hashimoto, R.-J. Rau, and L.-H. Chung, Coseismic deformation and tectonic implications of the 2016 Meinong earthquake, Taiwan, JpGU-AGU2017, SSS10-P07, Chiba, Japan, May 2017.

Hashimoto, M., T. Ozawa, T. Nishimura, H. Munekane, and M. Tobita, Postseismic deformation following the 1995 Kobe, Japan, earthquake detected by space geodesy, EGU2017, X2.257, EGU2017-2874, Vienna, Austria, April 2017.

Hashimoto, M., and T. Ozawa, Ground deformation near active faults in the Kinki, district, southwest Japan, detected by InSAR, 2016 AGU Fall Meeting, G22A-02, San Francisco, USA, December 2016.

Hashimoto, M., Observation of surface deformation with ALOS-2/PALSAR-2 in southern Taiwan before, during and after the Meinong earthquake, 2016 Taiwan-Japan Workshop on Crustal Dynamics, 13-13, Tainan, Taiwan, November 2016.

Fukahata, Y., and M. Hashimoto, InSAR data inversion to simultaneously estimate the dip angles and slip distribution of the two seismogenic faults at the 2016 Kumamoto earthquake, 2016 Taiwan-Japan Workshop on Crustal Dynamics, 17-17, Tainan, Taiwan, November 2016.

Takahashi, A., M. Hashimoto, J.-C. Hu, and Y. Fukahata, Identification of crustal block structures in Taiwan islands investigated by cluster analysis of super dense GNSS data, 2016 Taiwan-Japan Workshop on Crustal Dynamics,18-18, Tainan, Taiwan, November 2016.

Hashimoto, M., Observation of earthquakes with ALOS-2/PALSAR-2, CEOS2016, Tokyo, Japan, September 2016.

Hashimoto, M., Surface deformations associated with the Meinong, Taiwan, earthquake detected by InSAR, AOGS2016, Beijing, China, August 2016.

Hashimoto, M., Observation of ground deformation in the Osaka and Kanto plains with ALOS-2/PALSAR-2, IGARSS2016, Beijing, China, July 2016.

Hashimoto, M., Observation of the Gorkha, Nepal earthquake of April 23, 2015 with ALOS-2/PALSAR-2, American Geophysical Union 2015 Fall Meeting, G21A-1011, San Francisco, USA, December 2015.

Lindsey E., R. Natsuaki, X. Xu, M. Shimada, M. Hashimoto, D. Melgar, and D. Sandwell, Line of sight displacements from ALOS-2 ScanSAR interferometry, AGU 2015 Fall Meeting, G13B-04, San Francisco, USA, December 2015.

Hashimoto, M., Ground deformation in northern Kanto, Osaka and Nagoya detected by PALSAR/PALSAR-2, The 2nd PI Workshop for ALOS-2, S2-1-02, Tokyo, Japan, November 2015.

Hashimoto, M., High resolution monitoring of surface deformation with SAR, (Key-note Speech), French-Japanese Symposium on earthquakes & Triggered Hazards, 51-52, Orleans, France, September 2015.

Hashimoto, M., Study of deformation using ALOS-2/PALSAR-2, IGARSS2015, Milan, Italy, July 2015.

Sub-commission 3.1: Earth Tides and Geodynamics

Chair: *Janusz Bogusz (Poland)*
Vice-Chair: *Carla Braitenberg (Italy)*

SC 3.1 addresses the entire range of Earth tidal phenomena and dynamics of the Earth, both on the theoretical as well as on the observational level. The phenomena responsible for these variations include the full range of periodic and non-periodic occurrences such as solid Earth tides, ocean and atmospheric tidal loading, ocean, atmospheric and hydrologic non-tidal effects as well as plate tectonics and intraplate deformation. The periods range from seismic normal modes over to the Earth tides and the Chandler Wobble and beyond. Thus, the time scales range from seconds to years and for the spatial scales from local to continental dimensions. SC 3.1 national representatives are involved in:

- organization of International Symposium on Geodynamics and Earth Tide (GET Symposium held every four years) as well as other thematic conferences together with other Commission 3 SCs if possible;
- awarding of the outstanding scientists with the Paul Melchior Medal, formerly known as the Earth Tides Commission Medal;
- organization of special sessions at international meetings;
- organization of the comprehensive SC meeting together with the IGETS;
- publishing the outcome of the researches, either as stand-alone publications or as proceedings or special issues of scientific journals;
- cooperating with other Joint Study Groups (JSG), Joint Working Groups (JWG) or Inter-Commission Projects (ICP) and Committees (ICC);
- cooperate with GGOS, as mentioned above.

Summary of the Sub-commission's activities during the period 2015-2017

Meetings:

18th International Symposium on Geodynamics and Earth Tides (G-ET Symposium 2016), title of Meeting: "Intelligent Earth system sensing, scientific enquiry and discovery", venue: University of Trieste, Italy, date: June 5 (Sunday) to June 9 (Thursday) 2016, coordination: Carla Braitenberg. The Symposium attracted 105 attendants from 31 countries who presented 66 oral presentations and 40 posters. The contributions were grouped into the following sessions:

1. tides and non-tidal loading.,
2. geodynamics and the earthquake cycle,
3. variations in Earth rotation,
4. tides in space geodetic observations,
5. volcano geodesy,
6. natural and anthropogenic subsurface fluid effects,
7. instrument and software developments.

Nine invited lectures of half an hour each allowed insight into specific themes, as the principal outcomes of 18 years superconducting gravity in Medicina (Italy) (H.Wziontek), the lunisolar stress tensor and the triggering of earthquakes, the correction of observed free oscillation spectra due to local heterogeneities obtainable from tidal observations (W. Zürn), a review on the results of 40 years of long base laser strainmeter observations in California (D. Agnew), the geodetic observation of slow slip events (SSE) or giant silent earthquakes at

subduction zones (K. Heki), the role of earth tides in global plate tectonics (C. Doglioni), an overview of local to global geodetic monitoring of natural hazards and global change (H. Schuh), the separation of surface loading from time dependent tectonic deformation in GNSS observations (J. Freymueller), and a review of new developments of terrestrial and space based gravimetric instrumentation in China (Houze Xu). The program included a talk of the Rector of the University M. Fermeglia on 'The great energy challenge: how to avoid the 'perfect storm' and the President of the OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) M.C. Pedicchio.
Website: https://g-et2016.units.it/.

Special sessions at international meetings:

Joint International Workshop of the Sixth TibXS (Multi-observations and Interpretations of Tibet, Xinjiang and Siberia) during 25-29 July 2015, in Tianjin, China.
Joint International Workshop of the Seventh TibXS (Multi-observations and Interpretations of Tibet, Xinjiang and Siberia) during 26-30 July 2016, in Tianjin, China.

Paul Melchior Medal:

It's been a tradition of Earth Tides Symposia, that with the "Paul Melchior Medal" an outstanding scientists with a huge experience and high impact on to the Tidal Community who contributed significantly to develop the science and technology of tidal research used to be awarded. First Medal was given in 1997 to Paul Melchior and it has been named with the "Earth Commission Medal". After Paul Melchior passed away the name of the Medal was changed to honour his contribution to the development of tidal research.

The procedure of nomination to the 2016 Paul Melchior Medal was completed in 31st of October, 2015 with 5 successfully submitted nominations:
1. David Crossley;
2. Walter Zuern;
3. Trevor Baker;
4. Gerhard Jentzsch and
5. Shuzo Takemoto.

After that the Committee consisted of the past Awardees, Chair of the IAG's Sub-Commission 3.1 as well as 4 experienced tidalists who were not nominated, 8 people in total decided that 2016 Paul Melchior Medal will go to Trevor Baker.

Peer-reviewed publications:

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Presentations:

<u>Presentations given at the 18th International Symposium on Geodynamics and Earth Tides in Trieste, 2016:</u>

Orals:

First analyses of the new iOSG-type Superconducting Gravimeters at the J9 Gravimetric Observatory of Strasbourg and at the Low Noise Underground Laboratory of Rustrel, France, Severine Rosat (1), Jacques Hinderer (1), Jean-Paul Boy (1), Frédéric Littel (1), Daniel Boyer (2), Jean-Daniel Bernard (3), Yves Rogister (3), Anthony Mémin (4), Stéphane Gaffet (5), (1) IPGS - EOST, Strasbourg, (2) LSBB Underground Research Laboratory, UMS3538 CNRS, (3) EOST, Strasbourg, (4) Université Nice Sophia Antipolis, CNRS, IRD, Observatoire de la Côte d'Azur, (5) LSBB Underground Research Laboratory, UMS3538 AMU/CNRS/UAPV/UNS.

Strain tides observed by two geodetic laser strainmeters at Canfranc (Spain): clues on nonlinear and minor ocean tides in the Bay of Biscay. Antonella Amoruso, Luca Crescentini University of Salerno, Italy.

What uses in today’s research for non-superconducting gravimeter observations in Earth Tides and geodynamics modeling? Jean-Pierre Barriot (1), Bernard Ducarme (2) (1) Geodesy Observatory of Tahiti, (2) Catholic University of Louvain.

Analyses of continuous time-varying gravity and barometric records of a sea-floor gravimeter in the North Sea Severine Rosat, Jean-Paul Boy, Benjamin Escot, Jacques Hinderer IPGS - EOST, Strasbourg.

100 years Michelson-Gale’s interferometric water tube tilt meter experiment in USA and 50 years instrument development in Finland Hannu Ruotsalainen Finnish Geospatial Research Institute, NLS.

Tidal analyses of long-base tiltmeters at Rustrel (France), Sainte-Croix (France) and BFO (Germany) Severine Rosat (1), Sophie Lambotte (1), Umberto Riccardi (2), Jean-Paul Boy (1), Frédéric Boudin (3), Walter Zürn (4) (1) IPGS - EOST, Strasbourg, (2) DiSTAR, Università Federico II di Napoli, (3) UMR 8538, Ecole Normale Supérieure, Paris, (4) BFO, Karlsruhe Institute of Technology and University of Stuttgart.

Report of the first year of the International Geodynamics and Earth Tide Service (IGETS) Jean-Paul Boy (1), Jean-Pierre Barriot (2), David Crossley (3), Christoph Foerste (4), Jacques Hinderer (1), Bruno Meurers (5), Vojtech Palinkas (6), Spiros Pagiatakis (7), He Ping Sun (8), Hartmut Wziontek (9) (1) EOST/IPGS, Strasbourg, France, (2) University of French Polynesia, (3) Saint Louis University, USA, (4) GFZ, Potsdam, Germany, (5) University of Vienna, Austria, (6) Geodestic Observatory of Pecny, Czech Republic, (7) York University, Canada, (8) Chinese Academy of Sciences, Beijing, China, (9) BKG, Leipzig, Germany.

Processing SG data according to the requirements of the IGETS database, with Apache Point as an example David Crossley (1), Tom Murphy (2) (1) Saint Louis University, (2) Dept. Physics, UCSD, California..

Relation of different type Love-Shida numbers determined with the use of time-varying incremental gravitational potential Peter Varga (1), Erik Grafarend (2), Johannes Engels (2) (1) Seismological Observatory, Institute of Geodesy and Geophisics, (2) Department of Geodesy and Geoinformatics,, Stuttgart University.

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Investigation of the Solid Earth Tide Based on GPS Observation and Superconducting Gravimeter Data Arisauna Pahlevi (1), Kosasih Prijatna (2), Irwan Meilano (2), Ibnu Sofian (1) (1) Geospatial Information Agency for Indonesia, (2) Institute Technology of Bandung, Indonesia.

M2 tidal parameter modulation revealed by superconducting gravimeter Bruno Meurers (1), Michel Van Camp (2), Olivier Francis (3), Vojtech Pálinkáš (4) (1) University of Vienna, (2) Observatory of Belgium, Brussels, Belgium, (3) Faculté des Sciences, de la Technologie et de la Communication, University, (4) Research Institute of Geodesy, Topography and Cartography, Geodetic Observatory Pecný.

18 years continuous gravity time series at station Medicina: A benchmark for tidal analysis Hartmut Wziontek (1), Reinhard Falk (2), Klaus Schüller (3), Susanna Zerbini (4) (1) Bundesamt für Kartographie und Geodäsie, (2) Bundesamt für Kartographie und Geodäsie, Germany, (3) Research Initiative for Tidal Analysis (RITA), Thailand, (4) Dipartimento di Fisica e Astronomia, Università di Bologna, Italy.

Time stability of SG instrumental scale factor versus time stability of tidal parameters at the J9 Gravimetric Observatory of Strasbourg (1987 – 2016) Marta Calvo (1), Jacques Hinderer (2), Severine Rosat (2), Jean Paul Boy (2), Hilaire Legros (2), Frédéric Littel (2), Jean Daniel Bernard (2) (1) IGN-Spain, (2) IPGS/EOST Strasbourg France.

New gravimetric tide observations in the vicinity of Lake Nasser Khalid Zahran NRIAG.

The potential of the cross least squares wavelet analysis for estimating the time-frequency transfer function of atmospheric variations effect of superconducting gravity data Mahmoud Abd El-Gelil (1), Ebrahim Ghaderpour (2), Spiros Pagiatakis (2) (1) Sultan Qaboos University, Oman, (2) York University, Canada.

On GPS-based Ocean Tidal Loading Displacements and Their Potential to Constrain Mechanisms of Anelasticity Pierre-Michel Rouleau Memorial University of Newfoundland - Grenfell Campus.

Accuracy assessment of ocean tide models in China using GPS Peng Peng (1), Yan Hao-Ming (1), Yuan Lin-Guo (2), Zhu Yao-Zhong (1), Wu Ding-Cheng (1) (1) State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China, (2) Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 610031, China.

Validation of EOST loading service using global GPS solutions. Jean-Paul Boy (1), Pierre Baudet (2), Anthony Mémin (3), Patrice Ulrich (1) (1) EOST/IPGS, Strasbourg, France, (2) ESGT, Le Mans & EOST/IPGS, Strasbourg, France, (3) GeoAzur, Nice, France.

Influence of external forces on the triggering of quakes Peter Varga Seismological Observatory, Institute of Geodesy and Geophisics.

Mapping of tidal effects in the Pannonian basin – an effort to check location dependencies at microGal level Gábor Papp (1), Judit Benedek (1), Bruno Meurers (2), Márta Kis (3), András Koppán (3), Roman Leonhardt (4) (1) Geodetic and Geophysical Institute, MTA CSFK, (2) University of Vienna, Department of Meteorology and Geophysics, (3) Geological and Geophysical Institute of Hungary, (4) Zentralanstalt für Meteorologie and Geodynamik, Conrad Observatory.

Non-tidal gravity change and Vrancea intermediate-depth seismicity Lucian Besutiu Institute of Geodynamics of the Romanian Academy.

Investigation of the relationship between rock strain and radon concentration in the tidal frequency domain Gyula Mentes RCAES of HAS, Geodetic and Geophysical Institute.

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Observation of Earth Free Oscillation Modes Using Cross Least Squares Wavelet Method Mahmoud Abd El-Gelil, Mohammed Al-Shahri Sultan Qaboos University, Oman.

Long-Base Laser Strainmeters: Four Decades of Results Duncan Agnew, Frank Wyatt IGPP, Scripps Institution of Oceanography, UC San Diego.

Accessing power-law properties of post-seismic deformation in land movements Anna Klos (1), Addisu Hunegnaw (2), Machiel Simon Bos (3), Felix Norman Teferle (2), Rui Fernandes (3), Janusz Bogusz (1) (1) Military University of Technology, Warsaw, Poland, (2) University of Luxembourg, Geophysics Laboratory, FSTC, Luxembourg, (3) University of Beira Interior, Instituto D. Luis, R. Marquês d'Ávila e Boloma, Portugal.

Geodetic Studies of Slow Slip Events in Subduction Zones with Active Back-Arc Opening Kosuke Heki (1), Yoko Tu (2), Deasy Arisa (2) (1) Dept. Earth Planet. Sci., Hokkaido University, (2) Dept. Natural History Sci., Hokkaido University.

Investigation of relationships in time-domain between tectonic and tidal signals observed in the Geodynamic Laboratory of SRC and seismic events which occur in the Middle Odra Faults Zone (The Lower Silesian copper mining region) Marek Kaczorowski (1), Zbigniew Szczerbowski (2), Damian Kasza (3), Ryszard Zdunek (4), Michal Jozwik (5), Roman Wronowski (4) (1) Space Research Center of PAS, (2) AGH University of Science and Technology,, (3) Wroclaw University of Technology, (4) Space Research Centre, Polish Academy of Sciences, (5) AGH University of Science and Technology.

Interference of tectonic signals in subsurface hydrologic monitoring through Gravity and GNSS due to mountain building Carla Braitenberg (1), Tommaso Pivetta (2), Wenjin Chen (3), Enrico Serpelloni (4) (1) University of Trieste, (2) Dipartimento di Matematica e Geoscienze, University of Trieste, (3) Dipartimento di Matematica e Geoscienze, University of Trieste and School of Geodesy and Geomatics, Wuhan University, (4) INGV.

Constrain large earthquake source mechanism by using low frequency normal mode data Zhang Lingyun Institute of Geodesy and Geophysics, Chinese Academy of Sciences.

Earth's tides, plate motions, graviquakes and elastoquakes Carlo Doglioni (1), Guido Maria Adinolfi (2), Antonio Carcaterra (3), Eugenio Carminati (2), Marco Cuffaro (4), Eleonora Ficini (2), Patrizio Petricca (5), Federica Riguzzi (6), Emanuela Valerio (2) (1) Sapienza University Earth Sciences Department, INGV, (2) Sapienza University Earth Sciences Department, (3) Sapienza University DIMA, (4) IGAG-CNR, (5) GFZ-Potsdam, (6) INGV-Roma.

The role of tides and LOD in the case of earthquake triggering Pavel Kalenda (1), Lubor Ostřihanský (2), Jana Rušajová (3), Karel Holub (3) (1) IRSM Academy of Science, Czech Republic, (2) Prague, (3) IGN Academy of Science, Czech Republic.

Glacially induced seismicity in Europe Holger Steffen (1), Christian Brandes (2), Rebekka Steffen (3), Patrick Wu (4) (1) Lantmäteriet,Sweden, (2) Leibniz Universität Hannover, Germany, (3) Uppsala University, Sweden, (4) University of Hong Kong.

Seismological and geotechnical long-term monitoring of a closed down potash mine Astrid Gessert (1), Hubert Pruehl (2) (1) K-UTEC AG Salt Technologies, (2) LMBV mbH Bereich Kali-Spat-Erz.

Numerical Computation of Gravitational Field for General Three-Dimensional Objects Toshio Fukushima National Astronomical Observatory of Japan.

Crustal gravitational energy change caused by earthquakes in Tibet Jiangcun Zhou, Heping Sun, Jianqiao Xu Institute of geodesy and geophysics, Chinese academy of sciences.

A comparative study of gravity and crustal deformation performed through Superconducting Gravimeter and GPS in the Garhwal Himalayan Naresh Kumar, Vishal Chauhan, P.K.R. Gautam Wadia Institute of Himalayan Geology.

Determination of the transfer functions for OSG-057 (Lhasa) and OSG-065 (Wuhan) Xiaodong Chen Institute of Geodesy and Geophysics, CAS.

Assessing the seasonal signals between environmental loadings and gps coordinates with singular spectrum analysis Marta Gruszczynska (1), Anna Klos (1), Machiel Simon Bos (2), Jean-Paul Boy (3), Janusz Bogusz (1) Military University of Technology, Poland, (2) University of Beira Interior, Portugal, (3) Institut de Physique du Globe de Strasbourg, France.

Plio Quaternary Structuring Of Hamma Bouziain Basin, Constantine Region (North-East Of Algeria) Laziz Ouided, Boularak Moussa, Benabbas Chaouki Constantine University.

The geodynamics of Ny Alesund from ITRF2014 time series Marco Roggero (1), Vincenza Tornatore (2) (1) Politecnico di Torino, (2) Politecnico di Milano.

Technical possibilities and developments for seismological long-term monitoring in underground and surface mining Astrid Gessert, Thomas Schicht, Ronny Koehler K-UTEC AG Salt Technologies.

Monitoring high frequency Earth rotation by ring laser: on modeling the local tilts Monika Tercjak (1), Marcin Rajner (1), Aleksander Brzeziński (2) (1) Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology, Warsaw, Poland, (2) Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology, Space Research Centre, Polish Academy of Sciences, Warsaw, Poland.

Ultra rapid oscillations in Earth rotation parameters derived from GNSS data Jolanta Nastula (1), Robert Weber (2), Aleksander Brzeziński (3), Alexander Gruber (2), Maciej Kalarus (1), Elke Umnig (2), Agata Wielgosz (1) Space Research Centre of the PAS , 00-716 Bartycka 18a, Warsaw,Poland, (2) TU-Vienna, Department for Geodesy and Geoinformation,Gußhausstraße 27-29/E120 1040 Vienna Austria, (3) Warsaw University of Technology, Department of Geodesy and Cartography, Warsaw , Poland.

An alternative model for short period ocean tidal variations of Earth rotation (SPOT) Jan Hagedoorn (1), Okky Jenie (2), Tobias Nilsson (2), Maria Karbon (2), Harald Schuh (2), Matthias Madzak (3), Wolfgang Bosch (4) (1) Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, (2) Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Department 1: Geodesy, (3) TU Vienna, Department of Geodesy and Geoinformation, (4) DGFI-TUM Technical University Munich.

S1 tidal contributions to changes in length-of-day: mean atmosphere-ocean excitation estimates and a possible modulation through ENSO. Michael Schindelegger (1), David Salstein (2), David Einspigel (3) (1) TU Wien, Austria, (2) Atmospheric and Environmental Research Inc., U.S.A., (3) Dublin Institute for Advanced Studies, Ireland.

Excitation of Free Core Nutation by geophysical fluids Xiaoming Cui, Heping Sun, Jianqiao Xu Institute of Geodesy and Geophysics. Chinese Academy of Sciences.

Evaluating Tide Models for Operational Prediction of EOPs Richard Gross Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA.

Contributions of Geodesy to Monitoring Natural Hazards and Global Change Harald Schuh Helmholtz-Zentrum Potsdam - Deutsches GeoForschungsZentrum GFZ.

Separating Surface Loading Deformation from Time-dependent Tectonic Deformation Jeff Freymueller (1), Yuning Fu (2), Tim Jensen (3) (1) Geophysical Institute, University of Alaska Fairbanks, (2) Bowling Green State University, Ohio, USA, (3) DTU-Space, Denmark.

Long Period Tide Variation from Satellite Laser Ranging (SLR) Minkang Cheng, Center for Space Research, University of Texas at Austin.

Surface deformation study of La Palma Island using C-Band radar imagery and GNSS data Jose Fernandez (1), Joaquin Escayo (2), Antonio G. Camacho (2), Juan F. Prieto (3), Jordi J. Mallorquí (4) (1) Institute of Geosciences, CSIC, (2) Institute of Geosciences, CSIC-UCM, Madrid, Spain, (3) ETSI Topografía, Geodesia y Cartografía, UPM, Madrid, Spain, (4) Remote Sensing Lab, Dept. Signal Theory and Communications, UPC, Barcelona, Spain.

Contemprorary State of the Elbrus Volcanic Center (the Northern Caucasus). Vadim Milyukov (1), Andrey Gorbatikov (2), Alexey Mironov (3), Andrey Myasnokov (3), Eugeny Rogozhin (2) (1) Lomonosov Moscow University, Sternberg Astronomical Institue, (2) Instutute of Physics of the Earth, Russian Academy of Sciences, (3) Lomonosov Moscow University, Sternberg Astronomical Institute.

What is behind Campi Flegrei inflations and deflations? Clues from 35 years of geodetic monitoring. Luca Crescentini, Antonella Amoruso University of Salerno.

Using relative gravity measurements between surface and underground stations to assess the hydrology of the soil layers in between Jaakko Mäkinen (1), Ivars Liepiņš (2), Viesturs Sprogis (2), Jānis Sakne (2), Kalvis Salmiņš (3), Jānis Kaminskis (4), Reinhard Falk (5), David Stizza (6) (1) Finnish Geospatial Research Institute FGI, Masala, Finland, (2) Department of Geodesy and Cartography, Latvian Geospatial Information Agency (LGIA), Riga, Latvia, (3) Institute of Astronomy, University of Latvia, Riga, Latvia, (4) Institute of Geodesy and Geoinformation, Riga Technical University, Riga, Latvia, (5) Division of Geodesy, Federal Agency for Cartography and Geodesy (BKG), Frankfurt am Main, Germany, (6) National Geospatial-Intelligence Agency (NGA), St. Louis, USA (at the time of the measurements)

The Djougou (Benin, West Africa) permanent superconducting gravity station: 2010 – 2016 Marta Calvo (1), Basile Hector (2), Jean Paul Boy (3), Jacques Hinderer (3), Severine Rosat (3), Frédéric Littel (3), Jean Daniel Bernard (3) (1) IGN-Spain, (2) University Joseph Fourier - Grenoble 1, (3) IPGS/EOST Strasbourg France.

Parallel observations with three superconducting gravity sensors 2014-2015 at Metsähovi Geodetic Fundamental Station Heikki Virtanen (1), Arttu Raja-Halli (2) (1) Finnish Geospatial Research Institute - FGI, NLS, (2) Finnish Geospatial Research Institute- FGI, NLS.

Hybrid gravity monitoring of a geothermal reservoir: a case study in northern Alsace, France Jacques Hinderer (1), Marta Calvo (2), Séverine Rosat (1), Yassine Abdelfettah (1), Gilbert Ferhat (1), Umberto Riccardi (3), Basile Hector (4), Jean-Daniel Bernard (5), Fréderic Littel (1) (1) IPGS, Strasbourg, France, (2) IGN, Madrid, Spain, (3) University of Napoli, Italy, (4) LTHE, Grenoble, France, (5) EOST, Strasbourg, France

Observation of groundwater-related subsidence and thermal effects in tilt and strain measurements Victor Volkov (1), Jan Mrlina (2), Mstislav Dubrov (3), Vaclav Polak (2) (1) Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences, (2) Institute of Geophysics of the Czech Academy of Sciences, (3) Fryazino Branch Kotel'nikov IRE RAS.

Surface displacement due to groundwater exploitation in the Lorca (Murcia, Spain) region. Tamara Abajo (1), Jose Fernandez (2), Joaquin Escayo (2), Francisco Luzon (3), Pablo J. Gonzalez (4) (1) Institute of Geosciences, CSIC, (2) Institute of Geosciences, CSIC-UCM, Madrid, Spain, (3) 2. Universidad de Almería, Almería, Spain, (4) School of Earth and Environment - University of Leeds, Leeds, UK.

Plate movement and karstic underground water flow in fifty years of ultra broad band tilt observations in the Karst- implications for GNSS Carla Braitenberg (1), Ildiko' Nagy (1), Barbara Grillo (1), David Zuliani (2) (1) University of Trieste, (2) OGS-CRS.

Long-term variations of the cGNSS data at the N-Adria plate edge and relation with deep fluid movements. Giuliana Rossi (1), Paolo Fabris (2), David Zuliani (2) (1) OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, (2) OGS (Istituto Nazionale di Oceanografia e di Geofisica sperimentale)

Cansiglio Plateau: Ten Years Of Geodetic Observations In A Seismic And Karstic Area In North-Eastern Italy Barbara Grillo (1), Carla Braitenberg (1), Ildikò Nagy (1), Roberto Devoti (2), David Zuliani (3), Paolo Fabris (3) (1) University of Trieste, Italy, (2) INGV, Roma, Italy, (3) INOGS, CRS, Udine, Italy.

Modeling river storage from radar altimetry and remote sensing: validation using GRACE and GPS Jean-Paul Boy EOST/IPGS.

Non-tidal tilt and strain signals observed at the Geodynamic Observatory Moxa, Thuringia Thomas Jahr Institute of Geosciences, Friedrich Schiller University Jena.

Recent development of gravimeter research in China Houze XU Institute of Geodesy and Geophysics, Chinese Academy of Science.

The Automated Burris Gravity Meter for single and continuous observation Gerhard Jentzsch (1), Richard Schulz (2), Adelheid Weise (3) (1) Professor, retired, (2) Anpplied Gravimetry Dr.Schulz, Rosengarten / Kreis Schwäbisch-Hall, (3) Institute of Geosciences, General Geophysics, Friedrich Schiller University Jena.

A new PC control software for ZLS-Burris gravity meters. H. Richard Schulz Applied Gravity Dr. Schulz.

Superconducting Gravimeter Calibration Using Earthquake Signal Shaocong Luo, Jianqiao Xu State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics Chinese Academy of Sciences, Wuhan, China, 430077.

Verification of transfer functions of co-located Superconducting Gravimeters in time and frequency domain Hartmut Wziontek Bundesamt für Kartographie und Geodäsie.

More thoughts on AG-SG calibrations, drift assessment, and the transfer function of the iGrav system David Crossley (1), Marta Calvo (2), Severine Rosat (3), Jacques Hinderer (3) (1) Saint Louis University, (2) IGN, Spain, (3) CNRS UMR7516, IPGS, Strasbourg.

PreAnalyseExtended: An graphical analysis program for the investigation of (geophysical) time series André Gebauer Ludwig-Maximilians-University.

Atmosphere and ocean loading and their interactions with the earthquake cycle Victor Volkov (1), Jan Mrlina (2), Mstislav Dubrov (3), Vladimir Smirnov (3), Sergey Golovachev (3), Vaclav Polak (2) (1) Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences, (2) Institute of Geophysics of the Czech Academy of Sciences, (3) Fryazino Branch Kotel'nikov IRE RAS

Study of the background free oscillations and polar tide based on EEMD Miaomiao Zhang Institute of Geodesy and Geophysics. Chinese Academy of Sciences.

Gravity Analysis Of The Kef Basin And Surrounding Regions, Northwest Tunisia Nesrine Frifita (1), Kevin Mickus (2), Fouad Zargouni (1) (1) University of Sciences of Tunisia., (2) Missouri State University USA.

GeoGuard: an innovative service for continuous geodetic monitoring by means of single-frequency GNSS receivers Daniele Sampietro, Stefano Caldera, Eugenio Realini Geomatics Research & Development s.r.l., Italy.

Technical details of the modern Michelson-Gale type interferometric fluid level tilt meter of the Finnish Geospatial Research Institute, NLS, Finland Hannu Ruotsalainen Finnish Geospatial Research Institute, NLS.

Posters:

Observation of the Earth liquid core resonance by extensometers Dóra Bán (1), Gyula Mentes (2), Márta Kis (3), András Koppán (3) (1) Geodetic and Geophysical Institute, RCAES, HAS, (2) Geodetic and Geophysical Institute, RCAES, HAS, Hungary, (3) Geological and Geophysical Institute of Hungary, Hungary.

Tidal effects in the Earth's crust Dmitry Loktev, Alexander Spivak INSTITUTE OF GEOSPHERE DYNAMICS RAS, Russia.

Storm surges in the German Bight: Are loading effects detectable by the SG recording at the Geodynamic Observatory Moxa in Thuringia? Thomas Jahr (1), Adelheid Weise (1), Sylvin Müller-Navarra (2) (1) Institute of Geosciences, Friedrich Schiller University Jena, (2) Bundesamt für Seeschifffahrt und Hydrographie (BSH), Hamburg.

Absolute and Continuous Gravity measurements for Glacial Isostatic Rebound Hans-Georg Scherneck (1), Andreas Engfeldt (2), Christian Freier (3), Jan M. Johansson (4), Martin Lidberg (2), Per-Anders Olsson (2), Manuel Schilling (5), Ludger Timmen (5), Hartmut Wziontek (6) (1) Chalmers University of Technology, (2) Lantmäteriet, Gävle, Sweden, (3) Humboldt University Berlin, Germany, (4) Chalmers University of Technology, Onsala Space Observatory, Onsala, Sweden, (5) Leibniz University Hannover, Germany, (6) Bundesamt für Kartograhie und Geodäsie, Leipzig, Germany.

Investigation of the non-stationary ocean loading with ARTOFS and STORMTIDE ocean models Eva Schroth (1), Thomas Forbriger (2), Malte Westerhaus (3), Malte Müller (4), Avichal Mehra (5), Liyan Liu (5) (1) Geophysical Institute, Karlsruhe Institute of Technology, Germany, (2) Black Forest Observatory, Karlsruhe Institute of Technology, Germany, (3) Geodetic Institute, Karlsruhe Institute of Technology, Germany, (4) Research and Development Department, Norwegian Meteorological Institute, Oslo, Norway, (5) NCEP/EMC/Marine Modeling and Analysis Branch, NOAA Center for Weather and Climate Prediction, College Park, USA.

Use of Earth tide analysis for study of unstable aquifer regime. Evgeny Vinogradov, Ella Gorbunova, Alina Besedina Institute of Geospheres Dynamics.

IGETS Analysis Centre Tahiti (ICET): Status of GGP data processing Jean-Pierre Barriot (1), Bernard Ducarme (2), Youri Verschelle (1) (1) Geodesy Observatory of Tahiti, (2) Catholic University of Louvain.

Installation and initial results from the iGrav-027 superconducting gravimeter at Borowa Gora Geodetic-Geophysical Observatory Przemyslaw Dykowski, Jan Krynski, Marcin Sekowski Institute of Geodesy and Cartography.

Checking the gPhone-054 spring gravimeter after several years under intense seismo-volcanic activity conditions Sergio Sainz-Maza Aparicio, Marta Calvo García-Maroto, Beatriz Córdoba Hita, Jorge Pereda De Pablo Instituto Geográfico Nacional (Spain).

Extensometric observation of Earth tides and local tectonic processes at the Vyhne station, Slovakia Ladislav Brimich (1), Martin Bednarik (2), Peter Vajda (2), Dóra Bán (3), Ildikó Eper-Pápa (3), Gyula Mentes (3) (1) Earth Science Instituteof the Slovak Academy of Sciences , (2) Earth Science Instituteof the Slovak Academy of Sciences, (3) Geodetic and Geophysical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences.

A search for a correlation between Earth-tides and seismicity in Colombia-first results Gloria A. Moncayo (1), Jorge I. Zuluaga (1), Gaspar Monsalve (2) (1) Solar, Earht and Planetary Physics Group, Computational Physics and Astrophysics Group, Instituto de Física-FCEN, Universidad de Antioquia, (2) Departamento de Geociencias y Medioambiente, Facultad de Minas, Universidad Nacional de Colombia.

Physical explanation of tsunami, a shallow water wave its generation and disastrous effect Daya SHANKER Indian Institute of Technology Roorkee, Department of Earthquake Engineering

Understanding Baltic Sea loading Maaria Nordman, Heikki Virtanen, Mirjam Bilker-Koivula, Sonja Lahtinen Finnish Geospatial Research Institute, NLS, Finland.

Comparative analysis of new hourly ERP series derived from GNSS data and the high resolution VLBI series based on complex demodulation Aleksander Brzezinski (1), Jolanta Nastula (2), Robert Weber (3), Sigrid Boehm (3) (1) Warsaw University of Technology, Department of Geodesy and Cartography, Poland, (2) Space Research Centre of the Polish Academy of Sciences, Warsaw, Poland, (3) TU-Vienna, Department for Geodesy and Geoinformation, Austria.

Searching for Free Core Nutation Effects on Two Long Baseline Tiltmeters Umberto Riccardi (1), Jean-Paul Boy (2), Severine Rosat (2), Jacques Hinderer (2), Walter Zürn (3), Frederick Boudin (4) (1) Dip. Scienze della Terra (DiSTAR) Università "Federico II" di Napoli, (2) Institut de Physique du Globe de Strasbourg, IPGS, CNRS and University of Strasbourg (EOST) Strasbourg, France, (3) Black Forest Observatory, Schiltach, Germany, (4) Ecole Normale Supérieure, Paris, France.

An image segmentation based algorithm for imaging of slow slip earthquakes Mohammad Hazrati Kashi (1), Noorbakhsh Mirzaei (1), Behzad Moshiri (2) (1) Institute of Geophysics, University of Tehran, Tehran, Iran., (2) School of Electrical and Computer Engineering, Control and Intelligent Processing Centre of Excellence, University of Tehran, Tehran, Iran.

Analysis of effects related to earthquakes and seismic oscillations appearing in rock deformation and gravimeter recordings Marta Kis (1), András Koppán (1), Gyula Mentes (2), Dora Bán (2), Márta Kiszely (2), Katalin Gribovszky (2), László Merényi (1) (1) Geological and Geophysical Institute of Hungary , (2) Geodetic and Geophysical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences

Geodetic monitoring in Nepal: preliminary results from Gorkha earthquake (25 April 2015) Federico Morsut, Tommaso Pivetta, Giorgio Poretti, Carla Braitenberg Department of Mathematic and Geosciences, University of Trieste.

Research of the Earth Tides and GGP in China Heping SUN Institute of Geodesy and Geophysics, Chinese Academy of Science.

What drives the normal faults at the northern piedmont of the West Kunlun range? Xiaodian Jiang Ocean University of China.

Late Cenozoic Geodynamic Evolution Of Simav Fault And Surroundings, Nw Turkey Erdem Gündoğdu, Süha Özden Çanakkale Onsekiz Mart University, Turkey.

A study on the investigation of crustal deformation along the Iznik-Gemlik segment of the estern Part of North Anatolian Fault System Onur Yilmaz (1), Cengiz Zabci (2), Kerem Halicioglu (1), Bulent Turgut (1), Semih Ergintav (1) (1) Bogazici University Earthquake Research Institute, (2) Istanbul Technical University Geological Engineering Department.

Analysis of the Inter-Diking Deformation Pattern at the Ongoing DabbahuManda Hararo (Afar), Ethiopia Rift Segment Using GPS and InSAR Technique Esuablew Adem Yibrie Arba Minch University.

Evolution Of Jurassic Carbonate Platform (Ne Algerian) El Hadj YOUCEF BRAHIM Batna 2 University.

Neotectonics and seismicity of Algiers region Sahra Aourari CGS.

Detection of free Earth oscillations using the GNSS VADASE algorithm: results for the 2011 Tohoku-Oki earthquake Giorgio Savastano, Mattia Crespi, Augusto Mazzoni Geodesy and Geomatics Division-DICEA-University of Rome La Sapienza.

Reconstruction Of Changing Kinematic Parameters Of Tectonic Blocks Based On The Results Of Tide Gauge Measurements (The Territory Of Northern Europe Is Taken As An Example) Solomiya Dosyn.

Kinematics, Seismotectonics and Seismic Potential of The Eastern Alps From GPS and Seismic Deformation Data Enrico Serpelloni (1), Gianfranco Vannucci (2), Letizia Anderlini (3), Richard A. Bennett (4) (1) Istituto Nazionale di Geofisica e Vulcanologia, (2) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, (3) Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti, (4) Department of Geosciences University of Arizona, USA.

Tidal effects in VLBI analyzed with a Kalman filter Maria Karbon, Benedikt Soja, Tobias Nilsson, Robert Heinkelmann, Kyriakos Balidakis, Harald Schuh .GFZ

A comparison of slow slip events at Etna and Kilauea volcanoes mario mattia (1), Emily Montgomery-Brown (2), Valentina Bruno (1), Danila Scandura (1) (1) INGV Catania, (2) USGS.

Analysis of the Inter-Diking Deformation Pattern at the Ongoing Dabbahu- Manda Hararo (Afar), Ethiopia Rift Segment Using GPS and InSAR Technique Esubalew Adem Yibrie Arba Minch University.

On potential contribution of harmonic inversion method to studying volcanic unrest or reactivation Peter Vajda (1), Vladimír Pohánka (2), Jaroslava Pánisová (2) (1) Earth Science Institute, Slovak Academy of Sciences, (2) Earth Science Institute, Slovak Academy of Sciences, Slovakia.

A portable superconducting gravimeter in a field enclosure: comparison to traditional observatory gravimeters Michal Mikolaj (1), Andreas Güntner (1), Marvin Reich (1), Stephan Schröder (1), Hartmut Wziontek (2) (1) Helmholtz-Zentrum Potsdam - Deutsches GeoForschungsZentrum GFZ, (2) Federal Agency for Cartography and Geodesy (BKG), Branch Office Leipzig, Germany.

Local hydrology and the hydrological gravity signal observed by three superconducting gravimeter sensors at Metsähovi Geodetic Fundamental Station, Finland Arttu Raja-Halli (1), Heikki Virtanen (1), Jaakko Mäkinen (1), Tero Hokkanen (2), Risto Mäkinen (3) (1) Finnish Geospatial Research Institute, (2) Aalto University, Finland, (3) Finnish Environmental Institute.

Space and time characterization of non-tectonic strain changes in the Southern Alps as revealed by the analysis of GPS time-series Enrico Serpelloni (1), Adriano Gualandi (2), Enrico Scoccimarro (3), Micol Todesco (3), Adriano Cavaliere (3), Maria Elina Belardinelli (4), Francesco Pintori (4) (1) Istituto Nazionale di Geofisica e Vulcanologia, (2) California Institute of Technology, USA, (3) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, (4) Università degli Studi di Bologna, Italy.

The improved hydrological gravity model for Moxa observatory, Germany Adelheid Weise, Thomas Jahr Institute of Geosciences, Friedrich Schiller University Jena.

The Scintrex CG5 used for superconducting gravimeter (SG) calibration Bruno Meurers University of Vienna.

Moving-mass calibration of LCR-G gravimeters- Determination of beam-position dependent transfer functions in the Mátyáshegy Gravity and Geodynamical Observatory, Budapest. Marta Kis (1), András Koppán (1), László Merényi (1), Gábor Papp (2), Judit Benedek (2), Eszter Szűcs (2), Bruno Meurers (3) (1) Geological and Geophysical Institute of Hungary , (2) Geodetic and Geophysical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, (3) University of Vienna, Department of Meteorology and Geophysics.

An update of the main parameters of the SG064 (Yebes Station) Beatriz Cordoba (1), Marta Calvo (2), Javier López-Ramasco (3), Sergio Sainz-Maza (2) (1) Univresidad Carlos III de Madrid, (2) Observatorio Geofísica Central (IGN), (3) Observatorio de Yebes (IGN).

Time-Variable Gravity Signals and Their Uncertainties: An Assessment of the Current State of Knowledge Theresa Damiani, U.S. National Geodetic Survey- NOAA.

Time dependent analysis of the 10S2 Quintet Herbert Weidner private.

Gravity Monitoring at the Conrad Observatory (CO) Bruno Meurers (1), Diethard Ruess (2), Christian Ullrich (2), Anton Nießner (2) (1) University of Vienna, (2) Federal Office of Metrology and Surveying , Vienna, Austria.

Evaluation of water budget changes in a terrority of Poland Jolanta Nastula (1), Monika Birylo (2), Rzepecka Zofia (2) (1) Space Research Center Polish Academy of Science in Warsaw, (2) University of Warmia and Mazury in Olsztyn.

Other presentations:

Dykowski P., Krynski J., (2015): Time dependent corrections to absolute gravity determinations in the establishment of modern gravity control, Geophysical Research Abstracts, Vol. 17, EGU2015-817, EGU General Assembly 2015, 12 – 17 April, Vienna, Austria.

Dykowski P., Kryński J., Sękowski M., (2016): Installation and initial results from the iGrav-027 superconducting gravimeter at Borowa Gora Geodetic-Geophysical Observatory, 18th Geodynamics and Earth Tide Symposium 2016, 5 – 9 June 2016, Trieste, Italy.

Dykowski P., Kryński J., Sękowski M., (2016): Instalacja i pierwsze wyniki rejestracji grawimetru nadprzewodnikowego iGrav-027 w Obserwatorium Geodezyjno-Geofizycznym Borowa Góra, Seminarium „Współczesne problemy osnów geodezyjnych w Polsce" Komitetu Geodezji PAN, 14–16 września 2016, Grybów.

Dykowski P., Olszak T., (2016): Lokalna kampania porównawcza grawimetrów absolutnych A10-020 i FG5-230 w Obserwatorium Geodezyjno-Geofizycznym Borowa Góra, Seminarium „Współczesne problemy osnów geodezyjnych w Polsce" Komitetu Geodezji PAN, 14–16 września 2016, Grybów.

Dykowski P., Kryński J., Sękowski M., (2016): Initial analysis the iGrav-027 superconducting gravimeter records at Borowa Gora Geodetic-Geophysical Observatory, 1st Joint Commission 2 and IGFS Meeting Symposium GGHS2016 "Gravity, Geoid and Height Systems 2016", 19–23 September 2016, Thessaloniki, Greece.

B. Córdoba, M. Calvo, J. López-Ramasco, S. Sainz-Maza. An update of the main parameters of the SG064 (Yebes Station). 18th International Symposium on Geodynamics and Earth Tides, Trieste, June 2016.

Hans-Georg Scherneck, Andreas Engfeldt, Christian Freier, Jan M. Johansson, Martin Lidberg, Per-Anders Olsson, Manuel Schilling, Ludger Timmen, Hartmut Wziontek and Achim Peters: Absolute and Continuous Gravity measurements for Glacial Isostatic Rebound. Poster at ETS 2016, Trieste.

Rüdiger Haas, Gunnar Elgered, Thomas Hobiger, Hans-Georg Scherneck: The Global Geodetic Observing System: Unifying Geodesy in General and Height Systems in Particular. Poster at EGU 2015 Session G2.1, Vienna.

Hans-Georg Scherneck, Andreas Engfeldt, Christian Freier, Per-Anders Olsson, Manuel Schilling, Ludger Timmen, Hartmut Wziontek: Direct reduction of Absolute Gravimeter drop data using a Superconducting Gravimeter and a Seismometer. Oral at NKG Working group for Geodynamics Metting, Tallinn, March 2016.

Bogusz J., Boy J.-P., Klos A. „The atmosphere- and hydrosphere-correlated signals in GPS observations". European Geosciences Union General Assembly 2015, Vienna, Austria, 12-17 April 2015. Session G2.2 "The International Terrestrial Reference Frame: Elaboration, Usage and Applications", poster presentation No. EGU2015-5316 in English.

Klos A., Bogusz J., Figurski M. „Determination of seasonals using wavelets in terms of noise parameters changeability". European Geosciences Union General Assembly 2015, Vienna, Austria, 12-17 April 2015. Session G2.2 "The International Terrestrial Reference Frame: Elaboration, Usage and Applications", poster presentation No. EGU2015-386 in English.

Gruszczynski M., Bogusz J., Klos A., Figurski M. "Studies on spatio-temporal filtering of GNSS-derived coordinates". European Geosciences Union General Assembly 2015, Vienna, Austria, 12-17 April 2015. Session G1.2 "Mathematical methods for the analysis of potential field data and geodetic time series", PICO presentation No. EGU2015-303 in English.

Gruszczynska M., Bogusz J., Klos A. "Non-parametric estimation of seasonal variations in GNSS-derived time series". European Geosciences Union General Assembly 2015, Vienna, Austria, 12-17 April 2015. Session G1.2 "Mathematical methods for the analysis of potential field data and geodetic time series", PICO presentation No. EGU2015-649 in English.

Bogusz J., Rosat S., Klos A., Gruszczynska M. „Correlation at noise level between GPS and gravity data", 26th International Union of Geodesy and Geophysics, June 22-July 2 2015, Prague, Czech Republic, Session G04c "Earth Rotation and Geodynamics", oral presentation in English.

Klos A., Bos M. S., Bogusz J., Boy J.-P. "On the time-changeable signals in GPS time series", 26th International Union of Geodesy and Geophysics, June 22-July 2 2015, Prague, Czech Republic, Session G01p "Reference Frames", poster presentation in English.

Bogusz J., Klos A., Boy J.-B. "Time domain cross-correlation analysis for investigation of atmospheric and hydrospheric signals in GPS time series". 16th Czech-Polish Workshop ON RECENT GEODYNAMICS OF THE SUDETY MTS. AND ADJACENT AREAS, Srebrna Góra, Poland, November 5 - 7, 2015, oral presentation in English.

Kłos A., Bogusz J. „Acceleration of GNSS stations in noise analysis". 16th Czech-Polish Workshop ON RECENT GEODYNAMICS OF THE SUDETY MTS. AND ADJACENT AREAS, Srebrna Góra, Poland, November 5 - 7, 2015, oral presentation in English.

Gruszczyński M., Bogusz J., Kłos A. „Orthogonal transformation in extracting of common mode errors from continuous GPS networks". 16th Czech-Polish Workshop ON RECENT GEODYNAMICS OF THE SUDETY MTS. AND ADJACENT AREAS, Srebrna Góra, Poland, November 5 - 7, 2015, oral presentation in English.

Gruszczyńska M., Bogusz J., Kłos A. „Application of singular spectrum analysis for determination of the GPS time series seasonal components". 16th Czech-Polish Workshop ON RECENT GEODYNAMICS OF THE SUDETY MTS. AND ADJACENT AREAS, Srebrna Góra, Poland, November 5 - 7, 2015, oral presentation in English.

Klos A., Olivares G., Teferle F.N., Bogusz J., Hunegnaw A.: "Total impact of periodic terms and coloured noise on velocity estimates". GNSS Futures, IGS Workshop 8 - 12 February 2016, Sydney, NSW, Australia, session "Reference Frames", poster presentation in English.

Gruszczyńska M., Bogusz J.: „Implementation of Singular Spectrum Analysis to study the variability of the GPS time series". 5th International Conference for Young Researchers — Multidirectional Research in Agriculture, Forestry and Technology, 16-17 April 2016, Krakow, oral presentation in English.

Gruszczyński M., Bogusz J.: „Investigation of correlated signals in GNSS permanent networks". 5th International Conference for Young Researchers — Multidirectional Research in Agriculture, Forestry and Technology, 16-17 April 2016, Krakow, oral presentation in English.

Klos A., Olivares G., Teferle F.N., Hunegnaw A., Bogusz J.: "The combined effect of periodic signals and noise on the dilution of precision of GNSS station velocity uncertainties". European Geosciences Union General Assembly 2016, Vienna, Austria, 17-22 April 2016. Session G2.2 "The International Terrestrial Reference Frame: Elaboration, Usage and Applications". Poster presentation No. EGU2016-374 in English.

Gruszczynski M., Klos A., Bogusz J.: „The impact of seasonal signals on spatio-temporal filtering". European Geosciences Union General Assembly 2016, Vienna, Austria, 17-22 April 2016. Session G2.2 "The International Terrestrial Reference Frame: Elaboration, Usage and Applications". Poster presentation No. EGU2016-468 in English.

Gruszczynska M., Klos A., Bos M.S., Bogusz J.: „Investigation on the coloured noise in GPS-derived position with time-varying seasonal signals". European Geosciences Union General Assembly 2016, Vienna, Austria, 17-22 April 2016. Session G2.2 "The International Terrestrial Reference Frame: Elaboration, Usage and Applications". Poster presentation No. EGU2016-471 in English.

Bogusz J., Klos A., Bos M.S., Hunegnaw A., Teferle F.N.: "On the Impact of a Quadratic Acceleration Term in the Analysis of Position Time Series". European Geosciences Union General Assembly 2016, Vienna, Austria, 17-22 April 2016. Session G2.2 "The International Terrestrial Reference Frame: Elaboration, Usage and Applications". Poster presentation No. EGU2016-16816 in English.

Klos A., Bogusz J.,: "Impact of Seasonal Changes on Noise and Velocity Estimation". European Geosciences Union General Assembly 2016, Vienna, Austria, 17-22 April 2016. Session G1.2 "Mathematical methods for the analysis of potential field data and geodetic time series". Poster presentation No. EGU2016-9257 in English.

Klos A., Hunegnaw A., Teferle F.N., Ahmed F., Bogusz J.: "Assessment of seasonal signals and noise in ZTD and IWV time series". COST ES1206 sub-WG Workshop on Data Homogenisation, Brussels, 26-27 April 2016, oral presentation in English.

Hunegnaw A., Klos A., Hansen D., Teferle F.N., Abraha K., Bingley R., Bogusz J.: "A New Vertical Land Movements Data Set from a Reprocessing of GNSS at Tide Gauge Stations". IAG/CPGPS Joint 1st International Conference on GNSS+ (ICG+2016) - Advances, Opportunities and Challenges, Shanghai, China, oral presentation in English.

Klos A., Bos M.S., Fernandes R., Bogusz J.: "Power-law properties of post-seismic decay: Tohoku 2011 case study". 18th General Assembly of WEGENER, WEGENER 2016: Understanding Earth deformation at plate boundaries, oral presentation in English.

Gruszczynski M., Klos A., Bogusz J.: "Filtration of incomplete GNSS time series with probabilistic PCA". 17th Czech-Polish Workshop on Recent Geodynamics of the Sudeten and the Adjacent Areas, Ramzová, Czech Republic, October 20-22, 2016, oral presentation in English.

Gruszczynska M., Rosat S., Klos A., Bogusz J.: "Application of Multichannel Singular Spectrum Analysis to GNSS position time series". 17th Czech-Polish Workshop on Recent Geodynamics of the Sudeten and the Adjacent Areas, Ramzová, Czech Republic, October 20-22, 2016, oral presentation in English.

Bogusz J., Klos A., Bos M.S.: "Trajectory models of GNSS permanent stations with power-law process". 17th Czech-Polish Workshop on Recent Geodynamics of the Sudeten and the Adjacent Areas, Ramzová, Czech Republic, October 20-22, 2016, oral presentation in English.

Klos A., Bos M.S., Fernandes R., Bogusz J.: "Multi-trend approach to model the post-seismic deformation with temporal correlations". 17th Czech-Polish Workshop on Recent Geodynamics of the Sudeten and the Adjacent Areas, Ramzová, Czech Republic, October 20-22, 2016, oral presentation in English.

Klos A., Bos M.S., Fernandes R., Bogusz J.: “A new approach to post-seismic decay with temporal correlation”. American Geophysical Union Fall Meeting 2016, San Francisco, USA, 12-16 December 2016, Session G021: Separating and explaining multiple signals in geodetic data, oral presentation in English.

Gruszczynska M., Rosat S., Klos A., Bogusz J.: „Application of Multichannel Singular Spectrum Analysis to gravity time series”. American Geophysical Union Fall Meeting 2016, San Francisco, USA, 12-16 December 2016, Session G021: Separating and explaining multiple signals in geodetic data, poster presentation in English.

Gruszczynska M., Rosat S., Klos A., Bogusz J.: “Study on common seasonal signals in GPS time series and environmental loadings using Multichannel Singular Spectrum Analysis”, European Geosciences Union General Asembly 2017, Vienna, Austria, 23-28.04.2017, session 1.2 Mathematical methods for the analysis of potential field data and geodetic time series, PICO presentation in English.

Sub-commission 3.2: Crustal Deformation

Chair: Zheng-Kang Shen (China)
Vice-Chair: Banrjee (Singapore)

Summary of the Sub-commission's activities during the period 2015-2017

Meetings and Special Sessions:

AOGS 2016, 31 July - 5 August, 2016, Beijing, China:
SC3.2 hosted a special session, "Geodetic Observations, Modeling Of Earthquake Cycle Deformation, And Tectonics" (SE13), in the Asia Oceania Geoscience Meeting on August 1. 29 papers were presented, among which 18 were oral and 11 were poster papers. The number of participants of our session exceeded 100.

Peer-reviewed publications:

Tian, Y., and Z-K. Shen, Extracting the regional common-mode component of GPS station position time series from dense continuous network, J. Geophys. Res., in press, 2016.

Tao, W., T. Masterlark, Z.-K. Shen, and E. Ronchin, Impoundment of the Zipingpu reservoir and triggering of the 2008 Mw 7.9 Wenchuan earthquake, China, J. Geophys. Res., 120, 7033-7047, 2015.

Ge, W.-P., P. Molnar, Z.-K. Shen, and Q. Li, Present-day crustal thinning in the southern and northern Tibetan Plateau revealed by GPS measurements, Geophys. Res. Lett., 42, 5227-5235, doi:10.1002/2015GL064347, 2015.

Shen, Z.-K., M. Wang, Y. Zeng, and F. Wang, Strain determination using spatially discrete geodetic data, Bull. Seismol. Soc. Am., 105(4), 2117–2127, doi: 10.1785/0120140247, 2015.

Wang, F., M. Wang, Y. Wang, and Z.-K. Shen, Earthquake potential of the Sichuan-Yunnan region, western China, J. Asian Ear. Sci., 107, 232-243, doi:10.1016/j.jseaes.2015.04.041, 2015.

Sub-commission 3.3: Earth Rotation and Geophysical Fluids

Chair: *Jianli Chen (USA)*
Vice-Chair: *Michael Schindelegger (Austria)*

Overview

Mass transport in the atmosphere-hydrosphere-mantle-core system, or the 'global geophysical fluids', causes observable geodynamic effects on broad time scales. Although relatively small, these global geodynamic effects have been measured by space geodetic techniques to increasing, unprecedented accuracy, opening up important new avenues of research that will lead to a better understanding of global mass transport processes and of the Earth's dynamic response. Angular momenta and the related torques, gravitational field coefficients, and geocenter shifts for all geophysical fluids are the relevant quantities. They are observed using global-scale measurements and are studied theoretically as well as by applying state-of-the-art models; some of these models are already con-strained by such geodetic measurements.

The objective of the SC3.3 is to serve the scientific community by supporting research and data analysis in areas related to variations in Earth rotation, gravitational field and geocenter, caused by mass re-distribution within and mass exchange among the Earth's fluid sub-systems, i.e., the atmosphere, ocean, continental hydrosphere, cryosphere, mantle, and core along with geophysical processes associated with ocean tides and the hydrological cycle. SC 3.3 follows the program of activities defined by Com-mission 3. In order to promote the exchange of ideas and results as well as of analysis and modeling strategies, sessions at international conferences and topical workshops have been organized. In addition, SC 3.3 interacts with the sister organizations and services, particularly with the IERS Global Geophysical Fluids Centre and its operational component with four Special Bureaus (atmosphere, hydrology, ocean, combination) and its non-operational component for core, mantle, and tides.

Summary of the Sub-commission's activities during the period 2015-2017

Meetings and Special Sessions:

On behalf of SC3.3, a session on "Earth Rotation and Reference Frame" has been organized at the 2016 Asia Oceania Geosciences Society (AOGS) annual conference held in Beijing China in August 2016, with Dr. Jianli Chen (USA, Chair of SC3.3) as the main convener, Dr. Richard Gross (USA) and Dr. Michael Schindelegger (Austria, Vice-Chair of SC3.3) as co-conveners. This appeared to be the first ever AOGS session focusing on Earth rotation during the short 13-years history of AOGS (the first AOGS was held in 2014). The main consideration for proposing the session is to help promote related research in the Asia and Oceania regions, and broaden the solid Earth component at the AOGS.

For the same consideration, we have proposed another similar session (SE09: Earth Rotation and Reference Frame) at the upcoming 2017 AOGS annual conference to be held in Singapore. While the session sizes are relatively small, with ~ one dozen abstracts submitted in both 2016 and 2017, this is a good start in the AOGS community.

Peer-reviewed publications:

Adhikari, S. and Ivins, E. R., 2016. Climate-driven polar motion: 2003-2015. Science Advances, 2:e1501693, doi:10.1126/sciadv.1501693.

Chao, B.F. Dynamics of axial torsional libration under the mantle-inner core gravitational interaction. Journal of Geophysical Research: Solid Earth, 122, 1, 560-571 (2017) (10.1002/2016JB013515)

Chao, B.F., Hsieh, Y. The Earth's free core nutation: Formulation of dynamics and estimation of eigenperiod from the very-long-baseline interferometry data. Earth and Planetary Science Letters, 432, 483-492 (2015) (10.1016/j.epsl.2015.10.010)

Chen, J.L., C.R. Wilson, J.C. Ries, Broad-band assessment of degree-2 gravitational changes from GRACE and other estimates, 2002-2015, *J. Geophys. Res. Solid Earth, 121*, 2112-2128, doi:10.1029/ 2015JB012708, 2016.

Ding, H., Shen, W. Search for the 531-day-period wobble signal in the polar motion based on EEMD. Nonlinear Processes in Geophysics, 22, 4, 473-484 (2015) (10.5194/npg-22-473-2015)

Göttl, F., Schmidt, M., Seitz, F., and Bloßfeld, M., 2015. Separation of atmospheric, oceanic and hydrological polar motion excitation mechanisms based on a combination of geometric and gravimetric space observations. *Journal of Geodesy*, 89:377–390, doi:10.1007/s00190-014-0782-0.

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Sub-commission 3.4: Cryospheric Deformation

Chair: *Shfaqat Abbas Khan (Denmark)*
Vice Chair: *Matt King (Australia)*

Summary of the Sub-commission's activities during the period 2015-2017

During 2015-2017 we have organized three sessions at the AGU fall meetings.

- AGU Fall Meeting 2015:
  - Session G33A: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability
- AGU Fall Meeting 2016:
  - Session G33B: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability
  - Session G11B: Separating and Explaining Multiple Signals in Geodetic Data
- We expect 1-2 sessions at AGU Fall Meeting 2017.

- Workshop in 2015 on Glacial Isostatic Adjustment and Elastic Deformation at Geophysical Institute, University of Alaska Fairbanks, USA.
  - Session 1. Relative Sea Level & Ice History.
  - Session 2. GIA since the Little Ice Age.
  - Session 3. Solid Earth response to "rapid" stress change.
  - Session 4. Recent Changes in Greenland's Ice Sheet.
  - Session 3. Geodetic measurement of viscoelastic deformation.

In 2017 the following workshop on Glacial Isostatic Adjustment and Elastic Deformation is planned and will be held in Reykjavik, Iceland during September 5-7, 2017.

- Title: "Workshop on Glacial Isostatic Adjustment and Elastic Deformation", Website: http://www.polar.dtu.dk/english/workshop-on-glacial-isostatic-adjustment-and-elastic-deformation-2017
  - Session 1. Observations of present-day changes in glaciers, ice caps and ice sheets and the associated Earth deformation.
  - Session 2. Measurement and Models of Elastic Rebound.
  - Session 3. Glacial isostatic adjustment on a heterogeneous Earth.
  - Session 4. Reconciling models and observations of GIA.
- We expect 100-150 participants.

Sub-commission 3.5: Tectonics and Earthquake Geodesy

Chair: *Haluk Ozener (Turkey)*

Overview

SC 3.5, (WEGENER group), aims to encourage cooperation between all geoscientists studying the Eurasian/African/Arabian plate boundary deformation zone with a focus on mitigating earthquake, tsunami, and volcanic hazards. Towards these ends, it organizes periodic workshops and meetings with special emphasis on integrating the broadest range of Earth observations, sharing analysis and modelling approaches, and promoting the use of standard procedures for geodetic data acquisition, quality evaluation, and processing. WEGENER organizes dedicated meetings, arranges special sessions in other international meetings, organizes special issues in peer-reviewed journals, and takes initiative to promote and facilitate open access to geodetic databases.

Summary of the Sub-commission's activities during the period 2015-2017

Meetings:

18th General Assembly of WEGENER

WEGENER organizes bi-annual conferences to serve as high-level international forums in which scientists from all over the world share results, and strengthen collaborations between countries in the greater Mediterranean region and beyond.
In this respect, the 18th General Assembly of WEGENER was held in Ponta Delgada, Azores, Portugal between 12 and 15 September 2016. Around 100 scientists from all around the world attended the meeting. A total of 46 oral and 9 poster presentations were made under the theme "Understanding Earth deformation at plate boundaries".
The meeting was conducted on five different sessions as follows:

1. "*Current Plate Motions, Inter and Intraplate Deformation with a Focus on Europe, the Mediterranean, Africa and Middle East*",
2. "*Continental Faulting and Earthquake Cycle*",
3. "*Elastic surface displacements, surface and satellite gravity observations, global and regional sea-level change*",
4. "*Data and infrastructures, Instrumentation & Co-location for continuous monitoring of the changing Earth"* and
5. "*Transient signals in Geodetic Time Series: detection and modeling*".

Information and experience in the use of geodetic methods for geodynamic studies such as GPS, InSAR, and terrestrial methods were shared in a wide range of applications from large scale studies such as the studies of continental boundaries to small scale studies such as local observations focusing on single faults. Invited talks enabled the attendees to keep up with the latest research of world leading scientists and the latest technological developments in instrumentation, analysis, modeling, and interpretation. The meeting was carried out in a workshop form, including extensive and inclusive discussions of the results and the methods presented within each session.

Detailed information about the 18th General Assembly of WEGENER can be found at: http://wegener.segal.ubi.pt/

WEGENER Session in 2015 EGU (12-17 April 2015-Vienna)

A session titled “Monitoring and modelling of geodynamics and crustal deformation: progress during 34 years of the WEGENER initiative” was organized and convened by Haluk Ozener, Susanna Zerbini and Mustapha Meghraoui in the EGU General Assembly 2015. Presentations emphasized multidisciplinary studies of Earth deformation using geodetic techniques (GPS, InSAR, LiDAR, space/air/terrestrial gravity, ground-based geodetic observations), complementary tectonic and geophysical observations, and modeling approaches focusing on the European-Mediterranean and Northern African regions. In total, 21 studies were presented in two successive sessions. More detailed information can be found at:
http://meetingorganizer. copernicus.org/EGU2015/session/18028

WEGENER Session in 2016 EGU (17-22 April 2016-Vienna)

During the European Geosciences Union (EGU) General Assembly 2016, a session titled “Monitoring and modelling of geodynamics and crustal deformation: progress during 35 years of the WEGENER initiative” was convened by Dr. Haluk Ozener, Dr. Susanna Zerbini and Dr. Mustapha Meghraoui. Six oral talk and twenty five posters were presented in two successive sessions. More detailed information can be found at: http://meetingorganizer.copernicus.org/EGU2016/session/20161

WEGENER Session in 2017 EGU (23-28 April 2017-Vienna)

On behalf of SC3.5, a session on “Monitoring and modelling of geodynamics and crustal deformation: progress during 36 years of the WEGENER initiative” has been organized at the EGU General Assembly 2017, with Dr. Haluk Ozener (Chair of SC3.5) as the main convener, Dr. Susanna Zerbini, Dr. Matthias Becker and Dr. Sara Bruni as co-conveners. Six oral talk and seventeen posters were presented in two successive sessions. More detailed information can be found at: http://meetingorganizer.copernicus.org/EGU2017/session/22877

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Commission 3 Joint Study Group 3.1: Intercomparison of Gravity and Height Changes

Chair: *Séverine Rosat (France)*

Members

- *José Arnoso (Spain)*
- *Valentina Barletta (Denmark)*
- *Janusz Bogusz (Poland)*
- *Andrea Bordoni (Denmark)*
- *Yoichi Fukuda (Japan)*
- *Anthony Mémin (France)*
- *Laurent Métivier (France)*
- *Yves Rogister (France)*
- *Holger Steffen (Sweden)*

Webpage

A website was set up to coordinate and document the group activities:
http://iag-jsg.u-strasbg.fr/
It includes the terms of references, objectives, and contact information of the study group members, reports of the study group activities and a complete list of publications originating from the years 2015-2017.

Activities during the period 2015-2017

- Study of the noise characteristics of GNSS height change and Superconducting Gravimeter gravity change measurements: a paper (Bogusz et al.) is in revision.
- Influence of rheology on the gravity-to-height ratio: a first study has been performed for a homogeneous compressible Earth model with a Maxwell or a Burgers rheology and published in Ziegler et al. (2016). For the harmonic degree-2, the ratio between the gravity variation and the vertical surface displacement due to surface loading is almost constant and equal to -0.26 µGal/mm in the elastic domain, up to the relaxation time of the rheological model. In the viscoelastic domain, above 10,000 years, the gravity-to-height ratio tends to -0.08 µGal/mm. In between, the transition is smooth.
- Estimate of the geocenter motion by combining GNSS and gravity measurements: a first work has been published by Rogister et al. (2016) to show that time-varying surface gravity are independent of the terrestrial reference frame. In this study, a preliminary combination of GRACE solutions with surface gravity records has been used to correct hydrological effects that mask the degree-one geocenter motion. Indeed the separation of degree-one signal from other spectral content is impossible with a discrete network at the Earth's surface since spherical harmonics are not orthogonal any more. A synthetic simulation using atmospheric and hydrological surface loading predictions together with GRACE solution is in progress within a CNES-funded project.
- Organization of the "International workshop on the inter-comparison of space and ground gravity and geometric spatial measurements", to be held on 16-18 Oct 2017 in Strasbourg (France). The workshop website is at https://geodesy.sciencesconf.org/. It is funded by the University of Strasbourg, Institut de Physique du Globe de Strasbourg and the CNFGG (Comité National Français de Géodésie et de Géophysique – French contributor to the IUGG).

Relevant peer-reviewed publications by Joint Study Group members 2015-2017

Gruszczynska M., Klos A., Rosat S., Bogusz J. (2017). Deriving common seasonal signals in GPS position time series by using Multichannel Singular Spectrum Analysis, Acta Geodyn. Geomater., vol. 14, No. 3(187), 267-278, DOI: 10.13168/AGG.2017.0010

Métivier, L., Caron, L., Greff-Lefftz, M., Pajot-Métivier, G., Fleitout, L., Rouby, H. (2016). Evidence for postglacial signatures in gravity gradients: A clue in lower mantle viscosity, Earth Planet. Sc. Lett., 452, 146-156.

Rogister, Y., Mémin, A., Rosat, S., Hinderer, J. and M. Calvo (2016). Constraints provided by ground gravity observations on geocentre motions, Geophys. J. Int., 206, 1431-1439, doi:10.1093/gji/ggw220

Wang, H., Xiang, L., Jia, L., Wu, P., Steffen, H., Jiang, L., and Shen, Q. (2015). Water storage changes in North America retrieved from GRACE gravity and GPS data. Geodesy and Geodynamics 6(4), 267-273, doi:10.1016/j.geog.2015.07.002.

Ziegler Y., Rogister Y., Hinderer J., Rosat, S. (2016). Chandler Wobble and frequency dependency of the ratio between gravity variation and vertical displacement for a simple Earth model with Maxwell or Burgers rheologies, Int. Assoc. of Geod. Symposia, Prague (Czech Rep.), Springer Berlin Heidelberg, doi:10.10

Commission 3 Joint Working Group 3.1: Theory of Earth Rotation and Validation (joint with IAU)

Chair: *José Ferrándiz (Spain)*
Vice Chair: *Richard Gross (USA)*

Members
According to the Commission 3 bylaws for the current term, the JWG is structured in three sub-WGs that operate in coordination:

1. Precession/Nutation

Chair: *Juan Getino (Spain)*
Co-Chair: *Alberto Escapa (Spain)*

Members: *N Capitaine (France), V Dehant (Belgium), CL Huang (China), J Vondrak (Czech Republic)*
Correspondents: S Dickman (USA), M Folgueira (Spain), A Gusev (Russia), T Herring (USA), G Kaplan (USA), J Mueller (Germany), H Schuh (Germany), J Souchay (France), S Urban (USA), V Zharov (Russia)

2. Polar Motion and UT1

Chair: *Aleksander Brzezinski (Poland)*

Members: *C Bizouard, BF Chao (Taipei), J Nastula (Poland), D Salstein (USA), F Seitz (Germany)*
Correspondents: W Chen (China), CL Huang (China), W Kosek (Poland), J Ray (USA), C Ron (Czech Republic), H Schuh (Germany), W Shen (China), D Thaller (Germany), QJ Wang (China), YH Zhou (China)

3. Numerical Solutions and Validation

Chair: *Robert Heinkelmann (Germany)*

Members: *W Chen (China), D Gambis (France), B Luzum (USA), Z Malkin (Russia), M Schindelegger (Austria)*
Correspondents: BF Chao (Taipei), V Dehant (Belgium), E Gerlach (Germany), CL Huang (China), JF Navarro (Spain), ME Sansaturio (Spain), H Schuh (Germany), F Seitz (Germany), M Thomas (Germany), QJ Wang (China)

Activities and publications during the period 2015-2017

Web site:

A website was set up to facilitate and document the group activities: http://web.ua.es/en/wgterv>. Reports of many of the meetings and copies of the presentations can be found on-line on. Reports of the JWG meetings, including progress reports of the three SWGs and the whole JWG, minutes of sessions and discussions when relevant, and material provided by members, can be found on-line on it. The web site contains also a link to the documents elaborated by the previous Commission 3 WG on Theory of Earth rotation, joint with IAU.

Meetings:

The JWG has organized splinter meetings and special sessions at conferences of particular relevance for its activity, open to the interested conference attendants. The following took place so far:

- Open splinter meeting at the EGU General Assembly 2016. Vienna, April 20, 2016 (SMP14, http://meetingorganizer.copernicus.org/EGU2016/session/22333)
- Open splinter meeting at the EGU General Assembly 2017. Vienna, April 24, 2017 (SMP85, http://meetingorganizer.copernicus.org/EGU2017/session/26247)
- Session 8 at GAGER 2016, entitled: Open meeting on "Current situation, progress, and challenges of the theory of Earth rotation from the JWG TERV perspective". Reports of progress of all the SWGs were presented in this session, and afterwards there was a long and fruitful discussion whose minutes are available at: https://web.ua.es/es/wgterv/jwg-terv-meetings/open-meeting-at-gager2016.html

Currently, the entire JWG chairing people are strongly involved in the organization of a forthcoming meeting:

"Journées 2017, des Systèmes de Référence et de la Rotation Terrestre"
25 to 27 September 2017, Alicante, Spain. (https://web.ua.es/journees2017/index.html).
It is devoted to the study of the space-time celestial and terrestrial reference systems and their evolution with time, with the emphasis on the rotation of the Earth. This meeting intends to be a forum of advanced discussion that continue the successful series of *Journées "Systèmes de Référence spatio-temporels",* also supported by IAU and IAG, whose concluding edition was held in 2014. Its sub-title is ***"Furthering our knowledge of Earth Rotation"*** and addresses the challenges brought to Earth rotation by the accuracy requirements of GGOS, with a scope ranging from concepts and theoretical solutions to observational techniques and data analysis. Most of the Journées 2017 SOC is affiliated to the JWG as member or correspondent.

Research progresses:

Next we outline briefly some of the main the facts and ideas underneath the research activity of the members and correspondents and present a short selection of their contributions as well. More details are available on the reports of the JWG and its three SWGs available on-line on the JWG web site.

The space geodetic techniques have improved to the point that the theoretical results are judged less accurate than the observational results and therefore the current theory of the Earth's rotation is no longer adequate. This theory suffers from inconsistencies and at least several components of it require better modelling.

In precession-nutation theory, the consistency between the official theories IAU2000 and IAU2006 has been revised and new corrections derived to improve their mutual consistency and complement the corrections already recommended in the IERS Conventions (2010). The precession model has been re-assessed as well as a set of the minor contributions to the longitude rate. The current results suggest that the value of the Earth's dynamical ellipticity, an important geodetic parameter in Earth rotation, is affected at a level that produces non-negligible "indirect" effects on nutations. Other contributions to nutations are under study, either of new physical origin or better approximations to previous solutions. Although these corrections are small, several terms are above the GGOS accuracy threshold particularized to the Earth rotation parameters (EOP).

The free core nutation (FCN), which is of particular relevance for improving the prediction of the celestial intermediate pole offsets (CPO), has been addressed from different perspectives, ranging from new theoretical approaches to the development of new empirical models. Besides, new determinations of a set of nutation amplitudes from existing or newly developed VLBI solutions have been carried out recently. Those amplitude are classically used to fit theories, but for the consistency and accuracy sake's it has to be considered that the reference frames used in data analysis are not identical to the reference systems or frames used for theory; this topic is being investigated.

The polar motion theory has been extended to a triaxial Earth with a fluid core; while these effects are small they are systematic, not random, and should therefore be included in an updated theory according to the discussions inside the JWG. Other improvements of the Earth's interior modelling have been made or are in progress. As a first result of them, the theoretical estimates of the free periods, particularly Chandler's, have been brought closer to their observed values.

The knowledge of the geophysical excitation of the polar motion and UT1 at the different bands has also advanced inside the JWG, although more insight is needed, e.g. at high frequencies or regarding the excitation balance of the annual wobble. The quality and consistency of the implied geophysical models seems to be an unavoidable limiting factor. Among the validation issues we note the research performed on the consistency and actual accuracy of the EOP estimates and their relationship to the celestial and terrestrial frames and processing strategies used for their determination.

Selection of peer-reviewed publications co-authored by JWG members:

The following is an incomplete list of publications on the topic of the working group resulting from the activity of its members and correspondents.

Baenas, T., Escapa, A., Ferrándiz, J.M., Getino, J. Application of first-order canonical perturbation method with dissipative Hori-like kernel. International Journal of Non-Linear Mechanics, 90, 11-20 (2017) (10.1016/j.ijnonlinmec.2016.12.017)

Baenas, T., Ferrándiz, J.M., Escapa, A., Getino, J., Navarro, J.F. Contributions of the Elasticity to the Precession of a Two-layer Earth Model. The Astronomical Journal, 153, 2, id. 79, 11 pp. (2017) (10.3847/1538-3881/153/2/79)

Belda, S., Heinkelmann, R., Ferrándiz, J.M., Nilsson, T., Schuh, H. On the consistency of the current conventional EOP series and the celestial and terrestrial reference frames. Journal of Geodesy, 91, 2, 135-149 (2017) (10.1007/s00190-016-0944-3)

Belda, S., Ferrándiz, J.M., Heinkelmann, R., Nilsson, T., Schuh, H. Testing a new Free Core Nutation empirical model. Journal of Geodynamics, 94, 59-67 (2016) (10.1016/j.jog.2016.02.002)

Chao, B.F. Dynamics of axial torsional libration under the mantle-inner core gravitational interaction. Journal of Geophysical Research: Solid Earth, 122, 1, 560-571 (2017) (10.1002/2016JB013515)

Chao, B.F., Hsieh, Y. The Earth's free core nutation: Formulation of dynamics and estimation of eigenperiod from the very-long-baseline interferometry data. Earth and Planetary Science Letters, 432, 483-492 (2015) (10.1016/j.epsl.2015.10.010)

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Ding, H., Shen, W. Search for the 531-day-period wobble signal in the polar motion based on EEMD. Nonlinear Processes in Geophysics, 22, 4, 473-484 (2015) (10.5194/npg-22-473-2015)

Escapa, A., Ferrándiz, J.M., Baenas, T., Getino, J., Navarro, J., Belda-Palazón, S. Consistency Problems in the Improvement of the IAU Precession-Nutation Theories: Effects of the Dynamical Ellipticity Differences. Pure and Applied Geophysics, 173, 3, 861-870 (2017) (10.1007/s00024-015-1154-2)

Escapa, A., Getino, J, Ferrándiz J.M., Baenas T., Dynamical adjustments in IAU 2000A nutation series arising from IAU 2006 precession. Astron. & Astroph (accepted 2017).

Ferrándiz, J.M., Navarro, J.F., Escapa, A., Getino, J. Earth's Rotation: A Challenging Problem in Mathematics and Physics. Pure and Applied Geophysics, 172, 1, 57-74 (2015) (10.1007/s00024-014-0879-7)

Gattano C., Lambert S., Bizouard C. Observation of the Earth's nutation by the VLBI: how accurate is the geophysical signal, J. Geod. (2016) (10.1007/s00190-016-0940-7)

Glaser, S., König, R., Ampatzidis, D., Nilsson, T., Heinkelmann, R., Flechtner, F., Schuh, H. A Global Terrestrial Reference Frame from simulated VLBI and SLR data in view of GGOS. Journal of Geodesy, Online First (2017) (10.1007/s00190-017-1021-2)

Göttl, F., Schmidt, M., Seitz, F., Bloßfeld, M. Separation of atmospheric, oceanic and hydrological polar motion excitation mechanisms based on a combination of geometric and gravimetric space observations. Journal of Geodesy, 89, 4, 377-390 (2015) (10.1007/s00190-014-0782-0)

Karbon, M., Heinkelmann, R., Mora-Díaz, J., Xu, M., Nilsson, T., Schuh, H. The extension of the parametrization of the radio source coordinates in geodetic VLBI and its impact on the time series analysis. Journal of Geodesy, Online First (2016) (10.1007/s00190-016-0954-1)

Krásná, H., Malkin, Z., Böhm, J. Non-linear VLBI station motions and their impact on the celestial reference frame and Earth orientation parameters. Journal of Geodesy, 89, 10, 1019-1033 (2015) (10.1007/s00190-015-0830-4)

Liu, F.-C., Capitaine, N. Evaluation of a possible upgrade of the IAU 2006 precession. Astronomy & Astrophysics, 597, id. A83, 12 pp. (2017) (10.1051/0004-6361/201628717)

Madzak, M., Schindelegger, M., Böhm, J., Bosch, W., Hagedoorn, J. High-frequency Earth rotation variations deduced from altimetry-based ocean tides. Journal of Geodesy, 90, I11, 1237-1253 (2016) (10.1007/s00190-016-0919-4)

Malkin, Z.M. The second version of the OCARS catalog of optical characteristics of astrometric radio sources. Astronomy Reports, 60, 11, 996-1005 (2016) (10.1134/S1063772916110032)

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Malkin, Z. Connecting VLBI and Gaia celestial reference frames. Frontiers in Astronomy and Space Sciences, 3, id. 28 (2016) (10.3389/fspas.2016.00028)

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Nilsson, T., Soja, B., Balidakis, K., Karbon, M., Heinkelmann, R., Deng, Z., Schuh, H. Improving the modeling of the atmospheric delay in the data analysis of the Intensive VLBI sessions and the impact on the UT1 estimates. Journal of Geodesy, Online First (2017) (10.1007/s00190-016-0985-7)

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Nothnagel, A., Artz, T., Behrend, D., Malkin, Z. International VLBI Service for Geodesy and Astrometry - Delivering high-quality products and embarking on observations of the next generation. Journal of Geodesy, Online First (2016) (10.1007/s00190-016-0950-5)

Quinn, K.J., Ponte, R.M., Tamisiea, M.E. Impact of self-attraction and loading on Earth rotation. Journal of Geophysical Research: Solid Earth, 120, 6, 4510-4521 (2015) (10.1002/2015JB011980)

Ray, R.D. On Tidal Inference in the Diurnal Band. Journal of Atmospheric and Oceanic Technology, 34, 2, 437-446 (2017) (10.1175/JTECH-D-16-0142.1)

Rogister, Y., Mémin, A., Rosat, S., Hinderer, J., Calvo, M. Constraints provided by ground gravity observations on geocentre motions. Geophysical Journal International, 206, 2, 1431-1439 (2016) (10.1093/gji/ggw220)

Schindelegger, M., Salstein, D., Einšpigel, D., Mayerhofer, C. Diurnal atmosphere-ocean signals in Earth's rotation rate and a possible modulation through ENSO. Geophysical Research Letters, 44, 6, 2755-2762 (2017) (10.1002/2017GL072633)

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Zhou, Y., Zhu, Q., Salstein, D.A., Xu, X., Shi, S., Liao, X. Estimation of the free core nutation period by the sliding-window complex least-squares fit method. Advances in Space Research, 57, 10, 2136-2140 (2016) (10.1016/j.asr.2016.03.028)

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Zotov, L.V., Bizouard, C. Regional atmospheric influence on the Chandler wobble. Advances in Space Research, 55, 5, 1300-1306 (2015) (10.1016/j.asr.2014.12.013)

Meetings organized in full or in part as activities of the IAU/IAG JWG TERV in 2015-2017

2017

1. Conference:
   Title: ***Journées des Systèmes de Référence et de la Rotation Terrestre***
   Subtitle: ***"Furthering our knowledge of Earth Rotation"***
   25 to 27 September 2017, Alicante, Spain
   Supported by IAU & IAG.
   Members of C-3 in the SOC: Cheng-li Huang, Richard Gross, José M. Ferrándiz (Chair)
   https://web.ua.es/journees2017/index.html

2. Open splinter meeting at EGU 2017 (SMP85). April 24, 2017
   http://meetingorganizer.copernicus.org/EGU2017/session/26247

2016

Splinter meetings and special sessions at conferences

1. Open splinter meeting at EGU 2016 (SMP14). April 20, 2016
   http://meetingorganizer.copernicus.org/EGU2016/session/22333

2. Session 8 at GAGER 2016: Open meeting on *"Current situation, progress, and challenges of the theory of Earth rotation from the JWG TERV perspective"* and discussion
   https://web.ua.es/es/wgterv/jwg-terv-meetings/open-meeting-at-gager2016.html

Commission 3 Joint Working Group 3.2: Constraining Vertical Land Motion of Tide Gauges

Chair: Alvaro Santamaría-Gómez (France)

Members

- *Matt King (Australia)*
- *Tonie van Dam (Luxembourg)*
- *Tilo Schöne (Germany)*
- *Guy Wöppelmann (France).*

Progress of the activities

The JWG has collected vertical velocity estimates from 20 different global GPS solutions, including double-differenced and zero-differenced solutions, including PPP solutions (see table below). The number of available velocity estimates per solution varies between 75 and 12933, but we only considered sites for which at least three estimates were available. We removed sites for which a velocity discontinuity was known. We also paid attention to stations having the same ID but being located at different sites (beyond a radius of 100 km). With these constraints and the solutions being considered at this moment, the number of sites considered is 1132. Some of the solutions are presently outdated, for instance the old ITRF realizations of the first reprocessing solutions at the University of La Rochelle. These solutions were included only to assess velocity changes with the longer time series and the improvement of the GPS processing.

Velocity solutions collected by the JWG

Solution name	Number of stations	Provider
ITRF2014	910	itrf.ensg.ign.fr
ITRF2008	491	itrf.ensg.ign.fr
ITRF2005	219	itrf.ensg.ign.fr
CO2	305	Paul Rebischung
EM2	171	Paul Rebischung
ES2	283	Paul Rebischung
JP2	238	Paul Rebischung
MI2	695	Paul Rebischung
GF2	247	Paul Rebischung
GR2	208	Paul Rebischung
GT2	608	Paul Rebischung
UL2	554	Paul Rebischung
ULR6	544	www.sonel.org
ULR5	356	www.sonel.org
ULR4	266	www.sonel.org
ULR3	196	www.sonel.org
UTAS PPP	260	Matt King
JPL PPP	2416	sideshow.jpl.nasa.gov
NGL PPP	12933	geodesy.unr.edu
GFZ PPP	75	Zhiguo Deng

A preliminary combination of all these solutions has been carried out. The target reference frame is the ITRF2014 and the repeatability of the vertical velocities has been obtained for each site. The velocity error bars are not consistent amongst the submitted solutions so different weighting approaches have been considered. For each solution and site, a preliminary WRMS has been obtained. The solution WRMS indicates its agreement with respect to the average (combination) of the available solutions, after the weighting of each solution. The site WRMS provides the velocity repeatability amongst the solutions considered and represents an alternative assessment of the velocity uncertainty for each site.

Further steps

A continuous effort to include new global velocity solutions is maintained.
Large velocity differences were detected for the PPP solutions and further development of the combination is expected, particularly concerning the lack of velocity covariance for the PPP solutions.

In addition to these 20 solutions, the vertical velocities from the IGS TIGA reprocessed solutions have been recently submitted to the JWG (see table below) and will be integrated in the comparison.

For the last reprocessing at the University of La Rochelle (ULR6), three different velocity solutions exist (ULR6, UL2 and ULR TIGA). This makes a unique dataset to assess velocity differences produced during the stacking, alignment and cleaning of the series by different analysts.

An additional DORIS solution has been submitted and will be integrated in the comparison.

Recent velocity solutions available:

Solution name	Number of stations	Provider
GTZ TIGA	670	Addisu Hunegnaw
BLT TIGA	609	Addisu Hunegnaw
ULR TIGA	558	Addisu Hunegnaw
DORIS	116	Guilhem Moreaux

Commission 4 – Positioning and Applications

http://IAG-Comm4.gge.unb.ca

President: Marcelo Santos (Canada)
Vice President: Allison Kealy (Australia)

Structure

Sub-commission 4.1:	Emerging Positioning Technologies and GNSS Augmentation
Sub-commission 4.2:	Geo-spatial Mapping and Geodetic Engineering
Sub-commission 4.3:	Atmosphere Remote Sensing
Sub-commission 4.4:	Multi-constellation GNSS
Joint Study Group 0.10:	High rate GNSS (Report in ICCT)
Joint Study Group 0.14:	Fusion of multi-technique geodetic data (Report in ICCT)
Joint Study Group 0.17:	Multi-GNSS theory and algorithms (Report in ICCT)
Joint Study Group 0.20:	Space weather and ionosphere (Report in ICCT)
Joint Working Group 1.3:	Troposphere Ties (Report in Commission 1)

Overview

The main activity of IAG Commission 4, "Positioning and Applications", was its very first Symposium. It took place in Wroclaw, Poland, from September 4 to 7, 2016. The venue was the Didactic and Scientific Center of the Faculty of Environmental Engineering and Geodesy, on Grunwaldzki Square 24a. 67 geodesists participated in the event, with the presentation of 58 scientific contributions being 40 orals and 18 posters. Link to the presentation slides and posters is possible via the online programme at_http://www.igig.up.wroc.pl/IAG2016/?page=2. The Scientific Committee was composed by the members of Commission 4 Executive. The Local Organizing Committee, spearheaded by Tomasz Hadas, Krzysztof Sosnica, Anna Krypiak-Gregorczyk and Jacek Paziewski did a tremendous job, which deserved the accolades of all participants. During the event, several entities of Commission 4 held splinter meetings. Group photo with some of the participants is shown below.

Among all Commissions and the ICT, Commission 4 have never had a dedicated symposium on their own. This was the very first. The idea from now on is for Commission 4 to host its own symposium at the year after the IUGG General Assembly to spearhead its work. Therefore, you can write in your agendas the year 2020 for the second Commission 4 Symposium.

Sub-commission 4.1: Emerging positioning technologies and GNSS augmentation

Chair: *Vassilis Gikas (Greece)*
Vice Chair: *Günther Retscher (Austria)*

Overview

IAG Sub-Commission 4.1 comprises four Working Groups in total (i.e., WG4.1.1, WG4.1.2, WG4.1.3, and WG4.1.4), from which WG4.1.1 is a Joint WG with FIG WG5.5. During the current term 2015-17, SC4.1 activities were coordinated occasionally at conference meetings and remotely via electronic means. In addition, members from all SC4.1 WGs had the chance to meet physically during the IAG Com. 4 "Positioning and Applications Symposium", Wroclaw, Poland, Sept. 4-6. The official web site of IAG SC4.1 is http://iag-sc41.survey.ntua.gr/index.html.

Working Groups of Sub-commission 4.1:

WG 4.1.1: Multi-Sensor Systems
Chair: *Allison Kealy (Australia)*
Vice Chair: *Günther Retscher (Austria)*

Activities and publications during the period 2015-2017

A novel approach for positioning with Wi-Fi was initiated and developed at TU Wien (Vienna University of Technology) under the lead of Guenther Retscher. This approach for localization and tracking of mobile smartphone users is termed Differential Wi-Fi (DWi-Fi) by analogy with DGPS. From reference stations deployed in the area of interest differential measurement corrections are derived and applied at the mobile user side. Hence, range or coordinate corrections can be estimated from a network of reference station observations as it is done in common CORS GNSS networks. A low-cost realization with Raspberry Pi units has been realized for these reference stations. These units serve at the same time as Access Points (APs) broadcasting Wi-Fi signals as well as reference stations scanning the receivable Wi-Fi signals of the surrounding APs. As the RSS measurements are carried out continuously at the reference stations dynamically changing maps of RSS distributions, so-called radio maps, can be derived. The DWi-Fi concept was presented for the first time at the FIG Working Week in Christchurch, New Zealand, in May 2016. In the following, first promising test results were presented at the UPINLBS conference in Shanghai, PR China, in November 2016. To evaluate the DWi-Fi localisation capabilities and its performance two measurement campaigns with participation of the WG members Allison Kealy and Vassilis Gikas were carried out. The first one took place in September 2016 at TU Wien followed by another at the University of Melbourne in February 2017. In the planned field campaign at the Ohio State University in October 2017 DWi-Fi positioning plays an additional role to other localization techniques. The preparation of this field campaign is well under way. This development can also be seen as a joint work between WG 4.1.1 and 4.1.2 as applications for the DWi-Fi approach range from indoor positioning to CP of a pedestrian user group in combined out- and indoor environments.

EMPARCO (Efficient Management of Parking under Constraints). The project aims to develop positioning solutions for the management of large-scale parking facilities and depots, for either passenger vehicles or commercial fleets, under constraints including near-capacity demand, temporally constrained arrivals / departures, need for emergency evacuation. The positioning solution provided through the project resides on a combination of RFID CoO (Cell of Origin) approach coupled with Wi-Fi monitoring. The system is supported by an Ultra Wide Band (UWB) ranging system for validating the navigation solution provided.

Research at the University of Melbourne with other WG members concentrates on indoor positioning using mainly UWB, Wi-Fi and inertial sensors. A collaborative (or also referred to as cooperative) positioning (CP) approach is thereby adopted where a number of pedestrian users are located together within a group in the same neighbourhood. Furthermore, the practicability of using UAV's for mobile mapping is investigated. In this research UWB plays a major role in combination with inertial sensors and GNSS whereby CP is employed to navigate several UAV's together at the same time.

A "Field Campaign" is planned to take place with the participation of WG4.1.1 members at the Ohio State University in the first week of October 2017. The scope of this activity is to plan and undertake a number of collaborative field campaigns to support WG4.1.1 work on multi-sensor positioning systems.

Meetings and Conferences

The WG4.1.1 maintained a strong and active presence at the following international events through participation in coordinating, scientific and organizing committees, delivering tutorials, publishing papers and presentation, session chairing, etc.

- ION GNSS+, Tampa, Florida USA, Sept. 14-18, 2015
- Indoor Positioning and Indoor Navigation Conference (IPIN), Banff, Canada, Oct. 13-16, 2015
- 9th Int. Symp. on Mobile Mapping Technology (MMT), Sydney, Australia, Dec. 9-11, 2015
- FIG Working Week, Christchurch, New Zealand, May 2-6, 2016
- IAG Commission 4 Positioning and Applications Symposium, Wroclaw, Poland, Sept. 4-7, 2016
- ION GNSS+, Portland, Oregon USA, Sept. 12-16, 2016
- Indoor Positioning and Indoor Navigation Conference (IPIN), Madrid, Spain, Oct. 4-7, 2016
- Ubiquitous Positioning, Indoor Navigation an Location Based Services (UPINLBS), Shanghai, China, Nov. 3-4
- IGNSS 2016 Conference, Sydney, Australia, Dec. 6-8, 2016
- 10th Int. Symp. on Mobile Mapping Technology (MMT), Cairo, Egypt, May 6-8, 2017
- FIG Working Week, Helsinki, Finland, May 29-June 2, 2017
- 85th Vehicular Technology Conference, Sydney, Australia, June 4-7, 2017

Publications

Journal Publications

Retscher G., F. Obex (2015): InKoPoMoVer – Cooperative Positioning for Real-time User Assistance and Guidance at Multi-modal Public Transit Junctions, Journal of Applied Geodesy, Vol. 9, No. 3, September 2015, ISSN 1862-9016, DOI 10.1515/jag-2015-0006, pp. 198-206. http://www.degruyter.com/view/j/jag.2015.9.issue-3/issue-files/jag.2015.9.issue-3.xml

Kealy A., G. Retscher G., C. Toth, A. Hasnur-Rabiain, V. Gikas, D. A. Grejner-Brzezinska, C. Danezis, T. Moore (2015): Collaborative Navigation as a Solution for PNT Applications in GNSS Challenged Environments – Report on Field Trials of a Joint FIG/IAG Working Group, Journal of Applied Geodesy, Vol. 9, No. 4, December 2015, ISSN 1862-9016, DOI 10.1515/jag-2015-0014, pp. 244-263. http://www.degruyter.com/view/j/jag.2015.9.issue-4/issue-files/jag.2015.9.issue-4.xml

Antoniou C., Gikas V., Papathanasopoulou V., Danezis C., Panagopoulos A., Markou I., Efthymiou D., Yannis G., Perakis H. (2016): Localization and Driving Behavior Classification Using Smartphone Sensors in the Direct Absence of GNSS, Transportation Research Record: Journal of the Transportation Research Record, Vol. 2489, pp 66–76

Gikas V., Perakis H. (2016): Rigorous Performance Evaluation of Smartphone GNSS/IMU Sensors for ITS Applications, SENSORS, Vol. 16(8), 1240

Gikas V., Antoniou C., Retscher G., Panagopoulos A.D., Perakis H., Kealy A., Mpimis T. (2016): A Low-Cost Wireless Sensors Positioning Solution For Indoor Parking Facilities Management, Journal of Location Based Services, Vol. 10(3), 1–21

Kealy A., Goel S., Gikas V., Retscher G., Toth C., Brzezinska D., Lohani B. (2017): Cooperative Localization of Unmanned Aerial Systems Using Low Cost GNSS and MEMS Inertial Sensors, Journal of Surveying Engineering, https://doi.org/10.1061/(ASCE)SU.1943-5428.0000230

Retscher G., T. Tatschl (2017): Positionierung in Gebäuden mit differenziellem WLAN, Zeitschrift für Geodäsie, Geoinformation und Landmanagement (ZfV), Vol. 142, No. 2, pp. 111-125 (in German)

Conference Publications

Gikas V., Antoniou C., Mpimis A., Perakis H., Danezis C. (2015): Performance Evaluation of Vehicle Location Estimation in Heavily Obscured Environments Based on Contemporary Smartphones, 6th Int. Conf. on Indoor Positioning and Indoor Navigation (IPIN), Banff, Alberta, Canada, Oct. 13-16

Perakis H., Mpimis A., Gikas V., Papathanasopoulou V., Antoniou K. (2015): Driving Behavior Classification within Indoor Parking Facilities Based on Inertial Smartphone Data, 6th Int. Conf. on Indoor Positioning and Indoor Navigation (IPIN), Banff, Alberta, Canada, Oct. 13-16

Gikas V., Retscher G. (2015): An RFID-based Virtual Gates Concept as a Complementary Tool for Indoor Vehicle Localization, 6th Int. Conf. on Indoor Positioning and Indoor Navigation (IPIN), Banff, Alberta, Canada, Oct. 13-16

Retscher G., F. Obex (2015): A User Assistance and Guidance Service for Multi-modal Public Transit Situations Based on Cooperative Positioning. in: Papers presented at the 9th International Symposium on Mobile Mapping Technology, Sydney, Australia, Dec. 9-11, 7 pgs.

Kealy A., S. Goel, V. Gikas, G. Retscher G., C. Toth, D. A. Grejner-Brzezinska, B. Lohani (2015): Cooperative Localisation of UAVs Using Low Cost GNSS and MEMS Inertial Sensors. in: Papers presented at the 9th International Symposium on Mobile Mapping Technology, Sydney, Australia, Dec. 9-11, 11 pgs.

Gikas V., Antoniou C., Retscher G., Panagopoulos A.D., Perakis H., Kealy A., Mpimis A., Economopoulos T., Marousis A. (2015): A Low-cost RFID/WiFi Positioning Solution for Parking Facilities Management, 9th Int. Symp. on Mobile Mapping Technology, Sydney, Australia, Dec. 09–11

Retscher G., T. Tatschl (2016): Differential Wi-Fi – A Novel Approach for Wi-Fi Positioning Using Lateration. in: Papers presented at the FIG Working Week, Christchurch, New Zealand, May 2-6, 17 pgs. http://fig.net/resources/proceedings/fig_proceedings/fig2016/papers/ts06b/TS06B_retscher_tatschl_7973.pdf

Gikas V., Retscher G., Kealy A., Zhang K., Paffenholz J-A., Ruotsalainen L., Perakis H., Santos M. (2016): IAG SC 4.1 Emerging Positioning Technologies and Applications: Objectives and Structure for the Term 2015-19, European Navigation Conference, Helsinki, Finland, May 30–Jun. 02

Kealy A., Retscher G., Gikas V. (2016): Recent Developments on Multi-Sensor Systems within the IAG as a Driver for Robust Positioning and Navigation, IAG Commission 4 Symposium, Wroclaw, Poland Sept. 4–7

Mpimis T, Gikas V. (2016): An Advanced Instrumentation System Proposal for Monitoring Rowing Performance, IAG Commission 4 Symposium, Wroclaw, Poland Sept. 4–7

Ruotsalainen L., Dovis F., Gikas V. (2016): Robust Positioning for Urban Traffic: Motivations and Activity plan for the WG 4.1.4 established within the IAG SC 4.1 Emerging Positioning Technologies and GNSS Augmentation, IAG Commission 4 Symposium, Wroclaw, Poland Sept. 4–7

Retscher G., T. Tatschl (2016): Indoor Positioning Using Wi-Fi Lateration – Comparison of Two Common Range Conversion Models with Two Novel Differential Approaches. IEEE Xplore, 2016 Fourth International Conference on Ubiquitous Positioning, Indoor Navigation and Location Based Services (UPINLBS), Shanghai, China, Nov. 3-4, 10 pgs.

Goel S., A. Kealy, G. Retscher, B. Lohani (2016): Cooperative P2I Localization Using UWB and Wi-Fi. in: Papers presented at the IGNSS 2016 Conference, Sydney, Australia, Dec. 6-8, 16 pgs (paper 16)

Antoniou C., Gikas V., Papathanasopoulou V., Mpimis T., Perakis H., Kyriazis C. (2017): A Framework for Efficient Data Collection and Modeling of Indoor Parking Facilities Under Constraints, 96th TRB Annual Meeting Washington DC, USA, Jan. 8–17

Goel S., A. Kealy, B. Lohani, G. Retscher (2017): A Cooperative Localization System for Unmanned Aerial Vehicles: Prototype Development and Analysis. in: Papers presented at the 10th International Symposium on Mobile Mapping Technology, Cairo, Egypt, 7 pgs May 6-8, (Awarded best presentation)

Retscher G., A. Kealy, V. Gikas, H. Hofer, A. Ettlinger and F. Obex (2017): Cooperative Localization in Indoor Environments Using Constrained Differential Wi-Fi and UWB Measurements. in: Papers presented at the 10th International Symposium on Mobile Mapping Technology, Cairo, Egypt, May 6-8, 2 pgs.

Gikas V., Perakis H., Kealy A., Retscher G., Mpimis T., Antoniou C. (2017): Indoor Parking Facilities Management Based on RFID CoO Positioning in Combination with Wi–Fi and UWB, FIG Working Week, Helsinki, Finland, May 29 – June 2

Hofer H., G. Retscher (2017): Combined Wi-Fi and Inertial Navigation with Smart Phones in Out- and Indoor Environments. VTC2017-Spring Conference, Sydney, Australia, Jun. 4-7

Cooperation with other Organizations

WG 4.1.1 is a Joint WG with the FIG WG 5.5

WG 4.1.2: Indoor Positioning and Navigation

Chair: *Kefei Zhang (Australia)*
Vice Chair: *Ruizhi Chen (China)*

Activities and publications during the period 2015-2017

Research at the TU Wien (Vienna University of Technology): Guenther Retscher published a book chapter on Indoor Navigation in the Encyclopaedia of Geodesy:
Chapter 9-1. in: E.W. Grafarend (Ed.), Encyclopedia of Geodesy, Earth Sciences Series, Springer International Publishing Switzerland, ISBN: 978-3-319-02370-0 (Online), DOI 10.1007/978-3-319-02370-0_9-1, 7 pgs.
http://link.springer.com/referencework/10.1007/978-3-319-02370-0/page/z/1

Two novel approaches for positioning with Wi-Fi were initiated and developed at TU Wien (Vienna University of Technology). The first one is DWi-Fi (see report from WG 4.1.1) and the second Wi-Fi location fingerprinting with intelligent checkpoints (iCPs). In this approach the required workload in Wi-Fi positioning in the training is reduced by three quarters compared to common Wi-Fi positioning methods. It is based on a meaningful selection of reference points required in the fingerprinting training phase. The iCPs are waypoints along possible user trajectories. Positioning accuracies on the same level of a few meters are achievable with the iCP concept. In addition, the integration with MEMS based smartphone sensors has been developed further. Furthermore, developments at TU Wien concentrated on the use of ambient magnetic fields in indoor environments for localization of a mobile pedestrian user and a robot.

Research at the RMIT University: A commercial product - RMIT Survey System development. A GPS and Google Maps based iOS surveying system (APP) used for undergraduate surveying courses at RMIT University. The APP is downloadable at: https://itunes.apple.com/au/app/rmit-survey/id1225134466?mt=8

Publications

Journal Publications

Chen G, Meng X, Wang Y, et al. (2015): Integrated WiFi/PDR/Smartphone Using an Unscented Kalman Filter Algorithm for 3D Indoor Localization, SENSORS, 15(9): 24595-24614.

Li X, Wang J, Liu C. (2015): A Bluetooth/PDR Integration Algorithm for an Indoor Positioning System, SENSORS, 15(10): 24862-24885.

Wang J, Hu A, Liu C, et al. (2015): A Floor-map-aided WIFI/pseudo-odometry Integration Algorithm for an Indoor Positioning System, SENSORS, 15(4): 7096-7124.

Wang J, Hu A, Li X, et al. (2015): An Improved PDR/Magnetometer/Floor Map Integration Algorithm for Ubiquitous Positioning Using the Adaptive Unscented Kalman Filter, ISPRS International Journal of Geo-Information, 4(4): 2638-2659.

Hofer H., G. Retscher (2016): Smartphone Navigation anhand von „intelligenten Check-Points". Österreichische Zeitschrift für Vermessung und Geoinformation, VGI 2/16, pp. 61-71 (in German). http://www.ovg.at/de/vgi/ausgabe/1280/Keqiang Liu, Ruizhi Chen, Tianxing Chu, Yunjia Wang, Jingbin Liu, Yuwei Chen and Ling Pei. (2016): Recognizing Human Activities in Smartphones: A Comprehensive Algorithm Assessment of a Multiple Context Approach. Journal of Residuals Science & Technology, Vol. 13, No. 6, doi:10.12783/issn.1544-8053/13/6/98.

Keqiang Liu, Keqiang Liu, Yunjia Wang, Ruizhi Chen, Tianxing Chu, Jingxue Bi. (2016): A Survey of Human Activity Recognition Using Smartphones. Journal of Residuals Science & Technology, Vol. 13, No. 8, doi:10.12783/issn.1544-8053/13/8/385.

Keqiang Liu, Yunjia Wang, Lixin Lin, and Guoliang Chen (2017):An Analysis of Impact Factors for Positioning Performance in WLAN Fingerprinting Systems Using Ishikawa Diagrams and a Simulation Platform, Mobile Information Systems, Vol. 2017, Article ID 8294248, 20 pages, doi:10.1155/2017/8294248.

Ren, Y., Salim, F. D., Tomko, M., Bai, Y. B., Chan, J., Qin, K. & Sanderson, M.(2016):, D-Log: A Wi-Fi Log-based Differential Scheme for Enhanced Indoor Localization with Single RSSI Source and Infrequent Sampling", Journal of Pervasive and Mobile Computing.

Retscher G., H. Hofer (2017): Wi-Fi Location Fingerprinting Using an Intelligent Checkpoint Sequence. Journal of Applied Geodesy Vol. 11, No. 2, ISSN 1862-9016, 9 pgs

Conference Publications

Retscher G., H. Hofer (2015): A Novel Approach for Wi-Fi Fingerprinting Using Logical Sequences of Intelligent Checkpoints. IGNSS 2015 Conference, Surfers Paradise, Gold Coast, Queensland, Australia, July 14-16, 16 pgs.
http://www.ignss.org/Conferences/PastConferencePapers/2015ConferencePastPapers/2015NonPeerReviewedPapers/tabid/148/Default.aspx (paper 3)

Bai Y. B., R. Norman, Y. Zhao, S. Tang, S. Wu, H. Wu, G. Retscher, K. Zhang (2015): A New Algorithm for Improving the Tracking and Positioning of Cell of Origin. International Association of Institutes of Navigation World Congress IAIN, Prague, Czech Republic, October 20-23, 6 pgs. IEEE Xplore, 2015 International Association of Institutes of Navigation World Congress IAIN, ISBN 978-1-4673-7634-1, pp. 340-345.

Keqiang Liu, Ruizhi Chen, Tianxing Chu, Yunjia Wang (2015): Enhancing the Probability Models for Inference of Significant Activities Using a Real-time Learning Machine in Smartphone, 28th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2015), Tampa, Florida, Sept.,pp. 2055-2059.

Bai, Y. B., Wu, S., Holden, L., Wu, F., Kealy, A., Zhang, K. (2015): A New Approach for Wi-Fi Based Customer Tracking and Positioning in a Long Narrow Indoor Space, International Symposium on GNSS 2015, Kyoto, Japan

Bai, Y. B., Wu, S., Holden, L., Wu, F., Kealy, A., Zhang, K., (2015): A New Approach for Wi-Fi Based Customer Tracking and Positioning in a Long Narrow Indoor Space, International Symposium on GNSS 2015, Kyoto, Japan (Awarded the excellent paper and scholarship in student group.

Retscher G., H. Hofer (2016): Wi-Fi Location Fingerprinting Using an Intelligent Checkpoint Sequence. FIG Working Week, Christchurch, New Zealand, May 2-6, 16 pgs.
http://fig.net/resources/proceedings/fig_proceedings/fig2016/papers/ts06b/TS06B_retscher_hofer_7993.pdf

Ettlinger A., G. Retscher (2016): Use of Magnetic Fields in Combination with Wi-Fi and RFID for Indoor Positioning, in: Ullmann B. (ed.): Vienna Young Scientists Symposium, Vienna, Austria, June 9-10, ISBN: 978-3-9504017-2-1, pp. 84-85.

Bai, Y. B., Gu T., Hu, A. (2016): Integrating Wi-Fi and Magnetic Field for Fingerprinting Based Indoor Positioning System, 7th International Conference Indoor Positioning and Indoor Navigation (IPIN), Alcalá de Henares, Madrid, Spain, Oct. 4-6.

Ettlinger A., G. Retscher (2016): Positioning Using Ambient Magnetic Fields in Combination with Wi-Fi and RFID, 7th International Conference Indoor Positioning and Indoor Navigation (IPIN), Alcalá de Henares, Madrid, Spain, Oct. 4-6, ISBN: 978-1-5090-2424-7, 8 pgs. IEEE Xplore 2016 International Conference on Indoor Positioning and Indoor Navigation (IPIN), ISBN 978-1-5090-2425-4, 8 pgs.http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7743657

Retscher G., J. Joksch (2016): Analysis of Nine Vector Distances for Fingerprinting in Multiple-SSID Wi-Fi Networks. 7th International Conference Indoor Positioning and Indoor Navigation (IPIN), Alcalá de Henares, Madrid, Spain, Oct. 4-6, ISBN: 978-1-5090-2424-7, 5 pgs.

Hofer H., G. Retscher (2016): Combined Out- and Indoor Navigation with Smart Phones Using Intelligent Check Points. 13th International Symposium on Location-Based Services LBS 2016, Vienna, Austria, Nov. 14-16, 2016, pp. 82-90.

Kealy A., G. Retscher (2017): MEMS and Wireless Options in Cellular Phones for User Localization. ION Pacific PNT Conference, Honolulu, Hawaii, USA, May 1-4, 13 pgs.

Hofer H., G. Retscher (2017): Combined Wi-Fi and Inertial Navigation with Smart Phones in Out- and Indoor Environments. VTC2017-Spring Conference, Sydney, Australia, June 4-7, 5 pgs.

Other

Retscher G. (2016): Indoor Navigation. Chapter 9-1. in: E.W. Grafarend (Ed.), Encyclopedia of Geodesy, Earth Sciences Series, Springer International Publishing Switzerland, ISBN: 978-3-319-02370-0 (Online), DOI 10.1007/978-3-319-02370-0_9-1, 7 pgs. http://link.springer.com/referencework/10.1007/978-3-319-02370-0/page/z/1

Retscher G., F. Roth (2017): Wi-Fi Fingerprinting with Reduced Signal Strength Observations from Long-time Measurements. in: Gartner G, H. Huang (eds.), Progress in Location-Based Services 2016, Lecture Notes in Geoinformation and Cartography, ISBN 978-3-319-47289-8, DOI 10.1007/978-3-319-47289-8_1, pp. 3-24.

Research Projects

CUMT (China University of Mining and Technology): The research team at CUMT was part of a large consortium that involves both industry, academia and research organisations winning two large national grants (at the level of US$1-2 million each). Both projects are directly related to indoor positioning and emergency services from the Chinese national 13th five-year plan major research scheme funded the Chinese Ministry of Science and Technology.

Awards and Anniversaries

RMIT University: WMLoc System development. A Wi-Fi and magnetic based personal tracking System. Awarded the 4th position for smartphone-based tracking competition during the IPIN 2016 competition in Spain)

The excellent paper award (postgraduates) and corresponding scholarship at the ISGNSS conference in Japan, Nov. 2015.

Kick off meeting of the integrated intelligent indoor GIS technology project (from the Chinese national 13th five-year plan major research scheme funded by the Chinese Ministry of Science and Technology)

End-user needs analysis meeting held at CUMT (from the Chinese national 13th five-year plan major research scheme funded by the Chinese Ministry of Science and Technology)

WG 4.1.3: 3D Point Cloud based Spatio-temporal Monitoring

Chair: *Jens-Andre Paffenholz (Germany)*
Vice Chair: *Corinna Harmening (Austria)*

Activities and publications during the period 2015-2017

The WG was active in the period 2015-2017 in terms of recruiting a small core of interested people to share knowledge in the scope of 3D point cloud based spatio-temporal monitoring. For the next period the collaboration and interaction of the members will be improved with the goal of preparing a joined manuscript within the theme of the WGs topics. To start further collaboration among the members and interested people, the plan is to set-up a project corresponding to the WG at the social networking site ResearchGate (www.researchgate.net).

The chair and some members contributed to an outstanding loading test on an historic railway arch bridge. After 150 years in use the historic masonry arch bridge over the river Aller near Verden (Northern Germany) was taken out of service in October 2015 and was demolished in summer 2016. The time gap between decommission and demolition offered the unique chance for an experimental investigation of the load-deformation behaviour of the arch-row by load testing. A project team under the leadership of the Institute of Concrete Construction of the Leibniz Universität Hannover has carried out two load tests with a maximum load of 570 t (!) in March and June 2016. By means of the load tests the influence of the front wall and the sealing layer on the bearing behaviour could be detected and also quantified with a large number of local and global deformation measurements. The experimental results form the basis for an improvement of the calculation methods and models, allowing a more realistic evaluation of the bearing safety of existing arch bridges. Following Geodesy colleagues contributed to the loading test:

- Institute of Geodesy and Geoinformation Science, Technical University Berlin: 3D laser scanner and stereo cameras;
- Institute of Geodesy and Photogrammetry, Technical University Braunschweig: terrestrial radar sensor;
- Institute of Geodesy, Section Geodetic Measuring Systems and Sensor Technology Technical University Darmstadt: Profile laser scanner;
- Institute for Applied Photogrammetry and Geoinformatics, Jade University of applied sciences: Camera system;
- Geodetic Institute Hannover, Leibniz Universität Hannover: 3D laser scanner and laser tracker.

The results of the loading tests will be published within this year in the civil engineering as well as geodesy community. See the chair's webpage at the Geodetic Institute for details.

Meetings and Conferences

The members presented their individual and partially collaborative research results at the following conferences:

- 3rd Joint Int. Symposium on Deformation Monitoring (JISDM), Vienna (Austria), April 2016
- IAG Commission 4 Positioning and Applications Symposium, Wroclaw (Poland), September 2016
- 5th Int. Conference on Machine Control & Guidance (MCG), Vichy (France), October 2016
- 18. Int. Ingenieurvermessungskurs, Graz (Austria), April 2017
- One upcoming event with contributions of WG members is the INGEO2017 conference, Lisbon (Portugal), October 2017

Publications

Journal Publications

Bureick, J., Neuner, H., Harmening, C.& Neumann, I. (2016): Curve and surface approximation of 3D point clouds. In: avn 123 (11-12), S. 315–327

Harmening, C.& Neuner, H. (2017): Choosing the optimal number of B-spline control points. Part 2: Approximation of surfaces and applications. In: Journal of Applied Geodesy 11 (1). DOI: 10.1515/jag-2016-0036

Harmening, C.& Neuner, H. (2016): Choosing the Optimal Number of B-spline Control Points. Part 1: Methodology and Approximation of Curves. In: Journal of Applied Geodesy 10 (3). DOI: 10.1515/jag-2016-0003

Holst, C.& Kuhlmann, H. (2016): Challenges and Present Fields of Action at Laser Scanner Based Deformation Analyses. In: Journal of Applied Geodesy 10 (1). DOI: 10.1515/jag-2015-0025

Neuner, H., Holst, C.& Kuhlmann, H. (2016): Overview on current modelling strategies of point clouds for deformation analysis. In: avn 123 (11-12), S. 328–339

Wunderlich, T. A., Niemeier, W., Wujanz, D., Holst, C., Neitzel, F.& Kuhlmann, H. (2016): Areal deformation analysis from TLS point clouds – the challenge. In: avn 123 (11-12), S. 340–351

Conference Publications

Gikas, V.; Retscher, G.; Kealy, A.; Zhang, K.; Paffenholz, J.-A.; Ruotsalainen, L.; Perakis, H.; Santos, M.: IAG SC 4.1 "Emerging Positioning Technologies and GNSS Augmentation" Objectives and Structure for the Term 2015-19. Proceedings of the 2016 European Navigation Conference, Helsinki, Finland, May 30 - June 2, 2016, p. 4.

Kersten, T.; Paffenholz, J.-A.: Noise Analysis of High Sensitivity GNSS-Receivers for Direct Geo-Referencing of Multi-Sensor Systems. Presentation. IAG Commission 4 Positioning and Applications Symposium, Wroclaw, Poland, September 6, 2016.

Omidalizarandi, M., Paffenholz, J.-A., Stenz, U.& Neumann, I. (2016): Highly accurate extrinsic calibration of terrestrial laser scanner and digital camera for structural monitoring applications. In: Proceedings of the 3rd Joint International Symposium on Deformation Monitoring. JISDM2016. Vienna, 30 March - 01 April, S. 8.

Paffenholz, J.-A.& Stenz, U. (2017): Integration von Lasertracking und Laserscanning zur optimalen Bestimmung von lastinduzierten Gewölbeverformungen. In: Werner Lienhart (Hg.): Ingenieurvermessung 2017. Beiträge zum 18. Internationalen Ingenieurvermessungskurs Graz. Ingenieurvermessung 17. Graz, 25-29. April. Berlin/Offenbach: Herbert Wichmann Verlag, 373-388.

Paffenholz, J.-A.; Bureick, J.; Dmitri, D.; Link, J.: Synchronization aspects of sensor and data fusion in a research multi-sensor-system. In: Proceedings of the 5th International Conference on Machine Control & Guidance. Clermont-Ferrand, France, October 5-6, 2016.

Research Projects

- 3D point cloud-based quantification of soil erosion: Comparison of methods on different spatial scales
- Evaluation of methods for 3D point cloud acquisition by terrestrial laser scanner in static mode and optional on a moving platform as well as by UAV-based image acquisition with the goal of quantification of soil erosion of farmland in soil erosion monitoring areas in Lower Saxony, Germany.
- Jens-André Paffenholz with colleagues from Institute of Physical Geography and Landscape Ecology, Leibniz Universität Hannover
- Partially funded by Leibniz Forschungsinitiative FI:GEO

Cooperation with other Organizations

- Established link to DVW Working Group - Engineering Geodesy; Elected member Jens-André Paffenholz, guest member Christoph Holst
- Established links to ISPRS WG I/10 - Sensor Systems Verification, Benchmarks, Evaluation (Petra Helmholz) and ISPRS WG II/10 - 3D Mapping for Environmental & Infrastructure Monitoring (Daniel Wujanz)
- Improvement of link to FIG Commission 5 – Positioning and Measurement; In charge with Volker Schwieger

WG 4.1.4: Robust Positioning for Urban Traffic

Chair: *Laura Ruotsalainen (Finland)*
Vice Chair: *Fabio Dovis (Italy)*

Activities and publications during the period 2015-2017

In 2016 the Working Group 4.1.4 was formed. The first collaboration event was held during IAG Commission 4 Positioning and Applications Symposium at Wroclaw in September, where also new members were attracted. The first brainstorming about the goals and activities of the group took place at the ION GNSS 2016 meeting in Portland, Oregon and a teleconference about more detailed plans via Lync teleconference system in October.

During the teleconference meeting the relevant conferences and events were collected and agreed that all members would inform the group of the events they will participate case they would like to arrange a small meeting for everyone joining the event.

The group has also started to prepare two publications to both gather the knowledge inside the group to the information of its members and also to disseminate the status and gaps in the research of the WG subject. Different parts of the publication have been written already and now the papers are processed to be consistent and they will be submitted for selected publications during the summer period.

The idea of having a repository for data collected by group members has been discussed. The data could be processed by different research groups with their own methods. This would provide a good way of confirming the result obtained using different methods and comparing their performance. At present, a good repository is sought for.

Meetings and Conferences

The WG presented the goals and actions of the group in the following events:

- European Navigation conference 2016 in Helsinki, in May, poster presentation
- IAG Commission 4 Positioning and Applications Symposium" in Wroclaw, in September, oral presentation
- ITS World Congress 2015, Bordeaux , Oct. 5-9

Working group members will take part in the following events and promote the work of the group:

- SaPPART final event in Brussels, October 2017
- European Navigation Conference (ENC) in Lausanne, May 2017

Cooperation with other Organizations

During the first year of operation the group has established links between the following stakeholders for improved dissemination of the action deliverables and input of different user needs for the work:

- EU COST SaPPART in SaPPART meetings
- Other IAG SC 4 WGs in Commission 4 Symposium in Poland 2016
- FIG, this will be done during the FIG Working week in Helsinki
- GSA JUPITER- project
- Ertico
- Different stakeholders participating the eKnot roadshow in Torino 2017

Publications

Conference Publications

Gikas V., Kealy A., Paffenholz J-A, Perakis H., Retscher G., Zhang K., Ruotsalainen L., Santos M. (2016), IAG SC 4.1 "Emerging Positioning Technologies and GNSS Augmentation" In Proceedings of European Navigation Conference (ENC), June 30 - July 2, Helsinki, Finland

P.-Y. Gilliéron, L. Ruotsalainen, F. Peyret, S. Feng, J. Engdahl (2016): The SaPPART COST Action: Towards positioning integrity for road transport, In Proceedings of European Navigation Conference (ENC), June 30 - July 2, Helsinki, Finland

Dovis F., Ruotsalainen L., Gikas L. (2016): Robust Positioning for Urban Traffic: Motivations and Activity plan for the WG 4.1.4 established within the IAG SC 4.1 Emerging Positioning Technologies and GNSS Augmentation. IAG Commission 4 Positioning and Applications Symposium, Wroclaw, Poland, September 6, 2016.

C Cristodaro, F Dovis, L Ruotsalainen (2017): The Record and Replay Approach for GNSS Receiver Performance Assessment in Road Environment, In Proceedings of ION ITM, pp. January 30 - February2, Monterey, CA, pp. 1369-1375

Sub-commission 4.2: Geopatial Mapping and Geodetic Engineering

Chair: *Jinling Wang (Australia)*
Vice-Chair: *Michael J. Olsen (USA)*
Secretary: *Hsiu-Wen Chang (China-Taipei)*

Overview

Geodesy provides foundations for geospatial mapping and engineering applications. Modern geospatial mapping as a massive point positioning process has been evolving towards automatic operations, and at the same time, various engineering areas are increasingly relying on highly developed geospatial technologies to deliver improved productivities and safety with minimised negative environment impact. This Sub-Commission (SC) 4.2 will therefore endeavour to coordinate research and other activities that address the broad areas of the theory and applications of geodesy tools in geospatial mapping and engineering, ranging from construction work, geotechnical and structural health monitoring, mining, to natural phenomena such as landslides and ground subsidence. The SC4.2 will carry out its work in close cooperation with other IAG Entities, as well as via linkages with relevant scientific and professional organizations such as ISPRS, FIG, ISM, ICA, IEEE, ION, OGC.

SC 4.2 is composed of 4 working Groups. While each working group has conducted various activities, the Sub-Commission 4.2 has successfully organised one major event: The 9th International Symposium on Mobile Mapping Technology (MMT2015), Sydney, Australia, December 9-11, 2015, see the program details at www.mmt2015.org.

The MMT Symposium is the primary event jointly sponsored by International Association of Geodesy (**IAG**), the International Society of Photogrammetry and Remote Sensing (**ISPRS**) and the International Federation of Surveyors (**FIG**). In addition, for the first time, another two major international organisations, the International Society of Mine Surveying (**ISM**) and the International Cartographic Association (**ICA**), Australian Surveying and Spatial Sciences Institute (SSSI), and Spatial Industries Business Association (SIBA), Australian Robotics and Automation Association (ARAA) as well as Australian Network of Structural Health Monitoring (ANSHM) have also offered the official sponsorships to the MMT2015.

MMT2015 attracted about 300 registered participants from 35 countries/regions, and received 156 full paper submissions for the conference proceedings, with topics ranging from new mapping concepts, the state of the art of technology, multi-disciplinary approaches, new applications, to future trends. The program included three keynote presentations, two panel discussions, 27 technical sessions, and pre-symposium workshops. Among the papers presented at the Symposium, a total of 26 selected papers have been published in 3 refereed journals: 7 papers published in *Geo-spatial Information Science;* 13 papers published in the *Journal of Surveying Engineering*; 6 papers published in *Photogrammetric Engineering & Remote Sensing.*

One behalf of the Organising Committee of The 9th International Symposium on Mobile Mapping Technology (MMT 2015), General Chair Jinling Wang (Australia), Scientific Committee Chair Norbert Haala (Germany), Program Chair Charles Toth (USA) presented the "Outstanding Achievement Award" to Dorota A. Grejner-Brzezinska (USA), Naser El-Sheimy (Canada), Sheng Guo (China) in recognition of their pioneering contributions in developing and promoting mobile mapping technology.

(L. to R: J. Wang, N. Haala, S. Guo, N. El-Sheimy, D.A. Grejner-Brzezinska, C. Toth)

Working Groups of Sub-commission 4.2:

WG 4.2.1: Mobile Mapping Technologies and Applications

Chair: *J. Skaloud (Switzerland)*
Vice-Chair: *K.-W. Chiang (China-Taipei)*

Members

- *Hsiu-Wen Chang (Taiwan)*
- *Ismael Colomina (Spain)*
- *Davide Cucci (Switzerland)*
- *Michael Cramer (Germany)*
- *Craig Glennie (USA)*
- *Jen-kai Liao (Taiwan)*
- *Martin Rehak (Switzerland)*
- *Philipp Schaer (Switzerland)*
- *Guang-Je Tsai (Taiwan)*
- *Yi-Hsing Tseng (Taiwan)*
- *Julien Vallet (Switzerland)*
- *Jinling Wang (Australia)*
- *Ming Yang (Taiwan)*

Activities and publications during the period 2015-2017

Working Group 4.2.1 focuses on mobile mapping technology and applications. Mobile mapping technologies have been widely used to collect geospatial data for a variety of applications, for example, navigation and online geospatial information services. As mobile mapping sensors are becoming cheaper and easier to access, modeling and quality control procedures for major steps of mobile mapping should be further developed to ensure the reliability of geospatial data from mobile mapping systems. This working group conducts its work through coordinated activities among the members of the group as well as in collaborations with other professional organizations, such as ISPRS/FIG. Over the past two years, the following major activities are conducted:

EuroCOW 2016, The European Calibration and Orientation Workshop, 10-16 February 2016

The Chair and some members of the Working Group 4.2.1 organised the EuroCOW, the European Calibration and Orientation Workshop which was held from February 10th to February 12th, 2016 on the EPFL campus, located in Lausanne, Switzerland. This biennial meeting brought together the world experts, both from public and private sectors, to present and discuss the recent findings and developments on Sensor Calibration and Orientation. With the recent development of autonomous platforms, this traditional field of photogrammetry and geodesy integrates with robotics, computer vision and system control. The full papers from submitted to the EuroCOW 2016 are published in International Archive of Photogrammetry, Remote Sensing and Spatial Information Science at
http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-3-W4/index.html

EuroCOW 2017, Jointed held with ISPRS as a part of Hannover workshop, 6–9 June 2017, Germany

In mobile mapping related research on sensor calibration, image orientation, object extraction and scene understanding from images and image sequences, both geometry and semantics play an important role, and high quality results require appropriate handling of all these aspects. While individual algorithms differ according to the imaging geometry and the employed sensors and platforms, all mentioned aspects need to be integrated in a suitable workflow to solve most real-world problems (http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-1-W1/1/2017/isprs-archives-XLII-1-W1-1-2017.pdf). Under such observations, EuroCOW - European Calibration and Orientation Workshop, collaborating with other meetings (HRIGI - High-Resolution Earth Imaging for Geospatial Information, CMRT - City Models, Roads and Traffic, ISA - Image Sequence Analysis), co-organised a special event "Hannover workshop 2017". A total of 30 full papers were accepted for the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences at http://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-1-W1/index.html; while 99 papers are published in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-1/W1, 2017 (http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-1-W1/index.html)

Selected Publications

Lin, C.-A.; Chiang, K.-W.; Kuo, C.-Y. Development of INS/GNSS UAV-Borne Vector Gravimetry System, IEEE Geoscience and Remote Sensing Letters (Volume: 14, Issue: 5, May 2017), pp. 759 – 763

Chiang, K.-W.; Liao, J.-K.; Huang, S.-H.; Chang, H.-W.; Chu, C.-H. The Performance Analysis of Space Resection-Aided Pedestrian Dead Reckoning for Smartphone Navigation in a Mapped Indoor Environment. ISPRS Int. J. Geo-Inf. 2017, 6, 43.

Lai, Y.-C.; Chang, C.-C.; Tsai, C.-M.; Huang, S.-C.; Chiang, K.-W. A Knowledge-Based Step Length Estimation Method Based on Fuzzy Logic and Multi-Sensor Fusion Algorithms for a Pedestrian Dead Reckoning System. ISPRS Int. J. Geo-Inf. 2016, 5, 70.

Liao, J.-K.; Chiang, K.-W.; Zhou, Z.-M. The Performance Analysis of Smartphone-Based Pedestrian Dead Reckoning and Wireless Locating Technology for Indoor Navigation Application. Inventions 2016, 1, 25.

Kai-Wei Chiang, Jhen-Kai Liao, Guang-Je Tsai, Hsiu-Wen Chang * (2015, Dec). The Performance Analysis of the Map aided Fuzzy Decision Tree based on Pedestrian Dead Reckoning Algorithm in Indoor Environment. Sensors, 16(1), 34. 4.

Chiang, K.-W.; Tsai, M.-L.; Naser, E.-S.; Habib, A.; Chu, C.-H. (2015, Mar). New Calibration Method Using Low Cost MEM IMUs to Verify the Performance of UAV-Borne MMS Payloads. Sensors, 15, 6560-6585.

M. Rehak and J. Skaloud. *Time synchronization of consumer cameras on Micro Aerial Vehicles,* in Isprs Journal of Photogrammetry and Remote Sensing, vol. 123, num. 1, p. 114-123, 2017.

M. Khaghani and J. Skaloud. *Application Of Vehicle Dynamic Modeling In Uavs For Precise Determination Of Exterior Orientation.* 23rd Congress of the International-Society-for-Photogrammetry-and-Remote-Sensing (ISPRS), Prague, CZECH REPUBLIC, JUL 12-19, 2016. , International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences 41.

M. Rehak and J. Skaloud. *Applicability Of New Approaches Of Sensor Orientation To Micro Aerial Vehicles.* 23rd ISPRS Congress, Prague, Czech Republic, July 12-19, 2016. , International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences.

M. Khaghani and J. Skaloud. *Autonomous Vehicle Dynamic Model-Based Navigation for Small UAVs,* in Navigation-Journal of the Institute of Navigation, vol. 63, num. 3, p. 345-358, 2016.

M. Khaghani and J. Skaloud. *Autonomous Navigation Of Small Uavs Based On Vehicle Dynamic Model.*European Calibration and Orientation Workshop (EuroCOW), Lausanne, SWITZERLAND, FEB 10-12, 2016. , International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences.

M. Khaghani and J. Skaloud. *Evaluation of Wind Effects on UAV Autonomous Navigation Based on Vehicle Dynamic Model.* 29th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2016), Portland, Oregon, USA, September 12-16, 2016.

M. Khaghani and J. Skaloud. *Evaluation of Wind Effects on UAV Autonomous Navigation Based on Vehicle Dynamic Model.* 29th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2016), Portland, Oregon, USA, September 12-16, 2016.

J. Skaloud, I. Colomina, M. E. Parés, M. Blázquez and J. Silva et al. *Progress in airborne gravimetry by combining strapdown inertial and new satellite observations via dynamic networks.* 26th IUGG General Assembly, IAG Symposia, Prague, Czech Republic, June 22 - July 2, 2015.

R. Molinari, J. Balamuta, S. Guerrier and J. Skaloud. *An inertial sensor calibration platform to estimate and select error models.* IAIN World Congress 2015, Prague, Czech Republic, October 20-23, 2015.

S. Guerrier, R. Molinari and J. Skaloud. *Automatic Identification and Calibration of Stochastic Parameters in Inertial Sensors,* in Navigation-Journal Of The Institute Of Navigation, vol. 62, num. 4, p. 265-272,2015.

Y. Stebler, S. Guerrier and J. Skaloud. *An Approach for Observing and Modeling Errors in MEMS-Based Inertial Sensors Under Vehicle Dynamic,* in Ieee Transactions On Instrumentation And Measurement, vol. 64, num. 11, p. 2926-2936, 2015.

P. Clausen, J. Skaloud, P.-Y. Gilliéron, B. Merminod and H. Perakis et al. *Position accuracy with redundant MEMS IMU for road applications,* in European Journal of Navigation, vol. 13, num. 2, p. 4-12,2015.

M. Rehak and J. Skaloud. *Fixed-wing Micro Aerial Vehicle for Accurate Corridor Mapping.* UAV-g, Toronto, Canada, August 30-September 2, 2015.

J. Skaloud and D. Willli. *Prediction of phase ambiguity resolution based on signal intensity and geometry,*in Gps Solutions, vol. 19, num. 3, p. 467-474, 2015.

Working Group 4.2.2 Applications of Geodesy in Mining Engineering

Chair: *Jian Wang (China)*
Vice-Chair: *Frederick Cawood (South Africa)*

Members:

- *Abelardo Bethencourt Fernandez (Spain)*
- *Agrim. Diego Alejandro Piñón (Argentina)*
- *Alberto Hernández Moraleda (Spain)*
- *Aiguo Li (China)*
- *Afeni Thomas (Nigeria)*
- *Binghao Li (Australia)*
- *Dai Zhen (Germany)*
- *Fang Yang (China)*
- *Jinyun Guo (China)*
- *Kefei Zhang (Australia)*
- *Luciene Delazari (Brazil)*
- *Nesreen I Ziedan (Egypt)*
- *Vagner G. Ferreira (China)*
- *Vladimir Tikunov (Russia)*
- *Xiaolin Meng (UK)*

Activities and publications during the period 2015-2017

This study group aims at providing a platform for communicating the current research of the geospatial mapping, modern navigation and guidance technologies used in mining operations. The main focus in the past 2 years has been on several points that include underground/indoor positioning technology, new generation of positioning system for underground mine environments and GNSS and its synergized hazard monitoring. The group also aims to boost education and training of the geospatial technology used in mining operation for backward mine to increase safety. Hereafter, some of the work completed by individual group members in their research groups are summarized.

(1) Positioning in degenerated environment

In one study, a method based on the control points is used to determine the coordinates in advance in roadways of underground mine vehicles is proposed. the method, is necessary to correct the error state in INS / odometer integrated navigation system, which can increase the navigation accuracy. This method include three steps: i) to build a system dynamic model and observation model of INS /odometer integrated navigation system; ii) to propose a position modification filter equation based on known points; and iii) to produce a Parallel-Kalman filter to realize the dual filter of integrated navigation and INS /odometer integrated navigation system based on position modification for underground mine vehicle Overall, the results of the experiment indicated that the INS /odometer integrated navigation performance increased substantially by position modification of known points in roadways. Furthermore, the planimetric precision of real-time navigation increased from dozens of meters to meter scale which is able to meet the needs of navigation for underground mine vehicles.

In a second study, a tightly-coupled Global Position System (GPS)/Ultra-Wideband (UWB)/Inertial Navigation System (INS) cooperative positioning scheme using a Robust Kalman Filter (RKF) supported by V2I communication was developed and tested in degenerated environment. The scheme can provide ubiquitous location to be used in open-pit mine for miner navigation, trucker guidance and machine operating. An adaptive Robust Kalman Filter(RKF) was developed to further improve the reliability of the solution and the result proves that the RKF can eliminate the effects of gross errors. Additionally, the internal and external reliabilities of the system are enhanced when the UWB observables received from the moving terminals are involved in the positioning algorithm.

(2) Map aided underground/indoor positioning

An Improved PDR/ Magnetometers/Floor Map Integration Algorithm for Ubiquitous Positioning Using Adaptive Unscented Kalman Filter was proposed. Additionally, a scheme using a foot-mounted Inertial Measurement Unit (IMU) and a floor map to provide ubiquitous positioning in a number of settings, like in a supermarket as a shopping guide, for a fire emergency service for navigation, or a miner to be tracked was put forward. Firstly, several Zero-Velocity detection (ZDET) algorithms are compared and discussed when used in static detection of a pedestrian. By introducing the Zero-Velocity knowledge of the pedestrian, fusing magnetometers measurement, an improved Pedestrian Dead Reckoning (PDR) model is developed to constrain the accumulating errors of the PDR positioning. Secondly, the Correlation Matching Algorithm based on map projection (CMAP) is presented and zone division of a floor map is demonstrated for fusion of the PDR algorithm. At last, in order to use the knowledge of dynamic characteristics of a pedestrian trajectory, the Adaptive Unscented Kalman Filter (A-UKF) is applied to tightly integrate IMU, magnetometers and floor map for the ubiquitous positioning. The performance observed in a field experiment confirms that the proposed scheme can reliably achieve meter-level positioning.

Another scheme for indoor positioning by fusing floor map, WiFi and smartphone sensor data to provide meter-level positioning without additional infrastructure was advanced. A topology-constrained KNN algorithm based on a floor map layout provides the coordinates required to integrate WiFi data with pseudo-odometry (P-O) measurements simulated using a pedestrian dead reckoning (PDR) approach. One method of further improving the positioning accuracy is to use a more effective multi-threshold step detection algorithm, as proposed by the authors. The performance observed in a field experiment performed on the fourth floor of the School of Environmental Science and Spatial Informatics (SESSI) building on the China University of Mining and Technology (CUMT) campus confirms that the proposed scheme can reliably achieve meter-level positioning.

(3) New generation of positioning system for Underground Mine Environments

On 19 April 2017, a meeting on the study of the new generation of positioning system for Underground Mine Environments was held at Xuzhou, China, experts from the China University of Mining and Technology, the University of New South Wales and the RMIT University come to a conclusion that the new generation underground positioning system should include multi-sensors such as: accelerometer, magnetometer and gyroscope. In which the fusion algorithm should consider intelligence algorithm. The meeting also discussed a prototype for meter level accuracy positioning for persons and machines, to locate and manage the persons and machines, to navigate the persons in emergency in mine environment.

(4) Effort on building an international platform for geoinformatics communications

The chair and vice chair of this working group are working for building an international platform for communicating in related research and education area. The purpose is to involve several Universities and research institutes. As a starting point, Wits University and CUMT sponsored a joint research lab on 27 October 2016 at CUMT Nanhu Campus, Xuzhou, Jiangsu Province, China.

Eleven African scholars from nine African countries, namely, Liberia, Sudan, Gabon, Cameroon, Namibia, Madagascar, Togo, Zambia and Mozambique, participated in the opening ceremon.

For the moment, the core content of the lab include: (i) Geospatial positioning, GNSS system and equipment use(Including China BeiDou system) indoor positioning systems, real-time underground positioning systems linked to mine plan, remote sensing and positioning of mine hazards, hardware and software development and manufacturing of world-first technologies for underground mining; (ii) mobile and underground platforms, SLAM technology systems, mobile and underground platforms - Position, Navigate and Time (PNT) ,laser scanning for ground movement risk monitoring and modelling, autonomous rail systems with robotics; (iii) digital/smart mining, remote sensing technologies detecting risks, environmental monitoring and climate control underground, security video analytics, cloud computation, hazard/risk maps; (iv) education and training for African countries, training and education on GNSS , 21st century mining skills, skills to manufacture new technologies, installation and maintenance of technology systems designed in the joint laboratory, education and skills development for technicians and professionals of technology systems designed in the joint laboratory, mining law and policy unit covering African countries. This is only the first step. More efforts should be made by the members in future to boost the development of the platform.

The Digital Mining research laboratory at Wits University is also collaborating on digital mining technologies with NUST University in Pakistan on 21st century mining, including some research on national mineral policy and mining cadastre development. The ultimate objective is to use technology to put distance between mine workers and the typical risks they are exposed to on a daily basis. This objective is achieved by transferring surface digital technologies into the underground environment. Recently completed and existing research projects include: (i) Extension of surface real-time wireless communication systems into the underground environment. The challenge is for wireless systems to work reliably – all the time and for the system to cope with live streaming of data; (ii) On positioning, mapping and navigation, significant work includes test work that proves that sidewall survey stations meet the accuracy and other legal geospatial requirements for safe mining; research and installation of indoor-positioning systems that include both relative and absolute (geodetic) coordinates systems, and a testing facility for scanning and positioning from a moving platform; (iii) Action recognition and detection of abnormalities through combining positioning, video analytics and biometric information; (iv) Remote, visual, inspections through the development of an underground UAV with the capability to position, map, navigate and detect harmful volatile compounds and gases.

Selected publications

Ashraf, H. and Cawood, F.T. Geospatial Subsidence Hazard Modelling at Sterkfontein Caves. South African Journal of Geomatics, Vol. 4, No. 3, August 2015 and Position IT Feb 2016 edition.

Bojja, Jayaprasad, et al. "Pedestrian localization in moving platforms using dead reckoning, particle filtering and map matching." Acoustics, Speech and Signal Processing (ICASSP), 2015 IEEE International Conference on. IEEE, 2015.

Chen, Yan-Xiu. "Underground Coal Mine Positioning System Based on RSSI Positioning Algorithm Improved Through the BP Learning Training." Open Energy & Fuels Journal 8 (2015).

Du Y, Li B, Chen M. (2016) Surges induced in building electrical systems during a lightning strike. Electric Power Systems Research, 139: 68-74.

Grobler, HCI. Spatial positioning of sidewall stations in a narrow tunnel environment: A safe and accurate alternative to traditional mine survey practice. PhD Thesis, University of the Witwatersrand, South Africa, 2015.

Grobler H. (2016) Azimuth determination by gyroscope, 50 years later, has anything changed? International society of Mine Surveyors, Brisbane, Australia, September 2016, pp 105-112.

Han H, Wang J, Wang J, et al. (2017) Reliable partial ambiguity resolution for single-frequency GPS/BDS and INS integration. GPS solutions, 21(1): 251-264.

Hussain, I. Channel modelling and analysis of Wits Mock-Mine with different antenna parameters. MSc 50:50 Research Report, University of the Witwatersrand, South Africa, 2017.

Hussain, I., Cawood, F.T and Von Olst, R. Effect of Tunnel Geometry and Antenna Parameters on Through-The-Air Communication Systems in Underground Mines: Survey and Open Research Areas, Physical Communication (Elsevier), Mar 2017.

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Sun T, Ferreira V G, He X, et al. (2016) Water availability of São Francisco river basin based on a space-borne geodetic sensor. Water, 8(5): 213.

Wang G, Turco M, Soler T, Kearns T, Welch J (2017) Comparisons of OPUS and PPP solutions for subsidence monitoring in the greater Houston area. J. Surv. Eng. (accepted)

Wang J, Gao Y, Li Z, et al. (2016) A tightly-coupled GPS/INS/UWB cooperative positioning sensors system supported by V2I communication. Sensors, 16(7): 944.

Wang J, Hu A, Liu C, et al. (2015) A floor-map-aided WiFi/pseudo-odometry integration algorithm for an indoor positioning system. Sensors, 15(4): 7096-7124.

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WG 4.2.3: Mobile Structural Health Monitoring Systems

Chair: *Christian Eschmann (Germany)*
Vice Chair: *Johnson Shen (Australia)*

Members

- *Matthias Bartholmai (Germany)*
- *Edouard Burrier (France)*
- *João Caetano (Portugal)*
- *Hui Deng (China)*
- *Fuyang Ke (China)*
- *Patrick Neumann (Germany)*
- *Ralf M. Moryson (Germany)*
- *Björn Schäfer (Germany)*
- *Ali Al-Shaery (Saudi Arabia)*
- *Alexander Velizhev (Switzerland)*
- *Jinling Wang (Australia)*

Activities and publications during the period 2015-2017

Working Group 4.2.3 focuses on structural health monitoring (SHM) which is an issue of increasing importance when looking at more and more aging and critical infrastructure around the world. Both traditional and emerging geodetic techniques may be considered to carry out SHM tasks. In order to perform safety-related infrastructure inspections, robotic solutions are required to allow an automatic and reliable geospatial data acquisition for a comprehensive building database suitable for SHM analysis. Here the investigation of new mapping and navigation methods as well as non-destructive testing (NDT) sensors forms the basis for these mobile SHM systems. To develop such reliable autonomous systems, this working group will focus on current challenges such as the reproducibility and traceability of mobile NDT sensor data as well as the precise localization and navigation operations inside and/or in the areas close to infrastructures. Over the past two years, the working group members have conducted the following research activities:

(1) Studies on the possible usage of highly automated systems in the field of SHM

Due to the recent technological progress in robotics and sensor engineering, automated remote sensor systems finally are more and more accepted as an appropriate means even for critical investigations such as infrastructural inspection and monitoring. Regarding the usage of mobile - especially unmanned - systems in terms of future structural health monitoring applications, the requirements for those systems clearly point out important criteria concerning commercial implementation. Comprehensive studies have shown that both ground vehicle systems and their flying counterparts can be useful tools when it comes to optimizing monitoring processes. The automation of those systems is particularly difficult with regard to safe use with less as well as specially trained personnel. In addition, the integration of applications into common processes, e.g. in the case of remotely-piloted aircraft systems (RPAS) their integration into national or sovereign airspace, is still being limited due to national regulations.

Our conclusions are:
a) Redundancy of safety-related functions of unmanned systems (e.g. data link, power supply, communication) is an important basis for everyday economic use.

b) High degree of automation is necessary for any kind of SHM system with respect to user friendliness and safe usage in terms of urban applications.
c) Continuing R&D activities as a kind of lobbying for the establishment of a widespread acceptance on the official level of mobile systems as a comprehensive means for assessment purposes.

(2) Cloud Platform for SHM and Warming based on Multiple Sensors

The cloud platform SHM and Warming consists of GNSS and vision sensors, Cloud Service Center and APP. The GNSS stations can monitor the structure surface deformation at mm level accuracy in real time. The sensors can acquire the hydrogeological and atmospheric parameters. The vision sensors can detect the environment around the monitoring objects by image recognition technology. Then GNSS measurements and images can be sent to cloud service center via optical fibre or wireless network. And the structural health state parameters will be obtained in real time based on the multi-sensors and vision fusion on Cloud service center. At the same time, the cloud service center will forecast the structural health state parameters based on intelligent forecast model and historical data. The health parameters and warming message can be achieved and sent to managers by Web, E-mail or App. The GNSS and Sensor Cloud Platform is developed by the team led by Dr. Fuyang Ke at Nanjing University of Science Information and Technology and has been applied in many national key projects in China. It will be continuously improved for an artificial intelligence system in future.


Sensor installation for Cloud Platform for SHM and Warming at engineering sites in China

(3) Conferences, meetings, other WG activities

Since the topic of mobile SHM systems is quite diversified, activities have been carried out in the field of robotics, automation, flight system dynamics, data fusion as well as remote sensing. In this context, the working group team members therefor attended a variety of conferences, e.g. IMAV 2015, MMT2015, CBA-UAS 2016 and 19th WCNDT 2016, as well as related workshops. Due to past events and short-term changes, the 2016 WG meeting could not take place as planned but will be re-scheduled together with a second meeting in 2018.

Planned activities for the period 2017-2019

So far, working group meetings are scheduled to take place at the 12th ECNDT (European conference on Non-Destructive Testing) in Gothenburg, Sweden as well as at the ICRA 2018 (IEEE International Conference on Robotics and Automation) in Brisbane, Australia. In order to follow up on the aspect of limitations of airborne systems due to national regulations, discussions with the UAV DACH association will be continued on a European level, amongst others at the RPAS 2018 conference.

Selected publications

Caetano, J. V., Percin, M., van Oudheusden, B. W., Remes, B., De Wagter, C., de Croon, G. C. H. E., & de Visser, C. C. (2015). Error analysis and assessment of unsteady forces acting on a flapping wing micro air vehicle: free flight versus wind-tunnel experimental methods. Bioinspiration & biomimetics, 10(5), 056004.

Engelhardt, T., Konrad, T., Schäfer, B., & Abel, D. (2016). Flatness-based control for a quadrotor camera helicopter using model predictive control trajectory generation. In Control and Automation (MED), 2016 24th Mediterranean Conference on (pp. 852-859). IEEE.

Eschmann, C., & Wundsam, T. (2017). Web-Based Georeferenced 3D Inspection and Monitoring of Bridges with Unmanned Aircraft Systems. Journal of Surveying Engineering, 143(3), 04017003.

Deng H., Li H., Cheng S., Jiang Y (2017) Monitoring and analyzing dispalcement of large-span spoke type cable strcuture roof. Journal of Surveying Engineering, 143(4), 06017001.

Kurz, J. H., Moryson, R. M., Prybyla, D., Chassard, C., Wundsam, T., Exner, J. P. (2016). CURe MODERN-French-German Infrastructure Inspection, Urban and Regional Planning. 19th World Conference on Non-Destructive Testing, WCNDT 2016 : Munich, Gemany, 13-17 June 2016.

Neumann, P. P., Bennetts, V. H., Lilienthal, A. J., & Bartholmai, M. (2016). From insects to micro air vehicles—A comparison of reactive plume tracking strategies. In Intelligent Autonomous Systems 13 (pp. 1533-1548). Springer International Publishing.

Schäfer, B. E., Picchi, D., Engelhardt, T., & Abel, D. (2016). Multicopter unmanned aerial vehicle for automated inspection of wind turbines. In Control and Automation (MED), 2016 24th Mediterranean Conference on (pp. 244-249). IEE

WG 4.2.4: Building Information Modelling

Chair: *Mohsen Kalantari (, Australia)*
Vice Chair: *Michael Olsen (USA)*

Members
- *Behnam Atazadeh (Australia)*
- *Jack C.P. Cheng, (China)*
- *Yichuan Deng (China)*
- *Craig Hanock (China)*
- *Shubhi Harbola (India)*
- *Josh Plager (USA)*
- *Pingbo Tang (USA)*
- *Yelda Turkan (USA)*
- *Jinling Wang (Australia)*
- *Zita Ultmann (Australia)*

Activities and publications during the period 2015-2017

This new working group was formed in December 2015. The focus of our activities has been to grow membership in the working group, collaborate and develop relationships with similar working groups in other organizations, and formulate the scope for the committee. The members have been active in publishing work related to the objectives of the working group within their individual research groups. They are also participating in organizing several workshop events in collaboration with other entities. The working group has been an excellent forum to share these results with one another.

1. **Mobile Mapping Technology Conference** (December 2015, Sydney Australia). Several working group members presented publications at this conference. Some of these publications evolved into peer-reviewed Journal publications that were published in a special collection of the Journal of Surveying Engineering.
2. **FIG Working Week** (May 2016, Christchurch, New Zealand). WG members were active in presenting relevant publications to the WG at this conference. In addition, the working group had an initial meeting at the conference to begin planning events such as the 2017 FIG "BIM for Surveyors" workshop as well as the "BIM and GIS Integration" workshop (described below).
3. **IAG Commission 4 Symposium: Positioning and Applications** (September 2016, Wroclaw Poland). Vice-Chair Olsen attended the IAG Commission 4 meeting in Wroclaw Poland to represent the Working Group as well as present a paper at the symposium.
4. **BIM for Surveyors,** Joint Workshop with FIG, 28 May 2017. WG Members Kalantari, Olsen, and Handcock all presented at the workshop. Several additional speakers were invited to participate.
   Scope of the Workshop
   - Teaching theoretical background of the BIM method (concepts, workflows and standards)
   - Best practice presentations from large projects and SME (from surveyor's point of view)
   - Presentation of the latest software (surveying, integration and collaboration with BIM, CAD, GIS)

   Audience
   - International professionals from AEC-companies (engineering surveyors) and land administration agencies (land surveyors).

- Young professionals interested in this new technology for own projects
- Academics from different countries (just a few universities teach BIM until now)
- Selected students and young professionals from the FIG Young Surveyors Network.

Proceedings were published online at the FIG website: https://www.fig.net/fig2017/bim.htm

5. **International Workshop on Computing in Civil Engineering (IWCCE, ASCE Computing Division)** (June 2017, Seattle Washington). Working group member Pingbo Tang is the Vice Chair of the organizational committee for this conference and WG members Olsen and Turkan are serving on the Technical Committee. These WG members will present research related to topics of BIM, 3D modelling, and structural monitoring. The workshop will be used to connect with and identify additional members for the IAG working group as well as identify possible collaborations with the ASCE Computing Division with the working group.
6. **BIM and GIS Integration Workshop** 25 Oct 2017

   This is the first workshop organised by the International Association of Geodesy (IAG) on Building Information Modelling (BIM) and Geographic Information Systems (GIS) integration as an emerging area of research and development. Our working group has been actively planning this workshop.

   The effective integration of BIM and GIS provides opportunity for application across many domains including architecture, urban planning, disaster management, infrastructure engineering, facilities management, construction, policy and decision making.

   This workshop focuses on integration challenges and considers the technical, legal and institutional barriers in bringing BIM and GIS together. Topics will include, but are not limited to:

   - Legal and institutional considerations
   - Integrated collaborative environments
   - Standards in BIM and GIS
   - Level of details and level of development
   - Interoperability and geo-referencing
   - Integration for Decision Science and Risks
   - Automatic change analysis between BIM and GIS models
   - 3D visualisation
   - Virtual design and construction
   - Virtual reality and augmented reality
   - Algorithms to generate BIM/GIS models from point cloud data
   - BIM and GIS integration with 3D point clouds

   Details are available http://3dgeoinfo2017.com

Selected Publications

Kalasapudi, V. S., Tang, P., and Turkan, Y. (accepted) "A Computationally Efficient Approach for Automatic Change Analysis of Large-Scale Building Systems." Elsevier Journal of Automation in Construction. Accepted in March 2017, DOI:10.1016/j.autcon.2017.04.001.

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Aien, A., Rajabifard, A., Kalantari, M., Williamson, I. (2017). Review and Assessment of Current Data Models for 3D Cadastral Applications, Advances in 3D Geoinformation -Lecture Notes in Geoinformation and Cartography, DOI 10.1007/978-3-319-25691-7_24

Nolan, J., Eckels, R., Olsen, M.J., Yen, K.S., Lasky, T.A., and Rvani, B. (In Press). "Analysis of the multi-pass approach for collection and processing of mobile laser scan data," *Journal of Surveying Engineering,* Special Issue on Mobile Mapping Technology. http://dx.doi.org/10.1061/(ASCE)SU.1943-5428.0000224

Behnam Atazadeh, Mohsen Kalantari, Abbas Rajabifard, Serene Ho, Tom Champion (2016). Extending a BIM-based data model to support 3D digital management of complex ownership spaces, International Journal of Geographical Information Science, DOI: 10.1080/13658816.2016.1207775

Behnam Atazadeh, Mohsen Kalantari, Abbas Rajabifard (2016). Comparing Three Types of BIM-based Models for Managing 3D Ownership Interests in Multi-level Buildings, 5th International FIG Workshop on 3D Cadastres, 18-20 October 2016, Athens, Greece.

R Jin, C Hancock, L Tang, C Chen, D Wanatowski, L Yang, Empirical Study of BIM Implementation–Based Perceptions among Chinese Practitioners, Journal of Management in Engineering 33 (5), 04017025, 2017

R Jin, L Tang, C Hancock, L Allan, BIM-based Multidisciplinary Building Design Practice-A Case Study, 7th International Conference on Energy and Environment of Residential Buildings

Rahman, R. A., Alsafouri, S., Tang, P., Ayer, S. K. (2016) "Building Information Modeling Skills for Career Success." Academic Interoperability Coalition (AIC) 10th BIM Academic Symposium & Job Task Analysis Review, Gainesville, FL, USA, 4 – 5 April 2016.

Rahman, R. A., Alsafouri, S., Tang, P., Ayer, S. K. (2016) "Comprehending Building Information Modeling Skills of Project Managers based on Social Media Analysis." International Conference on Sustainable Design, Engineering and Construction, Tempe, AZ, USA, 18 – 20 May 2016

Mahmoudabadi, H., Olsen, M.J., & Todorovic, S., (2016). "Efficient point cloud segmentation utilizing computer vision algorithms." *Journal of Photogrammetry and Remote Sensing*, 119C, 135-150, doi: 10.1016/j.isprsjprs.2016.05.015

Roe, G.V., O'Banion, M.S., and Olsen, M.J. (2016). "Mobile Lidar Guidelines to Support Utility Asset Management Along Highways," Proc. UESI Pipelines Conference, 2016, Kansas City, Missouri.

Alomari, K., Gambatese, J., & Olsen, M.J. (2016). "The role of BIM and 3D laser scanning on jobsites from the perspective of construction project management personnel." Construction Research Congress, 2016, Puerto Rico.

Guo F., Jahren C.T., Turkan Y., Jeong D. (2016), Civil Integrated Management: An Emerging Paradigm for Civil Infrastructure Project Delivery and Management, ASCE Journal of Management in Engineering, 04016044.

Puri N., Turkan Y. (2016), Fusing 4D BIM and 3D Point Clouds for Dimensional Quality Control of Precast Concrete Slabs and Walls, Proc. of the 16th International Conference on Construction Applications of Virtual Reality (CONVR), Hong Kong.

Son H., Kim C., Turkan Y. (2015), Scan-to-BIM – An Overview of Current State of the Art and a Look Ahead, Proc. of 32nd International Symposium on Automation and Robotics in Construction (ISARC), Oulu, Finland.

Tang, P., Chen, G., Shen, Z., and Ganapathy, R. (2015). "A Spatial-Context-Based Approach for Automated Spatial Change Analysis of Piece-Wise Linear Building Elements." Computer-Aided Civil and Infrastructure Engineering, in press, DOI: 10.1111/mice.12174.

Alsafouri, S., Ayer, S., and Tang, P. (2015). "Mobile VDC Adoption in Practice." The 15th International Conference on Construction Applications of Virtual Reality (CONVR), October 5-7, 2015, Banff, Alberta, Canada.

Craig Hancock Llewellyn TangRuoyu Jin, H De Light, Luke Allan, (2016). Building Information Management and Modelling Teaching in Geospatial Engineering, Civil Engineering and Architecture, FIG Working Week 2016

Tashakkori, H., Rajabifard, A., Kalantari, M. (2015). A new 3D indoor/outdoor spatial model for indoor emergency response facilitation, Journal of Building and Environmen Building and Environment, V. 89, pp 170-182

Sabri, S., Pettit, C. J., Kalantari, M., Rajabifard, A., Lade, O., & Ngo, T. (2015). What are Essential requirements in Planning for Future Cities using Open Data Infrastructures and 3D Data Models?14th International Conference on Computers in Urban Planning and Urban Management, Boston, M

Sub-commission 4.3: Atmosphere Remote Sensing

Chair: *Michael Schmidt (Germany)*
Vice Chair: *Jaroslaw Bosy (Poland)*
Secretary: *Mahmut O. Karslioglu (Turkey)*

Overview

The SC 4.3 is composed of one Study Group and nine Working Groups. Besides, several SC 4.3 members participate in other IAG Joint Study Groups (JSG) related to atmosphere remote sensing, for instance, the IAG-ICCT JSG 0.20: “Space weather and ionosphere” chaired by Klaus Börger (Germany) and the IAG JSG 1.3: “Troposphere Ties” chaired by Robert Heinkelmann (Germany).

The most important meeting of the SC 4.3 chairs and vice chairs within the reporting period 2015 - 2017 took place on Monday, September 5th, 2016, during at IAG Commission 4 Symposium, at the Wroclaw University of Environmental and Life Sciences. Further SC 4.3 meetings happened during the SGI Workshops at the Technical University of Berlin in 2015 and 2016. Many splinter meetings of the Study and Working Groups took place, for instance, during the European Geosciences Union General Assemblies (EGU-GA) held in Vienna, Austria, in April 2016 and April 2017. In addition, members of the SC 4.3 organized and chaired several sessions within these and other conferences and symposia.

Concerning the SC 4.3. topic “Space Weather” a new GGOS Focus Area (FA 4) was accepted by the GGOS Coordinating Board Meeting on April 22nd, 2017 in Vienna. This FA 4 is titled “Geodetic Space Weather Research” and is chaired by Michael Schmidt; the vice chair is Klaus Börger.

On the next pages, the different Study and Working Groups of the SC 4.3 give an overview about their work within the last two years, i.e. the reporting period.

Study Groups of Sub-commission 4.3

SG 4.3.1: Ionospheric and Atmospheric Coupling Processes and Phenomena: Modeling and Measurements

Chair: *Lucie Rolland (France)*
Vice Chair: *Attila Komjathi (USA)*

No report was provided

Working Groups of Sub-commission 4.3

WG 4.3.1: Real-time Ionosphere Monitoring

Chair: *Alberto Garcia-Rigo (Spain)*
Vice Chair: *David Roma Dollase (Spain)*

Members

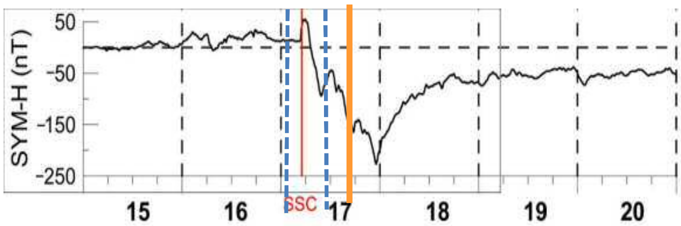
- *Andrzej Krankowski (Poland),*
- *Anna Krypiak-Gregorczyk (Poland),*
- *Attila Komjathy (USA),*
- *David Altadill (Spain),*
- *Denise Dettmering (Germany),*
- *Eren Erdogan (Germany),*
- *Estefania Blanch (Spain),*
- *Haris Haralambous (Cyprus),*
- *Ivan Galkin (USA),*
- *Jean-Marie Chevalier (Belgium),*
- *Jens Berdermann (Germany),*
- *Joachim Feltens (Germany),*
- *Loukis Agrotis (UK),*
- *Manuel Hernandez-Pajares (Spain),*
- *Martin Kriegel (Germany),*
- *Michael Terkildsen (Australia),*
- *Nicolas Bergeot (Belgium),*
- *Ningbo Wang (China),*
- *Panagiotis Vergados (USA),*
- *Raul Orús Pérez (The Netherlands),*
- *René Zandbergen (Germany),*
- *Reza Ghoddousi-Fard (Canada),*
- *Tamara Gulyaeva (Russia),*
- *Tim Fuller-Rowell (USA),*
- *Yannick Béniguel (France),*
- *Zishen Li (China)*

Activities and publications during the period 2015-2017

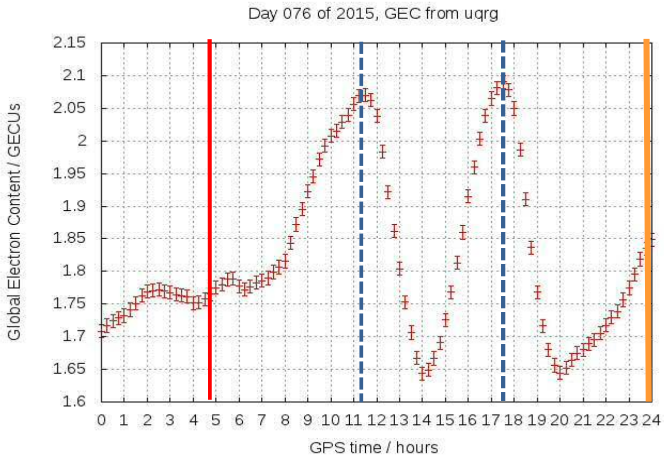
At first, a dedicated Google Form was distributed among the members in order to obtain their feedback on the interests and expectations on this WG as well as their real-time (RT) and near real-time (NRT) products. This served also to look for new potential objectives of the WG based on the interests of the members themselves.

Comparison of the different real time (RT) and near real time (NRT) results have been obtained for St. Patrick geomagnetic storm, showing the clear impact on different products, either based on GNSS or ionosonde analysis (covering multiple ionospheric parameters such as Total Electron Content (TEC), foF2, hmF2, B0 and the ionospheric disturbance W-index, scintillation S4 and σ_φ, among others). This research activity has led to two main publications: European Geosciences Union 2017 Poster presentation and IAG Commission 4 Positioning and Applications Symposium 2016 Oral presentation (see below).

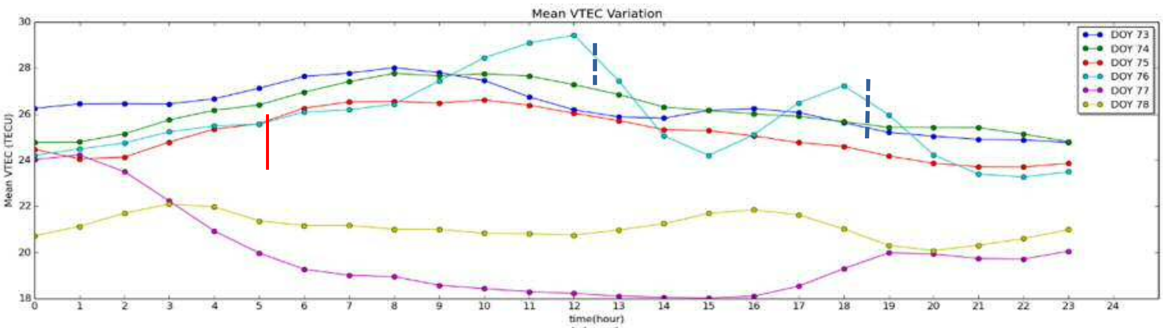
As it is shown in Figures 1 and 2 (built from different plots provided in the above-mentioned publications), existing RT and NRT ionospheric approaches complement very well to each other, allowing a detailed study of events like the St. Patrick's day ionospheric storm. In particular, the impact on ionosphere seems correlated with the geomagnetic activity. The different geomagnetic peaks (Kp peaks and local minima of Dst/SYM-H are correlated with Global Electron Content (GEC) peaks, VTEC measurements, digisonde measurements as well as ionospheric disturbances being monitored by members of the WG.



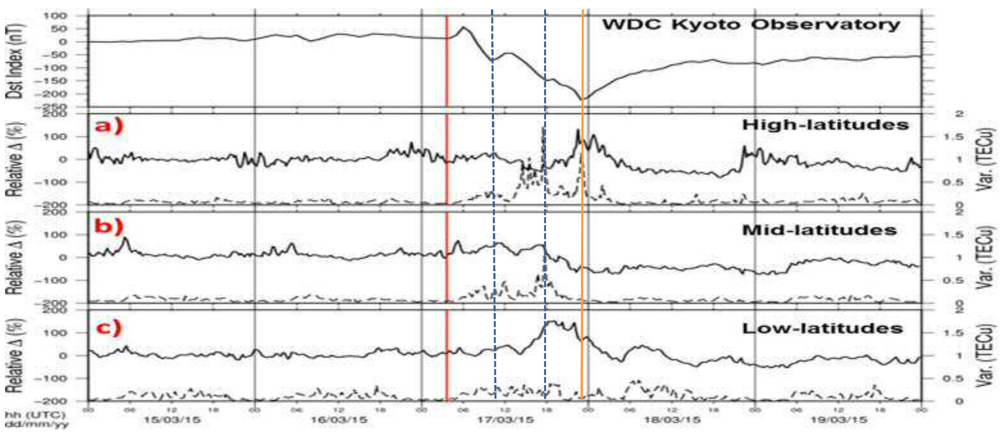
(1.a)



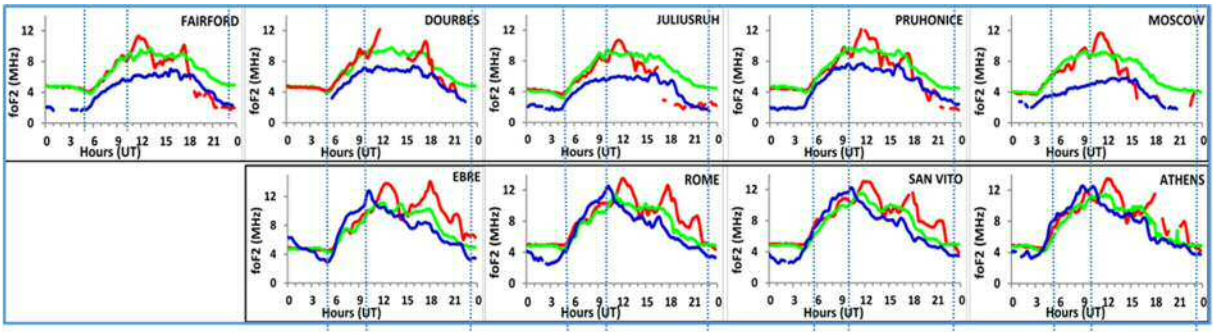
(1.b)



(1.c)

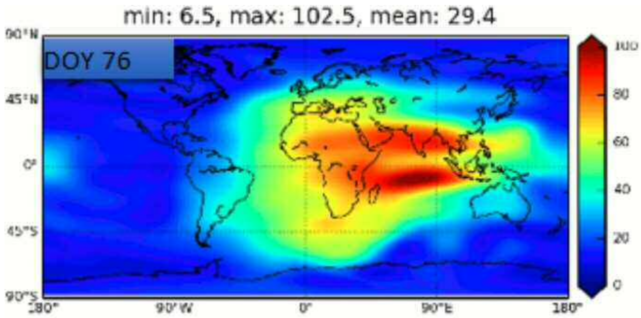


(1.d)

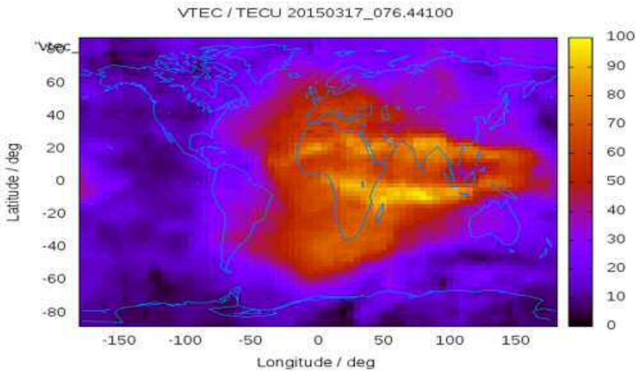


(1.e)

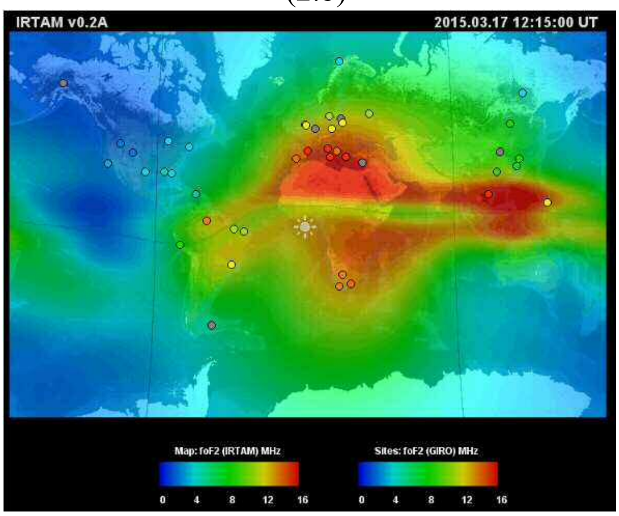
Figure 1: (1.a) SYM-H geomagnetic index, (1.b) Global Electron Content from UQRG GIMs, (1.c) mean VTEC variations of Data-Adaptive TUM-DGFI NRT maps, (1.d) ROB VTEC variations wrt previous 15 days at different latitudes, (1.e) foF2 maps for several digisondes



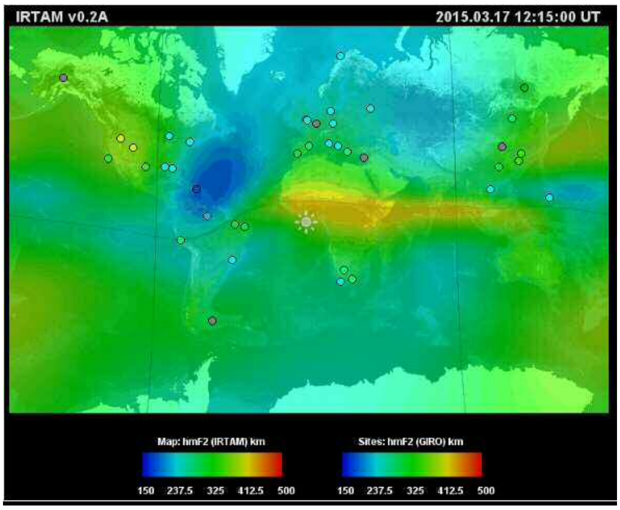
(2.a)



(2.b)



(2.c)



(2.d)

Figure 2: Doy 76, around 12h data. (2.a) DGFI/TUM GIM (2.b) UPC's URTG GIM (2.c and 2.d) foF2 and hmF2 global maps from IRTAM, UMASS Lowell.

Regarding the analysis of RT/NRT VTEC Global Ionospheric Maps (GIMs), which is another major goal within the team, a comprehensive study has been published at Beacon Satellite Symposium 2016 Poster presentation and a manuscript on this study is about to be submitted to Journal of Geodesy. This analysis can be extended based on existing real-time and near real-time ionospheric VTEC models within RTIM-WG, supporting the IONEX format.

In addition, the experiences on RT/NRT dissemination (format being used to encapsulate the products –e.g. RTCM SSR messages, IIWG SAO format, Net-CDF, own format– as well as the way to broadcast RT/NRT data to the potential users/scientific community –e.g. NTRIP caster, GIRO, local FTP–) are being looked for within the WG to promote discussion on this open topic. This has been done by means of a dedicated Google Form. Special attention is being paid on latency of the products as well as the possibility to combine real time VTEC global datastreams within the team, which could be a potential collaboration between IGS RT-WG and IAG's RTIM-WG.

Last but not least, an Oral presentation - entitled "Contributions to real time and near real time Ionosphere Monitoring by IAG's RTIM-WG" - has been accepted at IAG-IASPEI 2017, to be held in Kobe, Japan end of July/beginning of August. Also, it is worth mentioning that a splinter meeting was done at EGU 2017 congress.

RTIM-WG publications

García-Rigo, Alberto, et al.: RTIM-WG: IAG's Real Time Ionosphere Monitoring Working Group Current status, outcomes and first results, IAG Commission 4 Positioning and Applications Symposium, September 5, 2016, Wroclaw, Poland.

Roma-Dollase, David, et al.: Real Time Global Ionospheric Maps: a low latency alternative to traditional GIMs. Poster at Beacon Satellite Symposium 2016, June 27 2016, Trieste, Italy.

García-Rigo, Alberto, et al.: St. Patrick's Day 2015 geomagnetic storm analysis based on Real Time Ionosphere Monitoring". Poster presentation at European Geosciences Union 2017, April 2017, Vienna, Austria (Highlighted poster by the conveners of the session).

Other related publications by RTIM-WG members

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WG 4.3.2: Ionosphere Predictions

Chair: *Mainul Hoque (Germany)*
Vice Chair: *Eren Erdogan (Germany)*

Members

- *Claudia Borries (Germany),*
- *Nada Ellahony (Egypt),*
- *Adria Rovira Garcia (Spain),*
- *Abraham Stern (USA),*
- *Mahdi Alizadeh (Iran),*
- *Marta Cueto Santamaría (Spain),*
- *Aliaa Abd-Elnasser (Egypt),*
- *Alberto Garcia-Rigo (Spain),*
- *Manuel Hernandez Pajares (Spain),*
- *Norbert Jakowski (Germany),*
- *Jens Berdermann (Germany),*
- *Michael Schmidt (Germany), Enric Monte (Spain)*

Activities and publications during the period 2015-2017

To realize the WG 4.3.2 objectives and goals, group members accomplished individual activities as well as worked in cooperation with other group members. The progress during the period 2015-2017 is briefly described below.

The group members working at UPC-IonSAT have re-established the generation of predicted GIMs for one and two-days ahead (U1PG and U2PG, respectively). At the moment, an analysis on these data is being conducted before they are made public again through IGS. Apart from that, UPC-TALP is implementing new potential algorithms to improve forecasts -also for the short-term- and analysing the obtained results for years 2014 and 2016.

At DGFI-TUM, the focus for VTEC forecasting is on setting up a harmonic analysis based on Fourier series expansion extended by an Autoregressive Moving Average (ARMA) model.

To be more specific, the VTEC is represented by a series expansion in tensor products of polynomial B-splines in latitude and trigonometric B-splines in longitude. The corresponding series coefficients estimated by Kalman filtering are forecasted by the Fourier series and the ARMA model representing the deterministic and the stochastic model part. The Fourier coefficients are estimated from the time series of the B-Spline coefficients from the previous 5 days. Finally, the extrapolated series coefficients provide the forecasted VTEC values.

Rovira-Garcia et al. (2015, 2016) worked on extending ionosphere model to provide a world-Wide coverage, showing that it is able to reduce the convergence of Precise Point Positioning and its agreement with observations from Low Earth Orbit (LEO) satellites.

Besides above mentioned work, there are other specific tasks accomplished and published by the group members. These are briefly explained below:

Comparison among different TEC prediction approaches:

As an initiative from the working group WG 4.3.2, Hoque et al. (2017a) compared total electron content (TEC) prediction approaches/results from different centers contributing to this WG 4.3.2 such as German Aerospace Center (DLR), Universitat Politècnica de Catalunya (UPC), Technische Universität München (TUM) and GMV (see Table 1).

The presented work enables the possibility of comparing TEC prediction approaches/results from different centers. Different TEC prediction approaches outlined in the study will certainly help to learn about forecasting ionospheric ionization. More intensive validation studies using independent TEC data are planned.

TEC prediction at a GPS station:

An important characteristic of the GPS constellation is that the same satellite appears in the same part of the sky with a period of approximately 4 minutes less than one day. This brings the same ray path geometry when looking to the same satellite from a location on Earth. Hoque et al. (2016a, b) found that this repetition can be successfully used for predicting TEC along a receiver-satellite link. They proposed a new approach for predicting TEC at a GPS station assuming that looking to a satellite in the same part of the sky from the same location on Earth brings nearly the same geophysical conditions for link related TEC estimation. They found that during quiet ionospheric condition the approach can predict slant TEC at a mid-latitude station with mean and standard deviations from reference values of about 0 and 1.5 TECU (1 TECU = 1.e+16 el/m^2), respectively. During perturbed condition the mean and standard deviations are found as about 0 and 3.9 TECU, respectively. They found that the new approach can successfully predict slant TEC several hours in advance if severe ionospheric storms are excluded. The following Figure shows prediction performance at gope and adis stations during quiet and perturbed ionospheric condition.

Table 1: Comparison among different TEC prediction approaches (reprinted from Hoque et al. 2017a)

Center	**TEC**	**TEC prediction approach**	**TEC prediction performance**
DLR	NTCM	model-assisted (27-day median) TEC forecast algorithm taking benefit from actual trends of the TEC behavior at each grid point	over Europe,1 hour forecast, RMS error is below 4 and 5 TECU during quiet (20 May – 3 Jun 2015) and perturbed period (12-26 Mar 2015), respectively
UPC	TOMION	linear regression to a temporal window of TEC maps in the Discrete Cosine Transform (DCT) domain	global, up to 48-hour forecast, RMS discrepancy of U2PG wrt IGSG below 6 and 8 TECU during quiet & perturbed period, resp., considering JASON2 data as reference
DGFI-TUM	B-splines	Fourier series analysis of the B-spline coefficients using the last 5 days data sets	global, RMS deviations of the forecasted maps with respect to IGS final products exhibit around 5 and 7 TECU for the quiet and perturbed periods, respectively
GMV	--	ionospheric delay estimated from previous epochs using GNSS data and the main dependence of ionospheric delays on solar and magnetic conditions	over Europe, 0.5 hour forecast, RMS error below 3 TECU and over Latin American & Africa, 0.5 & 1 hour forecast, RMS error below 8 TECU

TEC prediction during solar eclipse:

Hoque et al. (2016c) investigated the possibility of modelling the TEC response and subsequent prediction during a solar eclipse. GNSS users can benefit from TEC depletion modelling during a solar eclipse. If the TEC depletion can be predicted in advance from such modelling activities, GNSS operators can either improve their broadcast delay/TEC information or inform users about the TEC depletion estimate depending on their location with respect to the eclipse path. Hoque et al. (2016) found up to 6 TECU depletion in the vertical TEC estimate around the shadow spot which can be 2-3 times higher in slant TEC estimates at low elevation angles, indicating range errors of up to 2 – 3 meter in single frequency GNSS positioning.

New TEC prediction model for current GNSS:

Very recently, Hoque et al. (2017b) investigated the possibility of driving Neustrelitz TEC Model (NTCM) by the GPS Klobuchar coefficients. Since Klobuchar model coefficients are estimated based on GNSS TEC data obtained during previous day, it is indeed a prediction model 24 hours ahead. Therefore, NTCM driven by Klobuchar parameter will predict TEC 24 hours ahead. They found that the NTCM driven by Klobuchar model parameters can perform significantly better than the mother Klobuchar model. Using post processed reference total electron content (TEC) data from more than one solar cycle, they found that on average the RMS modelled TEC errors are up to 40% less for the proposed NTCM model compared to the Klobuchar model during high solar activity period, and about 10% less during low solar activity period. Such an approach does not require major technology changes for GPS users rather requires only introducing the NTCM approach a complement to the existing ICA algorithm while maintaining the simplicity of ionospheric range error mitigation with an improved model performance.

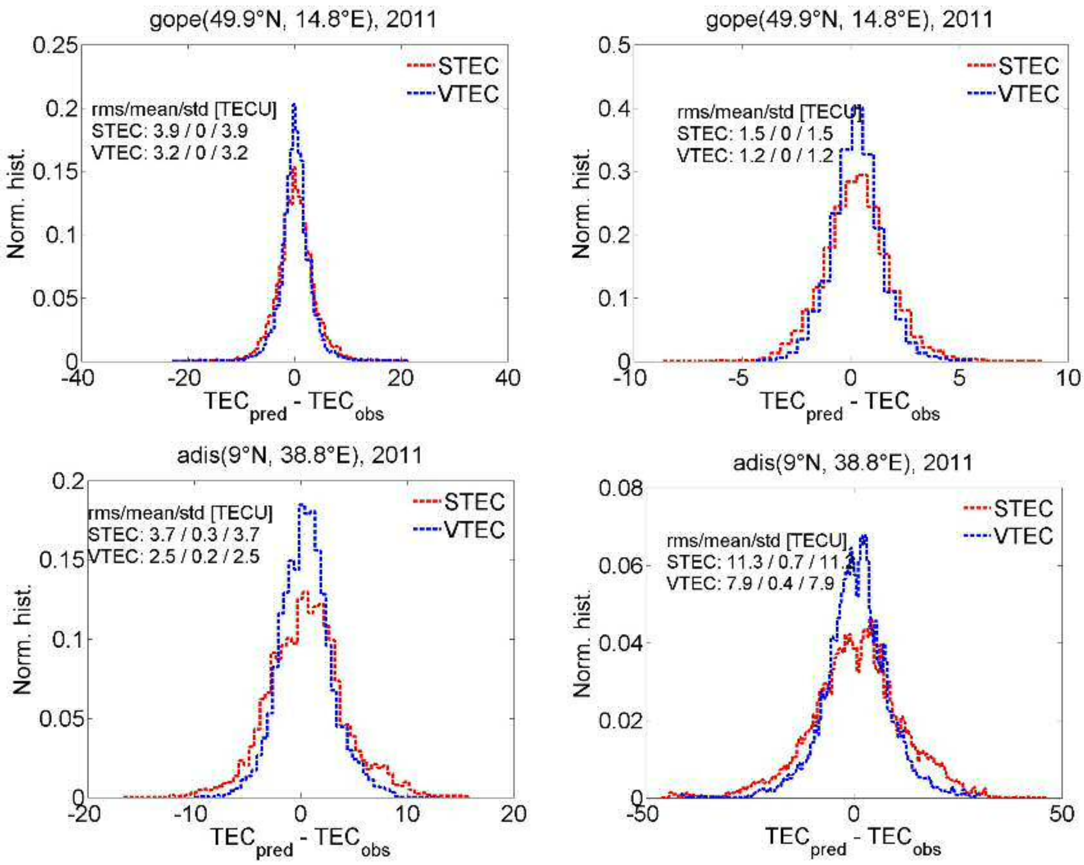

Figure 1: Prediction performance at gope and adis stations during quiet (left panels) and perturbed ionospheric period (right panels) (reprinted from Hoque et al. 2016b)

Recently Badeke et al. (2016) compared four empirical models such as 27-day median model, Fourier series based approach, NTCM and NeQuick 2 for a reliable 24 hour ahead forecast of the TEC over Europe. Their investigation shows that the 27-day median model performs better than other approaches during geomagnetically quiet conditions.

TEC prediction model for future GNSS:

Hoque and Jakowski (2015) and Hoque et al. (2015) proposed an alternative ionospheric correction algorithm called Neustrelitz TEC broadcast model NTCM-BC to be used as an ionosphere prediction model in future global satellite navigation systems. Like the GPS ICA or Galileo NeQuick, the NTCM-BC can be optimized on a daily basis by utilizing GNSS data obtained at the previous day at monitor stations. Their investigation using GPS data of about 200 worldwide ground stations shows that the 24 hour ahead prediction performance of the NTCM-BC is better than the GPS ICA and comparable to the Galileo NeQuick model. They found that the 95 percentiles of the prediction error are about 16.1, 16.1 and 13.4 TECU for the GPS ICA, Galileo NeQuick and NTCM-BC, respectively, during a selected quiet ionospheric period whereas the corresponding numbers are found about 40.5, 28.2 and 26.5 TECU during a selected geomagnetic perturbed period. However, in terms of complexity the NTCM-BC is easier to handle than the Galileo NeQuick and in this respect comparable to the GPS ICA.

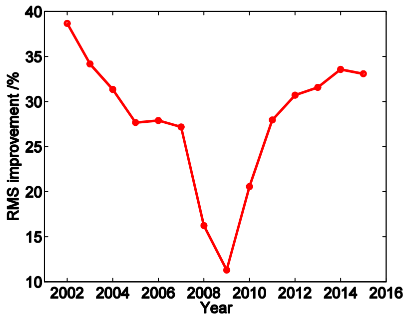

Figure 2: NTCM improvement with respect to the Klobuchar model (reprinted from Hoque et al. 2017b)

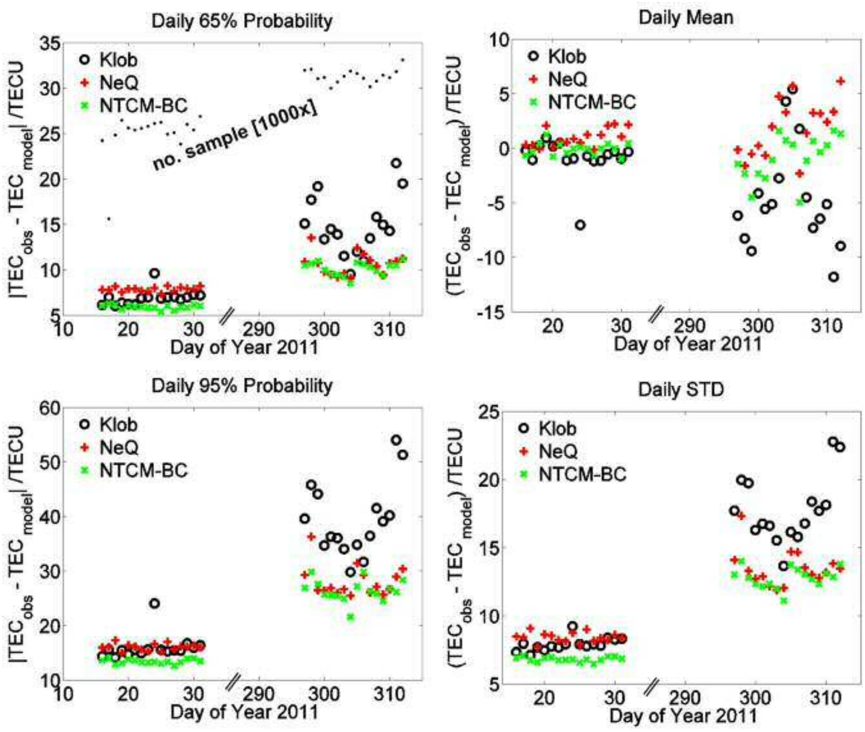

Figure 3: The top- and bottom-left plots show daily 65% and 95% probability of TEC prediction error, respectively, during quiet and perturbed days. The top- and bottom-right plots show corresponding daily mean and std values. The number of samples and corresponding scale are given in the top-left plot. (Reprinted from Hoque and Jakowski 2015)

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WG 4.3.3: Combination of Observation Techniques for Multi-Dimensional Ionosphere Modelling

Chair: *Mahdi M. Alizadeh (Iran)*

Members

- *Claudio Brunini (Argentina),*
- *Francisco Azpilicueta (Argentina),*
- *Robert Weber (Austria),*
- *Lyubka Pashova (Bulgaria),*
- *Mainul Hoque (Germany),*
- *Roman Galas (Germany),*
- *Jens Wickert (Germany),*
- *Robert Heinkelmann (Germany),*
- *Jens Berdermann (Germany),*
- *Eren Erdogan (Germany),*
- *Dudy Wijaya (Indonesia),*
- *Saeed Zare (Iran),*
- *Kinga Wezka (Poland),*
- *Anderzej Krankowski (Poland),*
- *Manuel Hernandez-Pajares (Spain),*
- *Lung-Chih Tsai (Taiwan),*
- *Mahmut O. Karslioglu (Turkey),*
- *Anthony Mannucci (USA),* Chen Peng (USA)

Activities and publications during the period 2015-2017

Co-organizing SGI 2015 Workshop in Berlin

The Satellite Geodesy and Ionosphere research (SGI2015) workshop was held at the Technical University of Berlin during 7 and 8 July 2015. The workshop initially aimed at bringing together geodesists and other scientists from all over the world to one meeting, dealing with geodetic sciences and ionospheric research. The workshop was co-organized by Mahdi Alizadeh from the Institute of Geodesy and Geoinformation Science of the Technical University of Berlin and Department 1 'Geodesy and Remote Sensing' of the German Research Centre for the Geosciences (GFZ). Within this workshop Michael Schmidt, chair of the IAG Sub-Commission 4.3 "Atmosphere Remote Sensing" presented the ToR of the Sub-Commission and the intention of establishing ionosphere-related working and study groups within the Sub-Commission. Discussions were carried out about the topics of different study/work
ing groups and the proposed chairpersons of each group (see IAG Newsletter – July 2015).

Organizing SGI 2016 Workshop in Berlin

The second Satellite Geodesy and Ionosphere research workshop (SGI2016) was held at the Technical University of Berlin during 8 and 9 August 2016 as an activity of IAG Joint Working Group 4.3.3 "Combination of Observation Techniques for Multi-dimensional Ionosphere Modeling". The SGI2016 was organized by the Institute of Geodesy and Geoinformation Science of the Technical University of Berlin, K.N.Toosi University of Technology at Tehran, Iran and Department 1 'Geodesy and Remote Sensing' of the German Research Centre for the Geosciences (GFZ) Potsdam. The workshop provided a great opportunity for scientists to meet in a friendly atmosphere and to share their research and latest findings. In the discussion session Michael Schmidt presented the activities of the IAG Sub-Commission 4.3: "Atmosphere Remote Sensing” during the last year and explained the study, working, and joint working groups established during since last year. Some information was given about the GGOS-Days in Frankfurt in October 2015 and that GGOS has already developed three focus areas. Discussions were carried out about establishment of a fourth Focus Area related to Atmosphere, including impact of both troposphere and ionosphere on modern society, long term variations of the atmosphere, and the role of atmosphere in gravity missions.

Within this workshop members of JWG 4.3.3 discussed their activities and their plan for the following year (see IAG Newsletter – August 2016).

Attending GGOS Bureau of Networks and Observations meeting in Vienna

Due to close relation of the aims of Working Group 4.3.3 and the IAGs’ Global Geodetic Observing System (GGOS), this working group was decided to act as a Joint Working Group with GGOS; therefore several correspondence were accomplished with Michael Pearlman, chair of GGOS to extend collaborations.

With this respect, on April 26th 2017, Mahdi Alizadeh was invited to participate in the GGOS Bureau of Networks and Observations meeting in Vienna. There he introduced the IAG sub-commission 4.3 and explained the aims and objectives of JWG 4.3.3, discussions were carried out about the possibilities of extending collaboration of the JWG and GGOS in the future (http://ggosdays.com/en/meetings/2017/bno_vienna_2017/).

Future plans

The JWG 4.3.3 members plan to extend collaboration with GGOS by performing consistent combination of various observation techniques for modeling the parameters of the ionosphere. Within this procedure, however, the stochastic information mostly is not incorporated appropriately, e.g., no correlations are considered in GPS observations, or the Radio Occulation measurements are used to compute electron density values via the Abel transform, but without considering the correlations. Another plan of the JWG 4.3.3 is the incorporation of COSMIC-2 and ionosonde data. These solutions would support GGOS and its goals very much and would also directly contribute to the new GGOS Focus Area, which is related to the Atmosphere. The future plans of the JWG 4.3.3 are all building blocks of future ionosphere products, which can be interpreted as GGOS outcome.

WG 4.3.4: Ionosphere and Troposphere Impact on GNSS Positioning

Chair: *Tomasz Hadas (Poland)*
Vice Chair: *Simon Banville (Canada)*

Members

- *Mainul Hoque (Germany),*
- *Jan Kaplon (Poland),*
- *Amir Khodabande (Australia),*
- *Thalia Nikolaidou (Canada / Greece),*
- *Junbo Shi (China),*
- *Rafal Sieradzki (Poland),*
- *Toshiaki Tsujii (Japan),*
- *Pavel Vaclavovic (Czech Republic),*
- *Duojie Weng (China),*
- *Kinga Wezka (Germany / Poland),*
- *Chaoqian Xu (China / Canada)*

Activities and publications during the period 2015-2017

Group members realized the goals of WG 4.3.4 in their individual activities as well as in cooperation with other group members. So far, studies concerned the impact of several ionosphere-related effects on GNSS positioning and GNSS signal propagation, as well as on Precise Point Positioning (PPP) supported with numerical weather prediction models.

On the cooperation level, members of WG concentrated on Higher-Order Ionospheric (HOI) effects. HOI, if not properly accounted for, can propagate into geodetic parameter estimates. For this reason, several investigations have led to the development and refinement of formulas for the correction of second- and third-order ionospheric errors, bending effects and total electron content (TEC) variations due to excess path length. Standard procedures for computing HOI terms typically rely on slant TEC computed either from global ionospheric maps (GIMs) or using GNSS observations corrected using differential code biases (DCBs) provided by an external process. Since both of these approaches are relying on external outputs, it was deemed suitable, in the context of the WG, to investigate another approach to mitigate HOI effects. Members of WG 4.3.4 have therefore investigated the feasibility of estimating slant ionospheric delay parameters accounting for both first- and second-order ionospheric effects directly within a PPP solution. The analysis conducted showed that, with a proper handling of the receiver DCB, the PPP method is able to mitigate HOI effects to the same level as existing approaches. The approach is however not entirely free from external inputs since GIMs are required for isolating the receiver DCB, unless the latter is provided to the PPP filter. A paper by Banville et al. (2017) summarizing these findings has been submitted to GPS Solutions and is currently under review.

Hoque et al. (2017) investigated HOI propagation effects on trans-ionospheric microwave links used in the time and frequency transfer applications. Such a metrology link must provide frequency and time comparison and dissemination with an uncertainty level of 10^{-18} and beyond. Their investigation shows that for achieving such an accuracy level the HOI propagation effects must be corrected for.

In a separate study Hoque et al. (2016) investigated the magnitude of HOI effects using worldwide ground-based GPS data from both quiet and perturbed ionospheric and geomagnetic activity periods. They found that the range computation between a satellite and a ground receiver during perturbed periods is affected by up to 10 cm due to HOI terms and can significantly degrade the accuracy of PPP especially during times of high TEC values. This indicates that the dual-frequency range equation should have additional terms for correcting HOI terms if centimeter level precision is required.

Sieradzki and Paziewski (2015, 2016) proposed to modify undifferenced phase observables using rate of TEC (ROT) corrections in order to mitigate the dynamic Total Electron Content (TEC) variations (ionospheric disturbances). The application of these corrections in a preliminary step of data processing allows leveling of ionospheric delays for particular arc and consequently treating this parameter as a constant during the entire session. The efficiency of the proposed algorithm was evaluated using rapid static positioning with the ionosphere-weighted model for different latitudes and ionospheric conditions, i.e. mid-latitudes affected by medium scale travelling disturbances and strongly disturbed high latitudes during space weather event on 17.03.2013. The results obtained for the modified algorithm have shown significant improvement of ambiguity success rate (ASR) for European and circumpolar ionosphere. The performed analysis has also confirmed that the application of the new approach leads to the continuous increase in ASR depending on session length. Finally, it is worth to notice that the proposed algorithm does not require any an external modelling of ionospheric conditions and can be easily implemented in multi-GNSS positioning, including both relative and absolute methods.

In other ionosphere-related studies, Fujiwara and Tsujii (2016) characterized the effects of equatorial plasma bubbles on received GNSS signals and derived the model of loss-of-lock probability. Wezka et al. (2016) were working on reliability monitoring of GNSS positioning under the influence of strong ionospheric perturbations (scintillations). Finally, Khodabandeh and Teunissen (2016) made use of S-system (singularity-system) theory and developed an undifferenced multi-frequency formulation of the GNSS observation equations. Such formulation enables one to interpret estimable forms of the GNSS parameters, including the first-order slant ionospheric delays. The estimability and precision of multi-frequency GNSS-derived slant Total Electron Content (TEC) was analyzed through closed-form expressions of the ionospheric solutions. The widely used phase-to-code levelling technique was generalized to its multi-frequency version. In particular, they showed that only certain specific linear combinations of the GNSS observables, i.e. the time-differenced data, contribute to the TEC solutions.

Troposphere-related research was also conducted by several group members. At the Geodetic Observatory Pecny (GOP), two software applications for tropospheric parameters estimation have been developed: G-Nut/Shu and G-Nut/Tefnut. While the former is based on meteorological information from a numerical weather model, the latter exploits GNSS data. In parallel, GOP have also developed another tool for precise positioning and investigated backward smoothing for precise GNSS applications (Václavovic and Douša, 2015). Each of these applications can be used for individual purposes, however, their combination is also highly valuable. Estimated tropospheric parameters can be introduced in precise positioning and improve precision and robustness of estimated station coordinates, particularly high-altitude components. This approach can be used offline as well as in real-time processing. To show benefits of introducing external tropospheric parameters in positioning, Václavovic et al. (2017) arranged an experiment with a hot air balloon, where a GNSS receiver was carried up to 2000 meters above the earth surface. They have demonstrated that external tropospheric corrections significantly helped in ZTD-height mutual decorrelation and hence improved the positioning performance. The improvement was most significant in case of poor satellite constellation. It was also demonstrated by Wilgan et al. (2017) that a troposphere model combined from GNSS and NWM data can significantly contribute to real-time PPP, improving the accuracy and precision of receiver height and reducing the initialization time.

Research was also conducted towards the improvements in troposphere modelling using GNSS data. An optimal weighting method based on posterior unit weight variances was developed for GPS PPP-based troposphere tomography (Jiming et al. 2016). A modified Saastamoinen model was proposed, in which systematic error were reduced from -3mm to nearly zero, compared with the benchmark values calculated by meteorological data from 91 radiosonde stations distributed worldwide (Zhang et. al, 2016). Moreover, Douša et al. (2015) monitored NWM forecast with near real-time GNSS products. Finally, the impact of real-time satellite clock errors on GPS PPP-based troposphere delay estimation was investigated by Shi et al., 2015. The authors found that among available satellite real-time products, those with better satellite clock precision yield more precise troposphere zenith delay.

Recent improvements in troposphere modelling using GNSS and NWM products as well as several demonstrations on how troposphere model can support (real-time) PPP (e.g. Yao et al. 2017), motivated some group members to design and perform a campaign with high-dynamic kinematic data. In this experiment, a GNSS antenna will be mounted on a UAV in order to record high-frequency (20 Hz) multi-GNSS data during a dynamic UAV flight, including rapid altitude changes. Meanwhile, several ground receivers located close to the area of experiment will act as reference stations, so that a reference flight track can be determined in state-of-the-art post-processing software. The goal is to identify drawbacks of classical real-time positioning techniques (RTK and PPP) and to develop potential alternatives. In particular, PPP with an advanced modelling of troposphere delay and mapping functions will be investigated. Troposphere parameters, zenith delay and mapping functions, will be derived from high-resolution regional NWM calibrated by real-time GNSS troposphere products derived from a sparse network of ground receivers. It is also planned to provide the observation data to GNSS community and establish a competition between various research group in determining the most accurate and precise flight track.

Last but not least, the WG 4.3.4 members Hadas and Kaplon represented the group in Local Organization Committee of the IAG Commission 4 Symposium in Wroclaw. It was a great opportunity to recruit more members, who have already contributed with their studies to the goals of this WG.

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WG 4.3.5: Ionosphere Scintillations

Chair: *Lung-Chih Tsai (Taiwan)*
Vice Chair: *Jens Berdermann (Germany)*

Members

- *Suvorova Alla (China-Taipei),*
- *Chi-Kuang Chao (China-Taipei),*
- *Kai-Chien Cheng (China-Taipei),*
- *Alexei V. Dmitriev (China-Taipei),*
- *Rui Fernandes (Portugal),*
- *Yoshihiro Kakinami (Japan),*
- *Chinmaya Kumar Nayak (India),*
- *Ernest Macalalad (Philippines),*
- *Charles L. Rino (USA),*
- *Michael Schmidt (Germany),*
- *Kuo-Hsin Tseng (China-Taipei),*
- *Sudarsanam Tulasiram (India)*

Activities and publications during the period 2015-2017

1st mini-workshop on Ionosphere Scintillations, Taoyuan, Dec. 4, 2015. The workshop presentations include: Use of GNSS for geophysical applications: from secular to second (Dr. Rui Manuel da Silva Fernandes), Recent surface deformation of the Himalaya and Adjoining Piedmont Zone of the Ganga Plain, Uttarakhand, India (Prof. Chung-Pai Chang, Taiwan), Mid-latitude ionospheric scintillations over Irkutsk (Dr. Alexei V. Dmitriev), Ionospheric irregularities in COSMIC data over Pacific and forbidden electrons (Dr. Alla Suvorova, Russia), Ionospheric observations, N_e specification, modeling, and their applications (Prof. Lung-Chih Tsai).

Dr. Rui Manuel da Silva Fernandes established a CORS (Continuously Operating Reference Station) GNSS system in December of 2015 at Chungli, and to support common researches on scientific and technical applications of GNSS.

2nd mini-workshop on Ionosphere Scintillations, Taoyuan, Feb. 19, 2016. The workshop presentations include: Space weather and its influence on the Ionosphere (Dr. Jens Berdermann), Ionospheric propagation of very low frequency radio waves and advances in solar flare analysis (Dr. Daniela Wenzel, Germany), Equatorial plasma bubbles observed from Equatorial Atmosphere Radar (EAR) over Indonesia (Dr. Sudarsanam Tulasiram), Advanced Ionospheric Probe onboard FormoSat-5 Satellite for ionospheric scintillation study (Prof. Chi-Kuang Chao), Mid-latitude ionospheric scintillations over Irkutsk (Dr. Alexei V. Dmitriev), H2020 project in Taiwan (Dr. Alla Suvorova), Ionospheric observations, N_e specification, modeling, and their applications (Prof. Lung-Chih Tsai).

Daniela Wenzel and Dr. Jens Berdermann established a station of the Global Ionospheric Flare Detection System (GIFDS) in February of 2016 at Chungli, Taiwan to receive very low frequency (VLF) radio signals transmitted from India, Australia, Hawaii, Japan, etc. The fifth station at the National Central University in Taiwan completed the flare detection network GIFDS. GIFDS can analyse VLF signals to identify solar flare events and their temporal progression. In addition GIFDS is able to measure and analyse sudden ionospheric disturbances (SIDs) in the D-layer Ionosphere caused by solar flares. Finally GIFDS can be used to study the impact of solar flare events on the occurrence and strength of ionospheric scintillations.

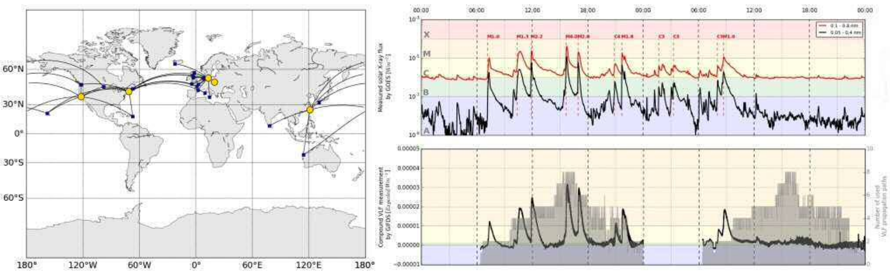

Figure 1: The GIFDS network and associated radio propagation paths (left panel) and Comparison of the compound VLF measurement with the GOES X-ray during solar flare activities (right panel).

3rd mini-workshop on Ionosphere Scintillations, Taoyuan, Dec. 2, 2016. The workshop presentations include: A configuration space model for stochastic ionospheric structure (Dr. Charles L. Rino, USA), The International Reference Ionosphere: from climate to real-time weather predictions for Earth's Ionosphere (Dr. Dieter Bilitza, USA), Recurrent ionospheric storms (Dr. Alexei V. Dmitriev), Atmospheric ionization by energetic electrons at the low latitudes (Dr. Alla Suvorova), Suppression of ionospheric scintillation during St. Patrick's Day geomagnetic super storm as observed over the anomaly crest region station Pingtung, Taiwan: A case study (Dr. Chinmaya Nayak, India).

Setup and first analysis of a small scale ionospheric disturbances using a high-rate GNSS network in Bahir Dar. Small scale ionospheric disturbances may cause severe radio scintillations of signals transmitted from global navigation satellite systems (GNSS). Consequently, small scale plasma irregularities may heavily degrade the performance of current GNSS such as GPS, Glonass or Galileo. Ionosphere modeling and monitoring over the African and South American sector is of great interest due to spread of the so called equatorial anomaly region over it. This region experiences equatorial plasma bubbles, blobs, irregularities which may cause scintillation especially during evening and nighttime hours. DLR installed and operates in Bahir Dar together with the partner institutions TUB and IEEA a small scale high rate GNSS receiver network (50 Hz) in order to estimate the drift velocity and the size of the so called "Plasma Bubbles".

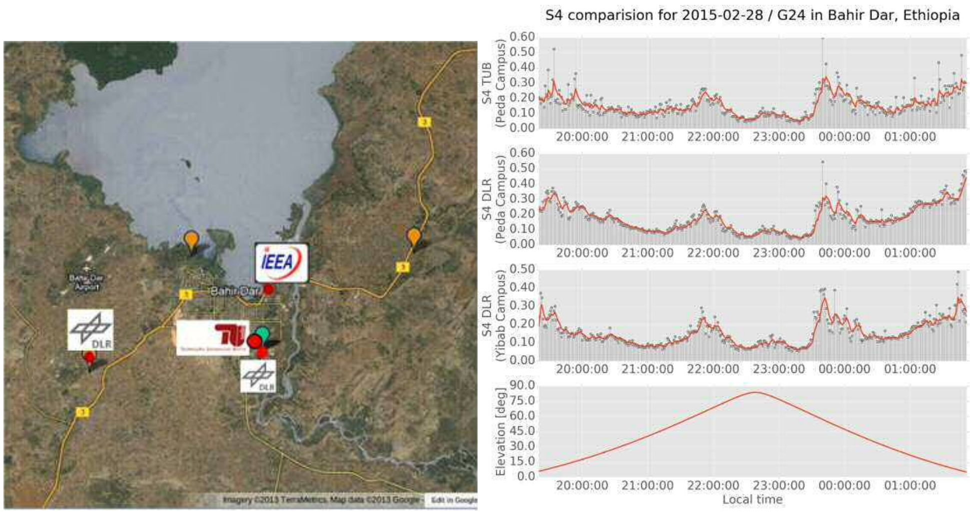

Figure 2: Small scale high-rate GNSS network of DLR,TUB and IEEA in Bahir Dar (left panel). The right panel shows the signature of S4 indices calculated for satellite G24 using different scintillation receivers and processors in comparison to the averaged elevation (below) [Kriegel at al 2017].

Publications

Ajith K K., S. Tulasi Ram, M. Yamamoto, T. Yokoyama, V. S. Gowtam, Y. Otsuka, T. Tsugawa, K. Niranjan (2015), Explicit characteristics of evolutionary type plasma bubbles observed from Equatorial Atmosphere Radar during the low to moderate solar activity years 2010-2012, *Journal of Geophysical Research*, 120, doi:10.1002/2014JA020878.

Ajith K. K., S. Tulasi Ram, M. Yamamoto, Y. Otsuka and K. Niranjan, On the fresh development of Equatorial Plasma Bubbles (EPBs) around the midnight hours of June solstice (2016), *Journal of Geophysical Research*, 121, doi:10.1002/2016JA023024.

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Tsai, L.-C., S.-Y. Su and C.-H. Liu (2016), Global morphology of ionospheric F-layer scintillations using FS3/COSMIC GPS radio occultation observations, *GPS Solutions*, doi:10.1007/s10291-016-0591-4.

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Wenzel, D., Jakowski, N., Berdermann, J., Mayer, Chr., Valladares, C., Heber, B. (2016), Global Ionospheric Flare Detection System (GIFDS), *Journal of Atmospheric and Solar-Terrestrial Physics*, 233-242, doi: 10.1016/j.jastp.2015.12.011.

WG 4.3.6: Troposphere Tomography

Chair: *Witold Rohm (Poland)*

Members

- *Hugues Brenot (Belgium),*
- *Michael Bender (Germany),*
- *Michal Kacmarik (Czech Republic),*
- *Toby Manning (Australia),*
- *Alain Gaiger (Switzerland),*
- *Zhizhao (George) Liu (Hong Kong China),*
- *Zohre Adavi (Iran),*
- *Laurent Morel (France),*
- *Gregor Moeller (Austria),*
- *Krzysztof Kroszczynski (Poland),*
- *Cédric Champollion (France),*
- *Yan Xin (Austria),*
- *Andre Sa (Portugal),*
- *Eric Pottiaux (Belgium)*

Activities and publications during the period 2015-2017

The Working Group is currently looking into three major topics:

Quality assurance factors in GNSS tomography processing [QUALITY]

Currently, we are investigating use of the following quality assurance indicators:

- linearised resolution operator (R) of the model space that provides information about the number of resolved parameters and the quality of the resolution,
- normalised misfit function is used to evaluate the apriori variance-covariance information contained in the apriori and observation part of the tomography normal equation system,
- iterative algorithms using variance component analysis are applied to ballance out the impact of observations and apriories,
- local and global tests based on the residual analysis are also in place.

Use of tomography retrievals in severe weather investigation [SEVERE]

The study of application of GNSS observation is base of two distinct cases:

1. Australian severe weather that involved testing of multiple tomography model settings and multiple models (TOMO2, BIRA, TUW, VUT, SWART) validating using data from radiosondes, Numerical Weather Model (analysis step) and Radio Occultation (Fig.1).

The testing involved 21 steps in total testing use of apriori data (step1 to step4 – major work in previous ToR), data stacking (step7 to step9), pseudo-slant solution (step10 to step13), data uncertainty on solution (step14 to step17), to test of the impact of more realistic uncertainty on solutions (step18 to step21).

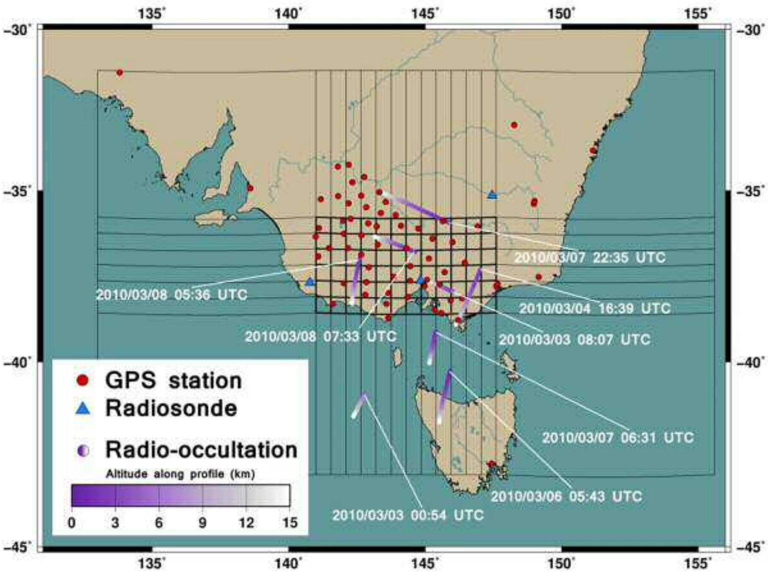

Figure 1: Location of CORS GPS stations, RS sites, RO profiles and the tomographic grid (in black).

The major outcomes are as follows:

- We show that the GNSS tomography results is comparable to the NWM ACCESS-R, retrieved from the analysis step and containing assimilated observations from: ATVOS, Radiosondes, buoys, ship, etc.. Moreover our solution is similar to the model in the location of radiosonde, which has largest weights in the assimilation system. This means that the model might have accuracy of analysis step of NWM, across the whole domain.
- In the case of stacked data, especially for 5 observation epochs every 30 minutes solved in one combined set of normal equations, tomography solution is better than ACCESS-R field in the bottom part of the troposphere below 2000m (Fig.2).
- Pseudo-observations introduced as an additional input tot he observation matrix does not improve solution,
- Adding more uncertainty to apriori data only cause the solution to stick less to the apriori, which cause to improve slightly solution aroud 2000m. Combination of data stacking and loosing constraints is optimal solution that stick to the apriori in the ground part and improves solution around 2000m.
- RO profile 2010_063_1639 located over Alpine region has strong inversion reproduced by tomography models but not visible in the ACCESS-R model, this might mean that ACCESS-R model have not resolved complex orography weather.

2. Poland, widespread precipitation. Another aspect of tomography monitoring for severe weather is linked with widespread precipitation. The applied tomography model (TOMO2) allows to get full picture of troposphere at all locations covered by GNSS network. In this study we investigate: 1) the meteorological correctness of the tomography retrieval, 2) whether the 15 new temporal and spatial resolution of the troposphere water vapour content will provide new information regarding these well studied events. Two events were investigated one in May 2014 and one in August/September 2014, the tomography retrievals compared with radiosonde profiles and numerical weather prediction (NWP) model. Currently, the retrieved data are analysed and prepared for presentation at EMS Annual Meeting: European Conference for Applied Meteorology and Climatology 2017 and publication in Atmospheric Measurement Techniques.

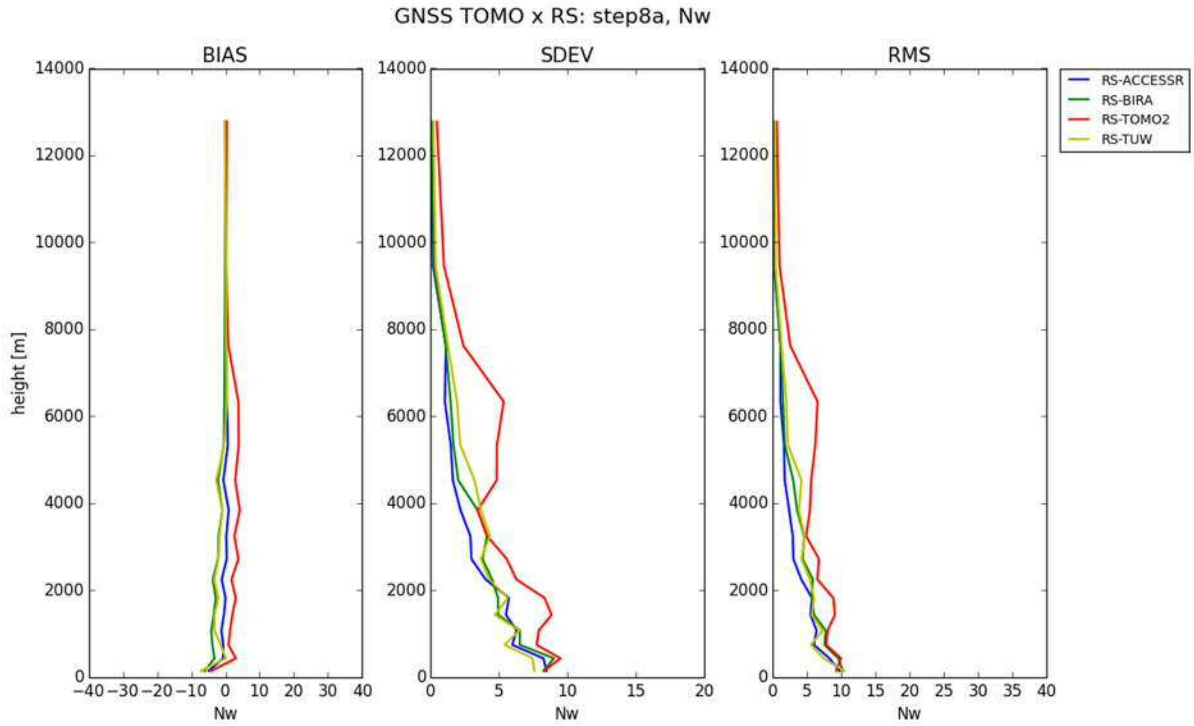

Figure 2. Statistics for wet refractivity computed as a mean, standard deviation and RMS of residuals between radiosonde and ACCESS-R, BIRA, TOMO2 and TUW.

Publications

Brenot, H., Rohm, W., Kacmarík, M., Möller, G., Sá, A., Tondas, D., Rapant L., Biondi R., Manning T., & Champollion, C. (2017, April). Cross-validation of GNSS tomography models and methodological improvements using CORS network. In *EGU General Assembly Conference Abstracts* (Vol. 19, p. 7078).

Brenot, H., Caumont, O., Bosser, P., Biondi, R., Bock, O., Ducrocq, V., & Van Roozendael, M. (2017, April). Interest of GNSS tomography for nowcasting in the frame of HyMeX. In *EGU General Assembly Conference Abstracts* (Vol. 19, p. 6979).

Use of tomography retrieval in weather system assimilation [ASSIMILATION]

Several studies were launched to investigate use of tomography retrievals in the numerical weather models: 1) Over part of Austria to study use of tomography retrieved relative humidity in generation of weather forecasts (Moeller et al., 2016) for intense rain, 2) Over Poland in standard weather conditions (Kryza et al., 2016). Both shows impact of GNSS tomography retrievals on weather parameters such as rain intensity, rain location, humidity and temperature.

Currently TUW and WUELS are investigating a case in East Germany and the western part of Czech Republic (Fig. 3), considered time period is between 29 May and 14 June 2013, the study is based on slant delays from benchmark campaign of the COST Action. Results are going to be assimilated in WRF model with gpsref operator (radio occultation operator) and radiosonde operator.

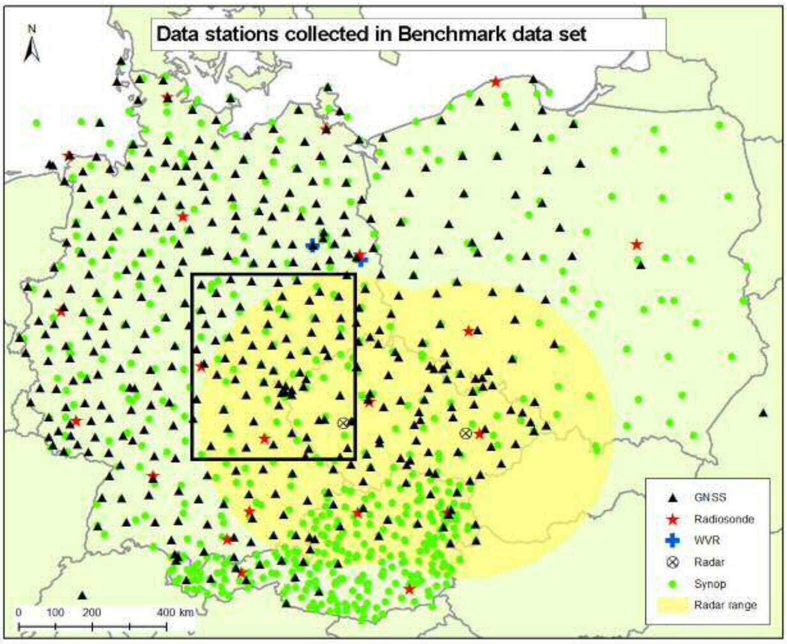

Figure 3. Location of tomography domain for investigated case of strong precipitation over Central Europe.

Publications

Kryza M., Guzikowski J., Werner M., (2016). *Assimilation of the GNSS tomography data into the Weather Research and Forecasting model*. Technical report

Möller G., et al. (2016).*GNSS tomography and assimilation case studies using the COST benchmark dataset*. COST Action ES1206, Working Group meeting, 1-2 September, GFZ, Potstdam, Germany

WG 4.3.7: Real-time Troposphere Monitoring

Chair: *Jan Dousa (Poland)*
Vice Chair: *Eric Pottiaux (Belgium)*

Members

- *Kefei Zhang, (Australia),*
- *Xiaoming Wang (Australia),*
- *Fabian Hinterberger (Austria),*
- *Thalia Nikolaidou (Canada),*
- *Junping Chen (China),*
- *Min Li (China),*
- *Pavel Václavovic (Czech Republic),*
- *Henrik Vedel (Denmark),*
- *Galina Dick (Germany),*
- *Xingxing Li (Germany),*
- *Rosa Pacione (Italy),*
- *Yoshinory Shoji (Japan),*
- *Felix Norman Teferle (Luxembourg),*
- *Siebren de Haan (Netherlands),*
- *Tomasz Hadaś (Poland),*
- *Jonathan Jones (United Kingdom),*
- *John Braun (USA)*

Introduction

Providing new real-time or ultra-fast tropospheric products, such as Zenith Total Delays (ZTD), horizontal tropospheric GRaDients (GRD), Slant Total Delays (STD), Integrated Water Vapour (IWV) maps or other derived products estimated using data from GNSS permanent networks, is a prerequisite for numerical and non-numerical weather nowcasting and severe weather event monitoring (Guerova et al, 2016). The Precise Point Positioning (PPP) processing strategy plays a key role in the production of real-time tropospheric products because of its high processing efficiency, and sensitivity to the absolute value of the tropospheric delay. It enables to exploit optimally data from all available GNSS multi-constellations, and supports the production of all interesting GNSS parameters such as ZTDs, GRDs or STDs. Most importantly, the PPP is supported with the global orbit and clock products provided by the Real-Time Service (RTS, Caissy et al., 2012) of the International GNSS Service, IGS (Dow et al., 2009).

The main objectives of the IAG WG 4.3.7 'Real-Time troposphere monitoring' have been refined and are:

Objective 1. : Stimulate the development of software that enable routine production of real-time/ultra-fast tropospheric products.
Objective 2. : Develop optimal strategies suitable for numerical or non-numerical weather nowcasting applications, and severe weather event monitoring.
Objective 3. : Demonstrate reliable high-temporal resolution real-time/ultra-fast production, assess applied method, software and precise real-time orbit and clock products.
Objective 4. : Evaluate real-time/ultra-fast tropospheric parameters and their potential for applications in meteorology.
Objective 5. : Setting up a link to the users, review product format and requirements.

Activities and publications during the period 2015-2017

Within the period 2015-2017, the COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC, http://gnss4swec.knmi.nl) played an initiative role in the coordination of the development and the evaluation of GNSS real-time tropospheric products. Within the period 2015-2017, the main achievements focused on the development of the software (objective 1), the design and operation of the GNSS4SWEC Real-Time Demonstration campaign (objective 3) by the Working Group 1 „Advanced GNSS processing Techniques" (Douša and Dick, 2017) and the evaluation/validation (objective 4).

Developing real-time/ultra-fast application software

Several working group members continued developing their software to produce reliable real-time/ultra-fast tropospheric products. This include the G-Nut/Tefnut software (Douša and Václavovic et al. 2013) developed by Geodetic Observatory Pecny (GOP), the EPOS-RT Software (Lit et al., 2014) from GFZ, GNSS-WARP from Wroclaw University of Environmental and Life Science (WUELS, Hadaś, 2015). They did not focus on developments of real-time ZTDs and GRDs productions only, but other related aspects such as, for example, GOP developed and assessed method for real-time STDs retrievals (Kačmařík et al. 2017). Another point investigated by WG members is the benefit of multi-GNSS for meteorological applications and developing truly multi-GNSS (GPS+GLO+GAL+BDS) real-time capable software and solutions (Hadaś, 2015, Li at al., 2015a, 2015b, 2015c, Lu et al., 2015, 2016a, 2016b, Václavovic et al. 2013).

The Real-Time Demonstration campaign

From April 2015 to April 2017, eight agencies contributed routinely to the GNSS4SWEC Real-Time Demonstration Campaign (Dousa and Dick, 2017). They provided real-time/ultra-fast solutions using six different software and using various flavours of processing options (Table 1). Seven contributors provided solutions from truly real-time processing engine. Additional contributors are still preparing their submissions to the Real-Time Demonstration Campaign.

Table 1: Contributions to GNSS4SWEC Real-Time Demonstration campaign

AC	Running agency	Software	Start	Update	Solutions
GOP	Geodetic Observatory Pecný, RIGTC	G-Nut/Tefnut	9.4. 2015	real-time	GPS, GLO, gradients
TUW	Technical University Vienna	TUW software	15.4. 2015	real-time	GPS
ROB	Royal Observatory of Belgium	G-Nut/Tefnut	23.4. 2015	real-time	GPS, GLO, gradients
ASI	Agenzia Spaziale Italiana/Centro di Geodesia Spaziale , Matera	Gipsy-Oasis	5.5. 2015	hourly	GPS, gradients
ULX	University of Luxembourg	BNC	15.6. 2015	real-time	GPS
TUO	Technical University of Ostrava	RTKLib	5.11.2015	real-time	GPS
BKG	Bundesamt für Kartographie und Geodäsie	BNC	1.3.2016	real-time	GPS, GLO
GFZ	Deutsches GeoForschungsZentrum	EPOS-RT	16.2.1017	real-time	GPS, GLO

In a spirit of workload sharing, several members focused on different objectives of the campaign. As an example, ROB has collaborated with GOP to contribute to the Real-Time Demonstration campaign using their G-Nut/Tefnut software (Václavovic et al. 2013) but with a particular focus on 1) a larger set of GNSS stations with various equipment (for assessment purposes), and 2) on the high spatial and temporal estimation of the parameters (aiming at a nowcasting exploitation in the Benelux region). To this aim, in addition to the standard network of (~30) stations proposed to participate to the Real-time Demonstration Campaign, ROB real-time solutions includes in total 185 GNSS stations (Figure 2), of which 76 belongs to the Belgian dense network.

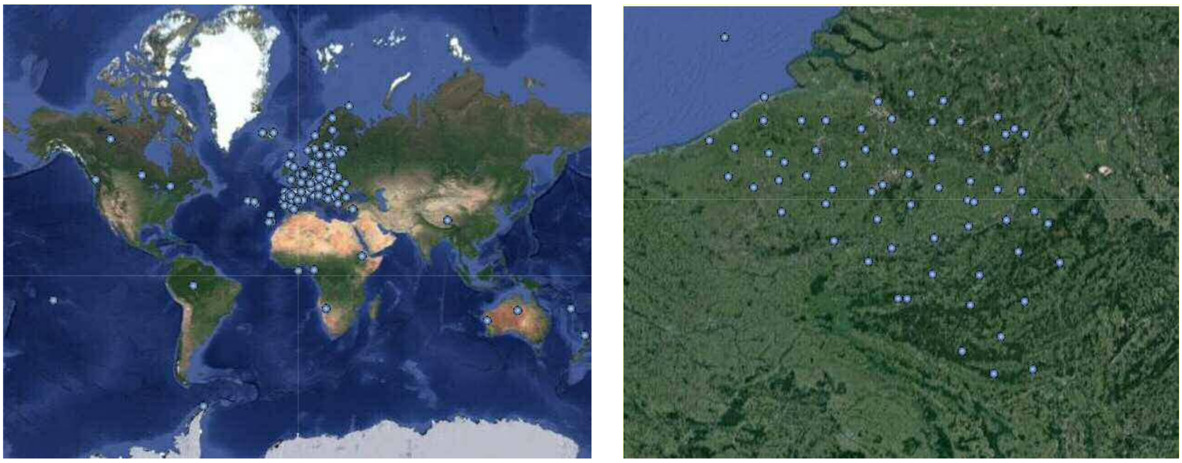

Figure 2: Left: network of 185 GNSS stations used in the operational real-time processing at ROB. Right: Zoom over Belgium showing the Belgian dense network.

Another example is ASI/CGS, which contributed to the GNSS4SWEC Real-Time Demonstration Campaign by focusing on testing the IGS Real-Time orbit and clock corrections in more conventional Near-Real-Time PPP using the Gipsy-Oasis software. Pacione and Shoene (2013) describes the processing scheme (Figure 3). Finally, GOP has also contributed by estimating ZTDs from numerical weather forecasts in Europe using the G-Nut/Shu software (Douša and Eliaš, 2014). It suggests a potential exploitation of external tropospheric corrections from these forecasts for real-time GNSS kinematic positioning. It also showed an overall accuracy of 10-12 mm, i.e. by a factor of 2 worse than GNSS real-time ZTDs and its degrading by about 1-2 mm in ZTD per 6 hours (Douša et al., 2015).

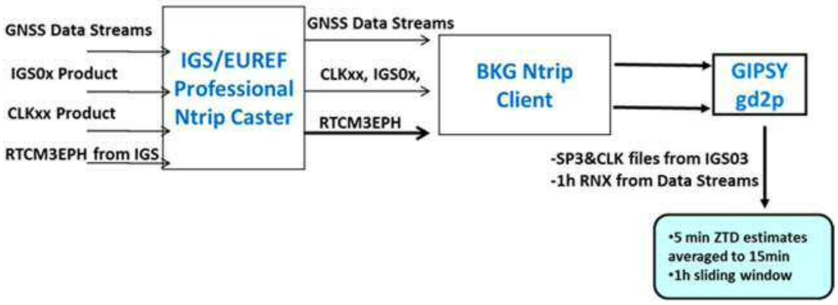

Figure 3: ASI/CGS Processing Scheme.

Real-time monitoring

GOP developed a dedicated web service for an easy monitoring and comparison of individual contributions to the Real-time Demonstration campaign (Figure 5). It is publicly accessible at http://www.pecny.cz/COST/RT-TROPO and enables visualising station time-series (ZTD and GRD components) from real-time solutions over past two months together with operational near real-time regional and global solutions from GOP contributing routinely to the EIG EUMETNET GNSS Water Vapour Programme, E-GVAP (http://egvap.dmi.dk).

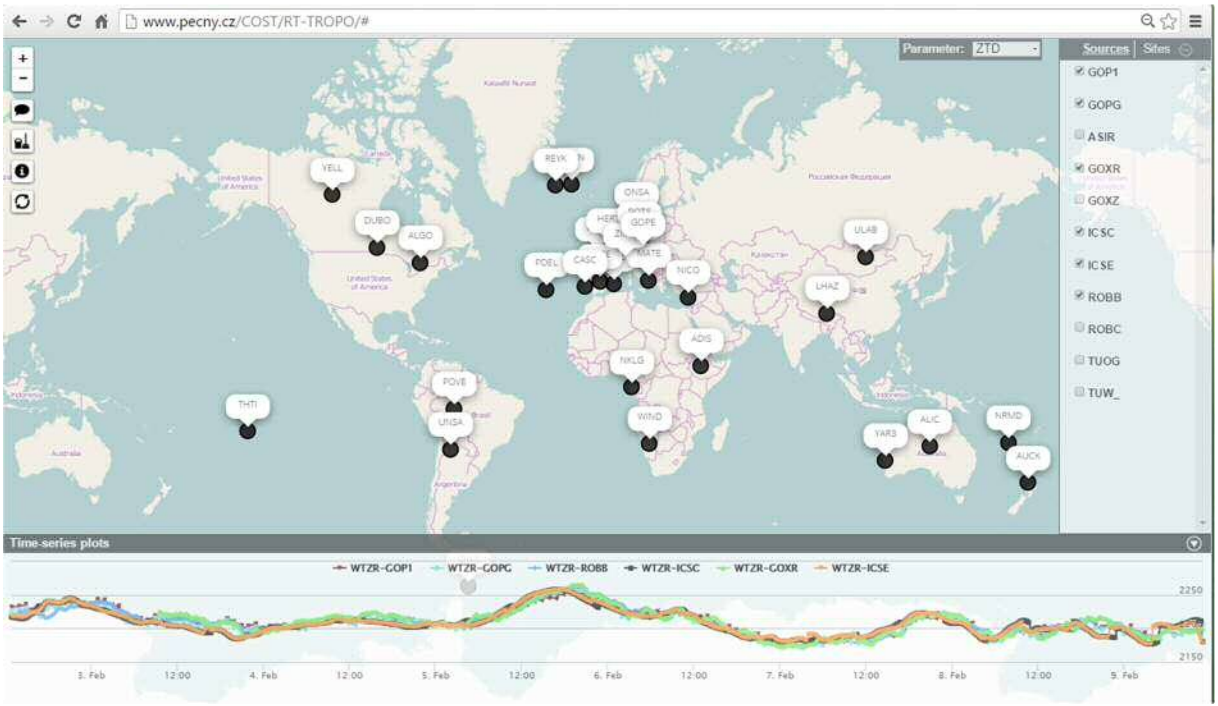

Figure 4: Web service for the monitoring of the GNSS4SWEC Real-Time Demonstration campaign.

A long-term evaluation over more than one year already demonstrated that stable solutions achieved a precision of 5-9 mm for real-time ZTDs estimated at a 5-minute sampling interval and with a maximum latency of ~1 minute. However, significant station-dependent biases are observed with an overall mean values within 0-5 mm in ZTD and some extreme values up to 10 mm. As an example, Figure 2 shows a one-year monthly statistics for the GOP solution.

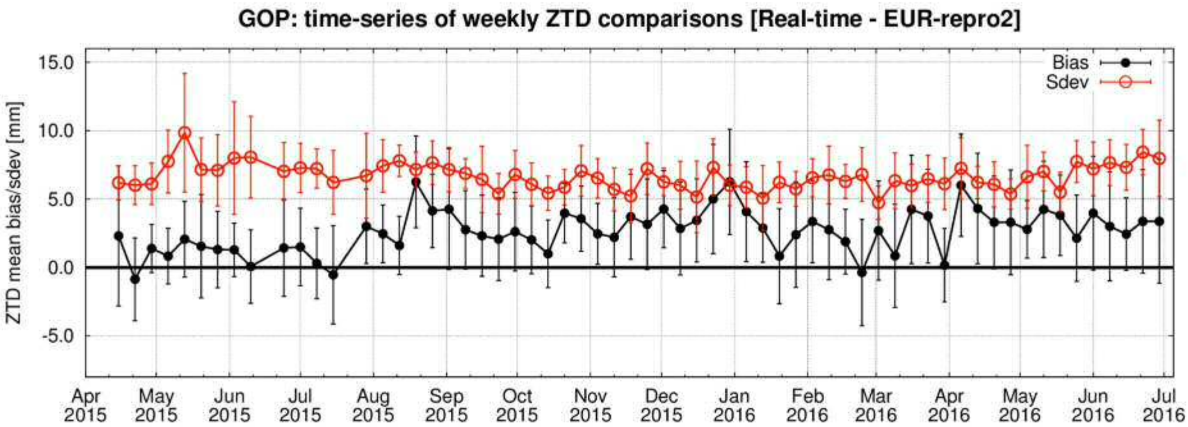

Figure 5: Long-term assessment of GOP real-time product: monthly mean biases and standard deviations over 38 European and global stations of the Real-Time Demonstration campaign.

In parallel to this centralized web service, several members developed their own monitoring and automatic validation procedures, focusing on their contributions and specific needs. WUELS developed an automatic assessment of real-time ZTDs by comparison with their near real-time solution and developed of an online tool to present the results graphically. Similarly, ROB carry out automatic validations of its real-time products w.r.t. to its near real-time solution for E-GVAP and w.r.t. to a post-processing PPP solution using the Bernese GNSS software 5.2. These comparisons reported similar precision/accuracy as mentioned by GOP is achieved (Pottiaux et al. 2015). ROB also developed a web interface that allows the monitoring of its real-time solutions and to represent the results of its validation procedures.

Product optimisation and validation

Existing operational real-time ZTD productions at GOP and University of Luxembourg have been evaluated in European and global scopes (Douša and Václavovic, 2014; Ahmed et al., 2016), and comparing to the standard near real-time regional and global products officially contributing to E-GVAP (Douša and Václavovic, 2016). In addition to the Real-Time Demonstration campaign, monitoring and validation, several members carried out offline studies to optimize their strategy/software. Indeed, fine-tuning processing methodologies (i.e. comparing various processing schemes over the same dataset and period) and assessing their results can barely be done in a true real-time operation setup. Offline studies based on simulating real-time processing overcome this problem. To this aim, GOP and ROB used the dense network of the GNSS4SWEC WG1 Benchmark campaign (Douša et al., 2016), together with archived real-time IGS global orbit and clock products, for optimizing their real-time strategy using simulated real-time mode (objective 2).

Using the offline studies, GOP has developed a hybrid scenario for a new flexible solution optimally mixing features of real-time and near real-time modes when exploiting real-time products and Kalman filter supported with a backward smoother (Václavovic and Douša, 2016). GOP also assessed three different IGS global precise orbit and clock products, and showed that it resulted in small impacts on differences in real-time ZTD estimates, but indicated an overall systematic error of 2 mm for ZTD compared to (Douša et al., 2017). Similarly, ROB has used its real-time simulated setup and the benchmark to produce 320 ZTD/gradient dataset flavours (based on different constraints, constellation, orbit and clock products...), that will be inter-compared and studied to define an optimized processing strategy. WUELS also worked on strategy optimization (Hadaś et al., 2017) and proper GNSS weighting, due to the quality of real-time products for various systems, satellite blocks and types (Kaźmierski et al., 2017). GFZ validated real-time products including precise orbit/clock corrections, tropospheric parameters (Li et al., 2015b).

Other related activities

In addition to the main objectives of this working group mentioned in the introduction, several members have worked on the link between empirical tropospheric models, Numerical Weather Models (NWM) and GNSS real-time processing software. In that context, the GNSS workgroup at the Shanghai Astronomical Observatory has developed the SHAtrop empirical tropospheric model. The model improves the accuracy of real-time tropospheric modelling by ~30% over China continent. The SHAtrop model provides real-time ZTDs and enables the capabilities of decimetre-level real-time PPP (Chen et al. 2015, 2017). GFZ also investigated the use of real-time NMM data to augment the real-time GNSS precise positioning (Lu et al., 2016c, 2016d). GOP demonstrated high-rate ZTD estimates and the use of NWM augmentation tropospheric corrections in GNSS high-rate observations carried out on board of a vertically flying hot-air balloon platform (Václavovic et al. 2017). Similarly, UNB used high-resolution NWM to augment their PPP processing (not yet in real-time) and investigated cases where the NWM information helps to stabilize solution and bring it to a sooner convergence.

As a first step towards developing true real-time tropospheric estimates and, thanks to the operation of Australian national positioning infrastructure (NPI) and GPSnet in the Victorian region, NRT ZTD information can be obtained with a very high spatial and temporal resolution for Victoria, Australia. Since 2015 a new Near Real-Time NRT ZTD monitoring platform has been established at SPACE Research Centre, RMIT. The platform can automatically retrieve GPS data from both NPI and the Victorian GPSnet and then determine NRT hourly ZTDs across about 154 stations. The ZTDs obtained are then converted to PWV by using surface meteorological observations (i.e. pressure and temperature). All the obtained NRT ZTDs are stored at the SPACE server with a delay of about half an hour, which provides valuable data source for the forecasting and study of severe weather events. At the moment, only the researchers at RMIT and the Australian Bureau of Meteorology can access the ZTD data, but we plan to make it accessible to the scientific community in the near future.

Link to the users, review product format and requirements

In a first step, the link with the user community (meteorologists, forecaster, nowcaster…) has been established via the Working Group 2 "Use of GNSS tropospheric products for high resolution NWP and sever weather forecasting" of the COST Action ES1206 (GNSS4SWEC) and via E-GVAP (objective 5). The use of real-time/ultra-fast tropospheric products for nowcasting and severe weather monitoring was advertised, and the user requirements and product format exchange was discussed (see also below). In Belgium, ROB established a first link with the forecasters of the Royal Meteorological Institute (RMI) to advertise this activity and its potential use in their day-to-day forecast operation. In the Czech Republic, GOP has initiated the link with a potential national user and data provider, Czech Hydro-Meteorological Institute and Land Surveying Office, respectively.

Working group meeting and outreach

The first IAG WG 4.3.7 working group meeting took place in Wroclaw (September 5-7, 2016), along with the IAG Commission 4 Positioning and Applications Symposium. Six members participated, discussing individual developments and future goals. These discussions were started already a week before during the COST Action ES1206 Working Group meeting in Potsdam (September 1-2, 2016) by several group members. Related presentations and important discussions between provider and user communities also took place during the E-GVAP annual meeting in Copenhagen, December 6-7, 2016), with a focus on completing the standardization of SINEX_TRO v2.0 format. Results from the GNSS4SWEC Real-Time Demonstration campaign, related developments, and product assessment were presented at the IAG C4 Symposium and at the COST ES1206 Final Workshop hold in ESTEC, Noordwijk (February 21-23, 2017).

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WG 4.3.8: GNSS tropospheric products for Climate

Chair: *Rosa Pacione (Italy)*
Vice Chair: *Eric Pottiaux (Belgium)*

Members

- *Araszkiewicz (Poland),*
- *F. Alshawaf (Germany),*
- *O. Bock (France),*
- *J. Dousa (Czech Republic),*
- *G. Dick (Germany),*
- *G. Halloran (United Kingdom),*
- *R. Heinkelmann (Germany),*
- *G. Liu Zhizhao (Hong Kong),*
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- *M. Santos (Canada),*
- *Y. Shoji (Japan),*
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- *S. Vey (Germany),*
- *F. N. Teferle (Luxembourg),*
- *J. Wang (United States)*

Corresponding Members

- *Klos (Poland),*
- *S. Zengin Kazanci (Turkey)*

Activities and publications during the period 2015-2017

The activities of this working group will continue within the main lines sketched by the WG3 during the COST Action ES1206 “Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate” (GNSS4SWEC: http: //gnss4swec.knmi.nl/).

The main objectives of this working group are: to assess existing reprocessed GNSS tropospheric products, foster the development of forthcoming reprocessing activities, test different homogenization methodologies to setup a common long-term homogenized data set to be re-used for climate trends and variability studies, review and update GNSS-based product requirements and exchange formats for climate, and promote their use for climate research, including a possible data assimilation of GNSS troposphere products in climate reanalysis.

The main targeted results and deliverables are data sets, reports and scientific papers, which will be elaborated in collaboration between the participants.

During the period 2015-2017, the activities has followed the timeline reported in Figure **6**.

Figure 6: Timeline and Achievements.

A dedicated website has been set-up (http://iag-gnssclimate.oma.be/index.php, Figure 7) in order to disseminate the main outcomes for each of the five scientific objectives, and a dedicated mailing list (http://mailman-as.oma.be/mailman/listinfo/iag.gnssclimate**)** has been established for the communication between the members. After an inquiry sent out to the members about their individual contribution(s), a work plan has been prepared and distributed. The work plan is also publicly available on the website at http://iag-gnssclimate.oma.be/Outreach/Documents.php.

Figure 7: Screenshot of the main page of the website

Below follows the status and on-going activities for each of the five scientific objectives.

Objective 1: REPRO

Assess existing reprocessed troposphere solutions and provide recommendations for the forthcoming reprocessing activities.

International Reprocessing Activities:

- EUREF Tropospheric 2nd Reprocessing Campaign
  http://www.epncb.oma.be/_productsservices/troposphere/
- TIGA Reprocessing Campaign
  http://adsc.gfz-potsdam.de/tiga/index_TIGA.html
- GRUAN Reprocessing Campaign
  http://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/gruan/

National Reprocessing Activities

- CORDEX.be Reprocessing Campaign (Belgium)
  http://cordex.meteo.be/
- Historical Reprocessing of the German Network (SAPOS)
- Reprocessing of the Japanese nationwide GNSS network (established mid-90's) to derive GNSS-based PWV using IGS's 2nd reprocessed ephemerides (IG2).

Monitoring and Assessment Activities:

- GOP-TropDB (Gyori and Dousa, 2016) was used for the evaluating all available EUREF, TIGA, IGS re-processing tropospheric products in 1996-2014.
- Developing IGS Troposphere working group web service for interactive metadata and statistics exploitations (Hackman et al., 2015).

Details are available at: http://iag-gnssclimate.oma.be/Work%20Packages/Reprocessing/index.php#status-and-ongoing-title.

Objective 2: HOMO

Set-up a common GNSS climate dataset on which different homogenisation methodologies can be tested. The homogenised common long-term data set can then be re-used for climate trends and variability studies within the community. On-going activities are a follow-up of the GNSS4SWEC sub-WG3 on data homogenisation

- Work on one or two long-term reference datasets (first Reference dataset: IGS-Repro1 screened and converted to IWV by O. Bock, second reference dataset: EPN-Repro 2).
- Apply different homogenisation methods/algorithms on these long-term reference datasets, and inter-compare their results, advantages, drawbacks…
- Identify the proper (standardized) strategy for the homogenization of GNSS-based long-term reference datasets.
- Apply this standardized strategy to the reference datasets, build a list of commonly identified inhomogeneities (instrumental change, break points, auxiliary data jumps…), and come up with a homogenized version of these reference datasets that can be re-used to study climate trends and time variability by the community.
- Apply different methods to improve our understanding of the stochastic properties of long-term tropospheric reference datasets for obtaining realistic uncertainties for the parameter estimates (e.g. long-term trend estimates).
- Create a long-term synthetic benchmark dataset based on parameters derived for real reference dataset and test different homogenization tools to study their performance (e.g. w.r.t. the presence of autoregressive noise).
- Assess homogenization technique on ERA-Interim and GOP-Repro2 products including semi-synthetic times-series (Elias et al, 2017).

Details are available at: http://iag-gnssclimate.oma.be/Work%20Packages/Homogenisation/index.php#status-and-ongoing-title

Objective 3: ASSIM

Advocate the data assimilation of GNSS troposphere products in Climate Re-Analysis. On-going activities:

- At University at Albany: use of GNSS PW (Precipitable Water) data to develop PW diurnal matrices and validate climate models.
- At the Met Office: in the framework of the European FP7 project UERRA (Uncertainties in Ensembles of Regional Re-analysis, http://www.uerra.eu/), assimilation trials of reprocessed ZTD into a 12 km European climate reanalysis beginning in 1979 are ongoing. To account for any systematic bias or bias change, the reprocessed ZTDs will have a bias correction applied before assimilation.
- At Hong Kong Polytechnic University: collaboration with the China Meteorological Administration (CMA) scientists to evaluate PW accuracy of CMA's weather satellites' various PW products, using GNSS-derived and other PW data (such as WVR, etc) as a reference.

Objective 4: FORMAT

Review and update GNSS-based product requirements and exchange format for climate. An effort on SINEX-TRO standardization is on-going in collaboration with the GNSS4SWEC WG3, E-GVAP, IGS, EUREF, and GRUAN. The collection, exchange format, and usage of meta-data information (particularly important for the processing and for the homogenisation) might be revisited in this context.

Objective 5: COOP

Strengthen the cooperation between geodesists and climatologists (see the following items):

Exploitation

To make the links between REPRO, HOMO and ASSIM objectives, the following research is ongoing at Research is on-going at GFZ

- Study of the climate evolution in Germany by comparing the temporal trends estimated from GNSS time series, their equivalent from ERA-Interim, and PWV drive from in-situ meteorological measurements (Alshawaf et al., 2016).
- Study of the sensitivity of linear trends determined by VLBI w.r.t. various analysis options. The use of different delay and gradient mapping functions (VMF1, Böhm et al. 2006; GPT2w, Böhm et al. 2015) did not revealed significant trend difference. The largest effect on the trends was found to be the usage of atmospheric pressure in the analysis. Different atmospheric pressure data for the analysis of space geodetic techniques results in significantly different IWV trends (Balidakis et al. 2017). The pressure time series need to be homogenized (Balidakis et al. 2016).
- Determination of linear trends of IWV from synchronized time series of VLBI (VieVS@GFZ, Nilsson et al. 2015), GNSS atmospheric parameters (TIGA reprocessing, Deng et al., 2016), and ERA-Interim (Direct Numerical Simulation software, Zus et al. 2012; 2014; 2015) at co-located sites. Linear IWV trends range between ±1 kg/m^2/yr, and the agreement between the techniques is rather low (sometimes the trends show even different signs).

Interaction with other research programmes

Collaboration/cooperation is on-going with researchers from national, European and international organisations through participation of experts to the working group activities:

1. IGS (The International GNSS Service, *http://www.igs.org*), including the IGS Troposphere and the TIGA (The GPS Tide Gauge Benchmark Monitoring, *http://adsc.gfz-potsdam.de/tiga/index_TIGA.html*) working groups.

2. EUREF (The Reference Frame Sub-Commission for Europe, *http://www.euref.eu*).
3. GRUAN (The GRUAN GNSS-PW Task Team, *http://www.dwd.de/EN/research/international_programme/gruan/tt_gnss-pw.html*).
4. E-GVAP (The EUMETNET EIG GNSS water VApour Program, *http://egvap.dmi.dk*).
5. European FP7 project UERRA (Uncertainties in Ensembles of Regional Re-analysis, *http://www.uerra.eu/*).
6. GEWEX water vapor assessment (G-VAP, *http://gewex-vap.org*).
7. IAG JWG 1.3: Tropospheric ties.

Forthcoming activities

An IAG workshop on 'Satellite Geodesy for Climate' is planned in September 19-21, 2017, in Bonn, Germany. This is a joint workshop between the IAG SC 2.6: 'Gravity and Mass Transport in the Earth System', the IAG JWG 2.6.1: 'Geodetic Observations for Climate Model Evaluation', and the IAG JWG 4.3.8: 'GNSS Tropospheric Products for Climate'. More information are available at *http://www.igg.uni-bonn.de/apmg/index.php?id=ws2017*.

A topical workshop on 'Data Homogenisation' is foreseen in October-November, 2017, Brussels, Belgium. This will be the 3rd workshop organised on this topic and a follow-up of the activities started during the COST Action ES1206 GNSS4SEC.

Outreach Presentations

The activities of the working group have been presented at the following conferences:

- IAG JWG 4.3.8: GNSS tropospheric products for Climate, R. Pacione, E. Pottiaux and JWG members, COST ES1206 Workshop, 8-10 March 2016, Reykjavik, Island.
- IAG JWG 4.3.8: GNSS tropospheric products for Climate, E. Pottiaux, R. Pacione and JWG members, IAG Commission 4 Symposium Wroclaw, Poland, 4-7 September 2016 http://www.igig.up.wroc.pl/IAG2016/.
- IAG JWG 4.3.8: GNSS tropospheric products for Climate: Objectives and Future Plans, R. Pacione, E. Pottiaux, and JWG members, EGU GA, Vienna 23-28 April 2017, http://meetingorganizer.copernicus.org/EGU2017/EGU2017-8332.pdf.

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WG 4.3.9: GNSS-R

Chair: *Felipe Nievinski (Brazil)*
Vice Chair: *Thomas Hobiger (Sweden)*

Members

- *Karen Boniface (France),*
- *Estel Cardellach (Spain),*
- *Rüdiger Haas (Sweden),*
- *Kosuke Heki (Japan),*
- *Yukihito Kitazawa (Japan),*
- *Kristine Larson (USA),*
- *Wei Liu (Germany),*
- *Manuel Martín-Neira (Europe),*
- *Miguel Ribot (Switzerland),*
- *Nicolas Roussel (France),*
- *Maximilian Semmling (Germany),*
- *Joakim Strandberg (Sweden),*
- *Sajad Tabibi (Luxembourg),*
- *Sibylle Vey (Germany),*
- *Kegen Yu (China),*
- *Wei Wan (China),*
- *Jens Wickert (Germany),*
- *Simon Williams (UK)*

Activities and publications during the period 2015-2017

A kick-off meeting was organized during the European Geophysical Union General Assembly on 20 April 2016. It was attended by Thomas Hobiger, Estel Cardellach, Maximilian Semmling, Yukihito Kitazawa, and Nicolas Roussel on site and Felipe Nievinski remotely. Felipe prepared and sent slides to the whole IAG WG prior to the meeting. Simon Williams provided comments via email. During the meeting, the ten objectives of the WG were reviewed and revised. Minutes of the meeting were prepared and circulated among WG members on 25 May 2016; a copy is provided as an annex.

We established liaisons with neighboring organizations, such as the Permanent Service for Mean Sea Level (PSMSL) and the IEEE Geosciences and Remote Sensing Society (GRSS). It should be noted that IEEEE GRSS has its own GNSS-R working group, though it has a broader scope than WG 4.3.9.

The WG scope has been clarified so as to contemplate two types of geodetic GNSS-R. It now includes both the retrieval of GNSS-R environmental parameters by means of geodetic instrumentation and the utilization of generic GNSS-R information to aid in geodetic positioning. Ground-based soil moisture retrievals derived from IGS tracking station data would be an example of the former type of geodetic GNSS-R. Airborne GNSS-R soil moisture retrievals, later used to correct for seasonal loading at co-located ITRF sites, would be an example of the latter type. It was proposed that GNSS-R tide gauges for sea level monitoring be the IAG WG flagship data product, as it is perceived as the most mature target for geodetic GNSS-R.

In June 2016 an abstract titled "Current status and future activities of the IAG/GGOS joint working group 4.3.9 on GNSS reflectometry" was submitted to the IAG Commission 4 Symposium. The poster was later presented, on 4-7 September 2016, by Jens Wickert in Wroclaw, Poland.

An inter-comparison campaign on GNSS-R for sea level monitoring was announced on 16 August 2016. It was planned as an opportunity to validate retrieval solutions from independent research groups under comparable conditions. Results will also serve to showcase the level of maturity attained with this technique as a potential GGOS data product. Measurements collected at a sea-facing location having a conventional tide gauge nearby were made available to the WG members. We have started with station GTGU at the Onsala Space Observatory for the one-year period from 1st July 2015 to 31 June 2016. The 1-Hz GNSS data (8 GB size) was generously provided by the team at Chalmers University (Rüdiger Haas, Thomas Hobiger, and Joakim Strandberg).

Five groups submitted retrieval solutions for the inter-comparison campaign: Chalmers University, Sweden; University of Luxembourg, Luxembourg and Federal University RGS, Brazil; GFZ Potsdam, Germany; University of Toulouse, France; and the National Oceanography Centre, UK. Initial comparison between GNSS-R and the conventional tide gauge indicate very high correlation (0.99), centimeter-level error (2-3 cm), and few-percent bias regression slope bias (1-4% overestimation) in sea level height for some solutions. Figure 1 and 2 illustrate the conditions.

In January 2017 the campaign goals and preliminary results were summarized and submitted as an abstract for the session "Geodetic remote sensing", part of the Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior. The event is to be held in Kobe, Japan, from July 30 to August 4, 2017 and the session is convened by Michael Schmidt and co-convened by WG members Jens Wickert and Felipe Nievinski.

Finally, the WG was well represented at the GNSS+R 2017 Workshop (Specialist Meeting on Reflectometry using GNSS and other Signals of Opportunity), 23-25 May 2017, in Ann Arbor, USA, with 15 presentations as listed in Annex I. Annex III lists other publications by WG members in the period 2015-2017.

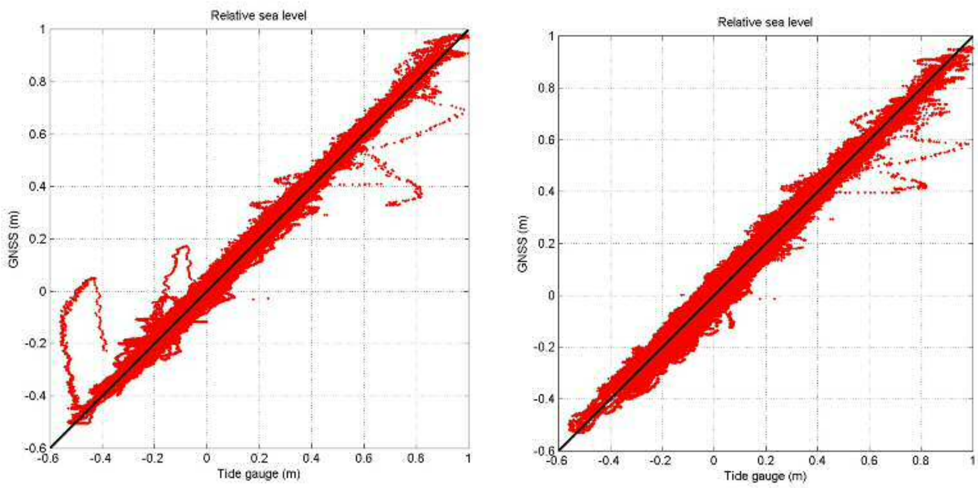

Figure 1: Two representative solutions of the GNSS-R sea level inter-comparison campaign.

Figure 2: Photograph of the first inter-comparison site at Onsala Space Observatory, Sweden.

Annex I: Presentations by WG members at the GNSS+R 2017 Workshop

- "IAG/GGOS inter-comparison campaign on SNR-based GNSS reflectometry for sea level monitoring" by Felipe Nievinski, Thomas Hobiger, Karen Boniface, Rüdiger Haas, Wei Liu, Nicolas Roussel, Joakim Strandberg, Sajad Tabibi, Sibylle Vey, Jens Wickert, and Simon Williams;
- "Tropospheric delays in ground-based GNSS multipath reflectometry – Towards a unified angular/linear refraction model using ray-tracing simulations" by Felipe Nievinski and Simon Williams;
- "GNSS multipath reflectometry for coastal sea level monitoring: Extended dynamic model based on the sea vertical acceleration" by Sajad Tabibi and Felipe Nievinski;
- "Troposphere self-calibration in ground-based GNSS-R" by Thomas Hobiger, Joakim Strandberg, and Rüdiger Haas;
- "Retrieving sea surface heights by inverse modeling of GNSS SNR data" by Joakim Strandberg, Thomas Hobiger, and Rüdiger Haas;
- "GNSS as a sea ice sensor – detecting coastal freeze states with ground-based GNSS-R" by Joakim Strandberg, Thomas Hobiger, and Rüdiger Haas;
- "Synoptic iGNSS-R altimetry from aircraft using SPIR" by Estel Cardelach et al.;
- "The Bi-Band Software PARIS Interferometric Receiver" by Estel Cardelach et al.;
- "Wavpy: an open-source tool for the GNSS+R community" by Estel Cardelach et al.;
- "The GRAIS project: one year of GNSS reflectometry in Antarctica" by Estel Cardelach et al.;
- "A Fram Strait Experiment: Sensing Sea Ice Conditions using Shipborne GNSS Reflectometry" by Maximilian Semmling, Jens Wickert, et al.;
- "A new era in space-borne GNSS Reflectometry: Potentials in near real time storm scale predictions" by Jens Wickert et al.
- "GNSS Reflectometry onboard the International Space Station with GEROS-ISS: Review of activities and current status" by Jens Wickert, Manuel Martin-Neira, Estel Cardelach, et al.;
- "Reduced GEROS-ISS Mission" by Manuel Martin-Neira, Jens Wickert, Estel Cardelach, et al.;
- "Snow Depth Estimation Based on Multipath Phase Combination of BDS Triple-Frequency Signals" by Kegen Yu et al.;
- "PBO H2O 2012-2017: Environmental Products from GPS Reflections" by Kristine Larson et al.

Annex II: Minutes of the kick-off meeting

The kick-off meeting started at 3 pm local time and lasted for 90 minutes. It was attended by Thomas Hobiger, Estel Cardellach, Maximilian Semmling, and Nicolas Roussel on site and Felipe Nievinski remotely. FN sent slides to the whole IAG WG prior to the meeting. Simon Williams (UK) provided comments via email. FN started reviewing the ten objectives as given in the terms of reference.

Objective #1, *"Identify GNSS-R products which have a strong relationship to IAG services and goals,"* lead to two forms of geodetic GNSS-R products: internal ones, with the IAG as a consumer (i.e., GNSS-R providing ancillary products for geodetic purposes); and external products, with the IAG as a producer (e.g., environmental by-products of geodetic instruments enabled by GNSS-R). The following possibilities of geodetic GNSS-R products were raised: sea level, snow depth, soil moisture, vegetation, and sea state. FN suggested that sea level could serve internally for ocean tidal loading and externally for coastal altimetry; SW found the internal contribution non-significant as it could only improve current tidal models at locations where no tide gauges exist. FN remarked that ground-based snow depth and soil moisture could serve internally as input for hydrological loading corrections in GNSS positioning and externally for weather/climate monitoring. MS mentioned that air- and space-borne platforms should be considered in addition to ground-based networks, especially for sea altimetry. FN remarked that retrievals of vegetation (biomass, greenness, etc.) and sea state (wind waves) were less well developed, and proposed GNSS-R tide gauges as the IAG WG flagship product, as it is perceived as the most mature target for geodetic GNSS-R.

Objective #2 was titled *"Foster and establish interactions with neighboring societies (e.g., IEEE GRSS) and cooperate with entities related to GNSS (e.g., the IGS), identifying common goals and detecting potential synergies."* FN added on the geodetic side the IGS Tide Gauge Benchmark Monitoring WG (IGS TIGA) and the Global Geodetic Observing System (GGOS); and on the oceanographic side the Global Sea Level Observing System (GLOSS), the Permanent Service for Mean Sea Level (PSMSL), and the Système d'Observation du Niveau des Eaux Littorales (SONEL). FN indicated the IAG WG could benefit from having liaisons with these organizations. EC had offered to bridge efforts with the IEEE WG, which she co-chairs. SW volunteered to serve as liaison with the PSMSL and IGS-TIGA, of which he is already a member. FN identified as shared goals with the IEEE WG two of its resources that had been recently publicized within the IAG WG: the GNSS-R discussion list, hosted by NASA/JPL, and which has a wider scope compared to the IAG WG mailing list; and the campaign spreadsheet, initiated by EC and recently augmented by MS, which could be further extended so as to include geodetic networks – EC advised to create a separate sheet in the IEEE WG spreadsheet for that. As for the IGS, common goals could include: mass loading corrections, improved site guidelines, and tide gauge leveling. With regard to oceanographic organizations, shared interests would be, again, tide gauge leveling and also shared GNSS data.

At this point EC was kindly invited to present an overview of GNSS-R opportunities, based on the technical report "State of the Art Description Document," prepared as a deliverable of the ongoing E-GEM project (available at <www.e-gem.eu>). EC first discussed the applicability of various GNSS-R retrieval algorithms in three platform altitudes (ground, air, and space) for a number of products: altimetry (sea level), scatterometry (sea wind and waves), sea surface salinity, soil moisture, vegetation/biomass, and the cryosphere (snow, sea-ice, and glaciers). Then she summarized how the GNSS-R spatial resolution varied with receiver altitude as well as transmitter elevation angle; and illustrated the global coverage for multiple GNSS constellations. Finally, EC described the latest and upcoming spaceborne GNSS-R missions, including UK-TDS1, 3Cat-2, CYGNSS, and GEROS-ISS. TH and MS asked about the data availability of the first ongoing mission; EC responded that vast quantities of delay-Doppler maps as well as a few raw data sets are freely available.

Discussion resumed on the objectives, with #3 reading "*Provide an online inventory of GNSS-R products relevant to geodesy and point to corresponding data archives*." FN pointed out the current scientific debate on reproducibility and open science in general, emphasizing that open data – including output retrievals, input measurements, and in situ validation – could help protect against unwarranted claims in the literature and serve as a solid foundation for further development in retrieval algorithms. FN indicated that geodetic GNSS-R products can be a result of a near operational service, one-off efforts, or can be periodically updated and extended for longer time series. It was proposed that the IAG WG could host a webpage linking to geodetic GNSS-R products, such as the PBO-H2O portal (University of Colorado Boulder) and eventually similar efforts by other research groups worldwide.

Objective #8 was considered next, as it was closely related to #3: "*Supplement the GNSS-R Campaign Spreadsheet (initiated by the IEEE GRSS) so as to list existing GNSS tracking stations that can be leveraged for reflectometry purposes.*" FN rephrased it as "build a list of publicly-known GNSS stations demonstrated for GNSS-R purposes in the literature." It could include both temporary campaigns and continuously-operating reference stations. While the previous objective #3 focused on products or output retrievals, the current objective #8 considered input measurements (#8). At least metadata should be provided in case any dataset is too large. Volunteers would be needed so as to draft such a listing; NR suggested that PhD students could be appropriate candidates.

Straddling the two previous objectives, #3 and #8, FN volunteered to curate a topical geodetic GNSS-R data repository, for researchers interested in publicizing their article's data (input, output, and validation) in machine-readable format. He envisioned leveraging existing software-as-a-service infrastructure – such as figshare, Dryad, and Dataverse – to facilitate citations and track usage (via, e.g., DataCite Digital Object Identifiers). Potential contributing authors would get credit for their data collection efforts and be allowed to impose preferred usage policies at their discretion.

Objective #5 is connected to both #3 and #8: "*Provide guidelines and define [data and metadata] formats for GNSS-R products being used for geodetic purposes [as well as geodetic measurements being used for GNSS-R purposes]*" [portions in brackets are absent in the official terms of reference]. FN argued that the format of output products may be left up to their respective data producers to specify, but the IAG WG could issue recommendations for input measurement formats. Possibilities include RINEX version 3 (which supports modernized and multi-GNSS SNR better than version 2), the software-defined radio format sponsored by the Institute of Navigation (<sdr.ion.org>), and an undetermined open format for delay-Doppler maps (DDM) as well as correlation-vs-delay waveforms. Finally, formats could be established for data elements at intermediate processing levels in a typical GNSS-R data workflow, linking instrument-oriented measurements on the one end to geophysical products on the other end. (For example, reflector heights are an intermediate quantity between signal-to-noise ratio and snow depth.) A more pressing need currently is the definition of a metadata format to support objectives #3 and #8, encompassing aspects such as temporal coverage (extent: start/end epochs; resolution: sampling rate, duty cycle, etc.), spatial coverage (extent: latitude/longitude limits; resolution: Fresnel or glistening zones), equipment (antenna: model, orientation, height; receiver: model, firmware, settings), retrieval (observable, algorithm), validation (coverage in time and space; error statistics), etc. Again, a call for volunteers was issued.

Objective #6 is "*Organize working meetings with GNSS-R experts, while also inviting stakeholders from the geodetic community to participate in such events,*" to which FN added: "present posters to update various communities (GNSS at large, non-geodetic GNSS-R, oceanographic, etc.) about our progress. The IAG WG is part of the IAG Commission 4, which will hold a symposium next September in Poland, and has abstracts due June 15; this would be a first opportunity to publicize our objectives and future plans. Another upcoming opportunity in is the AGU Fall Meeting in December, which has abstracts due around August 5. TH reminded about IGARSS 20116, July in Beijing, although abstracts were due last January. Besides these recurring annual events, other pertinent events are the GNSS+R Workshop in 2017, the IGS Workshop in 2018, and the IUGG Assembly in 2019. It was agreed that any attending member could represent the IAG WG in a poster presentation.

Objective #7 reads "*Extend IGS Site Guidelines [SG] so as to maximize the shared usefulness of new GNSS site installations for reflectometry applications.*" FN recalled that the SG were last update in July 2015 by the IGS Central Bureau and that it contains several elements pertinent to GNSS-R, such as section 6, "TIGA Stations" and section 2, "General Station Guidelines" (with subsection 2.1, Strict general guidelines, and 2.2, Recommended general guidelines). A number of proposals were made. TH mentioned the usefulness of having a sky visibility mask, i.e., a profile of elevation angle-vs-azimuth corresponding to the highest obstructions (or the lowest uninterrupted clearance) around a GNSS station. FN listed as additional proposal that station operators consider maximizing the potential of new sites for reflectometry purposes (e.g., by guaranteeing clearance/visibility at negative elevation angles to natural surfaces such as soil and sea and avoiding the built environment). TH asked if recommendations could be made about the proximity to surfaces, in terms of ideal horizontal distance and vertical height as well as their minimum and maximum limiting values. FN recalled the interplay between the height of the antenna above the surface on the one hand and both height and distance of obstructions such as trees. Further proposals were: operators to give preference to antennas with publicly available gain patterns; to provide additional photos (including panoramic); to indicate the existence of *in situ* measurements (tide gauges, soil moisture probes, snow depth sensors) and where their detailed metadata can be found. As with other objectives, the IAG WG needs volunteers to draft these proposals and study the existing site guidelines (e.g., section items 2.1.12, 2.1.37, 2.2.22, 2.2.8, 6.*, etc.).

The last remaining objectives were grouped together: #4, "*Evaluate the possibility to obtain formal errors for GNSS-R products in order to enable better combination with other data-sets;*" #9, "*Evaluate the feasibility of a pilot project on GNSS-R for coastal sea level monitoring, demonstrating its current level of maturity towards an operational service;*" and #10, "*Plan future inter-comparison campaigns for the cross-validation of theoretical model simulations and measurement parameter retrievals.*" Preliminary planning between the chair and vice-chair led to the idea of a sea level monitoring demonstration campaign with 3 sites for 3 months. If successful, it could serve as a model for future demonstrations for other environmental targets, such as snow depth, soil moisture, etc. Although many studies have been published about this topic, it would be the first time that a coordinated effort is made to compare and cross-validate solutions from different groups for a given common dataset. Making an analogy with the IGS, many groups worldwide perform GNSS satellite orbit determination, and their ephemerides solutions are routinely combined in a weighted average under the umbrella of the IGS analysis center. It was envisioned that an international GNSS-R sea-level service could be setup in a few years, and that the IAG WG should relay such a level of maturity to the geodetic and the oceanographic communities. TH offered Onsala, Sweden, as one of the three sites; there is *in situ* validation (conventional tide gauge) nearby. Any GNSS equipment, observable, and algorithm would be allowed; there would be an opportunity for setting up experimental receivers/antennas if any research group so desired. NR mentioned the Cordouan site in France. There was a call for other sites. Preliminary results are to be presented in a poster and final results would be submitted for publication in a journal.

Finally, a summary of current needs is:

- compile list of GNSS stations demonstrated for GNSS-R purposes in the literature;
- compile metadata documenting input measurements, output retrievals, and *in situ* data used in each study listed above
- define an initial metadata format;
- create webpage linking to GNSS-R products (routine or near operational rather than temporary or one-off efforts);
- create prototype of open science data curation platform for GNSS-R;
- draft proposed changes for IGS Site Guidelines;
- obtain sea-facing GNSS sites (with tide gauge nearby) for the demonstration.

Publications

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Sub-commission 4.4: Multi-Constellation GNSS

Chair: *Pawel Wielgosz (Poland)*
Vice Chair: *Yang Gao (Canada)*
Secretary: *George Liu (China)*

Overview

SC 4.4 is composed of two Study Groups and two Working Groups. Besides, several of SC 4.4 members participate in other IAG Joint Study Groups related to GNSS methods, i.e., IAG-ICCT JSG 0.10 "High-rate GNSS" and IAG ICCT JSG 0.17: "Multi-GNSS theory and algorithms".

The main meetings of the SC 4.4. take place during European Geoscience Union General Assemblies (EGU-GA) that are held every year in April in Vienna, Austria. The SC 4.4. organizes dedicated session at EGU, recently session G.1.4 "High-precision GNSS: methods, open problems and Geoscience applications" (http://meetingorganizer.copernicus.org/EGU2017/session/22871).

Study Groups of Sub-commission 4.4:

SG 4.4.1: Integrity Monitoring for Precise Positioning

Chair: Ahmed El-Mowafy (Australia)
Vice Chair: Aboelmagd Noureldin (Canada)

Members

- Ilaria Martini (Germany)
- Samer Khanafseh (USA)
- Jinling Wang (Australia)
- Nobuaki Kubo (Japan)
- Allison Kelley (Australia)
- Per Enge (USA)
- Naser El-Sheimy (Canada)
- Slawomir Cellmer (Poland)
- Pedro Francisco Navarro Madrid (Spain)

Activities and publications during the period 2015-2017

The study group addresses integrity monitoring (IM) for precise positioning, where several sensors can be used including GNSS, Inertial Measurement Units (IMU), Lidar, cameras and odometers. Precise GNSS positioning techniques include Precis Point Positioning (PPP), Real-Time Kinematic (RTK) or Network RTK. For a real-time user, integrity and performance-based monitoring is improtant for protection from faults, either in the system, the signals, augmentation systems, or that caused by jamming or spoofing. It is also vital to alert the user in case that the system cannot reach the target performance.

The group had online WebEx meetings and discussed challenges of IM for Precise positioning in land applications. In addition to the research carried out by individual group members in their research groups, we are currently together working in a research paper that addresses the vulnerabilities of multi-GNSS, the IMU and Lidar, and characterization of their errors. This includes identification of which faults are likely to occur that may present a threat or degrade quality of precise positioning, the nature of each threat, and its source, possible magnitude, duration and likelihood. For GNSS, these faults may be present in: i) all GNSS constellations navigation data; ii) their measurements; iii) augmentation systems (e.g. precise orbits and clock corrections or atmospheric corrections); and iv) user work environment (in open sky, urban environment, high multipath, etc.). A case study of vehicle positioning in intelligent transport systems has been selected as a future popular application. The next step of our program is to collaborate in the development of new IM algorithms.

Over the past two years, the group members have contributed in journal and conference publications that address integrity monitoring. The following section summarizes some of the research being carried out, including the research question, approach and key findings.

Summary of the research carried out

In one study, we studied continuous and trustworthy positioning for advanced driver assistance systems (ADAS). GNSS RTK, Doppler-based positioning, and low-cost inertial measurement unit (IMU) with car odometer data are combined in this study. To ensure reliable positioning, the system target integrity monitoring above 99%. Achieving this level, when combining different types of measurements that have different characteristics and different types of errors, is a challenge. A novel integrity monitoring approach is presented. A threat model of the measurements of the system components is discussed, which includes both the nominal performance and possible fault modes. A new protection level is presented to bound the maximum directional position error. The proposed approach was evaluated through a kinematic test in an urban area in Japan with a focus on horizontal positioning. Test results show that by integrating RTK, Doppler with IMU/odometer, 100% positioning availability was achieved. The integrity monitoring availability was assessed and found to meet the target value where the position errors were bounded by the protection level, which was also less than an alert level, indicating the effectiveness of the proposed approach. Figure 1 illustrates the horizontal protection level (HPL) bounding the Horizontal Positioning Error HPE for the integrated positioning systems.

A second study discusses the use of triple frequency data in Advanced Receiver Autonomous Integrity Monitoring (ARAIM). Currently, most ARAIM methods are designed to use dual-frequency ionosphere-free observations. These methods assume that receiver bias is absorbed in the common receiver clock offset and bound satellite biases by nominal values. However, most multi-constellation Global Navigation Satellite Systems (GNSS) can offer triple frequency data, which can improve observation redundancy, solution precision and detection of faults. In this contribution, we explore the use of this type of observations from GPS, Galileo and BeiDou in ARAIM. Nevertheless, the use of triple frequency data introduces receiver differential biases that have to be taken into consideration. To demonstrate the significance of these additional biases we first present a method to quantify them at stations of known coordinates and using available products from the International GNSS service (IGS). To deal with the additional receiver biases, we use a between-satellite single difference (BSSD) observation model that eliminates their effect. A pilot test was performed to evaluate ARAIM availability when using the triple-frequency observations. Real data were collected for one month at stations of known coordinates located in regions of different satellite coverage characteristics. The position error was always found to be bounded by the protection level proven initial validity of the proposed integrity model. Figure 2 shows some of the triple-frequency results demonstrating the vertical Protection level (VPL), vertical alert limit (VAL) and vertical position error (VPE) for airborne applications.

In another study, the current availability of ARAIM is experimentally investigated using real navigation data and GPS measurements collected at 60 stations across Australia. Sensitivity analysis of ARAIM availability due to changes in the elevation mask angle and the error model parameters *URA*, *URE*, and nominal biases for integrity and accuracy used for computation of the protection level is presented. It is shown that incorporation of other GNSS constellation with GPS in ARAIM is needed to achieve 99.9% Australia wide. The inclusion of BeiDou with GPS at two tests sites in Western and Eastern Australia demonstrated the promising potential of achieving this goal.

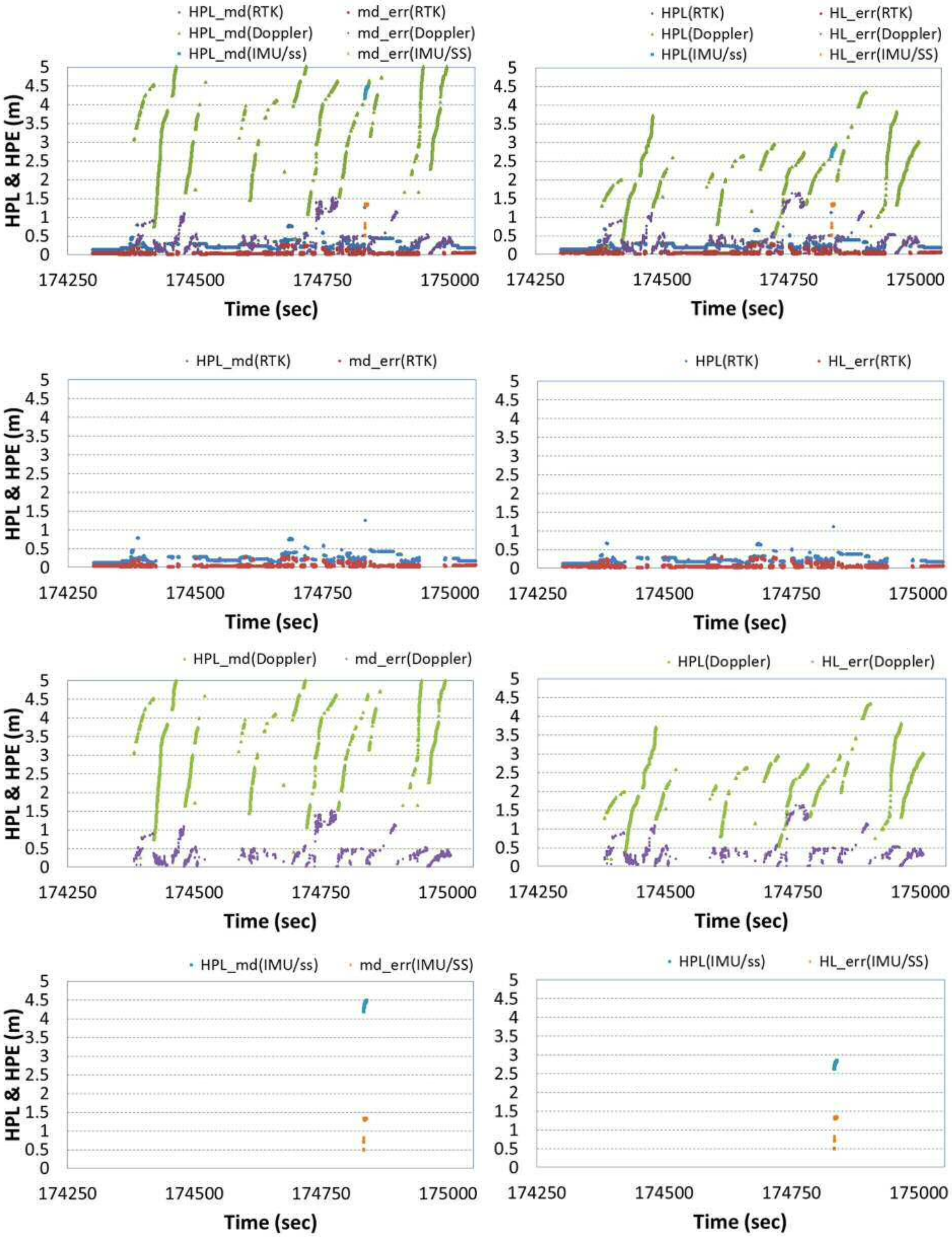

Figure 1. *HPL* and *HPE* linear 2D error for the integrated positioning systems - combined (top panel), RTK (2nd panel), Doppler Positioning (3rd panel), and IMU/SS positioning (bottom panel), $\beta = 1\times10^{-4}$.

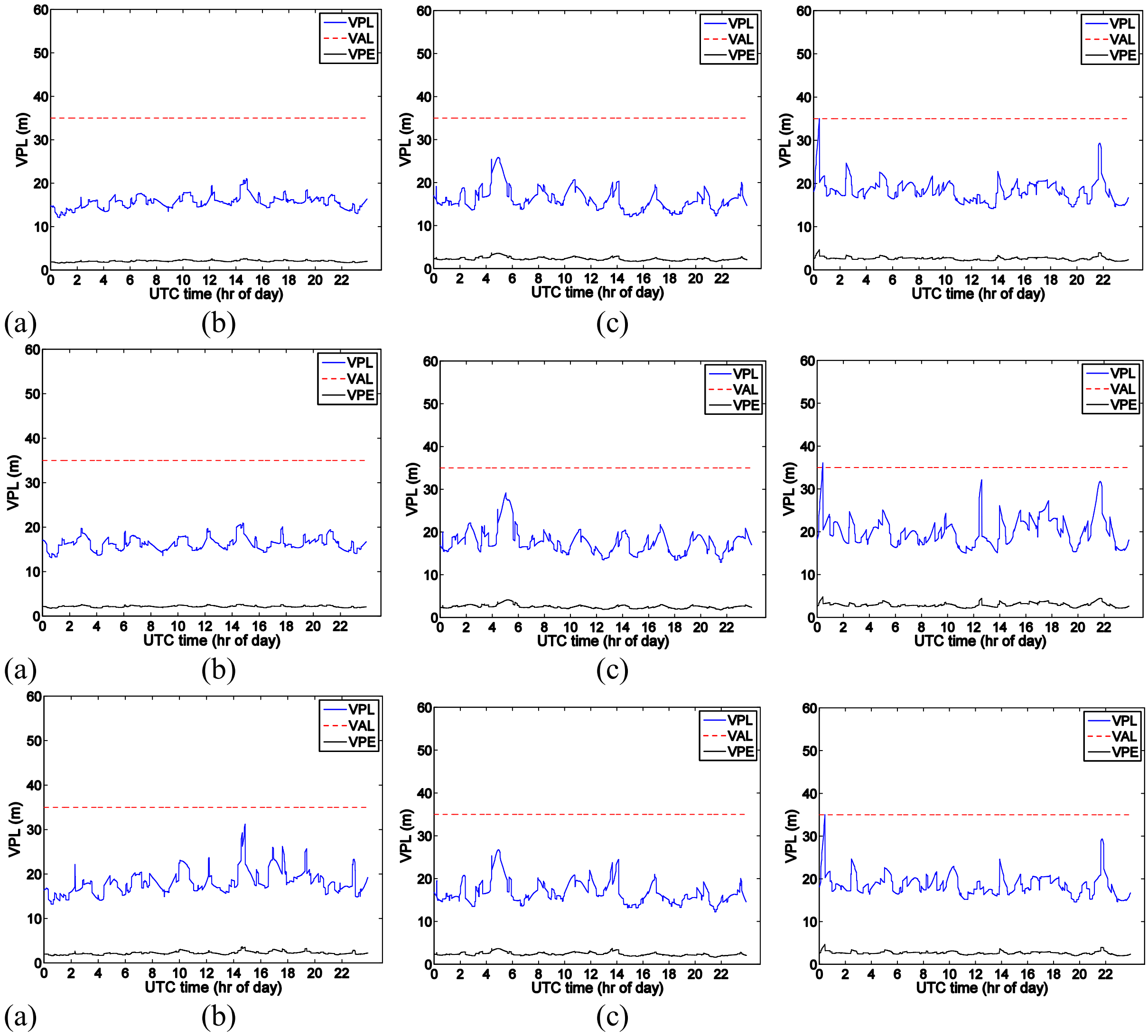

Figure 2. Time series of *VPL* (1m *URA*) and *VPE* with *VAL* using triple-frequency observations; GPS +Galileo +BeiDou (top panel); GPS and BeiDou (middle panel) and GPS with Galileo (bottom panel) on 19th June 2016 at IGS stations CUT0 (a), ZIM3 (b), and CPVG (C).

In another pilot study, availability of the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) when integrating various combinations of satellite constellations including; Galileo, GLONASS and BeiDou with GPS is investigated. The Multiple Hypothesis Solution Separation method was applied using one month of real data. The data was collected at stations of known positions, located in regions that have different coverage levels by the tested constellations. While most previous studies used simulated data, the importance of using real data is twofold. It allows for the use of actual User Range Accuracy (URA) received within the satellite navigation message, which is a fundamental component for computation of the integrity protection level; and the computation of vertical position errors to validate the integrity approach. Results show that the vertical position error was always bounded by the protection level during the test period and the ARAIM availability can reach 100% of the time when using all constellations even though some constellations are yet incomplete.

The Precise Point Positioning (PPP) is a popular positioning technique that is dependent on the use of precise orbits and clock corrections. One serious problem for real-time PPP applications such as natural hazard early warning systems and hydrographic surveying is when a sudden communication break takes place resulting in a discontinuity in receiving these orbit and clock corrections for a period that may extend from a few minutes to hours. A method is presented to maintain real-time PPP with 3D accuracy less than a decimeter when such a break takes place. We focus on the open-access International GNSS Service (IGS) Real-time Service (RTS) products and propose predicting the precise orbit and clock corrections as time series. For a short corrections outage of a few minutes we predict the IGS-RTS orbits using a fourth order polynomial, and for longer outages up to 3 hrs, the most recent IGS ultra-rapid orbits are used. The IGS-RTS clock corrections are predicted using a second order polynomial and sinusoidal terms. The models parameters are estimated sequentially using a sliding time window such that they are available when needed. The prediction model of the clock correction is built based on the analysis of their properties, including their temporal behavior and stability. Evaluation of the proposed method in static and kinematic testing shows that positioning precision of less than 10 cm can be maintained for up to two hours after the break. When PPP re-initialization is needed during the break, the solution convergence time increases; however, positioning precision remains less than a decimeter after convergence. Figure 3 shows the PPP results of kinematic tests in sea and on land using the proposed method.

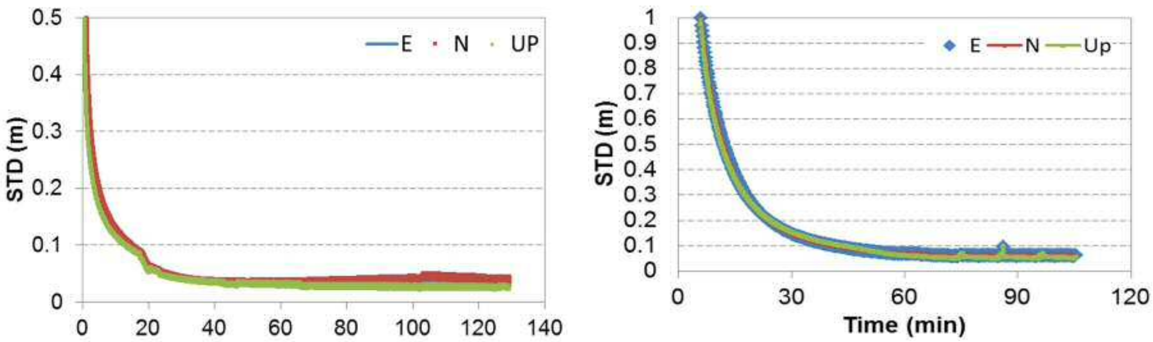

Figure 3. PPP results of the kinematic tests; shipborne (left) and vehicle (right).

Another study addressed the fact that detecting and repairing cycle slips and clock jumps is a crucial data pre-processing step needed in fault detection and exclusion (FDE) procedure when performing Precise Point Positioning (PPP). If left unrepaired, cycle slips and clock jumps can adversely affect PPP convergence time, accuracy and precision. Algorithms are proposed for detection and repair of cycle slips and clock jumps using multi-constellation and multi-frequency (MCMF) GNSS data. It is shown that availability of a third frequency enables reliable validation of detected cycle slips. This is because triple frequency analysis can identify the frequency on which the cycle slip occurred as part of the detection process. A clock jump detection and repair procedure is also proposed for a receiver with both carrier phase and code measurements showing jumps. The proposed method uses the average code and phase linear combination and applies to static data. A spline function is used to approximate the data for a pre-defined time window prior to each measuring epoch and a test is performed for detecting presence of a clock jump by comparing the interpolated value to measured value. The algorithm can effectively determine clock jumps for single frequency data from a single constellation as well as MCMF GNSS data. However, MCMF GNSS data adds redundancy, hence improves the reliability of the clock jump detection algorithm. It is recommended to detect and repair clock jumps when using PPP to allow improved modelling of the receiver clock offset in the dynamic model.

A method to compute the minimum HPL using the test statistic of normal distribution, which exploits advances in computational power to meet the requirement of Time to Alert (TTA), was proposed in one article to improve service availability. To obtain the minimum solution, two approximations used in traditional algorithms need exact solutions: the distribution of the horizontal position error and the determination of the worst case to ensure that the resulted HPL is able to accommodate all possible bias. This was validated where the optimal solution was achieved with a pre-defined accuracy and sufficient computational efficiency. Furthermore, the new HPL is used to determine if current approximated methods are conservative, where one of the methods does not meet the integrity requirement with given test statistic, error model and integrity risk definition.

The performance of online fault detection and isolation (FDI) algorithm under multiple fault scenarios was evaluated e.g., for two, three and four faults in the GNSS and GNSS/INS measurements under different conditions of visible satellites and satellite geometry. Besides, the reliability (expressed in terms of the minimal detectable bias - MDB) and separatebility (correlation coefficients between faults detection statistics) measures are also investigated to measure the capability of the FDI method. A performance analysis of the FDI method is conducted under the geometric constraints to show the importance of the FDI in terms of fault detectability and separability for robust positioning and navigation for real time applications.

For efficient IM, the focus in one study was on the quality assessment of precise orbit and clock products for the emerging Galileo, BeiDou, and QZSS systems. Products provided by Multi-GNSS Experiment (MGEX) over 2 years were used for evaluation. First, the products were assessed by orbit and clock comparisons among individual analysis centers (ACs), which give us an objective impression of their consistency. In addition, the precise orbits were verified by satellite laser ranging (SLR) residuals, which can be regarded as indicators of orbit accuracy. Moreover, precise point positioning (PPP) tests were conducted to further verify the quality of MGEX precise orbits and clocks. Orbit comparisons showed agreements of about 0.1–0.25 m for Galileo, 0.1–0.2 m for BeiDou MEOs, 0.2–0.3 m for BeiDou IGSOs, and 0.2–0.4 m for QZSS. The BeiDou GEO orbits, however, have the worst agreements having a few meters differences. Clock comparisons of individual ACs have a consistency of 0.2–0.4 ns for Galileo, 0.2–0.3 ns for BeiDou IGSOs, 0.15–0.2 ns for BeiDou MEOs, 0.5–0.8 ns for BeiDou GEOs, and 0.4–0.8 ns for QZSS in general. The SLR validations demonstrated an accuracy of about 0.1 m for the current Galileo, BeiDou IGSO/MEO orbits, and about 0.2 m for QZSS orbits. However, the SLR residuals of BeiDou GEO orbits showed a systematic bias of about −0.5 m together with a standard deviation of 0.3 m. Solutions of PPP with different products mostly agree well with each other, which further confirms the good consistency of orbits and clocks among ACs. After convergence, an accuracy of 1 mm to 1 cm for static PPP and a few centimeters for kinematic PPP was achieved using multi-GNSS observations and MGEX orbit and clock products. However, it should be noted that a few exceptions may exist throughout the evaluations due to the insufficient models, different processing strategies, and ongoing updates applied by individual ACs.

The scope of another study is on the evaluation of the performance of Galileo from the user point of view, such as Rail Transportation Management System (ERTMS), by using public data, mostly made available by the IGS and its MGEX. The analysis focuses on the open service for dual and single frequency users and covers the satellite orbit and clock errors, the signal-in-space availability, the positioning accuracy, the ranging bounding parameters, the integrity risk and the continuity risk. The Galileo satellite orbit errors are evaluated for the F-NAV messages on E5a frequency and for the I-NAV message on E1 and E5b frequencies. The broadcast ephemerides are generated from real-time streams of about 30 IGS multi-GNSS stations. Precise orbit and clock parameters as well as differential code biases are also estimated by the German Aerospace Canter (DLR). The Signal In Space Ranging Error (SISRE) as 95% in nominal condition is described and selected anomalies are identified. Outlier's exclusion approaches are used in order to assess nominal performance also in presence of anomalies. The satellite clock stability is analyzed using various GNSS stations connected to Hydrogen masers and some to the UTC network. The clock error is evaluated over arcs of 3 days based on the overlapping Allan deviation.

The second part of the study focuses on the user performance in the position domain with a particular focus on future integrity service for aviation and other applications. Signal-in-space parameters which are relevant for the Advanced RAIM concept and the generation of the Integrity Support Message are monitored and analyzed. The study focuses on two aspects, for which novel monitoring methodologies are described and used. Firstly, the bounding of the ranging error is addressed. Several bounding definitions and methods can be used for the generation of the User Range Accuracy (URA) each of them solves differently the problem of assessing statistic characteristics of the SISRE distribution tails with a limited sample size. The strict aviation integrity requirements (even stricter for rail applications) require extrapolation strategies in the online ground monitoring. On the other side the ARAIM ground monitoring can take advantage of the fact that it has to perform a bounding monitoring rather than a bounding estimation, which allows reaching confidence on higher percentiles with smaller sample size. This method will be used on the real Galileo data and results are presented and compared to state of art techniques. Secondly, the study discussed the continuity and integrity risk of the user. So far, most integrity and continuity requirements have been tailored to the aviation user needs. The risks are interpreted in an average sense, by computing probabilities of events over a certain period of time and scaling them to the duration of the specific operation. These approaches don't take into account that the continuity risk has per definition an evolution over time. The extension of ARAIM to other applications (rail, automotive, UAVs) with longer operation durations and higher level of criticism of the continuity requirements need more accurate methods. The study presents a model for the computation of the continuity risk where each satellite health status is modelled with a Markov process using the GPS Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR). The user continuity risk resulting from the ARAIM FDE is then computed propagating over time of the user healthy status.

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Working Groups of Sub-commission 4.4:

WG 4.4.1: Biases in Multi-GNSS data processing

Chair: *Xingxing Li (Germany)*
Vice Chair: *Jan Dousa (Czech Republic)*

Members

- Xingxing Li (GFZ German Research Center for Geosciences, Germany)
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- Pavel Vaclavovic (Geodetic observatory Pecny, Czech Republic)
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- Yidong Lou (Wuhan University, China)
- Bofeng Li (Tongji University, China)
- Shuanggen Jin (Shanghai Astronomical Observatory, China)
- Zishen Li (Academy of Opto-Electronics, China)
- Ningbo Wang (Institute of Geodesy and Geophysics, China)

Activities and publications during the period 2015-2017

1. **Multi-GNSS UPDs (uncalibrated phase dealys)**

A GCRE four-system UPD estimation model and multi-GNSS UD PPP AR method were developed. With data acquired from MGEX, IGS, CMONOC and HongKong CORS stations, the UPDs of GCRE four systems are estimated and the quality of UPD products in terms of temporal stability and residual distributions are also investigated, and then we evaluated the benefits of multi-GNSS to PPP AR. Our results show, that GCRE four-system PPP-AR enables the fastest time to first fix (TTFF) solutions and the highest accuracy for all three coordinate components compared to the single- and dual-system. An average TTFF of 9.21 min with 7° cut-off elevation can be achieved for GCRE PPP AR, which is much shorter than that of GPS (18.07 min), GR (12.10 min), GE (15.36 min) and GC (13.21 min). With observations length of 10 minutes, the positioning accuracy of the GCRE fixed solution is (1.84, 1.11, 1.53) cm while the GPS-only result is (2.25, 1.29, 9.73) cm for the east, north and vertical components, respectively. When the cut-off elevation is increased to 30°, the GPS-only PPP AR results are very unreliable while 13.44 min of TTFF is still achievable for GCRE four-system solutions.
A dataset of 30 days from DOY001 to 030 of 2017 with a tracking network consisting of about 148 MGEX/IGS stations is used for GPS UPD estimation. The mean STD of the 30-day WL UPDs is 0.023 cycles while the mean STD of NL UPDs at DOY001 is 0.03 cycles. The

percentage of residuals within ±0.15 cycles and within ±0.25 cycles are 94.8% and 98.7% for WL, 95.1% and 99.9% for NL, respectively. A global tracking network containing 67 MGEX stations are is used to estimate BDS UPDs. The influence of satellite-induced code biases is analyzed for BDS UPDs. Results show that the temporal stability of BDS WL UPDs is improved by 27.9%, 77.9% and 88.9% for GEO, IGSO and MEO satellites after code bias correction, while 1.7%, 17.6% and 22.6% are improved for BDS NL UPDs. Besides, the observations from the CMONOC and Hong Kong CORS network are also used for evaluate BDS UPDs. After the code bias correction, the mean STDs of CMONOC WL UPDs are improved by 16.7%, 27.6% and 85.9% for GEO, IGSO and MEO satellites and 11.7%, 12.1% and 74.4% are improved for Hong Kong CORS network. No obvious improvement is found for NL UPDs of regional network after code bias correction. When compared with global BDS NL UPDs, BDS NL UPDs estimated by Hong Kong CORS network is the more stable one with mean STDs of 0.031, 0.014 and 0.007 cycles for GEO, IGSO and MEO satellites. Thus, it is demonstrated that the higher temporal stability will be achieved for WL UPDs after the code bias correction and the small network will lead to a better results of NL UPDs. With a network of homogeneous receivers, the GLONASS UPDs were estimated with three mainstreaming types of receivers (TRIMBLE NETR9, JAVAD TRE_G3TH DELTA and LEICA) respectively. Results show that the WL UPDs estimated with TRIMBLE NETR9 all version receivers have the greatest stability with a mean STD of 0.0395 cycles, while the WL UPDs estimated with JAVAD TRE_G3TH DELTA version 3.6.7 receivers are the worst with a mean STD of 0.0565 cycles. For results of NL UPDs, UPDs estimated from LEICA receivers show the worst stability with the mean STD being of 0.117 cycles. For all type s of GLONASS UPDs, the percentages of NL residuals within ±0.25 cycles are close to 100%, while the percentages of WL residuals within ±0.25 cycles are 92.90%, 94.68%, 93.41% and 85.89% for TRIMBLE NETR9 all version receivers, TRIMBLE NETR9 5.15 receivers, LEICA receivers and JAVAD TRE_G3TH DELTA version 3.6.7 receivers, respectively. Although different version of receiver firmware has no influence on the temporal stability of GLONASS UPDs, it will cause a common deviation for NL UPDs comparing with the result of receivers with the same firmware version. It is necessary to select stations with the same receiver firmware version to conduct the GLONASS UPD estimation and PPP AR. Global and European networks are applied for the estimation of Galileo UPDs. The mean STD of global-network-derived WL UPDs is 0.01 cycles and that from European network is 0.02 cycles. The mean STDs of NL UPDs are 0.09 and 0.11 cycles for global and European networks, respectively. In terms of mean STD, global and European networks have comparable performance. However, the RMS of WL and NL residuals are 0.091 and 0.107 cycles for global network, 0.072 and 0.082 cycles for European network, which indicates that UPDs estimated by European network are more reliable.

2. **BDS satellite-induced code bias**

Since the satellite-induced and elevation-dependent code biases were observed for the 14 older BDS-2 satellites (C01-C14), an analysis and characterization of the code observations for the six newly launched satellites is required. The Multipath (MP) combination, Melbourne-Wübbena (MW) combination and Uncalibrated Phase Delays (UPDs) are calculated for all newly launched satellites on different frequencies. The results indicate that the newly launched BDS-2 satellite I6 has similar elevation-dependent code bias as the 14 older BDS-2 satellites while the satellite-induced code bias is negligible for the BDS-3 satellites. We also developed an improved elevation-dependent code bias correction model to mitigate satellite-induced code bias of the BDS satellites. The impact of code bias on MP combination, wide-lane ambiguity and UPD estimation were evaluated before and after the code bias correction. After applying the new correction model to the code observations, significant improvement is achieved in terms of the root mean square (RMS) of the MP series, the convergence time of the MW series and the quality of UPDs estimates for the I6 satellite and five older BDS-2 IGSO satellites C06-C10. No significant improvement is achieved for the results of MP series, MW series and UPD estimates for BDS-3 satellites since the derived correction values are nearly close to zero, which also indicates that the code biases are ignorable for the new-generation BDS-3 satellites on all frequency bands. This finding denotes a significant improvement for the new-generation BDS satellites and signals.

3. Inter-frequency Phase Bias

The triple-frequency carrier phase combination time series vary within 2 cm for all the satellites except G01, which reaches approximately 4 cm. Small bias variations, which reach up to ~2and 4cm respectively are observedfor C01 and G01. Such apparent bias variation, which is also known as inter-frequency clock bias (IFCB), signifies the difference of satellite clock offsets determined from two different signal pairs and provides an indication of thermally dependent inter-frequency biases. As the IFCBs for a certain satellite are identical for different receivers even though these are at different locations, the IFCBs could be completely eliminated as a common error by forming differences between receivers in precise relative positioning applications. However, without careful consideration of such biases, the satellite clock products derived from the first pair of carrier phase observations cannot be used for PPP using the second pair of carrier phase observations. This means that the presence of IFCB will limit the applicability of a common clock product for PPP applications. In line with our analysis, several researchers have also previously identified the presence of bias variations for GPS Block IIF and BeiDou-2 satellites. In contrast, no apparent bias variations can be recognized for the QZSS and Galileo satellites. Our findings for the first time indicate that all new-generation BeiDou-3 satellites show a good consistency of the B1C-B2b-B2a signals and exhibit no apparent bias variations. The absence of such bias variations simplifies the potential processing of multi-frequency PPP using observations from the new-generation BeiDou-3 satellites.

4. Differential code bias

Differential code biases (DCBs) of global navigation satellite system (GNSS) are required for code based positioning, ionospheric total electron content (TEC) extracting, as well as ambiguity resolution using code observation. In order to properly handle the code biases in GNSS data processing, the algorithm of IGGDCB (IGG stands for the Institute of Geodesy and Geophysics in Wuhan) has been developed for the estimation and analysis of the DBCs between all relevant signals of the currently changing GNSS environment. IGGDCB method is developed for the DCB estimation of current regional BDS satellites, which is also adaptable for GPS, GLONASS and Galileo constellations. The GNSS DCB processing activities and progresses conducted at IGG and Academy of Opto-Electronics (AOE) of the Chinese Academy of Sciences (CAS) include: (1) GPS and GLONASS DCB estimation in parallel with global ionospheric total electron content (TEC) modeling at the CAS ionosphere analysis center (IAC) of the IGS; and (2) routine CAS MGEX DCB products contribute to the IGS multi-GNSS experiment (MGEX) project.

CAS was nominated as a new IGS IAC during the IGS workshop 2016 held in Sydney, Australia. The global ionospheric maps (GIM) of CAS is generated by SHPTS (Spherical Harmonic plus generalized Trigonometric Series functions) method, which takes advantages of the spherical harmonic and the generalized trigonometric series functions on global and local scales, respectively. The daily satellite and receiver DCBs between the legacy GPS and GLONASS C1, P1, P2 and C2 signals are also included in the rapid and final GIM products, which is confirmed to perform at the same level of the DCBs provided by the Center for Orbit

Determination in Europe (CODE). CAS starts the routine upload of the rapid and final GIMs to the IGS from the beginning of 2017. CAS's GIM products covering the time span 1998-now are now available from CDDIS (cddis.gsfc.nasa.gov) and our own GIPP (ftp.gipp.org.cn/product/ionex/) ftp archives, with a latency of 1 and 3 days for rapid and final products, respectively.

The multi-GNSS DCBs generated at CAS also contribute to the IGS MGEX project in addition to the products provided by the German Aerospace Center (DLR). In spite of the legacy GPS and GLONASS signals, the new GPS civil signals as well as BDS and Galileo signals are also included in the data processing of CAS. It means that DCBs of all relevant signals of the GPS, GLONASS, BDS and Galileo satellites are determined in CAS's MGEX DCB products. Other than DLR's MGEX DCB product, which makes use of CODE's global ionosphere maps for ionospheric correction, CAS's product is derived on the basis of IGGDCB method, which employs local ionospheric model for the combined estimation of DCBs and ionospheric activities with the multi-GNSS observations. CAS's DCB product is generated on a daily with a new naming scheme proposed for future MGEX products, which has been routinely delivered to CDDIS and IGS repositories of the IGS since mid-October 2015, covering the time span 2013-now.

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Meetings and communications during the period 2015-2017

1) A Special Issue of *Advances in Space Research* on “Multi-constellation GNSS: Methods, Benefits, Challenges, and Geosciences Applications”;
2) We will organize a workshop on “Multi-GNSS Biases” in 2017, location still to be selected.

WG 4.4.2: Integer Ambiguity Resolution for Multi-GNSS PPP and PPP-RTK

Chair: *Xiaohong Zhang (China)*
Vice Chair: *Sue Lynn Choy (Australia)*

Members

- *Yang Gao (University of Calgary, Canada)*
- *Jianghui Geng (Wuhan University, China)*
- *Simon Banville (Natural Resources Canada, Canada)*
- *Sunil Bisnath (York University, Canada)*
- *José Miguel Juan (UPC, Spain)*
- *Baocheng Zhang (GNSS Research Centre, Curtin University, Australia)*
- *Pan Li (GFZ, Germany)*

Activities and publications during the period 2015-2017

1. Ambiguity resolved precise point positioning with GPS and BeiDou

A GPS + BDS fractional cycle bias (FCB) estimation method and a PPP AR model were developed using integrated GPS and BDS observations. For FCB estimation, the GPS + BDS combined PPP float solutions of the globally distributed IGS MGEX were first performed. When integrating GPS observations, the BDS ambiguities can be precisely estimated with less than four tracked BDS satellites. The FCBs of both GPS and BDS satellites can then be estimated from these precise ambiguities. For the GPS + BDS combined AR, one GPS and one BDS IGSO or MEO satellite were first chosen as the reference satellite for GPS and BDS, respectively, to form inner-system single-differenced ambiguities. The single-differenced GPS and BDS ambiguities were then fused by partial ambiguity resolution to increase the possibility of fixing a subset of decorrelated ambiguities with high confidence. To verify the correctness of the FCB estimation and the effectiveness of the GPS + BDS PPP AR, data recorded from about 75 IGS MGEX stations during the period of DOY 123-151 (May 3 to May 31) in 2015 were used for validation. Data were processed with three strategies: BDS-only AR, GPS-only AR and GPS + BDS AR. Numerous experimental results show that the time to first fix (TTFF) is longer than 6 h for the BDS AR in general and that the fixing rate is usually less than 35% for both static and kinematic PPP. An average TTFF of 21.7 min and 33.6 min together with a fixing rate of 98.6 and 97.0% in static and kinematic PPP, respectively, can be achieved for GPS-only ambiguity fixing. For the combined GPS+BDS AR, the average TTFF can be shortened to 16.9 min and 24.6 min and the fixing rate can be increased to 99.5 and 99.0%in static and kinematic PPP, respectively. Results also show that GPS + BDS PPP AR outperforms single-system PPP AR in terms of convergence time and position accuracy.

2. Multi-GNSS precise point positioning using raw observations

A joint-processing model for multi-GNSS (GPS, GLONASS, BDS and GALILEO) precise point positioning (PPP) is proposed, in which raw code and phase observations are used. In the proposed model, inter-system biases (ISBs) and GLONASS code inter-frequency biases (IFBs) are carefully considered, among which GLONASS code IFBs are modeled as a linear function of frequency numbers. To get the full rank function model, the unknowns are re-parameterized and the estimable slant ionospheric delays and ISBs/IFBs are derived and estimated simultaneously. One month of data in April, 2015 from 32 stations of the International GNSS Service (IGS) Multi-GNSS Experiment (MGEX) tracking network have been used to validate the proposed model. Preliminary results show that RMS values of the positioning errors (with respect to external double-difference solutions) for static/kinematic solutions (four systems) are 6.2 mm/2.1 cm (north), 6.0 mm/2.2 cm (east) and 9.3 mm/4.9 cm(up).One-day stabilities of the estimated ISBs described by STD values are 0.36 and 0.38 ns, for GLONASS and BDS, respectively. Significant ISB jumps are identified between adjacent days for all stations, which are caused by the different satellite clock datums in different days and for different systems. Unlike ISBs, the estimated GLONASS code IFBs are quite stable for all stations, with an average STD of 0.04 ns over a month. Single-difference experiment of short baseline shows that PPP ionospheric delays are more precise than traditional leveling ionospheric delays. The significant improvement of satellite visibility, spatial geometry, dilution of precision, convergence, accuracy, continuity and reliability that a combining utilization of multi-GNSS brings to precise positioning are also carefully analyzed and evaluated, especially in constrained environments.

3. *Modeling and Assessment of Triple-frequency BDS Precise Point Positioning*

The latest generation of GNSS satellites such as GPS BLOCK IIF, Galileo and BDS are transmitting signals on three or more frequencies, thus having more choices in practice. At the same time, new challenges arise for integrating the new signals. The modeling and assessment of triple-frequency PPP with BDS data were conducted. Firstly, three triple-frequency PPP models are developed. The observation model and stochastic model are designed and extended to accommodate the third frequency. In particular, new biases such as differential code biases and inter-frequency biases as well as the parameterizations are addressed. Then, the relationships between different PPP models are discussed. To verify the triple-frequency PPP models, PPP tests with real triple-frequency data were performed in both static and kinematic scenarios. Results show that the three triple-frequency PPP models agree well with each other. Additional frequency has a marginal effect on the positioning accuracy in static PPP tests. However, the benefits of third frequency is significant in situations of where there is poor tracking and contaminated observations on frequencies B1 and B2 in kinematic PPP tests.

4. *Rapid initialization of real-time PPP by resolving undifferenced GPS and GLONASS ambiguities simultaneously*

Rapid initialization of real-time precise point positioning (PPP) has constantly been a difficult problem. Recent efforts through multi-GNSS and multi-frequency data, though beneficial indeed, have not proved sufficiently effective in reducing the initialization periods to far less than 10 min. Though this goal can be easily reached by introducing ionosphere corrections as accurate as a few centimeters, a dense reference network is required which is impractical for wide-area applications. Leveraging the latest development of GLONASS PPP ambiguity resolution (PPP-AR) technique, we propose a composite strategy, where simultaneous GPS and GLONASS dual-frequency PPP-AR is carried out, and herein, the reliability of partial AR improves dramatically. We used 14 days of data from a German network and divided them into hourly data to test this strategy. We found that the initialization periods were shortened drastically from over 25 min when only GPS data were processed to about 6 min when GPS and GLONASS PPP-AR were accomplished simultaneously. More encouragingly, over 50% of real-time PPP solutions could be initialized successfully within 5 min through our strategy, in contrast to only 4% when only GPS data were used. We expect that our strategy can provide a promising route to overcoming the difficulty of achieving PPP initializations within a few minutes.

Selected publications during the period 2015-2017:

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Harima K, Choy S, Rizos C, Satoshi K (2016) Performance of Real-Time Precise Point Positioning in New Zealand. In: Proceedings of FIG 2016, Christchurch, New Zealand, 2-6 May.

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Meetings and communications during the period 2015-2017

1. Session: Precise Point Positioning (PPP). IEEE / ION PLANS Conference, 11-14 April, Savannah, Georgia 2016.
2. Session: Advanced Technologies in High Precision GNSS Positioning. ION GNSS+ 2015, 14-18 September, Tampa, Florida.
3. Session: High precision GNSS-PPP. ION International Technical Meeting 2017, 30 January-02 February, Monterey, California.
4. Session: Multi-GNSS and GNSS specialities and Geo-Dynamics and GNSS Analysis. FIG Working Week, Sofia, Bulgaria, 17-21 May 2015
5. Session: GNSS and National Datum. FIG Working Week, Christchurch, New Zealand, 2-6 May 2016
6. Session: GNSS. FIG Working Week, Helsinki, Finland, 29 May-2 June 2017
7. Session: GNSS PPP. IGNSS, Gold Coast, Australia, 14-16 July 2016
8. Session: PPP. IGNSS, Sydney, Australia, 6-8 December 2016

Inter-Commission Committee on Theory (ICCT)

http://icct.kma.zcu.cz

President: Pavel Novák (Czech Republic)
Vice President: Mattia Crespi (Italy)

Structure

Joint Study Group 0.10:	High-rate GNSS
Joint Study Group 0.11:	Multiresolutional aspects of potential field theory
Joint Study Group 0.12:	Advanced computational methods for recovery of high-resolution gravity field models
Joint Study Group 0.13:	Integral equations of potential theory for continuation and transformation of classical and new gravitational observables
Joint Study Group 0.14:	Fusion of multi-technique satellite geodetic data
Joint Study Group 0.15:	Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy
Joint Study Group 0.16:	Earth's inner structure from combined geodetic and geophysical sources
Joint Study Group 0.17:	Multi-GNSS theory and algorithms
Joint Study Group 0.18:	High resolution harmonic analysis and synthesis of potential fields
Joint Study Group 0.19:	Time series analysis in geodesy
Joint Study Group 0.20:	Space weather and ionosphere
Joint Study Group 0.21:	Geophysical modelling of time variations in deformation and gravity
Joint Study Group 0.22:	Definition of next generation terrestrial reference frames

Overview

Terms of reference

The Inter-Commission Committee on Theory (ICCT) was formally approved and established after the IUGG XXI Assembly in Sapporo, 2003, to succeed the former IAG Section IV on General Theory and Methodology and, more importantly, to interact actively and directly with other IAG entities, namely commissions, services and the Global Geodetic Observing System. IAG approved the continuation of ICCT at the IUGG XXIII Assembly in Melbourne, 2011. At the IUGG XXIV Assembly in Prague, 2015, ICCT became a permanent entity within the IAG structure. The structure of the ICCT is specified in the IAG by-laws.

The main objectives of the ICCT are:
- to be the international focal point of theoretical geodesy,
- to encourage and initiate activities to further geodetic theory,
- and to monitor research developments in geodetic modelling.

ICCT's Steering Committee 2015-2019

President	*Pavel Novák* (Czech Rep.)
Vice-President	*Mattia Crespi* (Italy)
Past-President	*Nico Sneeuw* (Germany)
Commission 1	*Geoffrey Blewitt* (USA)
Commission 2	*Roland Pail* (Germany)
Commission 3	*Manabu Hashimoto* (Japan)
Commission 4	*Marcelo Santos* (Canada)
GGOS	*Hansjörg Kutterer* (Germany)
IGFS	*Riccardo Barzaghi* (Italy)
IERS	*Jürgen Müller* (Germany)

During the 2015-2017 period, the ICCT Steering Committee met during regular meetings of the IAG's Executive Committee as their memberships largely overlap. The ICCT President informed members of the two committees about the structure of the ICCT, activities of its joint study groups and about ongoing organization of the next Hotine-Marussi Symposium on Mathematical Geodesy which will be organized by ICCT in 2018, see below. The next meeting of the committee will be organized during the Joint Scientific Assembly of IAG and IASPEI, Kobe, Japan, in August 2017.

Website

The ICCT website is hosted at http://icct.kma.zcu.cz by the web server of the Department of Geomatics, University of West Bohemia in Pilsen, and is powered by the MediaWiki Engine (similar to that used for the Wikipedia, a free, web-based multilingual encyclopaedia project). Due to this setup, the content of the ICCT Website can easily be edited by any authorized personnel (members of the ICCT Steering Committee and Chairs of the Study Groups). Thus, the website can be used by for fast and easy communication of ideas among the members of the Study Groups.

IX Hotine-Marussi Symposium

The highlight of the ICCT activities within the four-year period between IUGG General Assemblies is always the organization of the Hotine-Marussi Symposium on Mathematical Geodesy. Since the inception of ICCT, the already existing series of the Hotine-Marussi Symposia falls under the responsibility of ICCT. Earlier ICCT-organized symposia were the numbers VI (2006, Wuhan), VII (2009, Rome) and VIII (2013, Rome). The venue of the last two symposia was the Faculty of Engineering of the Sapienza University of Rome.

The next, IX, Hotine-Marussi symposium was supposed to be organized in 2017 following the traditional schedule of activities. However, based on the decision of the IAG Executive Committee, the next Hotine-Marussi symposium will be organized in early summer of 2018 in order to avoid the conflict with the IAG scientific meetings (next IAG scientific meeting will be organized this year in Kobe, Japan). The organization of the next Hotine-Marussi meeting is in preparation with two venue candidates (both in Italy) considered. Anticipated session topics will follow roughly the current study group structure of ICCT.

Further Meetings

The Hotine-Marussi Symposium is not the only scientific meeting with the visible presence of the ICCT. Session dedicated to recent general developments in geodetic theory were organized by ICCT-related personnel at the EGU General Assemblies 2016 and 2017 in Vienna. Other sessions on selected particular topics of theoretical geodesy related to joint study groups' activities were also organized at the EGU assemblies and at IAG's Commission 2 and Commission 4 meetings in Thessaloniki and Wroclaw, 2016. Other meetings and/or session are listed within reports of individual joint study groups in the following text.

Summary on activities of study groups

The activities of the ICCT are related namely to research activities carried out by members of its joint study groups. Their midterm reports specify main research areas under investigation, achieved results and outputs (namely publications and presentations). Based on the content of the submitted reports, it can be concluded that the joint study groups have been active, although the level of co-operation and/or interaction between its members is not necessarily the same for all the joint study groups. The level of detail and extent of the reports also vary and for the final report in 2019 more detailed instruction concerning the length, structure and level of detail will have to be explicitly specified. Some of the study groups also extended its memberships.

Most importantly, all chairmen but one delivered their report in time which confirms the main idea behind the current ICCT structure: involving young enthusiastic researchers as new study group chairmen who actively cooperate internationally at research topics which matter to current geodesy. Based on to-date activities of the groups, it is very likely they will stay operational until 2019 with the next Hotine-Marussi Symposium on Mathematical geodesy planned for 2018 highlighting the remaining two years of the period 2015-2019.

Only one study group did not submit its report; its continuation will be discussed at the ICCT and IAG EC meetings at the IAG/IASPEI Joint Scientific Meeting in Kobe, August 2017.

Joint Study Group 0.10: High-rate GNSS

Chair: *Mattia Crespi (Italy)*

Members

- *Juan Carlos Baez (Chile)*
- *Elisa Benedetti (United Kingdom)*
- *Geo Boffi (Switzerland)*
- *Gabriele Colosimo (Switzerland)*
- *Athanasios Dermanis (Greece)*
- *Roberto Devoti (Italy)*
- *Jeff Freymueller (USA)*
- *Joao Francisco Galera Monico (Brazil)*
- *Jianghui Geng (China)*
- *Kosuke Heki (Japan)*
- *Melvin Hoyer (Venezuela)*
- *Augusto Mazzoni (Italy)*
- *Nanthi Nadarajah (Australia)*
- *Yusaku Ohta (Japan)*
- *Ruey-Juin Rau (Taiwan)*
- *Eugenio Realini (Italy)*
- *Chris Rizos (Australia)*
- *Giorgio Savastano (USA)*
- *Nico Sneeuw (Germany)*
- *Peiliang Xu (Japan)*

Activities and publications during the period 2015-2017

Research

Considering the Terms of Reference of JSG0.10, and specifically its objectives and program of activities, see http://icct.kma.zcu.cz/index.php/JSG0.10, the work outlined in the following report has been developed and is presently ongoing.

1. Monitoring of ground shaking and displacement during earthquakes

GPS Seismology for moderate magnitude earthquake: analysis of the 31 October 2013 ML 6.4 Ruisui (Taiwan) earthquake, see (Hung et al., 2017)

The 31 October 2013 ML 6.4 Ruisui earthquake was well recorded by twelve 50-Hz, four 20-Hz and thirteen 1-Hz GPS receivers, and twenty-five strong motion stations located within the epicentral distance of about 90 km in eastern Taiwan. Kinematic positioning solutions estimated by four GNSS software (TRACK, RTKLIB, GIPSY and VADASE) were used to derive seismic waveforms and co-seismic displacements for this event; strong motion accelerometers were used to verify the capability of high rate GPS to detect body waves and surface waves, see Figure 1. Results showed that the coordinate repeatability of the GPS displacements time series are ~6 mm and ~20 mm standard deviation in the horizontal and vertical components respectively, after applying spatial filtering.

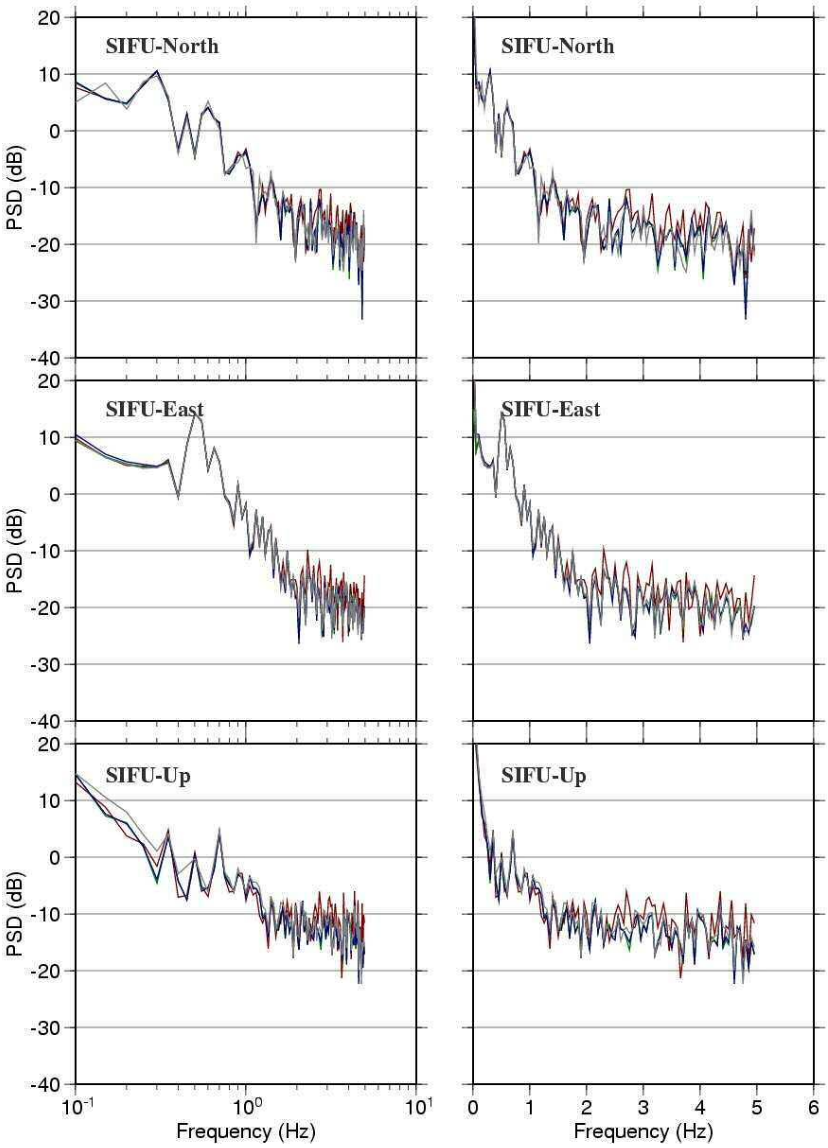

Figure 1: *Power spectral densities of the displacements time series at CGPS SIFU generated from the software TRACK (brown), GIPSY (green), RTKLIB in the PPP solution (blue) and VADASE (grey) in all three components*

Recent advances of the VADASE software to enhance reliability and accuracy of real-time displacement estimation, see (Fratarcangeli et al., 2017)

VADASE displacements might be impacted by two different effects: spurious spikes in velocities due to outliers (in this case, displacements, obtained through velocities integration, are severely corrupted), and trends in the displacements (mainly due to broadcast orbit and clock errors). Moreover, for applications to earthquakes (seismic inversion), it is quite useful to estimate in real-time the so-called coseismic displacement. These three issues (outliers in velocity, trends in displacements and real-time coseismic displacements) were addressed in recent advances of VADASE. Two strategies were introduced, respectively based on Leave-One-Out Cross Validation (VADASE–LOO) for a receiver autonomous outlier detection, and on a network augmentation strategy to filter common trend out (A–VADASE), see Figure 2. Moreover, a statistical test, based on the hypothesis of a constant mean level noise of the VADASE velocity estimates over few minutes, and a robust estimation procedure were introduced; they allow to estimate the overall coseismic displacement.

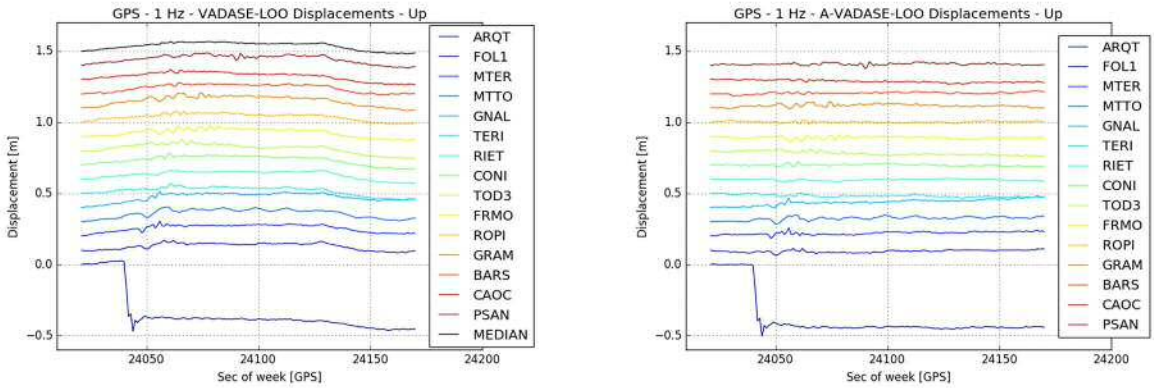

Figure 2: *Estimated displacements before (left) and after (right) trend removing by A–VADASE–LOO in the 150 s interval for the main shock of October 30, Mw 6.5 near Norcia (Perugia) earthquake, GPS time*

Error analysis of high-rate GNSS precise point positioning for seismic wave measurement, see (Shu et al., 2017)

A theoretical error analysis of PPP was carried out, together with the corresponding simulations within a short period of time, to fully understand the mechanism of mystified excellent performance of high-rate PPP within a short period of time. This analysis clearly indicated that the high-rate PPP errors consisted of two types: the residual systematic errors at the starting epoch, which affect high-rate PPP through the change of satellite geometry, and the time-varying systematic errors between the starting epoch and the current epoch. Also, real data experiments indicated that high-rate PPP can indeed achieve the millimetre level of precision in the horizontal components and the sub-centimetre level of precision in the vertical component to measure motion within a short period of time, see Figure 3. Moreover, the simulation results have clearly shown that the random noise of carrier phases and higher order ionospheric errors are two major factors to affect the precision within a short period of time. The experiments with real data have finally indicated that the precision of PPP solutions can degrade to the cm level in both the horizontal and vertical components, if the geometry of satellites is rather poor with a large DOP value.

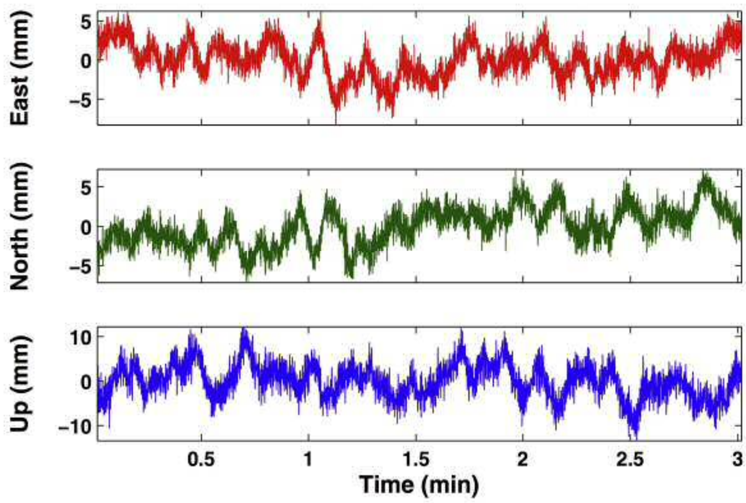

Figure 3: *PPP-derived displacements of waveform motion (mm)*

Integrated GPS/GLONASS for high-rate seismogeodesy, see (Geng et al., 2017)

The goal of this investigation is to check whether the positioning accuracy of high-rate GPS suffices in the identification of seismic signals, especially for relatively minor events. However, high-rate GPS is always obsessed by multipath effects. Although multipath effects can be partly mitigated through sidereal filtering, satellite orbits, atmosphere refractions, tides, etc. also contribute to the high-rate GPS noise. In addition, we have already been in a multi-GNSS environment where Russia's GLONASS has been in a full constellation since 2012 and the quality of its satellite orbit products by IGS has evolved into the quite similar level to the GPS counterpart. In this study, it was demonstrated that multi-GNSS will contribute significantly to reducing noise of high-rate displacements as compared to sidereal filtering, see Figure 4. The main conclusions are: 1) GPS sidereal filtering can potentially amplify errors on the lowest frequency band of a high-rate displacement time series; 2) integration with GLONASS reduces the noise of high-rate GPS by up to 40% over the entire frequency band of a displacement time series; and 3) high-rate multi-GNSS can be enhanced by sidereal filtering which is implemented to avoid complicating the noise spectrum.

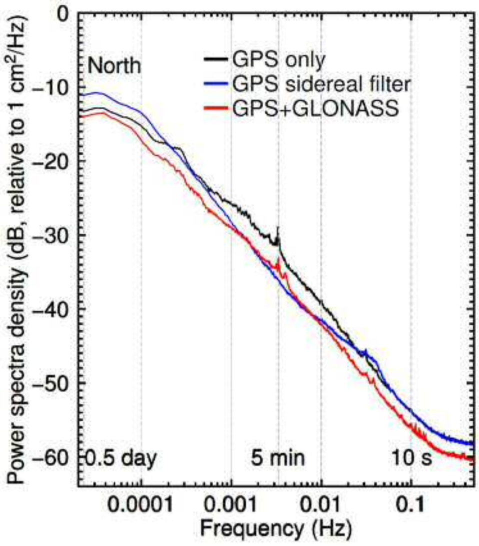

Figure 4: *Power spectral densities (PSD) of 1-Hz displacements in the north component derived from GPS-only, sidereally filtered GPS-only and integrated GPS/GLONASS solutions*

2. Tsunami early warning – Real-time detection of ionospheric perturbations

Real-time detection of Tsunami ionospheric disturbances with a stand-alone GNSS receiver: A preliminary feasibility demonstration, see (Savastano et al., 2017)

VARION (Variometric Approach for Real-Time Ionosphere Observation) is a novel algorithm able to estimate slant TEC (sTEC) variations in a real-time scenario. Using the VARION algorithm TEC variations at 56 GPS receivers in Hawaii as induced by the 2012 Haida Gwaii tsunami event were computed. TEC perturbations were observed with amplitudes of up to 0.25 TEC units and travelling ionospheric perturbations (TIDs), see Figure 5, moving away from the earthquake epicentre at an approximate speed of 316 m/s. A wavelet analysis to analyse localized variations of power in the TEC time series was performed and perturbation periods consistent with a tsunami typical deep ocean period were found. Finally, variations in TEC that correlate in time and space with the tsunami waves were assessed, see Figure 6.

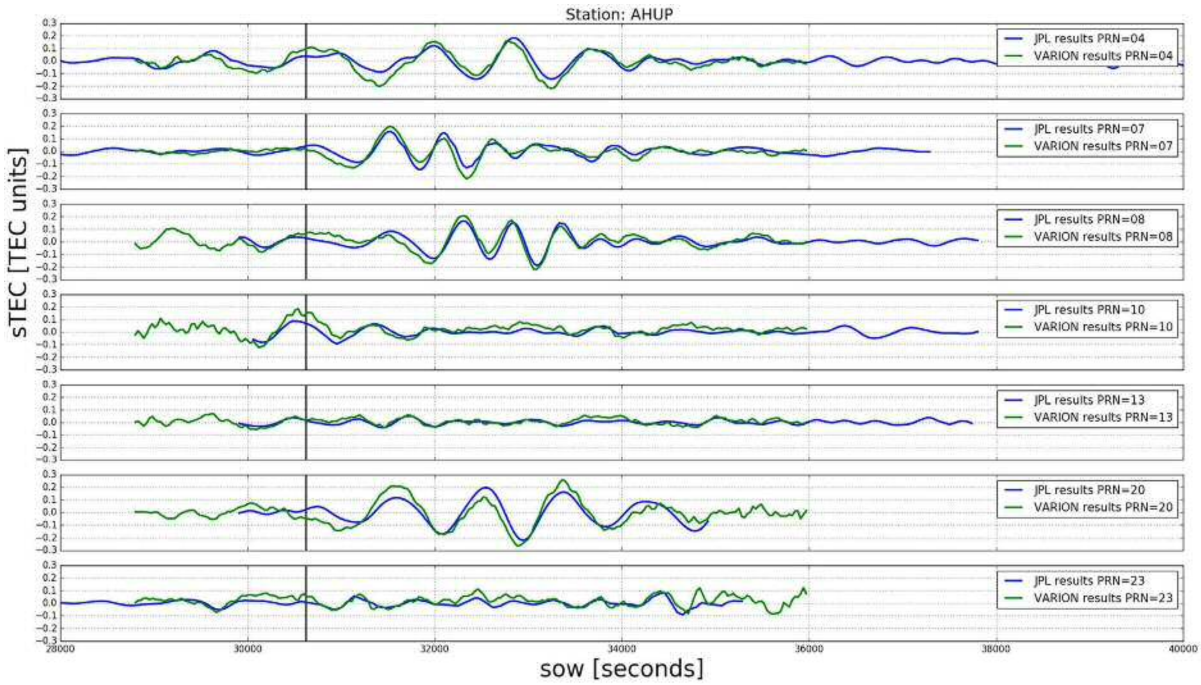

Figure 5. *Comparison between TEC time series obtained from the VARION and JPL techniques. TEC variations are computed for 7 satellites (PRNs 4, 7, 8, 10, 13, 20 and 23) in view from the AHUP station on the Hawaiian Islands. The black vertical line represents the time when the tsunami reached the Hawaiian Islands. TIDs were clearly detected, with good agreement between the two approaches.*

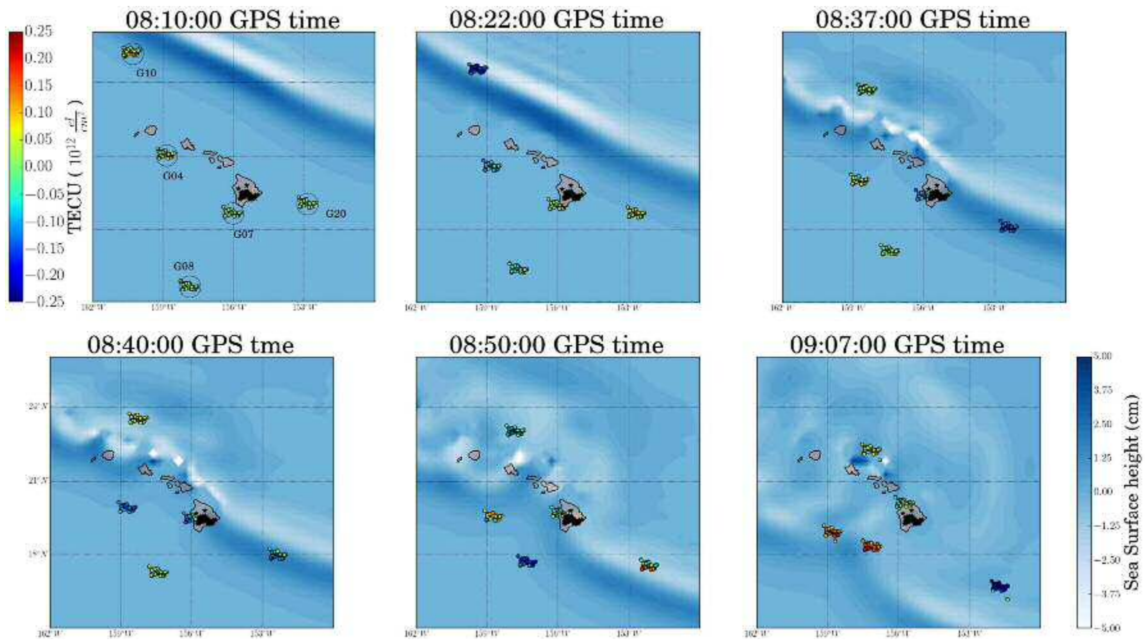

Figure 6. *Space-time sTEC variations at 6 epochs within the two hours interval (08:00 to 10:00 UT – 28 October 2012) at the SIPs for the 5 satellites showing TIDs, over-plotted the tsunami MOST model. TIDs are consistent in time and space with the tsunami waves.*

3. Real-time controlling landslides and the safety of structures

Exploiting performance of different low-cost sensors for small amplitude oscillatory motion monitoring: preliminary comparisons in view of possible integration, see (Benedetti et al., 2016)

The problem of low amplitude oscillatory motion detection through different low-cost sensors (LIS3LV02DQ MEMS accelerometer, Microsoft Kinect v2 range camera and uBlox 6 GPS receiver) was addressed. Several tests were performed using a one-direction vibrating table with different oscillation frequencies (in the range 1.5–3 Hz) and small challenging amplitudes (0.02 and 0.03 m). A Mikrotron EoSens high-resolution camera was used to give reference data. In the investigated time interval (in the order of tens of seconds) the results obtained indicate that displacements were detected with the resolution of fractions of millimetres with MEMS accelerometer and Kinect v2 and few millimetres with uBlox 6, see Table 1. MEMS accelerometer displays the lowest noise but a significant bias, whereas Kinect v2 and uBlox 6 appear more stable. The results suggest the possibility of sensor integration both for indoor (MEMS accelerometer + Kinect v2) and for outdoor (MEMS accelerometer + uBlox 6) applications and seem to be promising for structural monitoring applications.

Table 1: *Accuracy (RMSE), bias (mean) and noise (standard deviation) in test with 0.02 m amplitude*

		a [m/s^2]				v [m/s]				s [m]			
		RMSE	Mean	STD	R^2	RMSE	Mean	STD	R^2	RMSE	Mean	STD	R^2
f_1	MEMS	0.028	−0.002	0.028	0.99	0.004	0.000	0.004	0.99	0.0003	−0.0002	0.0002	0.99
	Kinect v2	0.415	−0.014	0.415	0.93	0.017	0.000	0.017	0.98	0.0009	−0.0005	0.0008	0.99
	uBlox	0.557	−0.003	0.557	0.85	0.029	0.000	0.029	0.95	0.0088	0.0000	0.0088	0.75
f_2	MEMS	0.037	−0.001	0.037	0.98	0.004	−0.001	0.004	0.99	0.0003	−0.0001	0.0003	0.98
	Kinect v2	0.651	−0.005	0.651	0.89	0.023	0.001	0.023	0.98	0.0010	0.0000	0.0010	0.99
f_3	MEMS	0.051	−0.005	0.051	0.98	0.004	−0.001	0.004	0.98	0.0003	−0.0001	0.0003	0.98
	Kinect v2	0.660	0.016	0.660	0.92	0.023	0.000	0.023	0.97	0.0009	0.0001	0.0009	0.99
f_4	MEMS	0.074	−0.007	0.074	0.93	0.012	0.011	0.007	0.93	0.0011	0.0010	0.0006	0.95
	Kinect v2	1.218	0.002	1.218	0.89	0.031	0.001	0.031	0.98	0.0009	0.0000	0.0009	0.99

4. Sensors integration

Comparison and integration of kinematic solutions from different sensors, in view of the realization of a unique device for high-rate observations embedding GNSS receiver and MEMS sensors, see (Benedetti et al., 2016)

The research was focused on the feasibility of merging the complementary benefits offered by MEMS accelerometers technology and GNSS, with an attention to low-cost sensors, in view of a low-cost integrated monitoring solution. The overall merging approach was set up at the level of the combination of kinematic results (velocities and displacements) coming from the two kinds of sensors, whose observations were separately processed, following to the so-called loose integration, which sounds much more simple and flexible thinking about the possibility of an easy change of the combined sensors, see Figures 7 and 8.

5. Providing detailed trajectories and kinematic parameters (not only position, but also velocity and acceleration) of high dynamic platforms

Accuracy assessment for kinematic estimation of position and velocity using pseudo-ranges and Doppler observables without ground truth applying a Monte Carlo-based numerical simulation, see (Boffi and Wieser 2016)

The ground truth is substituted by a reference trajectory (assumed to be the true one) and by a collection of assumptions about its geometry and its dynamics. A sensitivity analysis of the variable input parameter is performed, aiming to identify the influence of the uncertainties on the model output, see Figure 9.

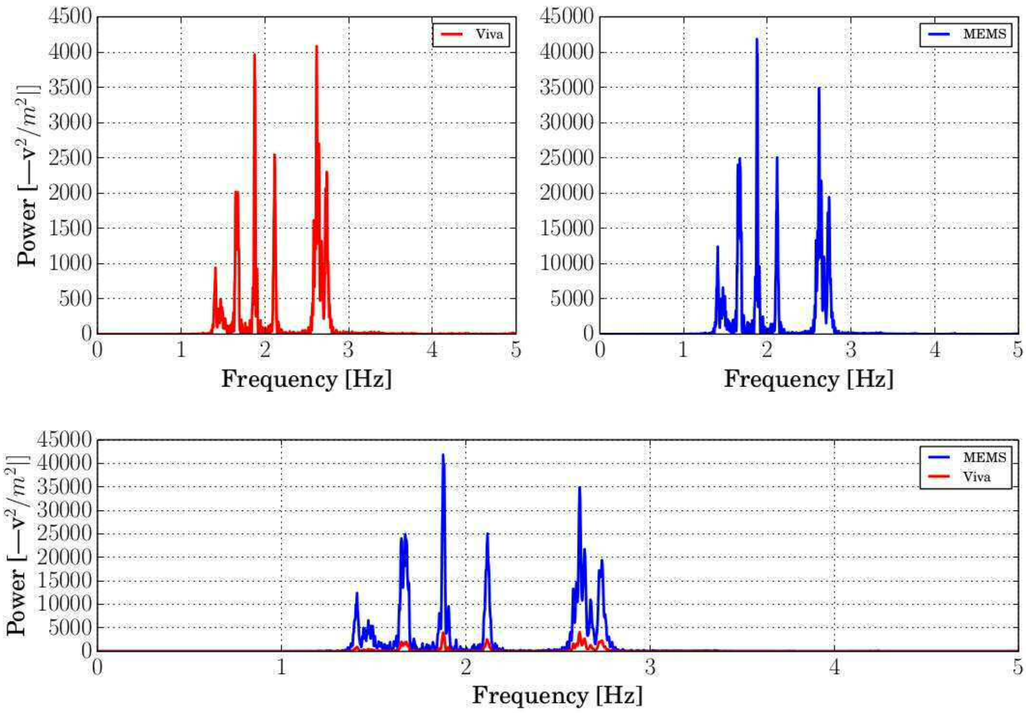

Figure 7: *GPS (10 Hz) and MEMS accelerometer (40 Hz) East velocity power spectra comparison*

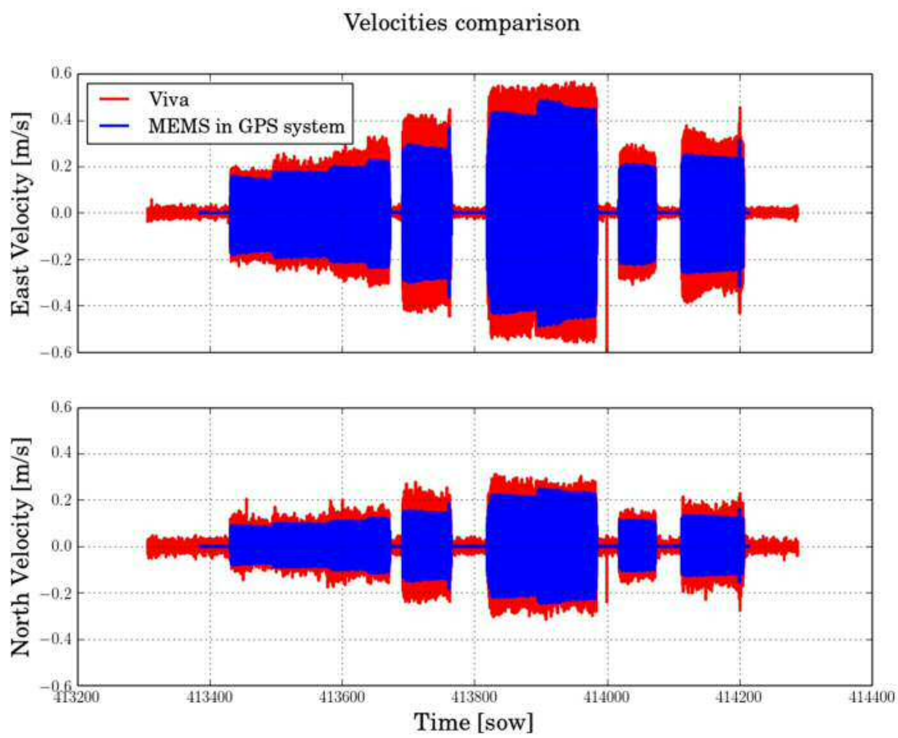

Figure 8: *GPS velocity solutions (10 Hz, computed with the VADASE software) in red compared with MEMS velocities (40 Hz, blue) transformed into the GPS reference system*

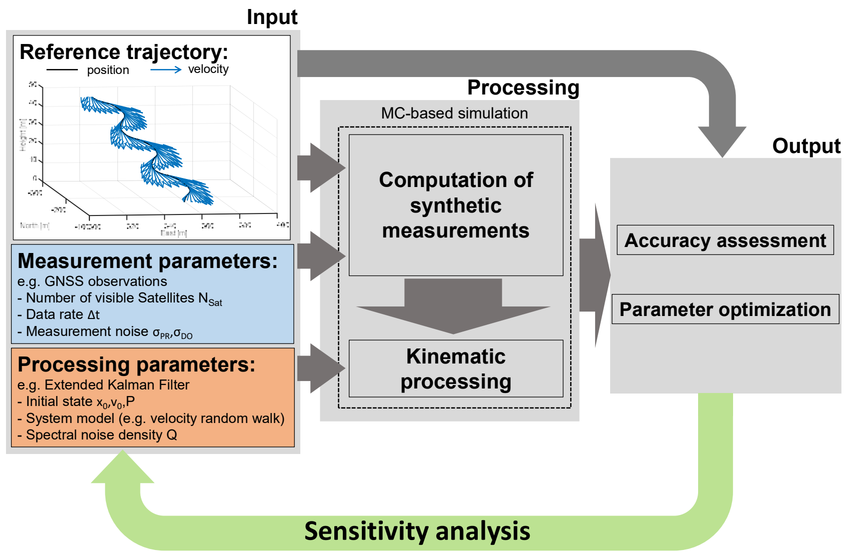

Figure 9: *Overview of the numerical simulation*

Investigation of a dynamics-based system noise adaption of an extended Kalman Filter for GNSS-only kinematic processing, see (Branzanti et al., 2016)

The MC-based approach is used to determine an optimum adaptive spectral noise density for each epoch, see Figure 10.

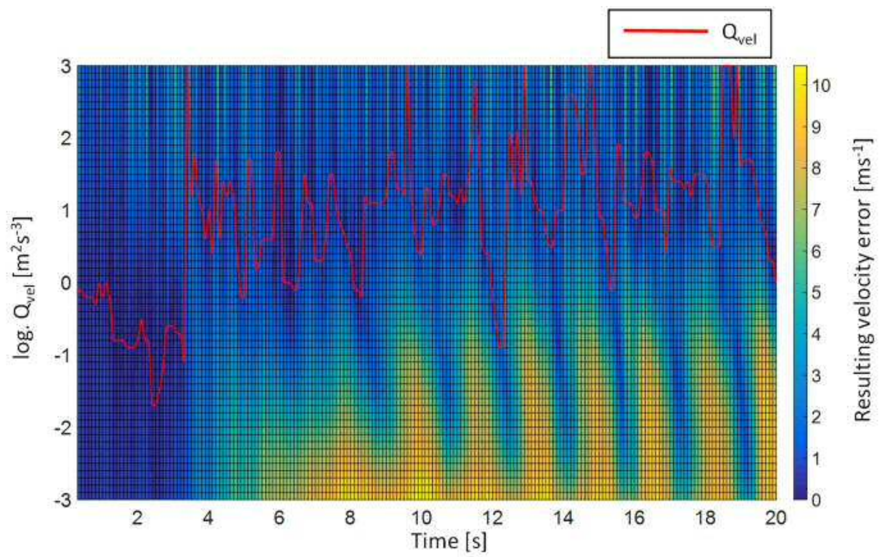

Figure 10: *Example of the identification of the optimal spectral noise density (Qvel) in a velocity random walk system model.*

Variometric approach for real-time GNSS navigation, see (Branzanti et al., 2016)

The Kinematic implementation of the Variometric Approach for Displacement Analysis Standalone Engine (Kin-VADASE) was investigated, giving a demonstration of its performances in the field of GNSS navigation. Kin-VADASE was applied to two test cases in order to estimate high rate (i.e., 10 Hz) kinematic parameters of moving vehicles. In this demonstration, data are collected and processed in the office, but the same results can be obtained in real-time through the implementation of Kin-VADASE in the firmware of a GNSS receiver. All the Kin-VADASE processing were carried out using double- and single-frequency observations in order to investigate the potentialities of the software with geodetic class and low-cost single frequency receivers. Root Mean Square Errors in 3D with respect to differential positioning are at the level of 50 cm for dual frequency and better than 1 meter for single frequency data, see Figure 11.

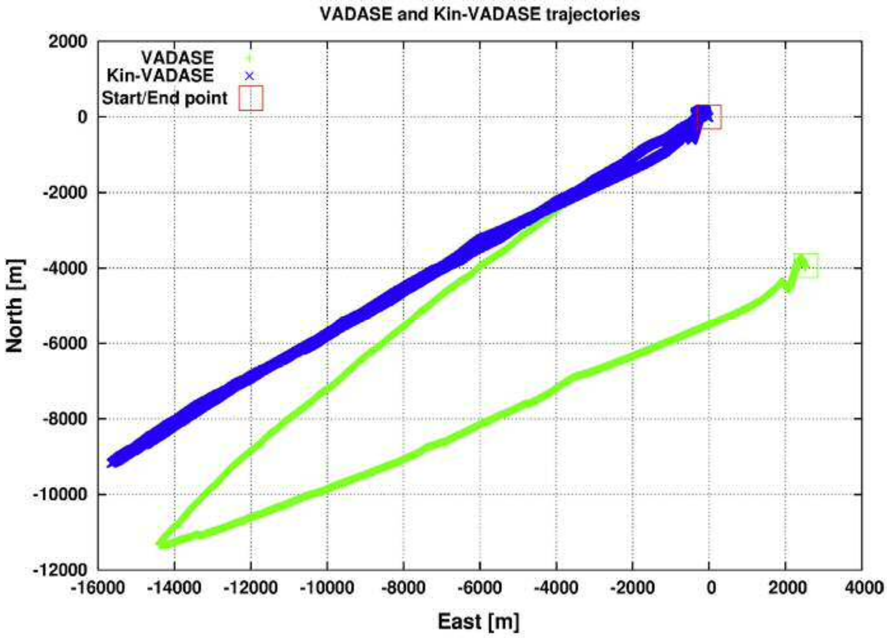

Figure 11: *Comparison between VADASE e KIN-VADASE*

6. Understanding geophysical/geodynamical processes mechanics

Investigations about the possibility to detect free oscillations (eigenmodes) of the Earth through a variometric approach (VADASE) were developed and are ongoing (Nico Sneeuw, Rudolf Widmer-Schnidrig, Giorgio Savastano, Mattia Crespi) – no publication at the moment.

7. High-speed terrestrial vehicles and athlete and sport vehicles monitoring

Application of GNSS for sport measurement for injury prevention and performance analysis, see (Boffi et al., 2016)

The proposed approach aims to substitute a comparison with a reference measurement when the latter is unfeasible or impossible (e.g., over an extended capture volume and under high-dynamics).

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Hung H, Rau R, Benedetti E, Branzanti M, Colosimo G, Mazzoni A, Crespi M (2017) GPS Seismology for moderate magnitude earthquake: lesson learned from the analysis of the 31 October 2013 ML 6.4 Ruisui (Taiwan) earthquake. Submitted to *Annals of Geophysics* (under review)

Fratarcangeli F, Savastano G, Pietrantonio G, D'Achille MC, Mazzoni A, Riguzzi F, Devoti R, Crespi M (2017) Static vs real-time coseismic offset comparison: the test case of 30 October, 2016 Central Italy earthquake. Submitted to Volume in honour of Emeritus Prof. Athanasios Dermanis, Aristotle University Thessaloniki (under review)

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Branzanti M, Colosimo G, Mazzoni A (2016) Variometric approach for real-time GNSS navigation: First demonstration of Kin-VADASE capabilities. *Advances in Space Research* 59: 2750–2763

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Editorial activity

Special Issue of Advances in Space Research on *High-rate GNSS: Theory, Methods, and Engineering/Geophysical Applications* 59(11): 2689-2830, Editor: Peiliang Xu (http://www.sciencedirect.com/science/journal/02731177/59/11)

This special issue is fully open access and aimed at the cutting edge accuracy potential of high-rate GNSS, its further possible improvement (by integration of multi-GNSS systems and/or with other sensors like Micro Electro-Mechanical System (MEMS) accelerometers), and applications. In details, the main covered topics are: 1) the analysis of the effect of a variety of error sources and high-rate products on high-rate precise point positioning, of the GNSS raw data quality and selection, and of the GNSS receiver tracking loop for high-rate GNSS applications; 2) the extension of the GNSS variometric approach for kinematic navigation applications, deformation and velocity measurement, aided with low-cost MEMS accelerometers; 3) the use of high-rate GNSS for the measurement of vibrations and accelerations of highly dynamical object motions and for structural health monitoring; and 4) the potential to establish a network real-time kinematic position and navigation system by using original GNSS observables.

Cooperation

The cooperation with the *GNSS Augmentation to the Tsunami Early Warning System Group* (GATEW), promoted and leaded by John LaBrecque within the GGOS Geohazards Monitoring Focus Area, was started.

Organization

1. Sessions at international congresses/symposia/workshops
   The *High-precision GNSS: methods, open problems and Geoscience applications* session at the European Geoscience Union 2017 General Assembly (April 2017) was organized. The organization of the *High-rate GNSS* session at the *IX Hotine-Marussi Symposium*, which will be held next year (June-July 2018) is ongoing.
2. Questionnaire
   It was launched a tentative questionnaire within the Members of the JSG for starting an inventory of methodologies, technologies and applications in high-rate GNSS

(https://goo.gl/forms/eAKxgKuCpHYJFVJE3). On the basis of the collected answers and comments, the preparation of an updated version of the questionnaire to be spread within the GNSS Community is ongoing.

External impact of the research

1. VADASE algorithm implemented by Leica in the firmware of GR series GNSS receiver since 2 September 2015 (http://blog.leica-geosystems.com/leica-vadase-is-worlds-first-autonomous-gnss-monitoring-solution-onboard-a-stand-alone-receiver)
2. VARION algorithm under incorporation into JPL's Global Differential GPS System as a novel contribution to future integrated operational tsunami early warning systems (https://www.nasa.gov/feature/jpl/scientists-look-to-skies-to-improve-tsunami-detection)

Joint Study Group 0.11: Multiresolutional aspects of potential field theory

Chair: *Dimitrios Tsoulis (Greece)*

Members

- *Katrin Bentel (USA)*
- *Maria Grazia D'Urso (Italy)*
- *Christian Gerlach (Germany)*
- *Wolfgang Keller (Germany)*
- *Christopher Kotsakis (Greece)*
- *Michael Kuhn (Australia)*
- *Volker Michel (Germany)*
- *Pavel Novák (Czech Republic)*
- *Konstantinos Patlakis (Greece)*
- *Clément Roussel (France)*
- *Michael Sideris (Canada)*
- *Jérôme Verdun (France)*

Corresponding members

- *Christopher Jekeli (USA)*
- *Frederik Simons (USA)*
- *Nico Sneeuw (Germany)*

Activities and publications during the period 2015-2017

The Study group had its first meeting at the 1st Joint Commission 2 & IGFS Symposium, 19-23 September 2016 in Thessaloniki. There, it verified its main objective, which is the mathematical description and numerical computation of the gravity signal of finite distributions. Specific areas of work have been identified, including the comparison and assessment between different analytical, numerical and hybrid solutions, applications over finite regions in the frame of classical terrain correction computations, band limited validation against available Earth gravity models, bibliographical survey and identification of multiresolutional techniques for expressing the gravity field signal of given distributions. Session G1.3 *Analytical, numerical and multiresolutional techniques for forward modelling of gravitational fields of mass distributions* has been organized at the EGU General Assembly 2017, 23–28 April 2017, in Vienna, which was convened by four members of the Study Group.

The Study Group is affiliated with IAG Commissions 2 (Gravity Field) and 3 (Earth Rotation and Geodynamics) and GGOS. Its webpage is http://icct.kma.zcu.cz/index.php/JSG0.11.

References

Amna I, Michel V (2017) Pseudodifferential operators, cubature and equidistribution on the 3D-ball – an approach based on orthonormal basis systems. *Numerical Functional Analysis and Optimization*, in press.

D'Urso MG (2015) The gravity anomaly of a 2d polygonal body having density contrast given by polynomial functions. *Surveys in Geophysics* 36: 391–425

D'Urso MG, Trotta S (2017) Gravity anomaly of polyhedral bodies having a polynomial density contrast. *Surveys in Geophysics*, DOI 10.1007/s10712-017-9411-9

Gutting M, Kretz B, Michel V, Telschow R (2017) Study on parameter choice methods for the RFMP with respect to downward continuation. *Mathematics of Computation and Data Science*, in press.

Hirt C, Reußner E, Rexer M, Kuhn M (2016) Topographic gravity modelling for global Bouguer maps to degree 2160: Validation of spectral and spatial domain forward modelling techniques at the 10 mGal level. *Journal of Geophysical Research* 121(9): 6846–6862

Kuhn M, Hirt C (2016) Topographic gravitational potential and second-order derivatives: an examination of approximation errors caused by rock-equivalent topography (RET). *Journal of Geodesy* 90(9): 883-902

Plattner A, Simons FJ (2017) Internal and external potential-field estimation from regional vector data at varying satellite altitude. *Geophysical Journal International*, in press.

Root BC, Novák P, Dirkx D, Kaban M, van der Wal W, Vermeersen LLA (2016) On a spectral method for forward gravity field modelling. *Journal of Geodynamics* 97: 22-30

Roussel C, Verdun J, Cali J, Masson F (2015) Complete gravity field of an ellipsoidal prism in spherical coordinates by Gauss-Legendre quadrature. *Geophysical Journal International* 203(3): 2220-2236

Šprlák M, Novák P (2015) Integral formulas for computing a third-order gravitational tensor from volumetric mass density, disturbing gravitational potential, gravity anomaly and gravity disturbance. *Journal of Geodesy* 89: 141-157

Tsoulis D, Patlakis K (2017) Investigating the effect of different terrain modelling techniques on the computation of local gravity anomalies, EGU General Assembly 2017, Session G1.3, *Analytical, numerical and multiresolutional techniques for forward modelling of gravitational fields of mass distributions*, 23–28 April 2017, Vienna.

Joint Study Group 0.12: Advanced computational methods for recovery of high-resolution gravity field models

Chair: *Róbert Čunderlík (Slovak Republic)*
Vice Chair: *Karol Mikula (Slovak Republic)*

Members

- *Jan Martin Brockmann (Germany)*
- *Walyeldeen Godah (Poland)*
- *Petr Holota (Czech Republic)*
- *Michal Kollár (Slovak Republic)*
- *Marek Macák (Slovak Republic)*
- *Karol Mikula (Slovak Republic)*
- *Zuzana Minarechová (Slovak Republic)*
- *Otakar Nesvadba (Czech Republic)*
- *Wolf-Dieter Schuh (Germany)*

Activities and publications during the period 2015-2017

Activities of JSG-0.12 during the period 2015–2017 have been mainly focused on further development of the advanced computational methods for recovery of high-resolution gravity field models. The numerical approaches based on (i) discretization methods like the boundary element method (BEM), finite element method (FEM) and finite volume method (FVM), (ii) meshless methods like the method of fundamental solution (MFS) and singular boundary method (SBM), and on (iii) others weak solution concepts, have been used:

- to solve numerically the geodetic boundary-value problems (GBVPs), see, e.g., Čunderlík 2016b, Čunderlík et al. 2016b, Holota 2016, Holota and Nesvadba 2017a,b, Macák et al. 2016 and Medľa et al. 2017,
- to process the GOCE satellite measurements, see Čunderlík 2016a,
- to develop nonlinear diffusion filtering of various geodetic data, see, e.g., Kollár et al. 2016a, and Čunderlík et al. 2016a.

To solve such problems in spatial domains while obtaining high-resolution numerical solutions, such approaches require parallel implementations and large-scale parallel computations on clusters with distributed memory using the Message Passing Interface (MPI).

In the following main activities investigated during the period 2015–2017 are briefly described: In case of FVM, an iterative approach to solve the nonlinear satellite-fixed GBVP has been developed. In this approach an unknown direction of the actual gravity vector together with the disturbing potential is updated in every iteration (Macák et al., 2016). An original method to treat the oblique derivative problem using an up-wind based FVM has been proposed. Namely, the second order up-wind numerical scheme have been derived for non-uniform grids above the real Earth's topography (Medľa and Mikula 2016). Such an approach has involved a construction of the non-uniform hexahedron 3D grids above the Earth's surface that is based on an evolution of a surface, which approximates the Earth's topography, by its mean curvature. To obtain optimal shapes of non-uniform 3D grid, the proposed evolution has been accompanied by a tangential redistribution of grid nodes. Afterwards, the Laplace equation has been discretized using FVM developed for such a non-uniform grid. The oblique derivative boundary condition has been treated as a stationary advection equation resulting to a new up-wind type discretization suitable for non-uniform 3D grids (Medľa et al., 2017).

To reduce a numerical complexity of the boundary integral approaches, e.g., the direct BEM with collocation or MFS and SBM as meshless methods, we have focused on elimination of the far zones interactions using the Hierarchical matrices (H-matrices). To compress the "far field parts" of the system matrices, the Adaptive Cross Approximation (ACA) algorithm have been implemented. It is based on the idea that numerically rank-deficient sub-blocks, which correspond to interactions of well-separated groups, can efficiently be compressed through an approach very similar to the column-pivoted LU decomposition. The first experiments (Čunderlík and Vipiana 2017) show that the ACA algorithm effectively reduces memory requirements and computational costs while giving practically the same results. It means that implementations of the H-matrices as a compression technique allow to increase considerably a level of the discretization w.r.t. available memory of the accessible HPC facilities. This is promising for further development of the boundary integral approaches for high-resolution gravity field modelling.

In case of nonlinear diffusion filtering, the existing method based on the regularized Perona-Malik model has been extended in order to avoid undesirable smoothing of local extremes. This has been treated by a modification of the diffusivity coefficient that now depends on a combination of the edge detector and mean curvature of the filtered function. A semi-implicit numerical scheme has been derived for this approach (Kollár et al., 2016a), which is based on a numerical solution of partial differential equations on closed surfaces using the surface FVM. Sensitivity parameters of the proposed "edge and extremes detector" have been experimentally tuned for different types of filtered data (Čunderlík et al., 2016a). The similar semi-implicit numerical scheme has been also derived for data given on 2D rectangular grids (Kollár et al., 2017).

The achieved results have been published in several papers (see below) and they were presented at the major geodetic conferences, e.g. at the EGU General Assemblies in Vienna (April 2016, and April 2017) within the session "Recent Developments in Geodetic Theory" or during the 1st Joint Commission 2 and IGFS Meeting – International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS-2016) in Thessaloniki (September 2016).

References

Čunderlík R (2016a) Precise modelling of the static gravity field from GOCE second radial derivatives of the disturbing potential using the method of fundamental solutions. *IAG Symposia Series* 144: 71-81

Čunderlík R, Kollár M, Mikula K (2016a) Filters for geodesy data based on linear and nonlinear diffusion. GEM - *International Journal on Geomathematics* 7(2): 239-274

Holota P (2016) Domain transformation and the iteration solution of the linear gravimetric boundary value problem. *IAG Symposia Series*, DOI 10.1007/1345_2016_236 (in press).

Kollár M, Čunderlík R, Mikula K (2016a) Nonlinear diffusion filtering influenced by mean curvature. In: ALGORITMY-2016 - 20th Conference on Scientific Computing, Proceedings of contributed papers, ISBN: 978-80-227-4544-4, pp. 33-43

Macák M, Mikula K, Minarechová Z, Čunderlík R (2016) On an iterative approach to solving the nonlinear satellite-fixed geodetic boundary-value problem. *IAG Symposia Series* 142: 185-191

Medľa M, Mikula K (2016) New second order up-wind scheme for oblique derivative boundary value problem. In: ALGORITMY-2016 - 20th Conference on Scientific Computing, Proceedings of contributed papers, ISBN: 978-80-227-4544-4, pp. 254-263

Medľa M, Mikula K, Čunderlík R, Macák M (2016) Numerical solution to the oblique derivative boundary value problem on non-uniform grids above the earth topography. *Journal of Geodesy* (accepted in June 2017).

Nesvadba O, Holota P (2016) An ellipsoidal analogue to Hotine's kernel: accuracy and applicability. *IAG Symposia Series* 144: 93-100

Nesvadba O, Holota P (2016) An OpenCL implementation of ellipsoidal harmonics. *IAG Symposia Series* 142: 195-203

Roese-Koerner L, Schuh W-D (2016) Effects of different objective functions in inequality constrained and rank-deficient least-squares problems. *IAG Symposia Series* 142: 325-331

Selected oral and poster presentations

EGU-2017 (Wien, April 2017)

Čunderlík R, Vipiana F (2017) Hierarchical matrices implemented into the boundary integral approaches for gravity field modelling. EGU2017-7294

Holota P, Nesvadba O (2017a) Weak solution concept and Galerkin's matrix for the exterior of an oblate ellipsoid of revolution in the representation of the Earth's gravity potential by buried masses. EGU2017-15962

Holota P, Nesvadba O (2017b) Laplacian versus topography in the solution of the linear gravimetric boundary value problem by means of successive approximations. EGU2017-19061

Kollár M, Čunderlík R, Mikula K (2017) Nonlinear diffusion filtering methods locally adapted to data features. EGU2017-7340

Macák M (2017) Domain decomposition methods in FVM approach to gravity field modelling. EGU2017-7232

GGHS-2016 (Thessaloniki, September 2016)

Brockmann JM, Schuh W-D (2016) Stochastic modelling of altimetric sea surface height measurements – refined AR models from iterative residual analysis. http://gghs2016.com/presentation-info/?presentation=747

Čunderlík R (2016b) Numerical solution of the oblique derivative BVP on the Earth's surface topography using BEM. http://gghs2016.com/presentation-info/?presentation=717

Čunderlík R (2016c) Off-sets between tide gauges estimated from the filtered GOCE-based satellite-only MDT. http://gghs2016.com/presentation-info/?presentation=740

Čunderlík R, Macák M, Minarechová Z, Mikula K (2016b) High-resolution modelling of the altimetry-derived gravity data using FVM. http://gghs2016.com/presentation-info/?presentation=695

Holota P, Nesvadba O (2016a) Modification of ellipsoidal coordinates and successive approximations in the solution of the linear gravimetric boundary value problem. http://gghs2016.com/presentation-info/?presentation=957

EGU-2016 (Wien, April 2016)

Čunderlík R, Špir R, Mikula K (2016c) Numerical solution of the exterior oblique derivative BVP using the direct BEM formulation. EGU2016-5735

Holota P, Nesvadba O (2016b) Construction of Galerkin's matrix for elementary potentials and an ellipsoidal solution domain based on series developments and general relations between Legendre's functions of the first and the second kind: Application in Earth's gravity field studies. EGU2016-5735

Kollár M, Mikula K, Čunderlík R (2016b) Non-linear diffusion filtering influenced by mean curvature. EGU2016-5837

Macák M, Mikula K (2016) Optimization of solving the boundary-value problems related to physical geodesy. EGU2016-6027

Medľa M, Mikula K, Macák M (2016) Finite volume method for geodetic boundary value problem. EGU2016-5789

Joint Study Group 0.13: Integral equations of potential theory for continuation and transformation of classical and new gravitational observables

Chair: *Michal Šprlák (Australia)*

Members

- *Alireza Ardalan (Iran)*
- *Mehdi Eshagh (Sweden)*
- *Will Featherstone (Australia)*
- *Ismael Foroughi (Canada)*
- *Petr Holota (Czech Republic)*
- *Juraj Janák (Slovakia)*
- *Otakar Nesvadba (Czech Republic)*
- *Pavel Novák (Czech Republic)*
- *Martin Pitoňák (Czech Republic)*
- *Robert Tenzer (China)*
- *Guyla Tóth (Hungary)*

Activities and publications during the period 2015-2017

As the objectives of JSG0.13 are primarily of the theoretical nature, its members have focused on mutual cooperation and publishing their findings in the international journals on geodesy and geophysics, including the high-ranked journals, such as Journal of Geodesy, Geophysical Journal International, Remote Sensing, Surveys in Geophysics, and Earth-Science Reviews. This effort has resulted in more than 30 peer-reviewed articles suggesting an active and actual field of research.

The list of selected peer-reviewed publications is provided below. The scientific articles have attempted to address all objectives of JSG0.13. The works by P. Novák, M. Pitoňák, and M. Šprlák have mainly been focused on theoretical and numerical aspects of the spherical integral transforms. I. Foroughi has considered the same geometrical approximation of the Earth, while exploiting the apparatus of the radial basis functions. On the other hand, the studies by P. Holota and O. Nesvadba have been devoted to the systematic solution of boundary value problems for the ellipsoidal (spheroidal) geometry. The scientific contributions by M. Eshagh and R. Tenzer have even reached beyond the specified objectives of JSG0.13 as the theoretical apparatus of integral transforms/equations may be exploited for numerous applications in geophysics.

One of JSG0.13 activities has been aimed to provide a bibliographic list of existing publications that cover the scopes of the study group. Four members of JSG0.13 published a review article that summarizes spherical integral transforms between various quantities of the gravitational field up to the components of the third-order gravitational tensor, see (Novák et al. 2017). The article includes an extensive list of publications devoted to the spherical integral transforms and may be of interest for scientists from many disciplines, e.g., geosciences, mathematics, and physics. It also represents a significant advancement towards the proposal of suitable generalized notation for a variety of classical and new integral equations in geodesy for the spherical approximation.

Members of JSG0.13 have actively presented their scientific achievements at major international conferences, such as IUGG 2015, ESA Living Planet 2016, IAG Gravity, Geoid and Height Systems 2016 Symposium, or the annual meetings organized by EGU and AGU. The members have usually participated and reported their results in the sessions on gravity field modelling, satellite missions, vertical reference systems, boundary value problems, or theoretical advances in geodesy. The list of selected oral and poster presentations is provided below.

Except for the scientific activities, members of JSG0.13 have also been responsible for organizing international conferences. Namely, P. Holota and O. Nesvadba organized the session G1.1 called "Recent Developments in Geodetic Theory", which is regularly held at EGU General Assembly, and is closely related to the objectives of the study group.

References

Eshagh M (2015) On the relation between Moho and sub-crustal stress induced by mantle convection. *Journal of Geophysics and Engineering* 12: 1-11.

Eshagh M (2016) A theoretical discussion on Vening Meinesz-Moritz inverse problem of isostasy. *Geophysical Journal International* 207: 1420-1431.

Eshagh M (2016) Integral approaches to determine sub-crustal stress from terrestrial gravimetric data. *Pure and Applied Geophysics* 173: 805-825.

Eshagh M (2016) On Vening-Meinesz-Moritz and flexural theories of isostasy and their comparison over Tibet Plateau. *Journal of Geodetic Science* 6: 139-151.

Eshagh M (2017) Local recovery of lithospheric stress tensor from GOCE gravitational tensor. *Geophysical Journal International* 209: 317-333.

Eshagh M, Ebadi S, Tenzer R (2017) Isostatic GOCE Moho model for Iran. *Journal of Asian Earth Sciences* 138: 12-24

Eshagh M, Hussain M (2016) An approach to Moho discontinuity recovery from on-orbit GOCE data with application over Indo-Pak region. *Tectonophysics* 690B: 253-262

Eshagh M, Hussain M (2015) Relationship amongst gravity gradients, deflection of vertical, Moho deflection and the stresses derived by mantle convections-a case study over Indo-Pak and surroundings. *Geodynamics, Research International Bulletin* 3(4): I-XIII

Eshagh M, Hussain M, Tenzer R, Romeshkani M (2016) Moho density contrast in central Eurasia from GOCE gravity gradients. *Remote Sensing* 8: 1-18

Eshagh M, Hussain M, Tiampo KF (2016) Towards sub-lithospheric stress determination from seismic Moho, topographic heights and GOCE data. *Journal of Asian Earth Sciences* 169: 1-12

Eshagh M, Romeshkani M (2015) Determination of sub-lithospheric stress due to mantle convection using GOCE gradiometric data over Iran. *Journal of Applied Geophysics* 122: 11-17

Eshagh M, Šprlák M (2016) On the integral inversion of satellite-to-satellite velocity differences for local gravity field recovery: A theoretical study. *Celestial Mechanics and Dynamical Astronomy* 124: 127-144

Eshagh M, Tenzer R (2015) Sub-crustal stress determined using gravity and crust structure models. *Computational Geoscience* 19: 115-125

Foroughi I, Afrasteh Y, Ramouz S, Safari A (2017) Local evaluation of Earth Gravitational Models, case study: Iran. *Geodesy and Cartography* 43: 1-13

Hamáčková E, Šprlák M, Pitoňák M, Novák P (2016) Non-singular expressions for the spherical harmonic synthesis of gravitational curvatures in a local north-oriented reference frame. *Computers and Geosciences* 88: 152-162

Holota P (2015) Domain transformation and the iteration solution of the linear gravimetric boundary value problem. In: 26th IUGG General Assembly, Prague, Czech Republic, June 22 - July 2, 2015, *IAG Symposia Series*, Springer. DOI 10.1007/1345_2016_236, pp. 1-6, ISSN 0939-9585.

Holota P (2015) Summation of series and an approximation of Legendre's functions in constructing integral kernels for the exterior of an ellipsoid: application to boundary value problems in physical geodesy. Leibniz Society of Science at Berlin, Scientific Colloquium Geodesy - Mathematic - Physics - Geophysics in honour of Erik W. Grafarend on the occasion of his 75th birthday, Berlin, Germany, February, 13, 2015. In: Leibniz Online, Jahrgang 2015, Nr. 19, 12 pp. Zeitschrift der Leibniz-Sozietät e.V., ISSN 1863-3285, (http://leibnizsozietaet.de/wp-content/uploads/2015/06/holota.pdf).

Nesvadba O, Holota P (2016) An ellipsoidal analogue to Hotine's kernel: accuracy and applicability. In: Jin S, Barzaghi R (Eds.) Third International Gravity Field Service (IGFS) General Assembly (IGFS2014), Proceedings of the Symposium in Shanghai, 30 June - 6 July, 2014, *IAG Symposia* Series 144: 93-100, doi: 10.1007/1345_2015_133, ISSN 0939-9585.

Nesvadba O, Holota P (2016) An open CL implementation of ellipsoidal harmonics. In: Sneeuw N, Novák P, Crespi M, Sansò F (Eds.): VIII Hotine-Marussi Symposium on Mathematical Geodesy. Proceedings of the Symposium in Rome, 17-21 June, 2013. IAG Symposia Series 142: 195-203, doi: 10.1007/1345_2015_59, ISBN 978-3-319-24548-5, ISSN 0939-9585.

Novák P, Šprlák M, Tenzer R, Pitoňák M (2017). Integral formulas for transformation of potential field parameters in geosciences. *Earth-Science Reviews* 164(1): 208-231

Pitoňák M, Šprlák M, Hamáčková E, Novák P (2016) Regional recovery of the disturbing gravitational potential by inverting satellite gravitational gradients. *Geophysical Journal International* 205(1): 89-98

Pitoňák M, Šprlák M, Novák P, Tenzer R (2017) Regional gravity field modelling from GOCE observables. *Advances in Space Research* 59(1): 114-127

Pitoňák M, Šprlák M, Tenzer R (2017) Possibilities of inversion of satellite third-order gravitational tensor onto gravity anomalies: a case study for central Europe. *Geophysical Journal International* 209(2): 799-812

Romeshkani M, Eshagh M (2015) Deterministically-modified integral estimators of tensor of gravitation. *Boletim de Ciências Geodésicas* 21: 189-212

Shahbazi A, Safari A, Foroughi I, Tenzer R (2016) A numerically efficient technique of regional gravity field modelling using radial basis functions. *Comptes Rendus Geoscience* 348: 99-105

Šprlák M, Eshagh M (2016) Local recovery of sub-crustal stress due to mantle convection from satellite-to-satellite tracking data. *Acta Geophysica* 64: 904-929

Šprlák M, Hamáčková E, Novák P (2015) Alternative validation method of satellite gradiometric data by integral transform of satellite altimetry data. *Journal of Geodesy* 89: 757-773.

Šprlák M, Novák P (2015) Integral formulas for computing a third-order gravitational tensor from volumetric mass density, disturbing gravitational potential, gravity anomaly and gravity disturbance. *Journal of Geodesy* 89: 141-157

Šprlák M, Novák P (2016) Spherical gravitational curvature boundary-value problem. *Journal of Geodesy* 90: 727-739

Šprlák M, Novák P (2017) Spherical integral transforms of second-order gravitational tensor components onto third-order gravitational tensor components. *Journal of Geodesy* 91: 167-194

Šprlák M, Novák P, Pitoňák M (2016). Spherical harmonic analysis of gravitational curvatures and implications for future satellite mission. *Surveys in Geophysics* 37(3): 681-700

Tenzer R, Eshagh M (2015) Subduction generated sub-crustal stress in Taiwan. *Terrestrial, Atmospheric and Oceanic Sciences* 26: 261-268

Tenzer R, Eshagh M, Jin S (2015) Martian sub-crustal stress from gravity and topographic models. *Earth and Planetary Science Letters* 425: 84-92

Tenzer R, Eshagh M, Shen W (2017) The subcrustal stress estimation in central Eurasia from gravity, terrain and crustal structure models. *Geoscience Journal* 21: 47-54

Tenzer R, Foroughi I, Pitoňák M, Šprlák M (2017) Effect of the Earth's Inner Structure on the Gravity in Definitions of Height Systems. *Geophysical Journal International* 209: 297-316

Selected oral and poster presentations

Foroughi I, Janák J, Kingdon RW, Sheng M, Santos M, Vaníček P (2015) Illustration of how satellite global field should be treated in regional precise geoid modelling. 12th EGU General Assembly, Vienna, April 2015.

Foroughi I, Vaníček P, Kingdon RW, Novák P, Sheng M, Santos M (2016) Poisson downward continuation of scattered Helmert's gravity anomalies to mean values on a raster on the geoid using Least Square. 13th EGU General Assembly, Vienna, April 2016.

Foroughi I, Vaníček P, Kingdon RW, Sheng M, Santos M (2015) Assessment of discontinuity of Helmert's gravity anomalies on geoid. Canadian Geophysical Union Meeting, Montreal, Canada.

Foroughi I, Vaníček P, Novák P, Kingdon RW, Goli M, Sheng M, Santos M (2016) Harmonic downward continuation of scattered point gravity anomalies to mean anomalies on a mesh on the geoid. Canadian Geophysical Union meeting, Fredericton, Canada.

Hamáčková E, Šprlák M, Pitoňák M, Novák P (2015). Comparison of third order potential derivatives based on recent satellite-based GGMs and on global isostatic topographic models. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P (2015) Summation of series and an approximation of Legendre's functions in constructing integral kernels for the exterior of an ellipsoid: application to boundary value problems in physical geodesy. Leibniz Society of Science at Berlin, Scientific Colloquium Geodesy – Mathematic – Physics – Geophysics in honour of Erik W. Grafarend on the occasion of his 75th birthday, Berlin, Germany, February, 13, 2015. In: Kolloquium der Leibniz-Sozietät am 13.02.2015 zum Thema "Geodäsie-Mathematik-Physik-Geophysik": Kurzbericht [on-line]. Leibniz-Sozietät der Wissenschaften zu Berlin, e.V.

Holota P, Nesvadba O (2015) Differential geometry of equipotential surfaces and its relation to parameters of Earth's gravity field models. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P, Nesvadba O (2015) Domain transformation and the iteration solution of boundary value problems in gravity field studies. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P, Nesvadba O (2015) Elementary potentials and Galerkin's matrix for an ellipsoidal domain in the recovery of the gravity field. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P, Nesvadba O (2015) Fundamental solution of Laplace's equation in oblate spheroidal coordinates and Galerkin's matrix for Neumann's problem in Earth's gravity field studies. 12th EGU General Assembly, Vienna, April 2015.

Holota P, Nesvadba O (2016) Combining terrestrial data and satellite-only models in Earth's gravity field studies: optimization and integral kernels. Living Planet Symposium of the European Space Agency, Prague, May 2016.
Holota P, Nesvadba O (2016) Construction of Galerkin's matrix for elementary potentials and an ellipsoidal solution domain based on series developments and general relations between Legendre's functions of the first and the second kind: application in Earth's gravity field studies. 13th EGU General Assembly, Vienna, April 2016.
Holota P, Nesvadba O (2016) Modification of ellipsoidal coordinates and successive approximations in the solution of the linear gravimetric boundary value problem. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.
Holota P, Nesvadba O (2016) Small modifications of curvilinear coordinates and successive approximations applied in geopotential determination. AGU Fall Meeting, San Francisco, December 2016.
Holota P, Nesvadba O (2017) Laplacian versus topography in the solution of the linear gravimetric boundary value problem by means of successive approximations. 14th EGU General Assembly, Vienna, April 2017.
Holota P, Nesvadba O (2017) Weak solution concept and Galerkin's matrix for the exterior of an oblate ellipsoid of revolution in the representation of the Earth's gravity potential by buried masses. 14th EGU General Assembly, Vienna, April 2017.
Nesvadba O, Holota P (2016) An improved methodology for precise geoid/quasigeoid modelling. 13th EGU General Assembly, Vienna, April 2016.
Nesvadba O, Holota P (2016) On the downward continuation stability in dependence of the topography roughness. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.
Novák P, Pitoňák M, Šprlák M (2015) Regional recovery of the disturbing gravitational potential from satellite observations of first-, second- and third-order radial derivatives of the disturbing gravitational potential. AGU Fall Meeting, San Francisco, December 2015.
Novák P, Šprlák M, Tenzer R, Pitoňák M (2016) Integral formulas for analysis of current and future satellite gravitational observations. AGU Fall Meeting, San Francisco, December 2016.
Novák P, Tenzer R, Pitoňák M, Šprlák M (2016) Accuracy of classical definition of the geoid-to-quasigeoid separation. 13th EGU General Assembly, Vienna, April 2016.
Novák P, Tenzer R, Pitoňák M, Šprlák M (2016) Effect of crustal and mantle density structure on the quasigeoid-to-geoid separation. 13th EGU General Assembly, Vienna, April 2016.
Pitoňák M, Eshagh M, Šprlák M, Tenzer R, Novák P (2017). Spectral combination of spherical gravitational curvature boundary-value problems. 14th EGU General Assembly, Vienna, April 2017.
Pitoňák M, Šprlák M, Hamáčková E, Novák P (2015) The effect of topographic and atmospheric masses on inversion of a satellite third-order gravitational tensor onto gravity anomalies. 26th IUGG General Assembly, Prague, June-July 2015.
Pitoňák M, Šprlák M, Novák P, Tenzer R (2016) Possibilities of the regional gravity field recovery from first-, second- and third-order radial derivatives of the disturbing gravitational potential measured on moving platforms. 13th EGU General Assembly, Vienna, April 2016.
Pitoňák M, Šprlák M, Novák P, Tenzer R (2016) Regional determination of gravity disturbances by inverting satellite gravitational gradients. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.
Pitoňák M, Šprlák M, Sebera J, Novák P, Hamáčková E (2016) Comparative study of the far zones effect on the spherical downward continuation. Living Planet Symposium of the European Space Agency, Prague, May 2016.
Šprlák M, Hájková J, Pitoňák M, Novák P, Tenzer R (2016) An analysis of geoid determination based on terrestrial observations of the radial gravity potential derivatives. 13th EGU General Assembly, Vienna, April 2016.
Šprlák M, Novák P (2016) Spherical gravitational curvature boundary-value problem. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.
Šprlák M, Novák P, Pitoňák M, Hamáčková E (2015) Solution of the boundary value problems with boundary conditions in the form of gravitational curvatures. AGU Fall Meeting, San Francisco, December 2015.
Šprlák M, Novák P, Pitoňák M, Hamáčková E (2015) Spherical harmonic analysis of third-order gravitational tensor components and its implications for future gravity-dedicated satellite mission designs. 26th IUGG General Assembly, Prague, June-July 2015.
Šprlák M, Petrš J, Pitoňák M, Novák P, Hamáčková E (2016) Possibilities of validation for GRACE satellite-to-satellite tracking data by integral transformations. Living Planet Symposium of the European Space Agency, Prague, May 2016.

Joint Study Group 0.14: Fusion of multi-technique satellite geodetic data

Chair: *Krzysztof Sośnica (Poland)*

Members

- *Toshimichi Otsubo (Japan)*
- *Daniela Thaller (Germany)*
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Activities and publications during the period 2015-2017

The activities of JSG0.21 were concentrated around the identification of systematic effects between different techniques of satellite and space geodesy. A proper identification and handling of systematics should in result improve the consistency between different observational techniques, and should help us to mitigate artefacts in the geodetic time series. Therefore, different observational techniques of space geodesy, which are capable of deriving the same parameters, are cross-validated and combined. Geodetic parameters that can be determined employing different techniques of space geodesy are thus the fundamental subject of interest in JSG0.21.

The activities of JSG0.21 in the period 2015-2017 included in particular:
1. development of an online service with the validation results of multi-GNSS orbits using Satellite Laser Ranging (SLR) data and for the identification of systematic biases at SLR stations and the assessment of the multi-GNSS orbit quality,
2. comparison and combination of low-degree Earth's gravity field coefficients (including geocenter motion) derived from SLR, GRACE and GNSS data,
3. comparison and assimilation of the tropospheric delays based on SLR, GNSS, radiosonde, and numerical weather models.

Online service for validation of multi-GNSS orbits using SLR

In the recent years the geodetic community could observe an advent of new GNSS systems. GLONASS reached its full operational capability in 2010. The constellation of Galileo satellites reached the number of 18 spacecraft in 2017, including two satellites in high eccentric orbits. BeiDou reached its full operational capability above Eastern Asia and is being now extended towards the global coverage. QZSS consists now of one QZS-1 satellite. More satellites and more systems impose not only opportunities for space geodesy, but also introduce considerable challenges for a proper combination of different systems.

All new GNSS systems have been equipped with laser retroreflector arrays (LRA) dedicated to SLR tracking of new GNSS systems. The International Laser Ranging Service (ILRS) initiated a series of special tracking campaigns devoted to tracking new Galileo spacecraft, as well as tracking of the whole GNSS constellation. Such an initiative introduces a challenge for

SLR stations, as the number of GNSS targets for tracking exceeds now 70 satellites, which is by far more than, e.g., 10 or 20 years ago. SLR observations to GNSS satellites allow for the validation of microwave-derived GNSS orbits, for the determination of GNSS orbital parameters, co-location in space on-board GNSS spacecraft and for the determination of global parameters, such as pole coordinates, length-of-day, geocentre motion, etc. Fusion of GNSS and SLR observations requires a profound investigation of biases and systematic effects affecting both techniques. Neglecting systematic effects may lead to a degradation of solutions and the absorption of various systematic effects by global geodetic parameters (Sośnica et al., 2015, 2017).

For the purpose of the investigation of SLR-GNSS biases, a new on-line service has been launched (Zajdel et al., 2017): multi-GNSS Orbit Validation Visualizer Using SLR (GOVUS, http://multi-slrgnss.rhcloud.com/slr/). The service has been developed in the framework of the JSG0.21 activities.

Orbit determination of new GNSS spacecraft is very challenging due to different construction of satellites (size and shape of satellite body, various absorption and reflection characteristics of satellite surfaces, different sizes of solar panels), different characteristics of the orbits (MEO, GEO, inclined, circular, eccentric, etc.), different revolution periods of satellites, different numbers of orbital planes, different power of transmitting antennas, and different nominal steering of spacecraft: yaw-steering, dynamic yaw-steering, and the normal altitude. All of those issues may generate systematic errors in estimated orbits when such effects are not properly taken into account. Today, the multi-GNSS orbits are generated by various MGEX Analysis Centers on the basis of microwave GNSS observations. SLR serves as an independent technique for the validation of orbit quality for new GNSS, as an indicator of orbit errors explicitly included in satellite orbits. Figure 12 shows an example of the distribution of SLR-GNSS residuals for GLONASS and Galileo tracked by Yarragadee (left); and Galileo and BeiDou tracked by Shanghai (right). The mean residuals to GLONASS are shifted toward negative values with a mean offset of -11 mm for Yarragadee. This shift is mostly caused by the satellite signature effect and is related to multi-photo detectors used at SLR sites (Sośnica et al., 2016). The mean SLR residuals for Galileo are shifted towards negative values due to missing modelling of antenna thrust and albedo for new spacecraft. Similar effect is visible for the both, Yarragadee and Shanghai stations.

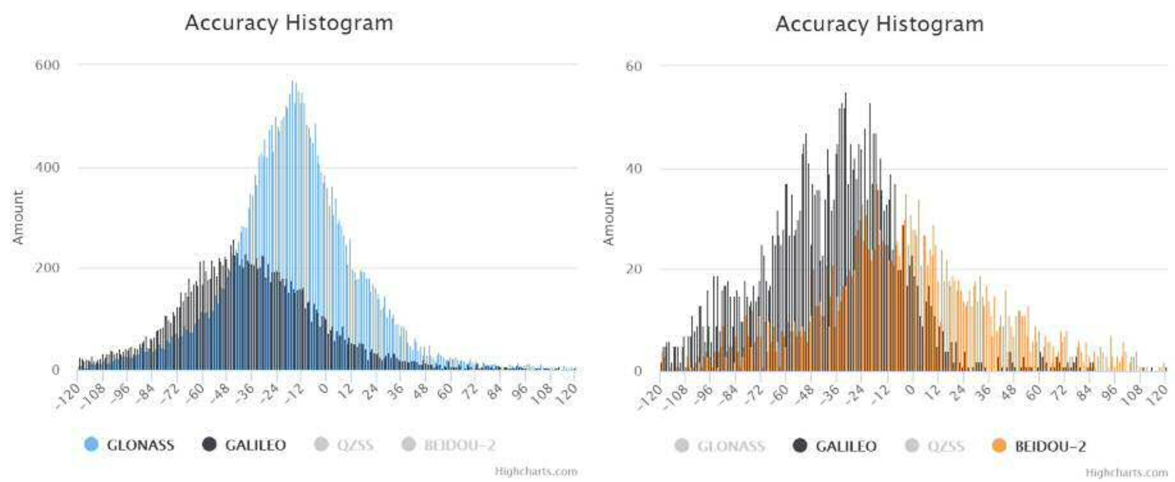

Figure 12. *Distribution of the SLR residuals in mm with respect to CODE microwave GLONASS, Galileo and Beidou orbits for Yarragadee (left) and Shanghai (right). Plots were generated using the on-line GOVUS service (http://multi-slrgnss.rhcloud.com/).*

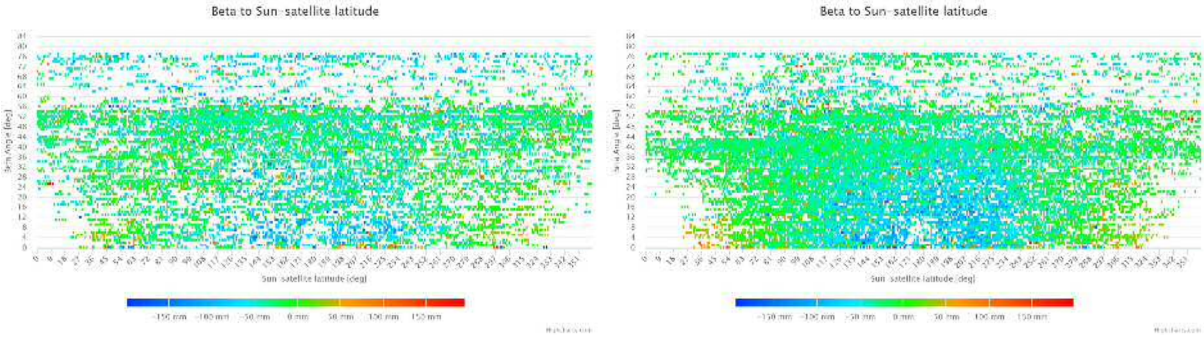

Figure 13. *SLR residuals as a function of the Sun elevation angle above the orbital plane (Beta) and the satellite argument of latitude with respect to the latitude of the Sun for Galileo IOV satellites (left) and Galileo (FOC) for the period 2016.0-2017.4. Plots were generated using the on-line GOVUS service (http://multi-slrgnss.rhcloud.com/).*

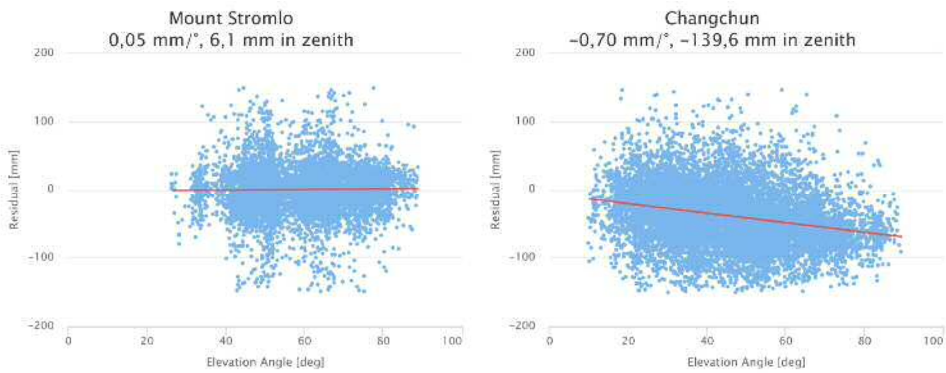

Figure 14. *Dependency between SLR residuals and the elevation angle of satellite over horizon for a station without systematic effects (Mount Stromlo, left) and a station with a clear systematic pattern (Changchun, right). Plots were generated using the on-line GOVUS service (http://multi-slrgnss.rhcloud.com/).*

SLR residuals can also be used for validation of the solar radiation pressure models, especially for the newly launched spacecraft. Figure 13 shows a comparison between SLR residuals for Galileo IOV (left) and Galileo FOC (right) when using the new Empirical CODE Orbit Model (ECOM2, Arnold et al., 2015; Prange et al., 2017). Figure 13 suggests that despite using ECOM2, many systematic effects still exist, which is visible for FOC satellites and low *Beta* angles.

The GOVUS service can be used not only for the assessment of the quality of multi-GNSS orbits, but also may serve as an indicator for various systematic errors affecting the SLR stations and limiting the consistency between SLR and GNSS techniques. Figure 14 shows a dependency between SLR residuals and the satellite elevation angle as seen from the SLR station for Mount Stromlo (left) and Changchun (right). In case of Changchun, a clear systematic effect is obtained which is a conjunction of the satellite signature effect and a bias at the station.

Combination of low-degree Earth's gravity field coefficients

The second main activity of JSG0.21 is related to cross-validation and combination of low-degree Earth's gravity field coefficients derived from GRACE and SLR data (Bloßfeld et al., 2017). In the framework of the EGSIEM project (European Gravity Service for Improved Emergency Management founded by the European Union's Horizon 2020 research and innovation programme, Jäggi et al., 2015) several European institutions combine their monthly gravity field models based on GRACE data. University of Bern, which is a leader in EGSIEM, proposed a similar solution for SLR gravity field models under the umbrella of EGSIEM. Five members of the JSG0.21 group are involved in generating SINEX files with normal equation systems containing the low-degree gravity field coefficients based on SLR data only. This activity was initiated in January 2017 in Bern starting with the adoption of common processing standards for all groups (Bloßfeld et al., 2017). The combined SLR solutions will help to minimize various systematic errors included in specific single solutions. The resulting SLR combined monthly gravity field models will be compared and combined with GRACE, which will help to further investigate observation-specific errors included in each of the observation techniques.

Degree-1 gravity field coefficients, corresponding to the geocenter motion, derived from GNSS, SLR and high-degree GRACE-based data were also compared using wavelet-based semblance filtering (Kosek, 2014; Wnęk et al., 2016). Such a solution allows identifying and extracting a common geophysical signal from the time series of geocenter coordinates based on different observation principles. Wavelet semblance enables also extracting technique-specific artefacts, such as draconitic years, from the geocentre series.

Comparison and assimilation of the tropospheric delays

The third area of activities within JSG0.21 was related to comparison and assimilation of the tropospheric delays based on SLR, GNSS, radiosonde, and numerical weather models. Figure 15 shows that the total refractivity of the troposphere is much better reconstructed when using a combination of GNSS and numerical weather model prediction (WRF) data employing the least squares collocation method (left) as compared to the solution based on GNSS-only (right). As a result, the combined GNSS-WRF model provides much more reliable information on the water vapour content than GNSS-only or WRF-only data (Wilgan et al., 2017a, 2017b).

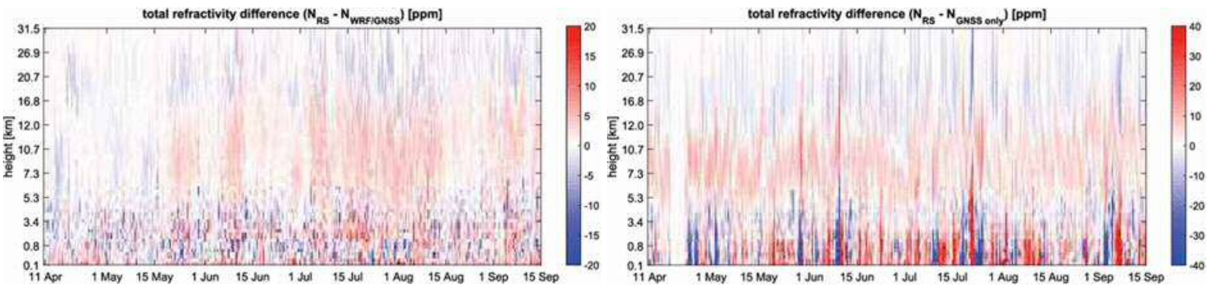

Figure 15. *Differences of the total refractivity derived from radiosondes (RS), numerical Weather Research and Forecasting (WRF) model combined with GNSS-derived parameters using the collocation method (left) and differences between total refractivity from RS and GNSS-only (right) in 2014, after Wilgan et al., (2017a).*

Improving the troposphere delay modelling is important not only for the recovery of the tropospheric state, but also for the improvement of GNSS positioning, using, e.g., Precise Point Positioning technique, and for SLR solutions. In the SLR solutions, the horizontal gradients of the troposphere delay are currently neglected both in the SLR operational products and in the reprocessed products which are used for the definition of the International Terrestrial Reference Frame. As a result, the horizontal components of SLR solutions are typically affected by systematic errors associated with the mismodeling of horizontal gradients of the troposphere delay, whereas in the other techniques, such as GNSS and VLBI, gradients are considered. However, most of the SLR stations are co-located with GNSS receivers; thus, it is possible to compare the SLR-derived and GNSS-derived gradients (see Fig. 16), even when the number of SLR is typically too small to derive gradients of a reliable quality. Using the numerical weather models as a source data for the SLR horizontal gradients may improve the quality and stability of SLR solutions (Drożdżewski and Sośnica, 2017).

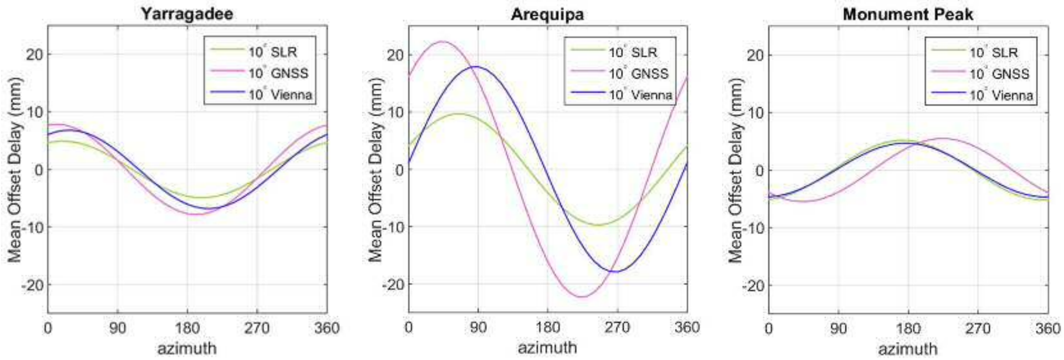

Figure 16. *Horizontal gradients of the troposphere delay derived from SLR, GNSS and numerical weather models (Vienna, Boehm et al., 2009) mapped onto the elevation angle of 10 arc-deg for Yarragadee, Arequipa, and Monument Peak (Drożdżewski and Sośnica, 2017).*

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Joint Study Group 0.15: Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy

Chair: *Jianliang Huang (Canada)*
Vice Chair: *Yan Ming Wang (USA)*

Members

- *Riccardo Barzaghi (Italy)*
- *Heiner Denker (Germany)*
- *Will Featherstone (Australia)*
- *René Forsberg (Denmark)*
- *Christian Gerlach (Germany)*
- *Christian Hirt (Germany)*
- *Urs Marti (Switzerland)*
- *Petr Vaníček (Canada)*
- *Yan Ming Wang (USA)*

Activities during the period 2015-2017

Activities are organized and reported by components of the JSG objectives as follows:

Spectral combination of different types of gravity data

Foroughi et al. (2015a) addressed the question of how a global gravity field model may best be used to fill spaces void of observed gravity data to arrive at a relatively homogeneous data coverage. Foroughi (2016b) formulated and came up with the best combination of a degree and order of reference field and integration cap size in the Stokes-Helmert approach to regional geoid computation. Also a new computational algorithm was tested. The resulting geoid for the Auvergne region is improved by 0.5 cm when compared to the GPS/levelling geoidal heights.

Due to progress in space and airborne technologies, more high quality gravity field related data are collected. These data are often complementary in their spectral contents, thus the challenge of geoid determination today is to combine multiple data types according to their error characteristics. Wang et al. (2016) discussed two methods of combination: the spectral combination and the least-squares collocation with emphasis on the first. The principle of spectral combination is as simple as a weighted spectral mean. The difficulty is to estimate the spectral weights for each data set realistically. This method establishes a mathematical framework for the combination of multiple types of gravity data for geoid determination. They also showed that the standard remove-compute-restore scheme is a special case of this method. The spectral combination method was applied for satellite, airborne and terrestrial gravity data in the US NGS's GSVS11 demonstrating the contribution of GRAV-D for the middle wavelength components of the gravity field (Jiang and Wang 2016).

Gerlach and Ophaug (2017) have derived combined geoid solutions from state-of-the-art satellite only models (based on relase-5 GOCE data) and terrestrial information. Combination was performed in the spectral domain using Wenzel's stochastic method as well as more deterministic methods like the classical Wong&Gore modification. The latter were chosen, because they were used earlier in our study area Norway; Wenzel's approach was chosen, because it is considered to be optimal in a certain sense. Thereby it is important to stress, that correlated noise for both satellite and terrestrial data have been assumed. The error estimates (error degree variances) for the satellite data were derived from the formal error description of the DIR and GOCO models, respectively (classical error degree variances were rescaled to fit the local amplitude of the error variance derived from an m-block approximation of the full error variance-covariance matrix). Error estimates of the terrestrial data are based on published correlated error models. They compared the combined solutions as well as existing regional geoid models to GNSS-levelling data to derive empirical error estimates. While comparison with older geoid models shows the general improvement brought by the satellite missions GRACE and GOCE (improving the overall RMS fit from around 8 cm before GRACE and GOCE, to currently around 3 cm), their own weighting schemas allow to give an estimate of the expected mean error of the terrestrial data. They could show that the dataset used, on average, is probably less accurate than the one used for the derivation of the European Gravimetric Quasigeoid EGG2015 (again on average). While the latter gives the best overall fit to independent data assuming an average error standard deviation of 0.2 mGal for the terrestrial data, they found that the error standard deviation of the Norwegian data set seems to be in the order of 2 mGal. Later comparisons with the latest version of the Nordic geoid NKG2015 showed a decrease of the error budget (down from around 3 cm to 2.5 cm) which leads to the conclusion that the Norwegian dataset has been improved recently. This latest dataset was not available for the investigations. Comparison of empirical and formal error budgets indicate that the overall error budget derived from comparison with GNSS-levelling is probably dominated by errors in the levelling data. Further investigations on the different error sources will be performed in the next study period.

Gravity reduction

Foroughi et al. (2015b) investigated the fit along the boundaries between downward continued gravity anomalies on the geoid obtained separately for one degree squares. The fit was assessed by statistical means and found to be rather good. Sheng et al. (2015) investigated the differences between the downward continued gravity anomalies in Helmert's and the NT spaces. They found out that the differences were inexplicably large and realized that these large differences were caused by insufficiently accurate evaluation of the FZ contribution in the case of the NT space. Consequently, the use of the Helmert space should be preferred. Kingdon and Vaníček (2015) formulated two different algorithms for determining gravity anomalies on the geoid in regions containing both positive and negative heights using simultaneous downward and upward continuation. It was found that both algorithms give comparable results. This research is to be continued when good real data become available. Kingdon et al. (2015) studied least-squares downward continuation of gravity anomalies in Helmert's space, introducing the concept and showing some sample applications. Foroughi et al. (2016a) further analysed the sensitivity of Poisson's integral to the location of points both on topography and on the geoid. Foroughi et al. (2016c) also studied three different scenarios for point location on topography – on a regular grid, combination of regular grid and scattered points and scattered points alone. Vaníček et al. (2016) discovered that during the iterative solution of the downward continuation problematic unique inverse problem—the solution stays within physically meaningful boundaries. As starting from some iteration, the process starts to model the effect of random errors and thus it makes no sense to seek an exact solution; instead the most probable solution in statistical sense should be preferred.

Sheng et al. (2016a. b) investigated how rigorously to transform gravity potential harmonic series into Helmert's space, after discovering that the development in [Vaníček P, Najafi M, Martinec Z, Harrie L, Sjöberg LE, 1996. Higher-order reference field in the generalized Stokes-Helmert scheme for geoid computation. *Journal of Geodesy* 70 (3): 176-182] was not correct. The changes (improvements) compared to the standard technique reach 24 cm in range and 1 cm in standard deviation (globally). Lin and Denker (2016) investigated the computation of topographic and atmospheric effects with tesseroids.

Applications of new tools such as the radial basis functions

It is known from literature that different methods for gravity field modelling – specifically Stokes's integration, least-squares collocation or representation in spherical splines – are equivalent in global applications. The application of one of the methods in a specific regional application may be a matter of an evaluation of pros and cons of the different methods, or a matter of availability of software tools, or experience of the user. As the application of spherical radial basis functions got increased interest in recent years, it is interesting to review the equivalence of this approach with the classical Stokes and collocation methods. Ophaug and Gerlach (2017) investigated the equivalence of these three methods in regional applications both from a theoretical as well as from a numerical point of view. They have used a set of synthetic gravity anomalies to perform regional geoid computation based on Stokes integration, collocation and spherical splines in an error free closed-loop simulation. Input data was a 5'x5' grid of gravity anomalies derived from EGM2008 to full resolution. Computations were performed for two test areas with smooth and moderately rough gravity field characteristics. They found that all methods agree on the sub-millimetre to millimetre level, where the largest deviations are due to discretization errors of Stokes integral equation. In general collocation provides the best results, but the spline representation is almost equivalent. They did not go into evaluation of pros and cons of the methods, but only investigated the numerical equivalence. However, it would be interesting to carry out further research on this in order to provide guidelines on which method may be the preferred one in a special situation, considering e.g. numerical burden. They did also not apply the methods to real datasets. This again is left to future research.

In the meantime, Lin et al. (2015, 2016) investigated the regional gravity field modelling based on a two-step point mass method with free depth, and compared it with the Least-Squares Collocation method. Numerical tests demonstrated close solutions between the two methods.

Independent validation of geoid/quasi-geoid models

The tilt of coastal mean sea level with respect to an equipotential surface can be estimated using two fundamentally different approaches. The geodetic approach is based on tide gauge and GPS observations, and a model of the geoid. The ocean approach uses a high-resolution, dynamically based ocean model to estimate mean dynamic topography. Along the Pacific coast of North America the two approaches give similar large-scale profiles with a minimum at about 408N and a maximum in the northern part of the Gulf of Alaska. Along the Pacific coast of Japan the geodetically determined coastal sea levels indicate an eastward drop of about 20 cm along the south coast and a further northward drop across Tsugaru Strait. Both of these features are reproduced by the ocean models (Lin et al. 2015).

Huang, J. and M. Véronneau (2015) assessed the GRACE and GOCE release 5 (R5) global geopotential models (GGM) using GPS-Levelling data, astronomic deflections of the vertical and terrestrial gravity data in Canada. The accuracy of the GOCE R5 models was estimated to be better than 4-5 cm up to spherical harmonic degree ~200. The traditional astronomic deflections appeared not accurate enough to measure improvements in the GOCE R5 models with respect to the GOCE R4 models. The analysis inferred that the GOCE contribution in EIGEN-6C4 is more accurate than the corresponding wavelength components in EGM2008.

In the Great Lakes region, the improvement of the geoid model by GRAV-D reaches decimetres using the lake surface height measured by satellite altimetry as an independent data set over Lake Michigan where the legacy gravity data have significant errors (Li et al. 2016).

In Perth, Western Australia, a modern digital astro-geodetic field campaign was completed in February 2017. Along a ~40 km long east-west traverse crossing the Perth Basin, vertical deflection data were collected at 37 field stations using two Q-Daedalus digital astronomical measurement systems (Guillaume and Bürki 2014; Hauk et al. 2016). The initial analysis of these new vertical deflection data indicates a precision of 0.2 arc-sec. They will be further utilised for the computation of astronomical quasigeoid profiles to provide an independent check on gravimetric quasigeoid models and GPS-levelling data. This is the first in Australia and indeed the Southern Hemisphere that has been acquired with modern digital astronomical instrumentation. The deflection data set will be made freely available to the geodetic community, e.g., for testing of future quasi/geoid or global geopotential models. This project was devised and led by Christian Hirt, and received financial support by the German Academic Exchange Service (DAAD) and Universities Australia. Local assistance came from Will Featherstone and Todd Lyon (Perth) and from C.R. Kennedy.

Anomalous topographic mass density effect on the geoid model

Forgoughi et al. (2015c) investigated whether a publicly available mid-scale geological map can be used to improve the geoid computed by the Stokes-Helmert process in Auvergne. Even though the improvement was not overwhelming, they showed a systematic improvement after applying the laterally varying topo-density variation effects. Tavakoli et al. (2016) did a study of an application of Kouba's refined form of Poisson's partial differential equation of gravity potential to the problem of topographical density determination.

Data type, distribution and quality requirements

Klu et al. (2015) did a test for the Stokes-Helmert technique of geoid computation with real, rather sparse data. Results confirmed that a relatively good geoid can be obtained even with sparse data.

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Joint Study Group 0.16: Earth's inner structure from combined geophysical sources

Chair: *Robert Tenzer (China)*

Members

- *Lars Sjöberg, Sweden*
- *Mohammad Bagherbandi, Sweden*
- *Carla Braitenberg, Italy*
- *Mirko Reguzzoni, Italy*
- *Xiaodong Song, USA*

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Joint Study Group 0.17: Multi-GNSS theory and algorithms

Chair: *Amir Khodabandeh (Australia)*

Members
- *Peter J.G. Teunissen (Australia)*
- *Pawel Wielgosz (Poland)*
- *Bofeng Li (China)*
- *Simon Banville (Canada)*
- *Nobuaki Kubo (Japan)*
- *Ali Reza Amiri-Simkooei (Iran)*
- *Gabriele Giorgi (Germany)*
- *Thalia Nikolaidou (Canada)*
- *Robert Odolinski (New Zealand)*

Activities and publications during the period 2015-2017

This report presents an overview of activities undertaken towards the objectives of the ICCT Joint Study Group 0.17 since 2015. The aim of the study group is to identify and investigate challenges posed by processing/integrating data of the next generation satellite navigation systems, developing optimal methods capable of multi-GNSS data processing, thereby articulating new algorithms and findings through journals, conferences and group discussions.

JSG Members' Activities

Undifferenced, uncombined multi-frequency formulation: Most of the current methods for GNSS data processing are based on forming combined observations (e.g., ionosphere-free, wide-lane and Melbourne-Wubbena combinations). These methods are therefore restrictive in the light of the development of new multi-frequency GNSS constellations. Odijk et al. (2015) presented an undifferenced, uncombined multi-frequency formulation of the GNSS observation equations and showed how one should interpret *estimable* forms of the GNSS parameters. They further applied their method to integer ambiguity resolution-enabled precise point positioning (PPP-RTK) and presented the positioning performance improvements that can be expected by multi-GNSS PPP-RTK setup (Figure 0.17). Further results on mutli-GNSS positioning are provided in (Odolinski and Khodabandeh 2016). As to the non-positioning applications, Khodabandeh and Teunissen (2016b) applied the method to the GNSS array model and analysed the estimability and precision of multi-frequency GNSS-derived slant Total Electron Content (TEC), showing that the variance of the TEC solutions follows the 1-over-n (1-over-f) rule and decreases the more the number of antennas/frequencies (n: number of array antennas, f: number of frequencies).

The advent of multi-GNSS mass-market receivers: A vast number of low-cost receivers, tracking satellites of multiple systems, have entered the market. Odolinski and Teunissen (2017a, b) showed, in contrast to their single-GNSS counterparts, that these receivers can offer high-precision positioning if one rigorously integrates their multi-GNSS data.

The triple-frequency BeiDou signals: Following the study on the stochastic model of triple-frequency BeiDou signals (Li 2016), Li et al. (2017) investigated the RTK performance of the extra-wide-lane observations available through the BeiDou triple frequencies. Given fast successful ambiguity resolution, the extra-wide-lane observations were shown to provide RTK solutions with the horizontal accuracy of 10 cm.

GLONASS FDMA signals: Banville (2016) presented a strategy for long-baseline ambiguity resolution applicable to the GLONASS L1/L2 FDMA signals. Benefiting from the frequency-spacing of the signals, ionosphere-free ambiguities were defined, improving the repeatability of static PPP solutions by more than 20 %.

GLONASS CDMA signals: Zaminpardaz et al. (2017) presented world-first results of the GLONASS L3 signals. They studied the noise characteristics, the integer ambiguity resolution performance, and the positioning performance. In particular, the GLONASS data were shown to have a lower noise level than that of GPS, particularly in case of the code data.

Group Discussion

We had a group discussion on the inter-system-biases (ISBs). The ISBs pop up in the multi-GNSS measurement setup, because the receiver instrumental delays are experienced in a way that is 'different' from system to system (the term 'system' refers to a satellite constellation). The members were invited to give their opinions about 1) significance, 2) estimation and 3) outlook of the ISBs for multi-GNSS positioning and non-positioning applications. A few members contributed to the discussion and provided their feedback. A summary is given as follows. A conservative way of dealing with the ISBs is to treat them as unknown and estimate them on the fly, often without any temporal constraints. Although this approach leads to a slightly weaker solution, but then one does not have to worry about any unit-specific bias that would not be properly accounted for by calibration values or by possible intra-day variations due to, e.g., temperature changes. In this perspective, the benefits of calibrating ISBs and the potential applications are limited to controlled environments where equipment (receiver type and firmware version) are well defined. On the other hand, there are methods that offer ISBs calibration. In particular for networks of a large number of receivers, a-priori ISBs calibration enables one to take a common pivot satellite among multiple systems, thus considerably increasing the GNSS network model's redundancy. The outlook would be that as part of the IGS analysis centers' work, all receiver manufacturers will be aligned to employ the same standards, presenting receiver instrumental delays with no ISBs. Several scenarios on properly handling the ISB parameters in the GNSS network models are presented in (Khodabandeh and Teunissen 2016a).

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Joint Study Group 0.18: High resolution harmonic analysis and synthesis of potential fields

Chair: *Sten Claessens (Australia)*

Members

- *Hussein Abd-Elmotaal (Egypt)*
- *Oleh Abrykosov (Germany)*
- *Blažej Bucha (Slovakia)*
- *Toshio Fukushima (Japan)*
- *Thomas Grombein (Germany)*
- *Christian Gruber (Germany)*
- *Eliška Hamáčková (Czech Republic)*
- *Christian Hirt (Germany)*
- *Christopher Jekeli (USA)*
- *Otakar Nesvadba (Czech Republic)*
- *Moritz Rexer (Germany)*
- *Josef Sebera (Italy)*
- *Kurt Seitz (Germany)*

Activities and publications during the period 2015-2017

Activities by members of the joint study group on high-resolution harmonic analysis and synthesis of potential fields have resulted in many new advances, and significant progress has been made towards many of the group's objectives. The main results over the period 2015-2017 are summarised below.

Algorithms and software for ultra-high degree spherical and spheroidal harmonic analysis and synthesis

A major challenge in the creation of efficient algorithms for ultra-high degree spherical and spheroidal harmonic analysis and synthesis is the precise and stable computation of associated Legendre functions (ALFs) of the first and second kind (or ratios thereof), plus its derivatives and integrals.

Fukushima (2015) reviews the X-number formulation for the computation of point values, derivatives, and integrals of ALFs of the first kind and point values and derivatives of oblate spheroidal harmonics of the second kind. The X-number formulation resolves the underflow problem in the computation of point values of ALFs of the first kind up to and beyond degree 216,000. Computation can be accelerated by implementation of a dynamic switch from the X-number to the ordinary floating-point number during recursions, and by application of folded parallel computation. Fukushima (2017) addresses the degradation of precision near the poles in the computation of ALFs by using a rectangular rotation of the spherical harmonic expansion to move the polar singularity to the equator.

Gruber and Abrykosov (2016) have focused on the applicability of transformations between spherical harmonic expansions and bivariate Fourier series to the computation of ALFs. In this approach, the ALFs are expanded in coefficients of harmonic functions. Fast and stable algorithms have been developed and evaluated. With this tool future high resolution gravity field models can be stably synthesised or analysed in regular grid representations, and using reduced or geodetic latitudes as well. Fukushima (submitted) also present an algorithm based on the Fourier series approach, using a three-term forward recurrence formula for the computation of the rectangle value of the Wigner d-function. The method stably provides accurate results for even extremely high degree and order (~10^9).

A Fortran95 software extension for ultra-high degree surface harmonic analysis was developed and released to the public by Rexer and Hirt (2015a). The software combines the Gauss-Legendre and Driscoll-Healy quadrature from the SHTOOLS software suite (www.shtools.org) with the Fukushima X-number algorithms for stable computation of ultra-high degree ALFs, and offers parallel processing capability. The new software can be considered an important "building block" for ultra-high degree gravity forward modelling with spectral techniques.

Nesvadba and Holota (2015) have developed an efficient streaming-parallel algorithm for the computation of oblate spheroidal harmonic functions and their derivatives. They utilise an Open Computing Language (OpenCL) implementation on a general-purpose graphic processing unit (GPGPU). The resulting algorithm is significantly more efficient than the "traditional" hypergeometric series approach on a CPU. They have also developed various techniques for numerical treatment of series of ALFs (first and second kind) of imaginary argument, some of which are presented in Holota and Nesvadba (2015).

Sebera et al. (2016a) present a novel ellipsoidal approach for updating high-resolution models over the oceans with new gridded data. This was done in spheroidal approximation to spheroidal degree 4430 (with Gauss-Legendre quadrature employed). This work includes a slight modification of the Legendre functions of the second kind in the Jekeli renormalisation, now allowing grid-wise calculations above degree 10,000. Sebera et al. (2016b) study the spheroidal approximation of both the oblate and prolate bodies in case of two asteroids. For the prolate case, the relations between curvilinear and Cartesian partial derivatives up to the second order are provided.

A new analytical method for solid spherical harmonic analysis from data on a spheroid is presented in Claessens (2016). The method uses a transformation between surface and solid spherical harmonic coefficients and is compared to an alternative method that uses the Hotine-Jekeli transformation with Sebera modification. Both methods achieve sub-micrometre precision in terms of height anomalies for a model to degree 2239. However, it was also shown that high and ultra-high harmonic expansions exhibit significant differences when a different type of latitude (geocentric or reduced) is used in the input grid.

A relatively new topic is the harmonic analysis and synthesis of gravitational curvatures (third-order gradients of the gravitational potential). The conventional spherical harmonic expansions of the gravitational curvatures in a local north-oriented reference frame depend on the first-, second- and third-order derivatives of the associated Legendre functions, and some of these expansions contain singular terms at the poles. Hamáčková et al. (2016) have developed new non-singular expressions for spherical harmonic synthesis of gravitational curvatures by transforming the conventional series to new simpler and non-singular forms based on relations between ALFs and their derivatives.

Bucha and Hirt have developed a new method for fast spherical harmonic synthesis at the topographic surface (not yet published). The currently used gradient approach does not work reliably for very high orders of the Taylor series (i.e., beyond the order of 50) and for extremely rough signals. In places where the gravity signal highly oscillates a high maximum harmonic degree of the expansion in a combination with a high Taylor series order is needed. The new method is based on an interpolation in the radial direction.

Fukushima (2016) presents harmonic expansions of external gravitational fields for ring-like objects, which cannot satisfactorily be expanded using spherical, spheroidal, or ellipsoidal harmonics. Instead, an expansion in terms of zonal toroidal harmonics is derived.

Convergence vs. divergence in spherical and spheroidal harmonic series

Often, spherical harmonic series expansions are evaluated inside the sphere encompassing all masses (Brillouin sphere), e.g., to predict the gravity field near the surface. Inside the Brillouin sphere, however, the external potential series may converge or may diverge, that is, produce invalid values. This holds similarly for spheroidal or ellipsoidal harmonic series expansions evaluated inside the Brillouin spheroid or ellipsoid.

Hu and Jekeli (2015) study the possible divergence effects and amplified omission errors in spherical, spheroidal, and ellipsoidal harmonic series for gravitational modelling of small moderately irregular bodies. Numerical tests for the Martian moons Phobos and Deimos show significant divergence in spherical and spheroidal harmonics already at low degrees, but less distinct divergence behaviour in ellipsoidal harmonics.

For Earth's topographic potential to degree-2160, convergence is often assumed and can indeed be taken for granted when synthesising gravity functionals at the Earth's surface (Hirt et al. 2016a), although there is evidence for minor, but measurable divergence in the spherical harmonic series at ultra-high degree. This finding may be important for the development of future ultra-high-resolution gravity fields with spectral techniques. However, the situation is entirely different for Earth's Moon due to its much rougher undulating surface and range in topographic elevation. A case study for the Moon (Hirt and Kuhn 2017) has investigated divergence effects in high-degree spherical harmonic series of the topographic potential by comparisons against accurate numerical integration. As key results, gravity on the lunar surface can be synthesised from the topographic potential coefficients to degree ~180 without divergence. Opposed to this, high-degree series (e.g., degree 1080 or degree 2160) produce invalid values when gravity functionals are synthesised at the rough lunar surface, see Figure 17. As such, the new investigations exemplify the problem of series convergence vs. divergence for the Moon and show that the Earth case is much less affected by divergence, presumably due to the overall smoother topography. For rugged planetary bodies, the findings necessitate the development or application of alternative techniques (e.g., combinations with interior potentials) to generate spectral gravity field models that are less affected by divergence.

Bucha has worked on an as yet unpublished alternative approach that would deliver a spherical harmonic series providing reliable results even at the topography. The approach is based on an iterative downward continuation of data from the topographic surface to the Bjerhammar sphere. The input data are given by the Newtonian integration in the spatial domain which is free of the divergence issue. From these data, a reliable spherical harmonic series can be obtained via downward continuation.

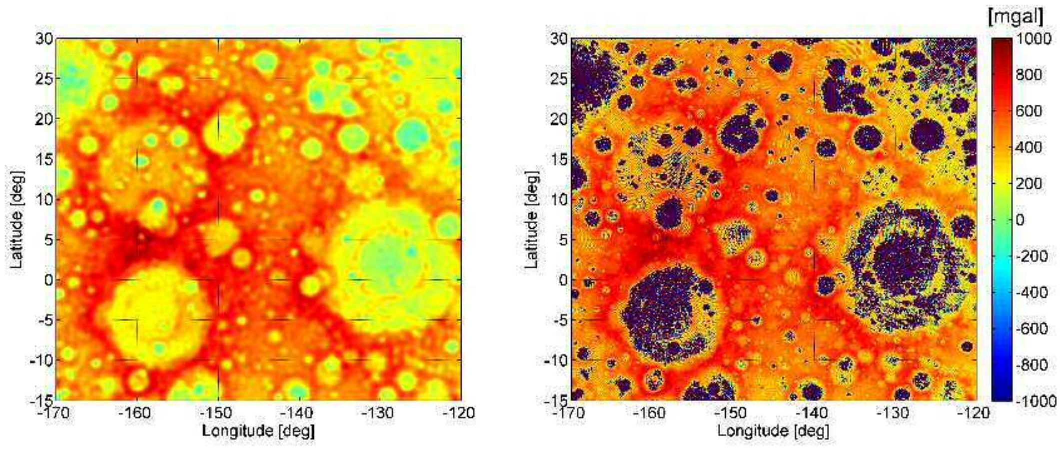

Figure 17. *Gravity implied by topography over the Far-side Highlands of the Moon, computed with spectral techniques. Left: to harmonic degree 360, Right: to harmonic degree 2160. The right panel shows invalid gravity values inside the craters, occurring as a consequence of series divergence in the spectral technique at high degrees over rugged terrain.*

High-resolution spherical and spheroidal harmonic models and degree variance models

High-resolution harmonic models are used for the description of gravitational potential fields, but also for the description of topographic or topographic-isostatic potential fields obtained through gravity forward modelling. Earth's near-surface masses are generally considered to be the main contributor to short-scale gravity field signals. High-resolution and up-to-date models of topography, water and ice masses are therefore important for detailed gravity forward modelling, and these have also been represented as harmonic models.

Hirt and Rexer (2015) have developed and publicly released the Earth2014 topography product compilation which describes Earth's shape, topography, water, bedrock and ice-sheets with 1 arc-min resolution, see Figure 18. The Earth2014 models improve over previous 1-arcmin compilation such as ETOPO due to the inclusion of newer ice and bathymetry data sets. The grids were expanded into ultra-high degree spherical harmonic coefficients to degree and order 10,800. The data can be used, e.g., for testing of ultra-high degree synthesis and analysis software, and deployed in gravity forward modelling with spectral methods (series expansions) and spatial methods (numerical integration). The Earth2014 is distributed via IAG's IDEMS elevation model service and ddfe.curtin.edu.au/models. In addition, Rexer and Hirt (2015a) harmonically analyse the constituents of planetary topographies (Earth, Moon, Mars) to ultra-high degree of up to ~46,000, see Figure 19.

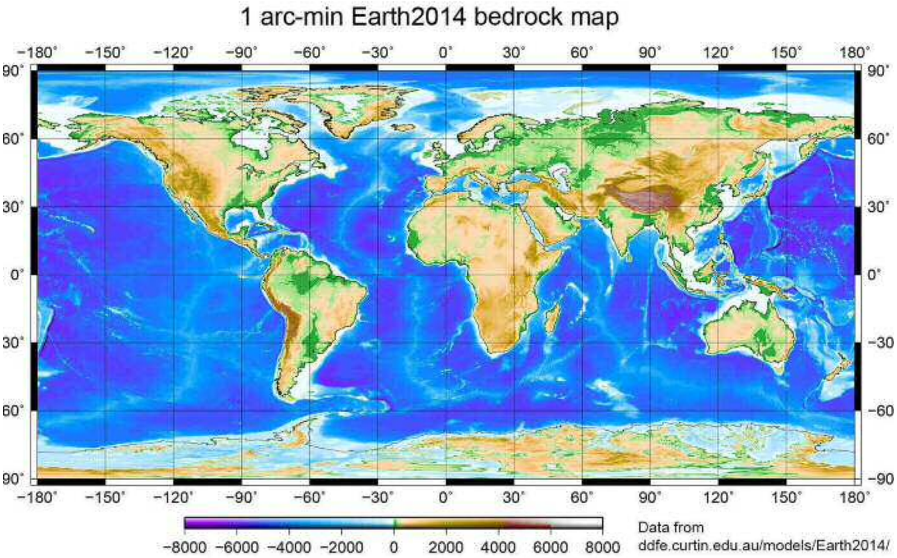

Figure 18. *Example of Earth2014 data layers – 1 arc-min resolution bedrock topography*

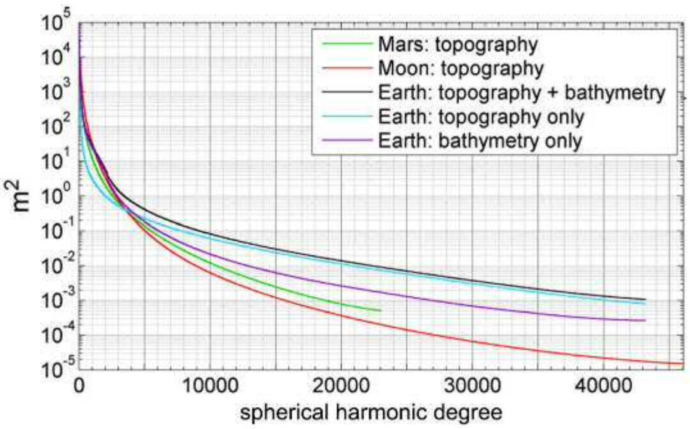

Figure 19. *Degree variance models for planetary topography models, computed from surface harmonic coefficients up to degree and order ~46,000*

A new technique for spectral-domain gravity forward modelling was introduced by Rexer et al. (2016). The new approach allows rigorous modelling of the topographic potential generated by multiple, arbitrarily (star)-shaped mass-layers relative to a mass-ellipsoid in spherical harmonics. Before this work, the potential of multiple mass-layers was forward-modelled relative to a mass-sphere or the potential of a single-layer was forward-modelled relative to a mass-ellipsoid, but no approach existed thus far that merged both techniques. The approach was applied in Rexer et al. (2016) to produce dV_ELL_Earth2014 model that describes the topographic potential of the Earth2014 model to 5-arcmin resolution (or spherical harmonic degree 2,190). The dV_ELL_Earth2014 model is distributed via IAG's ICGEM service. Rexer (2017) and Rexer et al. (2017) applied the methods to model the Earth2014 potential of topography, ice- and water-masses to degree 5400 without truncations or approximations.

Grombein et al. (2016) have also used the Earth2014 model to generate a high-resolution spherical harmonic representation of the Earth's topographic potential to degree 2190 (RWI_TOPO_2015). This study performs the gravity forward modelling in the space domain, followed by a least-squares spherical harmonic analysis. The RWI_TOPO_2015 model is also distributed via IAG's ICGEM service.

Abd-Elmotaal and Kühtreiber (2015) have developed a new algorithm to compute the ultra-high harmonic coefficients of the topographic-isostatic masses on the surface of the ellipsoid. The formulas are rigorous. Numerical studies reveal that the approach works well. Abd-Elmotaal et al. (in prep) compare this method with the method by Grombein et al. (2016). This study shows some differences in the frequency domain between the two tested approaches, but the differences in the space domain are much smaller.

The German GeoForschungsZentrum (GFZ) is currently developing a high-resolution terrain model that uses the advanced harmonic analysis developed by Gruber and Abrykosov (2016).

Some studies have used high-resolution harmonic models of the gravitational potential in combination with forward modelling to derive an accurate model of the gravity field in a local or regional area. Hirt et al. (2016b) explore high-degree spectral forward modelling to improve the gravity field over Antarctica. The Bedmap2 data set contained in the Earth2014 topography model was used to refine the gravity field over Antarctica beyond the resolution of current GRACE and GOCE gravity fields. The Earth2014 data set was used as input data to forward-model the implied gravity field in ellipsoidal approximation (i.e., field-generating masses arranged relative to an ellipsoid) and spherical harmonics to degree 2190. A combination technique based on normal-equations was applied to merge the forward model with gravity from the GRACE and GOCE missions. The resulting model (SatGravRET2014) was validated with gravity observations from the IAG Subcommission 2.4 "Gravity and Geoid in Antarctica" (AntGG) database. The work demonstrated that spectral forward modelling is capable of filling some gaps in short-scale gravity knowledge over Antarctica contained in current global geopotential models such as EGM2008.

Bucha et al. (2016) have developed a high-resolution regional gravity field over the Slovak Republic (Central Europe) via a combined approach using spherical harmonics (to degree 2190), band-limited spherical radial basis functions (the Shannon SRBF, to degree 21,600) and RTM technique. The model is developed from a dense terrestrial gravity database (3 – 6 stations per km^2), which allowed to model the gravity field up to harmonic degree 21,600. The model is validated against independent height anomalies, surface gravity data, deflections of the vertical and terrestrial vertical gravity gradients. This paper presents an alternative approach to the common spherical harmonic gravity modelling. It is especially useful when modelling the gravity field on a regional scale and up to an ultra-high spatial resolution. Spherical harmonic modelling up to degree 21,600 requires the determination of more than 466 million coefficients which cannot be done at the present time by the least-squares technique with the full normal equation matrix. On the other hand, in regional gravity field modelling via SRBFs, only about 78,000 coefficients had to be estimated, which is not difficult to achieve even with the full normal equation matrix.

Another example of a high-resolution harmonic models are surface harmonic expansions of specific gravitational functionals. Claessens and Hirt (2015) have derived a surface spherical harmonic expansion of gravity anomalies with respect to a geodetic reference ellipsoid. This is based on a rigorous transformation of solid spherical harmonic coefficients of a global gravity model. Contrary to earlier methods, it does not rely on approximations to the order of the second or third power of the eccentricity of the ellipsoid, which are shown to be insufficient at high and ultra-high degrees.

Finally, a spectral analysis of the GGMplus gravity maps to ultra-high resolution (equivalent to degree 90,000) was performed by Rexer and Hirt (2015b). Using 2D-DFT methods, a new degree variance model was developed that describes the decay of gravity signals over Earth's land areas to ~250 m resolution, see Figure 20. As improvement to previous works, the new degree variance model is supported through topography-implied gravity to degree ~90,000 [often, previous degree variance models were data-supported only to 100 or 10 km spatial scales, so subject to extrapolation errors when used to predict the short-scale signal characteristics of the gravity field]. The degree variance model developed may serve as a reference in comparisons with future ultra-high degree series expansions of the gravitational field. Also, it could be shown that the effect of the ellipsoidal or spherical arrangement of the field-generating masses on the power spectra is becoming more significant the shorter the spatial scale, so deserves due attention when applying degree variance models, e.g., to compute omission errors.

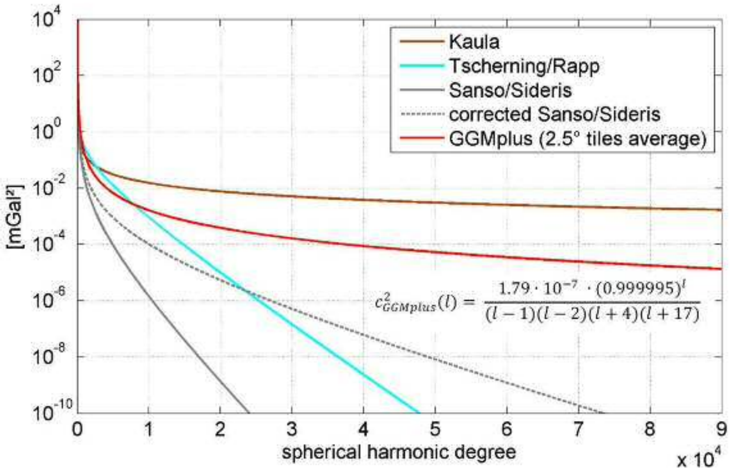

Figure 20. *Degree variance models from GGMplus (red curve) in comparison with other degree variance models*

Applications of high-resolution harmonic models

Recent advances in high-resolution harmonic modelling of potential fields have successfully been used to gain important insights and results.

One example is the computation of spherical harmonic Bouguer gravity anomalies, a frequently used approach used in planetary sciences, which is now becoming more popular with the Earth gravity modelling community. The Bouguer gravity is obtained in the spectral domain by subtracting the coefficients of the topographic potential from those of the observed potential (e.g., GOCE, EGM2008 or EIGEN-6C models). Hirt et al. (2016a) focus on the validation of the spectral-domain forward-modelling technique used to generate the harmonic coefficients of the topographic potential at 5 arc-min resolution. A full-scale numerical integration technique (Newtonian integrator by Curtin University) was applied in the space-domain to deliver the topographic potential independently from the spectral approach. It is known that the gravity field obtained through numerical integration contains gravity signals at scales much finer than the resolution of the field-generating topography. To ensure spectral consistency between the spectral-domain and spatial-domain solutions, the gravity field generated by the degree-2,160 topography was modelled to ultra-high degree of 21,600. The study revealed micro-Gal consistency between the two modelling techniques over most of the Earth's surface, see Figure 21.

Another example is the insight gained in the understanding of the correlation between the gravitational and topographic potential at small spatial scales, as the importance of the parameterisation and geometry applied has been revealed. When spectral techniques are used to model Earth's gravity field, parameterisations are possible in terms of spherical, spheroidal or ellipsoidal harmonics. On the other hand, when gravity forward techniques are applied, the field-generating masses can be arranged relative to a mass-sphere or mass-ellipsoid of revolution. The first case is sometimes denoted as spherical approximation level and the second case as ellipsoidal approximation level. In practice, approximation levels and parameterisations are often mixed, e.g., EGM2008 being a spherical harmonic representation using ellipsoidal approximation levels. Hirt et al. (2017) investigate how correlation measures – e.g., correlation coefficients or reduction rates – that are often formed between geopotential models (e.g., EGM2008) and topographic potential models (e.g., dV_ELL_Earth2014) depend on the parameterisation and approximation level. When the EGM2008 SHCs (spherical harmonic coefficients) are correlated with SHCs of the topographic potential model in ellipsoidal approximation, the resulting correlation measures have been found biased over most of the spectrum. In the previous example, the correlation between EGM2008 and topographic potential reaches a maximum near degree ~1,000, though it should be maximum near the full model resolution (near degree 2,160). The biases can be avoided by using either SHCs together with spherical approximation or EHCs (ellipsoidal harmonic coefficients) with ellipsoidal approximation (Figure 6). Then, maximum correlation is indicated near the shortest scales resolved by the global gravity field model (Hirt et al. 2017). While this may necessitate coefficient transformations prior to the correlation analysis, wrong or ambiguous conclusions regarding the model properties and gravity field composition can be avoided.

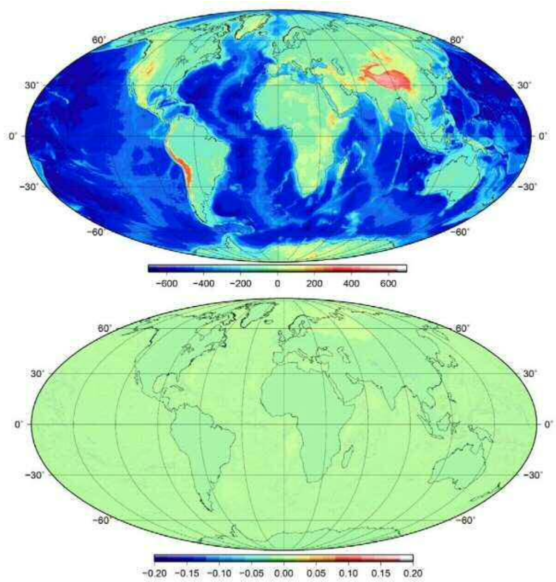

Figure 21 Top*: Gravity implied by Earth's topography to degree-2160, computed with numerical integration. Bottom: Differences between gravity implied by topography from numerical integration and spectral modelling to degree 21,600. Unit in mGal.*

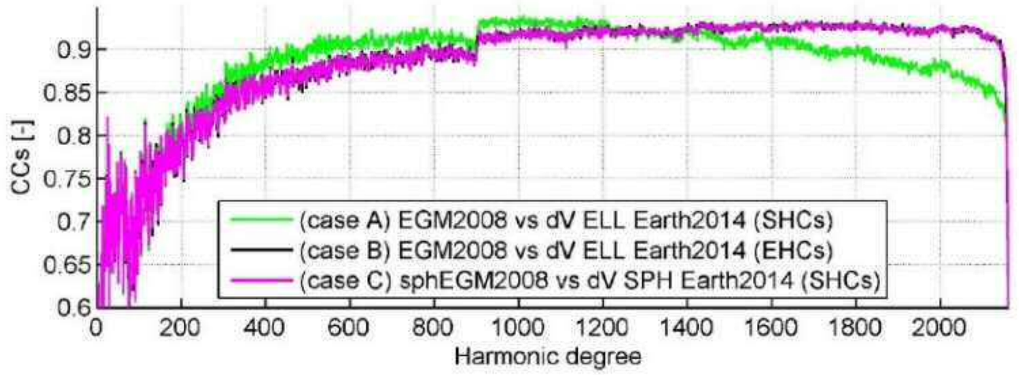

Figure 22. *Correlation between Earth's observed and topographic potential as a function of the harmonic degree. The green curve is biased, while the black and pink curves give more realistic information on the degree correlation (for details see Hirt et al. 2017).*

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Joint Study Group 0.19: Time series analysis in geodesy

Chair: *Wiesław Kosek*

Members

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- *Jan Vondrák (Czech Republic)*
- *Waldemar Popiński (Poland)*
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- *Sergei Petrov (Russia)*
- *Michel Van Camp (Belgium)*
- *Hans Neuner (Germany)*
- *Xavier Collilieux (France)*
- *Anna Kłos (Poland)*

Activities and publications during the period 2015-2017

The following activities were undertaken within JSG 0.19 Time series analysis in geodesy during the period 2015-2017.

The combination of the Fourier Transform Band Pass Filter with the Hilbert transform (FTBPF+HT) was applied to compute variable amplitudes and phases of seasonal and sub-seasonal oscillations in altimetric sea level anomaly (SLA) data. These oscillations are mostly irregular and cause an increase of prediction errors of the SLA data. The SLA data prediction errors for a few weeks in the future are usually considerable in geographic regions where amplitude maxima of the broadband annual oscillation and other shorter period oscillations are the largest (Kosek et al., 2015).

Time frequency analysis by the normalized Morlet wavelet transform (NMWT) of the differences between pole coordinates data and their predictions computed by combination of the least-squares and autoregressive (AR) forecasts from a few days to few weeks in the future in show wideband signals corresponding to chaotic short period oscillations and to the residual prograde Chandler and annual oscillations (Kosek and Kalarus, 2017; Brzezinski et al., 2016).

The FTBPF+HT and NMWT were used to compute the amplitude coherence functions between two real-valued time series e.g. length of day and some chosen time series representing solar activity. This function is defined as the correlation coefficient between amplitude variations of oscillations in the two series as a function of their periods (Kosek and Popiński, 2017).

A comparison of predictive skills of two Polish systems designed for sea level change (Prognocean and Prognocean Plus) with the EU-recognized MyOcean solution was performed (Swierczynska et al., 2016). The system uses satellite altimetric time series. Prognocean and Prognocean Plus are based on the data-based prediction methods which use deterministic and deterministic-stochastic approaches. It has been found that Prognocean Plus reveals smaller prediction errors than MyOcean does, however, the variability is better resolved by the latter system.

A new method for estimating oceanic depth vs. oceanic age in geologic time has been elaborated. The method is based on modelling bathymetric curve and basic relationship between age and area. For relatively long periods, the model predicts depth as a function of age with comparable accuracy to already existing models (Niedzielski et al., 2016).

To provide fully operational service for real-time PPP (Precise Point Positioning), the short-term 5-hour forecasts of Zenith Total Delay (ZTD) time series were computed using the AR and autoregressive moving average (ARMA) models (Wilgan, 2015).

A non-parametric wavelet decomposition was employed to investigate the non-linear motion of GNSS stations (Bogusz, 2015).

Bogusz et al. (2015a) focused on the quasi-annual changes in GNSS-derived time series from PPP solution obtained by JPL (Jet Propulsion Laboratory) from more than 300 globally distributed IGS (International GNSS Service) stations. They divided all stations into clusters characterized by similar quasi-annual curve estimated with wavelet decomposition. They concluded that the maximum vertical amplitude was at the level of 14 mm with the minimum equal to 13 mm, giving the peak-to-peak position changes up to 27 mm.

The common mode errors (CME) were estimated for a set of ASG-EUPOS permanent GPS stations with the stacking approach. The reduction of standard deviation estimated for the GPS position time series was noticed when CME was removed (Bogusz et al. 2015b).

Gruszczynski et al. (2016) estimated the CME using Principal Component Analysis (PCA) and removed it from the GPS position time series. An average reduction in velocity uncertainty of 0.2 mm/year, with a maximum reduction of 0.8 mm/year was noticed when CME was removed.

Bogusz and Klos (2016) proposed to model the seasonal part of the GPS position time series including all periodicities from 1st to 9th of tropical year, including also residual Chandler period and fortnightly frequencies. They found that this assumption of seasonal signals helped to improve the velocity uncertainty of 56% comparing to the classical approach of annual plus semi-annual curves.

Bogusz et al. (2016) investigated the long-range dependence with Hurst exponent and detrended fluctuation analysis to be present in the GPS data.

Gruszczynska et al. (2016) used 18 GPS stations from the area of central Europe and modelled the time-varying seasonal signal with Singular Spectrum Analysis (SSA). They found that the SSA-derived curves are more correlated with original data than Least-Squares Estimated-curves, proving that the amplitude of seasonal curves is time-variable.

The common seasonal signal for a set of European stations using Multichannel Singular Spectrum Analysis (MSSA) was extracted. It was concluded that the MSSA-curves contain only time-varying and common seasonal signal and leave the station-specific part, local phenomena and power-law noise intact (Gruszczynska et al., 2017).

The character of noise for a set of 115 European GPS stations which contributed to the newest release of the International Terrestrial Reference Frame (ITRF), i.e., ITRF2014 with Maximum Likelihood Estimation (MLE) was estimated (Klos and Bogusz, 2017). It was found that stations situated in the Central and Northern Europe are characterized by the spectral index between flicker and random walk noise, while stations in Southern and Western Europe: between white and flicker noise.

Different noise models for the EPN (EUREF Permanent Network) GPS stations were compared. It was found that a combination of white plus power-law noise model is the preferred noise model for weekly time series (Klos et al., 2015a).

Klos et al. (2016) used 42 stations from the IGS network from Europe. They showed that the coloured noise between white and flicker noise with the amplitudes between 3 to 6 mm/year$^{\kappa/4}$ for horizontal components and between 6 to 15 mm/year$^{\kappa/4}$ for the vertical ones is the best to describe the stochastic part of data. They proved that the amplitudes and spectral indices of noise are reduced after performing a spatio-temporal filtering.

Klos et al. (2015b) examined data from 115 permanent GPS stations. They estimated the values of skewness and kurtosis and found that these values clearly indicate the discrepancies between the assumed normality of the GPS time series and the reality, mainly due to stochastic and/or deterministic parts that are still present in the data.

Klos et al. (2015c) examined the stochastic properties of 18 Polish permanent GPS stations that belong to the EPN (EUREF Permanent Network) using Maximum Likelihood Estimation (MLE) to indicate the influence of monuments on the character of GPS data.

Klos et al. (2015d) showed how important the pre-analysis of data is, when one aims at the most reliable estimates.

Klos et al. (2017) employed 376 permanent IGS stations, derived as the official contribution to the ITRF2014. They modelled the seasonal signals in environmental models using the Improved Singular Spectrum Analysis (ISSA) approach and subtracted it from GPS vertical time series to leave the noise character of the time series intact.

Kowalczyk and Bogusz (2017) described an idea of determining the height changes with a use of Vertical Switching Edge Detection (VSED) algorithm estimated from PPP solution provided by NGL (Nevada Geodetic Laboratory) for more than 50 permanent stations located in Latvia, Lithuania and northeastern Poland.

A summary of research activities concerning theoretical geodesy performed during 2011-2014 was presented by Borkowski and Kosek (2015).

Hourly time series of Earth rotation parameters from VLBI observations in a single-session strategy were determined. Then, the S1 (period of 24 h) amplitudes for these time series were determined. First, the sine- and cosine-amplitudes were fitted with a classical least-squares approach, and, as an alternative approach, the so-called "stacked" day was generated, which was then used to derive the amplitudes (Girdiuk et al., 2016).

Estimation of the free core nutation (FCN) period is a challenging prospect, due to the non-stationary characteristics of celestial pole offsets (CPO). Instead of the direct Fourier Transform (FT) approach, the FCN period is estimated by another direct method, i.e., the sliding-window complex least-squares fit method (SCLF). The estimated uncertainty of the FCN period falls from several tens of days to several days from the FT to the SCLF method, which suggests that the SCLF method may serve as an independent direct way to estimate the FCN period (Zhou et al., 2016).

The study (Xu and Zhou, 2015) firstly employs the calculation of base sequence with different length, in 1–90 day predictions of EOP, by the combined method of least squares and autoregressive model, and find the base sequence with best result for different prediction spans, which we call as "predictions over optimized data intervals". Compared to the EOP predictions with fixed base data intervals, the "predictions over optimized data intervals" performs better for the EOP prediction, and particularly promotes our competitive level in the international activity of EOP Combination of Prediction Pilot Project.

Artificial neural networks and fuzzy inference systems to predict the polar motion starting from daily to up to 1 year in future were applied. Such methods are capable to learn the nonlinear behavior of the polar motion and use it successfully for prediction (Kucak et al., 2016).

Abbondanza et al. (2015) estimated the uncertainty in the observed positions of geodetic stations by applying the three-corner-hat method to second-order statistics computed from time series of the observed positions of geodetic stations located at the same site.

Wu et al. (2015) used a Kalman filter to determine terrestrial reference frames from time series of the positions of stations in geodetic networks, the associated EOPs, and ground survey measurements.

Least-squares model of the deformation of the sea floor caused by an earthquake was fitted to the time series of GPS site displacement and oceanic tsunami measurements (Fu et al., 2017).

The period and Q of the Chandler wobble are estimated by finding those values that minimize the power in the Chandler frequency band of the difference between observed and modeled polar motion excitation functions. The observations of the polar motion excitation functions that we used are derived from both space-geodetic polar motion observations and from satellite laser ranging (SLR) and Gravity Recovery and Climate Experiment (GRACE) observations of the degree-2 coefficients of the Earth's time-varying gravitational field (Nastula and Gross, 2015).

The problem of detecting discontinuities is fundamental for reliably estimating velocities from GNSS station position time series. Discontinuities may be related to equipment changes, earthquakes or ununderstood causes. In Gazeaux et al. (2015), GNSS position time series of a group of nearby stations are automatically assessed for discontinuity detection using an advanced mathematic method based on dynamic programming. It allows simultaneously estimating station-specific trends, seasonal signals and a common ground motion signal between all series as well as individual offsets in all-time series. Bertin et al. (2017) have worked on a similar model but by investigating offsets at a station by station basis. A dictionary of function has been proposed to model station displacements as well as station discontinuities.

The time-variable Earth gravity field harmonics from the GRACE satellite mission are used to determine seasonal and non-seasonal scales of polar motion excitation functions from global geophysical fluids, and particularly from the portion from land-based hydrology. Hydrological excitation functions of polar motion from the mass of equivalent water thicknesses (EWT) derived gravimetrically from the solutions of three GRACE processing centers, the Center for Space Research (CSR), JPL and the GeoforschungsZentrum (GFZ), are mutually compared. Additionally, we estimate the hydrological signal as well in a different manner, as a residual from geodetically observed polar motion, by subtracting atmospheric (pressure + wind) and oceanic (bottom pressure + currents) contributions (Nastula et al., 2016).

The problem of least squares function fitting using the orthogonal system of trigonometric functions for the observation model comprising complex-valued deterministic function observations in equidistant time moments is considered, where the observed function values are corrupted by multiplicative errors (errors in amplitude and phase) as well as additive noise (Popiński, 2016).

In the paper by Van Camp et al. (2016a) we revealed from continuous gravity measurements the evapotranspiration of a forested ecosystem at the mesoscale (~50 ha), by stacking hourly values.

In the paper by Van Camp et al. (2016b) we showed that 7 calibrations of a superconducting gravimeter (SG) using an absolute gravimeter (each during a few day) are needed to ensure calibration of the SG at the 1 per mille level with 99% confidence. This was achieved through LSQ analysis and bootstrapping. The attenuation bias is discussed as well (case of noisy x and y time series in the LSQ process).

Van Camp et al. (2016c) using Allan deviation analyzed the signature of climate-induced inter-annual mass transfers on repeated absolute gravity measurements, everywhere in the world.

Meurers et al. (2016) revealed statistically significant temporal variations of M2 tidal parameters. This requires performing tidal analysis, which consist in LSQ adjustment of observed tides vs. predicted ones by ephemeris.

PICO G1.2 Sessions titled "Mathematical methods for the analysis of potential field data and geodetic time series" were organized at the European Geosciences Union General Assemblies in 2015, 2016 and 2017 in Vienna, Austria. A number of about 50 contributions in total were presented at these sessions.

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Joint Study Group 0.20: Space weather and ionosphere

Chair: *Klaus Börger (Germany)*

Members

- *Michael Schmidt (Germany)*
- *Jürgen Matzka (Germany)*
- *Mahmut Onur Karslioglu (Turkey)*
- *Eren Erdogan(Germany)*
- *Barbara Görres (Germany)*
- *Ehsan Forootan (United Kingdom)*
- *Johannes Hinrichs (Germany)*
- *Niclas Mrotzek (Germany)*

Activities and publications during the period 2015-2017

Introduction

The principal goal of the Joint Study Group 0.27 is to investigate the impact of an extreme and severe space weather event – referred to as Carrington event – on geodetic techniques or, in an extended view, on technical systems and applications such as navigation, satellites, communication etc.

Achieved results

Firstly, all members of the Joint Study Group have designed and completed a **work programme**. For this purpose we have collected and discussed different ideas. Each member has presented his expertise and resources, which can be used for the cooperation. Eventually, we have defined distinctive milestones. Furthermore, the program describes in detail different steps; the relations between the single work packages; a responsible person for the particular milestones and a time schedule.

We started to put the program into practice by installing a **website** to provide information to interested people and – being more important – to serve as a platform for an internal exchange of news as well as of data and results. This website is available under www.igg.uni-bonn.de/apmg.

Two members of the Joint Study Group have worked on the **characterization of a superstorm**. At a first glance, this seems to be an easy matter, but it is far from being trivial, since we have to consider very complex relationships. Therefore a thorough analysis of previous solar events is necessary to extract regularities and to transfer a Carrington-event in our present time. Meanwhile, we accomplished a "preliminary data set" simulating a severe solar storm. The data set contains Kp- and ap-values as well as F10.7-indices. The data is delivered in standard formats, which is WDC for the Kp- and ap-values and which is FLUXTABLE.TXT for F10.7. Work on this issue is still going on in order to find parameters that characterize a today's Carrington-event in the best way.

Based on this fundamental step, another group has started to work on producing **ionosphere states** for the period of this solar storm. Basically, it's possible to take the above mentioned parameters as input for ionosphere models and then to compute the ionosphere for specific dates. The problem is that the models often are not designed for extreme events, and therefore quite a lot of adaption is required to use the simulated data as input. A different approach uses the Principal Component Analysis (PCA) by inverting the method, whereby the principal component of the dominant mode is substituted by e.g. a time series of a Carrington-event describing F10.7-index. The work on this subject is still in progress.

According to the work programme, the Joint Study Group investigates the effects of a solar superstorm. In detail, this means to examine the impact of a solar event on satellite motion (1); the impact of a solar event on GNSS (especially navigation) (2); the impact of a solar event on signal propagation w.r.t. communication-techniques (3); the impact of a solar event on re-entry computations(4); the impact of a solar event on the life-time of space debris (5) and the impact of a solar event on the International Space Station (6).

We partly started with the studies (1) to (6), and in particular for (1) we can present first results. Again, it is very important to point out that a Carrington-event is a very extreme storm. This means, we expect clear effects, but as the results show, the impact is drastic. Figure 23 shows the atmospheric drag for a LEO (height of 300 km) as a function of time.

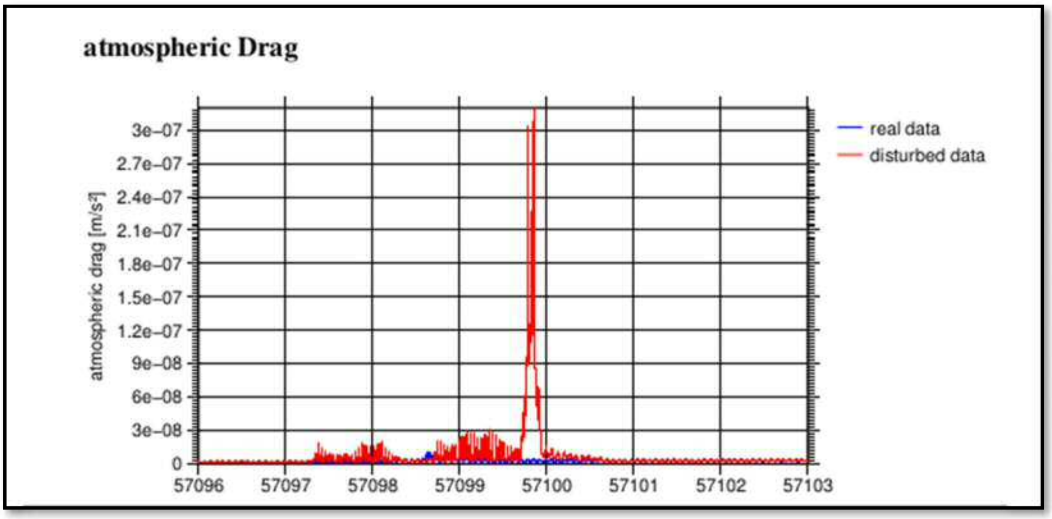

Figure 23: *Atmospheric drag for a test satellite*

The figure clearly shows, that the atmospheric drag enhances formidably. Consequently, the satellite experiences an enormous deceleration along track, when compared to an undisturbed satellite motion. Further computations show, that the satellite steadily gets lost and increasingly sinks.

These first results are very interesting and give a strong motivation for further and detailed analysis.

Further Activities

Members of the Joint Study Group visited conferences and workshops, in particular the "European Geosciences Union – General Assembly" in 2016 and 2017. Talks and posters were presented and some members had official positions like geodesy division president (Michael Schmidt) or session conveners. Furthermore Michael Schmidt has established a "Focus Area on Geodetic Space Weather Research" within GGOS.

Outlook

The Joint Study Group has done important and valuable work. The initiated investigations have to be continued and the whole work has to be aligned strictly to the goals of the work programme. For the year 2018 a workshop is planned. Of course, final results have to be found and these results are supposed to be presented in a paper.

Joint Study Group 0.21: Geophysical modelling of time variations in deformation and gravity

Chair: *Yoshiyuki Tanaka (Japan)*

Members

- *Shin-Chan Han (Australia)*
- *Guangyu Fu (China)*
- *Luce Fleitout (France)*
- *Johannes Bouman (Germany)*
- *Volker Klemann (Germany)*
- *Zdenêk Martinec (Ireland)*
- *Gabriele Cambiotti (Italy)*
- *Giorgio Spada (Italy)*
- *Masao Nakada (Japan)*
- *Jun'ichi Okuno (Japan)*
- *Yoshiyuki Tanaka (Japan)*
- *Taco Broerse (Netherlands)*
- *Riccardo Riva (Netherlands)*
- *Wouter van der Wal (Netherlands)*
- *Peter Vajda (Slovak Republic)*
- *Jose Fernandez (Spain)*
- *Benjamin Fong Chao (Taiwan)*
- *David Al-Attar (UK)*
- *Pablo J. Gonzalez (UK)*
- *Erik Ivins (USA)*

Activities and publications during the period 2015-2017

The research topics of the members, associated with time variations in deformation and gravity, cover a broad range. Here we report a brief summary of the selected results obtained by the members during 2015-2017. We set up a mailing list to share these results.

Earthquake and volcano problems

Han et al. (2016) revealed that the viscoelastic relaxation caused gravity change larger than the coseismic change for the 2006 Mw 8.3 thrust and 2007 Mw 8.1 normal fault earthquakes of the central Kuril Islands. Fuchs et al. (2016) obtained finely distributed fault slip model from GNSS and GRACE/GOCE satellite gravimetry for the coseismic and postseismic changes of the 2011 Tohoku-Oki earthquake. Broerse et al. (2015) analysed the GPS and GRACE data associated with the mantle relaxation due to the 2004 Sumatra-Andaman earthquake and found that the relaxation of the gravity field at GRACE resolution is much slower than what GPS observes over land in the back arc.

Crawford et al. (2017) developed a method that could be applied to both forward and inverse modelling of post-seismic deformation in a self-gravitating, heterogeneous and compressible Earth with a variety of linear and nonlinear rheologies. Tanaka et al. (2015) developed a method to compute viscoelastic postseismic deformation in a compressible, self-gravitating spherical Earth with 3D viscosity distributions.

Crustal deformations induced by earthquakes were modelled for the 2014 South Napa earthquake (Polcari et al., 2016) and the Illapel 2015 Mw8.3earthquake (Klein et al., 2017). Shirzaei et al. (2016) constructed a poroelastic model and explained the surface uplift and time-dependent seismic hazard caused by fluid injection in eastern Texas. Deformations associated with volcanic activities were also modelled for Canary Islands (Fernández et al., 2015), Mount Etna (Cannavò et al., 2015), Fogo volcano (González et al., 2015a) and Campi Flegrei (Tiampo et al., 2017). Fullea et al. (2015) modelled 3D lithospheric-uppermost mantle thermochemical structure beneath the Canary Islands by integrating geophysical and petrological data plus GOCE data. González et al. (2015b) detected and modelled hydrothermal pressurization before the 2010 Eruption of Mount Sinabung Volcano with InSAR data. Volcano gravimetry and related theoretical developments were carried out by Pohánka et al. (2015), Vajda et al. (2015), Vajda (2016) and Zahorec et al. (2016).

González et al. (2015c) published a book dedicated to the description of theoretical models, inversion techniques and their application to observational geodetic and geophysical data sets, including deformation and gravity data, in active geodynamic areas and affected by natural hazards.

Plate tectonics

Regional deformation associated with plate motion was studied by Palano et al. (2015), where a large-scale clockwise rotation of the Iberian Peninsula with respect to stable Eurasia was found for the first time. This pattern is considered to partly reflect the quasi-continuous straining due to viscous coupling of the NW Nubia and Iberian plate boundary. Elliott et al. (2016) found that the Gorkha earthquake ruptured the Main Himalayan Thrust fault and revealed the seismotectonics in the Kathmandu area with geodetic data, combined with geologic, geomorphological and geophysical analyses.

Loading problems

Klemann et al. (2015) provided an overview of the rheological features of the lithosphere and of the upper mantle with respect to deformations of the solid Earth in response to time-varying surface loading of an SNRVEI model. Spada (2017) gave a review regarding the basic elements of the GIA theory, emphasizing the connections with current sea-level changes observed by tide gauges and altimetry. Pail et al. (2017) provided an assessment of the goals that future space gravity missions should strive for, and articulate quantitatively what the resolution, repeat observation time and mission lifetime that would be required to advocate for a rational Earth observing space mission. Ocean and atmospheric sciences, solid earth deformation, including earthquakes and land hydrology and cryospheric mass balance were all addressed. The launch date for such an advanced future gravity mission, with a possible series of satellites, is after the year 2025.

Martinec et al. (2015) developed a method for computing the sensitivity of the GIA forward solution with respect to the Earth's mantle viscosity and the gradient of data misfit with respect to viscosity parameters. These methods enabled an efficient inverse modelling of GIA-related observations by avoiding redundant parameter estimates. Caron et al. (2017) used a Bayesian Monte Carlo approach with a Markov chain formalism to invert the global GIA signal simultaneously for the mechanical properties of the mantle including Maxwell and Burgers rheologies and the volumes of the ice sheets. Greff-Lefftz et al. (2016) used global seismic velocities and geoid, gravity and gravity gradients to constrain the viscosity profile within the mantle as well as the lateral density variations, based on a Monte Carlo search. Riva et al. (2016) showed how land ice wastage through the last century had caused non-linear, location dependent vertical land motion with several tenths of mm/yr over large parts of the continents.

Regional GIA was modelled by Klemann et al. (2015) for Laptev Sea and the East Siberian Sea, Wolstencroft et al. (2015) for Palmer Land, Konrad et al. (2015) and van der Wal et al. (2015) for Antarctica, and van der Wal and IJpelaar (2017) for Fennoscandia. Richter et al. (2016) used a 43 geodetic GNSS stations with sufficiently long time series to reconstruct the viscoelastic vertical deformation field associated with mantle/lithosphere uplift following the retreat of the Southern Patagonian Icefield from the times of the present day Little Ice Age into the present-day. Tanaka et al. (2015) modelled the glacial isostatic rebound in southeast Alaska and showed that neglect of compressibility could potentially underestimate the mantle viscosity by approximately 30%. Adhikari et al. (2017) used the horizontal deformation observed in continuous GPS data on bedrock to identify and quantify a wave of ice and water discharge in the Rink outlet glacier that occurs only during summers of nearly complete surface melting of southwestern Greenland.

Dill et al. (2015) investigated the influence of the elastic Earth properties on seasonal or shorter periodic surface deformations due to atmospheric surface pressure and terrestrial water storage variations, and showed that elastic response could become very sensitive to inhomogeneities in the crustal structure, when hydrological signals were localized. Adhikari et al. (2016a) derived a numerical global earth deformational model for use with short-term (elastic) responses with rotational feedback and sea-level responses that are gravitationally self-consistent. The key element that is new is that the traditional Love number-based calculations may be transformed and performed on a highly adaptable mesh system. Such a mesh can include model projections that run at high (2-km) resolution ice sheet models. This 2-km resolution is required for calculation of shear margin stress and strain-rates of fast-moving outlet glaciers whose interiors may be marine based. Han (2017) discovered and quantified seasonal mode of continental 3D deformation, induced by atmospheric and hydrological cycles.

Tides and Earth rotation

Chao and Ding (2016) theoretically estimated coseismic effects on global geodynamic quantities due to 43,304 major events that have occurred during 1976–2015. In particular, the polar motion excitations due to the few greatest earthquakes since 2004 have facilitated the abrupt turn of the pole path observed during these years. Lau et al. (2015) developed a generalized normal mode theory for the tidal response within the semi-diurnal and long-period tidal band, which involves a perturbation method that permits an efficient calculation of the impact of aspherical structure on the tidal response. Ding and Chao (2016) analysed global GPS and superconducting gravimeter observations to determine the lower-mantle anelasticity through the solution of the complex Love numbers at the Chandler wobble period. Cambiotti et al. (2016) investigated polar motion caused by not only coseismic deformation but also the seismic cycles at the global scale for the first time. Sun et al. (2016) developed a method to estimate C20 variations by combining the GRACE data with geophysical models including an ocean bottom pressure model and a glacial isostatic model (GIA). The result is available at http://www.citg.tudelft.nl/c20. Nakada et al. (2015) examined the geodetically derived rotational variations for the rate of change of degree-two harmonics of Earth's geopotential and true polar wander, combining a recent melting model of glaciers and the Greenland and Antarctic ice sheets. The GIA-induced J2 dot estimated from the observations was significantly different from the values adopted to infer the viscosity structure of the mantle in most previous studies. Adhikari and Ivins (2016b) used IERS data, global GRACE Release 05 fields, ancillary model and SLR-derived fields to determine that 3 geophysical components dominate the non-secular pole position at frequencies lower than that of the Chandler Wobble since 2002. The 3 components are Antarctic mass balance (at 400 km resolution), Greenland mass balance (400 km resolution), and total global water storage changes on land. Critical to the success of recovering the polar motion is to compute the rotational feedback, global Sea Level Equation, elastic field, gravity field and mass transport from land to ocean.

Highlights of our activities (selected)

Vajda et al. (2015) revealed the effect of the deformation-induced topo effect that consists of the Free Air Effect (FAE) and the Topographic Deformation Effect (TDE) which is the Newtonian attraction of the masses within the topographic surface deformation rind (volumetric domain between pre– and post–deformation topo surfaces). By numerical assessment they showed that the approximation of FAE based on the normal (theoretical) free air gradient (FAG) differed significantly from that based on the true (in situ) vertical gradient of gravity (VGG). They showed also that the TDE evaluated using high resolution high accuracy DEMs and numerical 3D Newtonian integration differed significantly from its approximation based on a Bouguer term. Work is in progress to analyze the DITE for various synthetic vertical displacement fields and to study other approximations of DITE.

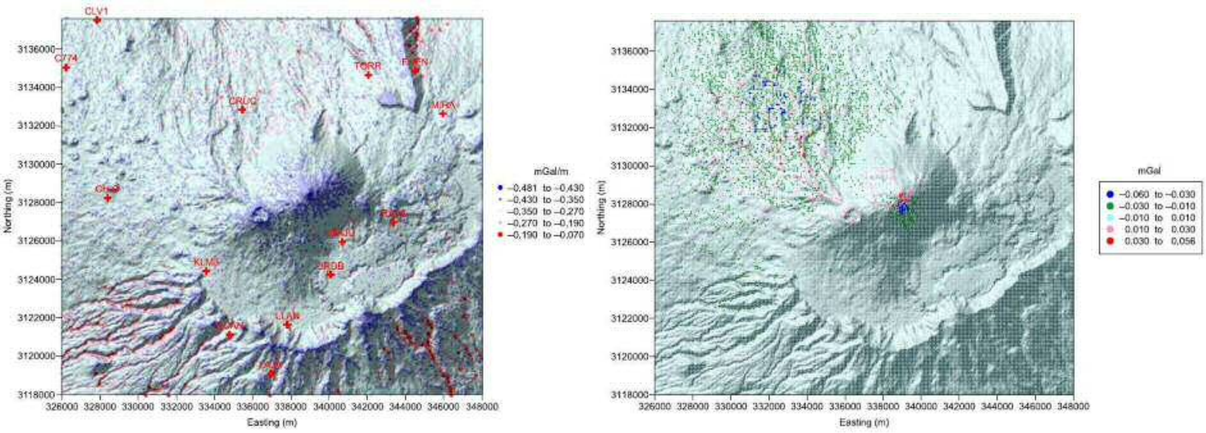

Figure 24: *Topographicaly predicted vertical gradient of gravity at CVC of Tenerife (left), differences between the TDE and its approximation by planar Bouguer effect at CVC of Tenerife (right)*

The benchmark study on solving the sea-level equation in GIA modelling is being supervised by Zdeněk Martinec (https://geofjv.troja.mff.cuni.cz/GIABenchmark/), where some of us are also participating in.

The sea-level load in GIA is described by the sea-level equation (SLE), which represents the mass redistribution between ice sheets and oceans on a deforming earth. Various levels of complexity of SLE have been proposed in the past. Despite various teams independently investigating GIA, there has been no systematic intercomparison amongst the solvers through which the methods may be validated. The goal of this activity is to present a series of benchmark experiments designed for testing and comparing numerical implementations of the SLE. The current benchmark uses an earth model for which Love numbers have been computed and benchmarked in Spada et al (2011). In spite of the significant differences in the numerical methods employed, the test computations performed so far show a satisfactory agreement between the results provided by the participants. The differences found can often be attributed to the different approximations inherent to the various algorithms.

Software development

Melini et al. (2015) developed a new tool for the computation of the Earth's response to surface loads (REAR). Bevis et al. (2016) reviewed methods to compute the geoelastic response to a disk load and provided a MATLAB function to implement this alhgorithm. Gao et al. (2017) opened a code for calculating viscoelastic postseismic deformation in a spherically symmetric, self-gravitating layered Earth.

Meeting and workshop organization (selected)

Wouter van der Wal organizes IAG Workshop on Glacial Isostatic Adjustment and Elastic Deformation, held on September 5-7, 2017, at Grand Hotel Reykjavik, Iceland (URL:http://www.polar.dtu.dk/english/Workshop-on-Glacial-isostatic-adjustment-and-elastic-deformation-2017). Gabriele Cambiotti proposed and organized the session for the 2016 AGU fall meeting, “Interrelation between seismicity and gravity field anomalies - New insights into earthquake rupture processes”. Jose Fernandez chaired the Session “Measuring changes at volcanoes using Geodesy: an update of methods and results” at AGU Fall Meeting, San Francisco, 14-18 December 2015".

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Joint Study Group 0.22: Definition and realization of global terrestrial reference frames

Chair: *Christopher Kotsakis (Greece)*

Members

- *Zuheir Altamimi (France)*
- *Michael Bevis (USA)*
- *Mathis Bloßfeld (Germany)*
- *David Coulot (France)*
- *Athanasios Dermanis (Greece)*
- *Richard Gross (USA)*
- *Tom Herring (USA)*
- *Michael Schindelegger (Austria)*
- *Manuela Seitz (Germany)*
- *Krzysztof Sośnica (Poland)*

Activities and publications during the period 2015-2017

The report was not submitted.

Global Geodetic Observing System

http://www.ggos.org

Chair: Hansjörg Kutterer (Germany)
Vice Chair: Ruth Neilan (USA)

Introduction

As the observing system of the IAG, GGOS facilitates a unique and essential combination of roles centering upon advocacy, integration, and international relations. GGOS also promotes high-level outcomes, such as the realization of the International Terrestrial Reference Frame through developing and maintaining working relationships among a variety of internal and external groups and organizations.

GGOS Structure

The GGOS structure is illustrated in Figure 1, below. The decision-making entities are the Consortium, the Coordinating Board and the Executive Committee. Standing Committees, the thematic working bodies of GGOS, are distributed over two bureaus, the Science Panel and the Focus Areas as well as affiliated organizations. Communications and outreach, including the new unified GGOS website are managed by the Coordinating Office. Recent changes in GGOS organizational nomenclature were implemented at the advice of the IAG, specifically the former items called "Themes" have been renamed to "Focus Areas," and similarly, the former "Working Groups" were re-titled to "Standard Committees" in 2016. In 2017 a new Focus Area "Geodetic Space Weather Research" was added.

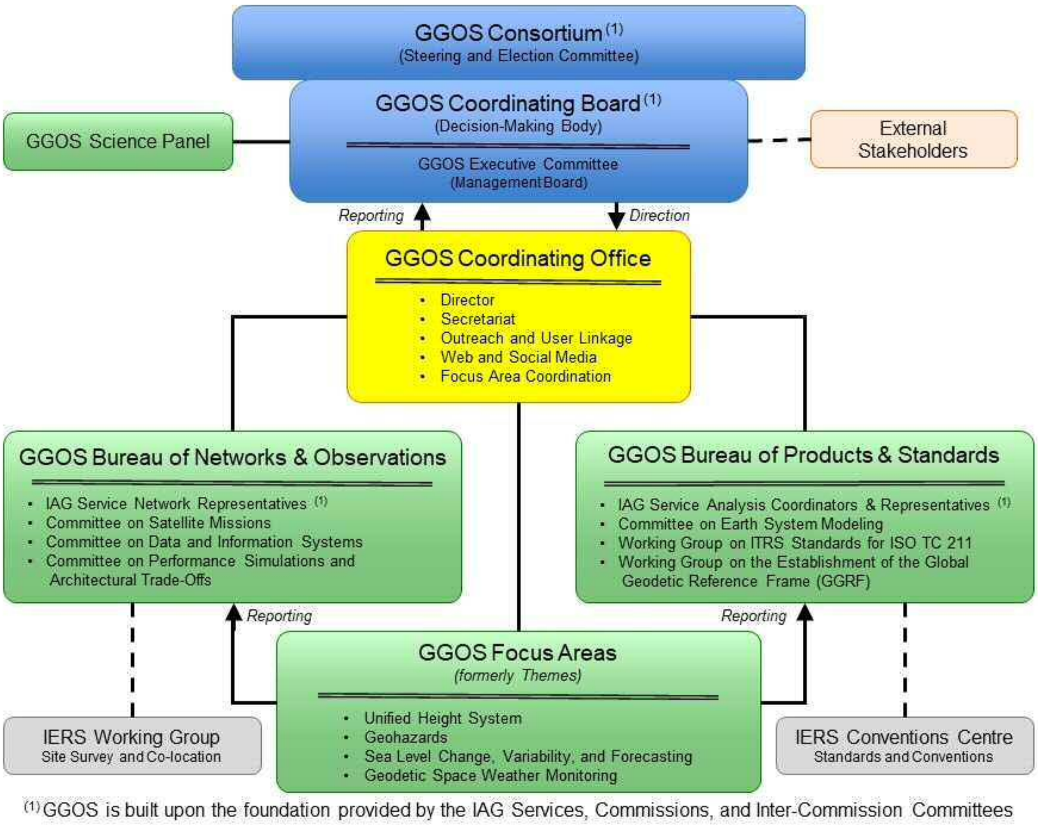

Figure 1. Organization chart of GGOS, as of mid-2017.

Overview

The period from 2015-2017 was an active time of growth and organization within GGOS. A summary of these activities, by component, is below. A key element touching on all elements of this overview was the revision and update of the GGOS Terms of Reference (ToR) in 2015 to reflect developments and strategic direction since the original ToR publication in 2011.

Consortium

The GGOS Consortium functions as the large steering committee and collective voice of GGOS, and is comprised of two members from each IAG service, commission, and inter-commission committee. According to the GGOS ToR, the Consortium membership is reviewed and refreshed every four years, which took place coincident to the 2015 IUGG General Assembly. The current members of the GGOS Consortium as result of this nomination procedure are compiled in the following table. According to the ToR, only the GGOS Consortium is allowed to accept new members. Because of retirement and changes in the services the table must be revised in September 2017.

The presiding chair of GGOS is also the chair of the GGOS Consortium. As the GGOS Consortium is supposed to meet annually, the meetings took place at the GGOS Days 2015 (Frankfurt am Main, Germany), 2016 (Boston, Massachusetts, USA) and will take place September 2017 (Jeju, South Korea).

Table 1: Members of the GGOS Consortium, as of May 2017

Services	**Name**	**Title**
GGOS	Hansjörg Kutterer	GGOS Chair
International Gravimetric Bureau (BGI)	Sylvain Bonvalot	Director
International Gravimetric Bureau (BGI)	Sean Bruinsma	Designated GGOS Representative
Bureau international des poids et mesures, BIPM	Felicitas Arias	Director BIPM Time Department
Bureau international des poids et mesures, BIPM	Gérard Petit	Principal Physicist BIPM Time Department
International Centre for Global Earth Models (ICGEM)	Franz Barthelmes	Director
International Doris Service (IDS)	Laurent Soudarin	Director
International Doris Service (IDS)	Pascal Willis	Chair
International Earth Rotation and Reference Systems Service (IERS)	Daniela Thaller	Director of the Central Bureau
International Geoid Service (IGeS)	Mirko Reguzzoni	President
International Geoid Service (IGeS)	Giovanna Sona	Director
International Geoid Service (IGeS)	Urs Marti	Designated GGOS Representative
International Geoid Service (IGeS)	Jianliang Huang	Designated GGOS Representative
International Gravity Field Service (IGFS)	Riccardo Barzaghi	Chair
International Gravity Field Service (IGFS)	Steve Kenyon	Director of the Central Bureau
International GNSS Service (IGS)	Ruth Neilan	Director
International GNSS Service (IGS)	Gary Johnston	Chair

The International Laser Ranging Service (ILRS)	Giuseppe Bianco	Chair of Governing Board
The International Laser Ranging Service (ILRS)	Erricos Pavlis	Chair of Analysis Working Group
International VLBI Service for Geodesy and Astrometry (IVS)	Axel Nothnagel	Chair
International VLBI Service for Geodesy and Astrometry (IVS)	Dirk Behrend	Coordinating Center Director
Permanent Service for Mean Seal Level (PSMSL)	Lesley J. Rickards	Director
Permanent Service for Mean Seal Level (PSMSL)	Mark Tamisiea	Designated GGOS Representative
International Geodynamics and Earth Tides Service (IGETS)	Jean-Paul Boy	Director
International Geodynamics and Earth Tides Service (IGETS)	Christoph Foerste	Designated GGOS Representative
International Geodynamics and Earth Tides Service (IGETS)	Alexander Kopaev	Designated GGOS Representative
Commission 1: Reference Frames	Geoff Blewitt	President
Commission 1: Reference Frames	Johannes Böhm	Vice-President
Commission 1: Reference Frames	Tonie van Dam	Designated GGOS Representative
Commission 2: Gravity Field	Roland Pail	President
Commission 2: Gravity Field	Jin Shuanggen	Vice-President
Commission 3: Earth Rotation and Geodynamics	Manabu Hashimoto	President
Commission 3: Earth Rotation and Geodynamics	Chengli Huang	Vice-President
ICCT	Pavel Novák	President
ICCT	Thomas Hobiger	Vice-President
ICCT	Dimitrious Tsoulis	Designated GGOS Representative

Coordinating Board

After finalizing the composition of the GGOS Consortium the members of the GGOS Coordinating Board (CB) were elected, also on a four-year cycle. The GGOS CB acts as the decision-making body of GGOS. The present members of the GGOS CB are indicated in the following table.

A new Focus Area in "Geodetic Space Weather Research" was added in 2017. The GGOS CB meets twice a year on the occasion of the EGU meeting in Vienna and the GGOS Days at several locations, Frankfurt 2015 and Cambridge/Boston 2016 as well as Jeju 2017 in September.

Position	Rights	Name
GGOS Chair	voting	Hansjörg Kutterer
GGOS Vice-Chair	voting	Ruth Neilan
Chair of GGOS Science Panel	voting	Richard Gross
Director of Coordinating Office	voting	Guenter Stangl
Director of Bureau of Networks and Communication	voting	Michael Pearlman
Director of Bureau of Standards and Conventions	voting	Detlef Angermann
IAG President	voting	Harald Schuh

Service representative	voting	Riccardo Barzaghi
Service representative	voting	Ruth Neilan
Service representative	voting	Christoph Foerste
Service representative	voting	Urs Marti
IAG Commissions Representative	voting	Pavel Novák
IAG Commissions Representative	voting	Roland Pail
Member-at-Large	voting	Ludwig Combrinck
Member-at-Large	voting	Luiz Poulo Souto Fortes
Member-at-Large	voting	Gary Johnston
Chair of GGOS Standard Committee on Satellite and Space Missions (SI)	non-voting	Roland Pail
Chair of GGOS Standard Committee on Data and Information Systems (DM)	non-voting	Guenter Stangl
Chair of GGOS Standard Committee on Contribution to Earth System Modelling (EM)	non-voting	Maik Thomas
Chair of GGOS Standard Committee on Performance Simulations and Architectural Trade-Offs (PLATO), a Joint Working Group with IAG Sub-Commission 1.2	non-voting	Daniela Thaller
Chair of GGOS Standard Committee on ITRS Standards	non-voting	Claude Boucher
Chair of Joint Working Group: "Establishment of the Global Geodetic Reference Frame (GGRF)"	non-voting	Urs Marti
Lead of Focus Area Unified Height System [UH]	non-voting	Laura Sanchez
Lead of Focus Area Natural Hazards [NH]	non-voting	John LaBrecque
Lead of Focus Area Understanding and Forecasting Sea-Level Rise and Variability [SL]	non-voting	Tilo Schöne
Lead of Focus Area Geodetic Space Weather Research	non-voting	Michael Schmidt
GGOS Portal Manager	non-voting	Guenter Stangl
Immediate Past Chair of the CB	non-voting	---
Representative of the GIAC/GIC*	non-voting	Per Erik Opseth

*Please note that GIAC was terminated end of 2016, so all references to GIAC or GIC are purely for historical purposes.

Executive Committee

Based on the members of the GGOS CB the members of the GGOS Executive Committee (EC) were nominated by the GGOS chair and approved by the GGOS CB. The present members of the GGOS EC are compiled in the following list. The role of the GGOS EC is to serve at the direction of the CB to accomplish day-to-day activities of GGOS tasks. The GGOS EC has had regular telecons on an approximately monthly basis since July 201,1 continuing the sequence of telecons under the previous structure.

Name	**Role**
Hansjörg Kutterer	GGOS Chair
Ruth Neilan	GGOS Vice-Chair
Guenter Stangl	Director of Coordinating Office
Michael Pearlman	Director of Bureau of Networks and Communication

Detlef Angermann	Director of Bureau of Standards and Conventions
Riccardo Barzaghi	Voting member
Pavel Novák	Voting member
Richard Gross	Chair of Science Panel, ex-officio permanently invited guest
Richard Gross	Representative of the President of the IAG, ex-officio permanently invited guest
Per Erik Opseth	Chair of GIAC, ex-officio invited guest
Allison Craddock	Former director of Coordinating Office, invited guest

Coordinating Office

Leadership of the GGOS Coordinating Office transitioned from Giuseppe Bianco of Agenzia Spaziale Italiana (Italian Space Agency, ASI), Italy, to Allison Craddock of Bundesamt für Kartographie und Geodäsie (Federal Agency for Cartography and Geodesy, BKG), Germany, in 2015. In 2016, Guenter Stangl of Bundesamt für Eich- und Vermessungswesen, (Federal Agency for Metrology and Surveying, BEV), Austria assumed the role and oversaw the complete transition of the CO to BEV. An overview of the main contacts is shown in the Figure 2 below.

A regular presence at the major conferences of geosciences, AGU and EGU, as well as GEO, was established. There was also a presence with presentations, posters and exhibition at the IUGG 2015, and will be at IAG/IASPEI in July 2017. Starting in May 2017, a GGOS page will be included in the IAG newsletter at least once a year.

The website http://www.ggos.org was shifted in May 2017 from ASI to BEV. The new GGOS website will be built from scratch, while maintaining key items and historical resources. This was agreed upon in August 2016 between the former GGOS CO director and the new one. The webpages are checked and renewed, partially by the different GGOS components, and partially by the GGOS CO. The next steps planned are to add online access to GGOS metadata as well as links to observations and products. The GGOS social media presence was initiated, with a twitter account @IAG_GGOS.

Figure 2. Organizational chart of GGOS external relations.

GGOS Science Panel

Chair: *R. Gross (USA)*

Members:

- G. Blewitt (USA)
- J. Bogusz (Poland)
- R. Gross (USA)
- T. Gruber (Germany)
- B. Heck (Germany)
- K. Heki (Japan)
- J. LaBrecque (USA)
- U. Marti (Switzerland)
- M. Merrifield (USA)
- M. Rothacher (Switzerland)
- Z.-K. Shen (China)
- J. Wickert (Germany)
- P. Wielgosz (Poland)

Purpose and Scope

The GGOS Science Panel is a multi-disciplinary group of experts representing the geodetic and relevant geophysical communities that provides scientific advice to GGOS in order to help focus and prioritize its scientific goals. The Chair of the Science Panel is a member of the Coordinating Board and a permanent guest at meetings of the Executive Committee. This close working relationship between the Science Panel and the governance entities of GGOS ensures that the scientific expertise and advice required by GGOS is readily available.

Activities and Actions

The objectives and tasks of the GGOS Science Panel are given in its 2017-2018 Implementation Plan. The Science Panel provides support to GGOS. During 2015-2017, this support included participation in Consortium, Coordinating Board, and Executive Committee meetings and conference calls. The Science Panel has been actively promoting the goals of GGOS by helping to organize GGOS sessions at major scientific conferences. During 2015-2017, GGOS sessions have been organized at:

- 2015 Asia Oceania Geosciences Society Annual Meeting in Singapore
- 2015 European Geosciences Union General Assembly in Vienna
- 2016 European Geosciences Union General Assembly in Vienna
- 2017 European Geosciences Union General Assembly in Vienna
- 2015 American Geophysical Union Fall Meeting in San Francisco
- 2016 American Geophysical Union Fall Meeting in San Francisco
- 2017 Japan Geophysical Union – American Geophysical Union Joint Meeting in Chiba, Japan

In addition to helping organize sessions at scientific conferences, the GGOS Science Panel also organizes topical science workshops in order to foster discussion about the geodetic observations and infrastructure required by different scientific disciplines. One such workshop was organized during 2015-2017:

International Symposium on Geodesy, Astronomy, and Geophysics in Earth Rotation (GAGER2016), Wuhan, China; 19-23 July 2016

The rotation of the Earth varies continuously, in both its rate of rotation and in the orientation of its axis with respect to either crust-fixed or space-fixed reference frames. Its study links together the fields of Geodesy, Astronomy and Geophysics. In this Symposium, over 50 participants from Asia, Europe, and the Americas met in Wuhan, China to assess our current ability to observe the Earth's time varying rotation, to assess our current understanding of the causes of the observed variations, to assess the consistency of Earth rotation observations with global gravity and shape observations, to explore methods of combining Earth rotation, gravity, and shape observations, and to identify improvements in the global geodetic observing system needed to further our understanding of the Earth's variable rotation. Peer-reviewed proceedings of the Symposium will be published as a special issue of *Geodesy and Geodynamics*.

Objectives and Planned Efforts for 2017-2019 and Beyond

During 2017-2019 the Science Panel will continue to participate in Consortium, Coordinating Board, and Executive Committee meetings and conference calls. In addition, the Science Panel will continue to help organize GGOS sessions at conferences and symposia including:

- American Geophysical Union Fall Meetings
- Asia Oceania Geosciences Society Annual Meetings
- European Geosciences Union General Assemblies
- International Association of Geodesy General and Scientific Assemblies

The Science Panel will also continue to organize topical science workshops in order to determine the requirements that different scientific disciplines have for geodetic data and products.

With the GGOS Bureau of Products and Standards, the Science Panel will help conduct a Gap Analysis to identify the gap between the data and products provided by the IAG and the needs of the user community. As part of this analysis, a list of Essential Geodetic Variables (EGVs) will be compiled along with observational requirements on those variables. This list of EGVs and their observational requirements can then be used to determine requirements on derived products like the terrestrial reference frame. This activity is part of the Science Panel's contribution to updating the GGOS2020 book.

GGOS Bureau of Networks and Observations

Director: *Mike Pearlman (USA)*

Prepared by: *Michael Pearlman, Carey Noll, Erricos C. Pavlis, Chopo Ma, Ruth Neilan, Frank Lemoine, Daniela Thaller, Guenter Stangl, Jürgen Müller, and Sten Bergstrand*

Membership

Standing Committees affiliated with this Bureau:
- GGOS Standing Committee on Satellite Missions
- GGOS Standing Committee on Data and Information Systems
- GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO)
- IERS Working Group on Survey and Co-location

Associated Members and Representatives:
- Director (Mike Pearlman/CfA USA)
- Secretary (Carey Noll/NASA USA)
- Analysis Specialist (Erricos Pavlis/UMBC USA)
- IERS Representative (Sten Bergstrand/SP Sweden)
- A representative from each of the member Services:
  - IGS (Ruth Neilan/JPL USA, Steve Fisher/JPL USA)
  - ILRS (Giuseppe Bianco/ASI Italy, Wu Bin/SHAO China)
  - IDS (Jérôme Saunier/IGN France, Pascale Ferrage/CNES France)
  - IVS (Hayo Hase/BKG Germany, Chopo Ma/NASA USA)
  - IGFS (Riccardo Barzaghi/PM Italy, George Vergos/UT Greece)
  - PSMSL (Lesley Rickards/BODC UK, Tilo Schone/GFZ Germany)
- A representative from each of the member Standing Committees:
  - PLATO (Daniela Thaller/BKG Germany, Benjamin Maennel/GFZ Germany)
  - Data and Information (Günter Stangl/OEAW Austria, Carey Noll/NASA USA)
  - Satellite Missions (Jürgen Müller/IfE Germany, Roland Pail/TUM Germany)
  - IERS Working Group on Survey Ties and Co-location (Sten Bergstrand/SP Sweden, John Dawson/GA Australia)

Activities, Actions, and Publications during 2015-2017

The Bureau

- Continued to provide a forum for the Services and Standing Committees/Working Groups to share and discuss plans, progress, and issues, and to develop and monitor multi-entity efforts to address GGOS requirements; meetings are held in conjunction with AGU and EGU each year; material from the meetings are posted on the GGOS website (http://www.ggos.org/Components/BNC/BNChome.html).
- Continued the Bureau's "Call for Participation in the Global Geodetic Core Network: Foundation for Monitoring the Earth System" and work with new potential groups interested in participating; a total of 19 submissions have been received covering 114 sites that included legacy core sites, legacy/new technology co-location sites, core and co-location sites under development, and sites offered for future participation; a summary of the CfP responses is available on the Bureau's website: (http://192.106.234.28/Components/BNC/update%20Apr2013/GGOS_CfPResponseSummaries_20150106.pdf). A number of other new stations will join once they are operational.

- Continued to advocate for new and increased network participation, encouraging formation of new partnerships to develop new sites, monitored the status of the networks; held meetings and communications with representatives from Russia, Italy, Brazil, Japan, Spain, France, and Saudi Arabia to discuss implementation of new stations and upgrade of legacy stations.
- Supported efforts for the integration of various ground observation networks within the GGOS affiliated Network; continued to maintain and update the “Site Requirements for GGOS Core Sites” document (with the IAG Services); the next major step will be to include the requirements for the gravity field once it is fully documented by the IGFS and the IGRF working group; Work with the IGFS in the definition of its requirements.
- Continued to promote and advocate for GGOS and the GGOS integrated global geodetic ground-based infrastructure through talks and posters at AGU, EGU, AOGS, APSG (China), JpGU-AGU, IAG, etc. and meetings and special presentations at GSI (Japan), IMPE (Brazil), IAP (Russia) etc.; supported efforts to integrate relevant parameters from other ground networks (gravity field, tide gauges, etc.) into the GGOS network to support GGOS requirements.
- Continued to maintain and update the inventory/repository of current and near-future satellite missions, highlighting those of most interest to GGOS; The current version should be online in mid-2017; continued advocating for new advocating new missions; wrote letters of support for the E-GRASP/Eratosthenes proposals; Need to stress greater cooperation between the PLATO and Missions Standing Committees. More details are provided in the Missions Standing Committee section below .
- Provided simulations and analyses to estimate how the data products will improve over time as the infrastructure improves. The next survey of current and projected network station capabilities will be undertaken in the second half of 2017. The results from the survey will be used to project network data quality capability 5 and 10 years ahead. Simulations on the e-GRASP/Eratosthenes mission and other co-location missions to strengthen the case for support and for network planning. More detail is provided in the Standing Committee on Performance Simulations & Architectural Trade-Offs (PLATO) section below.
- Continued development and implementation of a GGOS metadata system in two stages: a stage-one scheme (hosted by CDDIS) for GGOS and GGOS-relevant data products planned for demonstration by the end of 2017, and a longer term, stage-two implementation, for the full GGOS requirements including site and instrument information, based on an XML metadata scheme under development by the Geoscience Australia, UNAVCO, and the IAG. Additional details are provided in the Data and Information Standing Committee section below.
- Continued working on the establishment of a common terminology for all space geodesy techniques, a terminology that is also valid outside the space geodetic community; the DORIS community has adapted a common terminology, and improved its surveying procedures as well as communication of the results. The IGS terminology has done the same, but there are differences among the techniques; continued working on outreach to increase local survey participation and standardization. More details are provided in the IERS Working Group on Survey Ties and Co-Location section below.

Related Bureau Documentation

As part of the network activity, the Bureau has facilitated the creation of several key documents:

- “GGOS Site Requirements for Fundamental Stations” document: http://192.106.234.28/Components/BNC/update%20Apr2013/GGOS_SiteReqDoc_1207.pdf
- A guidelines document for site characterization of the GGOS network sites was developed, “The Global Geodetic Core Network: Foundation for Monitoring the Earth System”: http://192.106.234.28/Components/BNC/update%20Apr2013/GGOS_sitecategorization.pdf

- A plan to define the process by which GGOS determines the extent of the needed infrastructure, including the scope and specification of the network, conditioned on the existing or plausible technology available, "GGOS Infrastructure Implementation Plan": http://192.106.234.28/Components/BNC/GGOS_Infrastructure_Plan_V3_130321.pdf
- A plan to assess the current and future plans for a GGOS core network, including projections five to ten years in the future, "Space Geodesy Network Model": http://192.106.234.28/Components/BNC/candidatesites_130122.pdf
- Documents developed within the context of NASA's Space Geodesy Project, evaluating several sites as potential core sites; these documents are available from the SGP website at: http://space-geodesy.gsfc.nasa.gov/publications/papers.html
- A summary report issued from the TLS (Terrestrial Laser Scanner) Workshop that was held at NASA GSFC, September 08-10, 2008: http://192.106.234.28/Components/BNC/Summary%20report%20from%20the%20TLS%20(Terrestrial%20Laser%20Scanner).pdf

Websites

http://www.ggos.org/Components/BNC/BNChome.html
http://www.ggos-portal.org/lang_en/GGOS-Portal/EN/Themes/SeaLevel/seaLevel.html

Publications and Presentations

M. Pearlman, C. Ma, C. Noll, E. Pavlis, H. Schuh, T. Schoene, R. Barzaghi, S. Kenyon, "The GGOS Bureau of Networks and Observations and an Update on the Space Geodesy Networks", Abstract EGU2015-7420, presented at EGU 2015 General Assembly, April 13-17, 2015, Vienna, Austria, April 12-17, 2015.

M. Pearlman, E. Pavlis, C. Ma, C. Noll, D. Thaller, B. Richter, R. Gross, R. Neilan, J. Mueller, R. Barzaghi, S. Bergstrand, J. Saunier, M. Tamisiea, "Update on the Activities of the GGOS Bureau of Networks and Observations", Abstract No. 10095. Presented at European Geosciences Union General Assembly, April 17-22, 2016.

C. Noll, "GGOS: Global Geodetic Observing System", presented at 2016 WDS Members' Forum, Denver, Colorado, September 11, 2016.

G. Stangl, C. Noll, "GGOS: The Global Geodetic Observing System" (poster), presented at 2016 WDS Members' Forum, Denver, Colorado, September 11, 2016.

M. Pearlman, C. Noll, C. Ma, E. Pavlis, R. Neilan, J. Saunier, T. Schoene, R. Barzaghi, D. Thaller, S. Bergstrand, J. Mueller, "The GGOS Bureau of Networks & Observations: An Update on the Space Geodesy Network & the New Implementation Plan for 2017-2018", Abstract No. EGU2017-10698, presented at European Geosciences Union General Assembly 2017, Vienna, Austria, April 24-28, 2017.

M. Pearlman, H. Schuh, D. Angermann, C. Noll, "The Global Geodetic Observing System (GGOS) – Its Role and Its Activities". JpGU-AGU Joint Meeting, Chiba, Japan, May 22-26, 2017.

M. Pearlman, C. Ma, R. Neilan, C. Noll, E. Pavlis, J. Saunier, T. Shoene, R. Barzaghi, D. Thaller, S. Bergstrand, J. Mueller, "The GGOS Bureau of Networks and Observations: Activities and Plans". Presented at IAG-IASPEI, Kobe, Japan, July 30-August 04, 2017.

GGOS Standing Committee on Satellite Missions

Chair: *Jürgen Müller (Germany)*
Co-Chair: *Roland Pail (Germany)*

Members

Besides Chair and Co-Chair, CSM has quite an open team of members, associate members and guests to work on the various CSM tasks and to provide material for the website, presentation material, and other documentation. CSM has 1 or 2 meetings per year. The main work, however, is done via email exchange.

Purpose and Scope

The Committee on Satellite Missions (CSM), formerly GGOS Satellite Mission Working Group, was established in December 2008, under the lead of C.K. Shum. In December 2010, Isabelle Panet was appointed as new Chair, in December 2013 Roland Pail took over the role of the CSM Chair, followed by Jürgen Müller in December 2015.

The purpose and scope of CSM is the information exchange with satellite missions as part of the GGOS space infrastructure, for a better ground-based network response to mission requirements and space-segment adequacy for the realization of the GGOS goals. New space missions shall be advocated and supported, if appropriate.

CSM has been set-up as an international panel of experts, with consultants of national and international space agencies.

Satellite missions are a prerequisite for realizing a global reference for any kind of Earth observation. They are the key for monitoring change processes in the Earth system on a global scale with high temporal and spatial resolution. Therefore, beyond purely scientific objectives they meet a number of societal challenges, and they are an integral part of the GGOS infrastructure and essential to realize the GGOS goals. The role of CSM is to monitor the availability of satellite infrastructure, to propose and to advocate new missions or mission concepts, especially in case that a gap in the infrastructure is.

Activities and Actions

- New chair (Jürgen Müller) took over in December 2015.
- In 2016, the number of active committee members has been revised.
- An inventory of the GGOS satellite infrastructure has been collected, including some missions that only touch the GGOS needs. The list will be refined and updated in the 2017/2018 timeframe.
- A preliminary list of satellite contributions to fulfill the GGOS 2020 goals has been prepared. The list will be refined and updated in the 2017/2018 timeframe.
- In 2015 chaired by CSM (Roland Pail), the "Science and user requirements document for future gravity field missions" has been finalized and published, see www.dgk.badw.de/fileadmin/docs/b-320.pdf
- In 2016, CSM has contributed to ESA’s Earth Explorer 9 call by providing support letters (from GGOS chair) and by actively acting in the proposers’ teams (individual CSM members) of the two planned geodetic missions
    - E-GRASP/Eratosthenes (co-location of geodetic transmitters in space)
    - E.motion2 (gravity field mission)

- Close cooperation exists with the Bureau of Standards and Products, and the Sub-Commissions 2.3 and 2.6 of IAG. Additionally, there are strong interfaces to national and international space agencies.

Objectives and Planned Efforts for 2015-2017 and Beyond

1. Contribute to a CSM section on the GGOS website. A new website is available since early 2017. Here, close exchange with the GGOS Communication Office is planned.
2. Revise and maintain the inventory/repository of current and near-future satellite missions. A reduced list with the most important missions has been prepared in spring 2017 and is revised now by the CSM members. It shall continuously be extended and updated.
3. Evaluate and refine contributions of current and near-future missions to the GGOS 2020 goals. A revised version with the most important contents has been prepared in spring 2017 and is revised now by the CSM members. It shall continuously be extended and updated.
4. Support advocating new missions. New calls are expected in 2017/2018. Currently, the ESA EE9 mission proposal E-GRASP/Eratosthenes is supported.
5. Interface with other GGOS components to identify critical gaps in the satellite infrastructure and advocating new missions. Here, regular exchange is planned with PLATO, e.g., to stimulate dedicated simulations to better understand and overcome shortcomings with respect to the GGOS 2020 goals.
6. Support GGOS positions in preparation to CEOS/GEO meetings.
7. Support the Executive Committee and the Science Committee in the GGOS Interface with space agencies.

Most of the CSM tasks are ongoing activities. These tasks will require interfacing with other components of the Bureau; especially the ground networks component, the simulation activity (PLATO) as well as the Bureau of Standards and Products.

Website

http://www.ggosdays.com/en/bureaus/bno/committee-satellite-missions/

Publications and Presentations

Pail, R.; IUGG, Writing Team: Observing Mass Transport to Understand Global Change and Benefit Society: Science and User Needs, An international multi-disciplinary initiative for IUGG; in: Pail, R. (eds.) Deutsche Geodätische Kommission der Bayerischen Akademie der Wissenschaften, Reihe B, Vol. 2015, Heft 320, Verlag der Bayerischen Akademie der Wissenschaften in Kommission beim Verlag C.H. Beck.

GGOS Standing Committee on Data and Information Systems

Chair: *Guenter Stangl (Austria)*
Co-Chair: *Carey Noll (USA)*

Purpose and Scope

Develop a metadata strategy for all ground-based measurement techniques and data products that provides discoverability and interoperability, is easily transferable via web services, and is based on internationally recognized data exchange methods; the plan is to implement a metadata scheme in two stages: a stage-one scheme for GGOS and GGOS relevant data products and a longer term, stage-two scheme for the full GGOS requirements

The current focus of the WG is on developing standards for metadata that can be utilized by the space geodesy community. Metadata typically encompass critical information about the measurements that are required to turn these measurements into usable scientific data. Metadata also includes information that supports data management and provides a foundation for data discovery. Data centers extract metadata from incoming data sources and also augment that metadata with information from other sources. It is typical for data centers to store the metadata in databases in order to manage the data in their archives and to distribute both data and metadata to data users. Metadata can further be utilized by data discovery applications to allow users to find datasets of interest. In order to be effective, metadata need to be simple to generate and maintain. They must be consistent and informative for the archivist and the user.

GGOS is seeking a metadata schema that can be used by all of its elements for standardized metadata communication, archiving, and retrieval. First applications would be automated distribution of up-to-date stations configuration and operational information, data archives and catalogues, and procedures and central bureau communication. Several schemas that show promise have been under development by SOPAC (Scripps), GML (Australia/NZ), etc. The intent is that data need be entered only from an initial source (a station, a Data Center, an Operations Center, data products, etc.) and would then flow to and be integrated into those metadata files where users would have access. The plan is to organize a meeting, probably in early August at UNAVCO in Boulder, for representatives from the Services, the Data Centers, the Science Community, etc. to give each of the schema developers an opportunity to preach his wears and allow discussion on the pros and cons of each.

The objective is to try to come to closure on a schema that we could as a community adopt for general implementation. Groups would not be obligated to a rapid implementation schedule, but would commit to the agreed schema when they are ready to begin the process.

Activities and Actions

- CDDIS continues to construct collection-level metadata records for implementation in NASA EOSDIS (CMR)
- IGS continues development of Site Log XML metadata (lead: Fran Boler/UNAVCO)
    - Geosciences Australia (GA) has released GeodesyML
        - Implements an application schema for the Site Log XML metadata
    - Several IGS data centers and groups have worked with this schema and are implementing/refining
    - Use Cases are slowly being assembled
    - Software tools for text site log to XML site log conversion are being developed and will be available to all

Objectives and Planned Efforts for 2015-2017 and Beyond

- Adopt and implement a metadata system to provide access to GGOS relevant data products (December 30, 2017)
    - Define the data product requirements for the GGOS relevant metadata (February 15, 2017)
    - Present concept and plan for implementation (EGU 2017 and/or the GGOS CB meeting in April 2017)
    - Status report (IAG Assembly or other venue in July 2017)
    - Prototype of Phase 1 implementation (GGOS Days in October 2017)
    - Implementation of the operational data product metadata scheme (December 31, 2017)
- Adopt and implement a full metadata system including site information and relevant tools and capability (e.g., the Australian GL scheme)
    - Definition of the requirements; definition of Phase 1 (March 1, 2018)
    - Resolve issues and applicability of the Australian GL scheme and recommend schema (EGU 2018)
    - Metadata implementation plan including definition of tasks, roles, and distribution of tasks, and plans for integration of components (June 2018)
    - Demonstration of Phase 1 prototype (GGOS Days, 2018)
    - Demonstration of Phase 1 first operational system (June 2019)

GGOS Standing Committee on Performance Simulations & Architectural Trade-Offs (PLATO)

(Joint WG with IAG Commission 1)

Chair: *Daniela Thaller (Germany)*
Vice-Chair: *Benjamin Männel (Germany)*

Contributing Institutions (in alphabetical order):

- AIUB, Switzerland
- BKG, Germany
- CNES/IGN, France
- DGFI-TU Munich, Germany
- ETH Zürich, Switzerland
- GFZ/TU Berlin, Germany
- IfE University Hannover, Germany
- JPL, USA
- NASA GSFC/JCET, USA
- NMA, Norway
- TU Vienna, Austria

Purpose and Scope

- Develop optimal methods of deploying next generation stations, and estimate the dependence of reference frame products on ground station architectures
- Estimate improvement in the reference frame products as co-located and core stations are added to the network
- Estimate the dependence of the reference frame products on the quality and number of the site ties and the space ties
- Estimate the improvement in the reference frame products as other satellites are added, e.g., cannonball satellites, LEO, GNSS constellations
- Estimate the improvement in the reference frame products as co-locations in space are added, e.g., use co-locations on GNSS and LEO satellites, add special co-location satellites (GRASP, E-GRASP/Eratosthenes, NanoX, etc.)

Achievements over the past two years:

- Several projects related to simulation studies became funded (DGFI-TUM, AIUB, TU Vienna, GFZ)
- Simulations for the planned E-GRASP/Eratosthenes mission were carried out by several institutions; E-GRASP/Eratosthenes is a proposal for an ESA Earth-Explorer-9 Mission, with the science team led by Richard Biancale (CNES)
- Several geodetic software packages have been augmented by the capability to carry out realistic simulation scenarios (VieVS, DOGS, Bernese, Geodyn)
- Simulations for improved global SLR station network were carried out
- Simulations for an SLR station in Antarctica (Syowa, co-located with VLBI) were carried out, showing the benefit for geocenter
- The impact of the local ties (LT) on the reference frame products were studied regarding different stochastic models of the LT, selection of the LT, and the impact of systematically wrong LT. It was shown that the LT standard deviations of 1 mm or better lead to the best

datum realization of an SLR+VLBI-TRF. Simulating wrong LT indicate Wettzell, Badary and AGGO as important LT sites in the SLR and VLBI combination.
- Starting simulations for improved SLR tracking of GNSS satellites
- Simulations (and analysis of data as far as available) for new VGOS telescopes by using next generation broadband VLBI technology, showed that the GGOS requirements of 1 mm accuracy and 0.1 mm/year stability will likely be fulfilled for the reference frame.
- Simulations and analysis of VLBI tracking data of GNSS satellites and the Chinese APOD cube-satellite (i.e., using co-locations in space) were carried out using the Australian VLBI antennas for several sessions during 2016.
- Simulations related to more LLR data assuming millimeter ranging accuracies (up to three future single-prism reflectors on the moon and two additional LLR sites on the southern hemisphere) were carried out. The effect on the lunar reflector coordinates, the mass of the Earth-Moon system and two relativistic parameters (temporal variation of the gravitational constant and equivalence principle) was studied. Especially, the measurements to the new type of reflectors would lead to an improved accuracy of the estimated parameters up to a factor of 6 over a decade of new measurements.

Objectives and Planned Efforts for 2017-2019 and Beyond

- Examine trade-off options for station deployment and closure, technology upgrades, impact of site ties, etc. (December 31, 2017)
- Simulation studies "ground" to assess impact on reference frame products of: network configuration, system performance, technique and technology mix, co-location conditions, site ties (December 31, 2017)
- Simulation studies "space" to assess impact on reference frame products of: co-location in space, space ties, available satellites (October 31, 2018)
- Project future network capability over the next 5 and 10 year periods using projected network configuration in new system implementation; (February 28, 2018)
- Develop improved analysis methods for reference frame products by including all existing data and available co-locations (October 31, 2018)
- Analysis campaign with exchanged simulated observations (December 31, 2018)
- Status reports will be given at IAG Scientific Assembly (July 2017), GGOS days (October 2017) and REFAG Meeting (autumn 2018)
- Annual meetings are foreseen in conjunction with EGU General Assembly

Publications:

Ampatzidis D, König R, Glaser S, Schuh H (2016), The Assessment of the Temporal Evolution of Space Geodetic Terrestrial Reference Frames, IAG Symposia Series, DOI 10.1007/1345_2016_251

Glaser S, Ampatzidis D, König R, Nilsson T, Heinkelmann R, Flechner F, Schuh H (2016), Simulation of VLBI Observations to Determine a Global TRF for GGOS, IAG Symposia Series, DOI 10.1007/1345_2016_256

Glaser S, König R, Ampatzidis D, Nilsson T, Heinkelmann R, Flechner F, Schuh H (2017), A Global Terrestrial Reference Frame from simulated VLBI and SLR data in view of GGOS, Journal of Geodesy, DOI 10.1007/s00190-017-1021-2

Plank L, Hellerschmied A, McCallum J, Böhm J, Lovell J (2017), VLBI observations of GNSS satellites: from scheduling to analysis. J Geod, Springer, doi:10.1007/s00190-016-0992-8

Schuh H, König R, Ampatzidis D, Glaser S, Flechtner F, Heinkelmann R, Nilsson T (2016), GGOS-SIM – Simulation of the Reference Frame for the Global Geodetic Observing System, IAG Symposia Series, DOI 10.1007/1345_2015_217

IERS Working Group on Site Survey and Co-location

Chair: *Sten Bergstrand (Sweden)*
Co-Chair: *John Dawson (Australia)*

Members:
https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html

Purpose and Scope

The working group was established in 2004 as part of the IERS to homogenize local surveying activities at different space geodetic sites. In 2014, it was agreed that the working group would act also for GGOS under the IERS name. The overall goal is to provide a base necessary for rigorous terrestrial reference frame realizations, and to highlight the presence of technique- and/or site-specific biases. The main effort aspires to provide the means of an uncertainty assessment that can be included in the next ITRF.

Activities and Actions

- Recent work has first been to establish a general and common terminology to all techniques, which is also valid outside the space geodetic community, and to fulfill the local tie requirements set out in the GGOS book. The DORIS community has adapted the common terminology, and improved its surveying procedure as well as communication of results.
- IGS terminology has been adapted without alterations; the concepts are there, but the technique specific terminologies vary. The main focus of the IGS component has been a reassessment of existing sites rather than surveying as such.
- The ILRS maintains a list of current and historical sites. A combined effort from several institutes involved a common application to the European EMPIR program. The application fulfilled the acceptance criteria, but was not granted funding due to limited resources.
- The VLBI terminology concerning site surveys has been consolidated, and an automated terrestrial monitoring system for telescopes called Heimdall has been developed, as well as a complete model for telescope deformation.
- A campaign to examine the short-term combination of VLBI, GNSS and automated terrestrial monitoring at two baseline ends has been performed, with some processing left to be finished.

Objectives and Planned Efforts for 2017-2019 and Beyond

- Assess the ground truth uncertainty of different techniques to include in the next ITRF;
- Evaluate the VLBI-GNSS-terrestrial campaign of the Onsala-Metsähovi baseline; additionally, more sites should be surveyed. However, this is an activity that the respective station managers need to allocate funding for. The working group does not have the means to do this, and would appreciate any help to create a pull in this direction.

Website
https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html

GGOS Bureau of Products and Standards

Director: Detlef Angermann (Germany)
Vice Director: Thomas Gruber (Germany)

Members
- *Michael Gerstl (Germany)*
- *Robert Heinkelmann (Germany)*
- *Urs Hugentobler (Germany)*
- *Laura Sánchez (Germany)*
- *Peter Steigenberger (Germany)*

GGOS entities associated to the BPS:
- *Committee Contributions to Earth System Modelling, Chair: Maik Thomas (Germany)*
- *WG1 ITRS Standards for ISO TC211, Chair: Claude Boucher (France)*
- *WG2 Establishment of the Global Geodetic Reference Frame (GGRF), Chair: Urs Marti (Switzerland)*

Associated members of the BPS:
The IAG Services and other relevant entities involved in the definition and maintenance of standards and conventions designated their representatives as associated member of the BPS to support the BPS business and to ensure the interaction between the different components.

Position (IAG Service, …)	Representatives	Entity Contributing
IERS Conventions Center	Gérard Petit (2010-2016) Nick Stamatakos (since 2017)	BIPM (France) USNO (USA)
IERS Analysis Coordinator	Thomas Herring	MIT (USA)
IGS Representative	Urs Hugentobler (BPS staff)	TUM (Germany)
ILRS Analysis Coordinator	Erricos Pavlis	UMBC/NASA (USA)
IVS Analysis Coordinator	John Gipson	GSFC/NASA (USA)
IDS Representatives	Frank Lemoine, John Ries, Jean-M. Lemoine, Hugues Capdeville	GSFC/CSR (USA) CNES/GRGS (France)
IGFS Chair	Riccardo Barzaghi	Politec. Milano (Italy)
BGI Chair	Sylvain Bonvalot	IRD (France)
ISG President	Mirko Reguzzoni	Politec. Milano (Italy)
ICGEM Chair	Franz Barthelmes	GFZ (Germany)
IDEMS Director	Kevin M. Kelly	ESRI (USA)
IGETS Chair	Hartmut Wziontek	BKG (Germany)
Gravity Comm. (Corresp. Member)	Jürgen Kusche	Uni. Bonn (Germany)
IAG Representative to ISO	Johannes Ihde (2010-2016)	BKG (Germany)
IAG Comm. and Outreach	Josef Ádám	Uni. Budapest (Hungary)
IAU Representative	Robert Heinkelmann (BPS staff)	GFZ (Germany)
Control Body for ISO Geodetic Registry	Mike Craymer (Chair) Larry Hothem (Vice Chair)	NRCan (Canada) USA

Overview

The Bureau of Products and Standards (BPS) is a key component of IAG's Global Geodetic Observing System (GGOS). It supports IAG in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth, along with its temporal variations. The BPS is built upon existing observing and processing systems of IAG.

Mission and overall objectives of the BPS:

- to serve as contact and coordinating point for the homogenization of IAG/GGOS standards and products;
- to keep track of the adopted geodetic standards and conventions across all IAG components, and initiate steps to close gaps and deficiences;
- to focus on the integration of geometric and gravimetric parameters and to develop new products needed for Earth sciences and society.

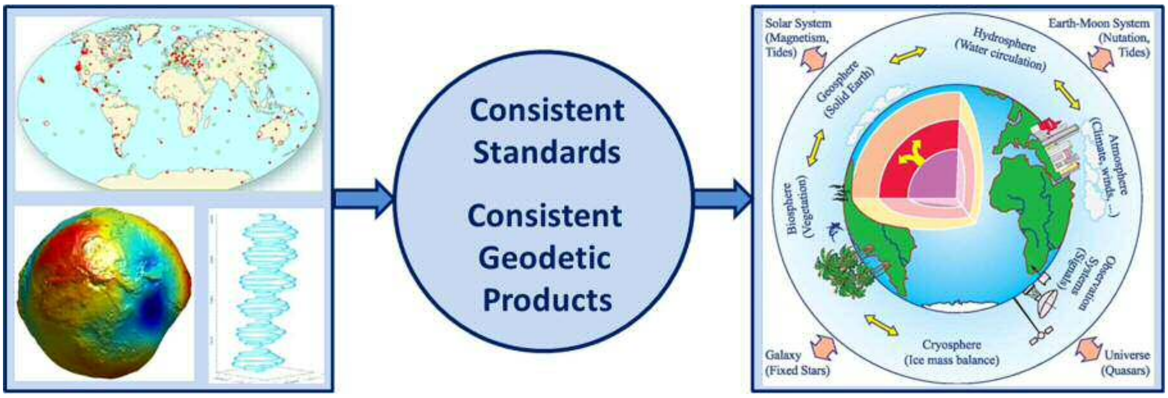

Figure 3. The integration of the three pillars of geodesy: geometry, Earth rotation and gravity field requires consistent standards to obtain consistent geodetic products as the basis for Earth system research and for precisely quantifying global change phenomena.

Activities during the period 2015-2017

During the period 2015-2017 the BPS performed the following activities:

- Internal BPS meetings of the staff members were held every two months to coordinate and manage the Bureau business.
- Evaluation of constants, standards and conventions used across the IAG components.
- Compilation of an inventory entitled "GGOS Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products" (published in the IAG Geodesist's Handbook 2016, Angermann et al., 2016).
- Focus on relevant IAG products: CRS/CRF, TRS/TRF, EOP, GNSS orbits, gravity field and geoid, vertical reference system.
- Assessment of the present status, identification of deficiencies, recommendations to resolve inconsistencies and to close gaps (interaction with IAG Services).
- Contributions to the Global Geodetic Reference Frame (GGRF) activities:
  a) BPS was involved in the writing of the IAG position paper "Description of the Global Geodetic Reference Frame (GGRF)", adopted by the IAG Executive Committee in 2016;
  b) IAG representation to the UN-GGIM GGRF Working Group for the Key Area "Data Sharing and Development of Geodetic Standards" (since 2017).

- Contribution to the definition and adoption of a new IAG conventional W_0 value (IAG resolution No. 1, 2015).
- The BPS acted as a proposer for the "New Work Item Proposal" ISO/TC 211: Revision of ISO 19111 "Geospatial Information – Spatial references by coordinates";
- Contribution to the development of new integrated products (e.g., GGRF, International Height Reference Frame (IHRF), atmosphere products, …)
- Presentation of BPS activities and achievements at scientific conferences (e.g., IAG, AGU, EGU, see selected publications and references below)
- Compilation of the BPS Implementation Plan 2017-2018. The planned schedule for the BPS communications and operational business is shown below.

	2017												2018											
GGOS communications with BPS participation																								
Coordinating Board meetings				X						X						X						X		
Consortium meetings										X												X		
EC telecons (monthly)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
CO/BNO/BPS/SP (quarterly)	X			X			X			X			X			X			X			X		
Reporting (1-page reports)				X						X						X						X		
Operational BPS bureau business																								
Internal BPS meetings	X		X		X		X		X		X		X		X		X		X		X		X	
BPS Board meetings				X						X						X						X		
Reporting of BPS entities				X						X						X						X		
Monitoring progress				X						X						X						X		

As an example taken from the BPS inventory, the present situation concerning numerical standards is summarized below:

- Different sets of numerical standards are in use within IAG (see below).
- Different time and tide systems are used in geodetic products.
- The IAG Resolution No. 16 (1983) recommends the zero tide system for gravity field parameters and zero (=mean) tide system for geometry (this is not fulfilled yet).
- The present situation concerning numerical standards and the different use of time and tide systems has to be correctly considered by the users of geodetic products; transformations are necessary if different parameters or standards were used.
- Thus the consistent use of geodetic products is very difficult (in particular for users who are not specialized in geodetic theory).
- A new Geodetic Reference System GRS20XX with new best estimates for the defining parameters should be developed.

Table 1: Numerical standards of conventional parameters presently in use within IAG. The defining parameters of the GRS80 are a, GM, J_2 and ω. The IAG Resolution No. 1 (2015) recommends a new conventional W_0 value of 62 636 853m^2s^{-2}. This W_0 value could be used as a defining parameter for a new GRS20XX, the semi-major axis a would then become a derived. Note the consequential decoupling of W_0 and L_G. The advantage of W_0 is that it does not depend on the tide system, which is not the case of the semi major axis a.

	a [m]	GM [10^{12} m^3 s^{-2}]	J_2 [10^{-6}]	ω [10^{-5} rad s^{-1}]	U_0 or W_0 [m^2 s^{-2}]
GRS80 (1979)	6 378 137	398.600 5	1 082.63	7.292 115	62 636 860.850
IERS Conv. (2010)	6 378 136.6	398.600 441 8	1 082.635 9	7.292 115	62 636 856.0 (1998)
EGM2008	6 378 136.3	398 600 441.5	1 082 636 1	7.292 115	
GRS20XX ?				7.292 115	62 636 853.4 (2015)

BPS board meetings during the period 2015-2017:

- IUGG General Assembly 2015, Prague, Czech Republik, June 27, 2015.
- GGOS Days, Frankfurt am Main, Germany, October 22, 2015.
- EGU 2016, Vienna, Austria, April 19, 2016.
- GGOS Days, Cambridge, USA, October 26, 2016.
- EGU 2017, Vienna, Austria, April 25, 2017.
- GGOS Days 2017, Juju Island, South Korea, September 18-22, 2017.

Selected Publications and Presentations:

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sánchez L., Heinkelmamm R., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of standards and conventions. IUGG General Assembly, Prague, Czech Republic, 2015-06-27.

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sanchez L., Heinkelmann R., Steigenberger P.: GGOS Bureau of Products and Standards: Recent activities and future work. EGU General Assembly, Vienna, Austria, 2016-04-19 (Poster).

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler, U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of Standards and Conventions used for the Generation of IAG Products. The IAG Geodesist's Handbook 2016, J Geod 90(10): 1095-1156, doi:10.1007/s00190-016-0948-z, 2016.

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler, U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of Standards and Conventions used for the Generation of IAG Products. In: Rizos C. Willis P. (Eds.) IAG 150 Years, IAG Symposia 143, 571-577, doi: 10.1007/1345_2015_165, 2016.

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sanchez L., Heinkelmann R., Steigenberger P.: The Bureau of Products and Standards and its key role within GGOS. EGU General Assembly, Vienna, Austria, 2017-04-25 (Poster).

Ihde J., Sánchez L., Barzaghi R., Drewes H., Foerste Ch., GruberT., Liebsch G., Marti U., Pail R., Sideris M.: Definition and proposed realization of the International Height Reference System (IHRS). Surveys in Geophysics 38(3), 549-570, doi:10.1007/s10712-017-9409-3, 2017.

Sánchez L., Čunderlík R., Dayoub N., Mikula K., Minarechová Z., Šíma Z., Vatrt V., Vojtíšková M.: A conventional value for the geoid reference potential W0. Journal of Geodesy 90(9), 815-835, 10.1007/s00190-016-0913-x, 2016.

Sánchez L., Sideris M.G.: Vertical datum unification for the International Height Reference System (IHRS), Geophysical Journal International 209(2), 570-586, 10.1093/gji/ggx025, 2017.

Committee on Earth System Modeling

Chair: Maik Thomas (Germany)

During the period 2015-2017 the activities concentrated on model intercomparisons, parameterization of model interactions, and data assimilation techniques. In particular, the following progress could be achieved:

- A module for a realistic representation of the elastic response of the lithosphere to short-term variations of surface mass loading has been developed and implemented into various model approaches.
- Several time series are operationally provided to the community via the GGFC/IERS Combination Center, e.g., time series of site displacements due to hydrological loading derived from model simulations applying the new loading module or effective angular momentum functions based on atmosphere-hydrosphere models.
- Kalman-based algorithms for the assimilation of (integral) geodetic observations have been implemented into stand-alone model components in order to improve numerical predictions of variations of surface deformation and Earth rotation parameters. Possible alternative techniques for the introduction of observational data into dynamically coupled models are under discussion.
- A strategy for the development of a tool for cross-validation and consistency tests of various geodetic monitoring products is being developed.
- Feasibility studies for the provision of error estimates based on single- and multi-model ensembles have been performed.

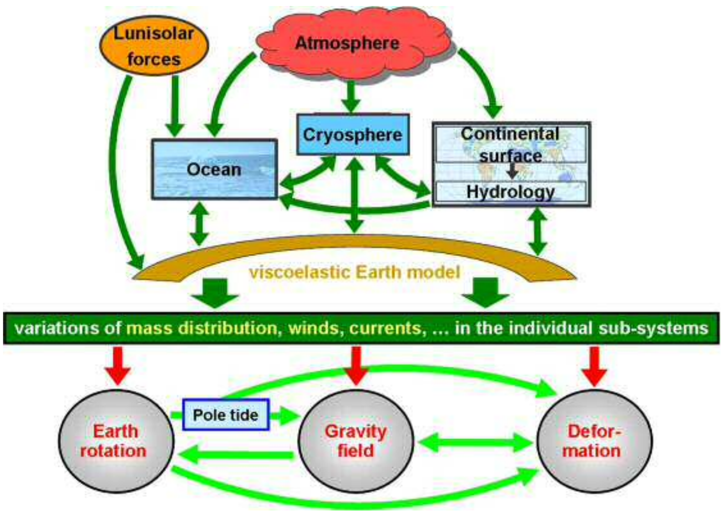

Figure 4. Concept of a modular Earth system model for geodetic applications.

Selected Publications:

Dill, R., Klemann, V., Martinec, Z., Tesauro, M.: Applying local Green's functions to study the influence of the crustal structure on hydrological loading displacements. Journal of Geodynamics, 88, p. 14-22, 2015.

Dobslaw, H., Bergmann, I., Dill, R., Forootan, E., Klemann, V., Kusche, J., Sasgen, I.: The updated ESA Earth System Model for future gravity mission simulation studies. Journal of Geodesy, 89, 5, p. 505-513, 2015.

Irrgang, C., Saynisch, J., Thomas, M.: Ensemble simulations of the magnetic field induced by global ocean circulation: Estimating the uncertainty. Journal of Geophysical Research, 121, 3, p. 1866-1880, 2016.

Konrad, H., Sasgen, I., Klemann, V., Thoma, M., Grosfeld, K., Martinec, Z.: Sensitivity of Grounding-Line Dynamics to Viscoelastic Deformation of the Solid-Earth in an Idealized Scenario. Polarforschung, 85, 2, p. 89-99, 2016.

Saynisch, J., Bergmann, I., Thomas, M.: Assimilation of GRACE-derived oceanic mass distributions with a global ocean circulation model. Journal of Geodesy, 89, 2, p. 121-139, 2015.

BPS WG1: ITRS Standards for ISO TC 211

Chair: Claude Boucher (France)

Members

- Detlef Angermann (Germany)
- Sten Bergstrand (Sweden) chair IERS WG Site surveys and collocations
- Claude Boucher (France) chair WG, ISO project leader
- Xavier Collilieux (France) IAG SC1.2 chair
- Thierry Gattacceca (France) ISO project editor
- Larry Hothem (USA)
- Ruth Neilhan (USA)
- Guy Woppelmann (France)

Purpose and Scope

The mission of the WG is to coordinate the IAG community in the support of the development of the ISO standard on ITRS.

In order to ensure this support, some specific objectives have been identified (this list may be updated if needed):
1. To establish the list of IAG contributors to the work of the WG.
2. To collect comments and proposals on any draft documents provided by the ISO TC211/19161-1.
3. To establish a glossary of geodetic terms in relation with the scope of the WG.

Activities and Actions

1 IAG contributors

The present status of WG members is given at the beginning of this report. Any update is welcome. In addition, some IAG related persons are members of the ISO committee, in addition to Thierry Gattacceca and myself: Zuheir Altamimi, Michael Craymer, Larry Hothem.

2 ISO TC211/19161-1

The group is presently working on a draft standard (presently version 1-5). As soon as this document will be approved as initial draft, it will be circulated in the WG for comments.

3 Glossary of terms

For information, here is the list of terms planned to be included in the terminology part of 19161-1:
- *Alignment to a TRF*
- *Coordinate system*
- *Geocentric Terrestrial Reference System (GTRS)*
- *Positioning process*
- *Satellite ephemeris*
- *Terrestrial Reference Frame (TRF)*
- *Terrestrial Reference System (TRS)*

BPS WG2: Establishment of the Global Geodetic Reference Frame (GGRF)

Chair: Urs Marti (Switzerland)

Members

- *Jonas Ågren (Sweden), Commission 2*
- *Detlef Angermann (Germany), Director of GGOS Bureau of Products and Standards*
- *Riccardo Barzaghi (Italy), IGFS*
- *Johannes Ihde (Germany), Working Group on Height Systems*
- *Hansjörg Kutterer (Germany), GGOS Chair*
- *Jaakko Mäkinen (Finland), Tidal Systems*
- *Pavel Novak (Czech Republic), ICCT*
- *Roland Pail (Germany), Commission 2*
- *Nikolaos Pavlis (USA), Global Gravity Field Models*
- *Laura Sánchez (Germany), Working Group on Height Systems*
- *Harald Schuh (Germany), IAG President*
- *Hartmut Wziontek (Germany), Global Gravity Reference Network*

Corresponding Members

- *Gary Johnston (Australia), Commission 1, UN GGIM WG*
- *Johannes Böhm (Austria), Commission 1*

Activities and Actions

This WG is a joint activity of IAG Commissions 1 and 2, the ICCT, the IERS and the IGFS. It works under the umbrella of the GGOS Bureau of Products and Standards (BPS).

The start-up meeting of this WG took place during the EGU Assembly 2016 in Vienna. In this meeting, the tasks of the WG discussed and defined. A clear separation between this WG and the UN GGIM WG on the GGRF was reached. Thus, the IAG WG will concentrate on the practical issues of the realisation of the GGRF and the setup of a consistent use of geometry and gravity field related quantities in the global reference frames. Key roles in this discussion play the realisation of the International Height Reference System (IHRS) and the definition and realisation of a global Absolute Gravity Reference System (see corresponding reports of these WGs).

At the GGHS2016 conference in Thessaloniki, a further meeting of the WG was held. Some concrete tasks were defined, such as:

- Work towards a conventional global reference gravity field model.
- Develop or define a global, conventional combined gravity field model and a conventional satellite-only model.
- Study the influence of permanent tide models on all kind of data (position, potential, gravity, gravity anomalies, heights, …) and develop transformation methods.
- Study the redefinition of a global GRS based on actual values of W_0 / GM / ω and derived quantities.
- Study the necessity to replace GRS80.
- Study relativistic effects and their influence on the GRS.
- Get an overview of parameters and models (e.g. tides, loading effects, atmosphere) used in products and conventions of IAG and other communities. (see BPS Inventory).
- Intensify the contacts to IAU and IERS.

Main discussion in Thessaloniki was the assignment of a conventional global gravity field model, where not all WG members agree that it is necessary. A second point of disagreement was, if it is really a good idea to replace GRS80 by a new model. A good summary of the main aspects can be found in “Considerations on a Concept for future handling Geodetic Parameters/Numerical Standards in Conventions” by J. Ihde.

The IAU assigned two contact persons to this WG: Catherine Hohenkerk (President of Divison A Commission ‘Fundamental Standards’ and Robert Heinkelmann. A contact person to the IERS is not assigned yet.

The concepts and activities of the WG were presented as well at TGSMM conference in St.Petersburg in April 2016 and during the GGOS days in Cambridge in October 2016.

Presentations and Publications

Angermann D. et al (2016): Inventory of Standards and Conventions used for the Generation of IAG products.

Angermann D. (2017): BPS Meeting at the EGU Vienna 2017.

IAG Executive Committee (2016): Description of the Global Geodetic Reference Frame. Position Paper. April 2016. https://iag.dgfi.tum.de/fileadmin/IAG-docs/GGRF_description_by_the_IAG_V2.pdf

Ihde J. (2016): The Role of Gravity and Height for the GGRF. Presentations at the EUREF Symposium May 2016, San Sebastian.

Ihde J. (2016): Future handling Geodetic Parameters/Numerical Standards in Conventions. Presentation at the GGOS Days October 2016, Cambridge.

Ihde J. (2016): Considerations on a Concept for future handling Geodetic Parameters/Numerical Standards in Conventions. November 2016.

Marti U. (2016): GGRF. Presentation at the EGU General Assembly. April 2016, Vienna.

Marti U. (2016): GGRF. Presentation at the GGHS2016 Conference. September 2016, Thessaloniki.

Marti U. (2016): Presentation at the GGOS Days October 2016, Cambridge.

Marti U., L. Vitushkin, H. Wziontek (2016): The Role of a new Global Absolute Gravity Reference System in Relation to the GGRF. Presentation at the TGSMM Conference. April 2016, St.Petersburg.

GGOS Focus Area "Unified Height Systems" and JWG 0.1.2 "Strategy for the Realization of the International Height Reference System (IHRS)"

Chair: Laura Sánchez (Germany)

Members
J. Ågren (Sweden),
M. Amos (New Zealand),
R. Barzaghi (Italy),
S. De Freitas (Brazil),
W. Featherstone (Australia),
T. Gruber (Germany),
J. Huang (Canada),
J. Ihde (Germany),
G. Liebsch (Germany),
J. Mäkinnen (Finland),
U. Marti (Switzerland),
P. Novák (Czech Republic),
M. Poutanen (Finland),
D. Roman (USA),
D. Smith (USA),
M. Véronneau (Canada),
Y. Wang (USA),
M. Blossfeld (Germany),
J. Böhm (Austria),
X. Collilieux (France),
M. Filmer (Australia),
B. Heck (Germany),
R. Pail (Germany),
M. Sideris (Canada),
G. Vergos (Greece),
C. Tocho (Argentina),
H. Denker (Germany),
D. Avalos (Mexico),
H. Wziontek (Germany),
M. Varga (Croatia),
I. Oshchepkov (Russia),
D. Blitzkow (Brazil),
A.C.O.C. Matos (Brazil),
J. Bouman (Germany).

Activities

The objectives and planned activities of the GGOS-FA "Unified Height System" are described in the Geodesist's Handbook 2016 (Drewes, H., et al., 2016, J Geod 90(10): 1091, DOI: 10.1007/s00190-016-0948-z). The main goal at present is the implementation of the International Height Reference System (IHRS) defined by the IAG 2015 Resolution No. 1 (ibid. page 981). The progress is summarized as follows:

- In December 2015, the joint working group (JWG) *Strategy for the Realization of the IHRS* was installed with the objective of developing an appropriate scheme for the realization of the IHRS; i.e., the establishment of the International Height Reference Frame (IHRF). This

JWG is supported by the International Gravity Field Service (IGFS), the IAG Commissions 1 and 2 (Reference Frames and Gravity field), the Inter-commission Committee on Theory (ICCT), the regional sub-commissions for reference frames and geoid modelling, and both GGOS Bureaus (Networks and Observations and Products and Standards).

- A brainstorming and definition of action items took place at a JWG meeting carried out during the International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS2016) in Thessaloniki (Greece) in September 2016. This JWG meeting was attended by 70 colleagues and allowed us to identify the activities to be faced immediately. A main output of this meeting are the criteria for the selection of IHRF reference stations:
    - collocation with fundamental geodetic observatories to ensure a consistent connection between geometric coordinates, potential and gravity values, and reference clocks (to support the implementation of the GGRF);
    - continuously operating reference stations to detect deformations of the reference frame;
    - preference of stations belonging to the ITRF and the regional reference frames (like SIRGAS, EPN, APREF, etc.);
    - collocation of GNSS stations with reference tide gauges and connection to the national levelling networks to facilitate the vertical datum unification;
    - availability of terrestrial gravity data around the IHRS reference stations as main requirement for high-resolution gravity field modelling (i.e., precise estimation of potential values).
- During the GGOS Days 2016 (Boston (MA), USA, October 2016), a preliminary station selection for the IHRF was performed. This selection is based on a global network with worldwide distribution, including a core network (to ensure sustainability and long-term stability of the reference frame) and regional/national densifications (to provide local accessibility to the global frame).
- Based on the conclusions of the meetings in Thessaloniki and Boston, regional and national experts were asked
    - to evaluate whether the preliminary selected sites are suitable to be included in the IHRF (availability of gravity data or possibilities to survey them), and
    - to propose additional geodetic sites to improve the density and distribution of the IHRF stations in their regions/countries.
- After the feedback from the regional/national experts, the first approximation to the IHRF is based on about 170 reference stations (Figure 5).
- With this preliminary selection, next efforts concentrate on the computation of the station potential values and the assessment of their accuracy. Different approaches are being evaluated:
    - As national/regional experts provided the JWG with terrestrial gravity data around some IHRF sites, a direct computation of potential values (and their accuracy) is being performed. In this case, following experiments are being conducted:
        - simulations about the distribution and quantity of gravity points needed around the IHRF stations,
        - simulations about the variation of potential values with time,
        - comparison of different mathematical formulations (least-squares collocation, FFT, radial basis functions, etc.).
    - Computation of potential values (and their accuracy) by national/regional experts responsible for the geoid modelling using their own data and.
    - Computation of potential values (and their accuracy) based on global gravity models of high-degree (like XGM2016, EIGEN-6C, EGM2008, etc.).
    - Recovering potential values from existing local quasi-geoid models.

- The comparison of the results obtained from these different approaches will provide a basis to outline further steps; especially, the identification of detailed standards and conventions for the IHRS realization and the implementation of a roadmap based on the available geodetic data.
- A web site summarizing the main characteristics of the GGOS-FA "Unified Height System" has been prepared and is now available at http://ihrs.dgfi.tum.de/. This information is also mirrored at http://www.ggosdays.com/en/focus-areas/unified-height-system/.

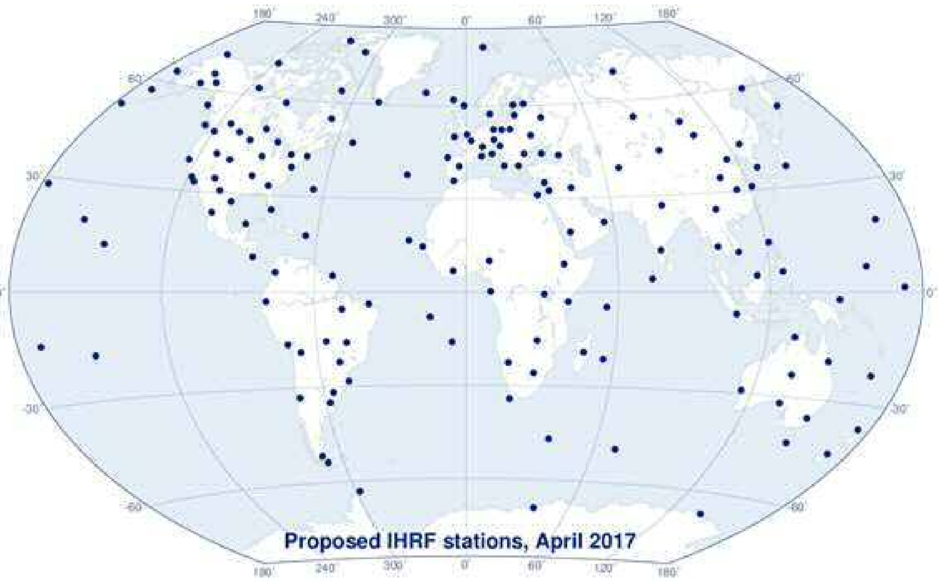

Figure 5. Proposed IHRF stations as of April 2017.

The activities reported in this document were (and are) possible thanks to the support of many colleagues. Their contribution is deeply acknowledged: M. Véronneau, J. Huang, D. Roman, M. Amos, I. Oshchepkov, S.R.C. Freitas. R.T. Luz, M. Pearlman, C. Estrella, C. Brunini, U. Marti, D. Piñon, D. Avalos, S.M.A. Costa, H. Denker, D. Blitzkow, J. Ågren, A.C.O.C. Matos, R. Pail, J. Ihde, R. Barzaghi, M. Sideris, J. Chire, A. Álvarez, C. Iturriaga, I. Liepiņš, N. Suárez, J. Krynski, R. Forsberg, G. Vergos, R. Ruddick, ...

Publications

Ihde J., Sánchez L., Barzaghi R., Drewes H., Foerste Ch., Gruber Th., Liebsch G., Marti U., Pail R., Sideris M.: Definition and proposed realization of the International Height Reference System (IHRS). Surveys in Geophysics, DOI: 10.1007/s10712-017-9409-3, 2017.

Sánchez L., Sideris M.G.: Vertical datum unification for the International Height Reference System (IHRS). Geophysical Journal International 209(2), 570-586, DOI: 10.1093/gji/ggx025, 2017.

Sánchez L., Martí U., Ihde J.: Le chemin vers un système de référence altimétrique global et unifié. Association Française de Topographie, Revue XYZ 150: 61-67, 2017.

Sánchez L., Čunderlík R., Dayoub N., Mikula K., Minarechová Z., Šíma Z., Vatrt V., Vojtíšková M.: A conventional value for the geoid reference potential W_0. Journal of Geodesy 90(9), 815-835, DOI: 10.1007/s00190-016-0913-x, 2016.

Gerlach C., Gruber Th., Rummel R.: Höhensysteme der nächsten Generation; in: Freeden, W.; Rummel, R. (eds.) Handbuch der Geodäsie, Vol. 2016, Springer, ISBN (Online) 978-3-662-46900-2, DOI: 10.1007/978-3-662-46900-2_7-1, 2016.

Lin, H., K. R. Thompson, J. Huang, and M. Véronneau (2016) Tilt of mean sea level along the Pacific coasts of North America and Japan, J. Geophys. Res. Oceans, 120, DOI: 10.1002/2015JC010920.

Véronneau, M. and J. Huang (2016) The Canadian Geodetic Vertical Datum of 2013 (CGVD2013), Geomatica, Vol. 70, No.1, 9-19, dx. DOI:.org/10.5623/cig2016-101.

Presentations

Sánchez L., Sideris M.G.: Vertical datum unification for the International Height Reference System (IHRS). European Geosciences Union General Assembly 2017, Vienna, Austria, 2017-04-27.

Sánchez L., Ihde J., Pail R., Gruber Th., Barzaghi R., Marti U., Ågren J., Sideris M., Novák P.: Towards a first realization of the International Height Reference System (IHRS). European Geosciences Union General Assembly 2017, Vienna, Austria, 2017-04-25.

Gruber Th.: Geodetic space sensors for height system unification and absolute sea level determination. Fourth Swarm Science Meeting & Geodetic Missions Workshop, Banff, Canada, 2017-03-22.

Willberg M., Gruber Th., Pail R.: Geoid Requirements for Height Systems and their Unification; Fourth Swarm Science Meeting & Geodetic Missions Workshop, Banff, Canada, 2017-03-22.

Marti U., Sánchez L.: Le système de référence altimétrique global. Commission Géopositionnement, Conseil national de l'information géographique, Paris, France, 2017-03-15.

Sánchez L., Ihde J., Pail R., Barzaghi R., Marti U., Ågren J., Sideris M., Novák P.: Strategy for the Realization of the International Height Reference System (IHRS). Symposium SIRGAS 2016, Quito, Ecuador, 2016-11-18.

Sánchez L.: Invitación a la realización del Sistema de Referencia Internacional de Alturas (IHRS) en la Región SIRGAS (in Spanish). Meeting of the SIRGAS Directing Council, Quito, Ecuador, 2016-11-17.

Sánchez, L. International Height Reference System (IHRS): Required measurements and expected products. GGOS Days 2016, Cambridge (MA), USA, 2016-10-26.

Sánchez L., Ihde J., Pail R., Barzaghi R., Marti U., Ågren J., Sideris M., Novák P.: Strategy for the Realization of the International Height Reference System (IHRS). GGHS2016: International Symposium on Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, 2016-09-22.

Andritsanos V., Vergos G., Gruber Th., Fecher T.: GOCE variance and covariance contribution to height system unification. GGHS2016: International Symposium on Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, 2016-09-22.

Willberg M., Gruber Th., Vergos G.: Height systems in Greece and its islands - some experimental results. GGHS2016: International Symposium on Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, 2016-09-21.

Sánchez L.: Working Group on the Strategy for the Realization of the International Height Reference System (IHRS): Brainstorming and definition of action items. Splinter meeting at the International Symposium on Gravity, Geoid and Height Systems 2016, 2016-09-21.

Gruber Th.: GOCE and Heights - How does the 3rd Coordinate benefit from it? ESA Living Planet Symposium 2016, Prag, Czech Republic, 2016-05-11.

Sánchez L.: GGOS Focus Area 1: Unified Height System: Present activities, GGOS Coordinating Board Meeting, TU Vienna, Vienna, Austria, 2016-04-16.

Sánchez L., Ihde J., Barzaghi R., Drewes H., Foerste Ch., Liebsch G., Marti U., Sideris M.: Establishment of an International Height Reference System in the frame of GGOS. Symposium SIRGAS 2015, Santo Domingo, Dominican Republic, 2015-11-19.

Ihde J., Sánchez L.: Physical Height and the GGRF, Earth Gravity Field and the GGRF, GGRF an Integrated Approach. GGOS Days 2015, Frankfurt a.M., Germany, 2015-10-22.

GGOS Focus Area "Geohazards"

Chair: John LaBrecque (USA)

Activities, Actions, and Publications during 2015-2017:

The Geohazards Focus Area (GFA) determined that it first initiative should be focused upon the application of GNSS upon improvement in tsunami warning. The publication of significant advances in real time technology and analysis laid a compelling case for the implementation of this geodetic capability. The GFA began its first initiative with a program to inform influential organizations of the important contributions that real time GNSS analysis towards and effective and efficient tsunami warning systems. These efforts included presentations (listed below and included in the GATEW Dropbox) at significant scientific and governmental meetings. This extensive speaking initiative resulted in the publication of supporting resolutions and recommendations as summarized in the GGOS GATEW Call for Participation. On April 1, 2016, the GGOS released the GATEW Call for Participation (CfP) in support of the IUGG-2015 (https://www.dropbox.com/sh/fg20mtydg136vx6/AABNr2kSnMo429nCxEHhBDfoa?dl=0).

GGOS Working Group on GNSS Augmentation for Tsunami Warning (GATEW)

Updated May 1, 2017

Country	Organization	Resources	Contact	Email
Australia	GeoScience Australia	Large National Real Time GNSS Network	John Dawson	John.Dawson@ga.gov.au
Chile	U.Chile, Department of Geophysics, CSN	Large National Real time Geodetic and Seismic Network	Sergio Barrientos, Sebastián Riquelme, Juan Baez	sbarrien@dgf.uchile.cl, sebastian@dgf.uchile.cl,jcbaez@csn.uchile.cl
China	GNSS Research Center, Wuhan University	First Real Time Asian Analysis Center	Jianghui Geng	jgeng@whu.edu.cn
Colombia	Geological Survey Colombia	Large Real Time GNSS Network, Regional Data Sharing with Brazil, Peru, Panama, Venezuela, COCONet Data Center	Hector Mora	hmora@sgc.gov.co
France	Institut de Physique du Globe de Paris	Strong research in tsunami coupled ionospheric waves and tracking	Giovanni Occhipinti	ninto.a.paris@gmail.com
Germany	GeoForschung Zentrum, Department Geoservices	Strong research and development of GNSS Early Warning including Indonesia and Oman projects	Harald Shuh, Jürn Lauterjung	schuh@gfz-potsdam.de, lau@gfz-potsdam.de
Italy	University of Rome Geodesy and Geomatics	Initiating research in GNSS Tsunami Warning	Mattia Crespi, Augusto Mazzoni	mattia.crespi@uniroma1.it , augusto.mazzoni@uniroma1.it
Mexico	Instituto de Geofísica, UNAM	Large National GNSS network and analysis system, COCONet Data Center	Enrique Cabral	ecabral@geofisica.unam.mx
New Zealand	GNS Science	Large National Network	Elisabetta D'Anastasion	E.DAnastasio@gns.cri.nz
New Zealand	Land Information New Zealand	Large National Network	Don Hansen	DHansen@linz.govt.nz
Sri Lanka	Survey Department of Sri Lanka	Strong interest in developing Tsunami Early Warning	P. Sangakkara,Mr A. Dissanayake	dsgpside7c@survey.gov.lk,addsgc@survey.gov.lk
USA	Georgia Tech	Significant focus on subduction zone activity and the generation of tsunamis	Andrew V. Newman	anewman@gatech.edu
USA	Jet Propulsion Laboratory	Real time expertise, Ionospheric mapping, global and operations, earthquake and tsunami warning	Attila Komjathy, Tony Yuhe Song	attila.komjathy@jpl.nasa.gov, Tony.Song@jpl.nasa.gov
USA	UNAVCO	Global GNSS networks, real time data systems, Global GNSS support	Linda Rowan	rowan@unavco.org
USA	READI Working Group	NASA-NOAA working group developing GNSS Based Tsunami Warning	Yehuda Bock, Timothy Melbourne	ybock@ucsd.edu, tim@Geology.cwu.edu
USA	NASA	NASA Solid Earth Science. Provides funding from GNSS Tsunami Warning development. Cooperating with NOAA in this effort.	Gerald Bawden	gerald.w.bawden@nasa.gov

Resolution 4 (http://www.iugg.org/resolutions/IUGGResolutions2015.pdf):
"Real-Time GNSS Augmentation of the Tsunami Early Warning System"

The International Union of Geodesy and Geophysics
Considering
− That large populations may be impacted by tsunamis generated by megathrust earthquakes,
− That among existing global real-time observational infrastructure, the Global Navigation Satellite Systems (GNSS) can enhance the existing tsunami early warning systems,
Acknowledging
− The need to coordinate with the UNESCO Intergovernmental Oceanographic Commission (IOC) and the established intergovernmental coordination framework to define GNSS network requirements, data sharing agreements and a roadmap for the development and integration of the GNSS tsunami early warning augmentation.
Urges
− Operational agencies to exploit fully the real time GNSS capability to augment and improve the accuracy and timeliness of their early warning systems,
− That the GNSS real-time infrastructure be strengthened,
− That appropriate agreements be established for the sharing of real-time GNSS data within the tsunami early warning systems,
− Continued support for analysis and production of operational warning products,

Resolves
− To engage with IUGG member states to promote a GNSS augmentation to the existing tsunami early warning systems.
− Initially to focus upon the Pacific region because the high frequency of tsunami events constitutes a large risk to the region's large populations and economies, by developing a prototype system, together with stakeholders, including scientific, operational, and emergency responders.

The GATEW CfP called upon the community of agencies and institutions to join the GATEW working group to support and promote GNSS Augmentation to Tsunami Early Warning system as recommended by IUGG 2015 Resolution 4.

During the first year of its release the working group for GNSS Augmentation to the Tsunami Early Warning (GATEW) grew to 16 agencies and institutions from 11 nations as listed above in the GFA membership above. The GATEW is functioning well and is likely to grow in importance in the months and years ahead as it moves from member recruiting and organization to program implementation.

First Meeting of the GATEW: The GATEW Working Group will hold its first meeting in Sendai Japan as part of the GTEWS 2017 workshop July 25-27, 2917. (https://geodynamics.org/cig/events/calendar/gnss-workshop/age/). The GGOS Geohazards Focus Area collaborated with the Association of Pacific Rim Universities (APRU), NASA, Rice University, Tohoku University to support this meeting of interested organizations in the advancement of the IUGG2015 Resolution #4. Over 90% of the GATEW organizations have registered for GTEWS2017 and GATEW fills a majority of the speaking positions. The GTEWS 2017 will provide an opportunity for GATEW membership to meet with representatives of non-GATEW agencies and institutions. GATEW will offer its organizational structure for the continuing promotion of international cooperation, infrastructure development and data sharing collaborations and agreements. The local organizing committee has expressed interest in publishing the findings of the GTEWS 2017 workshop.

The rapid growth of the GATEW working group in the past year will challenge the IAG definition of a working group. In the coming year the GGOS Coordinating Board should consider the transformation of the GATEW Working Group of the Geohazards Focus Area to a GGOS GATEW Program or similar structure in partnership with the IGS.

GATEW on line library: The GATEW maintains a library containing relevant documents, presentations, newsletters, videos and other files of interest to the GATEW community at the link https://www.dropbox.com/sh/fg20mtydg136vx6/AABNr2kSnMo429nCxEHhBDfoa?dl=0. The GFA will shift these files to the GGOS.org website when the GGOS Geohazards Focus Area web page is activated.

Presentations on GATEW were made at the following meetings with representative presentation files in the GATEW Online Library:

2014, June 23-27, IGS Workshop 2014 , Pasdena, CA. http://kb.igs.org/hc/en-us/articles/204125433-2014-IGS-Workshop-Summary-Recommendations

2015, June-22-July 2, IUGG-2015 Prague, Czech Republic

2015, August 10-15 , 9th ACES International Workshop, Chengdu, China

2015, August 24-28, Asia-Pacific Space Geodynamics Project-2015 Moscow, Russia, http://agora.guru.ru/display.php?conf=apsg-2015&page=program

2015, November 1-6, International Committee on GNSS-10, Boulder, US

2015, December 1-4, Asia-Pacific Regional Space Agency Forum (APRSAF 22) Bali, Indonesia

2015, December 14-18, AGU Fall Meeting, Session#8328 Global Naviga6on Satellite System for Natural Hazard Mitigation- Invited Talk, San Francisco, US

2016, February 8-12, International GNSS Service Workshop (IGS-2016) Sydney, NSW, Australia http://kb.igs.org/hc/en-us/articles/205944657-2016-IGS-Workshop-Information

2016,November 6-11, International Committee on GNSS-11, Sochi, Russia

2016, April 17-22, European Geosciences Union General Assembly-2016, Vienna, Austria

2016, May 3-5, COCONet Workshop, Punta Cana, Dominican Republic

2016, September 29-October 1, Subduction Zone Observatory Workshop, Boise, US

2016, November 14-16 8th Multi-GNSS Asia (MGA) Conference, Manila, Phillipines

2017, April 23-28, European Geosciences Union General Assembly-2017, Vienna, Austria

2017, July 3-7, 2017 IGS workshop 2017, Paris- http://kb.igs.org/hc/en-us/articles/216574478-2017-IGS-Workshop-Information

2017, August 15-18, Asia-Pacific Space Geodynamics Project-2017, Shanghai, China http://english.shao.cas.cn/rh/ca/201705/t20170502_176593.html

2017, December 11-15, AGU Fall Meeting, Gilbert F. White Distinguished Lecture, New Orleans, US

GGOS Focus Area “Sea-Level Change, Variability and Forecasting”

Chair: *Tilo Schöne (Germany)*
Co-Chairs: *CK Shum (USA), Mark Tamisiea (UK), Phil Woodworth (UK)*

Purpose and Scope

Sea level rise and its impact on human habitats and economic well being have received considerable attention in recent years by the general public, engineers, and policy makers. A GGOS retreat in 2010 has identified sea level change as one of the cross-disciplinary themes for geodesy. Sea Level is also a major aspect in other observing systems, like e.g. GEO or GCOS. The primary focus of GGOS Focus Area 3 is to demonstrate and apply geodetic techniques, under the umbrella of GGOS, to the possible mitigation or adaption of sea level rise hazards including studies of the impacts of its change over the world’s coastal and deltaic regions and islands, and to support practical applications such as sustainability. One major topic is the identification of gaps in geodetic observing techniques and to advocate enhancements to the GGOS monitoring network and Services where necessary.

Activities and Actions

Focus Area 3 has identified actions to be undertaken to advance geodetic techniques and technologies applied to sea level research. These are

- Identification or (re)-definition of the requirements for a proper understanding of global and regional/local sea-level rise and its variability especially in so far as they relate to geodetic monitoring provided by the GGOS infrastructure, and their current links to external organizations (e.g., GEO, CEOS, and other observing systems).
- Identification of organizations or individuals who can take forward each requirement, or act as points of contact for each requirement, where they are primarily the responsibility of bodies not related to GGOS.
- Identification of a preliminary set of practical or application (as opposed to scientific) pilot projects, which will demonstrate the viability, and the importance of geodetic measurements to mitigation of sea-level rise at a local or regional level. This identification will be followed by construction of proposals for pilot projects and their undertaking.

In the long-term, the aim is to support forecasting of global and regional sea level for the 21st century with an expected forecast period of 20 to 30 years or longer.
An open Call for Participation was issued in 2012. Special emphasis is given to local and regional projects which are relevant to coastal communities, and which depend on the global perspective of GGOS. Three projects have been accepted. Thus, GGOS Focus Area 3 now has approved “Landmark” projects:

The Use of Continuous GPS and Absolute Gravimetry for Sea Level Science in the UK (NERC British Isles continuous GNSS Facility (BIGF), University of Nottingham, UK), (NERC National Oceanography Centre (NOC), Liverpool, UK).

Revisiting the Threat of Southeast Asian Relative Sea Level Rise by Multi-Disciplinary Research (Delft University of Technology (DUT), Delft, Netherlands; University of Leeds, Leeds, United Kingdom; Ecole Normale Supérieure, Paris, France; Chulalongkorn University, Bangkok, Thailand; Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands)

Bangladesh Delta Relative Sea-Level Rise Hazard Assessment (Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, Ohio, USA; University of Bonn, Bonn, Germany; GeoForschungsZentrum Potsdam (GFZ), Germany) and additionally

Subsidence Monitoring in Urban Areas of the Republic of Indonesia with GNSS-controlled tide gauges and supporting methods (National Geospatial Agency (BIG) of Indonesia; Helmholtz Centre Potsdam GFZ, Germany; Institut Teknologi Bandung, Indonesia) together with the University of Cologne working on social aspects,

which is in preparation for submission.

All projects have their major focus on the combination of sea level and geodetic monitoring in an integrative approach. Also in the reporting period, Focus Area 3 continued communications with organizations, dealing with other than geodetic aspects of sea level monitoring. These are, e.g., the UNESCO International Oceanographic Commission Group of Experts (UNESCO/IOC GE) and the World Glacier Monitoring Service (WGMS). In Germany in 2016 a special research program (SPP 1889 - Regional Sea Level Change and Society, www.spp-sealevel.de) started and is dealing with many aspects relevant to GGOS Focus Area 3. Also cooperation with the IGS Tide Gauge Benchmark Monitoring Working is continued. A major step for GGOS Focus Area 3 was the alignment of its activities with the GGOS Bureau of Networks and Observations (B&O). The improvement of the observation network for sea level research is a major open topic. In 2015, the GLOSS Group of Experts (GLOSS-GE), the IGS TIGA-WG and the GGOS Focus Area 3 had submitted the Report "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges" for consideration by GGOS. This report is now accepted by the GGOS CB and the GGOS B&O.

The GNSS-controlled tide gauges are an important monitoring component in climate and geodetic science. Over the years, the network of collocated stations has been growing, not at least through the constant effort of IOC/GLOSS Group of Experts, the IGS TIGA-WG, and GGOS. Focus Area 3 plays a significant role in improving the network coverage and the establishment of local ties between GNSS and tide gauges.

Objectives and Planned Efforts for 2017-2019 and Beyond

- Review and Refine current and future aspects of geodetic contributions for sea level research with groups identified in AS-SL-01/AS-SO-02
- Work on to identify and contact emerging Focus Area 3 pilot projects
- Support Focus Area 3 projects
- Establish/improve the outreach activities with the help of the GGOS-CO
- Work with IGS/TIGA on results of the TIGA reprocessing
- Work with GGOS CB and GGOS B&O on the findings of the report "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges"
- Identify geodetic monitoring aspects relevant to Focus Area 3
- Maintain the GGOS web space for the Focus Area 3.

Website

http://www.ggos.org/en/focus-areas/sea-level-change-variability-and-forecasting/

Publications and Presentations

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Michael R. Pearlman, Chopo Ma, Ruth Neilan, Carey Noll, Erricos Pavlis, Jérôme Saunier, Tilo Schoene, Riccardo Barzaghi, Daniela Thaller, Sten Bergstrand, and Juergen Mueller: The GGOS Bureau of Networks and Observations: an update on the Space Geodesy Network and the New Implementation Plan for 2017 -18, Geophysical Research Abstracts, Vol. XX, General Assembly European Geosciences Union (Vienna 2017), http://meetingorganizer.copernicus.org/EGU2017/EGU2017-10814.pdf

Schöne, T., Shum, C., Tamisiea, M., Woodworth, P. (2015): GGOS Theme 3: Understanding and Forecasting Sea-Level Rise and Variability - Scientific programme, 26th IUGG General Assembly (Prague 2015). http://gfzpublic.gfz-potsdam.de/pubman/item/escidoc:1437893:5/component/escidoc:1437892/GGOS_Theme3

Tilo Schöne, Ck Shum, Mark Tamisiea, and Philip Woodworth: GGOS Focus Area 3: Understanding and Forecasting Sea-Level Rise and Variability, Geophysical Research Abstracts, General Assembly European Geosciences Union (Vienna 2017), http://meetingorganizer.copernicus.org/EGU2017/EGU2017-8814.pdf

Tilo Schöne, Ck Shum, Mark Tamisiea, and Philip Woodworth: GGOS Focus Area 3: Understanding and Forecasting Sea-Level Rise and Variability, 10th GEO European Projects Workshop 2016, Berlin, 31.5.-2.6.2016, https://ec.europa.eu/easme/en/geo-european-projects-workshop-2016

Communication and Outreach Branch

http://www.iag-aig.org

President: József Ádám (Hungary)
Secretary: Szabolcs Rózsa (Hungary)
Editor IAG Newsletter: Gyula Tóth (Hungary)

Introduction

The period of 2015-2019 is the fourth term in the operation of the Communication and Outreach Branch (COB) hosted at the Department of Geodesy and Surveying of the Budapest University of Technology and Economics (BME).

The Communication and Outreach Branch is one of the components of the Association. According to the new Statues (§5) of the IAG, the COB is the office responsible for the promotional activities of the IAG and the communication with its members.

The Terms of Reference and program of activities of the COB, and a short report on the IAG website ("IAG on the Internet"), were published in The Geodesist's Handbook 2016 (Drewes et al., 2016; Ádám and Rózsa, 2016; Rózsa, 2016), respectively.

In the past period of the fourth term (since the 2015 IUGG General Assembly in Prague till July, 2017) the COB's President attended the IAG Executive Committee (EC) meeting in two cases (Potsdam, April 25-26, 2016 and Vienna, April 28, 2017), while COB's Secretary represented COB on the UN GGIM WG (focus group on Outreach and Communication) meeting (Vienna, April 26, 2017) by telecons. A joint meeting of the IAG Office (H. Drewes and F. Kuglitsch), the IAG GGOS Coordinating Office (CO: G. Stangl, Ph. Mitterschiffthaler and M. Madzek) and the IAG COB (J. Ádám and Sz. Rózsa) was organized in Vienna at BEV in February 24, 2017, where the following topics were discussed:

- the structure and operation of the IAG/GGOS website;
- issues of the cooperation among the IAG Office (Munich), IAG GGOS CO (Vienna) and IAG COB (Budapest).

Note that the IAG COB's Secretary also attended at the Potsdam IAGEC meeting in April of 2016. Both the COB's President and Secretary participated at the IAG Retreat organized at Potsdam immediately after the EC meeting in April 25-26, 2016 (Beutler, 2016).
The COB provides communication, public information and outreach links, in particular via the official IAG Website and the monthly IAG Newsletters. These are the main activities of the IAG Communication and Outreach Branch.

The IAG Website

The Communication and Outreach Branch maintained the IAG Website. The website has been operational, no significant downtime has been experienced in the service. A regular update of the content has been carried out using the material provided by Association and Commission leaders, conference organizers and other members of the Association.

In the second half of the period the website has been redesigned after a consultation with the IAG Office and the Steering Committee members.

The event calendar of the website is currently redesigned according to the decision of the joint meeting of the COB, GGOS CO and the IAG Office in order to enable all of the aforementioned entities to use the same database for event calendars.

The IAG Website is visited by 30 to 50 users per day.

All organizers of the IAG meetings were asked to send the announcements for meetings as well as summarising reports on these events to the COB in order to put these texts into the IAG Website and IAG Newsletter informing the whole community.

Weekly visitors from June 2014 to June 2017.

The IAG Newsletter

The IAG Newsletter is regularly issued monthly, usually at the last working day of the month. Altogether 24 IAG Newsletters have been published from July 2015 till June 2017 and can be accessed on the IAG new website in HTML, HTML print version and in PDF formats. Since December 2016 the IAG Newsletter contains a new IAG/IUGG logo. We strive to publish only relevant information by keeping the Newsletter updated on a per-monthly basis. IAG Individual Members, IUGG and JB GIS Presidents and Secretaries as well as interested persons mainly in developing countries received it in PDF and/or text attachments, with a link in the e-mail message to access the actual HTML Newsletter on the IAG website. As of June 2017 the IAG Newsletter is sent to 843 subscribers by e-mail. Selected content of the electronic Newsletters were compiled and have been sent regularly to Springer for publication for 22 issues of the Journal of Geodesy (Vol 89/9 – 91/8).

Outreach Activities

The COB has been active in the publishing of information material in the reporting period. A new version of the IAG brochure has been published (16 coloured pages), which targets the wider public and decision makers by introducing Geodesy in general as well as the role of the Association to the readers (Ádám and Rózsa, 2017). It has a chapter on the Global Geodetic Observing System, and provides information on the IAG components (Commissions, Inter-Commission Committee, Services, etc.).

The brochure can be downloaded from the opening page of the IAG website, together with the updated IAG leaflet (Ádám and Rózsa, 2017).

H. Drewes and J. Ádám (2016) prepared a summary on "The International Association of Geodesy (IAG) – Historical Overview" which appeared in The Geodesist's Handbook 2016.

Since the website and the newsletter are living from the input of the IAG community, we regularly request (in the middle of the month) the Executive Committee (EC) members, service directors, IAG national delegates, etc to provide us any interesting news, notices, reports, scientific highlights, etc. Note that the four IAG Commissions, the ICCT, the GGOS and the 13 IAG Services maintain their individual websites (which all accessible via the official IAG website) and in some cases newsletters, therefore obviously it's hard to get materials from them. However, the IAG presence on social media needs more frequent geodesy news, short articles, new scientific highlights, reports on satellite missions, etc.

The EC at its meeting is San Francisco in December of 2015 decided to continue publishing short articles in GIM International journal. Therefore all commissions and services were requested to contribute once per year, and also to report about all IAG sponsored symposia. Since the SF-meeting every month, one report and/or article (up to one page) by a commission/service/symposium was available and submitted to the GIM International (and IAG Newsletter as well). Chris Rizos acts as the editor of the text and submit them to the GIM editors. The scheduling of the monthly report submissions is mainly organized by the COB President. Thus the IAG appeared and is visible monthly on the level of a wider community. We keep a balance of IAG EC stories, reports on major meetings, highlights of commissions and services, IAG schools, etc.

The COB also keeps track of all IAG related events by the meetings calendar.

Summary

In sum, the following activities were done:

a) the IAG website was updated, improved and continuously maintained;
b) two years ago IAG joined to both Facebook and Twitter;
c) the IAG Newsletter was regularly issued monthly and distributed electronically, and selected parts of them were prepared to publish in the Journal of Geodesy as IAG News;
d) regularly publishing IAG-related short articles in the GIM International journal;
e) new version of the IAG Leaflet was prepared, printed and distributed at different IAG meetings;
f) the large IAG Brochure was reprinted;
g) some works were made in preparation and for finalizing The Geodesist's Handbook 2016 (Drewes et al., 2016), and
h) many e-mail correspondences to the community as part of the outreach activities.

References

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Report 2015–2017 of the IAG Secretary General

http://iag.dgfi.tum.de

Secretary General: Hermann Drewes (Germany)
Assistant Secretary: Franz Kuglitsch (Germany)

Introduction

The duties of the IAG secretary General include
- to serve as secretary of the General Assembly, the Scientific Assembly, the Council, the Executive Committee and the Bureau; arrange for meetings of these bodies, distribute promptly the agenda and prepare and distribute the minutes of all their meetings.
- to act as Director of the IAG Office;
- to manage the affairs of the Association including finances as per Bylaws §42(b), attend to correspondence, and preserve the records;
- to circulate all appropriate information related to the Association;
- to prepare the reports of the Association's activities;
- to perform such other duties as may be assigned by the Bureau.

The function of the Secretary General is unpaid, and only expenses incurred in connection with the functions and duties are repayable.

Administrative activities

IAG Council

The Council met during the IUGG General Assembly 2015 in Prague, Czech Republic. The list of national correspondents forming the IAG Council was updated regularly in contact with the IUGG Secretary General. The Council was informed by e-mail about activities of the Bureau and the Executive Committee.

IAG Executive Committee (EC)

The Executive Committee is composed by the IAG President, immediate Past-President, Vice-President, Secretary General, the four Commission Presidents, the Chairperson of GGOS, the President of the COB, three representatives of the Services, and two members at large. Four EC meetings were held from July 2015 to April 2014: Prague, Czech Republic, July 2015, San Francisco, CA/USA, December 2015, Potsdam, Germany, April 2016, and Vienna, Austria, April 2017. Minutes were prepared for the EC members, and the meeting summaries were published by e-mail in the IAG Newsletter and in the Journal of Geodesy (Springer-Verlag). They are available online in the IAG Homepage (http://www.iag-aig.org) and in the IAG Office Homepage (http://iag.dgfi.tum.de).

IAG Bureau

The IAG Bureau, consisting of the President, the Vice-President and the Secretary General, had steady contact by e-mail, held teleconferences and met before EC meetings. The President and Secretary General participated in the IUGG Executive Committee Meetings.

IAG Office

The IAG Office assists the Secretary General in the administrative organization of all IAG business, meetings and events. This includes the budget management, the record keeping and fee accounting of the individual IAG membership, and the preparation and documentation of all Council and Executive Committee meetings with detailed minutes for the EC members and meeting summaries published in the IAG Newsletters and the IAG Homepage. Important activities were the preparation and execution of the joint IAG-IASPEI Scientific Assembly 2017, the edition of the Geodesist's Handbook 2016 as the organisational guide of IAG with the complete description of the IAG structure (reports, terms of reference, documents), and the Mid-Term Reports 2015–2017 (Travaux de l'AIG Vol. 40). The accounting of the Journal of Geodesy and the IAG Symposia series, both published by Springer, were supervised. Travel grants for young scientists to participate in IAG sponsored symposia were handled.

Communication and Outreach Branch (COB)

The task of the COB is the IAG public relation in particular by maintaining the IAG Homepage and publishing the monthly Newsletter online and in the Journal of Geodesy. It also keeps track of all IAG related events by the meetings calendar. The IAG newsletter is sent to all IAG Officers, individual members, the Presidents and Secretaries General of the IUGG Associations and liaison bodies. The COB prepared, printed and distributed the IAG leaflet and IAG brochure and participated in the preparation of the Geodesist's Handbook 2016.

Commissions and Inter-Commission Committee

The four IAG Commissions (Reference Frames, Gravity Field, Earth Rotation and Geodynamics, Positioning and Applications) and the Inter-Commission Committee on Theory established their structure and scientific programme for the period 2015 – 2019 (published in the Geodesists' Handbook 2016) and coordinated their implementation. They reported regularly to the EC and prepared the mid-term reports 2015 – 2017 for publication in the IAG Reports (Travaux de l'AIG). Each Commission maintained its individual Homepage and held several symposia, workshops and other meetings (see below). All of them are organising a symposium at the IAG-IASPEI Scientific Assembly 2017.

Services

There are thirteen IAG Services, which split into three general fields: geometry (IERS, IDS, IGS, ILRS, and IVS), gravity (IGFS, ICGEM, IDEMS, IGeS, IGETS and BGI) and overlapping (BIPM and PSMSL). All of them maintain their own Homepages and data servers and hold their administrative meetings (Directing Board or Governing Board, respectively). They published their structure and programme 2015 – 2019 in the Geodesists' Handbook 2016, and the progress reports 2015 – 2017 in the IAG Reports (Travaux de l'AIG). Most of the Services held international meetings (see below).

Global Geodetic Observing System (GGOS)

The GGOS is IAG's observing system to monitor the geodetic and the global geodynamic properties of the Earth as a system. A new structure was implemented during the period 2015 to 2017. It includes a Consortium composed by representatives of the Commissions and Services, the Coordinating Board as the decision-making body, the Executive Committee, and the Science Panel. The scientific work of GGOS includes Bureaus, Focus Areas, and Working

Groups. A new GGOS Coordinating Office was established for all organizational affairs, to maintain the GGOS website (www.ggos.org), an exhibit booth, and brochures and books. Several retreats (GGOS days) were held for updating the structure.

Coordination with other organisations

IAG maintains close cooperation with several organizations outside IUGG. There were frequent meetings with the Advisory Board on the Law of the Sea (ABLOS, together with IHO), Group on Earth Observation (GEO, with IAG as a participating organization), International Standards Organization (ISO, TC211 Geographic Information / Geomatics), Joint Board of Geospatial Information Societies (JBGIS), United Nations Offices for Outer Space Affairs (UN-OOSA, with participation in Space-based Information for Disaster Management and Emergency Response, UN-SPIDER, and International Committee on Global Navigation Satellite Systems, ICG), and the United Nations Global Geospatial Information Management (UN-GGIM).

Individual IAG membership

At present IAG counts 222 individual members, students are free of charge.

Meetings

IAG sponsored meetings from July 2015 to July 2017 were:

- International DORIS Service (IDS) Analysis Working Group Meeting, Greenbelt, MD, USA, 15-16 October 2015.
- International Laser Ranging Service (ILRS) Analysis Working Group Meeting, Matera, Italy, 24 October 2015.
- International Laser Ranging Service (ILRS) Technical Workshop 2015, Matera, Italy, 26-30 October 2015.
- Latin American Reference System (SIRGAS) Symposium, Santo Domingo, Dominican Republic, 18-20 November 2015.
- 9th International Symposium on Mobile Mapping Technology (MMT2015), Sydney, Australia, 9-11 December 2015.
- IGS Workshop, Sydney, Australia, February 15 – 19, 2016;
- 9th IVS General Meeting, Ekudeni (Johannesburg), South Africa, March 13 – 17, 2016;
- 3rd Joint Symposium on Deformation Monitoring, Vienna, Austria, March 30 – April 1, 2016;
- 4th IAG Symposium "Terrestrial gravimetry: Static and mobile measurements", Saint Petersburg, Russia, April 12 – 15, 2016;
- European Reference Frame Symposium (EUREF 2016), San Sebastian, Spain, May, 25 - 27, 2016;
- 18th Geodynamics and Earth Tide Symposium 2016, Trieste, Italy, June 5 – 9, 2016;
- Joint IAU/IAG/IERS Symposium "Geodesy, Astronomy and Geophysics in Earth Rotation (GAGER2016)", Wuhan, Hubei, China, July 18 – 23, 2016;
- Int. Symposium on Geodesy and Geodynamics (ISGG2016), Tianjin, China, July 22 – 26, 2016;
- 1st International Conference on GNSS+ (ICG+2016), Shanghai, China, July 27 – 30, 2016;
- IAG Commission 4 "Positioning and Applications" Symposium, Wroclaw, Poland, September 4-7, 2016;
- 18th General Assembly of WEGENER "Understanding earth deformation at plate boundaries", Ponta Delgada, Azores, Portugal, September 12-15, 2016;
- 1st Joint Commission 2 and IGFS Meeting, International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS2016), Thessaloniki, Greece, September 19-23, 2016;
- First International Workshop on VLBI Observations of Near-field Targets, Bonn, Germany, October 5-6, 2016;
- 20th International Workshop on Laser Ranging, Potsdam, Germany, October 9 – 14, 2016;
- GGOS Days, Cambridge, MA, USA, October 24 – 28, 2016;

- IDS Workshop, La Rochelle, France, October 31 – November 1, 2016;
- Reference Frame for South and Central America Symposium (SIRGAS2016), Quito, Ecuador, November 16 – 18, 2016;
- 1st International Symposium - Applied Geomatics and Geospatial Solutions, Rosario, Argentina, April 3 – 7, 2017;
- 9th IVS Technical Operations Workshop, Westford, MA, USA, April 30 – May 4, 2017;
- EUREF 2017 Symposium, Wroclaw, Poland, May 17 – 19, 2017;
- DORIS Analysis Working Group Meeting, London, UK, May 22 – 24, 2017;
- 21st Meeting of the Consultative Committee for Time and Frequency, Sèvres, France, June 6-9, 2017;
- 1st IUGG Symposium on Planetary Science, Berlin, Germany, July 3 – 5, 2017;
- IGS Workshop 2017, University of Paris-Diderot, France, July 3 – 7, 2017;
- IAG/GGOS/IERS Unified Analysis Workshop, Paris-Diderot, France, July 10 – 12, 2017;
- 2017 GNSS Tsunami Early Warning System Workshop, Sendai, Japan, July 25 – 27, 2017;
- IAG and IASPEI Joint Scientific Assembly, Kobe, Japan, July 30 – August 4, 2017.

The following IAG Schools were sponsored from July 2015 to June 2017:
- VII SIRGAS School on Reference Systems, Santo Domingo, Dominican Republic, 16-17 November 2015.
- 2nd IVS Training School on VLBI for Geodesy and Astrometry, Hartebeesthoek, South Africa, March 9 – 12, 2016;
- ISG Geoid School, Ulaanbaatar, Mongolia, June 6 – 10, 2016;
- SIRGAS School on Vertical Reference Systems, Quito, Ecuador, November 21 – 25, 2016;

Publications

The Journal of Geodesy, the official IAG scientific periodical with an Editor in Chief approved by the IAG Executive Committee, published continuously monthly issues in Springer-Verlag.

The IAG Symposia Series published the following volumes 2015-2017:
- VIII Hotine-Marussi Symposium on Mathematical Geodesy 2013, IAG Symposia Vol. 142, Springer 2016;
- IAG Scientific Assembly, Potsdam 2013, IAG Symposia Vol. 143, Springer 2016;
- 3rd International Gravity Field Symposium 2014, IAG Symposia Vol. 144, Springer 2017;
- International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH), IAG Symposia Vol. 145, Springer 2017;
- IAG Commission 1 Symposium REFAG 2014, IAG Symposia Vol. 146, Springer 2016.

The IAG Reports (Travaux de l'AIG) Vol. 39 (2015) and 40 (2017) include reports of all IAG components.

Awards, anniversaries, obituaries

The following medals and prices have been awarded:
- Levallois Medal to Rainer Rummel, Germany (2015);
- Bomford Prize to Yoshiyuki Tanaka, Japan (2015);
- Young Author Award to Xingxing Li, Germany (2015);
- Young Author Award to Olga Didova, The Netherlands (2016);
- 42 Travel Awards to young scientists for participation in 7 IAG sponsored symposia with a total of 30750 EURO (15 awardees for IAG-IASPEI 2017).

Obituaries were written for former IAG officers and outstanding geodesists who passed away:

- Bob Schutz, USA, 1940 – 2015;
- Suriya Tatevian, Russia, 1937 – 2015;
- Graciela Font, Argentina, 1940 – 2015;
- John Wahr, USA, 1951 – 2015;
- Hermann Seeger, Germany, 1934 – 2016;
- Alexander Kopaev, Russia, 1962 – 2016;
- Heinz Henneberg, Venezuela, 1926 – 2016;
- Barbara Kolaczek, Poland, 1931 – 2017;
- Bernard Guinot, France, 1925 – 2017;
- Klaus Linkwitz, Germany, 1927 – 2017.

Hermann Drewes, IAG Secretary General

International Bureau on Weights and Measures Bureau International de Poids et Mesures (BIPM) – Time Department –

http://www.bipm.org/metrology/time-frequency/

Director of Time Department: Elisa Felicitas Arias

Overview

The Time Department is one of the four scientific departments of the BIPM. The activities at the Time Department are focused on the maintenance of the SI second and the formation of the international reference time scales.

The BIPM provided until end of 2016, jointly with the US Naval Observatory, the IERS Conventions Centre, with the responsibility of the establishment and publication of the IERS Conventions, providing standards and models for applications in the fields of geodesy, geophysics and astronomy. This participation of the BIPM in this activity has been transferred to Paris Observatory, SYRTE Department (Systèmes de Référence Terre et Espace).

The establishment and maintenance of the International System of Units (SI) at the BIPM constitutes a fundamental contribution to the activities relating to the IAG.

International Time Scales at the BIPM

The BIPM Time Department maintains the atomic time scales Coordinated Universal Time (UTC); the UTC rapid solution (UTCr); and the realization of Terrestrial Time TT(BIPM).

Coordinated Universal Time (UTC) is computed every month and published *BIPM Circular T*. It is identical in rate to International Atomic Time TAI, their difference is the integral number of (leap) seconds inserted in UTC to approximate Earth's rotation time UT1. The frequency stability of UTC, expressed in terms of an Allan deviation, is estimated to 3×10^{-16} for averaging times of one month. About 500 industrial clocks located in about 80 national and international laboratories contribute to the calculation of the timescales at the BIPM. Some of these laboratories develop and maintain primary frequency standards – among them caesium fountains – that contribute to the improvement of the accuracy of TAI. Thirteen primary frequency standards contributed to improve the accuracy of TAI between January 2015 and July 2017, including eleven caesium fountains developed and maintained in metrology institutes in China, France, Germany, India, Italy, the Russian Federation, the United Kingdom and the USA. Measurements of a French rubidium secondary frequency standard have been also regularly reported and included for improving the accuracy of TAI. The scale unit of TAI has been estimated to match the SI second to about 2×10^{-16} in average over the period.

The laboratories contributing to the formation of UTC maintain representations of the international time scale denominated UTC(k). Routine clock comparisons of UTC(k) are undertaken using different techniques and methods of time transfer. All laboratories contributing to the calculation of UTC at the BIPM are equipped for GNSS reception. GPS C/A observations from time and geodetic-type receivers are used with different methods, depending on the characteristics of the receivers. Dual-frequency receivers allow performing iono-free solutions. Also combination of code and phase measurements of GPS geodetic-type receivers (GPS PPP) is used in the computation of UTC. A few time links are computed using the observations of GLONASS, and are used whenever possible for the computation of UTC, combined with GPS links. Some laboratories in Europe, North America and Asia are equipped of two-way satellite time and frequency transfer (TWSTFT) equipment allowing time comparisons independent from GNSS through geostationary communication satellites. Combinations of TWSTFT and GPS PPP links are computed whenever possible. The statistical uncertainty of time comparisons is at the sub-nanosecond level for the best time links. In the frame of the cooperation between the BIPM and the RMOs, the BIPM implements frequent campaigns for characterizing the delays of GPS equipment operated in a group of selected laboratories distributed in the metrology regions with the aim of decreasing the calibration uncertainty. Two campaigns to these laboratories have been concluded in the period of this report, resulting in a calibration uncertainty 1.5 ns at the moment of the measurements, what means an improvement in a factor of about 3 with respect to the previous 5 ns value conventionally assigned to calibrated equipment in the past. (http://www.bipm.org/jsp/en/ TimeCalibrations.jsp). In parallel, campaigns organized by the regions provided calibration of equipment with 2.5 ns uncertainty. TWSTFT links have been calibrated in Europe confirming nanosecond order uncertainty.

Research on time and frequency transfer techniques resulted in the achievement of 1 × 10-16 frequency transfer by GPS PPP with integer ambiguity resolution.

Work is ongoing for reducing the diurnal signature present in TWSTFT links. The diurnal noise can have amplitudes of about 2 ns, introducing a degradation to the uncertainty of time comparisons. Experiments using a Software Defined Radio (SRD) receiver show that a substantial reduction of the diurnal noise can be achieved in some time links.

The Time Department has been publishing the rapid solution UTCr every Wednesday (ftp://ftp2.bipm.org/pub/tai/Rapid-UTC/ and http://www.bipm.org/en/bipm-services/timescales/time-ftp/Rapid-UTC.html). About 50 laboratories contribute to UTCr, representing 70% of the clocks in UTC; in consequence the frequency stability of the rapid solution is similar to that of UTC.

Because TAI is computed on a monthly basis and has operational constraints, it does not provide an optimal realization of Terrestrial Time (TT), the time coordinate of the geocentric reference system. The BIPM therefore computes an additional realization TT(BIPM) in post-processing, which is based on a weighted average of the evaluation of the TAI frequency by the primary frequency standards. The last updated computation of TT(BIPM), named TT(BIPM16) has an estimated accuracy of order 3×10^{-16}.

In September 2016 the Time Department Data Base was open to users via web (http://webtai.bipm.org/database/html/). The data base contains all relevant information on the contribution of institutes to the realization of UTC.

Radiations other than the caesium 133, most in the optical wavelengths, have been recommended by the International Committee for Weights and Measures (CIPM) as secondary representations of the second. These frequency standards are at least one order of magnitude more accurate than the caesium. Their use for time metrology is conditioned by the progress in very accurate frequency transfer, allowing comparisons of these standards at the level of their performances. Substantial progress has been made in the use of optical fibres for frequency comparisons over up to 1000 km, but still work is to be done for extending these comparisons to time and for the implementation of permanent fibre links between UTC contributing laboratories. Intercontinental comparisons are still under study using space techniques. The time and frequency metrology community is engaged in a collective effort for solving this issue, since one of the interests is the redefinition of the SI second.

The computation of TAI is carried out every month and the results are published monthly in *BIPM Circular T*. Starting in January 2016, a htlm version of Circular T allows to access to complete information of each monthly computation (http://www.bipm.org/en/bipm-services/timescales/time-ftp/Circular-T.html). When preparing the *Annual Report*, the results shown in *Circular T* may be revised taking into account any subsequent improvements made to the data. Results are also available from the BIPM website (*www.bipm.org*), as well as all data used for the calculation. The broad real-time dissemination of UTC through broadcast and satellite time signals is a responsibility of the national metrology laboratories and some observatories, following the recommendations of the International Telecommunication Union (ITU-R).

Conventions and references

Since 2017, responsibility for the IERS Conventions had been transferred to Paris Observatory (SYRTE), who continues with this service jointly with the US Naval Observatory.

In the frame of the International Astronomical Union (IAU) activities, and in cooperation with the IERS Centre for the International Celestial Reference System, staff of the Time Department contributes to the elaboration of the third version of the International Celestial reference Frame (ICRF3).

On the adoption of a continuous reference time scale (without leap seconds)

The BIPM has actively participated to the work of the International Telecommunication Union (ITU) in the discussions on the adoption of a continuous time scale as the world reference, that involves interrupting the introduction of leap seconds in UTC.. The decision by the World Radiocommunication Conference 2015 (WRC-15) calls for further studies regarding current and potential future reference time-scales, including their impact and applications. A report will be considered by the World Radiocommunication Conference in 2023. Until then, UTC shall continue to be applied as described in Recommendation ITU-R TF.460-6 (https://www.itu.int/rec/R-REC-TF.460-6-200202-I/en) and as maintained by the BIPM. WRC-15 also calls for reinforcing the links between ITU and the International Bureau of Weights and Measures (BIPM). ITU would continue to be responsible for the dissemination of time signals via radiocommunication and BIPM for establishing and maintaining the second of the International System of Units (SI) and its dissemination through the reference time scale.

At the 21st Meeting of the Consultative Committee for Time and Frequency (CCTF), a recommendation on the definition of time scales (TAI, UTC) has been adopted, and will be submitted in November to the General Conference on Weights and Measures (CGPM). This CGPM resolution will be part of the work in preparation for the WRC-23.

Activities planned for 2017-2019

The ongoing BIPM Programme of Work has been adopted for the period 2016-2019. The following activities have not yet been executed, and have been proposed within the PoW:

- Calculation and dissemination of UTC through the monthly publication of *BIPM Circular T*; computation and improvement of the rapid UTC; computation of TT(BIPM)
- Improvement of techniques of time and frequency transfer, in particular
  - Introducing the SDR in regular TSWTFT time comparisons for UTC
  - Comparison of optical frequency standards requiring an accuracy at the level of 10^{-17} - 10^{-18};
  - Improving the algorithm of computation of uncertainties of UTC-UTC(k) taking into account the correlations and using redundant time link information.
- Testing novel statistical tools for clock noise characterisation in view of their application in the construction of the reference time scale;
- Continuing the cooperation with the IERS for the establishment of space references;
- Liaising with the relevant organizations, such as: IUGG, IAG and GGOS, IERS, IAU, ITU-R, IGS, and the International Committee for GNSS (ICG).

Publications during the period 2015-2017

External publications

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BIPM Publications

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Circular T (monthly), http://www.bipm.org/en/bipm-services/timescales/time-ftp/Circular-T.html.
Rapid UTC (*UTCr*) (weekly), http://www.bipm.org/en/bipm-services/timescales/time-ftp/Rapid-UTC.html.

International Earth Rotation and Reference Systems Service (IERS)

http://www.iers.org

Chair of the Directing Board: Brian Luzum (USA)
Director of the Central Bureau: Daniela Thaller (Germany)

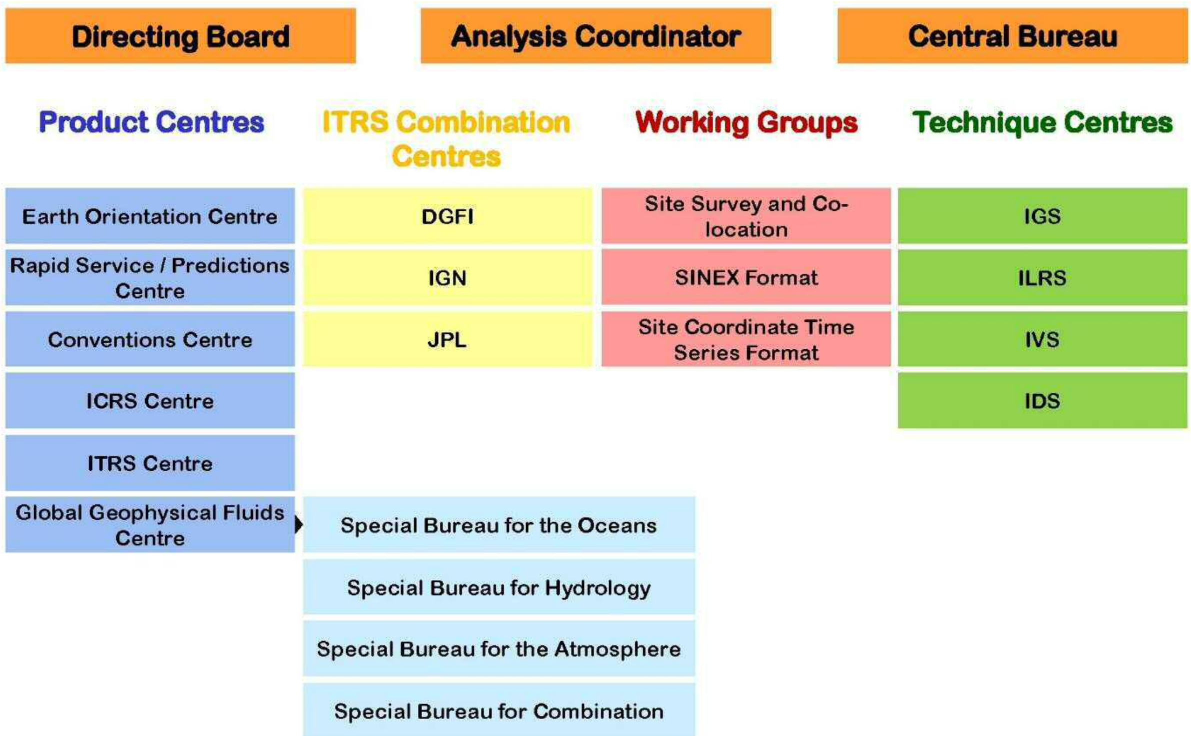
Structure

According to the Terms of Reference, the IERS consists of the following components:

- Directing Board
- Technique Centres
- Product Centres
- ITRS Combination Centre(s)
- Analysis Coordinator
- Central Bureau
- Working Groups

The Technique Centres are autonomous operations, structurally independent from the IERS, but which cooperate with the IERS.

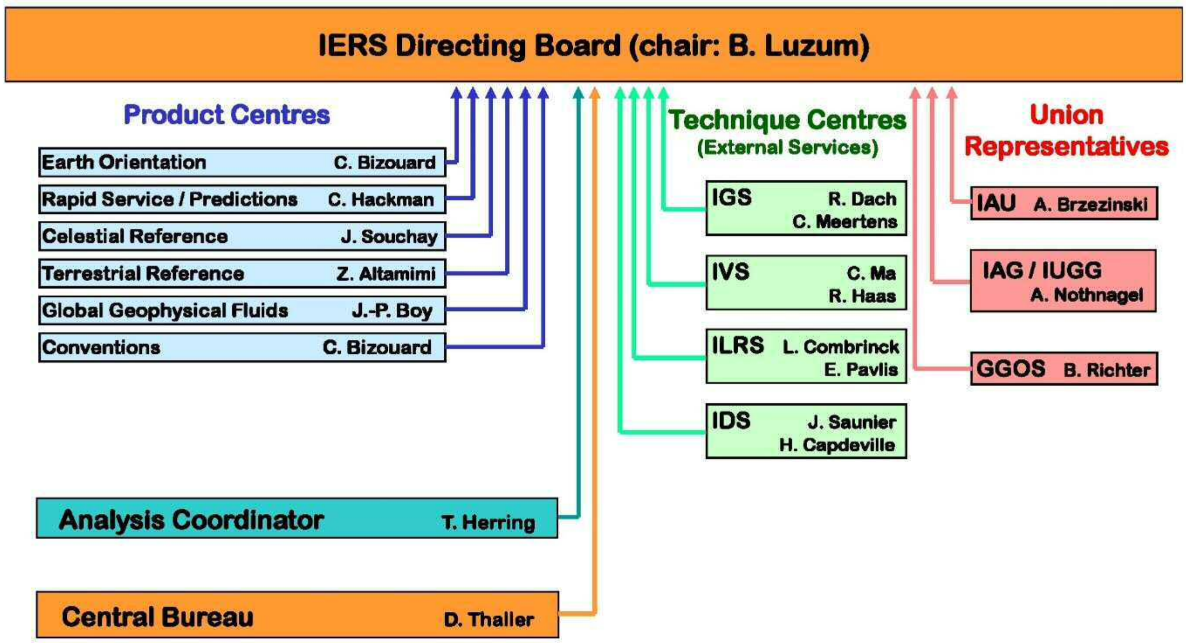
As of June 2017, the IERS consists of the following components:



Responsible persons are (as of June 2017):

- Product centres
  - Earth Orientation Centre: *Christian Bizouard (France)*
  - Rapid Service/Prediction Centre: *Christine Hackman (USA), Nick Stamatakos (USA)*
  - Conventions Centre: *Christian Bizouard (France), Nick Stamatakos (USA)*
  - ICRS Centre: *Bryan Dorland (USA), Jean Souchay (France)*
  - ITRS Centre: *Zuheir Altamimi (France)*
  - Global Geophysical Fluids Centre: *Jean-Paul Boy (France), Tonie van Dam (Luxembourg)*
    - Special Bureau for the Oceans: *Richard Gross (USA)*
    - Special Bureau for Hydrology: *Jianli Chen (USA)*
    - Special Bureau for the Atmosphere: *David Salstein (USA)*
    - Special Bureau for Combination: *Tonie van Dam (Luxembourg)*
- ITRS Combination Centres
  - Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM): *Manuela Seitz (Germany)*
  - Institut National de l'Information Géographique et Forestière (IGN): *Zuheir Altamimi (France)*
  - Jet Propulsion Laboratory (JPL): *Richard Gross (USA)*
- Analysis Coordinator: *Thomas Herring (USA)*
- Central Bureau: *Daniela Thaller (Germany)*
- Working groups
  - Working Group on Site Survey and Co-location: *Sten Bergstrand (Sweden), John Dawson (Australia)*
  - Working Group on SINEX Format: *Daniela Thaller (Germany)*
  - Working Group on Site Coordinate Time Series Format: *Laurent Soudarin (France)*

The current members of the Directing Board (representatives of scientific unions and of IERS' components) are:



Overview

The International Earth Rotation and Reference Systems Service continues to provide Earth orientation data, terrestrial and celestial references frames, as well as geophysical fluids data to the scientific and other operationally oriented communities.

Earth orientation data have been issued on a sub-daily, daily, weekly, and monthly basis, and new global geophysical fluids data were added. A new realization of the International Terrestrial Reference System (ITRF2014) was released in January 2016 and was adopted by the IERS product and technique centres in early 2017. Ongoing documentation of the ITRF2014 resulted in the release of the Journal of Geophysical Research: Solid Earth paper in 2016 and the first of the IERS Technical Notes being released in early 2017. Work on a new realization of the International Celestial Reference System (ICRF3) continued. The IERS Conventions (i.e. standards etc.) have been updated regularly. The Bureau de Poids et Mesures (BIPM) phased out their support of the IERS Conventions Centre in 2016. In response, the Observatoire de Paris joined with the U.S. Naval Observatory in co-directing the IERS Conventions Centre. The IERS Working Group on Combination at the Observation Level finished its activities in 2016.

The IERS continued to issue Technical Notes, Annual Reports, Bulletins, and electronic newsletters. It co-sponsored the symposium “Geodesy, Astronomy, and Geophysics in Earth Rotation (GAGER2016)”, which was held 18–23 July 2016 in Wuhan, Hubei, China.

The IERS Data and Information System (DIS) at the web site www.iers.org, maintained by the Central Bureau, has been updated, improved and enlarged continually. It presents information related to the IERS and the topics of Earth rotation and reference systems. As the central access point to all IERS products it provides tools for searching within the products (data and publications), to work with the products and to download them. The DIS provides links to other servers, among these to about 10 web sites run by other IERS components.

Publications

The following IERS publications and newsletters appeared between mid-2015 and June 2017:

- IERS Technical Note No. 38: Z. Altamimi, P. Rebischung, L. Métivier, X. Collilieux: Analysis and results of ITRF2014
- IERS Annual Reports 2014 and 2015
- IERS Bulletins A, B, C, and D (weekly to half-yearly)
- IERS Messages Nos. 270 to 332

IERS Directing Board

The *IERS Directing Board* (DB) met twice each year to decide on important matters of the Service such as structural changes, overall strategy, creating working groups, launching projects, changing Terms of Reference, etc.:

- Meeting No. 61 in San Francisco, December 13, 2015;
- No. 62 in Vienna, April 17, 2016;
- No. 63 in San Francisco, December 10, 2016;
- No. 64 in Vienna, April 23, 2017.

Among the most important decisions made by the DB in 2015–2017 were the following:

- New list of IERS Associate Members confirmed.
- Two IERS Technical Notes should be prepared on ITRF2014.
- Nutation series dEps / dPsi should be maintained.
- ITRS Combination Centres should compare the 9 co-located sites of the single technique solutions and the combined solution.
- Extend antenna serial number in SINEX format.
- Established roadmap to switch to ITRF2014.
- Publish a Technical Note on site survey guidelines.
- Close the IERS Working Group on Combination at the Observation Level.
- Elected Brian Luzum for a second term as Chair of the Directing Board.
- An external evaluation of ITRF should be done.
- Publish a Technical Note on 14 C04 series.

Technique Centres

The Technique Centres (TC) are autonomous independent services, which cooperate with the IERS:

- *International GNSS Service* (IGS)
- *International Laser Ranging Service* (ILRS)
- *International VLBI Service for Geodesy and Astrometry* (IVS)
- *International DORIS Service* (IDS)

For details about the work of the TCs, see their individual reports to IAG.

Product Centres

Earth Orientation Centre

Primary scientist: Christian Bizouard (France)

Overview

According to the IERS Terms of Reference, the IERS Earth Orientation Centre (EOC) is responsible for monitoring Earth Orientation Parameters including long-term consistency, publications for time dissemination (DUT1) and leap second announcements. Earth Rotation Parameters (ERPs: Polar motion, Universal Time (UT1), Length of Day (LOD) and Celestial pole offsets) are available to a broad community of users in various domains such as astronomy, geodesy, geophysics, space sciences and time. ERPs are initially collected in the form of combined solutions derived by the Technique Centres (IGS, IVS, ILRS and IDS). Two main solutions are computed: a long-term solution (IERS C01) that starts in 1846 and extends until the end of the previous year and the Bulletin B / C04 given at one-day intervals, which is published monthly with a 30-day delay (Gambis, 2004; Bizouard and Gambis, 2009; Gambis and Luzum, 2011). The EOC is located at Paris Observatory.

Activities and publications during the period 2015–2017

During the period 2015–2017 the EOC issued two leap seconds through Bulletin C (2015 July 1 and 2017 January 1).

An important issue is the maintenance of the consistency between the EOP system and both the International Terrestrial and Celestial Reference Frames (ITRF and ICRF). So far, Earth Orientation Parameters and the terrestrial frame are separately computed. This led in the past to increasing inconsistencies between both systems. All IERS reference solutions (C01, Bulletin B, C04 as well as Bulletin A derived by the Rapid Service/Predictions Centre, US Naval Observatory) were recomputed and aligned to the EOP solution associated to the new version of the ITRF (ITRF2014) in March 2017. Inconsistencies are now negligible compared to the current accuracies, i.e. limited to about 10 microarcseconds for polar motion and a few microseconds for UT1.

Recently C04 software and data base procedures have been upgraded. The celestial pole offsets are combined directly with respect to the IAU 2000 precession-nutation model. If IVS analysis centres provide them with respect to the IAU 1980 model, they are transformed into IAU 2000 consistent offsets according to a rigorous procedure based upon Standards of Fundamental Astronomy software libraries (SOFA). Moreover uncertainties are directly estimated from the formal uncertainties of the individual series and their weights reflecting the intra-technique dispersion (Bizouard et al., 2017).

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Rapid Service/Prediction Centre

Primary scientist: Christine Hackman (USA)
Production director and lead project scientist: Nick Stamatakos (USA)

Overview

The Rapid Service/Prediction Centre (RS/PC) provides high-quality Earth orientation estimates/predictions on a rapid turnaround basis, primarily for real-time-users. It issues the weekly IERS Bulletin A and corresponding data files, as well as daily and four-times-daily EOP estimate/prediction values. The centre also conducts research toward improving the accuracy and/or production robustness of its products. Lastly, the centre maintains a web-based Earth orientation matrix calculator that provides the full direction cosine matrix between celestial and terrestrial reference frames based on IERS conventions and given calendar date and time inputs.

Activities and publications during the period 2015–2017

The RS/PC successfully implemented the 30 June 2015 and 31 December 2016 leap seconds. It also successfully transitioned its products to the ITRF 2014 reference frame in March 2017. The RS/PC provided input to the National Institute of Standards and Technology (NIST; USA) in the NIST development of a Network Time Protocol UT1–UTC server, and set up an additional ftp download site for RS/PC products at the National Aeronautics and Space Administration (NASA; USA) Crustal Dynamics Data Information System (CDDIS) data archive. The cooperation of NIST and NASA is gratefully acknowledged.

The RS/PC continued to study the effects of implementing atmospheric angular momentum (AAM) and oceanic angular momentum (OAM) values/predictions in its EOP estimation/prediction algorithms, presenting results at the 2015 and 2016 American Geophysical Union (AGU) Fall Meetings and at the 2016 European Geosciences Union General Assembly. The RS/PC provided support to the IERS Conventions Centre regarding issues associated with the definition of mean pole, presenting its findings at the 2016 AGU Fall Meeting and spurring discussion that will be continued in a technical session at the July 2017 Global Geodetic Observing System (GGOS) Unified Analysis Workshop. The RS/PS also developed an improved simulation program allowing it to more easily pre-test the impact of modelling/data changes under consideration on its results.

Finally, the RS/PC will soon implement changes to its software to use the dX dY celestial pole offset observations for its core processing consistent with IERS Conventions 2010 precession and nutation models; this change will replace core processing done with the older $d\psi$ and $d\varepsilon$ paradigm.

Conventions Centre

Primary scientists: Christian Bizouard (France), Nick Stamatakos (USA)

Overview

The Conventions Centre is continuing work on technical updates to the IERS Conventions (2010), with updates of existing content, expansion of models, and introducing new topics as needed.

Activities and publications during the period 2015–2017

In 2016, the Paris Observatory (OP) took over responsibility for the co-chairmanship that was previously held by the Bureau International des Poids et Measures (BIPM); the other co-chairmanship is held by the US Naval Observatory (USNO). The Centre has created new web and ftp sites containing updated Conventions updates and associated software. Those sites are located at: http://iers-conventions.obspm.fr/ and http://maia.usno.navy.mil/conventions
(The same information can be found at both the Obervatoire de Paris and U.S. Naval Observatory Conventions websites.)
ftp site ftp://maia.usno.navy.mil/conventions .
The centre has also begun preparing for a future IERS Conventions update.

ICRS Centre

Primary scientists: Bryan Dorland (USA), Jean Souchay (France)

Overview

The IAU has charged the IERS with the responsibility of monitoring the International Celestial Reference System (ICRS), maintaining its current realization, the International Celestial Reference Frame (ICRF), and maintaining and improving the links with other celestial reference frames. Starting in 2001, these activities have been run jointly by the ICRS Centre (Observatoire de Paris and US Naval Observatory) of the IERS and the International VLBI Service for Geodesy and Astrometry (IVS), in coordination with the IAU.

Activities and publications during the period 2015–2017

Involvement by ICRS Centre personnel in the construction of the celestial reference frame from VLBI programs has continued, in particular from the participation in extensive observing programs. The ICRS Centre has fulfilled various tasks devoted to the monitoring of ICRF sources, the link with the dynamical system (in particular through LLR), the construction of new up-dates of the LQAC (Large Quasar Astrometric Catalogue) and of the LQRF (Large Quasar Reference Frame). The first Gaia data release in September 2016 provided the possibility of extensive comparisons between the preliminary Gaia optical reference frame and the ICRF, the results of which are very promising. Together with the new IAU Division 1 Working Group on ICRF3, the ICRS Centre started work to prepare the next ICRF, which is expected to be finished by 2018.

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ITRS Centre

Primary scientist: Zuheir Altamimi (France)

Overview

The main activities of the ITRS Centre during the period 2015–2017 include the maintenance of the ITRF network, database and website. The ITRS Centre, according to the IERS ToR, is responsible, among other duties, for the maintenance and update of the ITRF network database and its provision to the users through the ITRF website. The ITRS centre assigns DOMES numbers to geodetic tracking stations or markers as unambiguous identifications of points in space, independently from the technique of their tracking instruments.

The ITRF web site, available at <http://itrf.ign.fr>, provides an interface to consult the IERS network database. Site and point information can be requested online; it contains approximate coordinates of the sites, the list of their points as well as their descriptions, their DOMES numbers and the list of ITRF versions in which they have been computed. Subsets of points can be selected and their ITRF coordinates can be requested at any epoch in any ITRF version if their coordinates are provided in the requested ITRF version.

Activities and publications during the period 2015–2017

The main activities of the ITRS Centre during this period include:

- The ITRF network database, which contains the descriptions of the sites and points, is continually updated as DOMES numbers are assigned. DOMES number request form can be found on the ITRF web site <http://itrf.ign.fr>, and should be sent to domes@ign.fr. An updated list of all available DOMES numbers is available at <http://itrf.ign.fr/doc_ITRF/iers_sta_list.txt>. The IERS site information is available to the users through the ITRF website interface (see below). As a result of the ITRF2014 analysis, several new stations, mainly GNSS permanent stations where added to the ITRF network and database.
- The ITRS Centre has started the initial study analysis and preparation for a new design of the ITRF web site. It will be designed to provide more ITRF-related information to the users using more user-friendly interfaces. The specification document is finalized and the development started in 2013. The new web site which was expected to be operational beginning 2016 experienced some delay, unfortunately, and will be available hopefully around mid-2017.
- The ITRS Centre collects all new surveys operated by either IGN or the hosting agencies of ITRF co-location sites. The reports of these surveys are posted at the ITRF Website and available to users at <http://itrf. ign.fr/local_surveys.php>. The local ties SINEX files used in the ITRF combinations are also available on that web site.
- In preparation for the ITRF2014 analysis, several new local tie SINEX files and corresponding reports were submitted to the ITRS Centre. These new survey results were made available via the ITRF website after the release of the ITRF2014.
- The operational entity of the ITRS Centre at the IGN Survey department has prepared a document describing the IGN current practice of local survey that could help surveyors who do not know how to proceed and are not accustomed to working at mm precision. The document is in its final stage and will be published in a dedicated IERS Technical Note.
- Producing and publishing the ITRF2014, with a dedicated website: http://itrf.ign.fr/ITRF_solutions/2014/. See also the report of the ITRS Combination Centre at IGN France.

Global Geophysical Fluids Centre

Primary scientist: Jean-Paul Boy (France)
Co-chair: Tonie van Dam (Luxembourg)

Overview

The Global Geophysical Fluid Centre (GGFC) of the International Earth Rotation and Reference Systems Service (IERS) provides the community with models of geodetic effects (Earth rotation, gravity and deformation) due to the temporal redistribution of the Earth

geophysical fluids. These include fluid motions with the solid Earth (core and mantle) as well as motions at the Earth's surface (ocean, atmosphere and continental hydrology).
The GGFC is composed of four operational entities: the Special Bureau for the Atmosphere (SBA, chair: D. Salstein), the Special Bureau for the Oceans (SBO, chair: R. Gross), the Special Bureau for Hydrology (SBH, chair: J.-L. Chen) and the Special Bureau for the Combination Products (SBCP, chair: T. van Dam). The Atmosphere, Hydrology and Ocean SBs have been firmly established since the creation of the GGFC in 1998. The operational Combination Products SB was established in 2009 to host new datasets that model the mass movement of combined environmental fluids such as atmosphere + ocean. There is finally a non-operational component of the GGFC, the GGFC Science and Support Products, serving as a repository for models and data used regularly in data processing, but that do not change often.

Activities and publications during the period 2015–2017

The Special Bureau for the Atmosphere (SBA) is concerned with the atmospheric information that is needed for a number of geodetic issues. During the period of this report, the SBA updated all fields from atmospheric angular momentum (AAM).

The Special Bureau for the Oceans (SBO) is responsible for collecting, calculating, analysing, archiving, and distributing data relating to nontidal changes in oceanic processes affecting the Earth's rotation, deformation, gravitational field, and geocentre. Products from the ECCO/JPL ocean model were updated.

The Special Bureau for Hydrology (SBH) provides access to data sets of terrestrial water storage (TWS) variations from major climate and land surface models and GRACE (Gravity Recovery and Climate Experiment) satellite gravity measurements. The NASA GLDAS and GRACE data products are updated on a regular basis.

At the beginning of 2017, GFZ Potsdam as one of the providers of combinational products introduced major changes to their data series (atmospheric, oceanic and hydrological loading). GGFC organized sessions on global geophysical fluids at AGU Fall Meetings and EGU General Assemblies.

ITRS Combination Centres

Three ITRS Combination Centres (CCs) are responsible for providing ITRF products by combining ITRF inputs. Within the time frame covered by this report the CCs focused on the computation of the new ITRS realization 2014.

ITRS CC at DGFI-TUM

Primary scientist: Manuela Seitz (Germany)

Overview

DGFI-TUM has been acting as one of the ITRS Combination Centres within the IERS since 2001. The related activities are embedded into DGFI-TUM's research on the realization of Global Terrestrial Reference Frames within the research area Reference Systems.

Realizations of the ITRS are based on the combination of space geodetic observations of the four techniques VLBI, SLR, GNSS, and DORIS at globally distributed geodetic observatories. Respective input data are provided by the corresponding technique services (IVS, ILRS, IGS, IDS).

Activities and publications during the period 2015–2017

The CC DGFI-TUM computed the realization DTRF2014, which for the first time considers non-linear station motions caused by atmospheric and hydrological loading. The corrections are derived from the atmosphere model NCEP and the hydrology model GLDAS, respectively, and are provided by Tonie van Dam. The final DTRF2014 product comprises the solution SINEX files, an EOP file (including terrestrial and celestial pole coordinates, the rates of the terrestrial pole coordinates, UT1-UTC and LOD values), the model values introduced for non-tidal loading correction, the residual time series of station positions and translation time series of the DTRF2014 origin. The time series allow for a computation of the real station positions at each epoch of observation.

Furthermore, DGFI-TUM researched a consistent realization of ITRS, ICRS and the EOP. In particular the impact of the combination of station coordinates and of the combination of EOP on the CRF was investigated.

ITRS CC at IGN

Primary scientist: Zuheir Altamimi (France)

See the report of the ITRS Centre above.

ITRS CC at JPL

Primary scientist: Richard Gross (USA)

Overview

The ITRS Combination Centre at JPL focused on research regarding the representation of terrestrial reference frames by time series of smoothed positions of reference stations rather than by a parameterized model of the station positions. A Kalman filter and smoother for reference frames (KALREF) has been developed and used to determine time series representations of terrestrial reference frames.

Activities and publications during the period 2015–2017

Trial solutions using the same input SINEX files that were used to determine ITRF2005 and ITRF2008 were determined (Wu et al., 2015) as was JTRF2014 that was determined from the ITRF2014 input SINEX files (Abbondanza et al., 2017).

Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, T. van Dam, and X. Wu (2017), JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System, J. Geophys. Res. Solid Earth, submitted.

Wu, X., C. Abbondanza, Z. Altamimi, T. M. Chin, X. Collilieux, R. S. Gross, M. B. Heflin, Y. Jiang, and J. W. Parker (2015), KALREF—A Kalman filter and time series approach to the International Terrestrial Reference Frame realization, J. Geophys. Res. Solid Earth, 120, doi:10.1002/2014JB011622.

Analysis Coordinator

Analysis Coordinator: Thomas Herring (USA)

Overview

The Analysis Coordinator is responsible for the long-term and internal consistency of the IERS reference frames and other products. He is responsible for ensuring the appropriate combination of the Technique Centres products into the single set of official IERS products and the archiving of the products at the Central Bureau or elsewhere.

Activities and publications during the period 2015–2017

The work of the Analysis Coordinator focused on an analysis of the ITRF2014 extended model presentation of post-seismic deformation after large earthquakes and a comparison of recent diurnal and semidiurnal EOP models with the IERS Conventions (2010). He has also been looking at the scale differences between the SLR and VLBI systems that persist in ITRF2008 and coordinating with the IERS combination centres to better understand the origin of the difference. He organized and developed recommendations from the 2014 Unified Analysis Workshop held in Pasadena, CA (USA) and participated in preparing the 2017 Unified Analysis Workshop held in Paris, France.

Central Bureau

Director: Daniela Thaller (Germany)

Overview

The Central Bureau coordinates the work of the Directing Board and the IERS in general, organizes meetings and issues publications. It replies to questions of users regarding IERS products and general topics of Earth rotation and reference systems. It maintains an IERS Data and Information System (DIS) based on modern technologies for internet-based exchange of data and information like the application of the Extensible Markup Language (XML) and the generation and administration of ISO standardised metadata. The system provides general information on the structure and the components of the IERS, serves as a portal to websites of all IERS components and gives access to all products.

Activities and publications during the period 2015–2017

For most of the IERS products, metadata according to ISO 19115 were produced and are available through the IERS web pages on products and now also at the IERS ftp server ftp.iers.org.

Several tools for visualization and analysis of IERS data and products, developed in the framework of the German research unit “Earth Rotation and Global Dynamic Processes”, were improved and added to the IERS website. These are: Plot tool; EOP of today; Timescales; EOP Reader. Furthermore links to tools of other IERS components were added.

Based on the EOP Reader and on the Timescales tools, web services for Earth Orientation Parameters, leap seconds and time scales were developed.

It became apparent that the internal processes of the data management component of the IERS DIS are in need of improvements. The requirements were formulated and a contract was concluded. The optimized system is currently being tested.

The Central Bureau published and distributed IERS Technical Note No. 38, IERS Annual Reports 2014 and 2015, as well as IERS Messages Nos. 270 to 332. It compiled reports by IERS to IAU Commission 19, IAG and the ICSU World Data System.

Thaller, D. and S. Bachmann: The IERS Retreat: How to improve Earth Rotation products? in: N. Capitaine (ed.), Proceedings of the Journées 2013 "Systèmes de Référence Spatio-Temporels". Paris: Observatoire de Paris, 2015, pp. 175–180

Working Groups

Working Group on Site Survey and Co-location

Chair: Sten Bergstrand (Sweden)
Co-chair: John Dawson (Australia)

Overview

Areas of work of the Working Group on Site Survey and Co-location are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation.

Activities and publications during the period 2015–2017

Due to different national surveying procedures, local constraints etc., a detailed plan, handbook or instruction for how to perform a local survey has previously been disregarded. However, for the benefit of future surveying work the operational entity of IGN has been working on local survey guidelines. These will be published as IERS Technical Note 39 "IGN best practice for surveying instrument reference points at ITRF co-location sites".
Local survey campaigns were performed at Onsala space observatory, at Australian observatories (Katherine VLBI Observatory, Mt Stromlo Observatory and Kiribati), on Mauna Kea, Hawaii, and at many other sites.

Working Group on Combination at the Observation Level

Chair: Richard Biancale (France)
Co-Chairs: Daniel Gambis (France), Manuela Seitz (Germany)

Overview

The Working Group on Combination at the Observation Level (WG COL) reviewed the interest in combining techniques at the observation level for EOP and reference frames. Its main goal was to bring together groups capable to do combinations on the observation level and to improve the homogeneity, precision and resolution of the products. After 7 years of activities concluded its efforts in 2016.

Activities and publications during the period 2015–2016

The WG COL contributed to the ITRF2014 realization by combining geodetic techniques (DORIS, GNSS, SLR, and VLBI) at the Normal Equation Level. Twelve years of daily Normal Equations (NEQs) from 2002 to 2013 have been processed for each technique (Tab. 1). The combined Normal Equations at weekly bases in SINEX format has been produced and delivered to IGN for comparisons of the Earth Orientation Parameters solutions (EOP) and station positions with respect to the new reference frame ITRF2014.

Table 1: Parameters to estimate for comparison with ITRF2014 and added parameters for further studies

Parameters	SINEX format	GINS format	Sampling	Initial values
Polar motion	XPO, YPO	PX, PY	PWL @ 12Hr	IERS EOP 08-C04 series Interpolated @12h
Delta time UT1-TAI	UT1	PT	PWL @ 12Hr	IERS EOP 08-C04 series Interpolated @12h
Nutation angles X, Y corrections to the IAU2000A/2006 model	NUT_X, NUT_Y	NX, NY	PWL @ 12Hr	Set to 0.0
Station coordinates	STAX, STAY, STAZ	SX, SY, SZ	1/w @ mid epoch	ITRF2008
Radio sources coordinates right ascension & declination	RS_RA, RS_DE	QRA, QDE	1/w @ mid epoch	ICRF2
Added parameters not used for ITRF2013 purposes but proposed for GRGS studies				
Zenithal Troposphere Delay for wet component limited for stations (*)	ZBIAS: Adjustment of the wet component to the model	MZB	Every 2-hours: 00, 02, 04, ...20, 22hr per day	GPT/GMF model for radio waves and Mendes/Pavlis for optical waves
Troposphere gradient north & east limited for stations (*)	TGETOT, TGNTOT	MGE, MGN	1 pt/d @ 00Hr	gradient troposphérique per Day and per station
Possible parameters for future investments				
Polar motion rate	XPOR, YPOR	PXR, PYR	1pt/d @ 12Hr	Set to 0.0
Length of Day LOD	LOD	PTR	1pt/d @ 12Hr	IERS EOP 08-C04 LOD Interpolated @12h
Rate for nutation angle	NUTR_X, NUTR_Y	NXR, NYR	1pt/d PWL @ 12Hr	Set to 0.0

Conclusions about the COL activities have been presented during the closure meeting at the BKG in Frankfurt, February 19, 2016. The main result consists in having developed a new method to homogenize the terrestrial frame, Earth Orientation and celestial frame in a global solution. Further developments have been pursued in the context of the Earth Orientation Centre to produce and analyse the EOP solutions using this method and to maintain efforts studying this combination technique and analysing products.

Jean-Yves Richard, Daniel Gambis, Christian Bizouard, Sébastien Lambert, Olivier Becker, Teddy Carlucci, Sylvain Loyer, Laurent Soudarin, Géraldine Bourda, Antoine Bellanger, Florent Deleflie, David Coulot, Arnaud Pollet, Jean-Michel Lemoine, Richard Biancale, Jean-Charles Marty, Felix Perozanz, "GRGS Solutions EOP, TRF, CRF by multi technique Combination DORIS, GPS, SLR, VLBI at normal equation level, period 2002–2013", presented at COL meeting Federal Agency for Cartography and Geodesy (BKG), Frankfurt am Main, Germany, 19 February 2016.

Poster presentation: Jean-Yves Richard, Christian Bizouard, Sébastien Lambert, Olivier Becker, Richard Biancale, "A combined GNSS/VLBI solution for EOP and TRF", EGU2016, Vienna, 17–22 April 2016.

Working Group on SINEX Format

Chair: Daniela Thaller (Germany)

Overview

The SINEX (Solution INdependent EXchange) format is a well-established format used by the technique services of the IERS for several years. The aim of the working group is to maintain the SINEX format according to the needs of the IERS, the technique services (IDS, IGS, ILRS, IVS) and GGOS. The working group is the point of contact if any modifications or extensions are required. In order to have the best possible interaction with the groups working with the SINEX format (either as output or as input), the analysis and combination groups of all the technique services as well as the relevant components of the IERS and GGOS are represented within the working group.

Activities and publications during the period 2015–2017

The Working Group on SINEX Format has been working on modifications for representations of non-linear station motions due to post-seismic movements, of parameters describing radio source positions and of the antenna serial number, as well as on other topics. Also, there have been activities for setting up a more user-friendly SINEX description as a web interface for each block, which will be easier to maintain and to update and will be more user-friendly to implement or check.

Working Group on Site Coordinate Time Series Format

Chair: Laurent Soudarin (France)

Overview

The objectives of the Working Group on Site Coordinate Time Series Format, a joint WG of IERS and IAG, are a user-friendly format with data and metadata by definition of a common exchange format for coordinate time series for all geodetic techniques (DORIS, GNSS, SLR, VLBI) with all necessary information (data and metadata). The goal is to access products via web interfaces.

Activities and publications during the period 2015–2017

A meeting of the WG took place in Vienna, on April 15, 2015, during the EGU General Assembly week. Based on a non-exhaustive list of existing formats at IAG services and GPS time series providers, metadata and data have been examined. The content of existing formats have been listed and compared, regarding the metadata and the data. The examination allows to identify three types of metadata (file information, site information, and product information) as well as a list of variables forming the data block. The next step is to define the necessary elements for the time series exchange format (metadata content, data table, mandatory and optional inputs) as well as the units, the coordinate system, the date and time system.

Reports, meeting summaries, presentations and other documents of all working groups are available at the IERS web site.

International DORIS Service (IDS)

http://ids-doris.org/

Chairman of the Governing Board: Frank Lemoine (USA)

Overview

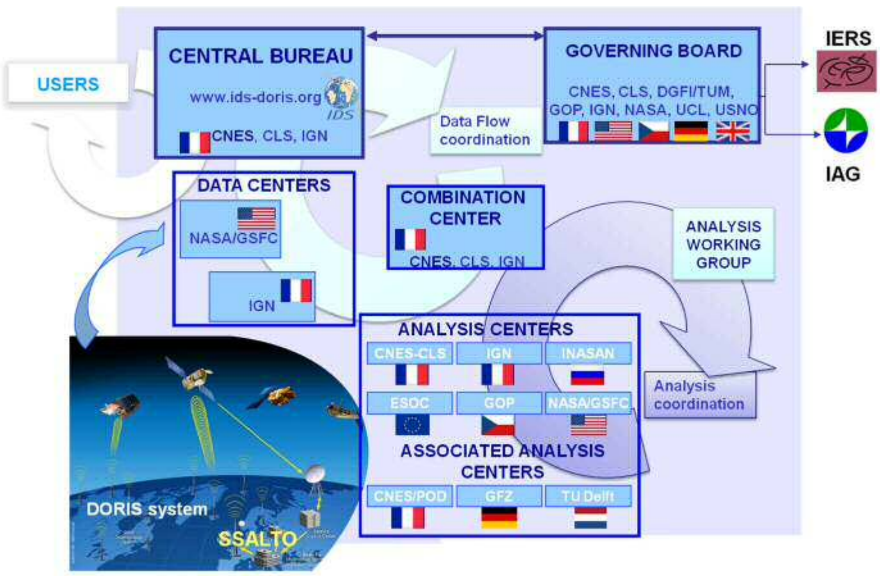
The leading achievement of the International DORIS Service (IDS) over the period 2015-2017 was the contribution to ITRF2014, the preparation of articles for the DORIS Special Issue in the journal "Advances in Space Research", and the initiation of a routine operational delivery of an IDS combination on a quarterly basis. Six IDS analysis centers (ACs) used five separate analysis packages to create IDS products as well as to reprocess all DORIS data since 1993 for inclusion in the DORIS combination for ITRF2014. The Combination Center in Toulouse creates the routine combinations in close collaboration with the Analysis Coordinators and the Analysis Centers. The components of the IDS meet regularly primarily during Analysis Working Group (AWG) meetings to discuss progress on current technical questions. The Governing Board of the IDS provides long-term direction while the Central Bureau manages the day-to-day activities brings its supports to the IDS components and operates the information system.

The current report presents the different activities held by all the components of the IDS for the period from the middle of 2015 to the middle of 2017.

Structure

The IDS organization is very similar to the other IAG Services. The service accomplishes its mission through the following components:

- Satellites carrying a DORIS receiver
- Network of tracking stations
- Data Centers
- Analysis Centers and Analysis Coordinator
- Combination Center
- Working Groups
- Central Bureau
- Governing Board



Activities

1. DORIS system

1.1 DORIS satellites

As described in Table 1.1, two new satellites were launched in early 2016: Jason3 and Sentinel3B, both using the new 7-channel DG-XXS DORIS receiver on-board the satellite. The DORIS constellation then steadily increased, including currently six satellites at altitudes of 720 and 1300 km, with near-polar or TOPEX-like inclination (66 deg).

Table 1.1: DORIS data available at IDS data centers, as of May 2017

Satellite	Start	End	Space Agency	Type
SPOT-2	31-MAR-1990 04-NOV-1992	04-JUL-1990 15-JUL-2009	CNES	Remote sensing
TOPEX/Poseidon	25-SEP-1992	01-NOV-2004	NASA/CNES	Altimetry
SPOT-3	01-FEB-1994	09-NOV-1996	CNES	Remote sensing
SPOT-4	01-MAY-1998	24-JUN-2013	CNES	Remote sensing
Jason-1	15-JAN-2002	21-JUN-2013	NASA/CNES	Altimetry
SPOT-5	11-JUN-2002	1-DEC-2015	CNES	Remote sensing
Envisat	13-JUN-2002	08-APR-2012	ESA	Altimetry, Environment
Jason-2	12-JUL-2008	PRESENT	NASA/CNES	Altimetry
Cryosat-2	30-MAY-2010	PRESENT	ESA	Altimetry, ice caps
HY-2A	1-OCT-2011	PRESENT	CNSA, NSOAS	Altimetry
SARAL/ALTIKA	14-MAR-2013	PRESENT	CNES/ISRO	Altimetry
JASON-3	17-JAN-2016	PRESENT	NASA/CNES/NOAA /Eumetsat	Altimetry
SENTINEL-3A	16-FEB-2016	PRESENT	GMES/ESA	Altimetry

In the next few years, more DORIS satellites are planned: Sentinel-3B, 3C, HY-2C, 2D, Jason-CS1/SENTINEL-6A Jason-CS2/SENTINEL-6B, SWOT (Surface Water Ocean Topography). Furthermore, other missions are under consideration. Of particular interest is an improved version of the E-GRASP/Eratosthenes proposal (ESA Earth Explorer-9 mission) which will be submitted to the new ESA/EE9 call, in June 2017. It will provide well-calibrated geodetic systems such as GNSS, DORIS, SLR, and VLBI, all on board the same spacecraft.

Figure 1.1 summarizes the evolution of the DORIS constellation since the launch of the SPOT-2 satellite in 1990, and includes satellites that are currently planned. It must be noted that in the past last years, four or more DORIS satellites have been available to IDS users, which is a key requirement for the precision of the geodetic products.

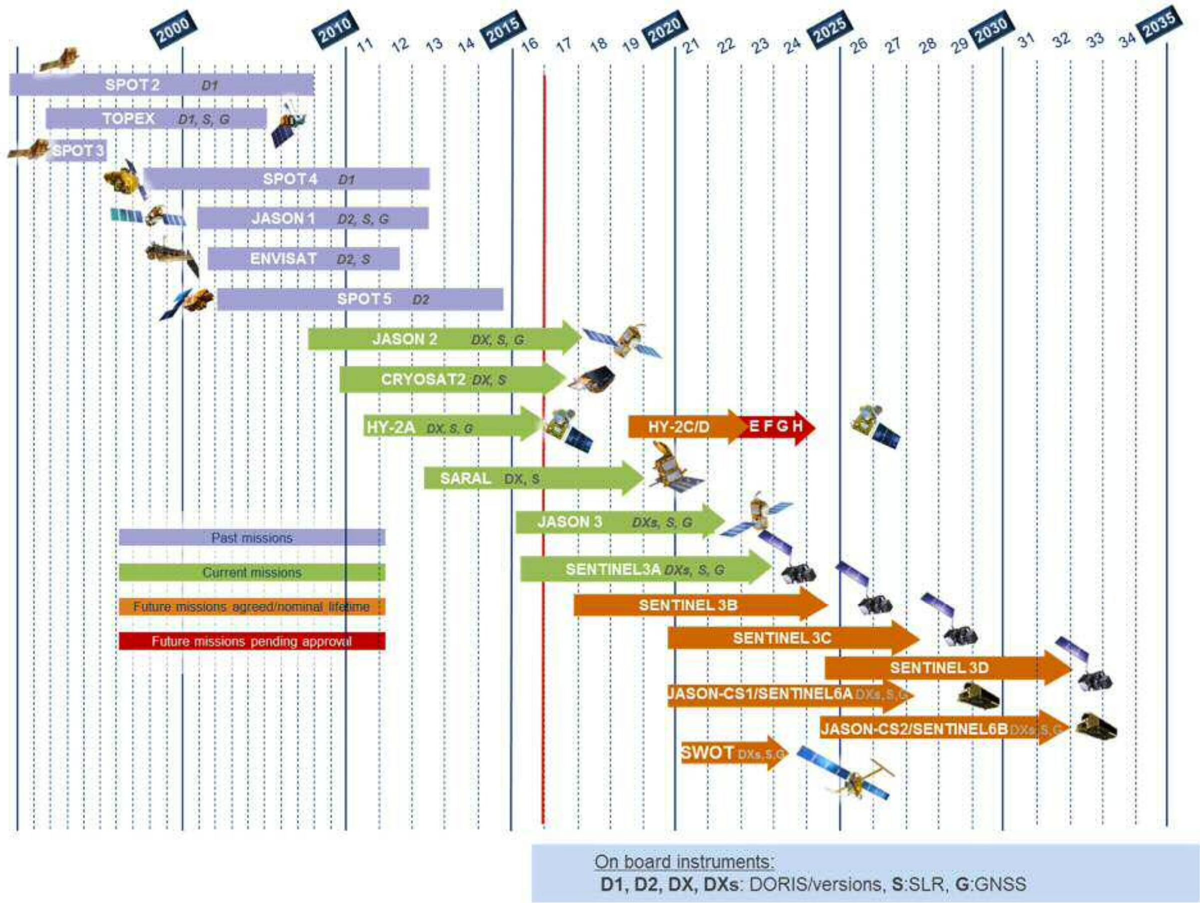


Figure 1.1: DORIS satellite constellation. As of March 2017.

1.2 DORIS network

DORIS has a globally distributed network of 56 permanent stations dedicated for precise orbit determination and altimetry with four master beacons and one time beacon. Two additional DORIS stations are used for other scientific purposes: Grasse (France) and Wettzell (Germany). See Figure 2.

The new DORIS station at the Geodetic Observatory Wettzell began operations in September 2016. With DORIS Wettzell becomes GGOS core site with all four of the space geodetic techniques.

We also note the newly installed DORIS stations at Goldstone, California (2015) and at Managua, Nicaragua (2016), both contributing to the robustness of the permanent network in North America. The installation of the station at Goldstone filled a gap in western North America, which appeared in 2010 after the closure of the Monument Peak DORIS station.

Overall, the DORIS network provided a very reliable service with the total number of operating stations approaching an annual average of 90% of active sites in 2015 and 2016, thanks to the responsiveness and the combined efforts of CNES, IGN and all agencies hosting the stations.

As regards the ground equipment, the 4th beacon generation is under development with a view to starting deployment from 2019. Designed with new electronic components and new architecture, this new beacon model aims at providing a better performance and reliability and will allow to install the antenna up to 50 m from the beacon (currently 10 m). This will improve options for placement of new stations, while still satisfying the station visibility constraint of minimizing obstructions at low elevation.

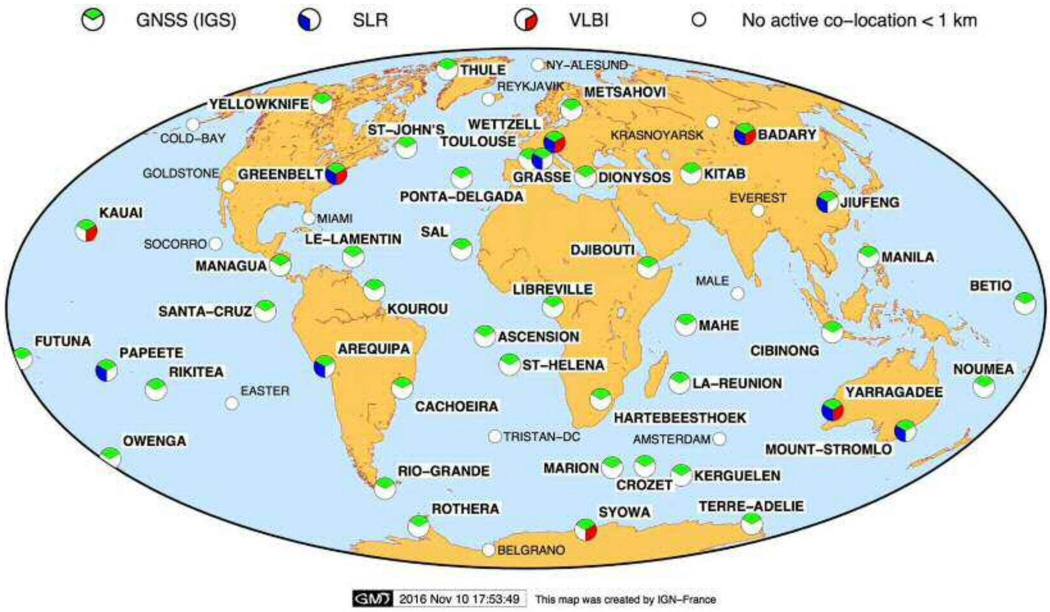


Figure 2: DORIS tracking network. Co-location with other IERS techniques as of Dec. 2016.

Efforts continue towards increasing the number of co-located sites, improving the monument stability at any new installation and carrying out high precision local tie surveys. There are currently several projects under way in Argentina, Guam, Spitsbergen (Ny Alesund), North Australia (Katherine), China and French Polynesia.

2. IDS organization

Like the other IAG Services, an IDS Governing Board (GB), helped by a Central Bureau (CB), organizes the activities done by the Analysis Centers (AC), the Data Centers (DC), and the Combination Center (CC).

2.1 Governing Board

In accordance with the Terms of Reference of the IDS, several positions within the Governing Board became vacant at the end of 2016. They concerned three members elected by IDS Associates (the representative of the Data centers, the representative of the analysis Center, one member at large) and four representatives appointed respectively by CNES (DORIS system), IGN (network), IAG and IERS. The CB coordinated the steps to update the GB membership for the next 4-year term (2017-2020). First, the CB contacted the relevant organizations to appoint their representatives; second, the CB organized the elections for the three vacant positions. In a final step for the GB elected its new chairman.

The members who were elected or appointed are:

- Frank Lemoine as Analysis Center Representative,
- Patrick Michael as Data Center Representative,
- Denise Dettmering as Member-at-Large,
- Pascale Ferrage, reappointed by CNES as the DORIS system representative,
- Jérôme Saunier, reappointed by IGN as the Network representative.
- Brian Luzum, reappointed by IERS as the IERS representative.
- Petr Štěpánek**,** nominated by IAG Executive Committee in February 2017 as the IAG representative to succeed Michiel Otten who served two terms.

The new Governing Board has designated Frank Lemoine as the new Chairperson of the IDS Governing Board for 2017-2020.

In addition, the CB carried out the selection of the Combination Center for 2017-2020. The call for proposals for the successor to the current Combination Center closed on October 15. Only one proposal was submitted, that of CNES/CLS who applies to continue the activities of the Combination Center. The GB accepts the application and selects it as the IDS Combination Center for a new period of four years, starting on January 1, 2017. Guilhem Moreaux (CLS) remains the representative of the Combination Center within the GB.

Table 2 IDS GB members since 2003, with members in office in 2017 indicated in bold.

Position	Term	Status	Name	Affiliation	Country
Analysis coordinator	**2015-2018**	Elected	**Hugues Capdeville**	CLS	France
			Jean-Michel Lemoine	CNES/GRGS	
	2013-2014	*Ext'd*	*Frank Lemoine*	*NASA/GSFC*	*USA*
	2009-2012	*E.b.GB*	*Frank Lemoine*	*NASA/GSFC*	*USA*
	2005-2008		*Frank Lemoine (subst.)*	*NASA/GSFC*	*USA*
	2003-2005		*Martine Feissel-Vernier*	*IGN/Paris Obs.*	*France*
Data Centers' representative	**2017-2020**	Elected	**Patrick Michael**	NASA/GSFC	USA
	2013-2016	*Elected*	***Carey Noll***	*NASA/GSFC*	*USA*
	2009-2012	*Elected*	*Carey Noll*	*NASA/GSFC*	*USA*
	2003-2008		*Carey Noll*	*NASA/GSFC*	*USA*
Analysis Centers' representative	**2017-2020**	Elected	**Frank Lemoine (chair)**	NASA/GSFC	USA
	2013-2016	*Elected*	***Pascal Willis (chair)***	*IGN+IPGP*	*France*
	2009-2012	*Elected*	*Pascal Willis (chair)*	*IGN+IPGP*	*France*
	2003-2008		*Pascal Willis*	*IGN+IPGP*	*France*
Member at large	**2015-2018**	Elected	**Marek Ziebart**	UCL	UK
	2013-2014	*Ext'd*	*John Ries*	*Univ. Texas/CSR*	*USA*
	2009-2012	*E.b.GB*	*John Ries*	*Univ. Texas/CSR*	*USA*
	2003-2008		*John Ries*	*Univ. Texas/CSR*	*USA*
Member at large	**2017-2020**	Elected	**Denise Dettmering**	DGFI/TUM	Germany
	2013-2016	*Elected*	***Richard Biancale***	*CNES/GRGS*	*France*
	2009-2012	*E.b.GB*	*Pascale Ferrage*	*CNES*	*France*
	2003-2008		*Gilles Tavernier (chair)*	*CNES*	*France*
Director of the Central Bureau	Since 2003	App.	**Laurent Soudarin**	CLS	France
Combination Center representative	Since 2013	App.	**Guilhem Moreaux**	CLS	France
Network representative	**2017-2020**	App.	**Jérôme Saunier**	IGN	France
	2013-2016	*App.*	***Jérôme Saunier***	*IGN*	*France*
	2010-2012		*Bruno Garayt (subst.)*	*IGN*	*France*
	2009	*E.b.GB*	*Hervé Fagard*	*IGN*	*France*
	2003-2008		*Hervé Fagard*	*IGN*	*France*
DORIS system representative	**2017-2020**	App.	**Pascale Ferrage**	CNES	France
	2013-2016	*App.*	***Pascale Ferrage***	*CNES*	*France*
IAG	**2017-2020**	App.	**Petr Štěpánek**	Geodetic Obs. Pecny	Czech Republic
representative	***2013-2016***	*App.*	***Michiel Otten***	*ESOC*	*Germany*
	2009-2012	*App.*	*Michiel Otten*	*ESOC*	*Germany*
	2003-2008		*Not designated*		
IERS representative	**2017-2020**	App.	**Brian Luzum**	USNO	USA
	2013-2016	*App.*	***Brian Luzum***	*USNO*	*USA*
	2009-2012	*App.*	*Chopo Ma*	*NASA/GSFC*	*USA*
	2003-2008		*Ron Noomen*	*TU Delft*	*Netherlands*

App. = Appointed ; Elected = Elected by IDS Associates ; E.b.GB = Elected by the previous Governing Board ; Ext'd = Extended term for two years linked to the set up of the partial renewal process

2.2 Central Bureau

The Central Bureau, funded by CNES and hosted at CLS, is the executive arm of the Governing Board and as such is responsible for the general management of the IDS consistent with the directives, policies and priorities set by the Governing Board. It brings its support to the IDS components and operates the information system.

The Central Bureau participated in the organization of the AWG meetings held at CLS in Toulouse (May 28 and 29, 2015), at NASA/Goddard Space Flight Center in Greenbelt, Maryland, (October 15 and 16, 2015), at the Faculty of Aerospace Engineering in Delft, Netherlands, (May 26 and 27, 2016), and of the IDS Workshop in La Rochelle, (October 31 to November 1st, 2016). It documented the Governing Board meetings held on these occasions.

Besides the regular updates of pages and additions of documents, the website was upgraded and enriched with new pages. The IDS video channel was created on YouTube (https://www.youtube.com/channel/UCiz6QkabRioCP6uEjkKtMKg) to host a set of existing videos for outreach, and new videos showing the DORIS-equipped satellites in orbit. These videos were produced with the Visualization Tool for Space Data (VTS) free software from CNES. The IDS web service (http://ids-doris.org/webservice) has been upgraded with a new plot tool to visualize the time series of Earth Orientation Parameters from the IDS Combination Center analysis.

At its meeting in Washington in October 2015, the Governing Board asked the Central Bureau to consider the publication of a newsletter. The intention is to improve the flow of information within the community of providers and users of DORIS data and products, to highlight the activities of the groups participating in the IDS, and to bring the DORIS and IDS news to a wider audience, from the host agencies to the other sister services. In March 2016, the Central Bureau proposed a draft to the Governing Board who approved the concept. So, the IDS Newsletter was created. Three issues were published in 2016, #1 in April 2016, #2 in July, and #3 in December. The issues are distributed via email to the subscribers to the DORISmail and a number of identified managers and decision-makers. They are also available from the IDS website (https://ids-doris.org/ids/reports-mails/newsletter.html).

The Central Bureau works with the SSALTO multi-mission ground segment and the Data centers to coordinate the data and products archiving and the dissemination of the related information. Data, meta-data and documentation of the two missions Jason-3 and Sentinel 3A launched in early 2016, were put online the IDS data and information sites as they become available.

During the change to the new file upload system at the CDDIS, the Central Bureau also interacted with the CDDIS staff, SSALTO, and the IDS components in order to ease the transition.

2.3 Data Centers

Two data centers currently support the archiving and distribution of data for the IDS:

- Crustal Dynamics Data Information System (CDDIS), funded by NASA and located in Greenbelt, Maryland USA
- l'Institut National de l'Information Géographique et Forestière (IGN) in Marne la Vallée France

Both of these institutions have archived DORIS data since the launch of TOPEX/Poseidon in 1992. The CDDIS (ftp://cddis.nasa.gov) runs fully redundant systems with both primary and secondary systems at different physical locations with access transparent to the end user. IGN in France uses two sites (ftp://doris.ign.fr) and (ftp://doris.ensg.ign.fr) which are exact mirrors of each other offering continued operational basis even if one of them is inaccessible due to a temporary failure. The data holdings between CDDIS and IGN are not mirrored between the sites but rely on data providers to upload data and products to both to ensure full coverage at each center.

On 1 December 2016, CDDIS moved its entire operations to new facilities associated with its parent organization the Earth Observing System Data and Information System (EOSDIS). At the same time, it moved away from the old ftp protocol to a https-based upload procedure for data uploads; this new procedure offers both web and command line interfaces. The move to https was necessitated by security and operational concerns. Before the transition all DORIS data and products were supplied by seven individuals/groups. On 1 December 2016, five (5) of the suppliers (GSFC, ESA, SSALTO, INA, IDS ACC) had made the transition to the new procedure with the remaining two groups (GOP, IGN) transitioning to the new procedure in March 2017.

2.4 Analysis Centers and Analysis Coordination

The activities of all the DORIS analysts of the years 2015 and 2016 were dominated by the IDS contribution to ITRF2014 and its evaluation, and the implementation of the data processing of DORIS RINEX. In 2016, the IDS Analysis Centers processed the data from the most recent DORIS satellites, Jason-3 and Sentinel-3A. The ACs analyzed the sensitivity to the South Atlantic Anomaly (SAA) of the respective satellite Ultra Stable Oscillators (USO).

Analysis working group meetings were held in Toulouse (France), May 28-29, 2015 (*hosted by Collecte Localisation Satellites*), in Greenbelt, Maryland (USA), October 15-16, 2015 (*hosted by NASA Goddard Space Flight Center in Greenbelt, Maryland, USA*) and in Delft (The Netherlands), May 26-27, 2016 (hosted by Technical University of Delft). An IDS Workshop was held in La Rochelle (France), October 31 to November 01, 2016, in conjunction with the Ocean Surface Topography Science Team (OSTST) meeting.

For ITRF2014, the six active analysis centers agreed to submit new SINEX solutions. In addition, the CNES POD center is a lead DORIS analysis center. They do not submit SINEX solutions for the IDS combination, but since they have prime POD responsibility for many of the DORIS satellites, they are the source for much of the spacecraft information needed for processing. In addition, they prepare the DORIS format 2.2 data (the range-rate format) that is used by the IDS ACs. We have also the participation by three other institutions: GFZ, TU/Delft, The University College/London. The GeoForschung Zentrum (GFZ) has participated in several of the IDS meetings, and focused on the POD analysis for altimeter satellites. TU/Delft is analyzing data from Cryosat-2, and has made available the spacecraft quaternions for use by other team members. UCL is interested in working with individual DORIS ACs on the refinement of non-conservative force modeling for DORIS satellites. GFZ was recognized by the Governing Board as an Associated Analysis Center (AAC) in October 2015. CNES POD and TU/Delft became AAC in May 2017.

So to summarize, the IDS includes six Analysis Centers and three Associated Analysis Centers who use seven different software packages, as summarized in Table 3. We also note which analysis centers on a routine basis perform POD analyses of DORIS satellites using other geodetic techniques (c.f. Satellite Laser Ranging (SLR), or GNSS). The multitechnique analyses are useful since they can provide an independent assessment of DORIS system performance, and allow us to validate more easily model changes and the implementation of attitude laws for the different spacecraft, in the event spacecraft external attitude information (in the form of spacecraft quaternions) is not available. We note that a representative of the Norwegian Mapping Authority (NMA) expressed in an interest in analysis of DORIS data, and also in multi-technique analyses. The participation of the NMA (Geir Arne Hjelle) and other potential IDS ACs continues to be encouraged.

Table 3: Summary of IDS Analysis Centers

Name	AC	AAC	Location	Contact	Software	Multi-technique
ESA	X		Germany	Michiel Otten	NAPEOS	SLR, GNSS
GOP	X		Czech Republic	Petr Stepanek	Bernese	
GRG	X		France	Hugues Capdeville	GINS	SLR, GNSS
GSC¶	X		USA	Frank Lemoine	GEODYN	SLR
IGN	X		France	Pascal Willis	GIPSY	
INA	X		Russia	Sergei Kuzin	GIPSY	
CNES		X	France	Alexandre Couhert	Zoom	SLR, GNSS
GFZ		X	Germany	Sergei Rudenko/Rolf Koenig	EPOS-OC	SLR, GNSS
TU Delft		X	The Netherlands	Ernst Schrama	GEODYN	SLR

Following the DORIS processing for the realization of the ITRF2014, there were still many substantive issues that remained to be addressed. Some issues, such as the jump in the DORIS scale (2012 and later) have been analyzed. The IDS scale jump in 2012 is now fully explained by a variation in the number of low-elevation measurements included in the processing. Indeed, the increase of the scale factor for Jason-2 and Cryosat-2 is linked to the change of tropospheric model used by CNES in its POD processing (GDR standards): from CNET (GDR-C) to GPT/GMF (GRD-D). It caused a reduction of the amount of data marked as "rejected" in the doris2.2 file (input DORIS data file) and then, an increase of the data used considered to be good in CNES pre-processing. The larger amount of data, especially at low elevation, could thus be the cause of the change observed in the scale factor. The date of change is mission dependent. The scale increase of the multi-satellite solutions is due to the jump of the scale of the Jason-2 and Cryosat-2 solutions as well as to the high scale of HY-2A, whose DORIS data became available starting in November 2011. So, IDS ACs need to do their own pre-processing, while the high scale observed on HY-2A remains an unelucidated issue.

Since 2008, starting with Jason-2, the satellites equipped with a DORIS receiver carry the new generation of receivers called DGXX which provides phase and pseudo-range measurements. They are distributed in a dedicated format, called RINEX/DORIS 3.0 derived from the RINEX/GPS format. One major advantage of these new measurements is that they are available with a very short latency. They also allow analysis centers to be less dependent on the CNES since the new data format provides the raw information that is necessary for computing the ionosphere delays and the precise time-tagging of the measurements. This was not the case for the former data format where this information was only given in a pre-processed form, following a pre-processing done by the CNES. While CNES supplies data files in doris2.2 and RINEX/DORIS 3.0 formats for the missions equipped with DGXX (Jason-2, Cryosat-2, HY-2A and Saral), only the latter format is available for the missions from Sentinel-3A and Jason-3 and following. To help ACs to implement the RINEX data processing in their software a dedicated web page about DORIS RINEX data was created on the IDS website:
http://ids-doris.org/about-doris-rinex-format.html

IDS completed an assessment of the three realizations of the Terrestrial Reference Frame which are the outcome of the "ITRF2014 effort": the ITRF2014 (IGN), DTRF2014 (DGFI) and JTRF2014 (JPL). While ITRF2014 and DTRF2014 are qualitatively similar, differing mainly by the Post Seismic Deformation model (PSD), which was introduced into the IGN solution, the JPL solution was quite different, being a time series of weekly solutions obtained through a Kalman filter process. Due to editing criteria the JPL solution contains less stations at a given time than the two other realizations, particularly at the beginning of the DORIS data period, in 1993. The three TRF realizations were evaluated in terms of DORIS observation residuals, orbit overlaps and transformation parameters of the DORIS network. All TRF realizations show a clear improvement over the previous realization, ITRF2008. Based on the different criteria used for evaluation, analysis by IDS components showed that the ITRF2014(IGN) realization provides the best overall performance. It is this realization that will serve as a basis for the operational processing of future DORIS data. For that purpose the ITRF2014 needs to be augmented (e.g. with new DORIS stations not present in the ITRF2014 solutions, or if necessary, correction of the position and velocity for the stations which had a short observation interval in the ITRF2014). This extension of ITRF2014 for the DORIS network is called DPOD2014: an update of the position/velocity of all stations is performed and aligned on the ITRF2014, leading to possible minor adjustment of older stations. A version of the DPOD2014 (DORIS extension of the ITRF for Precise Orbit Determination) was submitted by IDS Combination Center to the evaluation of the users at the beginning of 2017 and is described in more detail in the next section. More information about DPOD2014 is available from the URL: https://ids-doris.org/analysis-coordination/combination/dpod.html

The behavior of the various DORIS on-board oscillators in the vicinity of the high radiation area "South Atlantic Anomaly" (SAA) was also studied. DORIS ACs showed that all DORIS receivers are sensitive to the crossing of the SAA, though to different degrees. Thanks to the extremely precise time-tagging provided by the T2L2 experiment on-board Jason-2, A. Belli and the GEOAZUR team showed that the Jason-2 DORIS Ultra Stable Oscillator (USO) is approximately 10 times less sensitive to the SAA than that of Jason-1. The IGN AC has shown, thanks to the "DORIS PPP method" on uncorrected Jason-2 DORIS data, that the positioning error due to the SAA can reach up to 10 cm for some stations with this satellite. The GRG AC and C. Jayles from CNES both showed that Jason-3 is also sensitive to the SAA, at a level that is lower than that of Jason-1, but still 4 to 5 times higher than that of Jason-2. The CNES POD team showed that Sentinel-3A is also sensitive to the SAA. Using a novel method based on the clock determination of the GNSS receiver on-board Sentinel-3A, the CNES POD team showed that it is possible to obtain an accurate and continuous observation of the satellite's USO frequency excursions. One of the conclusions of these studies was that, while no noticeable effect of the SAA influence was shown on POD or reference frame transformation parameters, there is an important impact on the station position estimation for some stations in the vicinity of the SAA area. Building accurate models of frequency variations in response to the temperature and to the SAA radiation effects for each DORIS USO is therefore a task that is encouraged by the IDS community for the accurate position estimation of all DORIS stations.

ACs must complete the implementation of the DORIS/RINEX data processing in order to be able to process the data from Jason-3 and Sentinel-3A (available first quarter of 2016). The IDS will switch to ITRF2014 for operational products when the DPOD2014 becomes available. The next IDS Analysis working group meeting will be held in London (U.K.), May 22-24, 2017 (*hosted by University College London*).

2.5 Combination Center

In addition to its operational activities of evaluation and combination of all the individual ACs weekly solutions, the IDS Combination Center has been involved in several studies proposed by the AWG and the Analysis Coordinator such as the scale jump in 2012 and the evaluation of the three 2014 TRF realizations from DGFI, IGN and JPL.

DORIS position and velocity cumulative solution

In line with the successful IDS contribution to the ITRF2014, the IDS CC initiated the elaboration of a DORIS position and velocity cumulative solution. To validate the stacking procedure and the DORIS mean velocities, the IDS CC compared the DORIS velocities with global tectonic models as well as with GNSS velocities at co-located sites. The analysis of the velocity differences (Moreaux et al., 2016, Geophysical Journal Intl.) validated the new stacking procedure. Then, early in 2017, the IDS CC started to regularly (on a quarterly basis) process and deliver (via the IDS Data Centers) a DORIS position and velocity cumulative solution from the latest IDS combined series. So far, this solution does not include Post-Seismic Deformation corrections; a piecewise linear (position+velocity) model is used to describe the station motions. A dedicated webpage (https://ids-doris.org/analysis-coordination/combination/cumulative-solution.html) was also added to the IDS website to give further information on the IDS cumulative solution (ex: residual time series, DORIS-to-DORIS tie vector residuals, DORIS-to-GNSS tie vector comparisons, position and velocity differences with ITRF2014…).

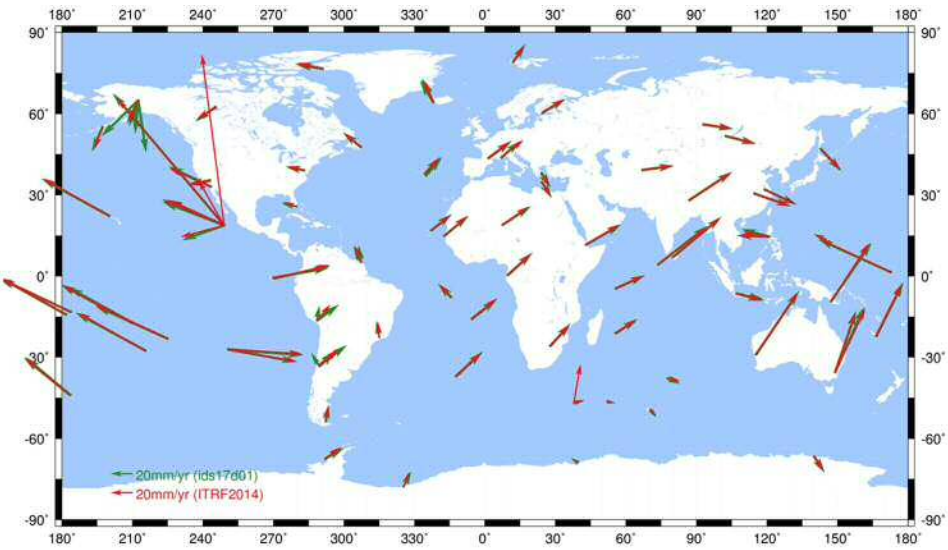


Figure 3 - Horizontal velocities of the DORIS sites from ITRF2014 (red) and the first DORIS cumulative solution

DPOD2014

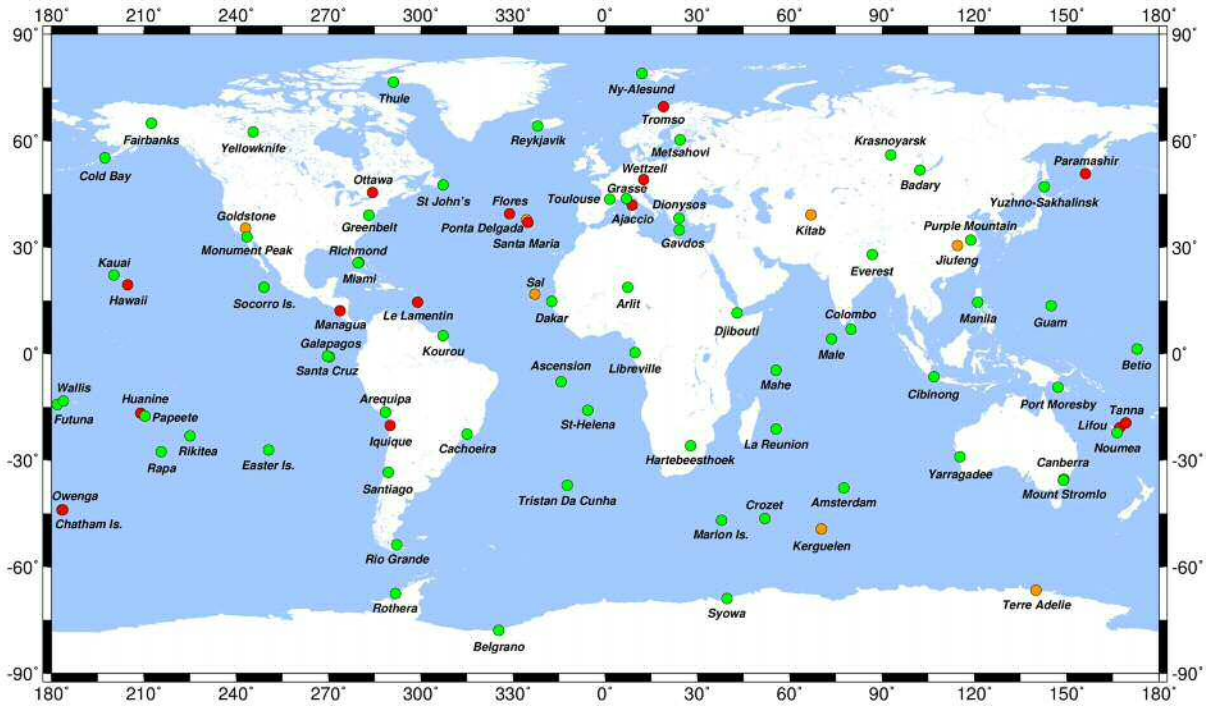


Figure 4 - DORIS sites in DPOD2014_v01 produced by the IDS Combination Center; green indicates sites in ITRF2014 and DPOD2014_v01; orange indicates sites in both coordinate sets but updated in DPOD2014_v01; red indicates sites **not** in ITRF2014, but included in DPOD2014_v01.

During the first 2015 IDS AWG held in Toulouse, the IDS CC agreed to take over from P. Willis the routine production of the DPOD: "the DORIS extension of the ITRF for Precise Orbit Determination". The DPOD solutions were initiated to overcome some intrinsic drawbacks of using the latest ITRF: i) some stations are added to the tracking network after the completion of the ITRF; ii) some stations might be affected by coordinate and/or velocity discontinuities that could occur after the realization of the ITRF; iii) the precision of the position and velocities of the stations with few observations at the time of the ITRF can be increased with a longer data span and; iv) some problems in geodetic technique data processing may be found after the computation of the ITRF (e.g. USO sensibility to the SAA). Based on the latest IDS position and velocity cumulative solution, the IDS CC constructs the DPOD2014 solutions aligned to the ITRF2014. After some IDS CC internal validation tests (including coordinate and velocity differences with the previous DPOD solution and ITRF realization), the IDS POD validation group lead by P. Willis performs some POD tests with many of the DORIS satellites. After approval by the POD validation group, the new version of DPOD2014 solution is released. DPOD2014 is available from the two IDS Data Centers and is added to the dedicated IDS website page (https://ids-doris.org/analysis-coordination/combination/dpod.html). The DPOD2014 will be updated twice a year.

<u>IDS products</u>

Table 4 presents the current IDS products available through the two IDS data centers. All Analysis Centers provided at a least a long-term weekly solution of SINEX files.

Table 4 Summary of IDS Products.

Type of Products	**Contributing Analysis Centers ¶**							
	ESA	**GOP**	**GRG§**	**GSC**	**IGN**	**INA**	**IDS✚**	**SSA**
Time series of SINEX solutions (***sinex_series***)	X	X	X	X	X	X	X	X
Global SINEX solutions (***sinex_global***)			X		X		X	
Geocenter time series (***geoc***)			X	X				X
Satellite Orbits (*orbits*)			X	X				X
Ionosphere products/sat. (***iono***)								X
Time series of EOP (***eop***)					X	X		
Time series of station coordinates (***stcd***)	X		X	X	X	X	X	X
Time series of SINEX solutions (***2010campaign***)		X	X	X	X	X		
	✚ Combination Center of the IDS. **§ The GRG analysis center was renamed from the "LCA" analysis center in 2015.** **¶ Previous analysis centers who have contributed products include GAU (Geoscience Australia) and CNES POD team under the ID "SOD"**							

3. IDS meetings and publications

3.1 Meetings

IDS organizes two types of meetings:

- IDS Workshops (every two years), opened to a large public and related to scientific aspects or applications of the DORIS systems
- Analysis Working Group Meetings (AWG) (when needed), more focused on technical issues, and usually attended by representatives of Analysis Centers.

Table 5 IDS Meetings (2015-2017)

Meeting	Location	Country	Dates
DORIS AWG Meeting	Toulouse	France	28-29 May 2015
DORIS AWG Meeting	Greenbelt	Maryland, USA	15-16 October 2015
DORIS AWG Meeting	Delft	Netherlands	26-27 May 2016
IDS Workshop	La Rochelle	France	31 ctober – 1 November 2016

3.2 Publications

During the last two years, IDS published several activity reports:

Willis, P., International DORIS Service (IDS), Report of the International Association of Geodesy 2011-2015, Travaux de l'Association Internationale de Géodésie, 2015. http://ids-doris.org/documents/report/IDS_Report_mid2011_mid2015_for_IAG.pdfhttp://ids-doris.org/documents/report/IDS_Report_2007_2011_for_IAG.pdf

Capdeville, H., Couhert, A., Ferrage, P., Kuzin, S., Lemoine, F., Moreaux, G., Noll, C., Otten, M., Rudenko, S., Saunier, J., Schrama, E., Soudarin, L., Stepanek, P., Willis, P. International DORIS Service Activity report 2014, 122 pages, 2015. http://ids-doris.org/documents/report/IDS_Report_2014.pdf

Capdeville, H., Couhert, A., Ferrage, P., Kuzin, S., Lemoine, F., Moreaux, G., Noll, C., Otten, M., Rudenko, S., Saunier, J., Soudarin, L., Stepanek, P., Willis, P. International DORIS Service Activity report 2015, 99 pages, 2016. http://ids-doris.org/documents/report/IDS_Report_2015.pdf

3.2 Peer-reviewed publications related to DORIS

Following two DORIS Special Issues published in Journal of Geodesy in 2006-2007, and Advances in Space Research in 2010, a third DORIS Special was launched in 2014. A total of 18 manuscripts passed the peer-reviewed process and were published in Advances in Space Research on December 15, 2016, in Volume 58, Number 12. This special issue is entitled "The scientific applications of DORIS in Space Geodesy" and is edited by Frank G. Lemoine and Ernst J.O. Schrama. The papers cover five themes: ITRF2014; DORIS Ultra Stable Oscillator (Jason-2); Precise orbit determination; DORIS System and Network; Intertechnique comparisons of DORIS products. The direct link to the special issue index is available at the following URL: http://www.sciencedirect.com/science/journal/02731177/58/12

IDS also maintains on its Web site a complete list of DORIS-related peer-reviewed articles published in international Journals (http://ids-doris.org/report/publications/peer-reviewed-journals.html). In the last two years, the following articles were published (by year):

In press

Kong, Q.; Guo, J.; Sun, Y., 2017. Centimeter-level precise orbit determination for the HY-2A satellite using DORIS and SLR tracking data, ACTA GEOPHYSICA, DOI: 10.1007/s11600-016-0001-x http://link.springer.com/article/10.1007/s11600-016-0001-x

Rudenko, S.; Neumayer, K.-H.; Dettmering, D.; Esselborn, S.; Schöne, T.; Raimondo, J.-C.; 2017. Improvements in precise orbits of altimetry satellites and their impact on mean sea level monitoring, IEEE Transactions on Geoscience and Remote Sensing, DOI: 10.1109/TGRS.2017.2670061

2017

Chen, P.; Yao, Y.; Yao, W., 2016. Global ionosphere maps based on GNSS, satellite altimetry, radio occultation and DORIS, GPS SOLUTIONS, 21(2), 639-650, DOI: 10.1007/s10291-016-0554-9

Gu, Y.; Yuan, L.; Fan, D.; You, W.; Su Y., 2017. Seasonal crustal vertical deformation induced by environmental mass loading in mainland China derived from GPS, GRACE and surface loading models, ADVANCES IN SPACE RESEARCH, 59(1), 88-102, DOI: 10.1016/j.asr.2016.09.008

2016

Altamimi, Z.; Rebischung, P.; Métivier, L.; Collilieux, X., 2016. ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, JOURNAL OF GEOPHYSICAL RESEARCH: Solid Earth, 121(8), 6109-6131, DOI: 10.1002/2016JB013098 OPEN ACCESS

Belli, A.; Exertier, P.; Samain, E.; Courde, C.; Vernotte, F.; Jayles, C.; Auriol, A., 2016. Temperature, radiation and aging analysis of the DORIS Ultra Stable Oscillator by means of the Time Transfer by Laser Link experiment on Jason-2, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2589-2600, DOI: 10.1016/ j.asr.2015.11.025

Bloßfeld, M.; Seitz, M.; Angermann, D.; Moreaux, G., 2016. Quality assessment of IDS contribution to ITRF2014 performed by DGFI-TUM, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2505-2519, DOI: 10.1016/j.asr.2015.12.016

Capdeville, H.; Štěpánek, P.; Hecker, L.; Lemoine, J.M., 2016. Update of the corrective model for Jason-1 DORIS data in relation to the South Atlantic Anomaly and a corrective model for SPOT-5, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2628-2650, DOI: 10.1016/j.asr.2016.02.009

Jayles, C.; Chauveau, J.P.; Didelot, F.; Auriol, A.; Tourain, C., 2016. Doris system and integrity survey, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2691-2706, DOI: 10.1016/j.asr.2016.05.032

Jayles, C.; Exertier, P.; Martin, N.; Chauveau J.P.; Samain E.; Tourain C.; Auriol A.; Guillemot P., 2016. Comparison of the frequency estimation of the DORIS/Jason2 oscillator thanks to the onboard DIODE and Time Transfer by Laser Link experiment, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2601-2616, DOI: 10.1016/j.asr.2015.08.033

Khelifa, S., 2016. Noise in DORIS station position time series provided by IGN-JPL, INASAN and CNES-CLS Analysis Centres for the ITRF2014 realization, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2572-2588, DOI: 10.1016/j.asr.2016.06.004

King, M. A.; Santamaría-Gómez, A., 2016. Ongoing deformation of Antarctica following recent Great Earthquakes, GEOPHYSICAL RESEARCH LETTERS, 43, 1918–1927, DOI: 10.1002/2016GL067773

Kuzin, S.; Tatevian, S., 2016. DORIS data processing in the INASAN Analysis Center and the contribution to ITRF2014, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2561-2571, DOI: 10.1016/j.asr.2016.07.010

Heinkelmann, R.; Willis, P.; Deng, Z.; Dick, G.; Nilsson, T.; Soja, B.; Zus, F.; Wickert, J.; Schuh, H., 2016. Multi-technique comparison of atmospheric parameters at the DORIS co-location sites during CONT14, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2758-2773, DOI: 10.1016/j.asr.2016.09.023

Lemoine, F.G.; Chinn, D.S.; Zelensky, N.P.; Beall, J.W.; Le Bail, K., 2016. The Development of the GSFC DORIS Contribution to ITRF2014, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2520-2542, DOI: 10.1016/j.asr.2015.12.043 OPEN ACCESS

Lemoine, J.M.; Capdeville, H.; Soudarin, L., 2016. Precise orbit determination and station position estimation using DORIS RINEXdata, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2677-2690, DOI: 10.1016/j.asr.2016.06.024

Moreaux, G.; Lemoine, F.G.; Argus, D.F.; Santamaría-Gómez, A.; Willis, P.; Soudarin, L.; Gravelle, M.; Ferrage, P., 2016. Horizontal and vertical velocities derived from the IDS contribution to ITRF2014, and comparisons with geophysical models, GEOPHYSICAL JOURNAL INTERNATIONAL, 207(1), 209-227, DOI: 10.1093/gji/ggw265

Moreaux, G.; Lemoine, F.G.; Capdeville, H.; Kuzin, S.; Otten, M.; Štěpánek, P.; Willis, P.; Ferrage, P., 2016. The International DORIS Service contribution to the 2014 realization of the International Terrestrial Reference Frame, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2479-2504, DOI: 10.1016/j.asr.2015.12.021

Rudenko, S.; Dettmering, D.; Esselborn, S.; Fagiolini, E.; Schöne, T., 2016. Impact of Atmospheric and Oceanic De-aliasing Level-1B (AOD1B) products on precise orbits of altimetry satellites and altimetry results, GEOPHYSICAL JOURNAL INTERNATIONAL, 204(3), 1695-1702, DOI: 10.1093/gji/ggv545

Saunier, J., 2016. Assessment of the DORIS network monumentation, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2725-2741, DOI: 10.1016/j.asr.2016.02.026

Saunier, J.; Auriol, A.; Tourain, C., 2016. Initiating and error budget of the DORIS ground antenna position Genesis of the Starec antenna type C, in DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2717-2724, DOI: 10.1016/j.asr.2016.02.013

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International GNSS Service (IGS)

https://www.igs.org

Chair of the Directing Board: Gary Johnston (Australia)
Director of the Central Bureau: Ruth Neilan (USA)

Introduction

Applications of the Global Navigation Satellite Systems (GNSS) to Earth Sciences and Position, Navigation and Timing technologies are numerous and growing. The International GNSS Service (IGS), a voluntary federation of government agencies, universities and research institutions, combines GNSS resources and expertise to provide the highest–quality GNSS data, products, and services in order to support high–precision applications for GNSS–related research and engineering activities. The IGS has been a service of the IAG since 1994.

Overview

The IGS has continued to support GNSS users through the 2015-2017 reporting period. The IGS provides essential products that contribute to the realization of ITRF and enable very high accuracy positioning using GNSS technologies in support of science and other societal applications. The Service also provides a number of experimental products, in a continuous effort to encourage technological and analytical improvement. IGS continues to refine the accuracy and consistency of its products by an ongoing process of technique improvement and reprocessing of past data sets in order to achieve the highest quality results.

The IGS continues to adapt and contribute to advances in technology, including ongoing and increased efforts for transitioning to a multi-GNSS service, as well as advancing real-time applications. Re-tooling and modernization of capabilities, as well as developing and extending relevant standards, have also been significant efforts within the IGS.

In addition to many technical achievements, the IGS continues with proactive efforts to sustainably maintain and develop the IGS organization and improve its management. Starting where the 2013-2016 Strategic Plan ended, a comprehensive questionnaire of IGS participants and the user community was undertaken, followed by a strategic planning process which took place in late 2016 and early 2017. The resulting 2017 Strategic Plan has been developed in response to feedback from the questionnaire, as well as retaining key elements of the previous strategic plan's goals and objectives. It also aims to recognize the extensive contribution of the IGS participants, and to encourage strong engagement with a broader stakeholder set that now rely implicitly on IGS products and services.

The IGS Terms of Reference, as well as the associate membership, have been reviewed annually by the Governing Board and relevant committees since 2011, with updates to both in the last year. All current IGS organizational documents and component membership rosters are maintained in the IGS Knowledge Base website: http://kb.igs.org/.

By working within the science community through (IAG/IUGG/ICSU) and the inter-governmental community through ICG / UN GGIM / US PNT AB and others, the IGS GB is ensuring the IGS retains its strong level of relevance and impact, and therefore sustainability.

Events and Milestones

MGEX Experiment Transition to Service and Pilot Project

The success of the MGEX experiment has demonstrated the inevitability of a transition of the IGS to a full multi–GNSS Service. Accordingly, the Governing Board decided to acknowledge this by terminating the "experiment" status and move MGEX to the status of a Pilot Project. Continued efforts are required to negotiate access to satellite specific information for new satellites from system providers, allowing for more realistic models of satellite behavior to be developed and utilized by the IGS AC's.

Wuhan Data Center

In 2015 the Governing Board endorsed the proposal by Wuhan University, China, to become an IGS Global Data Center. The Wuhan Data Center offers access to the full collection of IGS data and products to any user globally, especially those within the Asia Pacific Region. Importantly the data center gives direct access to the IGS data holdings to the very large research sector within China.

New Analysis Center Coordinator

IGS has continued with a very exciting work program and list of achievements from the IGS participants and contributing organizations. The role of Analysis Centre Coordinator (ACC) is now distributed across two centers, Geoscience Australia and MIT, in two continents, hemispheres apart, using combination software operating on Cloud computing services (Amazon Web Services).

IGS 2016 Workshop in Sydney, Australia

In 2016, the IGS had its first workshop to be held outside of North America or Europe, with the Sydney Workshop held in February 2016 at the University of New South Wales. This workshop, the first in South East Asia, and the first in the southern hemisphere, signaled the stronger involvement of BeiDou and QZSS into the IGS's GNSS futures and featured keynote presentations from Todd Humphreys (University of Texas at Austin), Jan Weiss (UCAR), and John Church (CSIRO), as well as over 50 plenary presentations and 57 posters. Keynotes, presentations, and posters may be viewed on the IGS website: http://www.igs.org/presents/workshop2016.

IGS-UN ICG Collaboration on GNSS Monitoring and Assessment

IGS played a key role in forming the United Nations International Committee on GNSS (ICG) International GNSS Monitoring and Assessment (IGMA) Task Force. Collaboratively with the IGS, the IGMA has now established the Joint GNSS Monitoring Project and Working Group, and completed the inaugural meeting of the working group concurrent with the Sydney IGS workshop. The Call for Proposals for participation in the IGS / ICG joint Monitoring and Assessment project is a pragmatic example of the IGS being flexible enough to respond to stakeholder requirements. That project aims to utilize existing skills within the IGS community to service a new user community as an extension to our current role of providing world class GNSS expertise. The Call for Participation had a strong response including a proposal from ESA to undertake the Monitoring and Assessment ACC function. Importantly this new joint project ensures the IGS continues to have strong influence with GNSS system providers. This strong relationship has been developed over many years by IGS participation in the ICG.

Publications, Presentations, Outreach

Comprehensive lists of IGS publications since 2015, as well as publications referencing IGS in that timeframe, may be found, organized according to IGS component, in the 2015 Technical Report as well as the 2016 Technical Report.

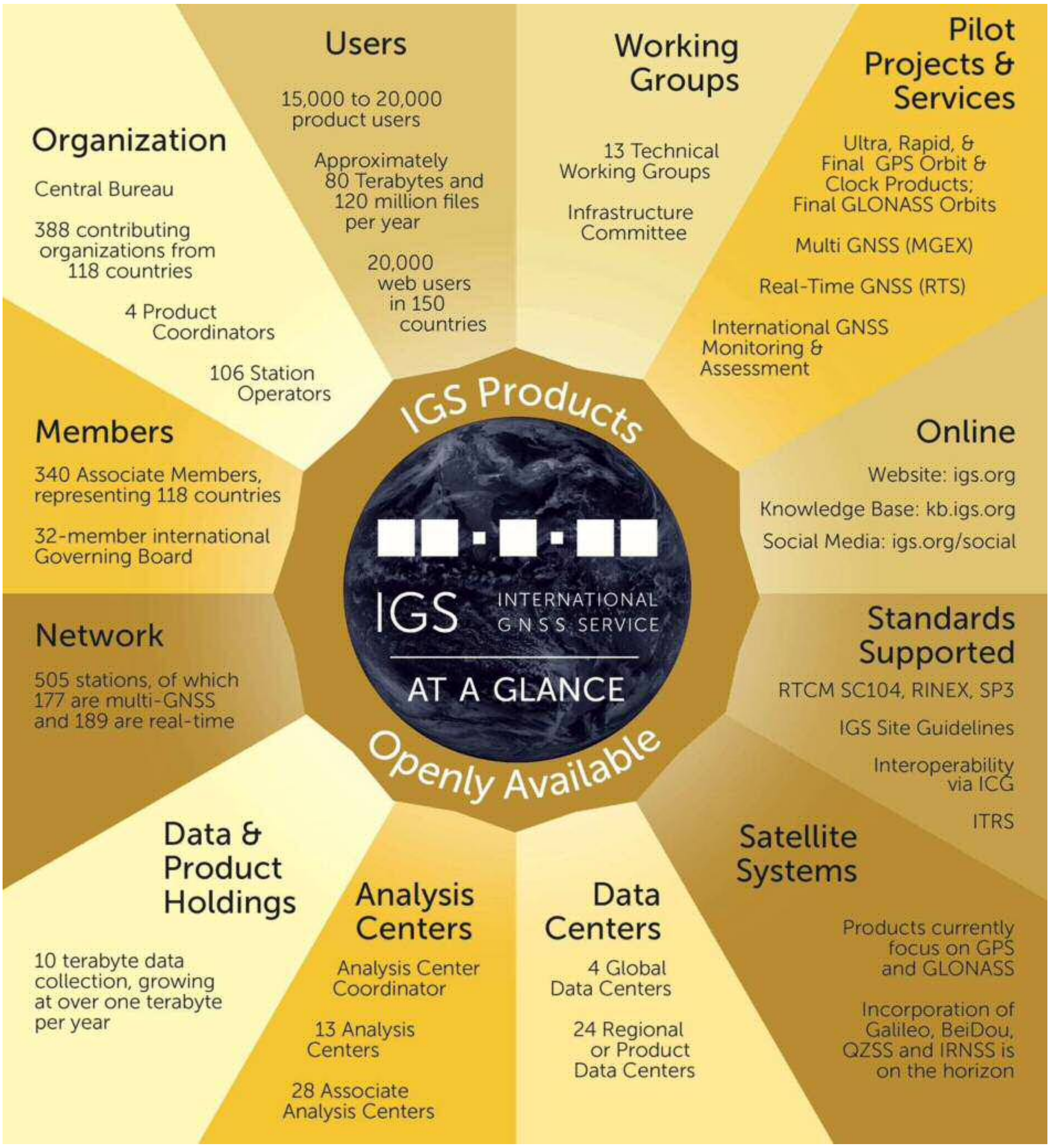

Figure 1: The IGS At-a-Glance

IGS Structure

The IGS is a self-governed federation of 388 contributing organizations from 118 countries around the world that collectively operate a global infrastructure of tracking stations, data centers and analysis centers to provide high quality GNSS data products. The IGS products are provided openly for the benefit of all scientific, educational, and commercial users. The IGS is governed by an international Governing Board (Table 1) that is elected by designated Associate Members who represent the principal IGS participants. Executive management of the IGS is carried out by the Central Bureau, as is coordination of the IGS Tracking Network and management of the IGS web portal that provides centralized access to IGS products and information. IGS products are generated by combining results from different Analysis Centers under the direction of the Analysis Coordinator and specific Product Coordinators. Introduction of new products and specific technical issues are addressed through Pilot Projects and Working Groups of technical experts (Table 2). The IGS organization is depicted in Figure 2.

Table 1: IGS Governing Board Members, as of May 2017

Status	First	Last Name	Affiliation	Country	Role	Service Years
EC-V	Gary	Johnston	Geoscience Australia	Australia	Board Chair	2010-2018
	Michael	Moore	Geoscience Australia	Australia	Analysis Center Co-Coordinators	2016-2019
EC-V	Chris	Rizos	University of New South Wales	Australia	IAG appointed	2004-2019
V	Carine	Bruyninx	Royal Observatory of Belgium Observatoire Royal de Belgique (ORB)	Belgium	IGS Network Representative	2011-2017
	Ken	MacLeod	Natural Resources Canada / Ressources naturelles Canada	Canada	RINEX-RTCM Working Group Chair	2012-2019
V	Felicitas	Arias	Bureau International des Poids et Mesures	France	BIPM/CCTF Representative	2005-Present
V	Zuheir	Altamimi	Institut National de l'Information Géographique et Forestière	France	IAG Representative	2011-2019
V	Paul	Rebischung	Institut National de l'Information Géographique et Forestière	France	IGS Reference Frame Coordinator	2017-2020
V	Laura	Sanchez	Deutsches Geodätisches Forschungsinstitut	Germany	Network Representative	2014-2017
V	Mathias	Fritsche	Deutsches GeoForschungs Zentrum (GFZ)	Germany	Analysis Center Representative	2015-2019
	Oliver	Montenbruck	Deutsches Zentrum für Luft- und Raumfahrt e. V.	Germany	Multi-GNSS Working Group Chair	2012-2020
	Tilo	Schöne	DeutschesGeoForschungsZentrum Potsdam	Germany	TIGA Working Group Chair	2001-2020
V	Loukis	Agrotis	ESA/European Space Operations Centre	Germany	Real-time Analysis Coordinator	2014-2017
V	Werner	Enderle	ESA/European Space Operations Centre	Germany	Appointed (IGS)	2016-2017
	Ignacio	Romero	ESA/European Space Operations Centre	Germany	Infrastructure Committee Chair	2010-2017
	Axel	Ruelke	Federal Agency for Cartography and Geodesy (BKG)	Germany	Real-time Working Group, Chair	2016-2019

V	Satoshi	Kogure	Japan Aerospace Exploration Agency (JAXA)	Japan	Appointed (IGS)	2014-2017
	Andrzej	Krankowski	University of Warmia and Mazury in Olsztyn	Poland	Ionosphere Working Group Chair	2007-2020
EC-V, IR	Rolf	Dach	Astronomical Institute, University of Bern	Switzerland	Analysis Center Representative	2015-2018
	Arturo	Villiger	Astronomical Institute, University of Bern	Switzerland	Antenna Working Group Chair	2017-2020
	Stefan	Schaer	Federal Office of Topography - swisstopo	Switzerland	Calibration & Bias Working Group Chair	2007-2020
	Marek	Ziebart	University College London	UK	Analysis Center Coordinator	2011-2020
EC-V	Ruth	Neilan	IGS Central Bureau, Jet Propulsion Laboratory	USA	Director of IGS Central Bureau	1994-Present
V	Shailen	Desai	Jet Propulsion Laboratory	USA	Analysis Center Representative	2012-2019
V	Richard	Gross	Jet Propulsion Laboratory	USA	IERS Representative	2015-2019
V	Thomas	Herring	Massachusetts Institute of Technology (MIT)	USA	Analysis Center Coordinator	2016-2019
	Carey	Noll	NASA Goddard Space Flight Center	USA	Data Center Working Group Chair	2006-2019
V	Michael	Coleman	Naval Research Laboratory	USA	IGS Clock Products Coordinator	2014-2017
V	Fran	Boler	UNAVCO	USA	Data Center Representative	2014-2017
	David	Maggert	UNAVCO	USA	Network Coordinator	2015-2019
EC-V, IR	Charles	Meertens	UNAVCO	USA	Appointed (IGS)	2011-2018
	Sharyl	Byram	United States Naval Observatory	USA	Troposphere Working Group, Chair	2016-2019

Table 2: IGS Working Groups and Projects

Working Group / Project	Activity	Chair
Antenna	Coordinates research in the field of GNSS receiver and satellite antenna phase center determination	Arturo Villiger
Bias and Calibration	Updates various bias values and related auxiliary information for consistent GNSS analysis (product generation), e.g., differential code biases; defines standards and data exchange formats in the field of GNSS biases	Stefan Schaer
Clock Products	Global sub-nanosecond time transfer, and IGS time-scale, jointly with the Bureau International des Poids et Mesures (BIPM)	Michael Coleman
Data Center	Coordination among IGS data centers and support for increasing number of products and real-time	Carey Noll
IGMA Monitoring	United Nations International Committee on GNSS (ICG) International GNSS Monitoring and Assessment (IGMA) Task Force and International GNSS Service (IGS) Joint GNSS Monitoring Working Group	Urs Hugentobler
Ionosphere	Ionospheric science research, global ionospheric maps	Andrzej Krankowski
Multi-GNSS WG and Multi-GNSS Extension (MGEX) Project	Determine actions necessary for IGS to co-opt new GNSS systems, European Union's Galileo system, China's BeiDou, and GPS modernization	Oliver Montenbruck
Real-time WG and Real-Time Service	Demonstrate for IGS real-time network and applications	Axel Rülke
Reference Frame	Global reference frame, Earth orientation, station positions and velocities determined by GNSS	Paul Rebischung
RINEX	Coordinates the development of GNSS observation, navigation and meta data formats	Ken MacLeod
Space Vehicle Orbit Dynamics	Improved understanding and modeling of satellite dynamics towards further improvement of precise orbit determination	Marek Ziebart
Tide Gauge (TIGA)	Monitor long-term sea-level change, attempt to de-couple crustal motion/subsidence at coastal sites from their tide gauge records	Tilo Schöne
Troposphere	Estimate water vapor in atmosphere from the GPS signal delay	Sharyl Byram
IGMA Joint Performance Monitoring	Aimed at creating an authoritative international GNSS monitoring and assessment system to benchmark the performance of available GNSSs	Tim Springer

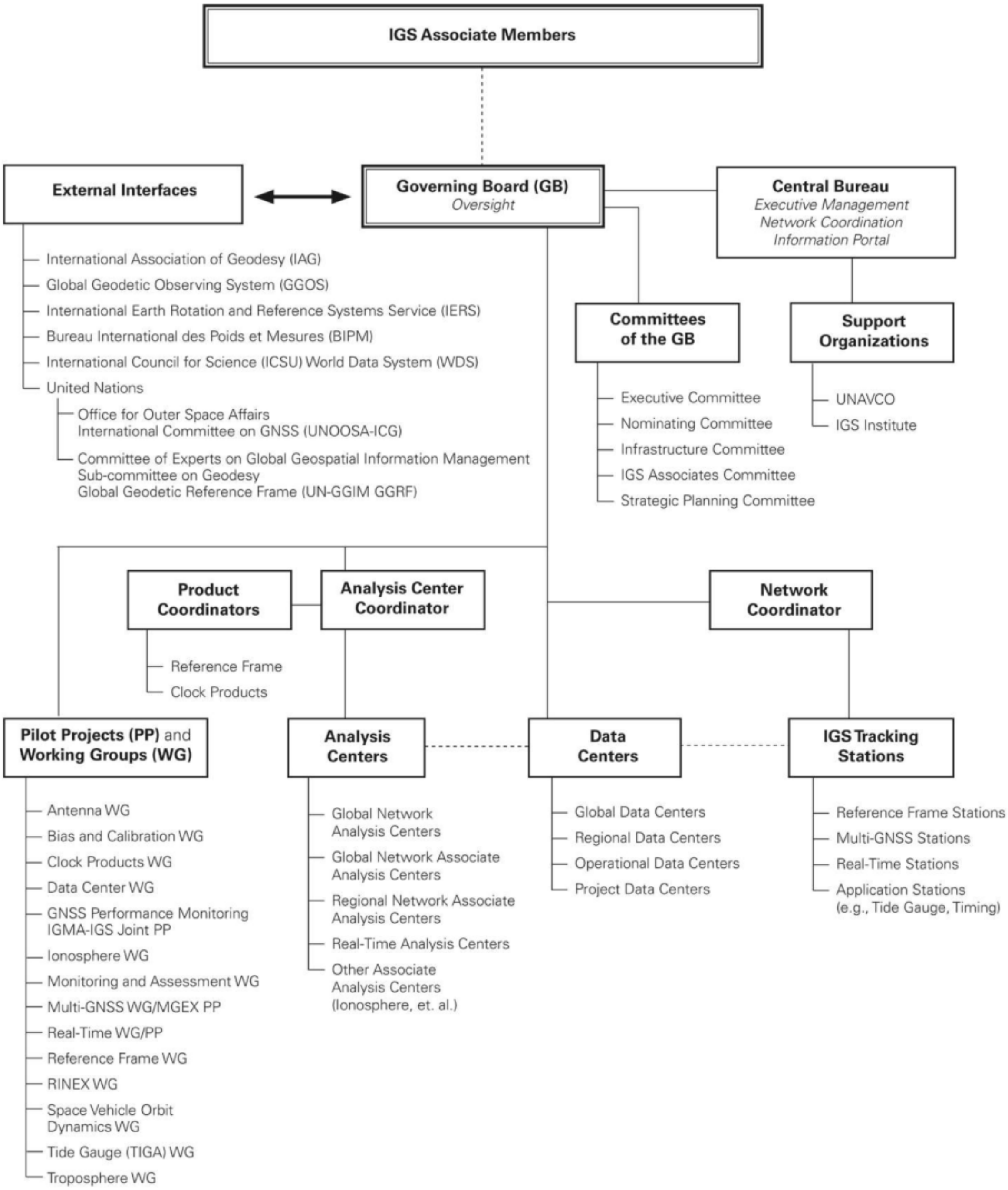

Figure 2: IGS Organization

Operational Activities

Delivery of core reference frame, orbit, clock and atmospheric products continued strongly, with further refinement of the Real-Time Service and considerable efforts being targeted towards development of standards. The transition to multi-GNSS also continued, with additional Galileo and BeiDou satellite launches bringing those constellations closer to operational status.

Over 500 IGS Network stations are maintained and operated globally by many institutions and station operators, making tracking data available at latencies ranging from daily RINEX files to real-time streams available for free public use (Figure 2). The transition of the IGS network to multi-GNSS capability has been led by the MGEX project team, with much assistance from the Central Bureau and Infrastructure Committee. The transition will has resulted in approximately 50% of IGS network stations being capable of tracking multiple GNSS constellations (GPS + GLONASS + one other) (September 2017). Within the network, 196 IGS stations are now capable of real-time data streaming in support of the IGS Real-Time Service.

The Central Bureau assumes responsibility for day-to-day management, interaction with station operators, and answering user questions and requests. The quantity of IGS tracking data held on permanently accessible servers at each of the four global data centers increases at almost 2 Terabytes per year to what is now approximately 10 Terabyte (over 100 million files). Significant additional storage capabilities are provided by regional data centers. It is estimated that approximately 20,000 users visit the IGS website and related resources each month.

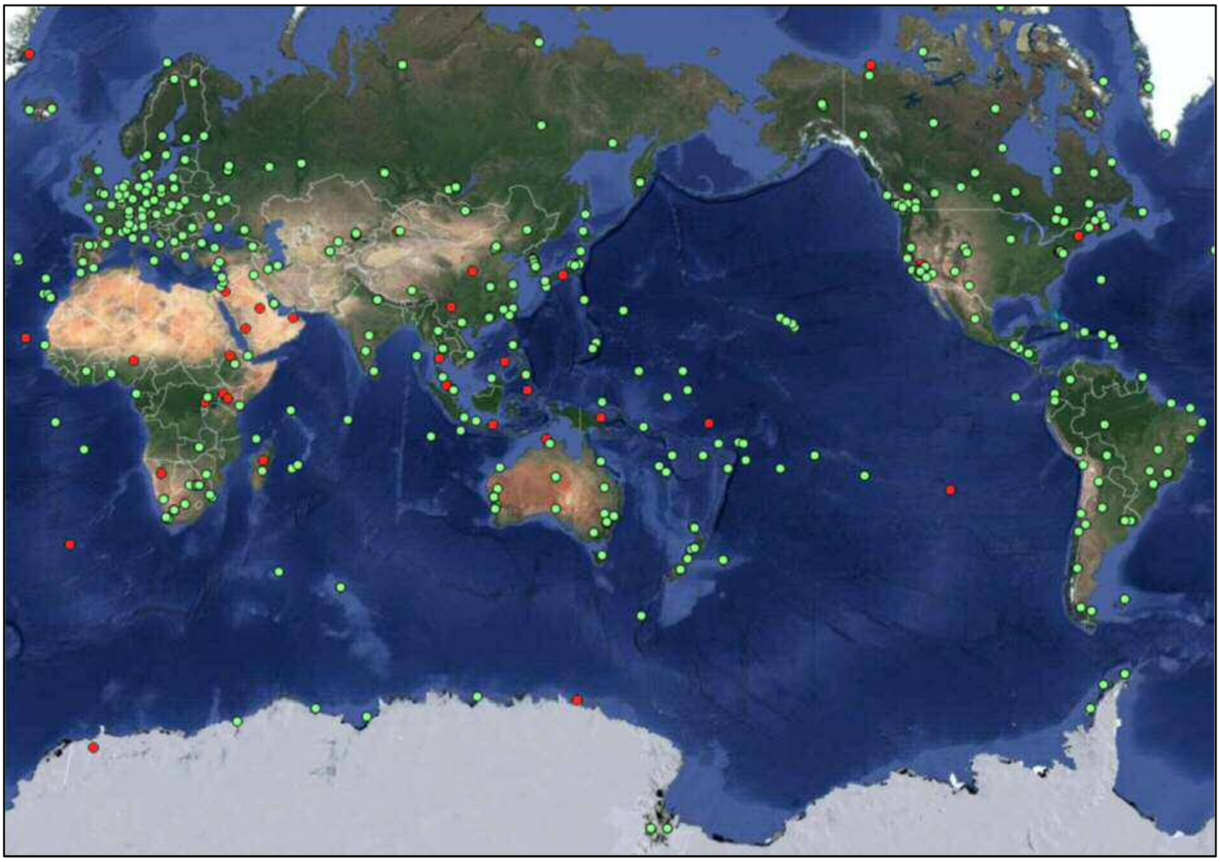

Figure 3: IGS Tracking Network

Thirteen analysis centers and 21 associate analysis centers utilize tracking data from between 70 and 350 stations, four times per day, to generate and verify the quality of highest precision products. Product coordinators combine these products on an operational basis and assure the quality of the products made available to the users. IGS product user activity documentation, courtesy of CDDIS, reveals that in 2017 (January-August), an average 106M GNSS files/12TB were downloaded per month; this includes GNSS data and product files. Focusing on IGNS product files only, then those totals are 26M GNSS product files/4.5TB on average per month. For Tropospheric downloads, CDDIS reports over 46M files totaling over 125 GB in 2016 from 500K unique hosts each month.

All these activities are performed on a daily basis, year-round, with high redundancy and reliability based on the pooled resources of more than 200 institutions worldwide. Only the daily contributions of a large number of engaged individuals makes this significant undertaking possible.

Product Quality

The IGS Analysis Centers have continued to improve product precision, consistency and availability. IGS "final" orbits now agree at a level of approximately 2 cm, and final satellite clock solutions agree at approximately 75 ps RMS with 20 ps standard deviation. The final X- and Y-pole solutions agree at approximately 0.03 mas, and the final length of day solutions agree at approximately 0.01 µs. Products have continued to be available to users, continuously meeting or exceeding the specified availability thresholds (Table 3).

Table 3: IGS Product Quality and Availability

GPS Satellite Ephemerides / Satellite and Station Clocks		Sample Interval	Accuracy	Latency	Continuity	Availability
Broadcast (for comparison)	Orbits	Daily	~100 cm	real time	Continuous	99.99%
	Sat. Clocks		~5 ns RMS; ~2.5 ns Sdev			
Ultra-Rapid (predicted half)	Orbits	15 min	~5 cm	predicted	4x daily, at 03, 09, 15, 21 UTC	99.70%
	Sat. Clocks		~3 ns RMS; ~1.5 Sdev			
Ultra-Rapid (observed half)	Orbits	15 min	~3 cm	3-9 hours	4x daily, at 03, 09, 15, 21 UTC	99.40%
	Sat. Clocks		~150 ps RMS; ~50 ps Sdev			
Rapid	Orbits	15 min	~2.5 cm	17-41 hours	daily, at 17 UTC	99.70%
	Sat. & Stn. Clocks	5 min	~75 ps RMS; ~25 ps Sdev			
Final	Orbits	15 min	~2 cm	12-18 days	weekly, every Thursday	100%
	Sat. & Stn. Clocks	Sat: 30 s; Stn.: 5 min	75 ps RMS; 20 ps Sdev			
Real-time	Orbits	5-60 s	~5 cm	25 seconds	Continuous	100.00%
	Sat. Clocks	5 s	300 ps RMS; 120 ps Sdev			

Note 1: Orbit accuracies are 1D mean RMS values over the three XYZ geocentric components. IGS accuracy limits, except for predicted orbits, are based on comparisons with independent laser ranging results and discontinuities between consecutive days. The precision is better.

Note 2: The accuracy (neglecting any contributions from internal instrumental delays, which must be calibrated separately) of all clocks is expressed relative to the IGS timescale, which is linearly aligned to GPS time in one-day segments. The standard deviation (SDev) values are computed by removing a separate bias for each satellite and station clock, whereas this is not done for the RMS values.

Note 3: Availability is the percentage of time that accuracy and continuity of service meet stated specification.

GLONASS Satellite Ephemerides	Sample Interval	Accuracy	Latency	Continuity	Availability
Final	15 min	~3 cm	12-18 days	weekly, every Thursday	100%

Geocentric Coordinates of IGS Tracking Stations *(over 250 Sites)*		Sample Interval	Accuracy	Latency	Continuity	Availability
Positions of Real-time Stations	Horizontal	daily	3 mm	1-2 hours	daily	100%
	Vertical		6 mm			
Final Positions	Horizontal	weekly	3 mm	11-17 days	weekly, every Wednesday	100%
	Vertical		6 mm			
Final Velocities	Horizontal	weekly	2 mm/yr	11-17 days	weekly, every Wednesday	100%
	Vertical		3 mm/yr			

Earth Rotation Parameters						
Ultra-Rapid (predicted half)	Polar Motion	daily integrations at 00, 06 12, 18 UTC	~200 μas	real time	4x daily, at 03, 09, 15, 21 UTC	99.70%
	Polar Motion Rate		~300 μas/day			
	Length-of-day		~50 μs			
Ultra-Rapid (observed half)	Polar Motion	daily integrations at 00, 06, 12, 18 UTC	~50 μas	3-9 hours	4x daily, at 03, 09, 15, 21 UTC	99.70%
	Polar Motion Rate		~250 μas/day			
	Length-of-day		~10 μs			
Rapid	Polar Motion	daily integrations at 12 UTC	~40 μas	17-41 hours	daily at 17 UTC	100%
	Polar Motion Rate		~200 μas/day			
	Length-of-day		~10 μs			
Final	Polar Motion	daily integrations at 12 UTC	0.03 mas	~11-17 days	weekly, every Wednesday	100%
	Polar Motion Rate		~150 μas/day			
	Length-of-day		0.01 ms			

Note 1: 100 µas = 3.1 mm of equatorial rotation; 10 µs = 4.6 mm of equatorial rotation.
Note 2: The IGS uses VLBI results from IERS Bulletin A to partially calibrate for LOD biases over 21-day sliding window, but residual time-correlated LOD errors remain.

Atmospheric Parameters	Sample Interval	Accuracy	Latency	Continuity	Availability
IGS Final Tropospheric Delay: zenith path delay (ZPD) plus north, east gradients	5 min	~4 mm for ZPD	~ 3 weeks	daily	100%
Ionosphere TEC Grid	2 hours; 5 deg (Lon.) x 2.5 deg (Lat.)	2-8 TECU	~11 days	weekly	100%
Rapid ionosphere TEC Grid	2 hours; 5 deg (Lon.) x 2.5 deg (Lat.)	2-9 TECU	<24 hours	daily	100%

Governance

The IGS has been proactive in advancing its organization and management. The IGS has taken these actions, among others, to improve governance and organizational performance:

Working Group charters and membership

All Working Group charters and membership rosters have been reviewed for relevancy and to assure the appropriate technical experts remain involved. Working Groups are also now invited to give updates on their respective workshop recommendations at regular Associate Member Open Meetings, held at least once between workshops.

Associate Membership Roster

The process for selecting associate members has been reviewed and updated by the IGS Governing Board, resulting in the formation of the Associate Membership Committee. The constituency of associate members is now reviewed continuously throughout the year on a case-by-case basis.

Performance Benchmark and Revised Strategic Plan

Throughout mid-2016, the Central Bureau led the development and distribution of strategic planning-themed surveys (questionnaires) to both the IGS community as well as the broader IGS stakeholder community. Feedback was collected and analyzed by the CB and GB during the strategic plan development process, and used to shape the goals and objectives of the 2017 Strategic Plan.

External Coordination

The IGS coordinates extensively with many external organizations to promote the IGS and develop key partnerships with participants and users:

International Association of Geodesy/Global Geodetic Observing System (IAG/GGOS)

The IGS coordinates extensively with GGOS, including membership of the Coordinating Board, Consortium, Science Panel and within the Bureaus. As a service of the IAG, IGS also coordinates with the IAG and its administration.

United Nations Office for Outer Space Affairs (UNOOSA) International Committee on GNSS (ICG)

The ICG Working Group D on Reference Frames, Timing and Applications is co-chaired by the IGS CB Director, as is the International GNSS Monitoring and Assessment System (IGMAS) Task Force. The annual ICG Meeting is typically attended by several IGS participants. Significant progress was made in supporting the development of a cooperative plan with the ICG to monitor performance and interoperability metrics between the different GNSSs, which is now embodied by a joint IGS-ICG Working Group on Monitoring and Assessment.

United Nations GGIM Sub-Committee on Geodesy (formerly Global Geodetic Reference Frame Working Group)

At the most recent session of the GGIM in New York (August 2017), the working group was officially re-established as a permanent Sub-Committee on Geodesy, to provide stability and long-term planning for the Global Geodetic Reference Frame (GGRF). Previously, the Committee of Experts also endorsed the GGRF Roadmap, which addresses each of the key areas of action described in the operational paragraphs of the 2015 UN General Assembly resolution. These efforts are anticipated to open additional avenues for international cooperation for the IGS and geodesy in general. For more information, please visit the UN-GGIM website: http://ggim.un.org/UN_GGIM_wg1.html.

International Earth Rotation and Reference Systems Service (IERS)

IGS and IERS have continued to extensively cooperate in the realization of ITRF, as well as reciprocally participating on each other's boards.

Radio Technical Commission for Maritime Services, Subcommittee on Differential GNSS (RTCM-SC104)

The IGS holds voting membership on this international standards organization for Differential GNSS, and chairs the RINEX WG.

International Federation of Surveyors (FIG)

FIG represents the single largest user community of IGS products, and is also a potential channel for extending the IGS network. IGS and FIG are coordinating to reach out to users, to conduct joint workshops, as well as to advocate for precision geodesy within organizations such as the ICG.

Regional Reference Frames

The IGS coordinates extensively at multiple levels with regional reference frame activities, such as AFREF, SIRGAS, APREF, NAREF, and EUREF.

Sea Level Activities

Through the Tide Gauge Working Group, IGS participates within the Global Sea Level Observing System (GLOSS) to precisely locate tide gauges within the ITRF.

Additionally, IGS has engaged with many user communities representing different regions and disciplines by participating in scientific workshops and conferences with presentations and chairing of sessions. Examples of conference and workshops attended include: International Council of Science/World Data System (WDS), the American Geophysical Union (AGU) and European Geosciences Union (EGU), the International Union of Geodesy and Geophysics (IUGG), the International Association of Geodesy (IAG), the Asia Oceania Geosciences Society, the U.S. Institute of Navigation, the China Satellite Navigation Conference, the Colloquium on Scientific Applications of Galileo, and others.

Working Group and Project Highlights

Adoption of the New IGS14/igs14.atx Framework

The IGS adopted a new reference frame, called IGS14, on 29 January 2017 (GPS Week 1934). At the same time, an updated set of satellite and ground antenna calibrations, igs14.atx, was implemented. IGS14 is the latest in a series of GNSS reference frames adopted by the IGS. These reference frames form the basis of the IGS products, and are derived from each new version of the International Terrestrial Reference Frame. Updating to IGS14 will align IGS products to ITRF2014, and increase precision of that alignment by integrating additional available reference frame stations with more precise and up-to-date coordinates. For more information, please see [IGSMAIL-7399] “Upcoming switch to IGS14/igs14.atx.”and “IGS14/igs14.atx: a new framework for the IGS products.”

Coincident with the IGS14 Reference Frame release, IGS adopted antenna calibration updates in igs14.atx. These updates include robot calibrations for additional ground antenna types, increasing the percentage of ground stations in the IGS network with absolute calibrations to over 90%. This will result in increased coordinate accuracy for stations equipped with these antennas. SINEX and ANTEX files, as well as network maps, post-seismic deformation models, and offsets are available for download via ftp from Institut National de l’Information Géographique et Forestière (National Institute of Geographic and Forestry Information, IGN) and École Nationale des Sciences Géographiques (National School of Geographic Sciences, ENSG.

Reprocessing Campaigns: repro2

Following the first reprocessing campaign performed by the IGS in 2008, a second reprocessing campaign (repro2) was finalized in 2015. Nine different ACs reanalyzed the history of GNSS data collected by a global tracking network back to 1994 using the latest available models and methodology. Besides supplying an improved consistent set of GNSS geodetic products, one major goal of the repro2 campaign was to provide the IGS input to the latest release of the International Terrestrial Reference Frame (ITRF2014). The individual AC products were combined into official IGS repro2 products called "ig2". Results from the repro2 terrestrial frame combinations are described in Rebischung et al. (2016; https://doi.org/10.1007/s00190-016-0897-6), while results from the repro2 orbit and clock combinations are summarized in

IGSMAIL-7411 (https://igscb.jpl.nasa.gov/pipermail/igsmail/2017/008601.html). Troposphere repro2 results are currently being processed and evaluated.

Multi-GNSS Global Experiment (MGEX)

In the beginning of 2016, the status of the Multi-GNSS Experiment (MGEX) of the IGS was changed to a Pilot Project by the IGS Governing Board. In 2016, the number of IGS multi-GNSS stations increased from almost 130 to about 180, see Figure 1. By September 2017 approximately half of the IGS network stations are MGEX capable. 196 stations also provide real-time streams, mainly via the dedicated MGEX caster (http://mgex.igs-ip.net/) but also via the IGS-IP caster (http://igs-ip.net). Both casters are operated by BKG and provide the real-time streams in different versions of the RTCM-3 MSM format. Six analysis centers (ACs) contribute orbit and clock products to MGEX: CNES, CODE, GFZ, JAXA, TUM, and Wuhan University. MGEX includes the new GPS signals, new Russian GLONASS signals, the Japanese QZSS, the Chinese BeiDou, and the European Union's Galileo.

Real-Time Service

The IGS-RTS is based on a global network of IGS stations providing data streams to the RTS observation broadcasters. There are several observation broadcasters in operation including the first level global casters at BKG, CDDIS and IGS Central Bureau. There are eight real time Analysis Centres (AC) which use different software packages to compute epoch-wise orbit and clock products. The large number of ACs ensures a high redundancy of the service on the one hand and a strong quality control

Thanks to the contributions from a large number of partners, the IGS RTS operates a dense high quality real time GNSS network. The observation data is used to derive orbit and clock products which allow user PPP at decimeter accuracy. A limitation is the convergence time of about 30 minutes and the latency of the combined products of 20-30s. The IGS RTS ensures open access to its data and products and supports open standards and data formats. Data and products are provided via TCP/IP connections. The range of applications is focused on scientific and educational topics, such as positioning, navigation and timing, Earth observations and research; and other applications that benefit the scientific community and society.

Infrastructure Improvements

The Infrastructure Committee (IC) has coordinated the adoption of the RINEX 3 data format standard to fully support all worldwide GNSS constellations. This has included coordinating actions across all IGS stakeholders from station data providers to data users. A long effort together with the IGS RINEX Working Group ensured that the receiver vendors would support the new standard and that they would provide the necessary data translation tools to generate RINEX 3 files correctly from their equipment. Additional tools were made available by individual IGS participants to modify, query, quality control and rename RINEX 3 files properly. The IC coordinated the transition from traditional file-naming of RINEX 3 files to their correct names and inclusion into the regular GNSS IGS data repositories around the world. RINEX 3 data usage continues to increase and the IC is finalizing the transition to new product format standards to accommodate new station identifiers adopted in the RINEX 3 transition.

Data Center Coordination

During the reporting period, the IGS Data Center Working Group (DCWG) worked with the Infrastructure Committee (IC) to integrate multi-GNSS data in RINEX Version 3 format into the operational directory structure at the Global Data Centers in order to promote the use of multi-GNSS data and the new RINEX format. The WG also coordinated a site metadata activity for managing the information contained in IGS site logs and to promote the use of the GeodesyML application schema for managing GNSS site metadata in general.

Receiver Independent Exchange Format (RINEX)

The RINEX Working Group has assumed leadership in maintenance and further development of the RINEX data exchange standard, in cooperation with RTCM-SC104, and has led the recent release of RINEX 3.03. The RINEX Working Group has worked in cooperation with the IC to prepare a plan to transition from RINEX 2.x to RINEX 3.x. Additionally, the RWG has encouraged and supported the development of open software tools for RINEX 3.x data handling and quality control.

Tide Gauge Benchmark Monitoring

The Tide Gauge Benchmark Monitoring Working Group (TIGA) of the IGS continues its support for climate and sea level related studies and organizations concerned herewith (e.g., GGOS, OSTST, UNESCO/IOC). The TIGA WG provides vertical geocentric positions, vertical motion and displacements of GNSS stations at or near a global network of tide gauges and works towards establishing local geodetic ties between the GNSS stations and tide gauges TIGA Network operator works with Tide Gauge and GNSS station operators to make existing stations available to TIGA, a main (ongoing) task is to update the current database of existing local ties between GNSS and tide gauge benchmarks. By the end of 2016 about 173 local ties information were made available at http://www.sonel.org/-Stability-of-the-datums.html?lang=en. The number stations directly committed to TIGA the number of ties has risen to 76, with 820 GNSS@TG stations (with 119 stations were decommissioned).

The TIGA-WG carried forward the GLOSS-Task “Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges. Report to Global Sea Level Observing System (GLOSS)” by King, M.A. (2014) for the densification and extension of the TIGA Observing Network to GGOS. The response by the GGOS Coordinating Board was received early 2017.

Improved Satellite Force Models

The Satellite Orbit and Dynamics Working Group has developed improved satellite radiation pressure models, which are available to IGS through the University College London website. These models are expected to improve the quality of the IGS orbit products once implemented by the IGS analysis centers. Discussions continue with GNSS system providers regarding IGS requests for specific engineering information for each satellite to assist with the correct modelling of satellite dynamics.

Bias and Calibration Research

The Bias and Calibration Working Group continues coordinating research activities related to bias retrieval, analysis, and monitoring. Presently, the group is considering C1W–C1C, C2W–C2C, and C1W–C2W differential code biases (DCB). Potential quarter-cycle biases between different phase observables (specifically between GPS L2W and L2C) are another issue to be dealt with. In the face of GPS and GLONASS modernization programs and upcoming GNSS, such as the European Galileo and the Chinese BeiDou, careful treatment of measurement biases in legacy and new signals becomes more and more crucial for combined analysis of multiple GNSS.

In 2016 and 2017, a GNSS bias reprocessing (for GPS/GLONASS) using the recently implemented observable-specific signal bias (OSB) parameterization was carried out at CODE for 1994-2016 RINEX data. The outcomes of this reprocessing effort are daily normal-equation (NEQ) files for GPS and GLONASS code bias parameters that are conform to both global ionosphere and clock analysis.

The combination of these daily bias results into a coherent long-term (1994-present) GPS/GLONASS bias product is another key achievement. Such a bias product is particularly useful for applications where calibration in the absolute sense are crucial (e.g., for GPS timing, or atomic clock comparisons). Additionally, CODE's classic GPS DCB product and the most resent GNSS bias results are made available using the Bias-SINEX Format Version 1.00.

Troposphere Product

The goal of the IGS Troposphere Working Group is to improve the accuracy and usability of GNSS-derived troposphere estimates. It does this by coordinating (a) working group projects and (b) technical sessions at the IGS Analysis Workshops. The Working Group is currently focusing on: automating comparisons of troposphere estimates obtained using different measurement or analysis techniques, standardization of the tropo_sinex format, and automated Analysis Center Estimate Comparisons.

Dr. Christine Hackman chaired the IGS TWG through December 2015. Dr. Sharyl Byram has chaired it since then and also oversees production of the IGS FTEs. IGS FTEs are produced within the USNO Earth Orientation Department GPS Analysis Division, which also hosts the USNO IGS Analysis Center. The United States Naval Observatory produces IGS Final Troposphere Estimates for nearly all of the stations of the IGS network. Each 24-hr site result file provides five-minute-spaced estimates of total troposphere zenith path delay (ZPD), north, and east gradient components, with the gradient components used to compensate for tropospheric asymmetry.

Daily zenith path delay estimates are being generated with an approximate three-week latency for all active IGS sites, based on Precise Point Positioning techniques. IGS Final Troposphere estimates are used by scientists worldwide to support climate-change and meteorological studies, and 46.3 million estimates files from over 1000 distinct hosts were downloaded in 2012 alone.

Ionosphere Product

Following the IGS Workshop 2014 in Pasadena, ionospheric fluctuation map products were established as a pilot project of the IGS service. The current product roster includes: final GIM (please note that GIMs also include GPS and GLONASS stations' and satellites' DCBs); rapid GIM; predicted GIM for 1 and 2 days ahead (pilot product).
Recent key accomplishments include:

- IGS Global ionosphere predicted products for 1 and 2 days ahead (pilot product). This new IGS products are currently based on predicted ionosphere maps prepared by UPC and ESA.
- IGS Global ionosphere maps with 1 hour time resolution. This new IGS products are currently based on ionosphere maps prepared by UPC, ESA and CODE.
- IGS Global Ionosphere Maps (GIMs) now include differential code biases (DCBs) for GLONASS satellites.
- The pilot phase of the new IGS ionospheric product - TEC fluctuations maps.

More Information

For greater detail about the aforementioned activities, efforts, and components, please refer to the IGS Technical Reports, available for download on the IGS Knowledge Base.

International Laser Ranging Service (ILRS)

https://ilrs.gsfc.nasa.gov

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Overview

The ILRS is the international source that provides Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data and data products for scientific and engineering programs with the main focus on Earth and Lunar applications. The basic observables are the precise two-way time-of-flight of ultra-short laser pulses from ground stations to retroreflector arrays on satellites and the Moon and the one-way time-of-flight measurements to space-borne receivers (transponders). These data sets are made available to the community through the CDDIS and the EDC archives, and are also used by the ILRS to generate fundamental data products, including: accurate satellite ephemerides, Earth orientation parameters, three-dimensional coordinates and velocities of the ILRS tracking stations, time-varying geocenter coordinates, static and time-varying coefficients of the Earth's gravity field, fundamental physical constants, lunar ephemerides and librations, and lunar orientation parameters.

SLR is one of the four space geodetic techniques (along with VLBI, GNSS, and DORIS) whose observations are the basis for the development of the International Terrestrial Reference Frame (ITRF), which is maintained by the IERS. SLR defines the origin of the reference frame, the Earth center-of-mass and, along with VLBI, its scale. The ILRS generates daily a standard product of station positions and Earth orientation based on the analysis of the data collected over the previous seven days, for submission to the IERS, and produces LAGEOS/Etalon combination solutions for maintenance and improvement of the International Terrestrial Reference Frame. The latest requirement is to improve the reference frame to an accuracy of 1 mm accuracy and 0.1 mm/year stability, a factor of 10–20 improvement over the current product. To address this requirement, the SLR community will need to significantly improve the quantity and quality of ranging to the geodetic constellation (LAGEOS-1, LAGEOS-2, and LARES) to support the definition of the reference frame, and to the GNSS constellations to support the global distribution of the reference frame.

The ILRS participates in the Global Geodetic Observing System (GGOS) organized under the IAG to integrate and help coordinate the Service activities and plans.

ILRS Structure

The ILRS Organization (see Figure 1) includes the following permanent components:

- Network of tracking stations
- Operations Centers
- Global Data Centers
- Analysis and Associate Analysis Centers
- Central Bureau
- Governing Board

- Standing Committees (SCs)
  - Analysis
  - Data Formats and Procedures
  - Missions
  - Networks and Engineering
  - Transponders
- Study Groups (SGs) and Boards
  - Laser Ranging to GNSS s/c Experiment (LARGE)
  - Quality Control Board
  - Software Study Group
  - Space Debris Study Group

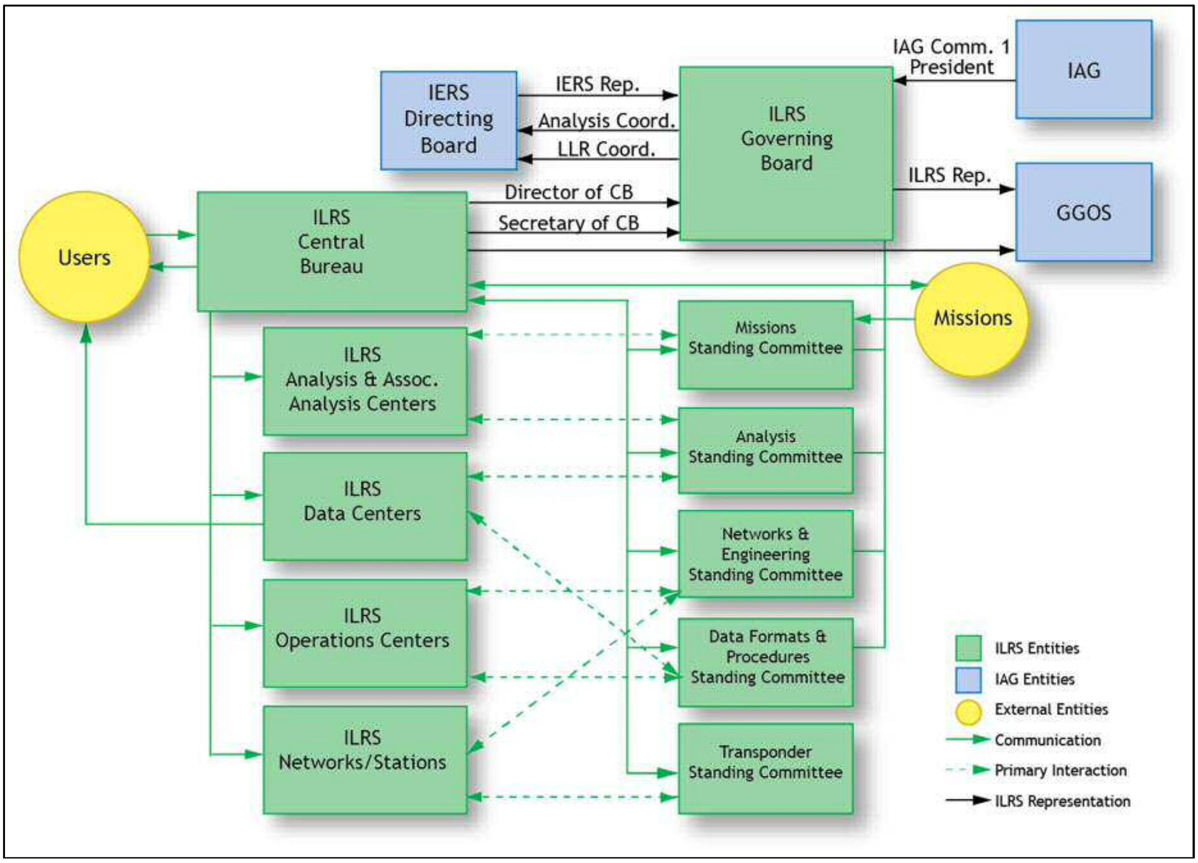

Figure 1. The organization of the International Laser Ranging Service (ILRS).

The role of these components and their inter-relationship is presented on the ILRS website (*https://ilrs.gsfc.nasa.gov/about/organization/index.html*).

The Governing Board (GB) is responsible for the general direction of the service. It defines official ILRS policy and products, determines satellite-tracking priorities, develops standards and procedures, and interacts with other services and organizations. The members of the current Governing Board, selected and elected for a two-year term, are listed in Table 1.

The Central Bureau (CB) is responsible for the daily coordination and management of the ILRS in a manner consistent with the directives and policies established by the Governing Board. The primary functions of the CB are to facilitate communications and information transfer within the ILRS and between the ILRS and the external scientific community, coordinate ILRS activities, maintain a list of satellites approved for tracking support and their priorities, promote compliance to ILRS network standards, monitor network operations and quality assurance of data, maintain ILRS documentation and databases, produce reports as required, and organize meetings and workshops. The CB operates the communication center for the ILRS. The CB performs a long-term coordination and communication role to ensure that ILRS participants contribute to the Service in a consistent and continuous manner and that they adhere to ILRS standards.

Permanent Standing Committees (SCs) and temporary Study Groups (SGs) provide the expertise necessary to make technical decisions, to plan programmatic courses of action, and are responsible for reviewing and approving the content of technical and scientific databases maintained by the Central Bureau. All GB members serve on at least one of the five SCs, led by a Chair and Co-Chair (see Table 1). The SCs continue to attract talented people from the general ILRS membership who contributed greatly to the success of these efforts.

Table 1. ILRS Governing Board (as of May 2017)

Name	Position	Country
James Bennett	Appointed, WPLTN	Australia
Giuseppe Bianco	Appointed, EUROLAS, Governing Board Chair	Italy
Ludwig Combrinck	Elected, Lunar Representative	South Africa
Urs Hugentobler	Ex-Officio, Representative of IAG Commission 1	Germany
Georg Kirchner	Appointed, EUROLAS, Networks and Engineering Standing Committee Co-Chair	Austria
Vincenza Luceri	Elected, Analysis Representative, Analysis Standing Committee Deputy Chair	Italy
David McCormick	Appointed, NASA	USA
Jan McGarry	Appointed, NASA, Transponder Standing Committee Co-Chair	USA
Horst Mueller	Elected, Data Centers Representative, Data Formats and Procedures Standing Committee Chair	Germany
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	USA
Toshimichi Otsubo	Appointed, WPLTN, Missions Standing Committee Chair	Japan
Erricos Pavlis	Elected, Analysis Representative, Analysis Standing Committee Chair	USA
Michael Pearlman	Ex-Officio, Director, ILRS Central Bureau	USA
Ulrich Schreiber	Elected, At-Large, Transponder Standing Committee Chair	Germany
Daniela Thaller	Appointed, IERS Representative to ILRS	Germany
Matt Wilkinson	Elected, At-Large, Networks and Engineering Standing Committee Chair	UK
TBN	Appointed, At-Large	
TBN	Appointed, At-Large	
Former Governing Board Members during 2015-2017		
Wu Bin	Appointed, WPLTN	China
Jürgen Müller	Elected, Lunar Representative	Germany

Data Products

The main ILRS analysis products consist of SINEX files of weekly-averaged station coordinates and daily Earth Orientation Parameters (x-pole, y-pole and excess length-of-day—LOD) estimated from 7-day arcs of SLR tracking of the two LAGEOS and two Etalon satellites. As of May 1, 2012, the official ILRS Analysis product is delivered on a DAILY basis by sliding the 7-day period covered by the arc by one day forward every day. This allows the ILRS to respond to two main users of its products: the ITRS Combination Centers and the IERS EOP Prediction Service at USNO. The former requires a single analysis per week; the latter however requires as “fresh” EOP estimates as possible, that the “sliding” daily analysis readily provides. Two types of products are distributed for each 7-day period: a loosely constrained estimation of coordinates and EOP and an EOP solution, derived from the previous one and constrained to an ITRF, which beginning on June 1, 2017, is ITRF2014. Official ILRS Analysis Centers (ACs) and Combination Centers (CCs) generate these products with individual and combined solutions respectively. Both the individual and combined solutions follow strict standards agreed upon within the ILRS Analysis Standing Committee (ASC) to provide high quality products consistent with the IERS Conventions. This description refers to the status as of May 2017. Each official ILRS solution is obtained through the combination of solutions submitted by the official ILRS Analysis Centers:

- ASI, Agenzia Spaziale Italiana
- BKG, Bundesamt für Kartographie und Geodäsie
- DGFI, Deutsches Geodätisches ForschungsInstitut
- ESA, European Space Agency
- GFZ, GeoForschungsZentrum Potsdam
- GRGS, Observatoire de Cote d'Azur
- JCET, Joint Center for Earth Systems Technology and Goddard Space Flight Center
- NSGF, NERC Space Geodesy Facility

Since 2016, the ILRS has released an additional operational product on a weekly basis through a pilot project. These official products are precision orbits in standard SP3c formatted files for the four satellite targets (LAGEOS-1, -2, and Etalon-1, -2).

Following the adoption of ITRF2014, the ASC plans to issue an extended version of the reference frame, the SLRF2017, which will include some two-dozen additional SLR sites that were not part of ITRF2014. The ASC will re-analyze all of the data received since 1983, using the new ITRF and new models for an improved standard product that are consistent with the currently released operational products. The ILRS products are available, via ftp from the official ILRS Data Centers CDDIS/NASA Goddard Space Flight Center and EDC/TUM/DGFI: *ftp://cddis.nasa.gov/slr/products/pos+eop* and *ftp://edc.dgfi.tum.de/pub/slr/products/pos+eop*).

The individual ILRS AC and CC product contributions as well as the combinations are monitored on a daily basis in graphical and statistical presentation of these time series through a dedicated portal hosted by the JCET AC at: *http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*

The main focus of the Analysis SC activities over the past two years was the improvement of modeling used in the reduction of the SLR data and generation of the official products for the development of ITRF2014, (Luceri et al., 2014). In particular, all ACs made major efforts to comply with the adopted analysis standards and the IERS Conventions 2010, the consistent modeling of low degree time-varying gravitation and the realistic modeling of the mean pole in computing the pole tide effects (Pavlis et al., 2014). Since the delivery of the preliminary and final versions of ITRF2014, the ASC has focused on evaluating them and providing feedback to ITRS for adjustments that led to the finally adopted version. The efforts to identify, quantify and contain systematic errors in the SLR data have continued with many new initiatives that ILRS feels necessary in order to improve data quality.

It is recognized that practices that will limit or mitigate the effect of systematic errors in the ILRS data, improve the final products through realistic description of geophysical processes, and strengthen the quality of the products include but are not limited to using LARES as an additional accurate target in developing the official products (Pavlis et al., 2015). In addition to that though, a new study group, the ILRS "Quality Control Board", with members from all areas of expertise within the service, has been established to generate tools and procedures that will help the station engineers identify with confidence and as quickly as possible, issues with their data, before they get too far down the production line. More details on the initial results from this new initiative are given under the section for the ILRS ASC.

Currently, the LLR group is in the process of developing a unique data set of all available LLR data in the newly adopted CRD format, in order to better serve the community and to conform with the ILRS standards.

Satellite Laser Ranging

ILRS Network

The present ILRS network includes over forty stations in 24 countries (see Figure 2); some of these stations are undergoing refurbishment and upgrade. During the last five years, new stations joined the ILRS network in Badary, Baikonur, Irkutsk, Svetloe, Zelenchukskaya, (Russia), Sejong (Korea), and Brasilia (Brazil) filling-in very important geographic gaps. The Russian groups have advanced the idea of placing two SLR stations at critical locations to help address the tracking load. They have co-located an SLR station with the NASA MOBLAS at Hartebeesthoek (South Africa) and have offered to place a system in Tahiti co-located with the NASA systems there. The Russians are also planning the installation of a new system in Ensenada (Mexico). The TIGO system, operational in Concepción (Chile) since 2002, was closed in 2014 and relocated to La Plata (Argentina); operations are expected to resume in late 2017. New stations, underway at Ponmundi and Mt. Abu (India) and in Metsahövi (Finland) are expected to be operational in late 2017 or early 2018. A new SLR station is planned for Yebes (Spain). The NASA Space Geodesy Project (SGP) is planning for construction of up to ten next generation SLR systems as part of core sites; the first of those systems are planned for deployment at McDonald, TX, Haleakala, HI and GSFC in the 2019–2021 timeframe. A fourth is being built in cooperation with the NMA for Ny Ålesund (Norway). Several systems are planned to replace current legacy systems. Large gaps are still very prominent in Africa and South America and discussions are underway with several groups in the hope of addressing this shortcoming.

Stations designated as operational have met the minimum ILRS qualification for data quantity and quality. In 2015, the ILRS Governing Board approved a new ILRS Pass Performance Standard of 3500 passes per year as an interim step toward a more comprehensive long-term strategy:

- 2 passes per week on each LEO satellite (2300 LEO passes per year)
- 4 passes per week on each LAGEOS satellite (600 LAGEOS passes per year)
- 2 passes per week on each HEO satellite (>3000 HEO passes per year)

In general, stations continue to improve their performance. Several stations dominated the network in the last three years, with the Yarragadee, Changchun and Mt. Stromlo stations being the strongest performers. The next group of stations with impressive contributions included Herstmonceux, Graz, Wettzell, Greenbelt, Zimmerwald, Monument Peak, Matera, and Potsdam. During the twelve-month period from April 2016 to March 2017, thirteen stations met the updated ILRS minimum requirement for total numbers of passes tracked (see Figure 3).

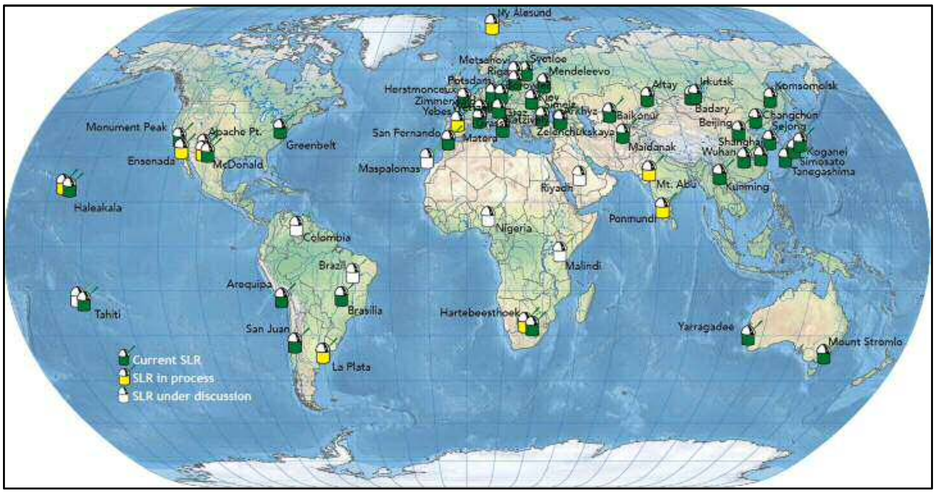

Figure 2. ILRS network (as of May 2017).

As shown in Table 2, several stations are now operating with kHz lasers and fast detectors, thereby increasing data yield and allowing them to be more productive with pass interleaving, a critical step as the number of satellites being tracked with SLR is increasing dramatically. Some stations have demonstrated mm precision normal points, a fundamental step toward addressing the new reference frame requirements.

Satellite Missions

The ILRS is currently tracking over ninety artificial satellites including passive geodetic (geodynamics) satellites, Earth remote sensing satellites, navigation satellites, and engineering missions (see Figure 4). The large list of satellites is saturating some stations that are not fully manned and strategies are being examined to try to maximize station data value. The stations with lunar capability are also tracking the lunar reflectors. In response to this large roster of satellites, as well as for support of tandem missions (e.g., GRACE-A/-B, TanDEM-X/TerraSAR-X) and general overlapping schedules, most stations in the ILRS network are tracking satellites with interleaving procedures.

The ILRS assigns satellite priorities in an attempt to maximize data yield on the full satellite complex while at the same time placing greatest emphasis on the most immediate data needs. Priorities provide guidelines for the network stations, but stations may occasionally deviate from the priorities to support regional activities or national initiatives and to expand tracking coverage in regions with multiple stations. General tracking priorities are set by the Governing Board, based on application to the Central Bureau and recommendation of the Missions Standing Committee
(see https://ilrs.gsfc.nasa.gov/missions/mission_operations/priorities/index.html).

Table 2. High-Repetition Rate ILRS Stations (as of May 2017)

Site Name	Station	Repetition Rate (Hz)
Altay	1879	300
Arkhyz	1886	300
Badary	1890	300
Baikonur	1887	300
Beijing	7249	1000
Brasilia	7407	300
Changchun	7237	1000
Graz	7839	2000
Herstmonceux	7840	2000
Irkutsk	1891	300
Komsomolsk	1868	300
Kunming	7820	1000
La Plata	7405	100
Mendeleevo	1874	300
Mount Stromlo	7849	100
Potsdam	7841	2000
Sejong	7394	5000
Shanghai	7821	1000
Svetloe	1888	300
Wettzell (SOS)	7827	1000
Zelenchukskaya	1889	300
Zimmerwald	7810	110

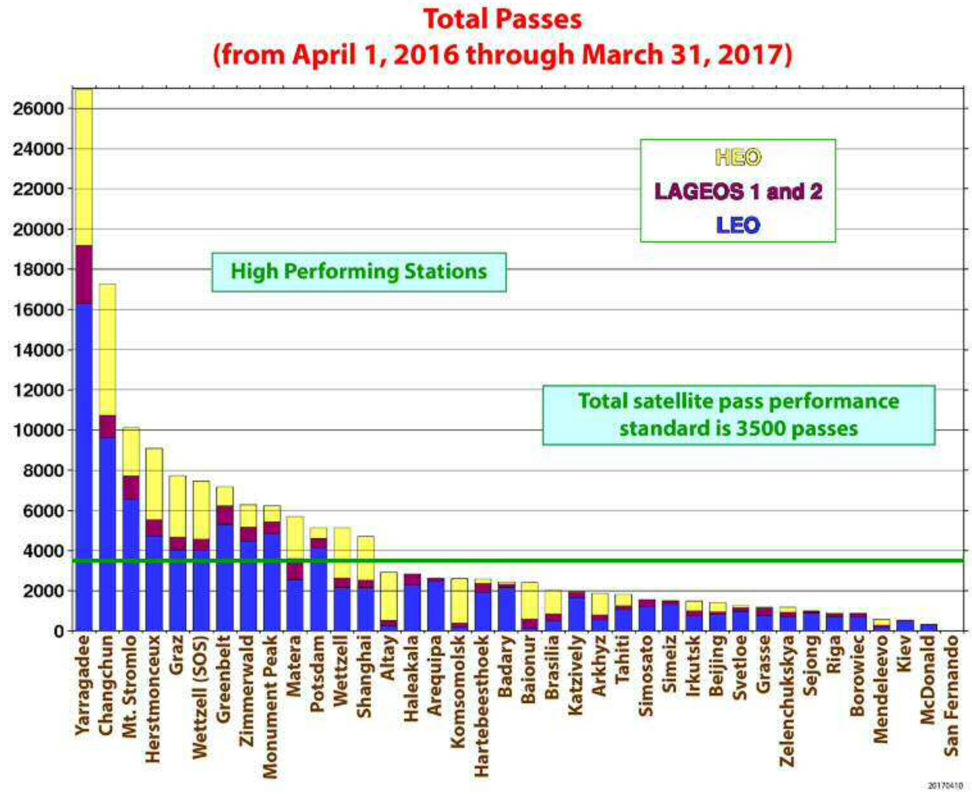

Figure 3. ILRS network performance (total passes), April 2016 through March 2017.

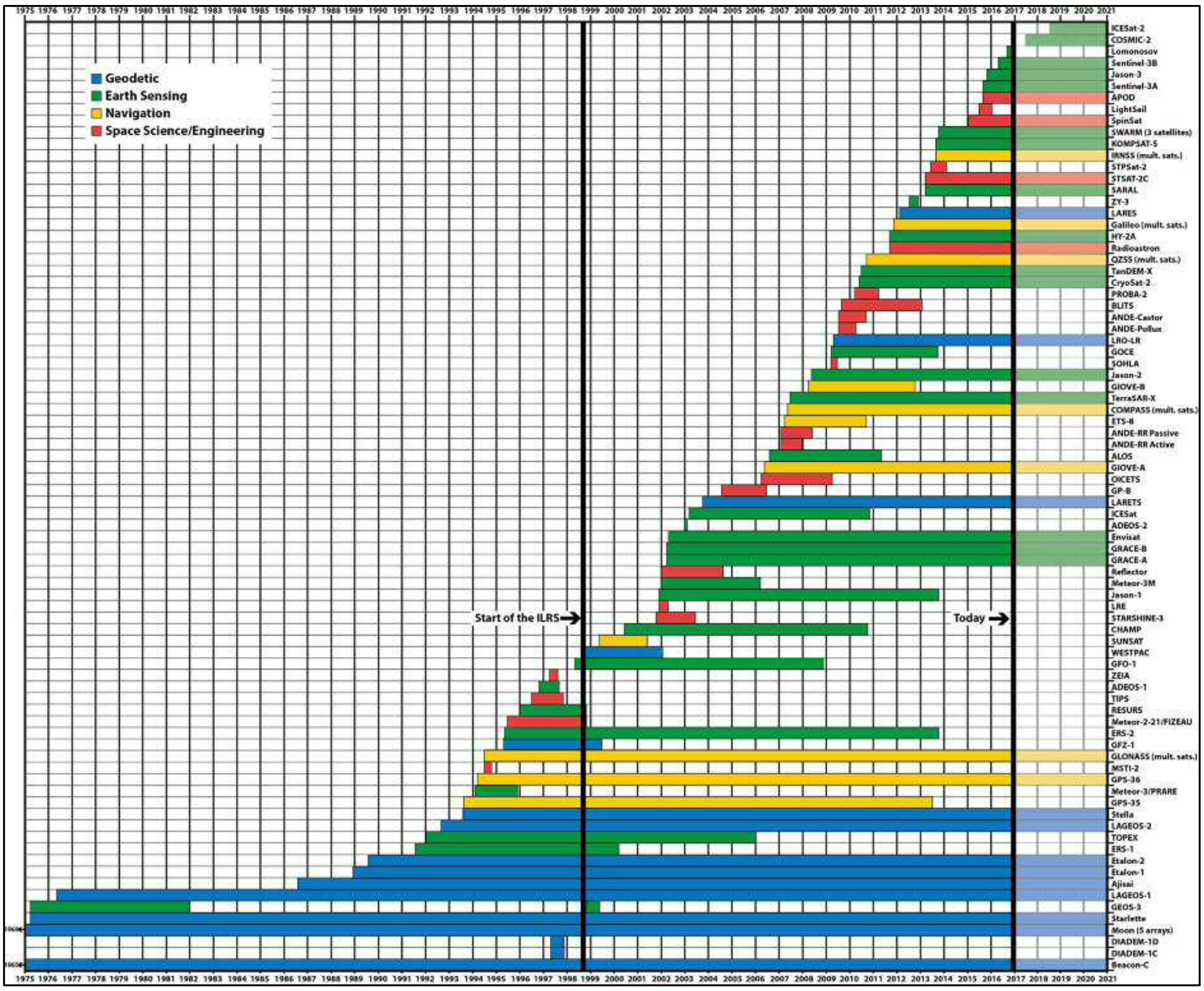

Figure 4. The past, current, and future ILRS satellite tracking list (as of May 2017).

Missions are added to the ILRS tracking roster as new satellites are launched and as new requirements are adopted; missions for completed programs are removed (see Figure 4). Significant effort was spent by the ILRS CB on restricted tracking procedures for the Sentinel-3A and Lomonosov missions to ensure that only authorized stations ranged to the satellites and did so only during authorized time periods to avoid any damage to vulnerable onboard instrumentation. The ILRS continues to track several satellites (e.g., Envisat, TOPEX/Poseidon, ETS-8) considered "space debris" to provide ephemerides and orientation data to help with trajectory/safety planning.

The tracking approval process begins with the submission of a Missions Support Request Form, which is accessible through the ILRS website (*https://ilrs.cddis.eosdis.nasa.gov/docs/2016/ilrsmsr_1604.pdf*).

The form provides the ILRS with the following information: a description of the mission objectives, mission requirements including any tracking restrictions, responsible individuals and contact information, timeline, satellite subsystems, and details of the retroreflector array and its placement on the satellite; a mission concurrence section grants the ILRS stations permission to perform laser ranging to the satellite. This form also outlines the early stages of intensive support that may be required during the initial orbital acquisition and stabilization and spacecraft checkout phases. A list of upcoming space missions that have requested ILRS tracking support is summarized in Table 2 along with their sponsors, intended application, and projected launch dates.

Table 2. Recently Launched and Upcoming Missions (as of May 2017)

Satellite Name	Sponsor	Purpose	Launch Date
Recently Launched			
Compass (5 new, 9 total satellites)	Chinese Defense Ministry	Positioning, navigation, timing	2007- present
Galileo (13 new, 18 total satellites)	ESA	Positioning, navigation, timing	2011- present
GLONASS (2 new, 24 total satellites)	Russian Federation Ministry of Defense	Positioning, navigation, timing	1989-present
IRNSS (3 new, 6 total satellites)	ISRO	Positioning, navigation, timing	2013-2016
Jason-3	CNES, NASA, Eumetsat, NOAA	Oceanography	Jan-2016
Lomonosov*	Scobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University	Upper atmospheric research	Apr-2016
PN-1A	BACC	Precise orbit determination	Sep-2015
Sentinel-3A*	ESA, Eumetsat	Marine observation	Feb-2016
Approved by ILRS for Future SLR Tracking			
APOD/PN -1B, -1C, -1D	Beijing Aerospace Control Center	Engineering	2015
COSMIC-2	UCAR	Atmospheric research, validation of GNSS orbits	2017
LightSail-B	Planetary Society	Engineering	2017
NISAR	NASA	Earth sensing	2020
QZS-2, -3, -4	Cabinet Office, Government of Japan	Positioning, navigation	2017
Sentinel-3B	ESA. Eumetsat	Oceanography	2017
Future Satellites with Retroreflectors			
GPS-III	U.S. DoD, DoT	Positioning, navigation, timing	2019
HY-2B, -2C, -2D	CNES, CNSA	Earth observation	2017-2019
ICESat-2	NASA	Ice sheet mass balance, sea level	2018
Sentinel-6	ESA. Eumetsat, NASA, NOAA	Ocean Altimetry	2020
SWOT	NASA, CNES	SAR altimeter	2020

Note: * denotes restricted tracking mission; only authorized stations perform laser ranging to the satellite

During this reporting period, over twenty GNSS satellites from four constellations were added to the ILRS priority list. In addition, and as shown in Table 2, four other satellites, including two restricted tracking missions, were launched and supported by the ILRS network. The ILRS tracking roster presently includes six GLONASS satellites, nine Compass satellites, eighteen Galileo satellites, five IRNSS satellites, and one QZSS satellite. Following discussions at the 2012 ILRS Technical Workshop, "Satellite, Lunar and Planetary Laser Ranging: Characterizing the Space Segment," in Frascati, Italy in November 2012, and agreements that were approved by the ILRS and GGOS after deliberations within the "LAser Ranging to GNSS s/c Experiment (LARGE)" Study Group meeting in April 2014, several stations routinely track segments of passes of all 24 active GLONASS satellites and beyond. The newer "high" satellites are using retroreflector arrays that satisfy the ILRS standard. As a result, stations are having greater ranging success.

Recently, the ILRS has become more involved in supporting Precision Time Transfer by laser ranging. The ILRS network is currently tracking the Jason-2 satellite (launched in 2008) which includes the Time Transfer by Laser Link (T2L2) instrument. The T2L2 instrument records the time of arrival of laser pulses. It provides a means to synchronize the clocks of the ILRS stations, as well as to characterize the performance of the DORIS Ultra Stable Oscillator (USO) onboard the Jason-2 spacecraft. The data from T2L2, as well as other information, have been used to derive a detailed model of the DORIS USO behavior, including direct modeling of radiation effects, passage through the South Atlantic Anomaly (SAA) and natural aging of the oscillator. Applying this USO model it is possible to synchronize the clocks used in the Laser Ranging station to the same international time scale (UTC) at around 5 ns accuracy. The analysis of the T2L2 data has revealed that many stations exhibit a bias w.r.t. to UTC, sometimes as high as a few microseconds (for example the prolific Yarragadee station had a long-term evolving bias of 1 microsec throughout 2013). While the ILRS requests that stations maintain their timing within 200 ns, the data from T2L2 reveal a source of error that has not previously been considered. Time biases at the level of less than 1 microsec are hard to resolve from the orbit determination analysis, so the data from T2L2 will allow us to characterize station timing behavior and examine its impact on the reference frame and ILRS products. The T2L2 project team led by Dr. Pierre Exertier (Grasse SLR observatory) have provided "corrected" SLR data to the ILRS analysis centers, based on analysis of data from T2L2.

A precise clock in space provides a worldwide access to high performance ground clocks. Here SLR plays an important role. It provides accurate range and time between clearly defined reference points on ground and in space. This represents a two-way measurement technique, the main ingredient of the "Einstein Synchronization" process, the only technique that can compare remote clocks with high accuracy. The European Space Agency (ESA) is developing the Atomic Clock Ensemble (ACES) experiment for flight on the International Space Station (ISS). The ELT (European Laser Timing) follows in the path of T2L2. The goal is to demonstrate an accuracy of time transfer at the level of 50 ps, with a perspective of 25 ps. The ELT payload consists of a corner cube retroreflector a SPAD detector, and an event timer. ELT will provide an alternative to time transfer via microwave link (MWL) and will provide superior accuracy.

Lunar Laser Ranging (LLR) Network

The LLR results are considered among the most important science return of the Apollo era. Of all the active ILRS observatories there are currently only four which are technically equipped to track retro-reflector arrays located on the surface of the Moon or on spacecraft orbiting around the Moon. In 2016, only two Lunar Laser Ranging (LLR) sites collected ranging data to the Moon: the Observatoire de la Côte d' Azur, France (63 NP's at 532 nm and 756 at 1064 nm (infrared)) and the APOLLO site in New Mexico, USA (273 NPs). Since the latter part of

2014, the Observatoire de la Côte d' Azur LLR station has been able to range with infrared wavelength (1064 nm), these data are available at their website (http://www.geoazur.fr) and are included in the statistics shown in Figures 5 to 7. Most of the Observatoire de la Côte d' Azur LLR data are now obtained using infrared instead of green (532 nm) laser pulses.

Unfortunately, no NPs have been obtained from the McDonald Observatory in Texas, USA. This means, a time series of LLR tracking at McDonald, which has run for four decades, has been interrupted. This discontinuation will adversely affect research utilizing LLR data as the McDonald station has been a major contributor to LLR data over a long period of time.

The LLR measurement statistics for 2016 (Figure 5) shows that about 75% of the data have been collected at the French MeO site near Grasse and about 25% of the data at APOLLO. Figure 6 illustrates the statistics for the observed retro-reflector arrays, where much better coverage of all reflectors was achieved than in previous years. Nevertheless, most of the data was obtained on the big Apollo 15 reflector array (48%), while the other four reflectors provided data at the 12-14% level. Figure 7 presents the entire LLR data set from 1970 to 2016 displaying the amount of data collected by each of the active LLR sites in each year. The total data yield over this period is about 22,000 NPs, recently averaging about 600 NPs per year. At the Observatoire de Paris, an "assisting tool" is available to support lunar tracking by providing predictions of future LLR observations as well as a validation of past LLR normal points. This tool and further information can be accessed via the ILRS website at *https://ilrs.gsfc.nasa.gov/science/scienceContributions/lunar.html*.

LLR data analysis is carried out by a few major LLR analysis centers: Jet Propulsion Laboratory (JPL), Pasadena, USA; Center for Astrophysics (CfA), Cambridge, USA; Paris Observatory Lunar Analysis Center (POLAC), Paris, France; Institute of Geodesy (IfE), University of Hannover, Germany. In the last few years, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan, have also increased their analysis activities. The six LLR analysis centers focus on different research topics (such as relativity, lunar interior, etc.). Some interest towards this end has also been shown by the Hartebeesthoek Radio Astronomy Observatory (South Africa) where an ex-Observatoire de la Côte d' Azur 1-m aperture telescope is being prepared for LLR use. In addition, various research projects have been successfully run combining LLR, GRAIL, and LRO data.

One general objective of LLR analysis is to improve accuracy from the current cm to the mm level. The various analysis centers continue their comparison initiative to mutually improve the various reduction codes. Recent activities also include comprehensive simulations to show the potential benefit of improved tracking with additional observatories and/or to new reflectors.

Above all, LLR remains one of the best tools to support lunar science, to study the Earth-Moon dynamics and to test General Relativity in the solar system (Müller et al. 2014). LLR analysis steadily reduces the margins for a possible violation of Einstein's theory of relativity and impressively underpins its validity – now in the 100th year of its existence.

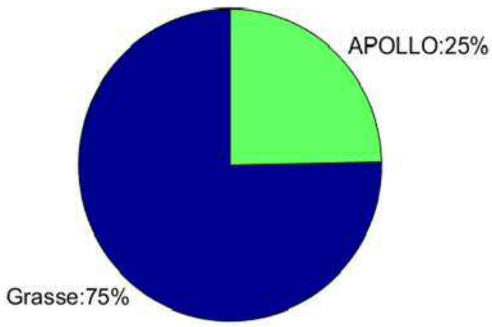

Figure 5. Observatory statistics in 2016.

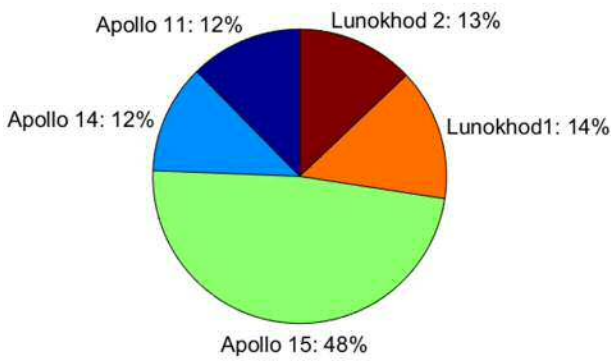

Figure 6. Reflector statistics in 2016.

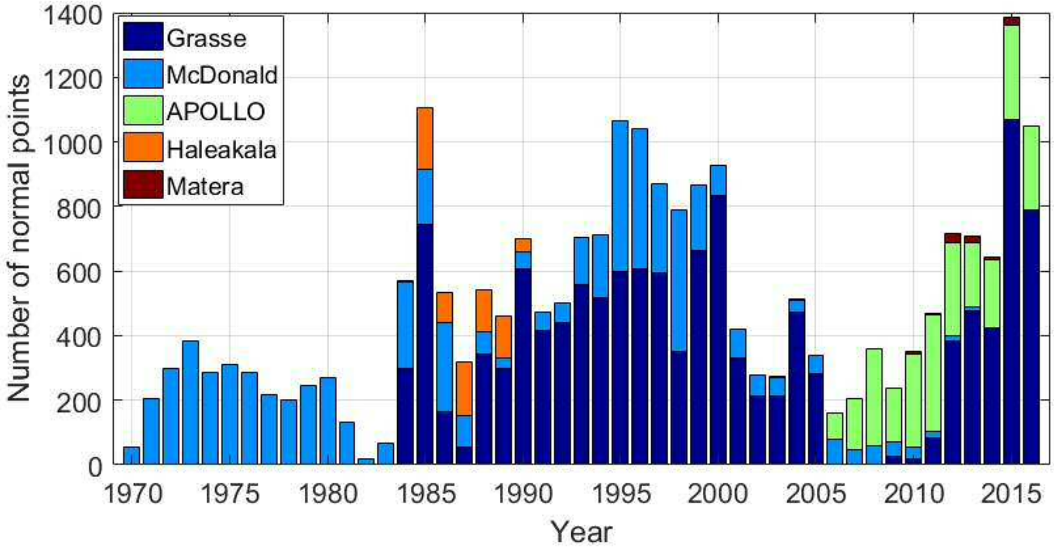

Figure 7. Data yield of the global LLR network of stations (through the end of 2016).

Recent Activities

General

The ILRS Governing Board approved an update to the ILRS Terms of Reference (ToR) (*https://ilrs.gsfc.nasa.gov/about/termsofref.html*) in mid-2016; the IAG accepted the revision and the new ToR was adopted in November 2016. The most significant change to the ILRS ToR was the addition of two At-Large members to the ILRS GB who will be appointed by the GB. Other changes addressed the addition of new SCs and clarifying terminology.

Standing Committee and Study Group Progress

All ILRS standing committees held meetings during ILRS workshops held during the reporting period (2015 ILRS Technical Workshop in Matera Italy and the 20th International Workshop on Laser Ranging in Potsdam Germany). The Analysis SC held additional meetings during the 2015, 2016, and 2017 EGU General Assemblies in Vienna Austria.

Analysis Standing Committee (ASC)

In addition to the production of the official ILRS ASC products, the ASC focused on two Pilot Projects (PP) during the reporting period: one was a continuation of the orbital product PP, which in early 2016 evolved into a bona fide official product as reported earlier under the “Data Products” section. The other PP was agreed at the ILRS Tech. Workshop in Matera, Italy, and the purpose of that effort was to develop an efficient analysis procedure that will monitor the long-term performance of systematic errors at stations. A test period of four years (2005 to end of 2008) was selected as the validation of the procedure and the products of the contributing ACs. Of the eight ACs, six contributed to the PP. In the initial phase a combination of all available contributions was performed and the comparison of the individual estimates to the combined result was used to validate the contributing series. In the next phase of the PP the procedure will be implemented as a standard product and the ASC will develop guidelines for identifying likely errors and notify the affected stations. This step is expected to be completed by mid-2017. A subsequent PP will introduce LARES as the fifth target to be used for the development of the official ILRS products and at the same time, the delivery of weekly averaged low-degree spherical harmonic coefficients of the gravitational field model. This PP is expected to be completed by the end of 2017. The co-chairs of the ASC are leading as guest-editors the publication of a special issue of the Journal of Geodesy, dedicated on Laser Ranging. The call-for-submissions resulted in over forty proposed contributions and the process is currently in the stage of the review of the abstracts by the guest-editors and the editor in chief to decide which of these will be accepted for publication in the special issue.

Data Formats and Procedures Standing Committee (DFPSC)

Discussions at DFPSC splinter meetings proposed modifications to the ILRS standard CPF and CRD formats that are needed to fine-tune handling of several issues, including transponder missions, day wrap-around, and the need for more lunar and software ancillary data; a study group within the SC will work on these changes. A new procedure was formulated and distributed to ILRS stations for handling the December 31 2016 leap second; this procedure, which mainly directed stations to stop tracking during the leap second, was moderately successful and will be reiterated for future occurrences of leap seconds.

Missions Standing Committee (MSC)

The MSC, working with the ILRS CB, completed a revision to the ILRS Missions Support Request form. This form is the vehicle used by mission sponsors to provide information required by the ILRS to enable the ILRS to determine if future laser ranging to the satellite is warranted. The form provides key contacts and parameters to allow the ILRS to use the SLR data in the development of science data products and to provide the missions with SLR data that supports their goals. The MSC also reviewed submitted request forms and provided recommendations and feedback to the CB and GB for future mission support. Missions approved during the reporting period include: COSMIC-2, LightSail-B, Lomonosov, NISAR, and Sentinel-3A/-3B.

Networks and Engineering Standing Committee (NESC)

The NESC developed a procedure that could be used by ILRS stations to take a series of measurements of their system's beam divergence; measuring laser beam intensities at satellite heights can inform missions of any potential hazard to sensitive on-board equipment. Results of the measurements submitted by participating stations were discussed at the 2016 workshop in Potsdam. The SC continues to review the ILRS Site Log format and consider modifications that would benefit the ILRS and mission operators. The NESC chair established a discussion forum to strengthen the connection, communication, and collaboration between international colleagues and share the experience and knowledge in the ILRS to address problems common to stations in the network. The NESC distributed a questionnaire to the stations about what is needed to address systematics; results from the questionnaire were presented at the NESC meeting in Potsdam.

Transponders Standing Committee (TSC)

Currently, the main focus for the TSC is on highly accurate time transfer, particularly ELT for ACES (expected launch in 2018) on the International Space Station. The SC is working with stations to implement requirements for the mission. During its meetings, the SC also discussed common view time transfer and cross system ranging via space debris targets for the direct detection of the laser return and diffusely scattered signal from the partner station. Experiments are underway between Wettzell and Graz.

Quality Control Board (QCB)

The ILRS Quality Control Board was organized at the 19th International Workshop on Laser Ranging to address SLR systems biases and other data issues that have degraded the ILRS data and their derived products. The board is a joint activity under the ASC and the NESC and meets by telecon on a monthly basis. Current activities include results from the ASC's "Station Systematic Errors Pilot Project" and development of tools for the stations to view system performance and examine systematic errors. The plan is to have these as web-based diagnostic tools by the latter part of 2017. Several AC's have been routinely examining the incoming SLR data and providing rapid feedback to the stations on suspect performance. The Board is also examining tools and procedures that would enhance data scrutiny at the stations.

Software Study Group (SSG)

The SSG works to identify existing software of use to ILRS stations. The SSG has worked with the ILRS CB to provide links to these software packages on the ILRS website. A set of lunar prediction, filtering, and normal pointing software is working its way through the open-sourcing process at NASA GSFC.

Space Debris Study Group (SDSG)

The SDSG was formed in 2014 to coordinate and assist stations in laser ranging to space debris targets. The SG also acts as an interface between the ILRS and the space debris activities within ESA. Early on, the SG organized several campaigns on TOPEX, Envisat, and other SD targets. Over the last three years, the number of stations tracking space debris has increased significantly. Measurements in multi-static/bi-color debris ranging measurements are being taken to uncooperative targets. "Stare and Chase" is another method for tracking uncooperative targets and has also been successfully tested. Significant results have been seen for science, POD, attitude motion, pre-entry data, and other applications.

Mission Campaigns

LARGE

During the 18th International Workshop on Laser Ranging in Japan in November 2013, the ILRS agreed to expand the ILRS network support for GNSS constellations. The ILRS and GGOS formed a joint study group, the LAser Ranging to GNSS s/c Experiment (LARGE) to define an operational GNSS tracking strategy to improve the ILRS response to GNSS user requirements and to clarify outstanding ILRS and IGS issues with the GNSS satellites and ground stations. The satellite constellations of interest with retroreflector arrays include GLONASS, BeiDou (Compass), Galileo, GPS, IRNSS, and QZSS. The GLONASS constellation is fully populated. BeiDou and Galileo constellations are in process. GPS satellites with laser retroreflector arrays will begin launching in the 2019 timeframe. When completed, the full GNSS complex should reach over 100 satellites.

Several GNSS tracking campaigns have been held since 2014, adjusting priorities to focus on a subset of the GNSS satellites. Some improvement has been seen, but it may also have been the result of stations becoming more familiar with GNSS tracking. Subsequent sessions examined the results in more detail (number of segments per pass, number of normal points per segment, "location" within the pass to acquire the data). More details can be found in a poster presented at the 2015 ILRS Technical Workshop in Matera (Noll et al., 2015). The ILRS is now in a mode of running three-month sessions on selected satellites in each of the GNSS constellations.

GREAT

Monthly campaigns continue on Galileo-201 with Galileo-202 as a backup, to study the behavior of on-board clocks and the gravitational redshift predicted by General Relativity. Launch problems placed in elliptical orbits which induce a periodic modulation of the gravitational redshift at the orbital frequency. Since these spacecraft have atomic clocks with good stability (a passive hydrogen maser clock on Galileo-201 and a rubidium clock on Galileo-202), a test of the variation of the redshift can be performed and an accumulated relativistic effect can be determined over the long term. In response to our Galileo mission request, the ILRS conducted monthly, week-long campaigns for a period of one year in support of the ESA funded experiment, GREAT (Galileo gravitational Redshift Experiment with eccentric sATellites). Stations were asked to observe each pass, sampling data from the beginning to the end, with one or two normal points, maximum of five minutes in duration, about every 50 minutes. The ILRS and the community await results from the experiment.

In addition to the LARGE and GREAT efforts, the ILRS has supported several other tracking campaigns, including the IRNSS constellation at geosynchronous orbits.

ILRS Meetings

The ILRS organizes yearly workshops, the biannual International Workshop on Laser Ranging and then ILRS Technical Workshops, oriented toward SLR practitioners, on the years between. Meetings of the Governing Board and standing committees are typically held in conjunction with these ILRS workshops. A summary of recent and planned ILRS meetings is shown in Table 3. Minutes and presentations from the workshops and these splinter meetings are available from the ILRS website (*https://ilrs.gsfc.nasa.gov/about/reports/workshop/index.html* and *https://ilrs.gsfc.nasa.gov/about/reports/meeting_reports.html*).

The ILRS also conducts meetings of the Central Bureau on a monthly basis. These meetings review network station operation and performance, as well as coordinate support of upcoming missions, monitoring and managing the ILRS infrastructure, and future directions and activities.

In May 2016, the ILRS celebrated forty years of supporting LAGEOS; the satellite was launched on May 04, 1976. To acknowledge the anniversary, the NASA Space Geodesy Program sponsored a symposium at NASA GSFC with several talks from speakers involved in the program over the last forty years. Links to information about the symposium as well as general information about LAGEOS, is available at the website: *https://lageos.cddis.eosdis.nasa.gov/Celebrating_40_years_of_LAGEOS.html*. Similarly, 30 years of Ajisai tracking was celebrated on August 13, 1986.

The ILRS co-sponsored several workshops over the last three years. The 2015 ILRS Technical Workshop was held in October 2015 in Matera Italy; the theme of the focused workshop was "Network Performance and Future Expectations for ILRS Support of GNSS, Time Transfer, and Space Debris Tracking" and address the topics that impact the quality of the data products and operations. Abstracts, presentations, posters, and papers from the workshop are online at the workshop's website: *https://cddis.nasa.gov/2015_Technical_Workshop/*.

In October 2016, the Helmholz Center Potsdam of the GFZ German Research Centre for Geosciences organized and hosted the 20th International Workshop on Laser Ranging in Potsdam, Germany. Over 170 attendees participated in the workshop. The theme for this workshop, "The Path Toward the Next Generation Laser Ranging Network" allowed attendees to present ideas for future advances in SLR technology and science; workshop materials, abstracts, presentations, posters, and papers, are available at the meeting's website *https://cddis.nasa.gov/lw20*. This workshop continued the "station clinic" session concept to address station operations topics; ILRS experts met in small groups of station engineers and operators to provide solutions to common station problems, information to maintain station stability, and guidelines for interacting with the analysts in determining station biases.

Table 3. Recent ILRS Meetings (as of May 2017)

Timeframe	Location	Meeting
April 2015	Vienna, Austria	ILRS Analysis Standing Committee meeting
October 2015	Matera, Italy	2015 ILRS Technical Workshop ILRS Governing Board meeting ILRS Standing Committee meetings
October 2016	Potsdam, Germany	20th International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Standing Committee meetings
April 2016	Vienna, Austria	ILRS Analysis Standing Committee meeting
April 2017	Vienna, Austria	ILRS Analysis Standing Committee meeting
October 2017	Riga, Latvia	2017 ILRS Technical Workshop ILRS Governing Board meeting ILRS Standing Committee meetings

Publications

Detailed reports from past meetings can be found on the ILRS website. ILRS Biannual Reports summarize activities within the service over the period since the previous release. They are available as hard copy from the CB or online at the ILRS website. The latest volume is the eighth published report for the ILRS and concentrated on achievements and work in progress rather than ILRS organizational elements. However, this report, the 2009-2010 ILRS Report, published in late 2012, was the last edition produced by the ILRS due to the extensive amount of work required to generate these documents. The ILRS CB is currently looking into issuing these reports in a more streamlined fashion.

The ILRS Central Bureau continues to maintain the ILRS website, installed on a CDDIS webserver at NASA GSFC. The website, *https://ilrs.gsfc.nasa.gov*, is updated several times per week as required. A bibliography of laser ranging publications is maintained on this website.
ILRS Analysis Center reports and inputs are used by the Central Bureau for review of station performance and to provide feedback to the stations when necessary. Special weekly reports on on-going campaigns are issued by email. The CB also generates monthly and quarterly Performance Report Cards and posts them on the ILRS website (*https://ilrs.gsfc.nasa.gov/network/system_performance/index.html*). These Report Cards evaluate data quantity, data quality, and operational compliance for each tracking station relative to ILRS minimum performance standards. These results include independent assessments of station performance from several of the ILRS analysis/associate analysis centers. The statistics are presented in tabular form by station and sorted by total passes in descending order. Plots of data volume (passes, normal points, and minutes of data) and RMS (LAGEOS, Starlette, calibration) are created from this information and available on the ILRS website. Plots, updated frequently, of multiple satellite normal point RMS and number of full-rate points per normal point as a function of local time and range have been added to the ILRS website station pages.

Other Activities

In April 2013, the ILRS was accepted as a network member of the International Council for Science (ICSU) World Data System (WDS). The WDS strives to enable open and long-term access to multidisciplinary scientific data, data services, products and information. The WDS works to ensure long-term stewardship of data and data services to a global scientific user community. The ILRS is a network member of the WDS, representing its two data centers and coordinating their activities within the WDS. The WDS requests that all members present a report every two years at its member's forum. In 2016, a poster (Noll and Pearlman, 2016) reviewing the ILRS was presented at the WDS Member's Forum in Denver CO.

Issues and Challenges

Several challenges are on the horizon for the ILRS as it moves forward. Many gaps remain in the ILRS network's geographic coverage, primarily in Latin America, Africa, and Oceania. The ILRS network consists of a mix of new and old technologies and levels of financial support and there is a lack of standardization in system hardware and operations. The number of satellite targets for the ILRS network tracking continues to increase and because of this increase, there is a need to implement more effective tracking strategies. Furthermore, there is a need to be more selective on the time spent on each target. Data quality issues continue to affect the ILRS products; efforts are underway to detect and reduce systematic errors.

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International VLBI Service for Geodesy and Astrometry (IVS)

http://ivscc.gsfc.nasa.gov

Chair of the Directing Board: Axel Nothnagel (Germany)
Director of the Coordinating Center: Dirk Behrend (USA)

Overview

This report summarizes the activities and events of the International VLBI Service for Geodesy and Astrometry (IVS) during the report period of 2015−2017.

Structure

The International VLBI Service for Geodesy and Astrometry (IVS) is an approved service of the International Association of Geodesy (IAG) since 1999 and of the International Astronomical Union (IAU) since 2000. The goals of the IVS, which is an international collaboration of organizations that operate or support Very Long Baseline Interferometry (VLBI) components, are

- to provide a service to support geodetic, geophysical and astrometric research and operational activities;
- to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique; and
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

They are realized through seven types of components (Network Stations, Operations Centers, Correlators, Analysis Centers, Data Centers, Technology Development Centers, and the Coordinating Center). The structure of the IVS and the interaction among the various components and external organizations is shown in Figure 1.

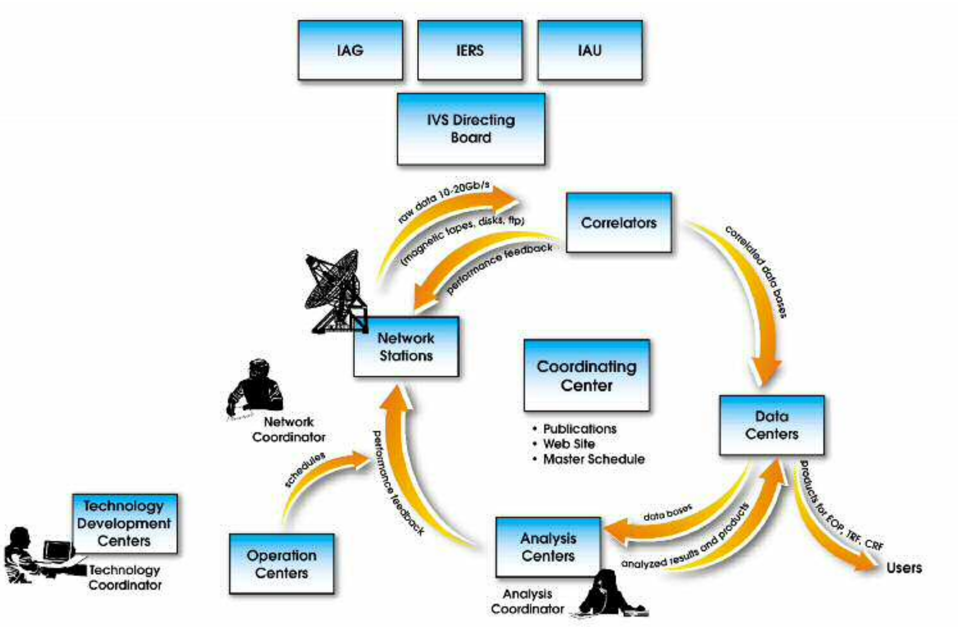

Figure 1. Organizational diagram of the IVS.

Being tasked by IAG and IAU with the provision of timely and highly accurate products (Earth Orientation Parameters, EOP; Terrestrial Reference Frame, TRF; Celestial Reference Frame, CRF), but having no funds of its own, IVS strongly depends on the voluntary support of individual agencies that form the IVS.

Activities

Meetings and Organization

The IVS organizes biennial General Meetings and biennial Technical Operations Workshops. Other workshops such as the Analysis Workshops and technical meetings are held in conjunction with larger meetings and are organized once or twice a year. Table 1 gives an overview of the IVS meetings during the report period.

Table 1. IVS meetings during the report period (2015−2017).

Time	**Meeting**	**Location**
4-7 May 2015	8th IVS Technical Operations Workshop	Westford, MA, USA
17-21 May 2015	22nd EVGA Working Meeting	Ponta Delgada, Azores, Portugal
21 May 2015	16th IVS Analysis Workshop	Ponta Delgada, Azores, Portugal
7-8 October 2015	IVS Retreat	Penticton, BC, Canada
23-26 November 2015	4th International VLBI Technology Workshop	Auckland, New Zealand
9-12 March 2016	2nd VLBI Training School	Hartebeesthoek, South Africa
13-17 March 2016	9th IVS General Meeting	Johannesburg, South Africa
18 March 2016	17th IVS Analysis Workshop	Johannesburg, South Africa
5-6 October 2016	1st International Workshop on VLBI Observations of Near-field Targets	Bonn, Germany
12-14 October 2016	5th International VLBI Technology Workshop	Westford, MA, USA
30 April - 4 May 2017	9th IVS Technical Operations Workshop	Westford, MA, USA
15-19 May 2017	23rd EVGA Working Meeting	Gothenburg, Sweden
17 May 2017	18th IVS Analysis Workshop	Gothenburg, Sweden

Noteworthy among the list of meetings are the IVS Retreat and the VLBI Training School. At the retreat, the IVS Directing Board plus six invited guests discussed the current and future challenges of developing the IVS to meet the needs and take advantage of the opportunities of the next decade. In a series of SWOT analyses (Strength, Weaknesses, Opportunities, and Threats) the current state was evaluated. It was concluded that the relationships of the IVS with some of the space agencies, research institutions and surveying and mapping agencies should be improved. A business plan was discussed indicating that if the IVS were to be established from scratch it would cost an initial investment of $200 million for a network of 30 observatories plus $70 million per year operating costs for daily UT1−UTC determinations. The findings of the retreat were used as the basis for preparing the Strategic Plan of the IVS for the Period 2016–2025 (see below).

The 2nd VLBI Training School was organized at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa, preceding the IVS General Meeting and following a meeting of the African VLBI Network. The purpose of the School was to help prepare the next generation of researchers to understand VLBI systems and inspire them in their future careers. Participants came from Kenya (10), Zambia (9), Germany (7), Austria (4), U.S.A. (4), China (2), Finland (2), France (2), Sweden (2), Ghana (1), Italy (1), and Spain (1). The VLBI School was the second such organized effort, following the previous training school held at Aalto University in Espoo, Finland in 2013. A large group of attendees included students from different countries in Africa with the aim to develop expertise in geodesy and especially VLBI as part of an effort to build new stations in Africa and integrate them into the global VLBI network.

The Directing Board determines policies, adopts standards, and approves the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. The Board members are listed in Table 2.

At the 26th IUGG General Assembly in Prague (July 2015) Ludwig Combrinck of HartRAO became the IAG Representative on the IVS Directing Board, replacing Harald Schuh of GFZ Potsdam. In March 2016, Gino Tuccari of the Italian Istituto di Radioastronomia (IRA/INAF) took over the position of IVS Technology Coordinator from Bill Petrachenko of Natural Resources Canada.

The IVS held Directing Board elections for three representative and three at-large positions in the period December 2016 to February 2017. The new sixteen Directing Board members elected Axel Nothnagel of the University of Bonn for a second term as chair of the IVS for the next four years (until spring 2021).

IVS Strategic Plan for the Period 2016–2025

Based on the discussions at the IVS Retreat, the IVS Directing Board developed a Strategic Plan for the Period 2016–2025. The main goal is to provide overall planning guidelines and to give the stakeholders and IVS Associates reasonable indications for the investments and activities needed. In the period 2016 to 2025 the IVS will enter the era of the VLBI Global Observing System (VGOS), which will be composed of a transition period and subsequent full VGOS operations.

The strategic plan was developed on the basis of the current composition and framework of the IVS' operations. The IVS acts as a truly international entity consisting of hardware distributed all over the world, a global organizational structure, and the associated personnel for organizing and administering the IVS. The IVS is not a formal global institution but a collaboration, which operates on a best-effort basis. The full potential of geodetic and astrometric VLBI can only be exploited if baselines beyond a length of about 6000 km are employed for Earth orientation parameter (EOP) and celestial reference frame (CRF) determinations. The same also applies to any terrestrial reference frame (TRF) application. Because of this it would be difficult for the IVS to be replaced by a single country running its own VLBI network, operating its own telescopes, correlating and analyzing the results, and producing the final VLBI products.

Table 2. Members of the IVS Directing Board during the report period (2015−2017).

a) *Current Board members (June 2017)*

Directing Board Member	Institution, Country	Functions	Recent Term
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Alessandra Bertarini	Reichard GmbH, Max-Planck-Institut für Radioastronomie, Bonn, Germany	Correlators and Operation Centers Representative	Feb 2015 − Feb 2019
Patrick Charlot	Bordeaux Observatory	IAU Representative	—
Francisco Colomer	Instituto Geográfico Nacional, Spain	Networks Representative	Feb 2017 − Feb 2021
Ludwig Combrinck	Hartebeesthoek Radio Astronomy Observatory, South Africa	IAG Representative	—
John Gipson	NVI, Inc./NASA GSFC, USA	Analysis Coordinator	—
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Thomas Hobiger	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2017 − Feb 2021
Chopo Ma	NASA Goddard Space Flight Center, USA	IERS Representative	—
Arthur Niell	Haystack Observatory, USA	Analysis and Data Centers Representative	Feb 2015 − Feb 2019
Evgeny Nosov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2017 − Feb 2019
Axel Nothnagel	IGG, University of Bonn, Germany	Analysis and Data Centers Representative, Chair	Feb 2017 − Feb 2021
Torben Schüler	BKG, Germany	Networks Representative	Feb 2015 − Feb 2019
Gino Tuccari	IRA/INAF, Italy	Technology Coordinator	—
Takahiro Wakasugi	Geospatial Information Authority, Japan	At Large Member	Feb 2017 − Feb 2019
Guangli Wang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2017 − Feb 2019

b) *Previous Board members in 2015−2017*

Rüdiger Haas	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2013 − Feb 2017
Alexander Ipatov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2015 − Feb 2017
Ryoji Kawabata	Geospatial Information Authority, Japan	At Large Member	Feb 2015 − Feb 2017
Jim Lovell	University of Tasmania, Hobart, Australia	Networks Representative	Feb 2013 − Feb 2017
Bill Petrachenko	Natural Resources Canada	Technology Coordinator	—
Harald Schuh	GFZ Potsdam, Germany	IAG Representative	—

The IVS is essential for the monitoring of the Earth orientation parameters and for the maintenance of the celestial and terrestrial reference frames. However, the IVS is little known for its products beyond the geodetic and astrometric communities. For this reason the organizational relationships of the IVS, external as well as internal, and the administration of the IVS must be developed further. In this context the IVS may benefit from the GGOS and UN-GGIM initiatives (Global Geodetic Observing System, UN-Global Geospatial Information Management), which will help to raise awareness in political circles of the needs for geodetic products.

Another challenge of the future is that many experienced colleagues have reached or are close to retirement age. Hence, an active recruiting and staff structure development is needed to replace them. An increased awareness of this issue is needed within the IVS components up to the highest level of their administrations.

On the product side, several separate requirements compete: accuracy, resolution, and timeliness. These need to be balanced for an optimum satisfaction of the product users. There may arise conflicts between what is actually feasible given the current economic and organizational circumstances and the users' desires for higher accuracy, resolution, and timeliness.

Working Groups

Working Group 7 on Satellite Observations with VLBI. This WG was established by the IVS Directing Board in May 2015. WG7 studies possibilities to observe Earth satellites with the VLBI ground network affiliated with the IVS. In particular the development of corresponding observing schedules, of the necessary technology at the observing stations, data correlation, and data analysis are looked into. Experts from the various fields, who are able to perform one or more of the different tasks, were brought together to enable observations of Earth satellites by VLBI.

Working Group 8 on Galactic Aberration. This WG was established by the IVS Directing Board in October 2015. WG8 investigates the issues related to incorporating the effect of galactic aberration in the analysis of the IVS. The aberration effect is not negligible in terms of future microarcsecond astrometry. The WG's main tasks are to look into which value of secular aberration to apply in an *a priori* model of aberration and to formulate a recommendation to the IAU working group working on the next realization of the International Celestial Reference Frame (ICRF3).

Observing Program and Special Campaigns

Observing Program

The observing program for 2015–2017 with the legacy S/X system (production system) included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with 9–12 stations, depending on station availability. These networks were designed with the goal of having comparable x_p and y_p results. Data bases are available no later than 15 days after each session. There are daily 1-hour UT1 Intensive measurements on five days (Monday through Friday, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA), on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Tsukuba (Japan), and on Monday mornings (Int3) in the middle of the 36-hour gap between the Int1 and Int2 Intensive series on the network Wettzell (Germany), Ny-Ålesund (Norway), and Tsukuba (Japan).
- TRF: Bi-monthly TRF sessions with 14–18 stations using all stations at least two times per year.
- CRF: Bi-monthly sessions using the Very Long Baseline Array (VLBA) and up to eight geodetic stations, plus astrometric sessions to observe mostly southern sky sources.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Triennial ~two-week continuous VLBI observing campaigns to produce continuous VLBI time series and to demonstrate the best results that VLBI can offer, aiming for the highest sustained accuracy. During the report period the organization of the CONT17 campaign has commenced (see below).

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products. On average, a total of about 1650 station days per year were used in around 200 geodetic sessions during the year keeping the average days per week which are covered by VLBI network sessions at 3.5.

With the VGOS broadband system (future system under development to be operational in the early 2020ies) a network of 3–5 stations observed a test session roughly every other week for about 26 sessions per year. While in 2015 and early 2016 the lengths of the sessions were limited to one, two, or six hours, from mid-2016 onward the test sessions were extended to the full 24-hour duration. The test sessions are being used to shake out problems with the new system and establish standard operational procedures.

CONT17

Preparations are underway to organize the next continuous VLBI observing campaign in 2017. CONT17 is planned to be observed from 0 UT on November 28 to 24 UT on December 12 of 2017. Unlike the previous CONT campaigns, CONT17 will have three observing networks: two legacy S/X networks to probe the accuracy of the VLBI estimates of the EOP and to investigate possible network biases; one VGOS broadband demonstration network to be observed for part of the full CONT17 period only as an initial indication of VGOS capabilities. The respective networks are depicted in Figures 2 and 3.

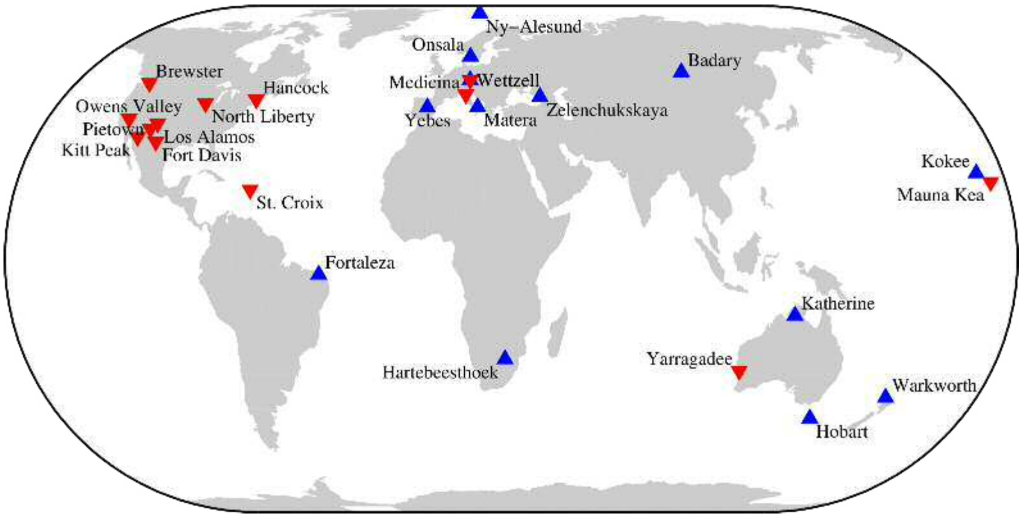

Figure 2. CONT17: Two legacy S/X networks of 26 stations at 25 sites.

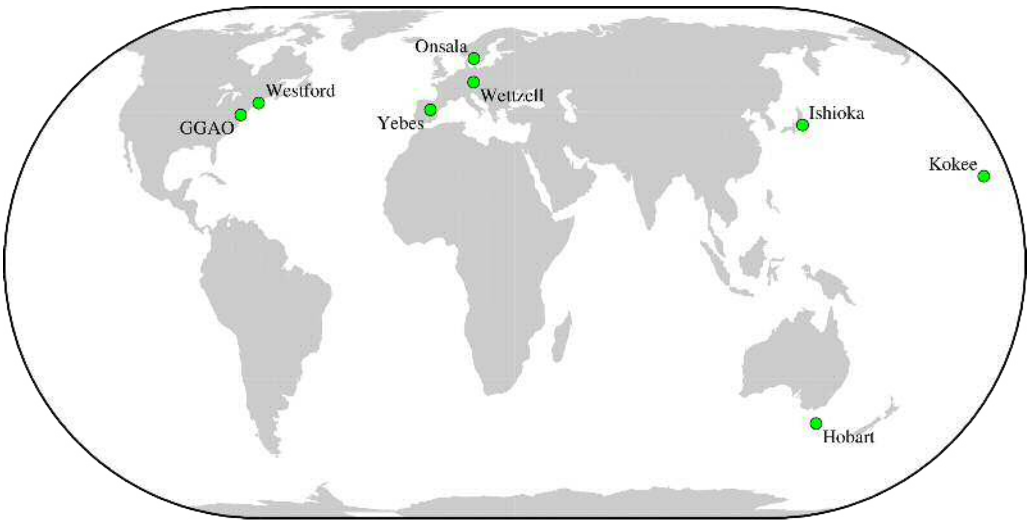

Figure 3. CONT17: VGOS broadband network of up to eight VGOS stations.

The legacy S/X networks are expected to have EOP formal errors of about 15 µas for x_p and y_p and 0.8 µs for dUT1, while the VGOS demonstration network will be slightly worse with around 22 µas for x_p and y_p and 0.8 µs for dUT1 (mostly due to the smaller network size with its sub-optimal geographical distribution).

Analysis

ITRF2014

In 2013, the IERS requested the geometric services (IDS, IGS, ILRS, and IVS) to contribute to the determination of the next International Terrestrial Reference Frame (ITRF). Initially it was anticipated to include data through 31 December 2013, with the various techniques providing their solutions in early 2014. Then the data coverage period was changed to include all available data through 2014, with a firm deadline for submissions to the IERS of 28 February 2015. Ten IVS Analysis Centers submitted solutions to the IVS Combination Center. The software and the number of ACs using it are, in order of popularity: (a) Calc/Solve (five), (b) VieVS (two), (c) Geosat (one), (d) Occam (one), and (e) Quasar (one). The IVS Combination Center compared the input from the various ACs and produced a combined solution for use by the IERS Combination Centers (DGFI, IGN, and JPL). In the process of comparing the input from different ACs numerous issues were uncovered, most of which were subsequently fixed. Two of the submissions had such serious problems that they were not used in the IVS combination solution.

ITRF2014 differs from previous ITRFs in that it includes models for post-seismic deformation (PSD) at sites that had earthquakes. These models were derived by using data from GPS receivers located at these sites. Previously, PSD was handled on an ad-hoc basis by different VLBI analysis packages. For example, Calc/Solve estimated splines for sites. Several IVS ACs compared the use of ITRF2014 vs. ITRF2008, and the general consensus was that ITRF2014 was a better a priori model.

In December 2016, the IERS Directing Board requested that the geometric services begin using ITRF2014 in their analysis as soon as possible. In order to have a smooth transition the IVS Analysis Coordinator requested that the IVS ACs submit two sets of SINEX files: one using ITRF2008 and the other ITRF2014 until a sufficient number of ACs had made the transition. GSFC began doing so in October 2016, and GFZ in January 2017. Several ACs indicated that they would switch over to ITRF2014 in the beginning of 2017.

Transition to Multi-tone Phase Calibration

In VLBI measurements the measured delays are corrupted by unknown and unstable phase shifts in the signal as it travels down the signal path from the front end to the sampler. Many of these effects can be removed through the use of phase calibration. The most common approach is to inject a calibration signal near the front of the signal chain. The calibration signal consisting of a set of tones (‘phase-cal tones’) equally spaced in frequency and derived from the station frequency standard. These signals are extracted during the correlation process and used to adjust the phases prior to fringe-fitting. Since the spurious phase shifts are frequency dependent, each frequency channel is calibrated independently. Historically, only a single phase-cal tone was used in each frequency channel.

Due to the ever broader channel bandwidth and advances in correlator software, for the past several years the correlators have been able to use multiple phase-cal tones in each channel. This latter approach is called multi-tone phase-cal. Naively, the use of multiple phase-cal tones should reduce the noise. A verification by correlating the CONT14 data set with both multi-tone and single-tone phase calibration revealed that multi-tone was generally slightly better than single-tone. On average, the multi-tone sessions had ~1% more observations. The session fit was slightly better, again on the ~1% level, indicating that the data within a session was less noisy and more consistent. Lastly, the RMS baseline scatter across all of the CONT14 sessions was generally lower. All of these are arguments for using multi-tone phase-cal. However, it also turned out that for Zelenchukskaya there was a difference of 8 mm in the vertical position (3-sigma level) depending on whether you used multi-tone or single-tone phase-cal. There are differences for other stations, but none of these are greater than 1-sigma. These issues were discussed publicly within the IVS at a few occasions (e.g., IVS Analysis Workshop in Ponta Delgada, a special meeting devoted to this subject held at MIT Haystack Observatory in October 2016). Following a recommendation coming out of these discussions, the IVS Directing Board decided to switch over to multi-toned phase-cal for all sessions observed on or after 1 January 2017. It is expected that this will yield an improvement in the quality of the data; but it may also introduce a discontinuity in some station positions.

Technology Development

The main focus of the IVS technology development was placed on the build-out of the next-generation VLBI system (VLBI Global Observing System, VGOS) network and achieving operational readiness with the various installations of the signal chain realizations. Figure 3 shows the currently available VGOS broadband stations, while Figure 4 indicates the network anticipated for the year 2020. That is, over the next several years a number of new VGOS stations will come online. Operational readiness for the existing VGOS stations was worked on in a series of test sessions of 1-, 2-, 6-, and 24-hour lengths. These tests uncovered a number of smaller and larger issues of high-level, low-level, and transient nature that were successively ironed out or identified and actively being worked on. In the near future the focus is likely to shift from the station side to the data transport and correlation parts of the processing chain. Here the use of cloud services and distributed correlation to deal with the large amount of data are aspects that will be investigated.

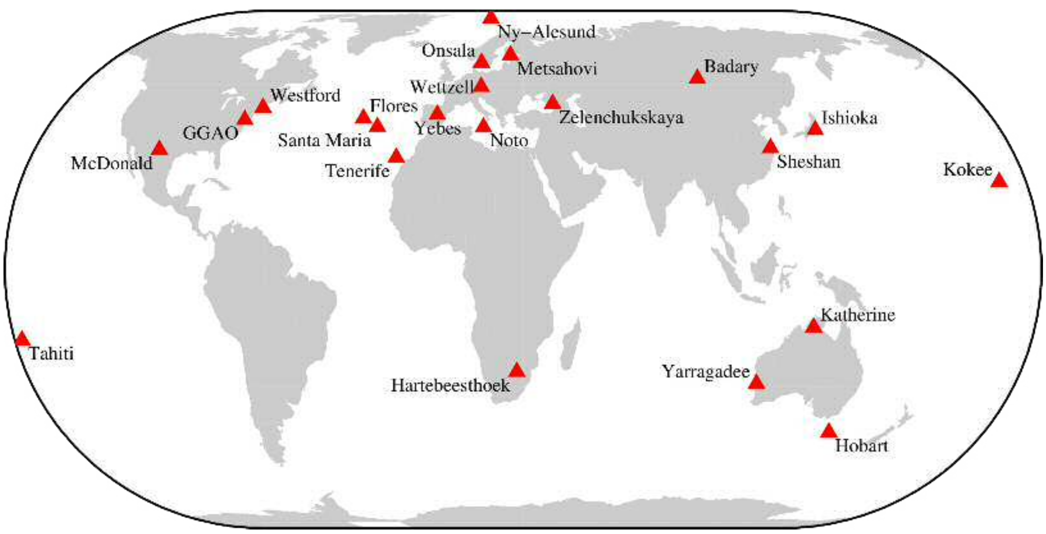

Figure 4. VGOS broadband network as of early 2017.

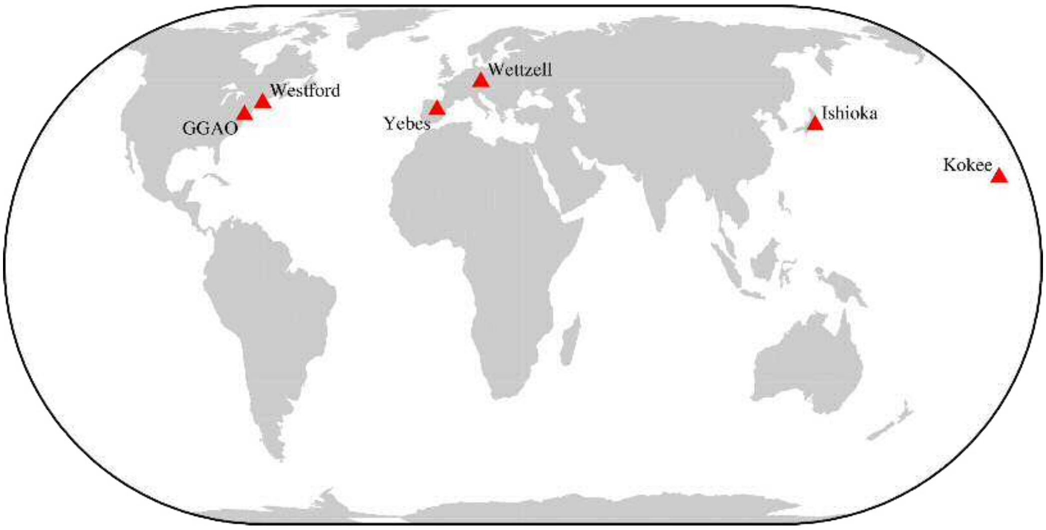

Figure 5. VGOS broadband network anticipated for 2020.

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A. Nothnagel, D. Behrend, A. Bertarini, P. Charlot, L. Combrinck, J. Gipson, E. Himwich, R. Haas, A. Ipatov, R. Kawabata, J. Lovell, C. Ma, A. Niell, B. Petrachenko, T. Schüler, G. Wang: "Strategic Plan of the IVS for the Period 2016–2025". In: D. Behrend. K.D. Baver, K. Armstrong (eds.), International VLBI Service for Geodesy and Astrometry 2016 General Meeting Proceedings, NASA/CP-2016-219016, Greenbelt, MD, USA, pp. 3–11, 2016.

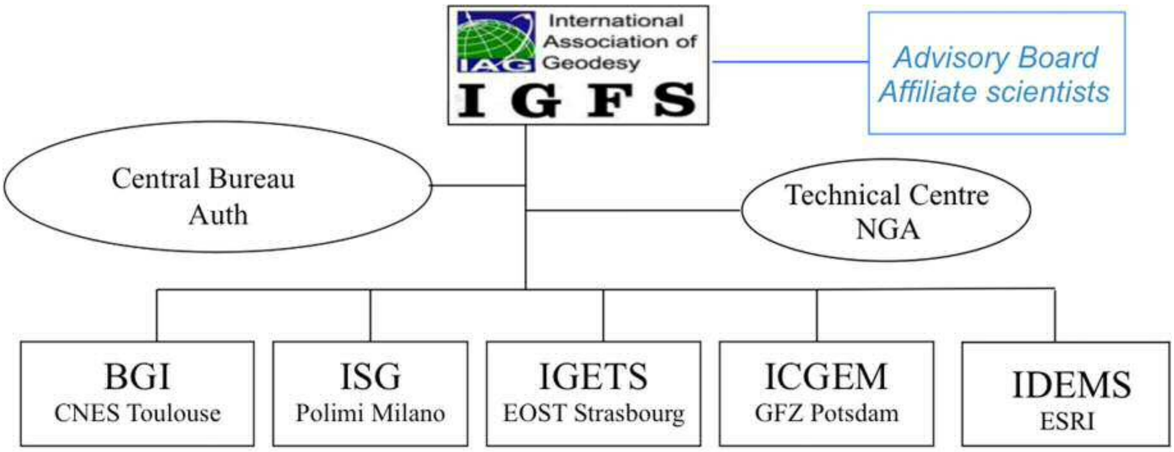
International Gravity Field Service - IGFS

http://igfs.topo.auth.gr/

Chairman: Riccardo Barzaghi (Italy)
Director of the Central Bureau: George Vergos (Greece)

The IGFS structure

The present day IGFS structure is summarized in the following chart



BGI (Bureau Gravimetrique International), Toulouse, France
ISG (International Service for the Geoid), Politecnico di Milano, Milano, Italy
IGETS (International Geodynamics and Earth Tides Service), EOST, Strasbourg,France
ICGEM (International Center for Global Earth Models), GFZ, Potsdam, Germany
IDEMS (International Digital Elevation Model Service), ESRI, Redlands, CA, USA
Auth (Aristotle University of Thessaloniki), Thessaloniki, Greece
NGA (National Geospatial-Intelligence Agency), USA

IGFS coordinates the activities of the Gravity Services (BGI, ISG, IGETS, ICGEM, IDEMS) via its Central Bureau at the Aristotle University of Thessaloniki (Greece), the Advisory Board and the Technical Centre at NGA (USA).
The members of the IGFS Advisory Board are:

- S. C. Kenyon (USA)
- J.-P. Barriot (French Polynesia)
- S. Bonvalot (France)
- F. Barthelmes (Germany)
- U. Marti (Switzerland)
- R. Pail (Germany)
- S. Bettadpur (USA)
- H. Denker (Germany)
- Y. Wang (USA)
- L. Sanchez (Germany/Columbia)
- L. Vitushkin (Russia)
- M. G. Sideris (Canada)
- J. Huang (Canada)
- A. Eicker (Germany)

- R. Forsberg (Denmark)
- T. Gruber (Germany)
- M. Reguzzoni (Italy)
- I. N. Tziavos (Greece)
- K. Kelly (USA)
- H. Abd-Elmotaal (Egypt)
- Y. Fukuda (Japan)

Through this structure, the interaction between the Gravity Services proved to be effective and able to provide users with the required gravity products. Another important task of IGFS is to be an interface between the Gravity Services and GGOS. Particularly, in this respect, the IGFS actions have been performed in strict contact with the GGOS Bureau of Products and Standards, the Bureau of Network and Observations and GGOS Focus Area on "Unified Height Systems". Finally, IGFS is cooperating with IAG Commissions and Inter-Commission Committee on Theory through Joint Working and Study Groups, namely:

- JSG 3.1: Intercomparison of Gravity and Height Changes (joint with Commissions 1, 2 and 3)
- JWG 0.1.2: Strategy for the Realization of the International Height Reference System (joint with GGOS, Commission 1, ICCT)
- JWG 2.1.1: Establishment of a global absolute gravity reference system (joint with Commission 2)
- JWG 2.2.1: Integration and validation of local geoid estimates (joint with Commission 2)

Overview

In the period 2016-2017, IGFS activities were mainly addressed on one side to improve the internal organization and, on the other side, to strength the connections with GGOS and IAG Commission 2. Parallel to that, standard activities have been also performed, i.e. actions related to: coordinate collection, validation, archiving and testing of gravity field related data; coordinate exchange of software of relevance for gravity field activities; coordinate courses on gravity field estimation; distribute information materials related to the earth's gravity field.
Although most of these activities have been performed in a direct way by the related Gravity Services, they have been supervised and harmonized by IGFS.

The internal structure has been revised. A new Central Bureau has been established since, after IAG/IUGG in Prague, OGS decided to end this activity. The call for the IGFS CB was sent out at the beginning of 2016 and on April 1st, 2106 the new CB, hosted at the Aristotle University of Thessaloniki (Greece), started its activity. Furthermore, in 2016, the ICET Service evolved in the new International Geodynamics and Earth Tides Service (IGETS) aiming at extending and integrating the activities of the International Centre for Earth Tides (ICETS) and of the Global Geodynamics Project. Also, in 2016, the International Digital Elevation Model Service (IDEMS) was moved from De Montfort University (UK) to ESRI Company (USA) which is now in charge for distributing data and metadata on DEMs.

All this reorganization procedures were managed and carried out by IGFS in cooperation with its Advisory Board and in agreement with the IAG EC.

In the near future, a new service is going to be added to IGFS. This will be the International Combination Service for Time-variable Gravity Field Solutions (COST-G), the continuation within the framework of IGFS of the H2020 European Gravity Service for Improved Emergency Management project (EGSIEM). One of the main objectives of EGSIEM was to unify the knowledge of the GRACE community in order to come to a standardisation of gravity-derived products describing mass transport in the system Earth. The key role of this data is widely known in the geodetic community and it is thus of extreme importance to have this service under the IGFS umbrella.

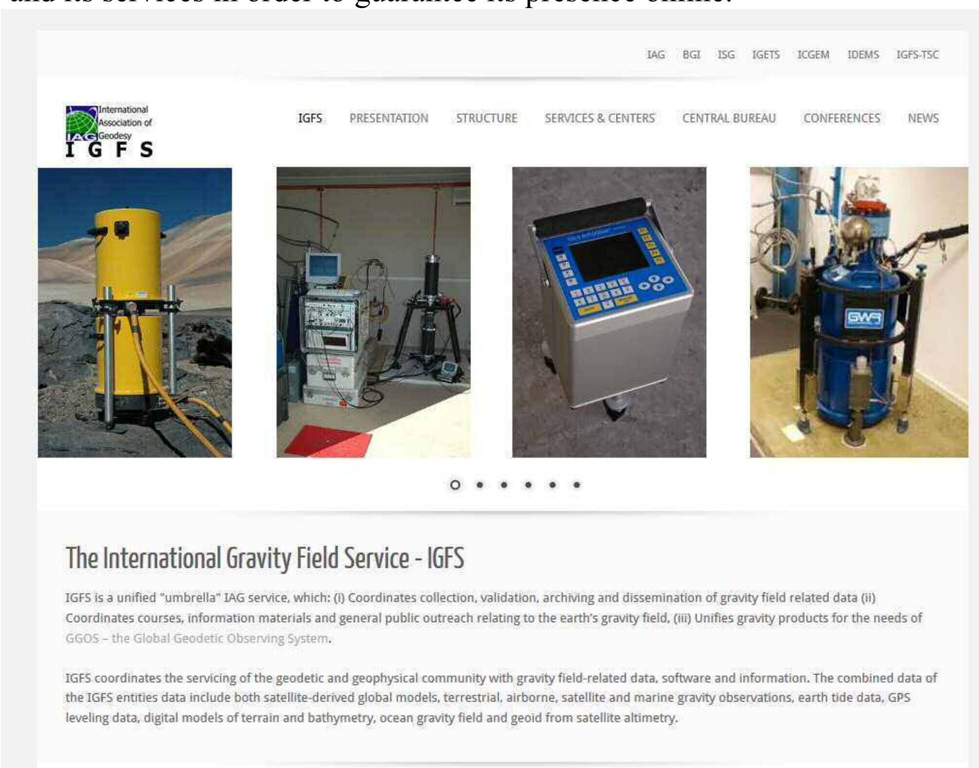
As mentioned, external actions were mainly performed in connection with GGOS activities. IGFS representatives attended the GGOS Days Meetings held in Frankfurt, Germany (October 21st-23rd, 2015) and Cambridge, USA (October 24th-27th, 2016). IGFS representatives have been also involved in the GGOS Bureaus meetings held in San Francisco (during AGU 2015, 2016) and Vienna (during EGU 2016, 2017). Through these activities, a closer cooperation between the Gravity Filed Services and the Geometric Services of IAG was reached. Furthermore, standards on gravity metadata were developed (based on the GGOS Bureau of Products and Standards recommendations) and implemented in the new IGFS web page. IGFS actions in GGOS were also performed within the framework of the Focus Area on "Unified Height Systems". In this respect, IGFS actively participated to the definition of the International Height Reference System/Frame (IHRS/IHRF).

Cooperation with IAG Commission 2 is based on the activities of several Joint Working and Study Groups that have been established at the last IAG/IUGG Assembly in Prague. Also, on September 19th-23rd, 2016, IGFS and Commission 2 co-organized the 1st Joint Commission 2 and IGFS Meeting in Thessaloniki, named "International Symposium on Gravity, Geoid and Height Systems 2016". This conference series will be continued in the forthcoming future since Commission 2 and IGFS are planning to organize the second joint meeting on the first half of September 2018, in Copenhagen.

Finally, IGFS is managing the Geomed2 project, an ESA supported project, for the computation of the geoid and the DOT in the Mediterranean area. This project involves most of the Gravity Services related to IGFS.

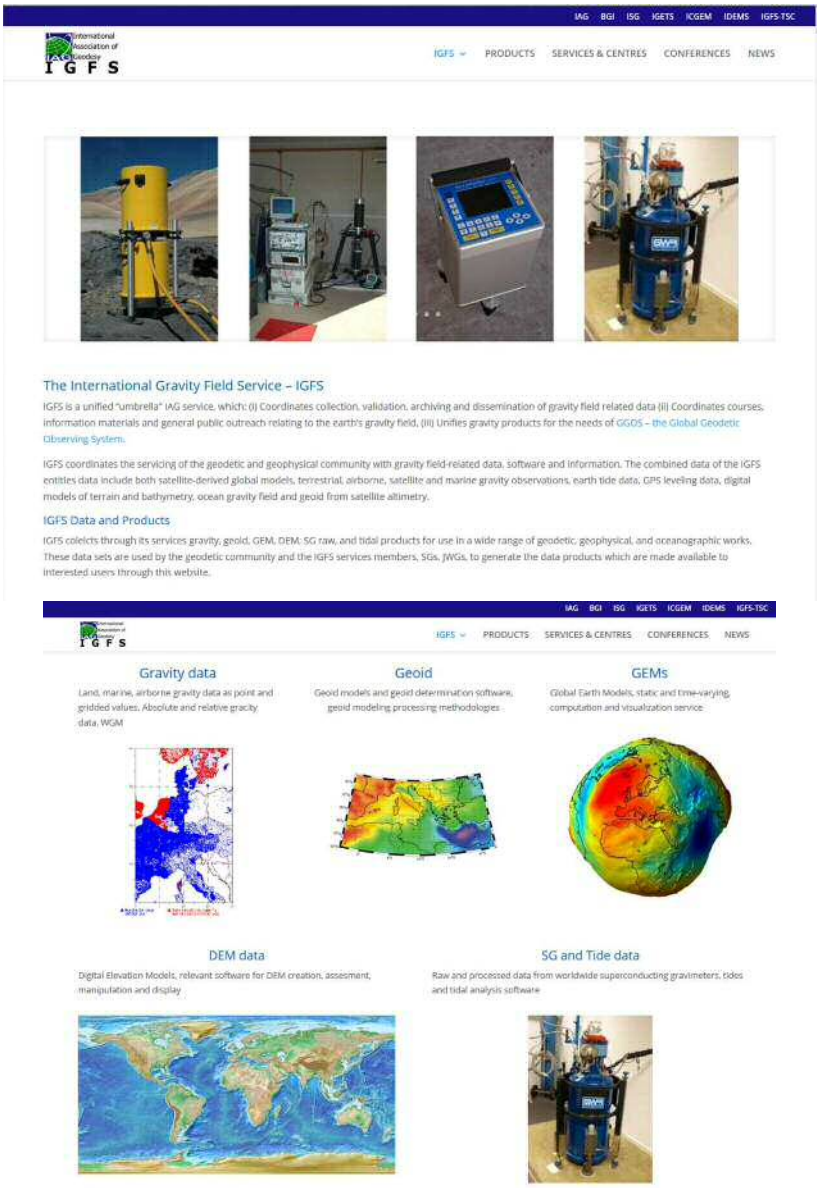
The IGFS Central Bureau and the IGFS web page

With the International Gravity Field Service (IGFS) Central Bureau (CB) being hosted at the Department of Geodesy and Surveying (DGS) of the Aristotle University of Thessaloniki (AUTH) since April 2016, an effort was put forth in order to update its presence in the web and make the IGFS data and products more visible to the interested scientific and user community. To that respect, a first webpage has been created presenting mostly administrative information for IGFS and its services in order to guarantee its presence online.



The first update of the IGFS webpage online since April 2016

Given the need to promote the work carried out by IGFS Services and Centers, a new updated webpage has been recently created focusing more on the data and products availability, so that interested users can acquire them directly from the available portals (see figures below). In the new webpage layout, the availability of gravity, geoid, GEM, DEM, SG and tide data through the IGFS services portal is more visible, while a news section has been created as well to direct to IGFS related conferences, updates, etc.



The recently updated IGFS webpage, online since October 2016

Finally, two mailing lists have been developed within IGFS CB:
igfs-products@lists.auth.gr: the scope of this list if to provide updated information on the new data and products that become available from the IGFS Services. New data and products such as GEMs, DEMs, gravity, geoid, SG, tide, etc. will be posted and shared to all list members. Subscription to the list is free. The list can be accessed at https://lists.auth.gr/sympa/info/igfs-products
igfs-standards@lists.auth.gr: the scope of this list is to provide a forum for idea exchange within the IGFS CB, AB and IAG Commission2 SC, towards the introduction of new and the update of old IGFS conventions and standards. The igfs-standards mailing list is open to all, but pending approval of the IGFS CB, given the more administrative nature of the list. The list can be accessed at https://lists.auth.gr/sympa/info/igfs-standards.

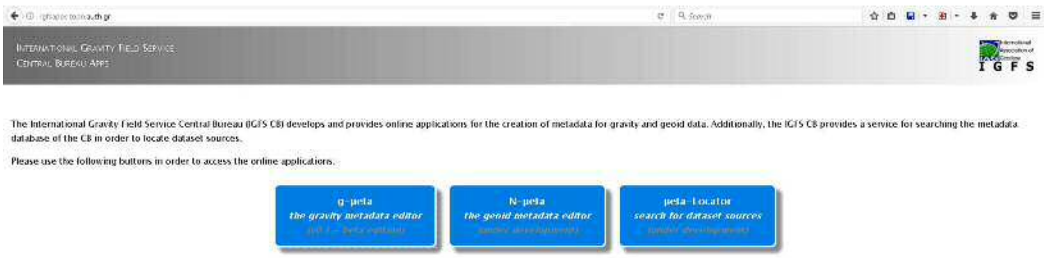
Finally, IGFS has gained presence in public media, both in Facebook (@InternationalGravityFieldService) and Twitter (@igfscb) in order to increase both its visibility and the influence of its products.

IGFS and GGOS

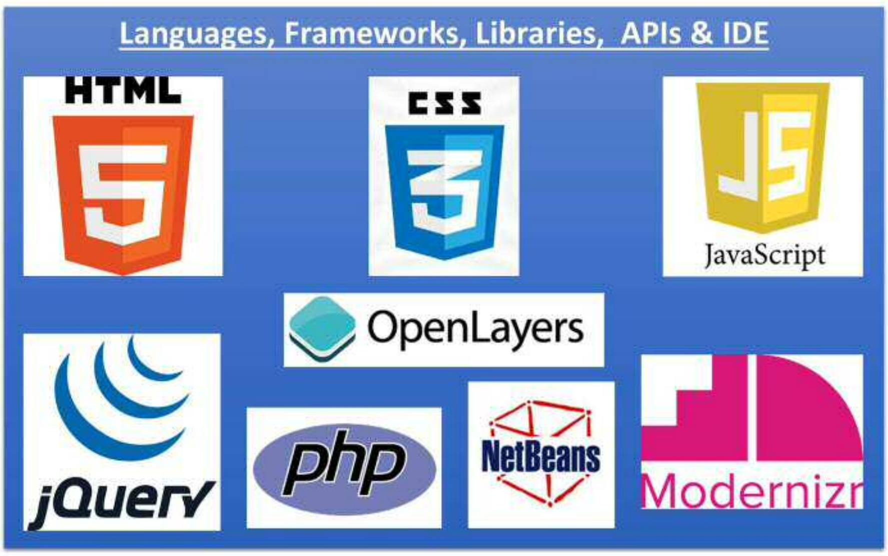
- Gravity metadata structure g-μeta

The IGFS CB has developed, within the IGFS web-page, an IGFS-applications front-end where three main components have been established. The first one refers to the generation of metadata for both relative and absolute gravity observations, either original and gridded ones. The rest refers to metadata for geoid models as well as a geodatabase and geolocator for the visualization of all products offered by IGFS and its services.

IGFS generated a dedicated web-server hosted by a Virtual Machines Host (VMWare) of the Aristotle University of Thessaloniki targeting at minimum downtime, automatic backup and being monitored automatically for threats. The main technologies and modules employed for the metadata generation are HTML5, CSS3, java scripting, jquery, php, netbeans and Modernizr. The application has succeeded to be lightweight, compatible with portable devices, adhere to user needs and extensible.



The IGFS applications front-end (g-μeta, N-μeta and μeta-Locator)



Technologies and modules used for the development of the IGFS metadata

Moreover, it provides code in popular programming languages for integrating the functionality of g-μeta and N-μeta in existing applications. The g-μeta includes both mandatory and optional fields related to the gravity data acquisition standards, processing methodology, tide corrections applied, owner information, geospatial referencing etc.. It requires a complicated validation procedure carried out both on the client and the server side.

Five main categories have been foreseen as: 1) Identification information, 2) Standards and conventions, 3) Data and Data quality information, 4) Distribution information and 5) Metadata reference information. All categories comply with ISO19115-1 adopted also by GGOS. The sub-categories within each main field are presented in the following figures.

1.Identification Information
Citation
Description
Time Period of Content
Status
Spatial Domain
Keywords
Constraints
Points of Contact
Security Information

2.Standards and Conventions
General Standards and Conventions
Earth's Gravity Field
Earth Orientation Parameters
Tidal Conventions
Station Coordinates and corrections for absolute gravity

3.Data and Data Quality Information	
Attribute Accuracy	Gravity Data Type
Logical Consistency	Gravity Accuracy
Completeness Report	Position Accuracy

4.Distribution Information
Distributor
Standard Order Process

5.Metadata Reference Information
Metadata Creation Date and Creator Information
Metadata Prototype Information

Implemented categories within the IGFS g-μeta metadata generator.

- *The International Height Reference System/Frame*

The International Height Reference System/frame (IHRS/IHRF) is one of the key issues in IAG and GGOS. The proper estimation and modelling of global phenomena of the system Earth requires the definition of a reliable reference system/frame. This system/frame must be theoretically defined and established at a given level of precision and accuracy related to the studied phenomena. As it is well known, IAG provides the scientific community with the ITRSnn/ITRFnn. This global reference frame is a fundamental infrastructure that allows monitoring e.g geodynamical phenomena such as deformations of the Earth crust in seismogenic areas. At the moment, a corresponding physical reference system/frame for the reliable description of changes in the Earth's gravity field is still missing. IGFS has been actively involved in the definition of such a system since the IHRS/IHRF is basically related to the gravity field and its estimation. As a matter of facts, the aim of this project is to study the methodology for defining the IHRS and to realize it as global frame of points where the W(P) values are estimated. IGFS strictly co-operated with GGOS focus area on "Unified Height Systems" and Commission 2 on such topic and contributed to the paper by Ihde at al. (2017) that has been published on this subject on Survey in Geophysiscs. At the same time, IGFS is also involved in the definition of the Global Geodetic Reference System/Frame (GGRS/GGRS) that includes the definition of the new global gravity reference system that will replace IGSN71.

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Recent IGFS activities

- 1st Joint IGFS and Section 2 meeting "Gravity, Geoid and Height Systems 2016"

1st Joint Symposium of IAG Commission 2 and IGFS, co-organized by GGOS Focus Area 1

The GGHS2016 "Gravity, Geoid and Height Systems 2016" Meeting was the first Joint Commission 2 and IGFS Symposium co-organized with GGOS Focus Area 1 "Unified Height System". It took place in Thessaloniki, Greece between September 19-23, 2016 at the premises of the Aristotle University of Thessaloniki (Main Ceremony Hall of the Aristotle University of Thessaloniki). Its main focus was on methods for observing, estimating and interpreting the Earth gravity field as well as its applications.

GGHS2016 continued the long history of IAG's Commission 2 Symposia, GGG2000 (Banff, Canada), GG2002 (Thessaloniki, Greece), GGSM2004 (Porto, Portugal), GGEO2008 (Chania, Greece), GGHS2012 (Venice, Italy), with those of IGFS, 1st IGFS Meeting 2006 (Istanbul Turkey), 2nd IGFS Meeting 2010 (Fairbanks, Alaska, USA), 3rd IGFS Meeting 2014 (Shanghai, China) under a unified umbrella, the latter being decided during the XXVI IUGG General Assembly in Prague.

GGHS2016 was composed by 6 sessions spanning the entire 5 days of the program.

For GGHS2016, 211 abstracts have been received, out of which 94 have been scheduled as oral presentations and 117 as posters. 204 participants from 36 countries participated in the conference. It should be particularly emphasized that this symposium was able to attract also the young generation of scientists, since 35% of the total number of participants were either MSc Students or PhD candidates.

Distribution of GGHS2016 participants

A focused view of the distribution of GGHS2016 participants over Europe

The scientific program of GGHS2016 was of outstanding quality and showed significant scientific advancements in several fields of gravity field research, which are briefly summarized in the following:

- Session 1: Current and future satellite gravity missions
  (Chairs: Thomas Gruber and David Wiese)
  - For the satellite gravity mission GRACE continued improvements in data processing are still being achieved (better backgrounds models, Level 1 and Level 2 data processing). This generates steadily increasing interest in using GRACE products for societally-relevant decision making, such as drought/flood forecasting.

- Therefore, the community is continuing to push for continuity and improved future gravity missions after GRACE-FO. Simulation efforts are being carried out to optimize such a mission in terms of data processing (reducing aliasing errors), instrument requirements, etc.
- The continued assessment of GOCE data is leading to improved understanding of the measurement time series and influential environmental parameters.

o Session 2: Global gravity Field Modelling
 (Chairs: Nikolaos Pavlis and Shuanggen Jin)
 - New modelling developments regarding high-resolution global gravity models (XGM2016, EGM2020) indicate significant improvement in accuracy. Component models of topography and isostasy are valuable tools for data reduction and geophysical interpretation.
 - Major advances have been achieved in computational methods, such as high-resolution modelling and solving large systems, and 2D Fourier series representation.
 - New and future data products (e.g., Antarctic polar cap, high-resolution marine gravity field) have become available, and innovative observation concepts based on relativity and quantum optics have been developed.

o Session 3: Local/regional geoid determination methods and models
 (Chairs: Urs Marti and Hussein Abd-Elmotaal)
 - An improvement of the least squares collocation (LSC) technique with better inverse stability and covariance function sampling and representation, and also an iterative approach to better estimate covariances by a feedback approach, have been presented.
 - Major improvements of the analytical continuation technique of the gravity field have been made, aiming to stabilize the solution by smoothing the topography and take the effect of such smoothing as a forward modeling.
 - Also, an iterative approach for solving the fixed BVP has been adopted, aiming to reduce the memory requirement and needed CPU time.
 - Further improvements have been achieved in the activities of the IAG sub-commissions on gravity and geoid, e.g., in Europe and Africa.

o Session 4: Absolute and Relative gravity: observations and methods
 (Chairs: Leonid Vituskin and Jakob Flury)
 - Several highlights of innovative observations technologies have been presented, such as measurement results from test campaigns with a new French transportable quantum gravimeter.
 - Very good and robust results from strap-down airborne gravimetry with a German system, flown side by side with a traditional Lacoste-Romberg sensor, could be achieved.
 - Interesting absolute gravimetry campaigns from New Zealand and Saudi Arabia were undertaken.

o Session 5: Height systems and vertical datum unification
 (Chairs: Michael Sideris and Laura Sanchez)
 - Important considerations for the realization of the International Height Reference System (IHRS), especially, determination of potential values, time-dependent changes, consistency with the geometric coordinates, have been made.

- Innovative approaches to determine gravity potential values with precise clocks have been proposed.
- Strategies for the combination of different geodetic data (GNSS/levelling, gravity, GGMs, tide gauge registrations, MDT) for the vertical datum unification have been presented.

o Session 6: Satellite altimetry and climate-relevant processes
(Chairs: Ole Andersen and Annette Eicker)
- It could be demonstrated, that altimetry improves in precision due to new sensors and new geodetic missions, advancing our understanding particularly in coastal and artic regions.
- Together with GOCE it brings new knowledge to oceanography.
- New insights and refined understanding of mass transport processes on various timescales have been gained, and
- advances in post-processing and optimum filter and leakage correction techniques for GRACE and future gravity missions have been made.

35 of the abstracts accepted and presented at the GGHS2016 conference (either oral or poster) have been submitted as papers for publication in the official peer-reviewed IAG Symposia Series at Springer Publisher.

- *The 12th Geoid School*

IGFS has been involved, together with ISG, in the organization of the 12th International Geoid School that was planned during the IAG/IUGG in Prague (June 2015). The school was held on June, 6th-10th, 2016, at Campus 5, Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar, Mongolia. The Local Organizing Committee was set up by the Mongolian University of Science and Technology (MUST), MonMap Engineering Services Co., Ltd, as a local hosting organizations, and the Mongolian Association of Geodesy, Photogrammetry and Cartography (MAGPC). 30 people attended this Geoid school. 15 students were from Mongolia and the remaining were from 9 different countries, namely: Bhutan, China, India, Latvia, Mongolia, Philippines, Poland, Russia and Sri Lanka.

The participants to the 12th International Geoid School, Ulaanbaatar, Mongolia

During the four lesson days the following topics were discussed:

- General Theory on Gravity Field (F. Sansò)
- The Height Datum Unification (M. Sideris)
- Terrain Effect Computation and Remove/Restore (R. Forsberg)
- Residual Geoid Estimation (R. Barzaghi)
- Global Geopotential Models (S. Holmes)

- *The Geomed2 Project*

IGFS has proposed and managed the GEOMED2 Project that started in 2015 and will end in mid 2018.

The main aim of the proposed GEOMED2 project is the determination of a high-accuracy and high-resolution geoid model for the Mediterranean Sea using land and marine gravity data and GOCE/GRACE based Global Geopotential Models. The processing methodology is based on the well-known remove-compute-restore method following both stochastic and spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data. Within a pre-processing step, all available gravity observations for the wider Mediterranean basin has been collected, validated, homogenized and unified in terms of their horizontal and gravity system, so as to derive a gravity data base that is used for the determination of the geoid. The so-determined geoid model will form the basis for height-system unification within the Mediterranean Sea and will allow to derive high-resolution models of the Mean Dynamic Topography (MDT) to be used in estimating the circulation in the Mediterranean Sea.

The Mediterranean Sea has always been of economic and ecological importance to its surrounding countries. So, a better understanding of its currents is necessary for the management of fishery resources, potential pollution, and maritime security. In the context of this project, currents will be derived from the Mean Dynamic sea surface Topography (MDT), which will be calculated by subtracting the estimated geoid from the available high resolution Mean Sea Surface (MSS) models based on the combination of ERS-1/2, Envisat, TOPEX/Poseidon, Jason-1/2 and Cryosat-2 altimeter data.

The project is based on the cooperation between IGFS related Services (BGI, ICGEM, ISG) and the following scientific institutions:

- Politecnico di Milano, Italy
- Aristotle University of Thessaloniki, Greece
- GET UMR 5563, Toulouse, France
- SHOM, Brest, France
- OCA/Géoazur, Sophia-Antipolis, France
- DTU Space, Kopenhagen, Denmark
- General Command of Mapping, Ankara, Turkey
- University of Zagreb, Zagreb, Croatia
- University of Jaén, Jaén, Spain

Since the beginning of this project, which is financially supported by ESA, IGFS has organized four meetings in which the scientific problems related to the project topics were analysed and discussed. Presentations on GEOMED2 were given at EGU2016 and EGU2017 in Vienna. At the forthcoming IAG/IASPEI 2017 Conference in Kobe (Japan), four abstracts on the project have been submitted and accepted as oral/poster presentations.

International Centre for Global Earth Models (ICGEM)

http://icgem.gfz-potsdam.de/

Franz Barthelmes, Elmas Sinem Ince, Sven Reißland

Overview

The ICGEM service which was established in 2003 as a new service of International Gravity Field Service (IGFS) continues to make the global gravity field models available to public. The service does not only provide the model coefficients publicly available but also presents an interactive platform for the interested users to calculate and visualize the global gravity field functionals and also a discussion forum for users to raise their questions or convey their messages and feedback. Since the beginning of the service, the user profile has changed and widely expanded. Now, users practicing other disciplines (e.g., planetary science, geology) or users working in industry, mapping companies and agencies are also interested in ICGEM products and they communicate ICGEM team closely for further information and analyses.

In order for users to benefit the current ICGEM products and coming GRACE-FO mission products more efficiently, ICGEM has launched the new ICGEM service which is designed to improve the users experience with the service outcomes. Also, the new service is more flexible from the point of administration and promises continuous improvement. The new ICGEM website is designed to encourage the researchers to use the latest model products for education and research purposes. The complete list of ICGEM service products can be found in Geodesist's Handbook 2016 and recently published Frequently Asked Questions of ICGEM Service. Below is a summary of the activities that have been initiated and performed during 2016-2017.

Services

New ICGEM Server

The ICGEM Service has been renewed from technical, administration and presentation perspectives which was a very important step to develop a new flexible platform for future applications and plans particularly applicable to GRACE-FO mission. The programs used in the calculation service have not been changed. Therefore, the calculations in the new platform are identical to the calculations of previous service settings. Following up the launch of GRACE-FO, new products are planned to be made available under the same environment.

Models and their Evaluations

Apart from the 153 static models that was previously available through the ICGEM service, 8 new models have been added to the list. Similar to the previous ones, these models are provided in the standardised self-explanatory format and in the form of spherical harmonic coefficients with DOI numbers assigned to each.

The static models, temporal models as well topography related models can be found under Gravity Field Models. Figure 1 shows a screenshot of the table of the static models. User can access the reference of the model that was provided to ICGEM on the same page and access to the links to download the model coefficients, calculate the gravity functionals and also to visualize the geoid and gravity anomalies.

Spectral comparisons of the models with respect to one of the latest combined models, EIGEN-6C4 can be found under "Evaluation of Models". Moreover, user can access the overall root mean square results of the model-derived geoid comparisons with respect to GNSS/levelling-derived geoid undulations as presented in Figure 2. The columns can be reordered by simply clicking on the title of the column. The comparisons are limited to 6 different regions (USA, Canada, Europe, Australia, Japan, and Brazil) at the moment and will be extended as the GNSS/levelling data from other countries become available.

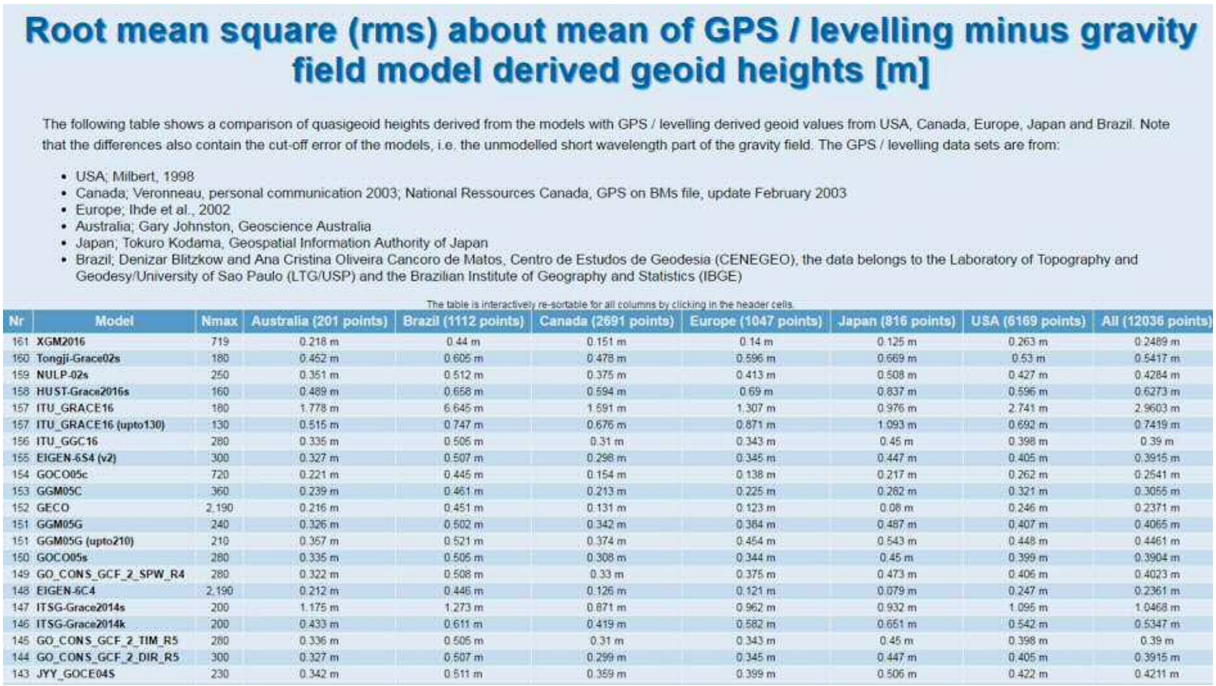
We kindly ask the authors of the models to check the links to the original websites of the models from time to time. Please let us know if something has changed.

The table can be interactively re-sorted by clicking on the column header fields (Nr, Model, Year, Degree, Data, Reference).

The links **calculate** and **show** in the last columns of the table directly invoke the *Calculation Service* and *Visualization page* for the selected model.
For models with a registered **doi** ("digital object identifier") the last column contains the symbol ✓, which directly opens the page on "http://dx.doi.org/".
If you click on the reference, the complete list of references can be seen.

Nr	Model	Year	Degree	Data	References	Download	Calculate	Show	DOI
161	XGM2016	2017	719	A, G, S(GOCO05s)	Pail, R. et al, 2017	gfc zip	Calculate	Show	✓
160	Tongji-Grace02s	2017	180	S(Grace)	Chen, Q. et al, 2016	gfc zip	Calculate	Show	✓
159	NULP-02s	2017	250	S(Goce)	A.N. Marchenko et al, 2016	gfc zip	Calculate	Show	✓
158	HUST-Grace2016s	2016	160	S(Grace)	Zhou, H. et al, 2016	gfc zip	Calculate	Show	✓
157	ITU_GRACE16	2016	180	S(Grace)	Akyilmaz, O. et al, 2016	gfc zip	Calculate	Show	✓
156	ITU_GGC16	2016	280	S(Goce), S(Grace)	Akyilmaz, O. et al, 2016	gfc zip	Calculate	Show	✓
155	EIGEN-6S4 (v2)	2016	300	S(Goce), S(Grace), S(Lageos)	Förste, C. and Bruinsma, S.L., 2016	gfc zip	Calculate	Show	✓
154	GOCO05c	2016	720	(see model), A, G, S	Fecher, T. et al, 2016	gfc zip	Calculate	Show	✓
153	GGM05C	2015	360	A, G, S(Goce), S(Grace)	Ries, J. et al, 2016	gfc zip	Calculate	Show	✓
152	GECO	2015	2190	EGM2008, S(Goce)	Gilardoni, M. et al, 2016	gfc zip	Calculate	Show	
151	GGM05G	2015	240	S(Goce), S(Grace)	Bettadpur, S. et al, 2015	gfc zip	Calculate	Show	
150	GOCO05s	2015	280	(see model), S	Mayer-Gürr, T. et al, 2015	gfc zip	Calculate	Show	
149	GO_CONS_GCF_2_SPW_R4	2014	280	S(Goce)	Gatti, A. et al, 2014	gfc zip	Calculate	Show	
148	EIGEN-6C4	2014	2190	A, G, S(Goce), S(Grace), S(Lageos)	Förste, Christoph et al, 2014	gfc zip	Calculate	Show	✓
147	ITSG-Grace2014s	2014	200	S(Grace)	Mayer-Gürr, T. et al, 2014	gfc zip	Calculate	Show	
146	ITSG-Grace2014k	2014	200	S(Grace)	Mayer-Gürr, T. et al, 2014	gfc zip	Calculate	Show	
145	GO_CONS_GCF_2_TIM_R5	2014	280	S(Goce)	Brockmann, J. M. et al, 2014	gfc zip	Calculate	Show	
144	GO_CONS_GCF_2_DIR_R5	2014	300	S(Goce), S(Grace), S(Lageos)	Bruinsma, S. L. et al, 2013	gfc zip	Calculate	Show	
143	JYY_GOCE04S	2014	230	S(Goce)	Yi, Weiyong et al, 2013	gfc zip	Calculate	Show	
142	GOGRA04S	2014	230	S(Goce), S(Grace)	Yi, Weiyong et al, 2013	gfc zip	Calculate	Show	
141	EIGEN-6S2	2014	260	S(Goce), S(Grace), S(Lageos)	Rudenko, Sergei et al, 2014	gfc zip	Calculate	Show	
140	GGM05S	2014	180	S(Grace)	Tapley, B.D. et al, 2013	gfc zip	Calculate	Show	
139	EIGEN-6C3stat	2014	1949	A, G, S(Goce), S(Grace), S(Lageos)	Förste, C. et al, 2012	gfc zip	Calculate	Show	
138	Tongji-GRACE01	2013	160	S(Grace)	Shen, Y. et al, 2013	gfc zip	Calculate	Show	
137	JYY_GOCE02S	2013	230	S(Goce)	Yi, Weiyong et al, 2013	gfc zip	Calculate	Show	

Figure 1: A screenshot from the table of static models in the new website.



Root mean square (rms) about mean of GPS / levelling minus gravity field model derived geoid heights [m]

The following table shows a comparison of quasigeoid heights derived from the models with GPS / levelling derived geoid values from USA, Canada, Europe, Japan and Brazil. Note that the differences also contain the cut-off error of the models, i.e. the unmodelled short wavelength part of the gravity field. The GPS / levelling data sets are from:

- USA; Milbert, 1998
- Canada; Veronneau, personal communication 2003; National Ressources Canada, GPS on BMs file, update February 2003
- Europe; Ihde et al., 2002
- Australia; Gary Johnston, Geoscience Australia
- Japan; Tokuro Kodama, Geospatial Information Authority of Japan
- Brazil; Denizar Blitzkow and Ana Cristina Oliveira Cancoro de Matos, Centro de Estudos de Geodesia (CENEGEO), the data belongs to the Laboratory of Topography and Geodesy/University of Sao Paulo (LTG/USP) and the Brazilian Institute of Geography and Statistics (IBGE)

The table is interactively re-sortable for all columns by clicking in the header cells.

Nr	Model	Nmax	Australia (201 points)	Brazil (1112 points)	Canada (2691 points)	Europe (1047 points)	Japan (816 points)	USA (6169 points)	All (12036 points)
161	XGM2016	719	0.218 m	0.44 m	0.151 m	0.14 m	0.125 m	0.263 m	0.2489 m
160	Tongji-Grace02s	180	0.452 m	0.605 m	0.478 m	0.596 m	0.669 m	0.53 m	0.5417 m
159	NULP-02s	250	0.351 m	0.512 m	0.375 m	0.413 m	0.508 m	0.427 m	0.4284 m
158	HUST-Grace2016s	160	0.489 m	0.658 m	0.594 m	0.69 m	0.837 m	0.596 m	0.6273 m
157	ITU_GRACE16	180	1.778 m	6.645 m	1.591 m	1.307 m	0.976 m	2.741 m	2.9603 m
157	ITU_GRACE16 (upto130)	130	0.515 m	0.747 m	0.676 m	0.871 m	1.093 m	0.692 m	0.7419 m
156	ITU_GGC16	280	0.335 m	0.505 m	0.31 m	0.343 m	0.45 m	0.398 m	0.39 m
155	EIGEN-6S4 (v2)	300	0.327 m	0.507 m	0.298 m	0.345 m	0.447 m	0.405 m	0.3915 m
154	GOCO05c	720	0.221 m	0.445 m	0.154 m	0.138 m	0.217 m	0.262 m	0.2541 m
153	GGM05C	360	0.239 m	0.461 m	0.213 m	0.225 m	0.262 m	0.321 m	0.3055 m
152	GECO	2,190	0.216 m	0.451 m	0.131 m	0.123 m	0.08 m	0.246 m	0.2371 m
151	GGM05G	240	0.326 m	0.502 m	0.342 m	0.384 m	0.487 m	0.407 m	0.4065 m
151	GGM05G (upto210)	210	0.357 m	0.521 m	0.374 m	0.454 m	0.543 m	0.448 m	0.4461 m
150	GOCO05s	280	0.335 m	0.505 m	0.308 m	0.344 m	0.45 m	0.399 m	0.3904 m
149	GO_CONS_GCF_2_SPW_R4	280	0.322 m	0.508 m	0.33 m	0.375 m	0.473 m	0.406 m	0.4023 m
148	EIGEN-6C4	2,190	0.212 m	0.446 m	0.126 m	0.121 m	0.079 m	0.247 m	0.2361 m
147	ITSG-Grace2014s	200	1.175 m	1.273 m	0.871 m	0.962 m	0.932 m	1.095 m	1.0468 m
146	ITSG-Grace2014k	200	0.433 m	0.611 m	0.419 m	0.582 m	0.651 m	0.542 m	0.5347 m
145	GO_CONS_GCF_2_TIM_R5	280	0.336 m	0.505 m	0.31 m	0.343 m	0.45 m	0.398 m	0.39 m
144	GO_CONS_GCF_2_DIR_R5	300	0.327 m	0.507 m	0.299 m	0.345 m	0.447 m	0.405 m	0.3915 m
143	JYY_GOCE04S	230	0.342 m	0.511 m	0.359 m	0.399 m	0.506 m	0.422 m	0.4211 m

Figure 2: Evaluation of the models in 6 countries and all data available areas wrt to GNSS/levelling derived geoid undulations.

The Calculation Service

An improved user-friendly web-interface to calculate gravity functionals from the spherical harmonic models on freely selectable grids, with respect to a reference system of the user's choice, is provided. The following functionals are available for gravity field model computations:

- pseudo height anomaly on the ellipsoid (or at arbitrary height over the ellipsoid)
- height anomaly (on the Earth's surface as defined)
- geoid height (height anomaly plus spherical shell approximation of the topography)
- gravity disturbance
- gravity disturbance in spherical approximation (at arbitrary height over the ellipsoid)
- gravity anomaly (classical and modern definition)
- gravity anomaly (in spherical approximation, at arbitrary height over the ellipsoid)
- simple Bouguer gravity anomaly
- gravity on the Earth's surface (including the centrifugal acceleration)
- gravity on the ellipsoid (or at arbitrary height over the ellipsoid, including the centrifugal acceleration)
- gravitation on the ellipsoid (or at arbitrary height over the ellipsoid, without centrifugal acceleration)
- potential on the ellipsoid (or at arbitrary height over the ellipsoid, without centrifugal potential)
- second derivative in spherical radius direction of the potential (at arbitrary height over the ellipsoid)
- equivalent water height (water column)

Filtering is possible by selecting the maximum degree of the used coefficients or the filter length of a Gaussian averaging filter. The models from dedicated time periods (e.g. coefficients of monthly solutions from GRACE) are also available after non-isotropic smoothing (decorrelation).

A screenshot of the new interface is presented in Figure 3. Now the user can select the calculation area using the grid selection tool by simply changing the boundaries of the area on the figure visually or enter exact latitude and longitude values to the boxes provided under the figure. The calculated grids (self-explanatory format) and corresponding plots (See Figure 4) are available for download after a few seconds or a few minutes depending on the functional, the maximum degree expansion chosen and the number of grid points.

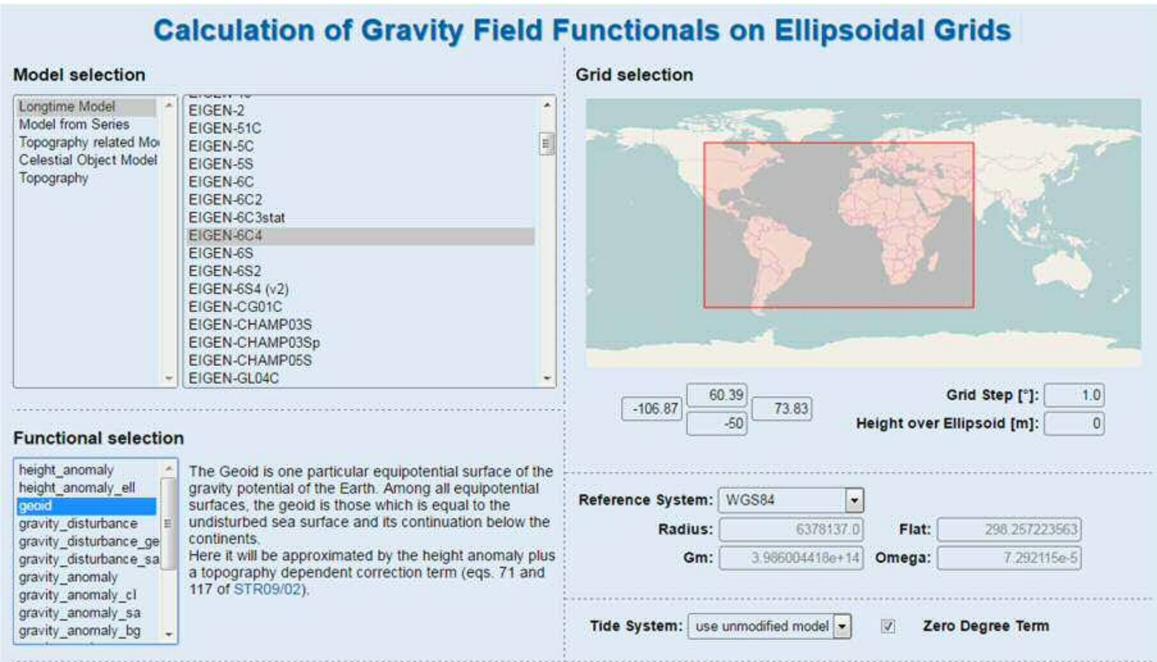


Figure 3: A screenshot of the calculation service with the improved function of grid selection.

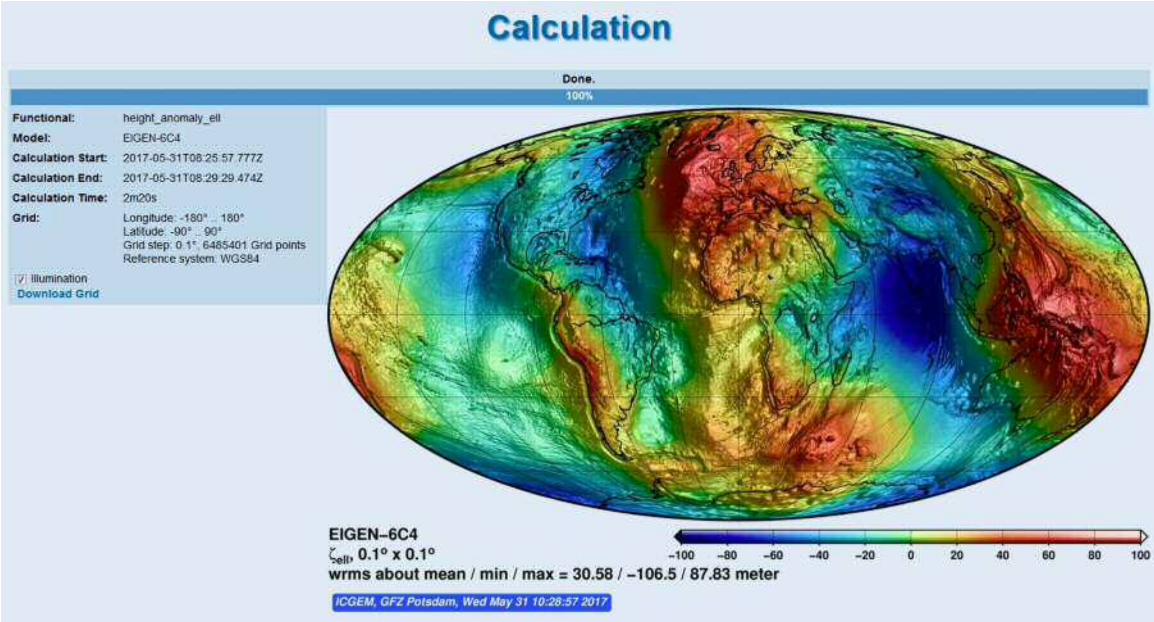


Figure 4: An example of geoid undulation computed using the calculation service.

3D Visualization

An online interactive visualisation of the static models (height anomalies and gravity anomalies), temporal models, trend and annual amplitude and spherical harmonics as illuminated projection on a freely rotatable sphere is available on the new server too (See Figure 5). Static model visualization enables to visualize the differences of two models with a selected grid interval and spherical harmonic degree expansion. Zoom in and out functions are available.

Visualization of temporal models provide computation of geoid undulation and water column from different daily and monthly models with an option of unfiltered or filtered model coefficients. The visualization tool can be used for animation purposes. Visualization of trend and annual amplitude of GRACE measurements that are collected between 2002 and 2015 are also available. Lastly, visualization of spherical harmonics with selected degree and order and rotation option is available for educational purposes.

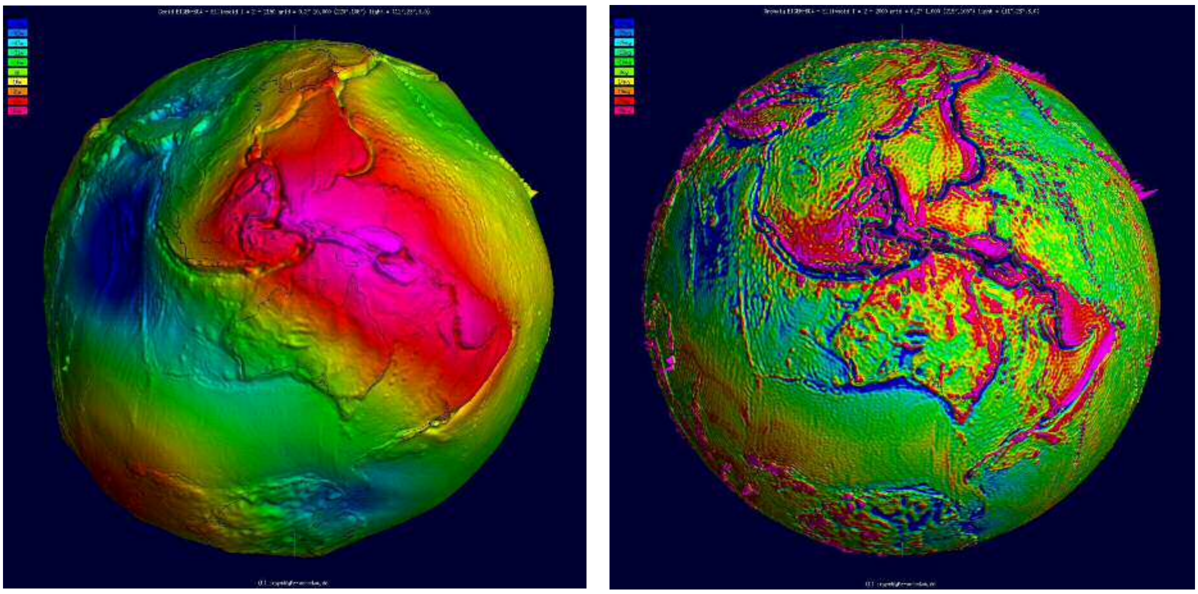


Figure 5: Visualization of geoid undulations (left) and gravity anomalies (right) that are computed based on one of the recent combined global gravitational field model EIGEN-6C4 expanded up to its highest degree and order.

Discussion Forum

Since the interaction between the users and ICGEM team members involves extensive communications via the service and as well as e-mails, the definition of the guest book needs to be redefined. The old guest book is modified as a forum which represents the current status of the platform better.

The new version of this page should give the users the opportunity to discuss things among themselves or answer each other's question as it is the case in most of the forums. In the following stages, sub-sections for different topics will be created.

Anyone without any registration requirement should still be able to write comments in the forum. However, an approval from the ICGEM team is required in order the comment to be available on the website.

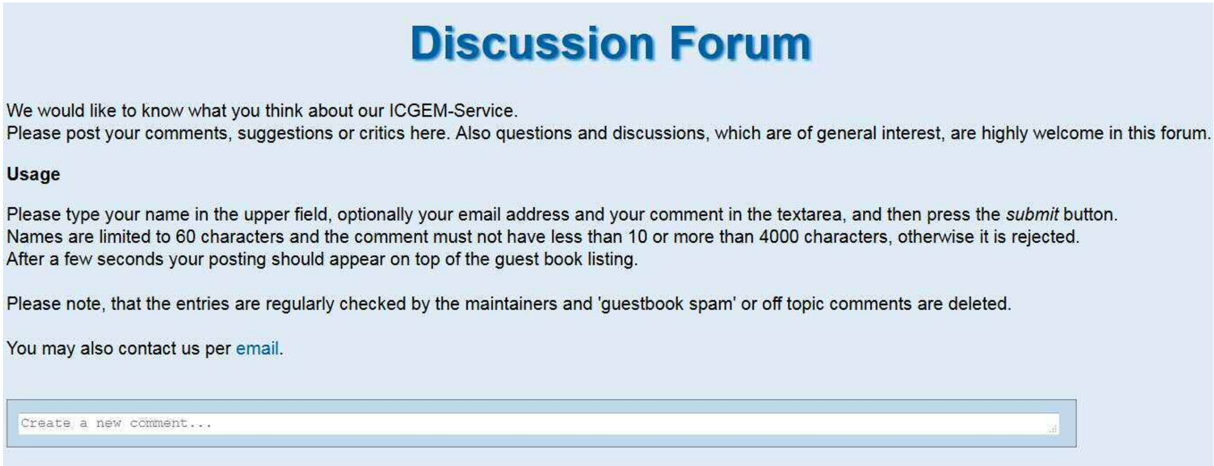


Figure 6: A snapshot from the new interface of the discussion forum.

FAQs (Frequently Asked Questions)

Apart from the discussion forum, FAQs selected from the users' most frequently asked questions are listed and prepared as a pdf document for the users' convenience. The questions are answered to meet the needs of both the users from different disciplines and industry related background, as well the ones who are expert in the field of physical geodesy. Eventually, the FAQs can be expanded and modified depending on the users' interest and responses. The last version of the FAQs can be accessed via http://icgem.gfz-potsdam.de/faq.

Data Policy

Access to global gravity field models, derived products and tutorials, once offered by the centre, is unrestricted for any external user.

ICGEM Team

Elmas Sinem Ince (since 2016)
Sven Reißland (since 2016)
Franz Barthelmes
Wolfgang Köhler (until 2016)

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Publications

Barthelmes, F.; Köhler, W. (2012): International Centre for Global Earth Models (ICGEM), Journal of Geodesy, The Geodesists Handbook 2012, 86(10), 932-934.

Barthelmes, F.; Köhler, W (2010): ICGEM - The International Centre for Global Earth Models, Second International Symposium of the International Gravity Field Service (Fairbanks, USA 2010).

Barthelmes, F.; Köhler, W. (2010): ICGEM - a Web Based Service for Using Global Earth Gravity Field Models. IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements (TG-SMM2010) (Saint Petersburg, Russia 2010).

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Barthelmes, F. (2009): Definition of Functionals of the Geopotential and Their Calculation from Spherical Harmonic Models: Theory and formulas used by the calculation service of the International Centre for Global Earth Models (ICGEM), http://icgem.gfz-potsdam.de, Scientific Technical Report 09/02, Revised Edition, January 2013, Deutsches GeoForschungsZentrum GFZ, DOI 10.2312/GFZ.b103-0902-26

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Barthelmes, F.; Köhler (2006): ICGEM - The International Centre for Global Earth Models, General Assembly European Geosciences Union (EGU) (Vienna, Austria 2006).

International Digital Elevation Model Service (IDEMS)

https://idems.maps.arcgis.com/home/index.html

Director: Kevin M. Kelly (USA)

Structure

The Governing Board (GB) of IDEMS consists of five members who oversee the operation and general activities of the service. The GB is structured as follows:

Director of IDEMS:	*Kevin M Kelly (USA)*
Deputy Director of IDEMS:	*Jianbin Duan (USA)*
IAG/IGFS representative:	*Riccardo Barzhagi (Italy)*
Advisory member:	*Christian Hirt (Australia/Germany))*
Advisory member:	*Michael Kuhn (Australia)*

Overview

IDEMS is a recently revived service of IAG operated by Environmental Systems Research Institute (Esri) (http://www.esri.com/). The new IDEMS website was developed and is maintained by Mr Kevin M. Kelly of Esri, and scientific content provided by Dr Christian Hirt of TU Munich. IDEMS provides a focus for distribution of data and information about digital elevation models, spherical-harmonic models of Earth's global topography, lunar and planetary DEM, relevant software and related datasets (including representation of Inland Water within Digital Elevation Models) which are available in the public domain.

IDEMS Website Usage

IDEMS became operational on April 6, 2016. Over the last year, the IDEMS website has been continually updated with new DEM datasets, both terrestrial and planetary. IDEMS serves as a repository of links to DEM data providers rather than a DEM data storage facility. Table 1 lists the current content available from the IDEMS website:

Table 1. Current IDEMS Website Content

Data Type	No. of data sources
Earth models	3
DEM Studies	5
Global DEM and bathymetry	11
Planetary terrain data	8
Software and Apps	1

Table 2 shows the most popular IDEMS content by the number of views per content item:

Table 2. Most Popular IDEMS Website Content

Data Type	No. of views
Global bathymetry	268
Elevation Coverage Map	178
DEM/DDM Research Papers	57
Getting Started with IDEMS	55
Global Terrain DEM	39
Elevation Layers	31
Topographic Earth Models	31
SRTM30_PLUS topography/bathymetry (30 arc-sec grid), 2014	27

International Geodynamics and Earth Tide Service (IGETS)

http://igets.u-strasbg.fr/

Chair of the Directing Board: Hartmut Wziontek (Germany)
Director of the Central Bureau: Jean-Paul Boy (France)

Structure

- Directing Board: H. Wziontek, J.-P. Boy, V. Palinkas, J.-P. Barriot, C. Foerste, H.-P. Sun, B. Meurers, D. Crossley, J. Hinderer, S. Pagiatakis, S. Bonvalot, N. Sneeuw
- Central Bureau: J.-P. Boy
- Data Center: C. Förste, C. Voigt

Overview

The primary objective of the International Geodynamics and Earth Tide Service (IGETS) is to provide a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS continues the activities of the Global Geodynamic Project since it was established at the IUGG general assembly in Prague 2015.

After the first IGETS business meeting at the 18th International Symposium on Geodynamics and Earth Tides in June 2016, the chair of the service was elected.

Status of the Analysis Centers

Different product levels are derived from the gravity and atmospheric pressure data recorded with the superconducting gravimeters. Products of Level 1 are the raw data without pre-processing which are downsampled to 1 min resolution. The pre-processing of these data, i.e. elimination of gaps, spikes, steps and disturbance is continued as a Level 2 product.

Two IGETS Analysis Centers, at the University of French Polynesia (Tahiti) and at EOST (Strasbourg, France) provide different products. While the first is in charge of processing Level 2 data from the raw Level 1 data, i.e. gravity and pressure data corrected for all major disturbances, the second center is in charge of producing the Level 3 data, i.e. gravity residuals after correction of all major geophysical signals.

During the reporting period, 360 months of data were processed to Level 2 data. Most of the active stations have been updated until mid of 2016. Stations Cibinong, Conrad, Onsala and Yebes were processed for the first time while several stations are still operating with the same instrument for more than 18 years: Cantley, Membach, Medicina, Metsahovi and Strasbourg.

A new product currently in progress are the Level 3 data which are derived from Level 2 data by reducing tidal and non-tidal gravity variations. Tidal models are specific for each station and cover the effects of solid Earth tides and ocean tide loading which are obtained from harmonic analysis of the Level 2 records. For that purpose the updated program ETERNA by Klaus Schüller (ET34-X-V60) was tested at two stations (Bad Homburg and Membach). Earth rotation effects (polar motion and length-of-day variations) are corrected based on the EOP C04 series of IERS. Non-tidal loading effects due to atmospheric, oceanic and hydrological mass-redistributions are reduced with the products provided by the EOST Loading Service (Boy and Lyard, 2008; Boy and Hinderer, 2006; http://loading.u-strasbg.fr/) and the Atmospheric Attraction Computation Service ATMACS (Klügel and Wziontek (2009), http://atmacs.bkg.bund.de/). The Level 3 product is currently in preparation.

Table 1: Status of Level 2 data by January 2017:
Cibinong, Conrad, Onsala and Yebes have been preprocessed for the first time
n: number of preprocessed months
N: number of days effectively used in the global tidal analysis
STD: standard deviation of the global analysis (ETERNA)

Code	Location	SG Instr.	ICET Code	RAW	Corrected	n (months)	N (days)	STD (nm/s^2)
AP	Apache Point, USA	SG046	00466090	160700	160232	13	2091	1.16
BA*	Bandung, Indonesia	T008	00084100	030600	030622		1104	2.94
BE*	Brussels, Belgium	T003	07790200	000900	000901		¶6692	1.64
BF	Black Forest, Germany	CD056_L CD056_H	01560716 02560716	160300 160300	160322 160322	30 30	2037 2043	0.64
BH	Bad Homburg, Germany	(T001) CD030_L CD030_U SG044	 01300734 02300734 00440734	 070400 070400 160900	 070422* 070422* 160122	 11	¶1005 2222 2218 3210	0.69
BO*	Boulder, USA	C024	00246085	031000	031022		1850	0.95
BR*	Brasimone, Italy	T015	00150515	991200	991222		1428	0.78
CA	Cantley, Canada	T012	00126824	161000	160322	12	5809 ¶7404	0.84
CB	Canberra, Australia	C031	00314204	151200	152122	12	6455	0.53
CI	Cibinong	CT022	00224102	120520	120520	28	872	1.11
CO	Conrad, Austria	C025	00250699	131122	131122		2130	2.95
ES	Esashi, Japan	T007	00072849	081200	081222?	→20040 225	2274	1.51
HS	Hsinchu, Taiwan	T048	00482695	090600	090622 •		898	1.45
KA	Kamioka, Japan	T016	00162828	130700	130722		3006	0.78
KY*	Kyoto, Japan	T009	00092823	030600	030622	→20020 731	1533	1.97
MA*	Matsushiro, Japan	T011	00112834	080600	080622		3954	0.61
MB	Membach, Belgium	C021	00210243	120900	120922 •	09	5907	1.49
MC	Medicina,Italy	C023	00230506	160100	160122	11	6511	2.25
ME	Metsahovi, Finland	T020 OSG073_N6 OSG073_N7	00200892 01730892 02730892	150900 150100 150400	150922 150122 150422	21 12 15	5409 ¶5935 356 381	1.23
MO	Moxa, Germany	CD034_L CD034_U	01340770 02340770	161000 161000	160122 160122	23 23	5538 5700	3.69
NY	Ny Alesund, Norway	C039	00390005	120100	120122		3776	1.01
OS	Onsala, Sweden	OSG54	00540875	161100	160322	04	2442	0.71
PE	Pecny,CZ	OSG050	00500930	160700	160722	19	3323	0.89
PO*	Potsdam, Germany	T018	00180765	980900	980912		2250	1.17
ST	Strasbourg, France	(T005) C026	 00260306	 150400	 150422	 04	¶3272 6222	1.16
SU	Sutherland, South Africa	CD037_L CD037_U SG052	01373806 02373806 00523806	161000 161000 161000	160422 160422 160422	16 16 16	4874 4729 2670	0.68
SY	Syowa, Antarctic	T016	00169960	030100	030122*	→20001 231	1279	0.61
TC	Tigo, Concepcion, Chile	RT038	00387621	150400	150422	04	3544	0.54
VI*	Vienna, Austria	C025	00250698	061200	061222		3402 ¶4278	0.56
WE	Wettzell, Germany	(SG103) CD029_L CD029_U CD030_L CD030_U	01030731 01290731 02290731 01300731 02300731	980900 101000 101000 160900 160900	980921* 101022* 101022* 160122 160122	 11 11	¶726 4264 4226 1997 2013	2.69
WU	Wuhan, China	T004	00322647	120700	120712 •		3844	1.25
YS	Yebes, Spain	OSG64	00640435	160300	160322	09	1538	0.54
					TOTAL	360		0.86
								2.27

* instrument stopped • preprocessed by station operator ( ) not included in IGETS
¶ data before 1997/07 included → end of the global analysis

References:

Boy, J.-P., and Lyard, F. (2008). High-frequency non-tidal ocean loading effects on surface gravity measurements, Geophys. J. Int., 175, 35-45, doi: 10.1111/j.1365-246X.2008.03895.x.

Boy, J.-P., and Hinderer, J. (2006). Study of the seasonal gravity signal in superconducting gravimeter data, J. Geodyn., 41, 227-233, doi: 10.1016/j.jog.2005.08.035

Klügel, T. and Wziontek, H. (2009). Correcting gravimeters and tiltmeters for atmospheric mass attraction using operational weather models. Journal of Geodynamics, 48(3–5):204-210.

Status of the IGETS Data Center

The IGETS data sets are stored on a FTP server and are freely available after user registration. The number of IGETS users has been rapidly increasing since the launch in summer 2016 (see Fig. 1). The new data base server is hosted by GFZ Potsdam (Germany) and is accessible via http://igets.gfz-potsdam.de.

Currently data from 35 stations are available, globally distributed, provided by 25 producers covering a time span of up to 20 years. Records from superconducting gravimeters made by GWR of compact (CT) and observatory (OSG) type are predominant. However, recently data from a transportable superconducting gravimeter GWR iGrav and a LaCoste & Romberg spring gravimeter were added for station Borowa Gora, Poland. Furthermore, there are some operators of iGrav and gPhone gravimeters who are indicating to send their data to the IGETS data base in the near future.

All relevant information on the IGETS data base were compiled in the scientific technical report Voigt et.al. (2016), comprising station and sensor information, available data sets, directory structure, file name convention, repair codes and file formats. Data descriptions originating to a large part from Global Geodynamics Project (GGP) were updated and extended for IGETS.

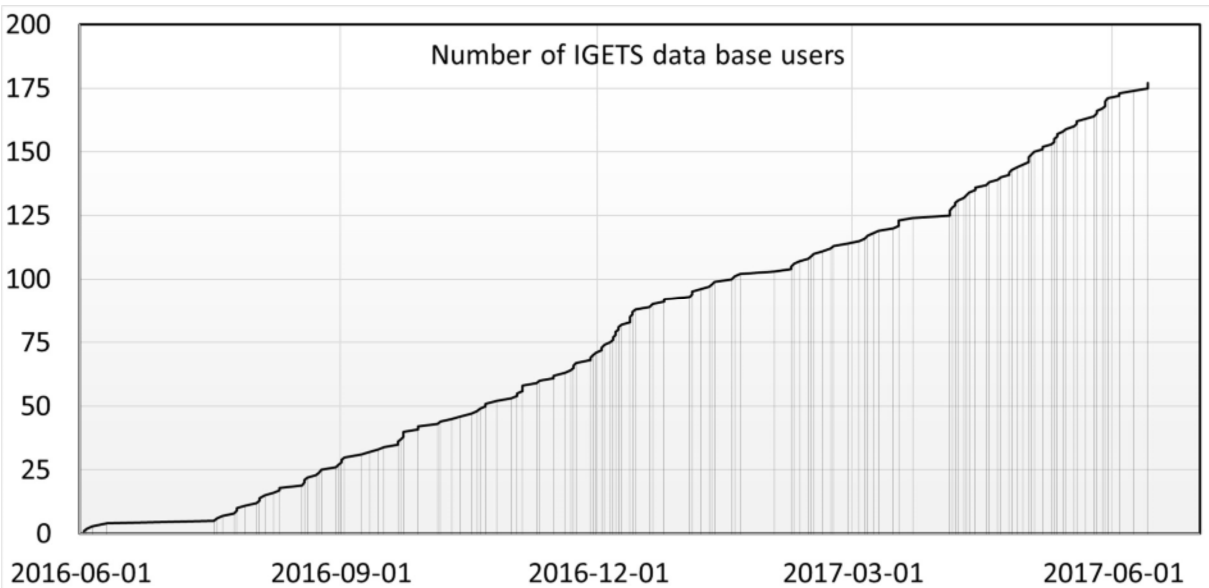

Fig. 1 Number of IGETS data base users since the launch in summer 2016

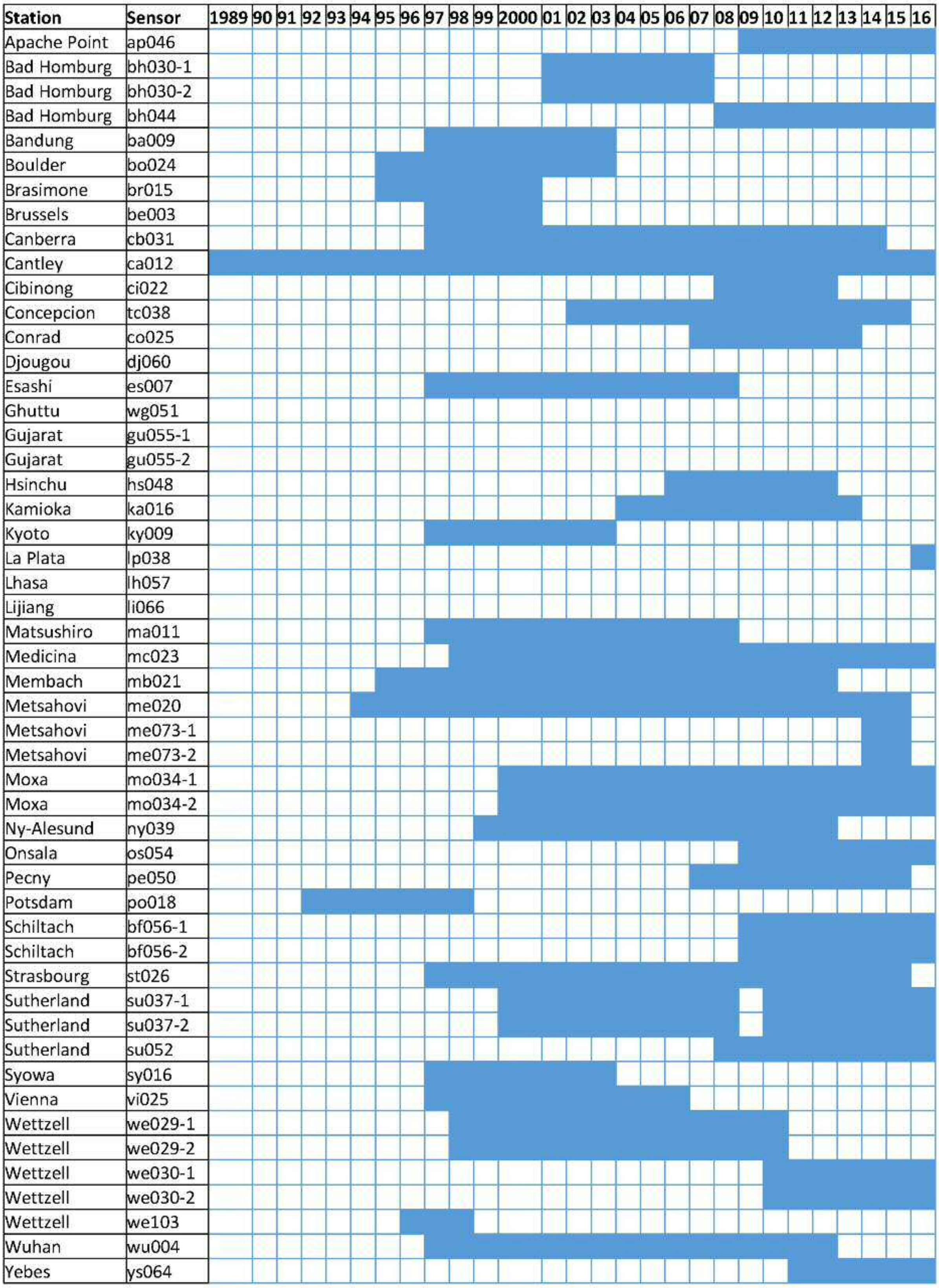

Fig. 2 Time span of the data coverage of the IGETS data base until end of 2016.

References:

Voigt, C., Förste, C., Wziontek, H., Crossley, D., Meurers, B., Pálinkáš, V., Hinderer, J., Boy, J.-P., Barriot, J.-P., Sun, H. (2016): Report on the Data Base of the International Geodynamics and Earth Tide Service (IGETS), (Scientific Technical Report STR - Data ; 16/08), Potsdam : GFZ German Research Centre for Geosciences

Data Publication and Citation – DOI

IGETS established the provision of digital object identifiers (DOI) for the data sets of every station. DOIs are unique and persistent identifiers used to reference and link the individual data sets. The advantages are a clear reference to data sets, to link scientific results with associated publications, an improvement of the access to scientific data and an enhancement of the visibility of research data, encouraging new research to be conducted, and foster scientific cooperation.

For Level 1 data, the DOI is assigned for each station, i.e. one for all sensors of a station referencing the station operators. The DOIs of the Level 1 data sets resolve to DOI landing pages with an overview of the station and the data. For data of Level 2 and Level 3, the DOI are assigned for all IGETS stations in total.

Meetings

A first meeting was held on 06.06.2016 in Trieste during the 18th International Symposium on Geodynamics and Earth Tides. An introduction to the database updates was given by C. Voigt and aspects of the documentation of instrumental parameters by the calibration file were discussed. At the symposium, the progress during the first year was presented by J.-P. Boy and a status update of the Analysis Centre Tahiti (ICET) was given by J-P. Barriot.

A second meeting was held on 26 and 27.04.2017 at the EGU in Vienna with station reports, a report about the IGETS database and a discussion about the current status of the different product levels. The IGETS database was presented with a poster.

References:

Barriot, J-P., Ducarme, B. Verschelle, Y (2016): IGETS Analysis Centre Tahiti (ICET): Status of GGP data processing, Poster presentation, 18th International Symposium on Geodynamics and Earth Tides, Trieste

Boy, J.-P., Barriot, J.-P., Crossley, D., Foerste, C., Hinderer, J., Meurers, B., Palinkas, V., Pagiatakis, S., Sun H.-P., Wziontek, H. (2016): Report of the first year of the International Geodynamics and Earth Tide Service (IGETS), Presentation, 18th International Symposium on Geodynamics and Earth Tides, Trieste

Voigt, C., Förste, C., Wziontek, H., Crossley, D., Meurers, B., Pálinkáš, V., Hinderer, J., Boy, J.-P., Barriot, J.-P., Sun, H. (2017): The Data Base of the International Geodynamics and Earth Tide Service (IGETS), Geophysical Research Abstracts, Vol. 19, EGU2017-4947, EGU General Assembly 2017

Bibliography

A list of publications related to IGETS was compiled and is available at the IGETS web page at http://igets.u-strasbg.fr/biblio.php.

International Gravimetric Bureau
(Bureau Gravimétrique International, BGI)

http://bgi.obs-mip.fr

Director: Sylvain Bonvalot (France)

Structure

The BGI is the scientific service of IAG aimed at ensuring the data inventory and the long term availability of the gravity measurements acquired at the Earth surface. Its main task is the collection, validation and archiving of all kind of gravity measurements (relative or absolute) acquired from land, marine or airborne surveys and the diffusion of the derived data and products to a large variety of users for scientific purposes. The BGI activities are coordinated with those of other IAG gravity services (ISG, IGETS, ICGEM, IDEMS) through the International Gravity Field Service (IGFS).

The BGI has its central bureau in Toulouse (France) and operates with the support of various institutions from France (CNES, CNRS/INSU, IGN, IRD, SHOM, BRGM, IFREMER, Universities of Toulouse, Paris, Strasbourg, Montpellier and Le Mans) and from Germany (BKG). Its directing board includes representative of the supporting institutions and a representative of IAG and of IGFS.

For more information on the BGI structure and membership, see the following references:

- The International Gravimetric Bureau. In: "The Geodesist's Handbook, 2016", H. Drewes, Eds. (International Association of Geodesy). Journal of Geodesy, *Journal of Geodesy* DOI:10.1007/s00190-016-0948-z
- BGI website : http://bgi.obs-mip.fr/

Overview

During the 2015-2017 reporting period, the BGI has continued to support scientific and other users of gravity data. The BGI mainains the 4 global reference databases for relative gravity measurements (from land and marine surveys), for absolute gravity measurements and for reference gravity stations. BGI continues its activity of compilation, validation, archiving and distribution of the surface measurements of the Earth's gravity field. It also realize and distributes derived products (global or regional grids of gravity anomaly) and gravity processing or analysis software's. During the 2015-2017 period, also has carried out regional gravity data compilation and validation for international projects related with geoid or gravity anomaly computations (GEOMED-2, ALP-Array, etc.) and has participated as co-chair of the IAG Joint Working Group for the realization of the Global Absolute Gravity Data Reference System. Finally, BGI is also involved in the evaluation of innovative instrumentations for static and dynamic measurements of the Earth gravity such as absolute gravity meters based on cold-atoms technologies.

Activities

1. Global gravity databases and products

Most of the databases and services provided by BGI are available from the BGI website (http://bgi.obs-mip.fr). It gives access to the four global database of gravity observations: 1) Relative measurements from land surveys; 2) Relative measurements from marine surveys; 3) Reference gravity stations related to the former IGSN71 and Potsdam 1930 networks, 4) Absolute measurements.

1.1. Relative gravity database

The most frequent service BGI can provide is the consultation and retrieval of gravity data and information over local or regional areas. Data requests are made through the BGI website at the following links. Few millions of relative data are currently distributed each year to scientific users. For larger areas (regional to global), BGI also propose grids of gravity anomalies (free air, Bouguer, isostatic).

- land database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Land-Gravity-data

- marine database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Marine-Gravity-data

1.2. Absolute gravity database

The global database for absolute gravity measurements is jointly operated by BGI and BKG (Bundesamt für Kartographie und Geodäsie, Germany). This relational database (AGrav) is capable of storing information about stations, instruments, observations and involved institutions. By this, it allows the exchange of meta-data and the provision of contact details of the responsible institutions as well as the storage and long term availability of gravity data and processing details. The database can be accessed from two mirrored sites at BGI and BKG.

- absolute database: http://bgi.obs-mip.fr ; http://agrav.bkg.bund.de/agrav-meta/

A simple exchange format (project files) which includes all relevant information and is known by the majority of users, was selected. In this way the upload of data to the database is possible by any contributor, using a web based upload form. The provided information ranges from meta-data (localization of stations) up to full information on the absolute determination of the gravity field on a given site (raw or processed data, description of measurement sites, etc.). The collection and archiving of absolute gravity data has been continued in 2015-2017.

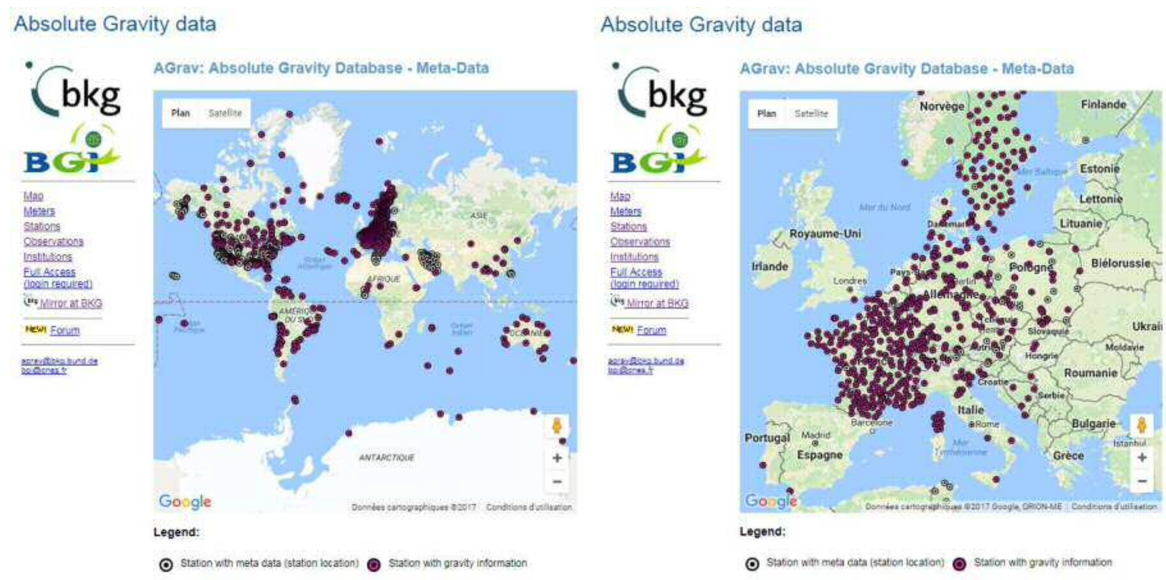

Figure 1: WEB interface of the Absolute Gravity database (BGI-BKG)
Current status (06/2017) : 1147 stations / 4031 observations / 73 instruments / 63 institutions

An improved version of the database has been also initiated (development in progress) in order to support the project of realization of the international absolute gravity reference system (IAG/IGFS/GGOS initiative) and to provide a better link between observations provided by both absolute and superconducting gravity meters. This new version (see presentations at EGU2017 and IAG/IASPEI 2017) keeps a similar structure but will provide new functionalities as for instance: interactive maps, plot of time series, link to superconducting gravity times series, etc.

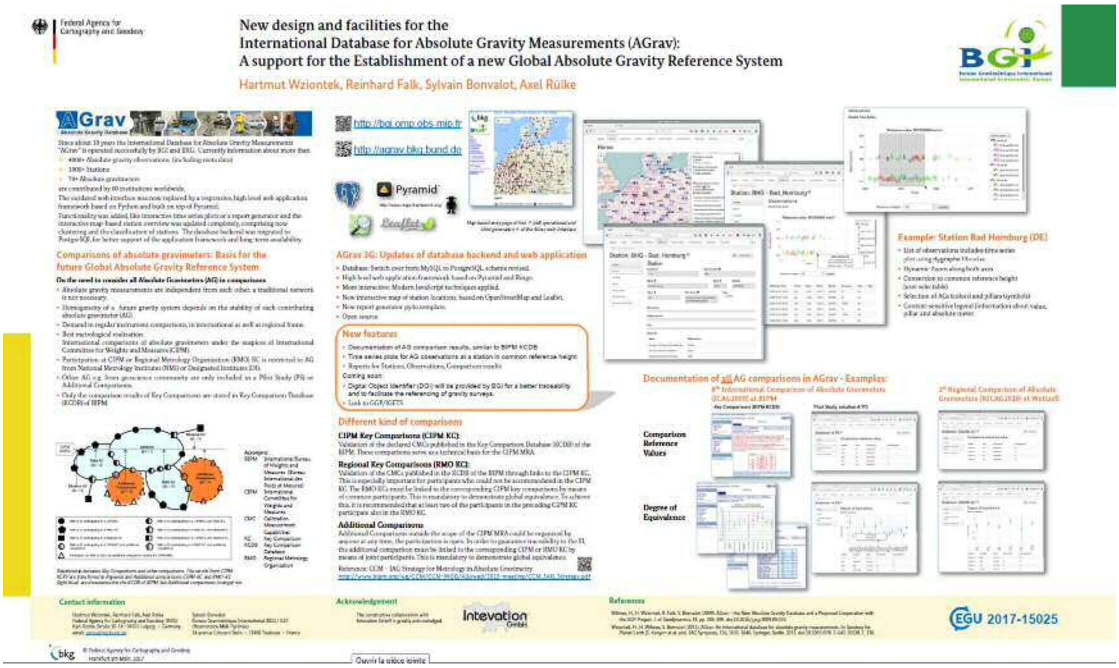

Figure 2: On-going development of the new AGrav version (Wziontek et al., EGU 2017)

1.3. Regional or global gravity anomaly grids

The BGI provided new access or links to high resolution global or regional grids of gravity anomaly such as those derived from the World Gravity Map (Bonvalot et al., *CGMW World Gravity Map*, 2012 ; Balmino et al., *Journal of Geodesy*, 2012) ; EGM2008 (Pavlis et al., *JGR* 2012) or GGMPlus (Hirt et al., *GRL*, 2013).

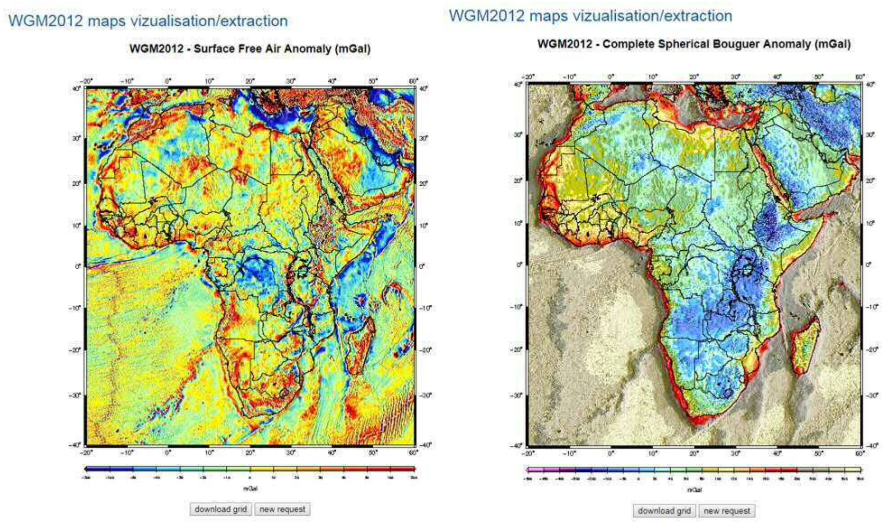

Figure 3: Examples of grid extraction from the global WGM2012 gravity model (http://bgi.obs-mip.fr/data-products/Grids-and-models/wgm2012)

2. Contribution to regional gravity projects

During the reporting period, BGI has contributed to the GEOMED2 project which aims at computing an updated estimate of the geoid in the Mediterranean area. It has specially performed gravity data compilation and validation using marine gravity measurements collected over the entire Mediterranean basin. The GEOMED2 is currently in progress and should be finalized in 2018. Details on this work are given in: Barzaghi et al., (2017a, 2017b, 2016, 2015), Lequentrec-Lalancette et al. (2016) and Bruinsma et al.(2017).

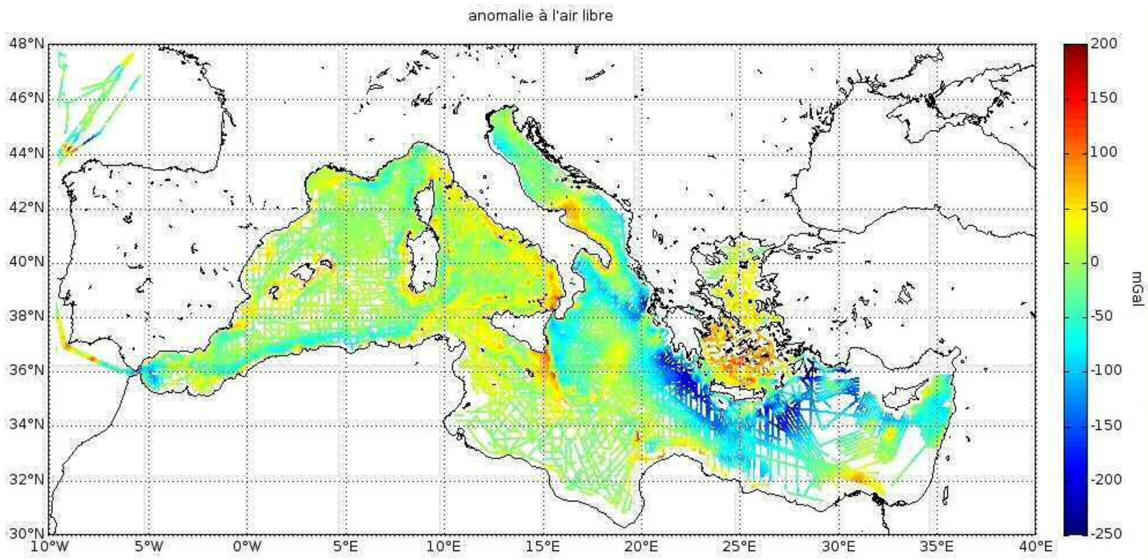

Fig. 4: Free air gravity anomalies over Mediterranean Sea from marine data analysed at BGI for the GEOMED2. (see Lequentrec-Lalancette et al., *IAG Symposia Series*. 2016).

3. Contribution to the definition of the International Absolute Gravity Reference System

We chair the IAG JWG 2.1.1 "Establishment of the International Absolute Gravity Reference System" (Chair: H. Wziontek, Co-Chair: S. Bonvalot). This IAGRS aims at fulfilling the following objectives:

(1) The need for accurate and long term stable reference provided by a primary network of reference stations where gravity is monitored with absolute gravimeters. Such primary network is already a central part of the IAG resolution 2 (2015) and should also contribute to the infrastructure of GGOS Core sites.

(2) The need for secondary network of gravity stations which ensures accessibility of the system by a global set of sites, compatible with the above defined reference level, to any user. The aim of this secondary network is to identify and make accessible the largest number of absolute gravity values observed worldwide from field surveys of laboratory measurements to provide absolute reference to any purpose (relative gravity surveys, calibration lines, etc.). This secondary network must be considered as well in order to establish a replacement for IGSN 71.

The main objectives of this future network has been described in Wilmes et al. (2016) and presented at a dedicated splinter meeting during EGU 2017.

4. Contributions to absolute gravimetry

BGI teams are also involved in the evaluation of innovative instrumentations for measuring the Earth gravity field (such as cold-atoms gravity meters). For instance, we are contributing to the evaluation of the new Absolute Quantum Gravity (AQG) meter recently developed by MUQUANS (https://www.muquans.com). This evaluation includes characterization of performances and accuracy, sensibility analysis and comparisons with reference gravity meters such as the FG5 and A10 Micro-g LaCoste instruments or other cold-atoms gravity meters (Bonvalot et al., 2016a, 2016b; Pereira and Bonvalot, 2016).

BGI also continued the development of software or utility tools dedicated to gravity data validation and processing. In this context, an application (MGL_QuickView) dedicated to provide a fast synthetic plot of absolute gravity measurements taken with FG5 and A10 meters is made available for users (http://bgi.obs-mip.fr/activities/software_developments).

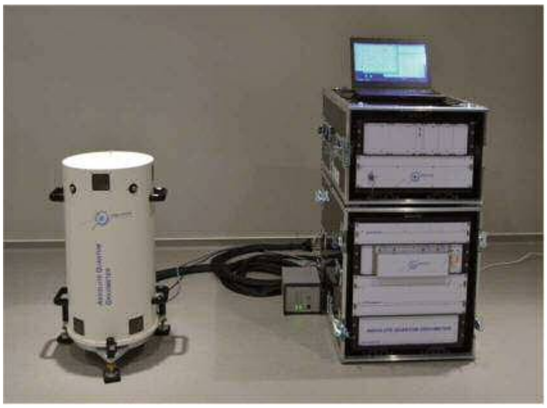

Fig 5a: Absolute Quantum Gravity (AQG) meter recently developed by MUQUANS (https://www.muquans.com)

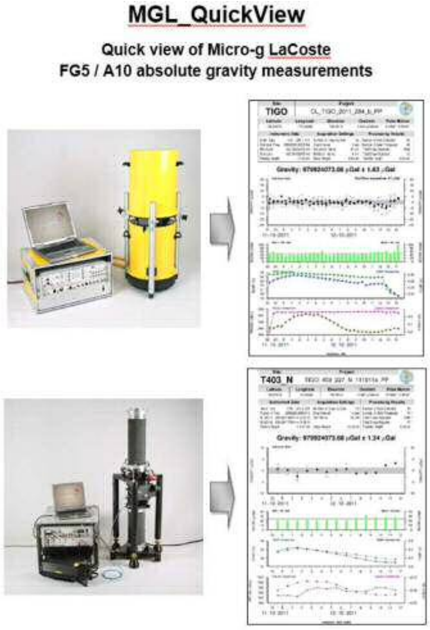

Fig 5b: MGL_QuickView utility tool: Quick view of Micro-g LaCoste FG5 / A10 absolute gravity measurements (Gabalda and Bonvalot, 2016)

Scientific events

International meetings (as scientific committee)

- 09/2016 : GGHS - Joint IAG / IGFS Meeting. Thessaloniki, Greece
- 04/2016 : 4th IAG Symposium on Terrestrial Gravimetry. St. Petersburg, Russia

International meetings

- 08/2017 : IAG/IASPEI Joint Assembly 2017 ; Kobe, Japan
- 04/2017 : EGU General Assembly 2017 ; Vienna, Austria
- 12/2016 : AGU General Assembly 2016 ; San Francisco, USA,
- 09/2016 : GGHS - Joint IAG / IGFS Meeting, Thessaloniki, Greece
- 05/2016 : ESA Living Planet Symposium ; Pragua, CSR,
- 04/2016 : EGU General Assembly 2016 ; Vienna, Austria,
- 04/2015 : EGU General Assembly 2015 ; Vienna, Austria

International project workshops and splinter meetings

- 03/2017 : Workshop on "Absolute Gravity Reference System" ; EGU, Vienna, Austria
- 03/2017 : Workshop on "ALP-Array project" ; EGU, Vienna, Austria
- 03/2017 : Workshop on "IGETS/BGI databases" ; EGU, Vienna, Austria
- 03/2017 : 3rd GEOMED-II Workshop ; Roma, Italy
- 09/2016 : CNES-NASA Workshop « Atom Interferometry / Space Geodesy » ; Paris, FR
- 02/2015 : 2nd GEOMED-II Workshop ; Thessaloniki, Greece

IAG structure & working groups

- IAG JWG 2.1.1 : "Establishment of a Global Absolute Gravity Reference System (AGRS)" (Chair: H. Wziontek, Co-Chair: S. Bonvalot)
- Advisory Board of IGFS - http://igfs.topo.auth.gr/structure.html/
- Consortium member of GGOS - http://www.ggos.org/
- IAG Sub-commissions : « Gravimetry, Gravity networks », « Absolute Gravimetry »

Publications / Communications

Selected publications

Assessment of GOCE Geopotential Models. *Newton's Bulletin,* Issue n° 5, June 2015. BGI-ISG (Eds). http://bgi.obs-mip.fr/publications/newton_bulletin

Balmino, G. et S. Bonvalot (2016). *Gravity anomalies.* In:_E.W. Grafarend (ed.), *Encyclopedia of Geodesy*, © Springer International Publishing Switzerland 2016. DOI:10.1007/978-3-319-02370-0_45-1.

Bonvalot, S. (2016). The International Gravimetric Bureau. In "The Geodesist's Handbook 2016", H. Drewes (ed). (International Association of Geodesy). *Journal of Geodesy* DOI:10.1007/s00190-016-0948-z

Lequentrec-Lalancette, MF.; Salaün, C.; Bonvalot, S.; Rouxel, D.; Bruinsma, S. (2016). Exploitation of marine gravity measurements in the validation of global gravity field models. *IAG Symposia Series*. IUGG General Assembly in Prague, 2015. © Springer International Publishing Switzerland 2016. DOI:10.1007/1345_2016_258

Pallero, J.L.G., Fernandez-Martınez, J.L., Bonvalot, S., Fudym, O. (2015). Gravity inversion and uncertainty assessment of basement relief via Particle Swarm Optimization. *Journal of Applied Geophysics.* DOI:10.1016/j.jappgeo.2015.03.008

Pallero, J.L.G., Fernandez-Martınez, J.L., Bonvalot, S., Fudym, O. (2017). 3D gravity inversion and uncertainty assessment of basement relief via Particle Swarm Optimization. *Journal of Applied Geophysics.* Volume 139, April 2017, Pages 338–350. http://dx.doi.org/10.1016/j.jappgeo.2017.02.004.

Peirera, F. et S. Bonvalot (2016). *Cold atom absolute gravimetry.* In:_E.W. Grafarend (ed.), *Encyclopedia of Geodesy*, © Springer International Publishing Switzerland 2016. DOI 10.1007/978-3-319-02370-0_30-1.

Wilmes, H., L. Vitushkin, V. Palinkas, R. Falk, H. Wziontek, S. Bonvalot (2016). Definition and Realization of a Global Absolute Gravity Reference System. *IAG Symposia Series*. IUGG General Assembly in Prague, 2015. © Springer International Publishing Switzerland 2016. DOI:10.1007/1345_2016_245

Selected communications

2017

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Note for BGI users & contributors / Attribution of DOI

The contribution to the BGI databases of worldwide scientists, agencies or institutions involved in relative or absolute gravity data acquisition is crucial for improving the global knowledge of the Earth gravity field and providing the best service to the IAG/GGOS community. It is reminded that any dataset or metadata derived from land, marine or airborne surveys or from compilation works (point data or grids) can be deposited as public or proprietary information. This enables BGI to ensure a long term archiving of the data and to validate the incoming gravity observations in a global reference frame and restore them (public data only) in standard and unified formats useful for various users.

In order to better reference and acknowledge these contributions, a **DOI (Digital Object Identifier)** will be attributed to any gravity dataset or product deposited at BGI. This new service will ensure a proper reference to authors and institutions who have acquired or compiled gravity data and a better traceability of improvements provided by these local or regional surveys to the global gravity data coverage. Users are also invited to make reference to the following DOI for acknowledging BGI services or data.

Recommended citation: Bureau Gravimetrique International (BGI). **DOI:10.18168/BGI**

Contacts for updating BGI databases or obtaining DOI for data, products or software:
bgi@cnes.fr ; agrav@bkg.bund.de

International Service for the Geoid (ISG)

http://www.isgeoid.polimi.it/

President: Mirko Reguzzoni (Italy)
Director: Giovanna Sona (Italy)

Structure

The Service is currently provided by two centers, one at the Politecnico di Milano (Italy) and the other at NGA (USA).

In addition to the president and the director, the ISG staff is composed by other scientists (F. Sansò, R. Barzaghi, A. Albertella, D. Carrion, C.I. De Gaetani and L. Rossi) as well as a secretary (C. Vajani).

The ISG advisory board is composed by the following scientists with expertise in the field of geoid determination:

- N. Pavlis (USA)
- M. Sideris (Canada)
- J. Huang (Canada)
- R. Forsberg (Denmark)
- U. Marti (Switzerland)
- H. Denker (Germany)
- L. Sánchez (Germany)
- I. Tziavos (Greece)
- W. Kearsley (Australia)
- D. Blitzkow (Brazil)

ISG is currently involved in the Joint Working Groups JWG 2.2.1 of Sub-commission 2.2 “Integration and validation of local geoid estimates”.

Overview

In the period 2015-2017, the main scientific activities of ISG have been related to the following research lines:

- local/regional geoid estimation;
- merging of local geoid estimates, defining a unified height datum;
- school organization and scientific support to researchers on geoid estimation;
- ISG geoid repository and website update.

As for the geoid estimation, the main effort has been devoted to the GEOMED-II project. The goal of this project is the computation of a high-accuracy and high-resolution geoid model for the Mediterranean Sea employing land and marine gravity data and GOCE/GRACE based global models. Moreover, the Italian geoid model has been recomputed, after validating the existing gravity database.

As for the local geoid merging, this activity has been performed in the framework of the JWG2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2. The output will represent a new product of ISG and aims to be a contribution in the frame of GGOS for the establishment of an International Height Reference System (IHRS).

According to tradition, during this two-year period ISG organized an international school on geoid determination and height datum definition. The school was held at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar, Mongolia, from 6th to 10th June, 2016. The total number of participant was 30, half of them coming from abroad.

Last but not least, to maintain the main ISG purpose of collecting, analysing and redistributing local and regional models, the ISG geoid repository has been continuously updated and the ISG website has been modified accordingly. In particular, the webpage of each model has been "standardized" in the sense of providing the same type of information. Moreover, all public models are redistributed with a unique ASCII format.

Local/regional geoid estimation

In the last two years, the activities on local/regional geoid estimation have been focused on the GEOMED-II project and the ITALGEO model update. The former is dedicated to the computation of a geoid model for the Mediterranean Sea. It is sponsored by the European Space Agency (ESA) and by all the participating Institutions. Apart from the IGFS, BGI and ISG services, the project partners are:

- Politecnico di Milano (Italy),
- GET, SHOM and OCA/Geoazur (France),
- Aristotle University of Thessaloniki (Greece),
- DTU Space (Denmark),
- General Command of Mapping (Turkey),
- University of Zagreb (Croatia),
- University of Jaén (Spain).

The processing methodology is based on the well-known remove-compute-restore approach using both stochastic and spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data.

The input data come from the BGI database and from the project partners, in particular classified gravimetric data from Italy, Greece, Croatia and Turkey were used. In the preliminary phases of the processing, all the available gravity observations for the wider Mediterranean basin have been homogenized in terms of their horizontal system and are being validated and homogenized in terms of gravity system. An outlier rejection has been performed and some biases have been identified. These biases have a negative impact on the covariance function estimation and, of course, on the geoid estimation. Local analyses and comparisons are being performed to remove these biases.

The geoid grids will be computed by the collocation method using the GRAVSOFT software. The result will be compared with EGM2008 and DTU13 for blunder detection. Stokes and FFT-based geoid models will be also determined and compared with the collocation-based ones. The accuracy of the estimated geoid will be assessed through comparisons to GPS/levelling and altimeter data.

For the time being, preliminary computations have been performed to test the processing chain. In particular, a test of the collocation method and a test of the FFT-based method have been performed. The test consisted in first estimating the EGM2008 undulation residuals starting from EGM2008 gravity anomalies residuals ($\Delta g|_{2190}$-$\Delta g|_{1100}$) and then comparing the estimates to the actual EGM2008 undulation residuals ($N|_{2190}$-$N|_{1100}$, see Figure 1). This allowed to check the procedure and to choose the best FFT kernel modification for the GEOMED-II computation.

A lot of effort has been dedicated to investigate and properly determine topographic effects over both land and marine areas to efficiently reduce land and marine gravity data towards geoid determination. In fact, over land areas, the latest SRTM-based DTMs offer high-accuracy and high-resolution information on the topographic variations, in the sense that they properly model the high-frequency contributions of the topographic masses. Over marine regions, the situation is quite different, since the resolution of the available DBMs is not always capable to remove the high frequencies that are present in shipborne marine gravity data. On the other hand, marine gravity data do not often have the necessary spatial resolution to rigorously model the high frequencies depicted in the DBM. Aliasing effects on the estimated topographic effects will be also investigated and the corresponding errors introduced in gravity anomalies and geoid heights will be taken into account. Then, the DTM/DBM combination that provides the overall best results, in terms of the smoothness of the residual gravity anomalies, will be outlined along with the final topographically corrected gravity anomalies and geoid indirect effects.

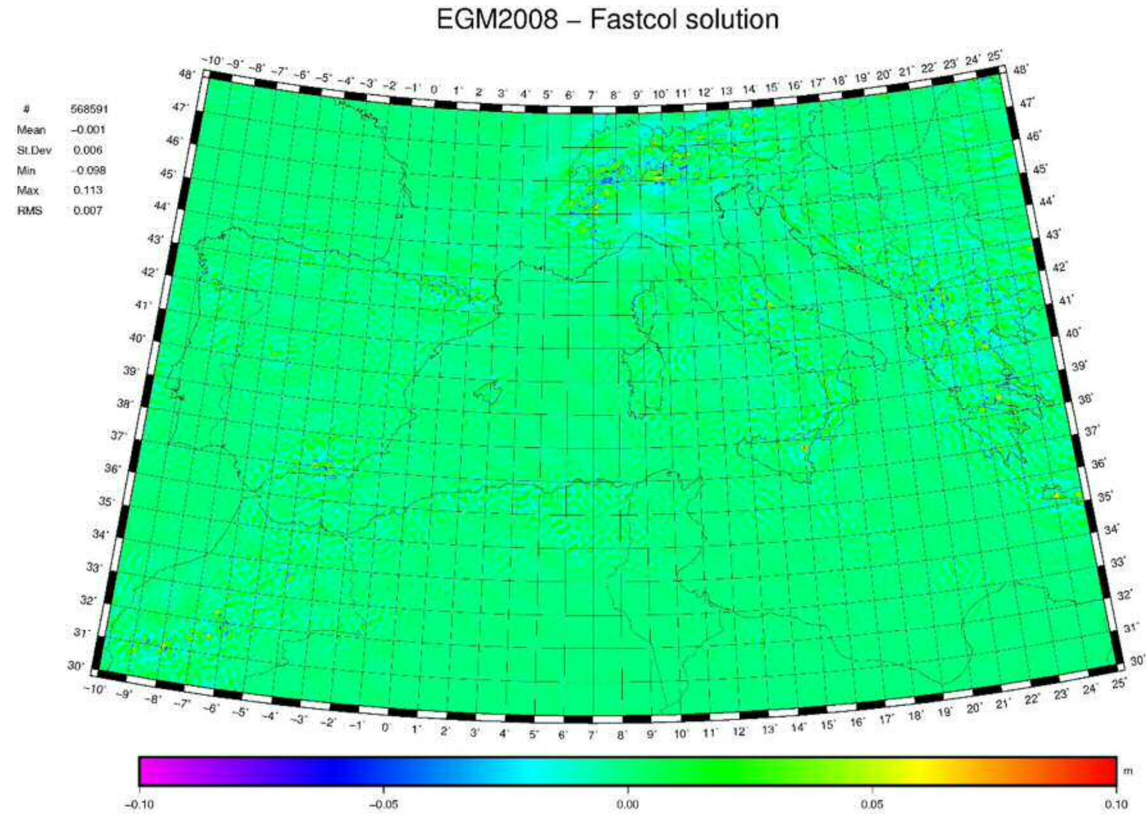


Fig. 1: Differences between EGM2008 undulation residuals ($N|_{2190}$-$N|_{1100}$) and collocation estimates starting from EGM2008 gravity anomalies residuals ($\Delta g|_{2190}$-$\Delta g|_{1100}$).

The new Italian gravimetric geoid (ITALGEO15) has been computed after a thorough revision of the available gravity database. The database has been homogenized in terms of horizontal and gravity reference systems and an outlier rejection has been performed mainly through local consistency checks.

This resulted in an improvement in the differences of the geoid with respect to the GPS/levelling data, after reference system adjustment, see Figure 2. The standard deviation of the differences decreases of two centimetres with respect to the previous release of the Italian geoid (ITALGEO05), see Table 1.

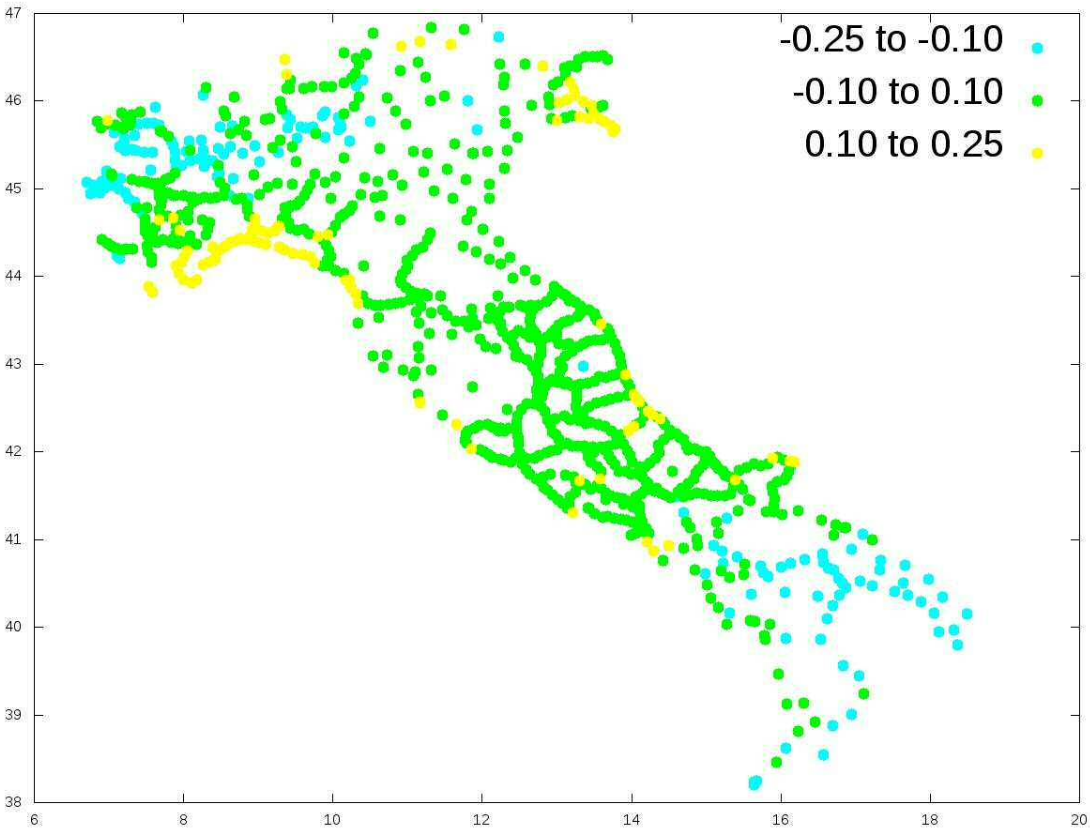


Fig. 2: Differences between GPS/levelling and ITALGEO15 gravimetric geoid after reference system adjustment (units in m).

	ITALGEO05	ITALGEO15
# Values	956	956
Mean [m]	0	0
St. Dev. [m]	0.114	0.090
Min [m]	-0.292	-0.235
Max [m]	0.294	0.235

Table 1: Statistics of the differences of ITALGEO05 and ITALGEO15 gravimetric geoids with respect to the GPS/levelling over the continental territory.

Merging of local geoid estimates

The large availability of local/regional geoid/quasigeoid models in the ISG archive fosters the study and the development of a merging strategy to produce unified models between neighbour countries. The proposed method consists of first estimating biases and systematic effects by a least-squares adjustment of the local geoid residuals with respect to a satellite-only model, and then correcting the remaining distortions along the national borders to better join the local geoid models. This investigation is performed in the framework of the JWG2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2.

A preliminary test has been implemented on a subset of European models, including the following countries (the name of the used model in brackets):

- France (QGF98)
- Corsica (QGC02)
- Italy (ITALGEO05)
- Iberian Peninsula (IBERGEO2006)
- Belgium (BG03)
- Switzerland (CHGEO2004Q)
- Greece (GreekGeoid2010).

For each model, a subset of about 1000 points on land and inside the national borders has been selected for the bias and trend estimation. The digital terrain model (DTM) for each country has been derived from SRTM.

The reference geoid has been synthesized from the GOCO-05S satellite-only global model up to spherical harmonic degree and order 280 and has been subtracted to the local solutions. For the moment, neither the contribution of global models at higher degrees, e.g. using EGM2008, nor a residual terrain correction (RTC) has been further subtracted to the geoid residuals.

The geoid commission error of the reference model has been modelled by propagation from the block-diagonal error covariance matrix of the GOCO-05S coefficients, while the omission error above degree 280 has been modelled by using EGM2008 degree variances. A white noise with a standard deviation of 5 cm has been attributed to each local geoid model.

By using the computed geoid residuals and this stochastic modelling, a bias and a trend for each local model have been estimated by least-squares adjustment. The systematic effect *S* included into each local geoid has been modelled as follows:

$$S(\varphi,\lambda)=b_1+b_2(\varphi-\varphi_0)+b_3\cos\varphi(\lambda-\lambda_0)$$

where φ_0 and λ_0 are the mean latitude and longitude, respectively. The result of this adjustment is reported in Table 2. The estimated biases and trends are shown in Figure 3, while the residuals before and after the de-trending procedure are displayed in Figures 4 and 5.

	France	*Corsica*	*Italy*	*Iberia*	*Switzerland*	*Belgium*	*Greece*
$\hat{b}_1$	-1.067	0.344	0.246	-0.930	-0.617	-0.140	0.305
$\hat{b}_2$	1.466	21.090	-10.247	-1.826	-3.492	2.452	-0.733
$\hat{b}_3$	-4.753	-81.137	-0.873	-0.697	-2.379	-0.261	11.248
$\hat{\sigma}_{b_1}$	0.002	0.042	0.004	0.002	0.004	0.008	0.005
$\hat{\sigma}_{b_2}$	0.056	6.459	0.121	0.069	0.975	1.656	0.229
$\hat{\sigma}_{b_3}$	0.069	16.943	0.140	0.060	0.476	1.459	0.333

Table 2: Estimated biases and trends with their error standard deviations (units in m).

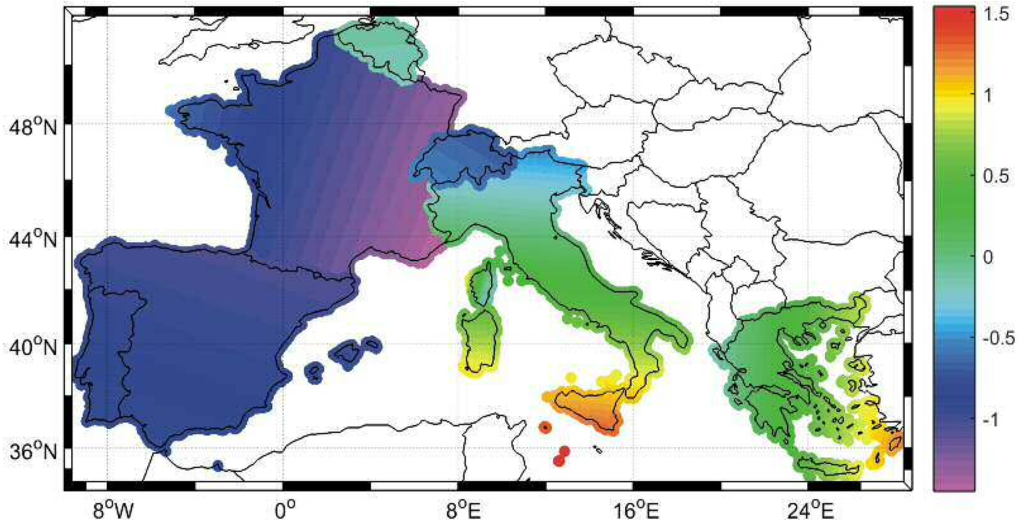


Fig. 3: Estimated biases and trends (units in m).

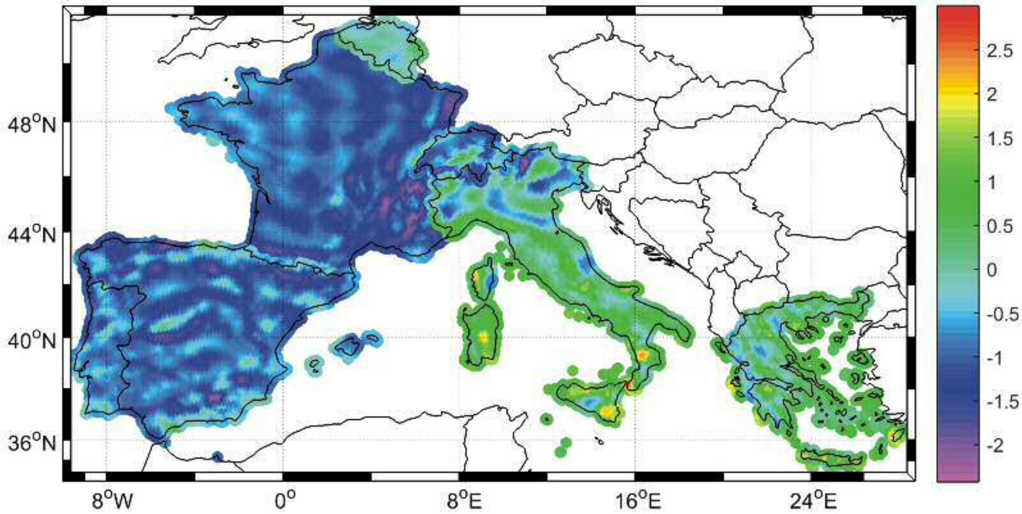


Fig. 4: Geoid residuals with respect of GOCO-05S before the de-trending procedure, i.e. as the models are stored in the ISG archive (units in m).

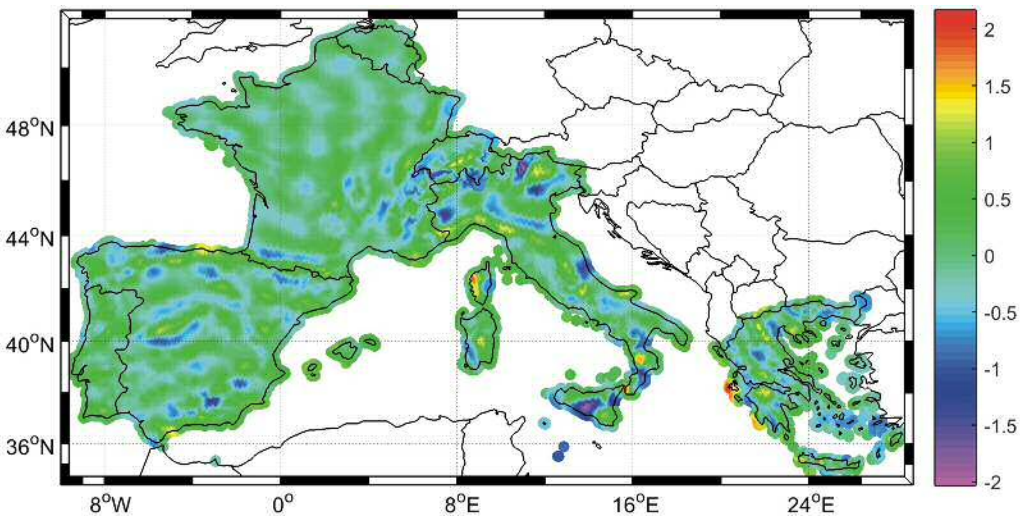


Fig. 5: Geoid residuals with respect of GOCO-05S after the de-trending procedure (units in m). Discontinuities at national borders are significantly reduced.

School organization and scientific support to researchers on geoid estimation

One of the main tasks of ISG consists in organizing or supporting technical schools on geoid estimation and related topics. The XII International IGS School was held in Mongolia from 6th to 10th June, 2016, at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar. This was the second geoid school held in Asia after the one in Johor-Baru, Malaysia, at the Department of Survey and Mapping, from 21st to 25th February, 2000.

The Local Organizing Committee (LOC) was composed by representatives from the following institutions/organizations:

- Mongolian University of Science and Technology (MUST),
- MonMap Engineering Services Co., Ltd,
- Mongolian Association of Geodesy, Photogrammetry and Cartography (MAGPC),
- Administration of Land Affairs, Geodesy and Cartography (ALAGAC),
- Ministry of Construction and Urban Development (MCUD).

A dedicated website was setup at the address: www.monmap.mn/geoidschool2016/ reaching more than 300 accesses by June. Over 100 online registration form submissions were collected, but many of willing participants from developing countries were not able to attend the school due to lack of budget and travel support. In the end, 30 participants coming from 9 different countries (Bhutan, China, India, Latvia, Mongolia, Philippines, Poland, Russia and Sri Lanka) attended the school, see Figure 6.

As usual, the program was structured to be self-contained for any participant at graduate level with basic knowledge of geodesy, including theoretical lectures and computer exercises based on the available software. The invited teachers were:

- Prof. F. Sansò, Politecnico di Milano, Italy,
- Prof. R. Barzaghi, Politecnico di Milano, Italy,
- Prof. M. Sideris, University of Calgary, Canada,
- Prof. R. Forsberg, National Space Institute, Denmark,
- Dr. S. Holmes, SGT Inc. USA.

The school program was the following:

- General theory on gravity field (6th June),
- The height datum unification (6th June),
- Terrain effect computation and remove/restore - theory and practical exercises (7th June),
- Residual geoid estimation - theory and practical exercises (8th June),
- Global geopotential models - theory and practical exercises (9th June),
- Presentations and case studies (10th June).

During the last day, a final session was given to summarize the school topics and distribute training certificates to the participants. Lecture notes of the courses were also distributed, as well as a CD-ROM containing software and data for exercises. The CD-ROM was freely distributed to the participants after a declaration of non-commercial use. An ice-break dinner and two sightseeing tours were organized by LOC, just before and after the school.

Apart from organizing the XII International Geoid School in Mongolia, in the last two years ISG provided educational activities and supported studies related to geoid estimation theory and in general to physical geodesy by hosting at Politecnico di Milano, Italy, the following students and researchers:

- A PhD student of the Center of Geodesy and Geodynamics of Nigeria, who is developing his thesis on the national gravity field estimation. For his studies he was hosted at Politecnico di Milano during two periods: 7-11 September 2015 and in spring 2016.
- A researcher of the Faculty of Petroleum and Renewable Energy and Earth Sciences at the University of Ouargla, Algeria. He was interested to the precise local geoid determination from the GRACE and SRTM satellite data with the aim of studying the tectonic activity in Algeria. He was hosted at Politecnico di Milano in autumn 2015.

- Two researchers of the Service of Surveying of the National Institute of Cartography of Cameroun, who came at Politecnico di Milano in November 2015 for a first training session on geoid computation. After that, they maintained frequent contacts with ISG staff, and a second training session was scheduled for the end of 2016, now shifted in September 2017.
- A PhD student from the University of Curitiba, Brazil, who spent three months at Politecnico di Milano, from March to September 2016, developing studies on the height datum problem.
- A PhD student from the Technical University of Denmark (DTU) spent three months at Politecnico di Milano, from October to December 2016, working together with ISG staff on radar-altimetry, gravimetry and gravity field estimation.
- Usually, further contacts follow the hosting period, to strengthen the cooperation and to provide scientific support when researchers and students come back to their countries.

Fig. 6: Group photo of people organizing and attending the XII International IGS School.

ISG geoid repository and website update

In the last two years, the ISG archive of local/regional geoid models has been continuously updated. Not only the latest release of a model is stored in the archive, but also outdated versions are collected in order to keep memory of the work done in the past and to allow for comparisons. The full (or almost the full) series of the official geoid models are available for some countries, like US, Canada, Italy, France, Norway, Japan, Australia, New Zealand. Three possible policy rules are considered for the model distribution: “public” if it can be freely downloaded from the website, “on demand” in case the authors asked to be informed before distributing the model, and “private” if it is just included in the archive but it cannot be distributed to the users.

Therefore, the aim of the "private" policy is to inform users that a model exists without publishing any data through the ISG service. More than 150 models are currently available in the ISG database, whose composition is reported in Tables 3, 4 and 5 (last update of the statistics was on 30th June 2017). The global coverage of the available gridded geoid models, together with their spatial resolution, is shown in Figure 7. Metadata of all models are managed through Data Citation Index by Clarivate Analytics.

Europe	62
North America	36
Africa	17
Asia	15
Oceania	13
South America	9
Antarctica	4
Arctic	3
Total	159

Table 3: Number of models per continent in the ISG archive.

< 1991	4
1991 – 1995	14
1996 – 2000	39
2001 – 2005	21
2006 – 2010	45
2011 – 2015	33
> 2015	3
Total	159

Table 4: Number of models per year in the ISG archive.

Public	113
On-Demand	18
Private	28
Total	159

Table 5: Number of models per policy-rule in the ISG archive.

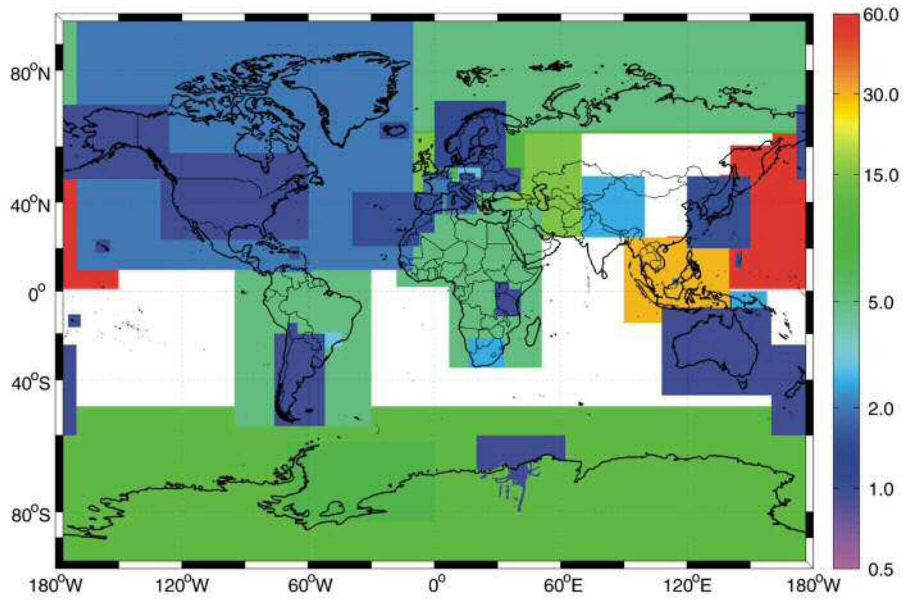


Fig. 7: Spatial coverage of the gridded geoid models available at ISG. Colourbar shows the highest spatial resolution per location (log10 scale, unit: arc-minutes).

The ISG website is updated simultaneously to the ISG archive. For each geoid model that is stored in the archive a dedicated webpage is available on the website, containing information about the model name, year, authors, contact person, type (gravimetric, geometric or hybrid, geoid or quasi-geoid) and policy rule. There is a short description of the model characteristics, at least one bibliographic reference and a model figure.

If the model is classified as "public", the corresponding data file can be downloaded from the webpage in a unique ASCII format (.isg), whose specifications are provided in the website. After authors' authorization, the "on demand" models can be distributed to users in the same ASCII file format. The webpage of each model can be reached from a complete list of available geoids or by clicking on a geographical map.

Apart from the geoid repository, the website has been updated in the home page, in the section dedicated to the geoid schools and in the one on the on-going projects. News section has been continuously kept up-to-date. No papers have been submitted to Newton's Bulletin in the last two years. The current home page of the ISG service is shown in Figure 8. Some statistics on the website access are displayed in Figure 9.

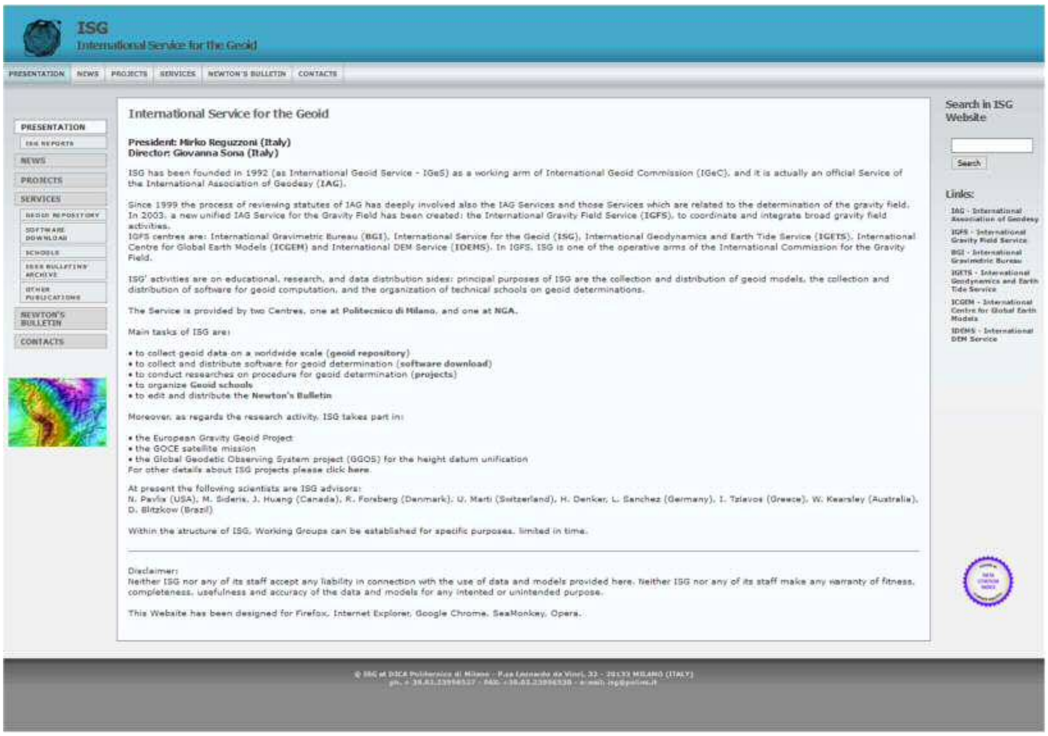


Fig. 8: Home page of the ISG website.

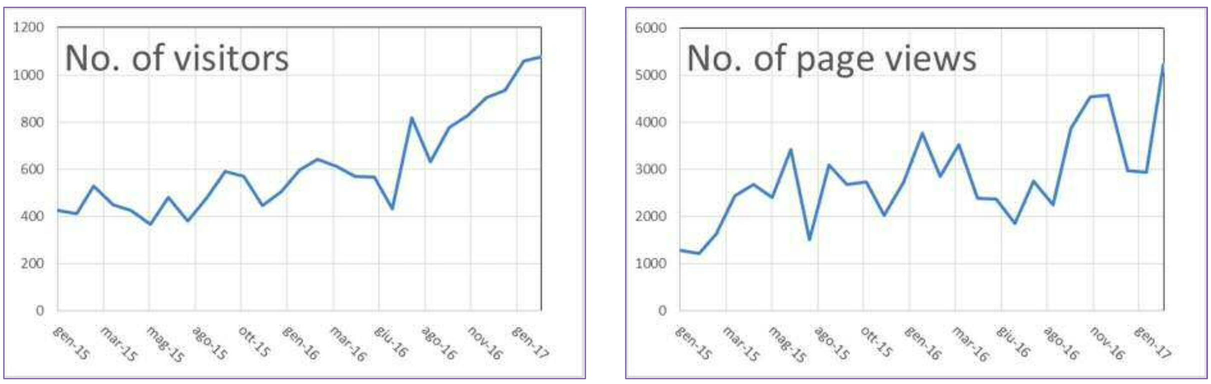


Fig. 9: Statistics on the number of visitors and page views of the ISG website.

JWG 2.2.1: Integration and validation of local geoid estimates

Chair: *M. Reguzzoni (Italy)*
Vice Chair: *G. Vergos (Greece)*

Members:
- *G. Sona (Italy)*
- *R. Barzaghi (Italy)*
- *F. Barthelmes (Germany)*
- *M.F. Lalancette (France)*
- *T. Basic (Croatia)*
- *H. Yildiz (Turkey)*
- *N. Kuhtreiber (Austria)*
- *H. Abd-Elmotaal (Egypt)*
- *W. Featherstone (Australia)*
- *Jianliang Huang (Canada)*
- *Cheinway Hwang (Taiwan)*
- *Shuanggen Jin (China)*
- *G. Guimaraes (Brazil)*

Overview

A detailed description of the activities performed by this working group during the period 2015-2017 can be found in the report of the Sub-commission 2.2, also including numerical results and publications.

Permanent Service for Mean Sea Level (PSMSL)

http://www.psmsl.org

Director: Lesley J. Rickards (UK)

Overview

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long-term sea level change information from tide gauges and also provides a wider Service to the sea level community. The PSMSL continues to be responsible for the collection, publication, analysis and interpretation of sea level data. PSMSL is hosted by the National Oceanography Centre (NOC), Liverpool with funding provided by the UK Natural Environment Research Council. PSMSL operates under the auspices of the International Council for Science (ICSU) and became a regular member of the ICSU World Data System in 2015.

The primary aim of the PSMSL is providing the global data bank for long term sea level information from tide gauges. PSMSL has continued to increase its efforts in this regard and over the last 2 years over 5000 station-years of data were entered into the PSMSL database, increasing the total PSMSL data holdings to over 69700 station-years. In addition, the PSMSL, together with the British Oceanographic Data Centre (BODC), are responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly values and higher frequency) from the Intergovernmental Oceanographic Commission's Global Sea Level Observing System (GLOSS) core network.

New and updated products have been made available over the last two years including trend maps and associated uncertainty values; links with the Système d'Observation du Niveau des Eaux Littorales (SONEL) have been further developed to provide information about the geocentric height and vertical rate of movement of some tide gauges; and data from *in situ* ocean bottom pressure (OBP) recorders from all possible sources is being made available through PSMSL. A change was made to some of the longest time series at the PSMSL where sea level values were reported as means of high and low waters, typically called mean tidal level (MTL). This is in contrast to the average of higher frequency reading taken over the entire tidal cycle, which is called mean sea level (MSL). To make these combined records more transparent, and to cause the minimum disruption to the current set of records, a flag has been added indicating MTL values in a MSL record. BODC in collaboration with PSMSL has also taken the lead in data archaeology and rescue through GLOSS.

PSMSL staff have continued to be active in a variety of international meetings, working groups, conferences and workshops over the last 2 years including those organised by the Global Geodetic Observing System (GGOS), IOC GLOSS, European Geophysical Union (EGU), EuroGOOS, International Marine Data and Information Systems (IMDIS) and the G7 Global Ocean Observing Workshop. In addition, PSMSL has answered many enquires relating to sea level and have appeared on radio and television discussing aspects of sea level change. PSMSL staff have also co-organised and contributed to tide gauge and sea level training courses. Annually statistics are collated on the number of peer-reviewed published papers that use the PSMSL dataset. For the last five years there are over 330 papers in 97 distinct journals, and the number of citations has increased every year to around 70 citations per year.

1 Introduction

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long-term sea level change information from tide gauges and bottom pressure recorders. Established in 1933 by Joseph Proudman, who became its first Secretary, the PSMSL is responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges and also provides a wider Service to the sea level community. The PSMSL is embedded within the National Oceanography Centre (NOC) at Liverpool, and is funded by the UK Natural Environment Research Council (NERC, the parent body of NOC). The PSMSL also reports to the International Association for the Physical Sciences of the Oceans (IAPSO) and is a service of the International Association of Geodesy (IAG). PSMSL also has a key role in the Intergovernmental Oceanographic Commission's (IOC's) Global Sea Level Observing System (GLOSS) and contributes to the IAG Global Geodetic Observing System (GGOS).

Towards the end of 2015, the PSMSL was accepted as a regular member of the International Council for Science World Data System (ICSU-WDS). The ICSU-WDS has a rigorous application process and PSMSL was very pleased to gain membership to this interdisciplinary body, which means that the PSMSL is regarded as a trustworthy facility in terms of authenticity, integrity, confidentiality and data availability and services. The goal of the ICSU-WDS is to create and co-ordinate global 'communities of excellence' for scientific data services.

The primary aim of the PSMSL is the provision of the global databank for long-term sea level information from tide gauges. PSMSL has continued to increase its efforts in this regard and between mid-2015 and mid-2017 over 2000 station-years of mean sea level data were entered into the PSMSL database each year, increasing the total PSMSL data holdings to over 69700 station-years from 2337 stations. In addition, the PSMSL, together with the British Oceanographic Data Centre (BODC), is responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly or higher frequency values) from the IOC's GLOSS Core Network.

The PSMSL database contains monthly and annual mean values of sea level. The dataset and ancillary information are provided free of charge and are made available to the international scientific community through the PSMSL website (www.psmsl.org). Accompanying metadata includes station descriptions and their locations, types of instrumentation and, where available, frequency of data collection as well as notes on other issues of which users should be aware (e.g. earthquakes that are known to have occurred in the vicinity or subsidence due to local groundwater extraction). The free access to data by users is central to the PSMSL's mission and conversely no supplier is ever paid for their data nor are licensing terms ever entered into.

New products developed include relative sea level trend maps with associated uncertainty values; links with the Système d'Observation du Niveau des Eaux Littorales (SONEL) have been further enhanced to facilitate distribution of additional geodetic data; and data from *in situ* Ocean Bottom Pressure recorders from all possible sources are being made available through PSMSL. PSMSL, in collaboration with BODC, has also taken the lead in sea level data archaeology and rescue primarily through GLOSS. The PSMSL mailbox psmsl@noc.ac.uk responds to requests for information from national tide gauge agencies, decision makers (local councils, Parliamentary enquiries), the media and the general public.

2 Mean Sea Level Data received by PSMSL up to mid-2017

Figure 1 shows the amount of data received by the PSMSL over the last 5 years indicating how many station years have been added to the database each year and from how many stations. The number of active stations remains at about 800, but the number of station years can vary considerably from year to year. This may be due to a data provider reviewing and resupplying their historical dataset or if a backlog of data has been supplied. Figure 2 shows the stations which have provided data during 2017, or in 2016 (but not so far in 2017).

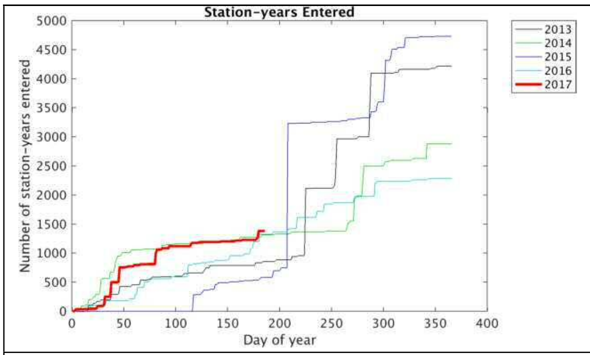


Figure 1a: Number of station years added to the PSMSL database during 2013-2017

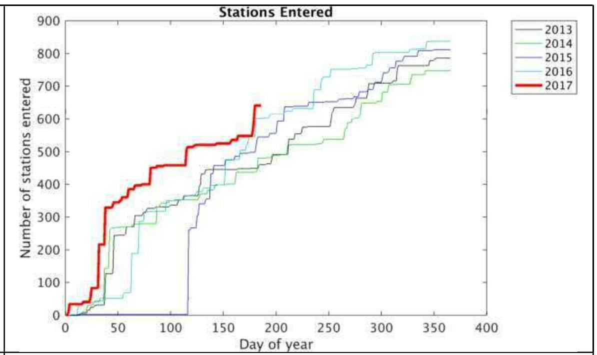


Figure 1b: Number of stations with data added to PSMSL database during 2013-2017

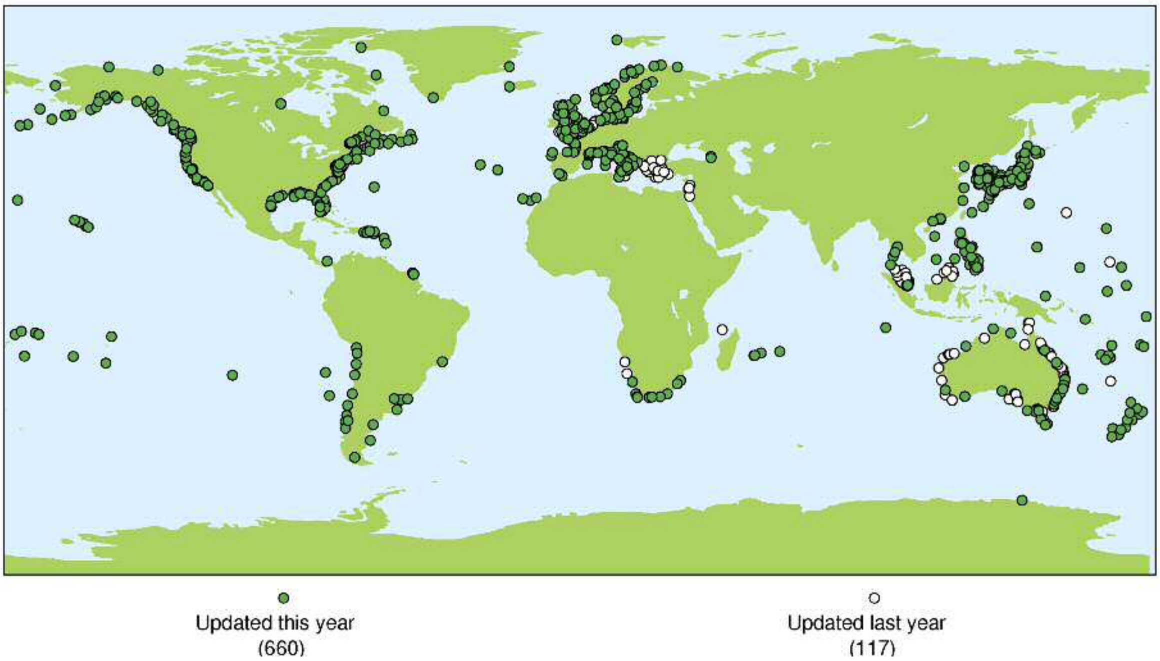


Figure 2: New data received by PSMSL between January 2016 and June 2017

Figure 3 gives a more detailed view of the data held by PSMSL, indicating where data have been supplied in the past – in particular, the decline in the number of stations in the Arctic is noticeable. 777 stations have provided data from 2013 or later, with a further 196 providing data from 2010-2012. These (973 stations) can all be considered as active stations, but there are 987 stations for which no data have been supplied since before 1995. Some of these have undoubtedly ceased to operate; for others contact with the operators is being actively pursued. New stations are also coming on line providing near-real-time data for tsunami monitoring, but a number of these do not yet supply quality controlled mean sea level values to the PSMSL; these are also being sought to add to the dataset.

Whilst many geographic regions regularly supply mean sea level data (e.g. North America, Europe, Japan, Australia, New Zealand, South Africa, India), there are still gaps in data receipts from the Arctic and Antarctic, parts of South East Asia, South and Central America, and Africa; these are presently being targeted to try to improve data flow. African countries have received special attention through the Ocean Data and Information Network for Africa (ODINAfrica) projects and the Indian Ocean Tsunami Warning System (IOTWS); new tide gauges have been installed, but ongoing maintenance for some of these sites is a major issue.

Although data flow has improved considerably over the last decade some of the gauges require a higher level of maintenance. To facilitate this close links are maintained with the University of Hawaii Sea Level Center (UHSLC) and other international sea level data centres.

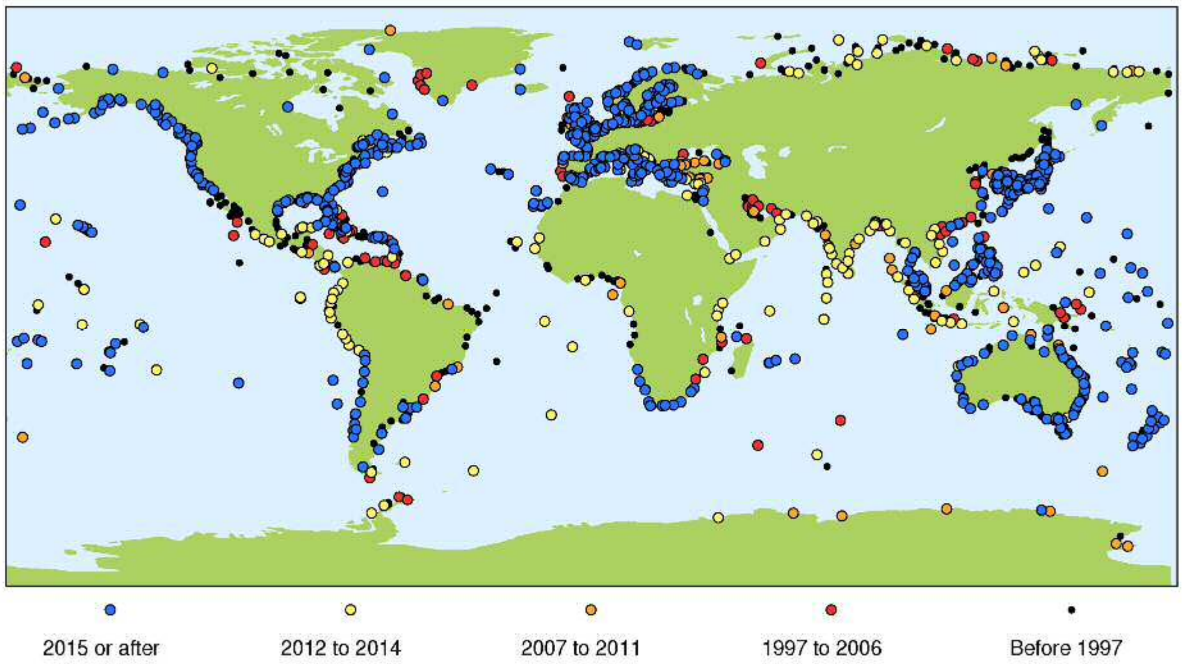


Figure 3: Year of most recent data received by PSMSL

In Figure 4 below, the uneven distribution of data supply is further illustrated; pale blue shows the data receipts from the Northern Hemisphere while the dark blue area of the plot shows the data receipts from the Southern Hemisphere.

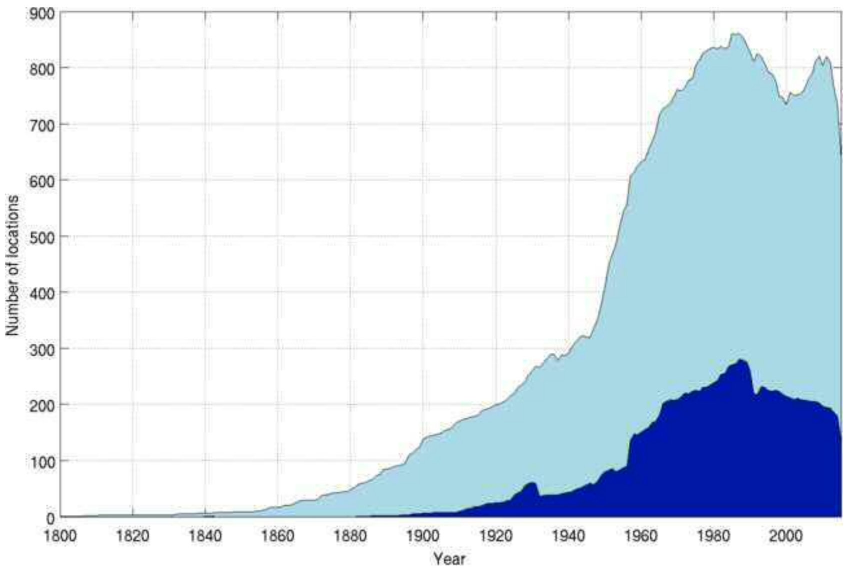


Figure 4: North-south hemisphere distribution of data received by PSMSL

The distribution of the longest time series also reflects this, as shown in Figure 5. The Southern Hemisphere has only a small number of time series of over 100 years; most are found in the Northern Hemisphere. Overall western Europe, North America and Japan have most of the longest records, and also have a high proportion of records of 50 to 100 years, although Australia, New Zealand, South Africa, Chile and Argentina also have a number of records of this length. The Arctic and Antarctic have very few records of greater than 50 years, and a number of the Russian Arctic tide gauges are no longer operational.

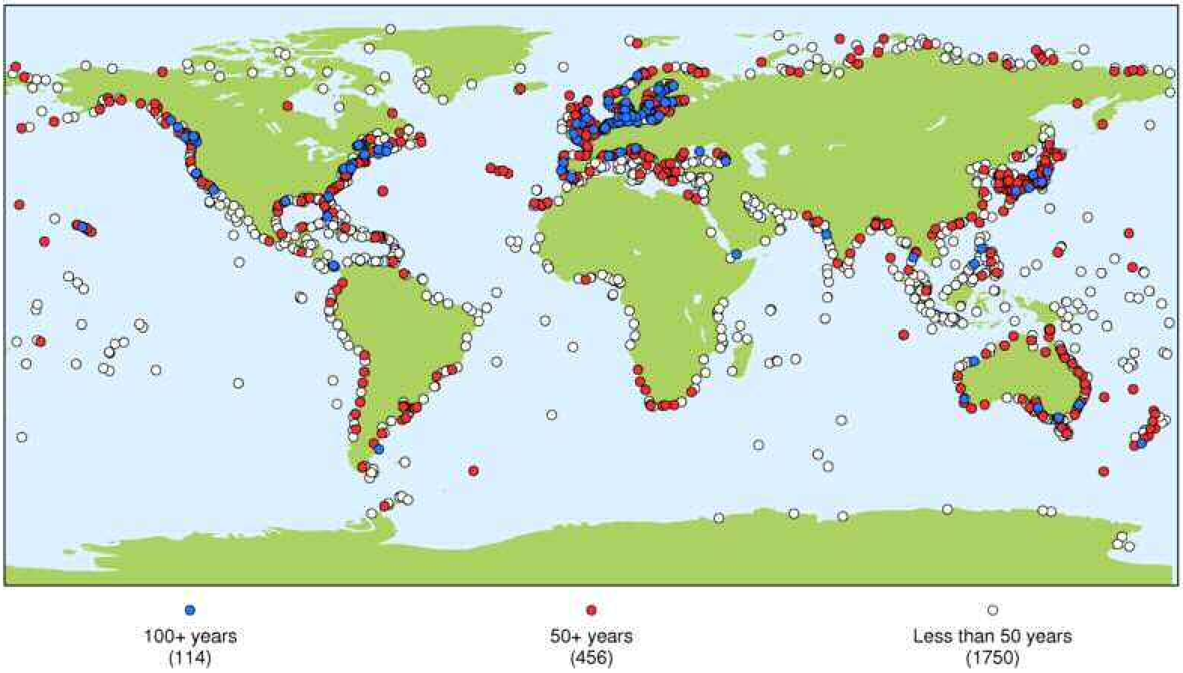


Figure 5: Distribution of long tide gauge records

3 Interactive map showing long-term trends

The web pages illustrating the trends in the tide gauge dataset have been updated with the 10 January 2017 release of the dataset. Links with SONEL have been further developed to facilitate distribution of additional geodetic data. With this year's update, which includes the new data obtained during 2016, a new method of determining the trends was introduced. Details are given on the Methods page of the PSMSL website (http://www.psmsl.org/products/trends/methods.php). The new method takes into account that the variability in the tide gauge time series may not be independently random, but may be correlated over different time spans. This correlated variability can decrease our ability to determine if a long-term trend in sea level is occurring at the tide gauge, or in other words, increase our uncertainty in the estimated trend. The pop-up boxes for each tide gauge shown on the trends map now include an uncertainty estimate. Both the estimated trend and the uncertainty will change as one changes the time span chosen by moving the sliders. Secondly, in order to calculate these results, monthly means are now used instead of annual means. Example trend maps are shown below (Figure 6).

4 Changes to Mean Sea Level Time Series with some Mean Tide Level values

PSMSL has introduced a change to some of the longest time series held in the database. In some older time series, the sea level values were reported as means of high and low waters, typically called Mean Tide Level (MTL). This is in contrast with the average of higher frequency readings taken over the entire tidal cycle, which is called Mean Sea Level (MSL). As these differ, this could introduce an artefact into estimates of the long-term trends where a time series includes both types of value. To improve transparency in these combined records, and to cause the minimum disruption to the current set of records, a flag has been introduced indicating MTL values in a MSL record and an estimate of the annual average difference (MTL-MSL) has been added to the Revised Local Reference (RLR) time series. More detail of the changes is available on the PSMSL website.

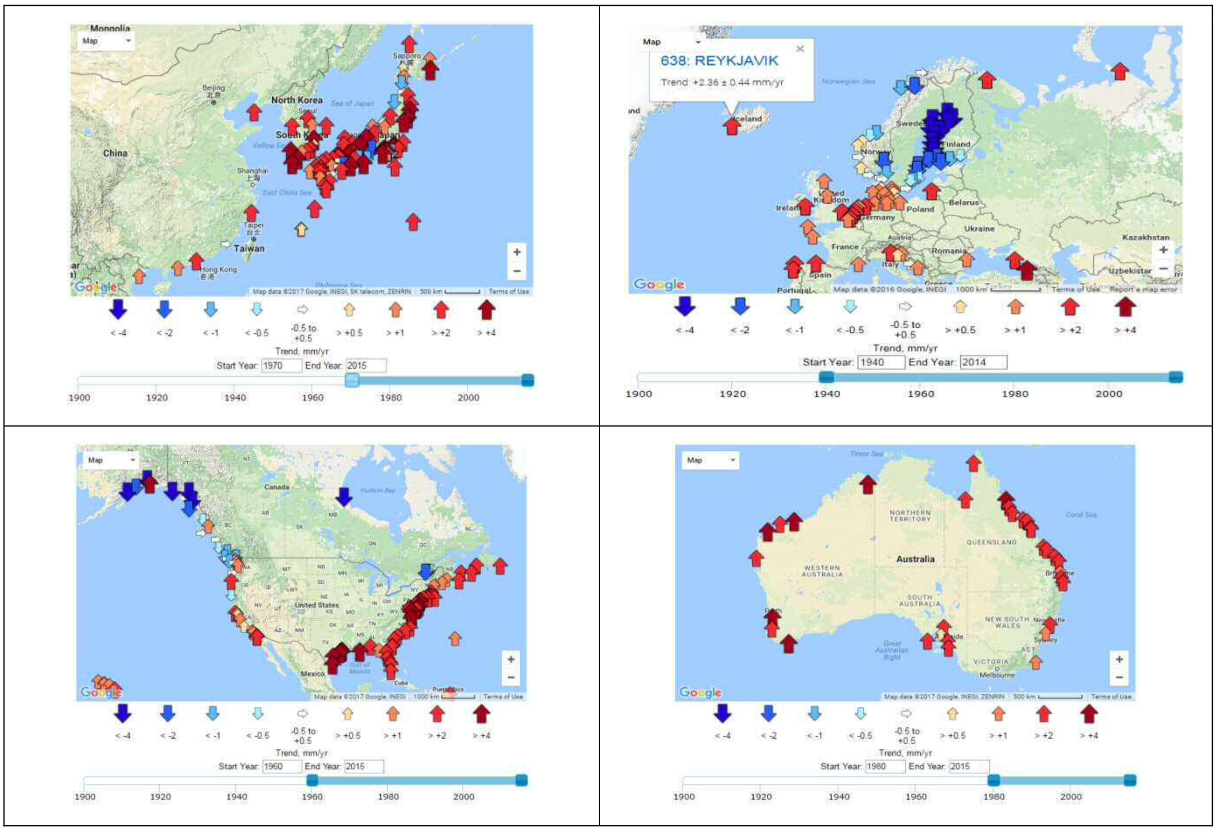


Figure 6. Interactive Relative Sea Level Trends Map

5 Ellipsoidal Links for Revised Local Reference Data

The mean sea level data distributed by PSMSL are heights above a local datum. For the Revised Local Reference (RLR) dataset, the stability of the local station datum is ensured by fixing its height to a geodetic benchmark assumed to be on reasonably stable ground. The measurements taken from tide gauges in this way are known as relative mean sea level; height is measured relative to the local land. As a result, the data can be affected by vertical movement of the land. For some analyses we may wish to attempt to remove the land movement signal from the tide gauge record, for example, for reconstruction of historical global mean sea level, or to compare sea level measured by tide gauges with sea level measured by satellite altimetry. One solution to both of these cases is to use continuous Global Navigation Satellite System (GNSS) measurements from a receiver located near the tide gauge. The GNSS receiver measures heights relative to an ellipsoid and can be used to estimate the rate of vertical movement of the local land mass. The tide gauge datum can be associated with these estimates if routine geodetic levelling campaigns are carried out between the tide gauge benchmark and the GNSS receiver.

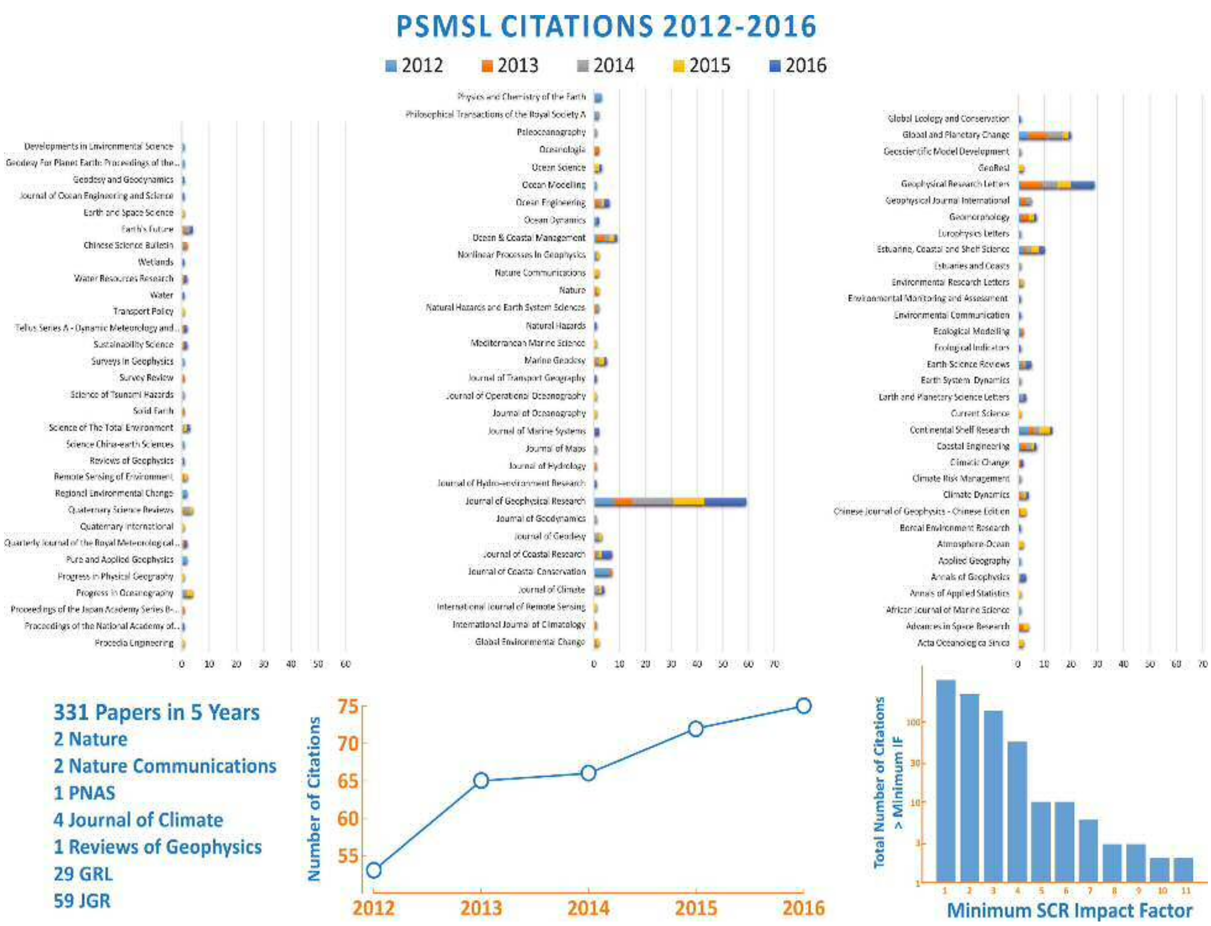
PSMSL have been working in collaboration with colleagues at SONEL, the GLOSS data centre for GNSS measurements, to make it easier to connect PSMSL RLR data with SONEL's GNSS data. Where a link to a GNSS receiver can be established, the PSMSL information section of the station page will note that a link to the ellipsoid is available. The reference ellipsoid used for the University of La Rochelle GPS solutions is GRS80.

6 Author Archive

During 2016, Peter Hogarth has liaised with Prof. Philip Woodworth to work on some of the historic data series available through the PSMSL. As a result, he has recently published an article in Journal of Geophysical Research investigating acceleration of sea level rise. In the course of this research, he has extended the tide gauge time series available for several locations. He has made available to us his extensive notes and the additional data.

7 Number of Citations for PSMSL data series for the period 2012-2016

Annually we collate statistics on the number of peer-reviewed published papers that use the PSMSL dataset. We do this in a number of ways. Firstly, we find papers that have cited either Holgate *et al* [2013] or Woodworth and Player [2003] in Web of Science and Scopus (the upper section of Figure 7 below shows the number of citations per year for these two papers from 2004 onwards). Not all papers will have cited either of these papers so we also perform full text searches for "PSMSL" or "Permanent Service". These papers are then manually filtered to remove any papers that are not actually referring to PSMSL. We note that it is very easy to miss papers that use our dataset but have not referred to us directly so our statistics are likely to be biased low. Figure 7 (lower section) below shows the statistics for the last five years. There are over 330 papers in 97 distinct journals ranging from a variety of subject areas including oceanography, quaternary research, geodesy, climate, environment and multidisciplinary. The top three journals in terms of total publications are Global and Planetary Change (20; JCR impact factor 3.548); Geophysical Research Letters (29; JCR impact factor 4.456) and Journal of Geophysical Research (59; JCR impact factor 3.318). Other notable citations come from Nature (2; IF 38.138), Nature Communications (2; IF 11.329), PNAS (1; 9.423), and Reviews of Geophysics (1; 11.444). There were over 61 citations in journals with impact factors greater than 4. Overall, we have seen the number of citations increase every year to around 70 citations per year.



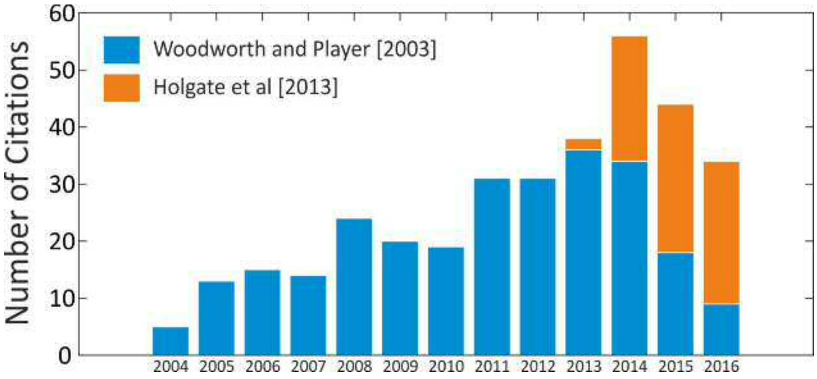


Figure 7: Statistics of PSMSL Data Set Citations

8 Global Sea Level Observing System (GLOSS) Core Network Status

The Global Sea Level Observing System (GLOSS) was established by the Intergovernmental Oceanographic Commission (IOC) in 1985 to provide coordination for global and regional sea level networks in support of, and with direction from, the oceanographic and climate research communities. Various tide gauge networks have contributed to GLOSS, each with a different focus and each changing over time as research and operational priorities evolve.

The main component is the GLOSS Core Network (GCN), a global set of 290 tide gauge stations (Figure 8) that serves as the backbone of the global *in situ* sea level network. The network is designed to provide an approximately evenly distributed sampling of global coastal sea level variation. Ideally, each station should provide data on a variety of timescales for use in different applications; for example, real-time data can be useful for tsunami monitoring, whereas monthly and annual mean data can be used to monitor long-term changes in sea level. In addition, sites should also be fitted with GNSS equipment to monitor land movement at or near the site. Further information on GLOSS is available in the GLOSS Implementation Plan 2012 and on the GLOSS web-site (www.gloss-sealevel.org).

For many years PSMSL has produced maps showing the status of the Core Network from its perspective, and more recently has been generating additional maps, automatically updated weekly, showing the status for the other GLOSS data streams (e.g. real-time, fast-mode, delayed-mode and TIGA/GNSS). Figure 9 presents how PSMSL currently sees the status of the GLOSS Core Network. The map indicates whether a station is considered currently operational (green marker), has been operational in the past (orange marker), or has never operated successfully (white marker).

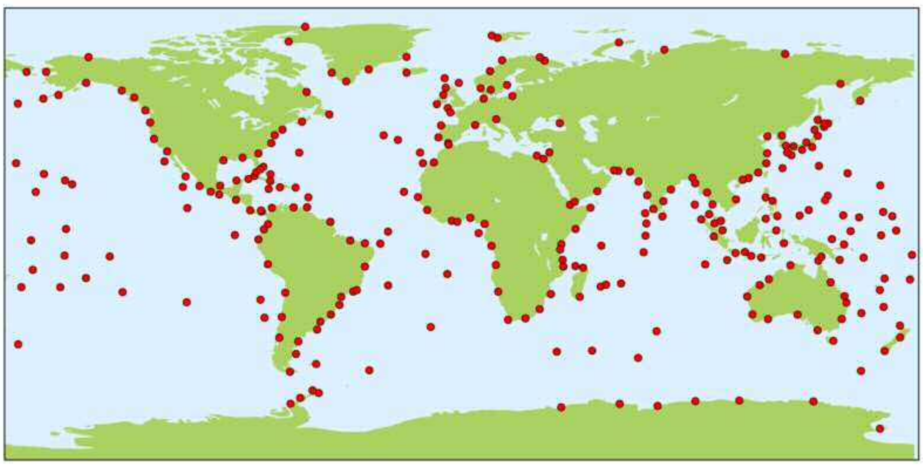


Figure 8. GLOSS Core Network

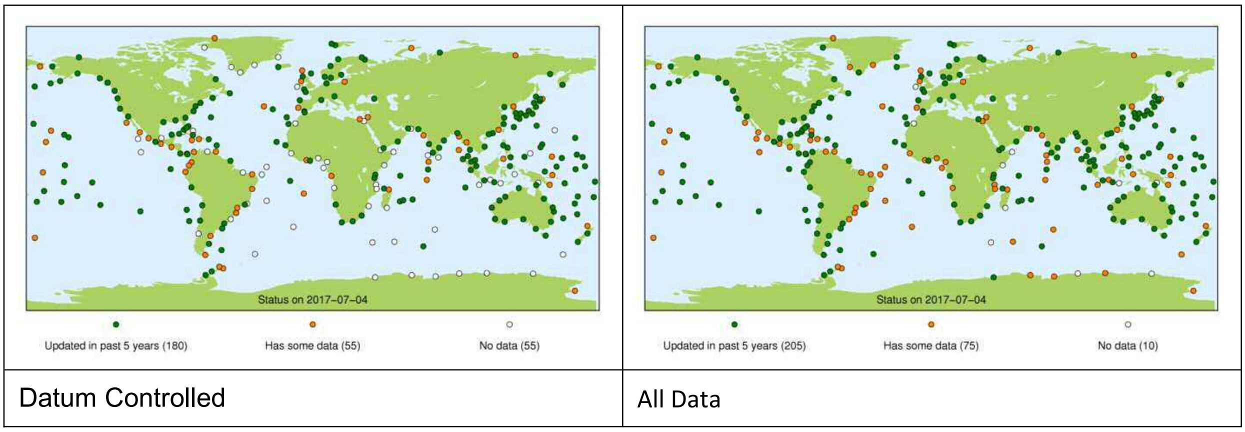


Figure 9. GLOSS Status from a PSMSL perspective

9 GLOSS Delayed-Mode high frequency data centre

The GLOSS Delayed Mode Data Centre is operated by the BODC in collaboration with PSMSL. It has the responsibility for assembling, quality controlling and distributing the “final” version of GLOSS sea-level data sets, as well as all supporting metadata information (including benchmark details). The Delayed Mode Centre handles hourly (or sub-hourly) values, together with ancillary variables (e.g. atmospheric pressure) where these are available, from the GLOSS Core Network and long term trends stations. BODC and PSMSL generally rely on member countries to provide the final version of the hourly (or sub-hourly) time series with all quality control assessments applied and documented. The Delayed Mode Centre will, on request from member countries, form and provide the PSMSL with monthly averages based on the final data sets received. Recently PSMSL has been working with BODC to provide improved access to the GLOSS Delayed-mode data set via the PSMSL web-site as shown in Figure 10 below. This is a work in progress and will be further developed during the remainder of 2017.

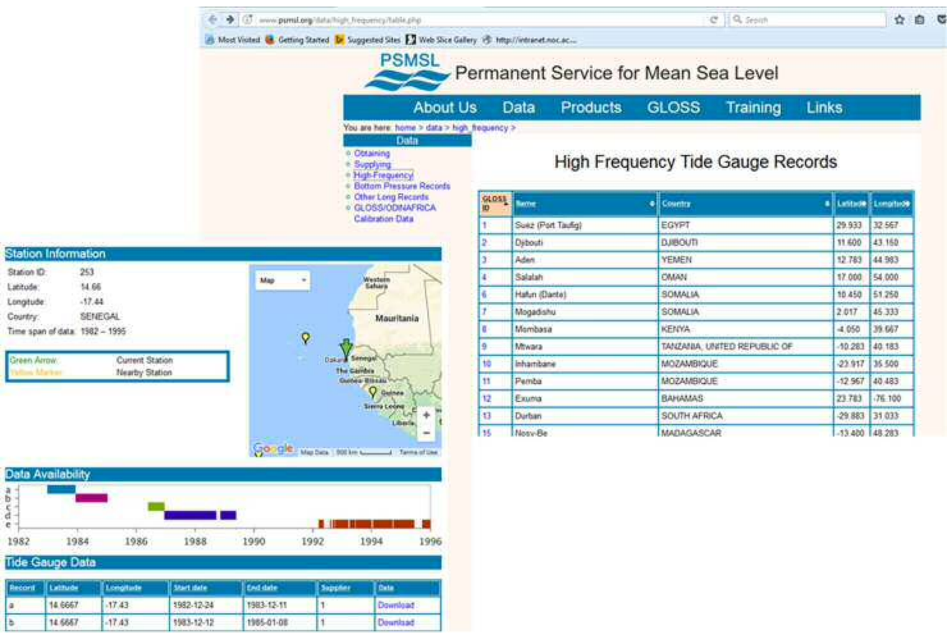


Figure 10: GLOSS Delayed-mode data set access

10 Data Archaeology in collaboration with GLOSS

PSMSL has also taken the lead in data archaeology through the IOC GLOSS programme. Many historical tide gauge data still exist in non-digital form. These mostly paper-based datasets are of great potential value to the sea level community for a range of applications, the most obvious being the extension of existing sea level time series as far back as possible in order to understand more completely the timescales of sea level change. Figure 11 illustrates the results of a number of data rescue projects undertaken by various sea level groups worldwide, some of which include data going back to dates prior to 1850. The GLOSS data archaeology sub-group, under the leadership of Elizabeth Bradshaw, is collating tools and guidelines for the scanning, digitising and quality control of historical tide gauge charts and sea level ledgers. In the future, coordination of a tide gauge data rescue project with the Atmospheric Circulation Reconstructions over the Earth (ACRE) programme (carrying out rescue of air pressure data) could result in interesting synergies. The other major form of analogue sea level data is handwritten ledgers. Transcribing these is labour intensive and usually undertaken by people entering numbers by hand. GLOSS is exploring other methods for use in the future; one possibility is to have a Citizen Science approach as with the OldWeather project run in partnership with ACRE. An alternative approach is to investigate the adaption of Handwritten Text Recognition technology for use with handwritten tide gauge ledgers.

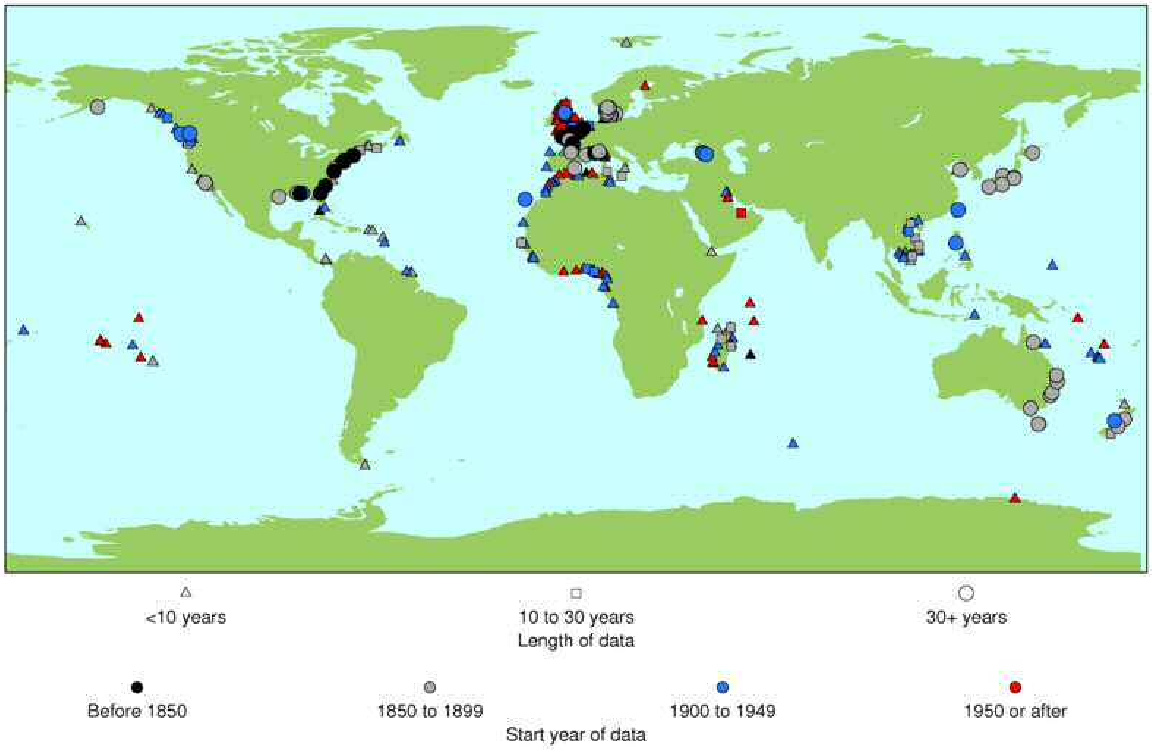


Figure 11: GLOSS Tide Gauge Data Archaeology

11 Global Extreme Sea Level Analysis (GESLA)

The Global Extreme Sea Level Analysis (GESLA) project grew out of the interest of several people in learning more about changes in the frequency and magnitude of extreme sea levels. The first GESLA dataset (GESLA-1) was assembled by Philip Woodworth (National Oceanography Centre, Liverpool), Melisa Menendez (University of Cantabria) and John Hunter (University of Tasmania) around 2009 and contained a quasi-global set of 'high frequency' (i.e. hourly or more frequent) measurements of sea level from tide gauges around the world.

GESLA-1 was used first in a study of sea level extremes by Woodworth and Menendez (JGR, 2010). It has since been used in a number of other published studies of extremes including the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

After some years it became apparent that GESLA-1 needed updating, which has resulted in the present GESLA-2 dataset comprising 37000 station years of information from 1300 stations (as of February 2016). The three original people have been joined in GESLA by Marta Marcos (University of the Balearic Islands) and Ivan Haigh (University of Southampton).

It can be seen that, while the study of extreme sea levels has been the main interest, the availability of as large a quasi-global sea level dataset as possible enables many other types of study, such as changes in ocean tides. The oceanographic community needs a global dataset such as GESLA, that is regularly updated and extended to include new historic data as it becomes available. Steps are now being taken to see how that might be accomplished in the future.

12 Training and capacity building

The PSMSL is also involved with developing training information, and organising training courses, for operators of tide gauges and users of their datasets. Recent training includes a Sea Level Training Course for Tide Gauge Operators during October 2016 in Rodney Bay, St. Lucia. It was funded jointly by NOC, under the UK Commonwealth Marine Economies (CME) Programme, and the IOC. It included staff from PSMSL, NOC, UHSLC, National Oceanic and Atmospheric Administration (NOAA) and the Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (CARIBE-EWS).

13 Visitors to the PSMSL

The PSMSL welcomed a number of visitors from mid-2015 0nwards. These included Aimee Slangen, Sea Level Scientist from the Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Netherlands; John Church, Climatologist from CSIRO, Australia; and Barbel Weidig, our contact and data provider for BSH Rostock, Germany. Visiting for the European Space Agency Project meeting 'GOCE++ Dynamic Topography at the Coast and Tide Gauge Unification' meeting were Guy Woppelmann, Professor of Earth Sciences at La Rochelle University, France, and his associate Mederic Gravelle as well as Professor Per Knudsen, Head of Geology from DTU Space, Technical University of Denmark.

Elizabeth Bradshaw (BODC) has been involved with demonstrating the working of the Doodson-Lege tidal prediction machine on display in the NOC Liverpool atrium to visitors attending the Centre.

14 National and International Meetings

PSMSL staff have continued to be active participants in a number of meetings, Dr. Mark Tamisiea has attended meetings of the Global Geodetic Observing System (GGOS) while others were involved with the G7 Global Ocean Observing workshop which took place at the NOC during March. Dr. Simon Williams and Dr. Svetlana Jevrejeva also attended the Geodesy workshop at Herstmonceux during July.

Several PSMSL staff, including Dr. Angela Hibbert and Dr. Simon Williams, who together presented a poster entitled 'Uncertainties in UK Sea Level Trends', were involved with the 17th Biennial Conference of the Challenger Society for Marine Science held at Liverpool University during 5-8th September 2016. Dr. Andy Matthews gave a talk on the 'History of the PSMSL and its Current Operation' and also presented a poster of 'Mean Tidal Level data in the PSMSL dataset' at the same meeting. Miss Elizabeth Bradshaw was the lead on a PSMSL/BODC/GLOSS poster 'Sea Level Data Rescue - filling the gaps in the dataset'. Andy Matthews also presented a talk on metadata at the specialist interest group Marine Science Data Management at the end of the Challenger meeting.

Elizabeth Bradshaw was invited to represent and deliver an overview presentation of GLOSS at the EU funded HYDRALAB+ project event held at the Institute of Hydro-engineering of Polish Academy of Sciences, Gdansk, Poland in September. At the International Conference of Marine Data and Information Systems (IMDIS) conference in Gdansk Poland in October, Andy Matthews gave a similar metadata presentation. Elizabeth Bradshaw presented a poster on 'The future for the Global Sea Level Observing System (GLOSS) Sea Level Data Rescue'.

During November Andy Matthews together with Elizabeth Bradshaw attended the Ocean Surface Topography Science Team Meeting (OSTST) at the La Rochelle University gave a joint talk on metadata standardization at the International Workshop on Sea Level Measurement Technologies held by the EuroGOOS Tide Gauge Task Team. Andy Matthews also presented a poster about the PSMSL and links with GNSS data from SONEL. Angela Hibbert also supplied a poster at the same meeting and attended a Chartered Institute of Ecology and Environmental Management (CIEEM) meeting in London about the Southern Ocean.

PSMSL staff were also involved when the NERC research vessel RRS Discovery was moored on the Liverpool Waterfront for a showcase event 'Into the Blue' during 4-7th October, among those visiting the ship were local public, schools and businesses. This is only the second time the ship has visited Liverpool.

Dr. Lesley Rickards is a member of the ICSU World Data System Scientific Committee and chairs the sub-committee on Membership and Accreditation. She has been closely involved in the development and implementation of the accreditation criteria. This has led to co-chairing a joint working group between the World Data System and the Data Seal of Approval, under the auspices of the Research Data Alliance (RDA), as the two organisations harmonise the catalogues of criteria for a basic level of certification. She has attended two recent RDA meetings, the 8th Plenary in Tokyo and a UK RDA meeting in Birmingham, UK, to promote the agreed certification.

15 PSMSL Staff and Advisory Group

Funding for PSMSL comes from NERC *via* NOC. Between 2015 and 2016 this has been approximately equivalent to 3 full time staff, but in reality all of those listed in the table below have contributed to PSMSL, and as ever, we are grateful to others in the NOC Sea Level and Technology Groups who contribute to or represent PSMSL at meetings, conferences, or other fora. We said goodbye to Mark Tamisiea who left PSMSL to move back to the USA during the year. He has made a considerable contribution to PSMSL, for which we would like to thank him. We wish him well in his new role.

<table>
<tr><td>Dr. Lesley Rickards, Director</td><td>Dr. Svetlana Jevrejeva, Senior Scientist</td></tr>
<tr><td>Mrs. Kathy Gordon, Data Manager</td><td>Dr. Mark Tamisiea, Senior Scientist</td></tr>
<tr><td>Dr. Andrew Matthews, Data Scientist</td><td>Dr. Simon Williams, Senior Scientist</td></tr>
<tr><td rowspan="2">Miss Elizabeth Bradshaw, Data Scientist, BODC</td><td>Dr Angela Hibbert, Scientist</td></tr>
<tr><td>Prof. Philip Woodworth, Scientific Advisor</td></tr>
</table>

The PSMSL is also served by an Advisory Group which at present consists of Dr. R. Neilan (JPL, USA), Prof. G. Mitchum (University of South Florida, USA), Dr. Guy Wöppelmann (Université de La Rochelle, France), Dr. P. Knudsen (Danish National Space Institute), Dr. R. Bingley (Nottingham University, UK), and Dr. T. Aarup (IOC, UNESCO).

16 Summary and forward look

The last two years were once again active ones for PSMSL with regard to important workshops and conferences, and busy with regard to data acquisition and analysis. The functions provided by the PSMSL are in as much demand as ever, and new products continue to be developed and activities have expanded. Future plans include:

- Improved integration of the mean sea level dataset with higher frequency data and improving the quality of accompanying metadata;
- Keeping contact with data suppliers (the trend being to acquire data from websites rather than direct supply) and ensuring that data made available in real-time are also contributed to PSMSL;
- Continue collaboration with SONEL (IGS TIGA Working Group data centre) and with GGOS;
- Expansion of ocean bottom pressure record section and data;
- Further develop data archaeology with the Group of Experts on GLOSS;
- Redevelopment of capacity building/training material.
- Contribute to WDS metadata catalogue and training pages
- Mint a Digital Object Identifier (DOI) for PSMSL dataset (in collaboration with BODC)
- Refreshing and further updating the PSMSL web-site

Annex 1: Selected Papers published during 2016

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Annex 2: Stations received from individual countries (2016-17)

American Samoa	1		Martinique	1
Antarctica	1		Mauritius	2
Argentina	1		Mayotte	1
Australia	80		Micronesia, Federated States of	1
Belgium	3		Monaco	1
Bermuda	1		Myanmar	1
Canada	39		Namibia	2
Chile	12		Nauru	1
China	6		Netherlands	11
Cocos (Keeling) Islands	1		New Caledonia	5
Cook Islands	1		New Zealand	13
Croatia	5		Norway	23
Cuba	12		Panama	1
Fiji	2		Papua New Guinea	1
France	32		Philippines	21
French Guiana	2		Portugal	3
French Polynesia	5		Puerto Rico	7
Georgia	2		Réunion	1
Germany	3		Russian Federation	4
Greece	17		Saint Pierre and Miquelon	1
Greenland	3		Samoa	1
Grenada	1		Singapore	10
Guadeloupe	1		Solomon Islands	1
Guam	2		South Africa	10
Hong Kong	6		Spain	44
Iceland	1		Svalbard and Jan Mayen	2
India	14		Sweden	23
Indonesia	1		Thailand	5
Isle of Man	1		Tonga	1
Israel	6		Tuvalu	1
Italy	33		United Kingdom	48
Japan	99		United States	116
Jersey	1		United States Minor Outlying Islands	1
Kiribati	1		Uruguay	1
Korea, Republic of	46		Vanuatu	1
Malaysia	18		Virgin Islands, U.S.	4
Malta	1		Wallis and Futuna	1
Marshall Islands	3			

Annex 3: Data Suppliers 2016-17

Supplier	Country	No. of stations
Servicio de Hidrografia Naval, Argentina	Argentina	1
Australian Ocean Data Centre, NSW	Australia	1
National Tidal Centre	Australia	86
NSW Public Works	Australia	10
Agency for Maritime and Coastal Services	Belgium	3
Canadian Hydrographic Service	Canada	39
Servicio Hidrografico y Oceanografico de la Armada (SHOA)	Chile	12
National Oceanographic Data Centre	China	6
Hidrografski Institut, Split	Croatia	5
Cuban National Tidal Service	Cuba	12
Danish National Space Center	Denmark	3
Institut Geographique National, France	France	1
Service Hyd. et Ocean. de la Marine (SHOM)	France	50
Dept. of Oceanology and Meteorology, Georgia	Georgia	2
Bundesamt fur Seeschifffahrt und Hydrographie, Hamburg	Germany	3
Hellenic Navy Hydrographic Service	Greece	17
Hong Kong Observatory	Hong Kong	6
Icelandic Coast Guard - Hydrographic Department	Iceland	1
Survey of India	India	14
Survey of Israel	Israel	6
Instituto Talassografico di Trieste	Italy	1
ISPRA	Italy	31
University of Ferrara	Italy	1
Geographical Survey Institute	Japan	25
Japan Meteorological Agency	Japan	54
Japan Oceanographic Data Centre, MSA	Japan	20
National Oceanographic Research Institute	Korea, Republic of	46
Department of Survey and Mapping	Malaysia	18
Malta Maritime Authority	Malta	1
Meteo-France	Martinique	1
Meteorological Services, Mauritius	Mauritius	2
Rijkswaterstaat	Netherlands	11
Land Information New Zealand (LINZ)	New Zealand	12
Norwegian Hydrographic Service	Norway	24
National Mapping And Resource Information Authority	Philippines	21
Instituto Hidrografico, Lisbon	Portugal	3
World Data Center B1	Russian Federation	5
Maritime Port Authority of Singapore	Singapore	10
Directorate Of Hydrography, SA	South Africa	12
Dr. Josep Pascual Massaguer	Spain	1
Instituto Espanol de Oceanografia	Spain	11
Puertos del Estado	Spain	32
Swedish Met. and Hyd. Institute	Sweden	23
Oceanographic Division, Hydrographic Department	Thailand	5
Channel Coastal Observatory	United Kingdom	10
National Oceanography Centre / Environment Agency	United Kingdom	38
Port of London Authority	United Kingdom	2
NOAA / NOS	United States	133
Panama Canal Commission	United States	1
University of Hawaii Sea Level Center (UHSLC)	United States	4
Servicio de la Armada de Uruguay	Uruguay	1

Annex 4: Acronyms

ACRE	Atmospheric Circulation Reconstructions over the Earth
BSH	*Bundesamt für Seeschifffahrt* und Hydrographie (Federal Maritime and Hydrographic Agency), Germany
BODC	British Oceanographic Data Centre
CARIBE-EWS	Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions
CIEEM	Chartered Institute of Ecology and Environmental Management
CME	Commonwealth Marine Economies
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
DOI	Digital Object Identifier
DTU	Danmarks Tekniske Universitet (*Technical University of Denmark*)
EuroGOOS	European Global Ocean Observing System
GCN	GLOSS Core Network
GESLA	Global Extreme Sea Level Analysis
GGOS	Global Geodetic Observing System
GLOSS	Global Sea Level Observing System
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
IAG	International Association of Geodesy
IAPSO	International Association for the Physical Sciences of the Oceans
ICSU-WDS	International Council for Science – World Data System
IMDIS	International Conference of Marine Data and Information Systems
IGS	International GNSS Service
IOC	Intergovernmental Oceanographic Commission
IOTWS	Indian Ocean Tsunami Warning System
IPCC	Intergovernmental Panel on Climate Change
JCR	Journal Citation Reports
MSL	Mean Sea Level
MTL	Mean Tide Level
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration, USA
NOC	National Oceanography Centre, UK
ODINAfrica	Ocean Data and Information Network for Africa
OSTST	Ocean Surface Topography Science Team Meeting
PNAS	Proceedings of the National Academy of Sciences of the USAmerica
PSMSL	Permanent Service for Mean Sea Level
RDA	Research Data Alliance
RLR	Revised Local Reference
SONEL	Système d'Observation du Niveau des Eaux Littorales
TIGA	IGS Working Group Tide Gauge Benchmark Monitoring Project
UHSLC	University of Hawaii Sea Level Center

Advisory Board on the Law of the Sea (ABLOS)

https://www.iho.int/srv1/index.php?option=com_content&view=article&id=416&Itemid=374&lang=en

Chair: John Brown, United Kingdom (IHO)
Vice-Chair: Niels Andersen, Denmark (IAG)

Structure

Chair: John Brown, United Kingdom (IHO)
Vice-Chair: Niels Andersen, Denmark (IAG)
Secretary: David Wyatt (IHB)
Members IHO: Brazil, Japan, Republic of Korea, United Kingdom
Members IAG: Canada, Chile, Denmark, Indonesia
Ex Officio: UN DOALOS and IHB
Observers: Australia, Bangladesh, India, Japan, United Kingdom

Meetings Held During Reporting Period

ABLOS 22 19, 23 October 2015, IHB Monaco
ABLOS 8 Conference 20 – 22 October 2015, IHB Monaco
ABLOS 23 26 – 28 October 2016, Seoul, Republic of Korea

Future Meetings

ABLOS 24 9 & 12 October 2017, IHB Monaco
ABLOS 9 Conference 10 – 11 October 2017, IHB Monaco

Report on the Work Program

The 22nd Business Meeting of ABLOS was held at the International Hydrographic Bureau in Monaco on 19th and 22nd October 2015. The 8th ABLOS Conference, titled '*UNCLOS: Advances in Managing the Blue World*' took place 20-22 October 2015 and was held at the Novotel, Monaco.

All ABLOS members and observers from Australia, Brazil, Canada, Chile, Denmark, India, Indonesia, Japan, Republic of Korea and the United Kingdom were present; a representative from Suriname also attended both events. The Chair, Professor Sunil Bisnath (IAG – Canada), welcomed all Board members and observers to the business meeting.

The first session of the business meeting completed final preparations for the 8th ABLOS Conference. The revisions identified for chapter 3 of Edition 5.0.0 of the Manual on Technical Aspects of the United Nations Convention on the Law of the Sea - 1982 (TALOS Manual - C-51) were discussed. The revision time frame and process were decided with a target completion in 2016 for consideration by the 8th meeting of the Hydrographic Standards and Services Committee. Japan agreed to provide the revised chapter 3 text for review by the Editorial Board, under the leadership of Mr Chris Carleton, to progress this work.

ABLOS members and observers discussed notable topics from the various conferences, seminars and workshops that they had attended and undertaken since the previous business meeting. The meeting also discussed the material for the ABLOS capacity building training course and reviewed ways to develop it further.

The meeting reviewed the Terms of Reference and Rules of Procedure for the ABLOS, noting there was no requirement for amendments at present. They agreed that the future of ABLOS and its work should be considered by all members before the next business meeting. It was noted that the Terms of Reference should be used as the basis for a review of the tasks set and the work undertaken. Participants were asked to consider whether some tasks had been completed and whether there were any activities which were not addressed in the Terms of Reference. The status of current Board members was reviewed. Dr Niels Andersen, IAG representative due to complete his term in January 2016, expressed a desire to serve for a further 4 years. Dr Sobar Sutisna (IAG representative) indicated that he would be standing down in 2017 and Professor Sunil Bisnath (IAG representative) would complete his second term in 2017. The Board unanimously supported the reappointment of Dr Andersen and Professor Bisnath. The Chair was directed to request the IAG Executive to consider reappointing Dr Andersen and Professor Bisnath and to identify a suitable replacement for Dr Sutisna. In addition the ABLOS requested the Chair to investigate with the IAG Executive the appointment of an IAG Observer to ABLOS for the development of potential future IAG members to ABLOS.

The 8th ABLOS Conference was attended by approximately 60 delegates. 25 different IHO Member States were represented, namely Algeria, Australia, Brazil, Canada, Chile, Denmark, France, Germany, Greece, India, Indonesia, Japan, Monaco, Netherlands, New Zealand, Nigeria, Norway, Oman, Portugal, Republic of Korea, Singapore, Suriname, Thailand, United Kingdom and USA. The Conference included 28 presentations covering a wide variety of topics and issues in relation with the theme "UNCLOS: Advances in Governing the Blue World". President Robert Ward welcomed the delegates on behalf of the IHO. The opening key note address was given by Rear Admiral Nick Lambert, former National Hydrographer of the United Kingdom, and the closing presentation was given by Professor David Freestone, The George Washington University, USA. The general theme of the conference was. An overview of the contributions of the IHO and the IAG to the implementation of UNCLOS were provided by Director Gilles Bessero and Professor Sunil Bisnath respectively. The presentations on various aspects of the Law of the Sea generated numerous questions and comments in plenary and much discussion in the margins during the breaks.

A presentation was given at the 8th ABLOS Conference by DOALOS, which highlighted the effectiveness of S-121 (Marine Limits and Boundaries) as a medium for maritime limits and boundaries data. It was strongly recommended that States Parties consider using this format for lodging information to which they desire the UN to give due publicity.

On completion of the ABLOS Conference, Mr John Brown (UK) assumed the role of Chair and Dr Niels Andersen (Denmark) was elected as Vice-Chair. It was agreed that the next Business Meeting would take place in Seoul, Republic of Korea, 26-28 October 2016 and the next ABLOS Conference would take place in Monaco on 10 and 11 October 2017 under the title '*Pushing the limits of UNCLOS*', partly in recognition of the need to consider regulation of activities in the sea Area Beyond National Jurisdiction (ABNJ).

UN-GGIM: Geospatial Societies – Previously the Joint Board of GIS

https://www.fig.net/jbgis/

Chairperson: Dave Lovell (UK)
Manager: Louise Friis-Hansen (Denmark)

Introduction

UN-GGIM: Geospatial Societies (previously The Joint Board of Geospatial Information Societies - JBGIS) is a coalition of the Presidents, Secretaries-General or equivalent office bearers or their nominees that lead recognised international organisations involved in the coordination, development, management, standardisation or regulation of geospatial information and related matters.

The purpose of UN-GGIM: Geospatial Societies is to provide, where possible, a collective and unified voice at the international level regarding geospatial affairs, especially to the United Nations and other global geospatial information stakeholders and to assist in the coordination of relevant activities between the organisations in which they hold office.

The current members of UN-GGIM: Geospatial Societies are:

- Global Spatial Data Infrastructure (GSDI) Association
- IEEE Geoscience and Remote Sensing Society (IEEE-GRSS)
- International Association of Geodesy (IAG)
- International Cartographic Association (ICA)
- International Federation of Surveyors (FIG)
- International Geographical Union (IGU)
- International Map Industry Association (IMIA)
- International Society of Photogrammetry and Remote Sensing (ISPRS)

UN-GGIM: Geospatial Societies typically meets once a year at a location linked to one of the conferences of the member organisations, or to meetings conducted by the UN initiative on Global Geospatial Information Management (UN-GGIM).

Previously UN-GGIM: Geospatial Societies was called the Joint board of Geospatial Information Societies

Meetings

The JBGIS meets normally once a year. Wherever possible the meeting is linked to a conference or other meeting of one or more of the organisations represented by the members.

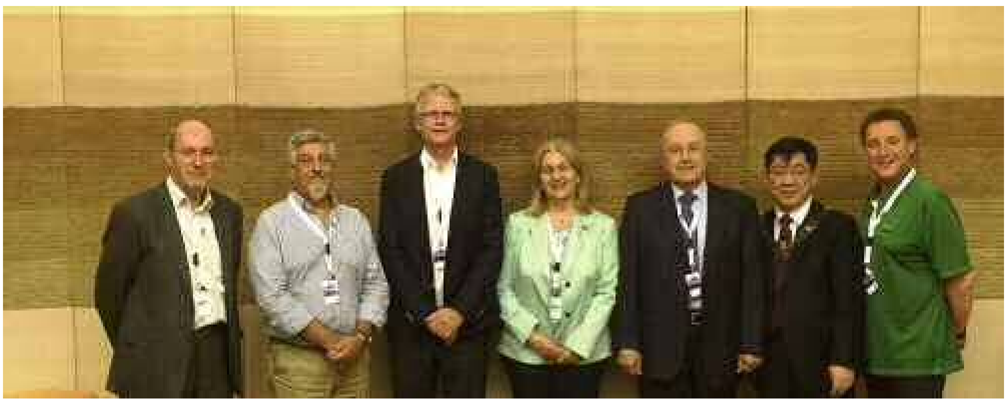

Fig. 1: Participants at the JBGIS meeting in Prague, July 2016

Next meeting of the JB GIS is scheduled in connection with the UN-GGIM in August 2017 in New York, USA (tentative)

Representatives

GSDI	President:	David J. Coleman, Canada
	Secretary General:	Roger Longhorn, USA
	Past President:	Abbas Rajabifard, Australia
IAG	President:	Harald Schuh, Germany
	Secretary General:	Hermann Drewes, Germany
	Past President:	Chris Rizos, Australia
ICA	President:	Menno-Jan Kraak, The Netherlands
	Secretary General:	László Zentai, Hungary
	Past President:	Georg Gartner, Austria
GGRS	President:	Adriano Camps, Spain
	Representative:	Anthony K. Milne, Australia
FIG	President:	Chryssy Alex. Potsiou, Greece
	Director:	Louise Friis-Hansen, Denmark
IGU	President:	Vladimir Kolossov, Russia
	Past-President:	Ronald F. Abler, USA
	Secretary General:	Michael Meadows, South Africa
IMIA	President:	Ron Lofton, USA
	Board Member:	Mark Cygan, USA
ISPRS	President:	Chen Jun, China
	First Vice President:	Orhan Altan, Turkey
	Secretary General:	Lena Halounova, Czech Republic

References

The Value of Geoinformation for Disaster and Risk Management (VALID)
http://www.un-spider.org/sites/default/files/VALIDPublication.pdf

Journal of Geodesy

http://link.springer.com/journal/190

Editor in Chief: Jürgen Kusche (Germany)

Activity Report

Journal of Geodesy (JoG) is an international journal concerned with the science of geodesy and related inter-disciplinary sciences. JoG is the official scientific journal of the IAG and it publishes monthly research articles, review papers, and short notes. Its publishing company, based on an agreement with IAG, is Springer Heidelberg.

The Editor-in-Chief (EiC) is responsible for the scientific content of the journal. He makes the final decision on whether a manuscript is accepted for publication. He is advised by an Editorial Board (EB). The current EB comprises 20 members (associate editors) from 17 countries:
S. Bettadpur (USA), T. v. Dam (Luxemburg), D. Dong (China), Y. Gao (Canada), M. Hernandez-Pajares (Spain), T. Hobiger (Sweden), A. Hooper (UK), C. Huang (China), A. Jäggi (Switzerland), W. Keller (Germany), Z. Malkin (Russia), B. Meyssignac (France), M. King (Australia), R. Riva (The Netherlands), W.-D. Schuh (Germany), I. Tziavos (Greece), S. Verhagen (The Netherlands), M. Vermeer (Finland), P. Wielgosz (Poland), P. Xu (Japan).

JoG uses the Editorial Manager (EM), a web-based peer review system, which allows easy manuscript submission, provides author information and e-mail updates, and helps reducing the turnaround time. In recent years, EM has added automated workflows e.g. for plagiarism checking and authorship change requests.

JoG publishes special issues on topics of general interest to the geodetic community, where all contributions must be of highest standards. These are then physically combined in one issue (but normally published online once individually accepted). The most recently published special issue (July 2017, Volume 91, Issue 7) on "VLBI contribution to reference frames and Earth's rotation studies" has been dedicated to the 50-year anniversary of the first Very Long Baseline Interferometry (VLBI) experiments, and two other special issues (on "Satellite Laser Ranging" and on "Reference Systems") are currently in preparation.

Indeed, JoG would like to encourage authors to (1) submit review papers and (2) initiate special issues related to topics of high interest to the geodetic community. JoG publishes short notes once in a while when topics are timely and of interest to a broad readership.

Impact Factor

The Impact Factor (IF) of JoG has shown some variability over the last years; the current (2016) Impact Factor is 2.949, based on Thomson Reuters JCR (Journal Citation Report). Measured by the IF, JoG is among the top 10 journals of Springer's Earth Science & Geography journals: rank 8 out of 92 in 2016. For the last 3 years JoG has seen the following evolution of IF and citations:

Table 1: JoG Impact Factor and total journal article citations for 2014-2016

Year	Impact Factor	Citations
2014	2.699	2502
2015	2.486	2881
2016	2.949	3838

Submissions and acceptance

The number of submissions has steadily increased with about 20 additional submissions each year. The top 10 countries with the highest number of submissions are China, Germany, US, France, Australia, Canada, Iran, Italy, Netherlands, and the UK.

Table 2: JoG submitted and accepted manuscripts (per calendar year) for 2014-2016

Year	submitted	accepted
2014	237	84
2015	247	77
2016	271	97

The acceptance rate is quite stable, around 34%.

Review statistics and turnaround time

The JoG knows a nominal review period of 28 days. Table 3 shows some statistics of the review process. Indeed, the average number of days to complete a review is nearly stable at about 32. However, as it is obvious from the table, in order to obtain three reviews (which is nominal) the associate editors have to invite, on average, five potential reviewers. The other observation is that turnaround times measured in days from submission to first decision are slightly increasing; this can be largely explained by the increased editorial load from receiving more submissions.

Table 3: JoG number of review invitations and completed reviews and average turnaround time (submission to first decision in days) for 2014-2016

Year	Review invitations	Completed reviews	Average Turnaround time
2014	887	563	53.1
2015	953	596	56.1
2016	1297	787	59.9

Data policy

In 2016, the EB has decided to adopt a policy of (1) encouraging data sharing, and (2) requiring statements of data availability from authors. The latter is currently in the process of implementatio

IAG Symposia Series

http://www.springer.com/series/1345

Editor-in-Chief: Jeff Freymueller (USA)
Assistant Editor-in-Chief: Laura Sánchez (Germany)

Overview

The IAG Symposia Series is a book series of peer-reviewed proceedings of selected IAG Symposia organized by the International Association of Geodesy. It deals primarily with topics related to Geodesy as applied to the Earth Sciences and Engineering: terrestrial reference frame, Earth gravity field, geodynamics and Earth rotation, positioning and engineering applications. We plan to rename the series to the "IAG Topical Series" in the future.

Volumes are available online at the Springer web site (http://www.springer.com/series/1345), since volume 101 (Global and Regional Geodynamics, 3-5 August 1989), published in 1990. Most recent volumes are also available from the Springer web site as e-Books. It must be noted that articles published in the IAG Symposia Series since 2000 are referenced in the ISI Web of Knowledge, implying that their citations are used in the ISI Web of Science (Thomson SCI). A request was sent to Scopus (Elsevier) to add this book series of peer-reviewed proceedings to their database. Recently, I learned that some of the recent volumes have no yet been indexed by these services, and we will address this problem soon. Until 2015, the de facto Editor-in-Chief of this series is the IAG President, but the IAG Statutes and By-Laws were then changed to appoint a separate Editor-in-Chief.

Following the IUGG General Assembly in Prague (July 2015), the new Editor-in-Chief is Jeffrey Freymueller, with Laura Sanchez serving as the Assistant Editor-in-Chief. The review procedure is carried out using the Spring Editorial Manager system (http://www.editorialmanager.com/iags), which allows full electronic manuscript submission and management of the peer-review process. Editors are selected for each symposium from the list of convenors, taking into account the number of expected symposium manuscripts. Specifications for authors are provided to all authors through the Springer web site. These specifications include the length of article and format description. Written procedures are also provided to all editors to allow a fair and homogeneous review process within all sessions and within all the IAG Symposia. For each manuscript, two independent experts are selected by the editors to review the submitted manuscript. Based on the returned reviewers reports, the editor makes a decision, which needs to be confirmed by the Editor-in-Chief. To improve communication with the authors, monthly reports are sent out by the Editorial Manager system. Information emails are also sent out to authors, while papers are handled by Springer Production, until their final publication online and in print.

Structure and activities

The following paragraphs provide information on the IAG symposia volumes published or under review process in the 2015-2017. Pascal Willis handled the final stages of all of the volumes prior to the Prague IUGG. Most of these were nearly completed before 2015, but delayed due to publication delays within Springer. Others still had some remaining editorial work, mostly on the final few straggling papers.

Volumes

Volume 142
International Symposium on VIII Hotine-Marussi Symposium on Mathematical Geodesy
Rome, Italy, June 17-21, 2013
Editors: Nico Sneeuw, Pavel Novàk, Mattia Crespi, Fernando Sansò
Published

Volume 143
Scientific Assembly of the International Association of Geodesy: IAG 150 Years
Potsdam, Germany, September 1-6, 2013
Editor: Pascal Willis
Published

Volume 144
3rd International Symposium on Gravity Field Service (IGFS)
Shanghai, China, June 30-July 6, 2014
Editor: Shuanggen Jin
Published

Volume 145
International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH)
Matsushima, Japan, July 22-26, 2014
Editor: Manabu Hashimoto
Published

Volume 146
International Symposium on Reference Frames for Applications in Geosciences (REFAG2014)
Kirchberg, Luxembourg, October 13-17, 2014
Editor: Tonie van Dam
Published

Volume 147
Earth and Environmental Sciences for Future Generations (2015 IUGG General Assembly)
Prague, Czech Republic, June 22 – July 2, 2015
Editors: Jeffrey T. Freymueller, Laura Sanchez
Publication expected in fall 2017

Volume 148
International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS16)
Thessaloniki, Greece, September 2016
Editors: Riccardo Barzaghi, Roland Pail, George Vergios
Publication expected in 2018

Review Process

All submissions are screened automatically using the using the iThenticate software, which is designed to detect plagiarism and self-plagiarism. Self-plagiarism is by far the most common such problem. The iThenticate software can be fooled at times, and some cases of fairly high overlap can be harmless (for example, reference citations can be flagged as overlaps, and it is hard to avoid some overlaps in sections that summarize mathematics). We did not reject outright any submissions in 2015-2017, but we always alerted the editors. In one case, an author was requested to revise the paper to reduce overlap prior to sending it to reviewers.

After the Prague volume, we reduced the number of reviewers needed from 3 to 2. The main reason for this was the time involved – with each additional reviewer there is an additional possibility of delay as the reviewer is slow to respond to invitation, slow to review, etc. This change worked well for the GGHS2016 volume. With two reviewers there is a chance that the reviews will be significantly in conflict, although I personally found this to be true sometimes even with 3 reviewers. In this case, the handling editor can call on his or her own expertise, or ask for an additional review.

Future Outlook

Laura Sanchez and I have worked out an effective division of labor, although we were a bit slow in getting started on the Prague volume. We are keeping track of each other's schedules so that we can step in for the other, and in routine periods I am doing the editorial decisions on papers and Laura is doing the reminders to editors.

Last year Springer implemented a series of automated reminders for editors, similar to those used for Journal of Geodesy. This has made it easier to keep on track. Reviewers who don't reply, or who are late, are difficult for many editors to keep track of without regular reminders.

All work from the IAG side is now complete on all volumes up through the Prague volume, and we are simply waiting for all production to be complete. Pascal Willis completed all editorial work on these volumes. I think in all cases, all papers are final and now we are only waiting for Springer to finalize the publication.

Springer has had a significant delay in moving from completed editorial work (from our point of view) to published books. Their say technical and internal problems have now been resolved, and we anticipate publication of the remaining volumes soon.

We have investigated the possibility of making the IAG Topical Series open access, which would make it considerably more attractive to potential authors. However, as of now the cost of this is still too high. We are in the process of negotiating a new contract with Springer, for purely e-book publication of all future volumes.

Submission Statistics

The number of submission greatly depends of the number of IAG Symposia per year and also on the number of manuscripts submitted to each meeting. In general, the number of submissions appears to be down from past years. This probably reflects the many publication options that authors have, and their growing preference for higher profile publications, as compared to a Symposia series.

Table 1: Number of manuscripts submitted to recent IAG Symposia. Two earlier symposia are also given for comparison.

IAG Symp. volume	IAG Symposium	Location	Date	Number of submissions (articles)
147	IAG General Assembly	Prague, Czech Republic	June 22 – July 2, 2015	61
148	GGHS 2016	Thessaloniki, Greece	September 2016	34
139	IAG General Assembly	Melbourne, Australia	June 28 – July 1, 2011	109
140	GGHS2012	Venice, Italy	October 9-12, 2012	61