National Aeronautics and
Space Administration

NASA/TM—2016–218221

Marshall Space Flight Center
Research and Technology Report 2015

NASA/TM—2016–218221

Marshall Space Flight Center

Research and Technology Report 2015

A.S. Keys, M.L. Tinker, A.D. Sivak, and H.C. Morris, Compilers
Marshall Space Flight Center, Huntsville, Alabama

Acknowledgments

The points of contact and coordinator at Marshall Space Flight Center (MSFC) for this Technical Memorandum (TM) are Mike Tinker (256–544–4973) and Heather Morris. The MSFC Office of Center Chief Technologist recognizes Troy Farsoun, Vicki Hocutt, and Mary Vaughn of the MSFC Scientific and Technical Information Group for assisting in the development of this report. The Center Chief Technologist, Andrew Keys, Deputy Chief Technologist, Mike Tinker, Technologist, Amy Sivak, and Technologist, Heather Morris, provided the support, knowledge, insight, and decisions needed for compilation of this TM.

For additional copies of this report contact:

NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681–2199, USA
757–864–9658

This report is available in electronic form at
<http://www.sti.nasa.gov>

FOREWORD

Marshall Space Flight Center is essential to human space exploration, and exploration propels technological advancements. As we solve the challenges of expanding human presence deeper into the solar system than ever before, we advance technology on Earth, further scientific knowledge and discovery, create new economic opportunities, and continue to lead the world in space exploration.

The investments in technology development we made in 2015 not only support the Agency's current missions, but they will also enable new missions. Some of these projects will allow us to develop an in-space architecture for human space exploration; Marshall employees are developing and testing cutting-edge propulsion solutions that will propel humans in-space and land them on Mars. Others are working on technologies that could support a deep space habitat, which will be critical to enable humans to live and work in deep space and on other worlds. Still others are maturing technologies that will help new scientific instruments study the outer edge of the universe–instruments that will provide valuable information as we seek to explore the outer planets and search for life.

While each project in this report seeks to advance technology and challenge our way of thinking, it is important to recognize the immense variety of work being done in support of our mission. This report highlights Marshall's reputation for solving complex problems and shows the progress that has been made this past year. These scientists, researchers, and technologists are enabling technology that will facilitate NASA's ability to fulfill the ambitious goals of innovation, exploration, and discovery for years to come.

I hope you enjoy reviewing this report. It has been an exciting year and has set the stage for even more progress in 2016.

Todd A. May
Center Director
Marshall Space Flight Center

INTRODUCTION

I am honored to present the Marshall Space Flight Center Research and Technology Report for 2015. Our immensely talented workforce is pursuing a wide variety of research and technology efforts, and this document showcases their impressive work. From early stage innovations developed in the Center Innovation Fund program to advanced technologies that were investigated to enable future Space Launch System capabilities, the efforts detailed in this report should advance the current state of technology such that future NASA missions are enabled.

Marshall's technologists achieved significant accomplishments in projects funded by Human Exploration and Operations Mission Directorate (HEOMD), including the Advanced Exploration Systems Program and Space Launch System Advanced Development. The HEOMD work was managed by the Space Launch Systems Office and the Flight Programs and Partnerships Office.

Outstanding progress was also achieved in technology projects funded by Space Technology Mission Directorate (STMD), including efforts in the Technology Demonstration Missions Program, Centennial Challenges Program, Game Changing Development, Center Innovation Fund, Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR), and Small Spacecraft Technology Program. These efforts were managed by the Science and Technology Office and the Flight Programs and Partnerships Office.

Technology efforts at MSFC funded by the Science Mission Directorate (SMD) included work in the Astrophysics Division and the Planetary Science Division's Mars Exploration Program. This work was managed by the Science and Technology Office.

Finally, MSFC Center Management and Operations funded efforts such as the Technology Investment Program, Center discretionary investments, and Dual-Use Technology Cooperative Agreement Notice. This work was managed by the Office of Strategic Analysis and Communications and the Center Strategic Development Steering Group.

The innovations described within this report may serve to not only enhance and enable NASA's near-term programs and projects, but could also provide the solutions required for future Mars missions, human and robotic exploration of other solar system bodies, and destinations beyond. I trust that you will enjoy reviewing the Marshall research and technology accomplishments of 2015.

Andrew S. Keys

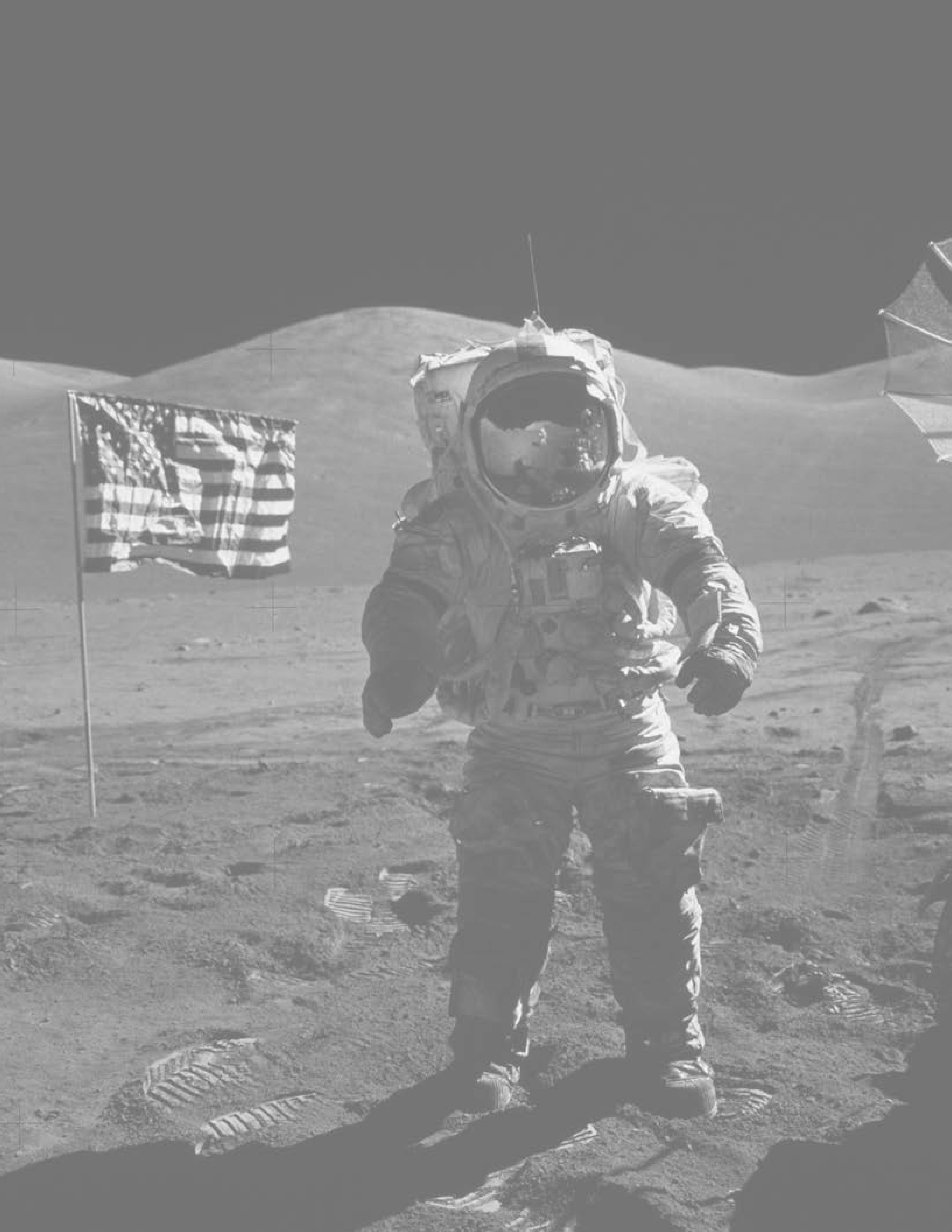
Andrew Keys
Center Chief Technologist
Marshall Space Flight Center

TABLE OF CONTENTS

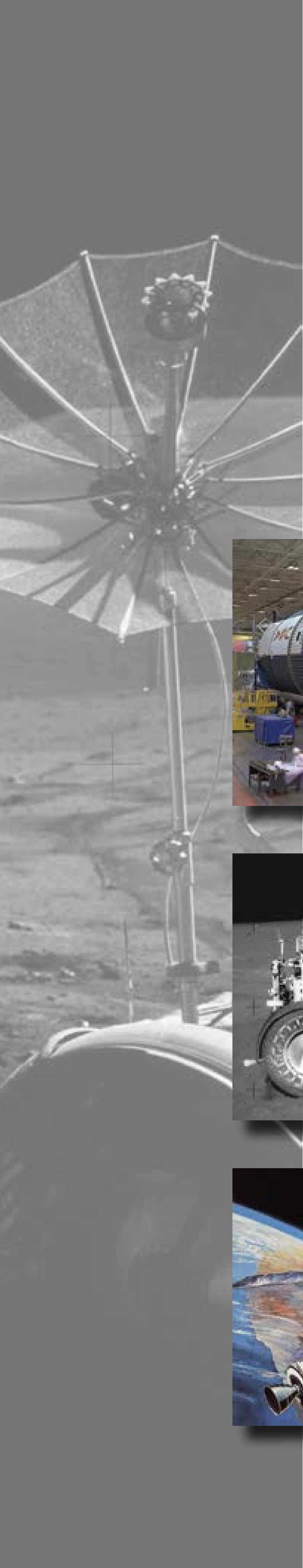
TABLE OF CONTENTS (Continued)

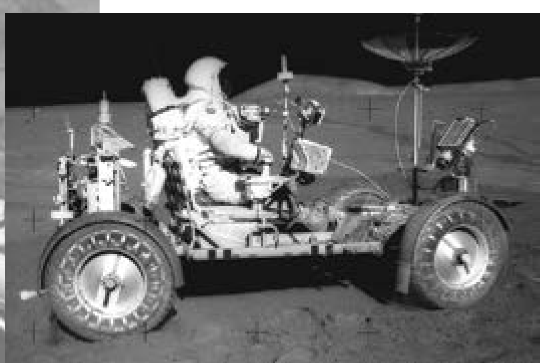
TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)



Human Exploration and Operations Mission Directorate





Human Exploration and Operations Mission Directorate

Advanced Exploration Systems

In-Space Manufacturing Project

Project Manager(s)

Niki Werkheiser/ZP30
(256) 544–8406

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

In-Space Manufacturing (ISM) is a portfolio of project activities that will result in the technologies and capabilities required for sustainable, on-demand manufacturing and repair during exploration missions. Key components of this portfolio include the following:

- 3D Printer Project — A 3D printer uses additive manufacturing technology (AM) to fabricate objects. Additive manufacturing is the process of creating 3D objects from a computer aided design (CAD) model where material is deposited layer by layer. This project was the first technical demonstration of a 3D printer in space (at the International Space Station (ISS)) and was made possible through a Small Business Innovation Research (SBIR) award.[1] Figure 1 shows ISS Commander "Butch" Wilmore holding a 3D-printed sample container. This printer arrived at the ISS in September 2014, and a group of ISS-printed specimens were sent back to NASA Marshall Space Flight Center for extensive material characterization tests to determine the microgravity effect on 3D-printed items. Work is also ongoing to develop a catalog of ISS-utilized items that could be 3D printed onorbit to meet future needs.

- In-Space Recycler Development — Several SBIRs have been awarded to fund a technical demonstration of safe and reliable operation of an on-orbit material recycler. The purpose of this activity is to demonstrate the ability to recycle obsolete or damaged 3D-printed parts into feedstock for the on-orbit 3D printing of new items.

Figure 1: ISS Commander Wilmore holding a 3D-printed sample container.

- Science, Technology, Engineering, and Math (STEM) Outreach:
  - Future Engineers Program[2] — This activity is a K–12 STEM challenge made possible through a Space Act Agreement between NASA and the American Society of Mechanical Engineers.
  - NASA/GrabCAD Public Challenge[3] — GrabCAD is an online community of nearly two million designers. The Advanced Exploration Systems ISM project issues an innovative public challenge to design a 3D-printed handrail clamp assembly in lieu of the traditionally manufactured part used today on ISS.

Anticipated Benefits

The ISM project is responsible for developing the manufacturing capabilities that will provide on-demand, sustainable operations (with reusable materials) during NASA exploration missions (in-transit and on-surface). The lessons learned from this project will be used for the next generation 3D printer on the ISS as well as for any future AM technology NASA plans to use (such as metals or electronics ISM) on both the ISS and deep space missions.

Mission Applications

The capability to produce hardware on demand using 3D printing technologies will directly lower cost and decrease risk by having the exact part or tool needed in the time it takes to print. This project is the first step towards realizing a 'machine shop' in space, which is a critical enabling component of any deep space exploration mission. Successful development of a material recycler will allow deep space missions to reuse existing material and require less original feedstock for printed parts.

Notable Accomplishments

- 3D Printer Technical Demonstration — This initial printer produced all planned parts and is scheduled for additional operation/crew time in November 2015. Data analysis of the material characterization of initial parts printed on ISS will be complete in December 2015 and will determine if there are any significant effects due to printing in a microgravity environment. The project team continues to optimize the utilization of limited Agency resources. The team has worked tirelessly to publicize project accomplishments. More than 1,100 publications have been circulated in national media. Per the NASA Office of Communications metrics (as of March 2015), the media article website view potential for the 3D printer technical demonstration, based on reach of publications, was estimated at 7,286,969,861 and the web-calculated publicity value was $1,201,729,035. "Top 10 Ways ISS is Helping Us Get to Mars," listed manufacturing in space as the best way ISS is helping us get to Mars.[4]

- Recycler SBIR Awards — Includes SBIR phase I awards to recycle packaging materials (foam, bubble wrap, plastic bags, etc.) and a phase II SBIR for on-orbit demonstration to recycle 3D printed parts back into feedstock (see fig. 2).

Figure 2: Recycler for on-orbit demonstration as part of Phase II SBIR to recycle 3D-printed parts back into feedstock.

- STEM Outreach:
  - Future Engineers Program — The teen winner of the first challenge will see his or her part printed on the ISS as the first student-designed part ever 3D printed in space. The Future Engineers Program was awarded the American Society of Association Executives highest honor of the Summit Award for its meaningful impact and inspiration as a national STEM challenge, and was selected as the winner of the "Best Student Challenge" category for the Five Years of Excellence in Federal Challenge and Prize Competitions Awards.
  - NASA/GrabCAD Public Challenge — This challenge resulted in nearly 500 entries in three weeks, which was one of the largest GrabCAD challenge results to date.

References

1. NASA Johnson Space Center: "First Parts Manufactured in Space Video," <https://www.youtube.com/watch?v=gLY04N7chOs>, 2015.

2. Future Engineers Challenge and Winners, <www.futureengineers.org>, 2015.

3. GrabCAD, "NASA Handrail Clamp Assembly Challenge," <https://grabcad.com/challenges/nasa-handrail-clamp-assembly-challenge>, 2015.

4. NASA, "Top 10 Ways ISS is Helping Us Get to Mars," <https://www.nasa.gov/mission_pages/station/research/news/iss_helps_get_to_mars>, September 15, 2015.

Nuclear Thermal Propulsion

Project Manager(s)

Sonny Mitchell/ZP30
(256) 544–7306

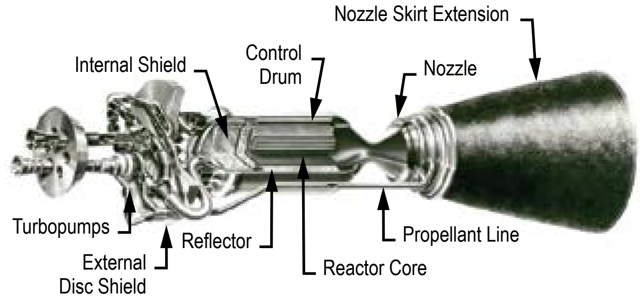
Michael G. Houts/ZP30
(256) 544–8136

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

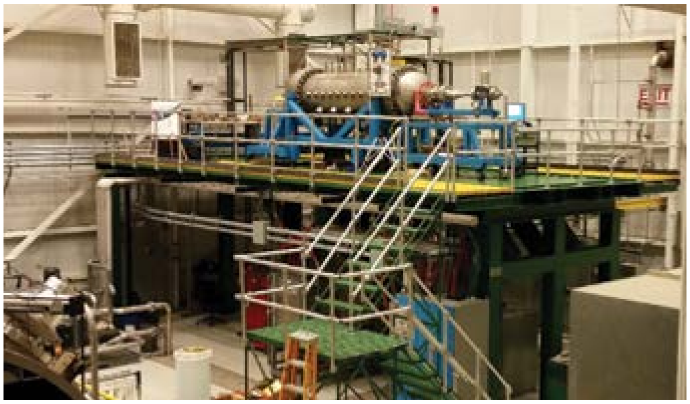
Project Description

Development efforts in the United States for nuclear thermal propulsion (NTP) systems began with Project Rover (1955–1973), which completed 22 high-power rocket reactor tests. Results indicated that an NTP system with a high thrust-to-weight ratio and a specific impulse >900 s would be feasible. John F. Kennedy, in his historic special address to Congress on the importance of space on May 25, 1961, said, “First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth…” This was accomplished. He also said, “Secondly… accelerate development of the Rover nuclear rocket. This gives promise of someday providing a means for even more exciting and ambitious exploration of space… to the very end of the solar system itself.” The current NTP project focuses on demonstrating the affordability and viability of a fully integrated NTP system with emphasis on fuel fabrication and testing and an affordable development and qualification strategy. The goal is to enable NTP to be considered a mainstream option for supporting human Mars missions and other missions beyond Earth’s orbit.



NTP engine schematic.

NTP fuel element fabrication.

(a)  (b) 

(a) NASA Marshall Space Flight Center test facility and (b) view of a recent fuel element test.

Anticipated Benefits

The fundamental capability of NTP is game changing for space exploration. A first generation NTP stage could provide high thrust at a specific impulse above 900 s, roughly double that of state-of-the-art chemical engines. The energy comes from fission, not chemical reactions, resulting in effectively unlimited energy density. NTP enables the shortest trip times to Mars and beyond, reducing astronaut exposure to galactic radiation and time in zero-g. An NTP system would require approximately four less Space Launch System (SLS) launches for a human Mars mission, potentially saving billions of dollars. The system would result in reduced propellant mass and an increase in payload capacity.

Mission Applications

Near-term NTP systems would provide a foundation for the development of significantly more advanced, higher performance systems. The role of NTP in the development of advanced nuclear propulsion systems could be analogous to the role of the DC-3 in the development of advanced aviation. Progress made under the NTP project could help enable both advanced NTP systems and advanced Nuclear Electric Propulsion. Combined with current technologies, the vision to go beyond the Moon and to the very end of the solar system can be realized with NTP.

Notable Accomplishments

Dedicated fuel materials and processing laboratories at Oak Ridge National Laboratory (ORNL) and NASA Marshall Space Flight Center (MSFC) have fabricated fuel elements of various materials (some incorporating depleted uranium) for testing. Recent tests of a graphite surrogate (hafnium) fuel element were run in the Environmental Test System (NTREES) test facility, achieving a temperature of 2,820 K in a flowing hydrogen environment. This type of testing can help resolve potential thermal hydraulic issues (including fuel endurance) while lowering cost and time needed to develop nuclear systems. Laboratories and test facilities at ORNL and MSFC are licensed to handle depleted uranium for fabrication and testing. Studies were completed examining various options for viable ground testing of an engine system. The use of low enriched uranium is being investigated to potentially reduce cost and schedule and increase programmatic flexibility.

References

Houts, M.: “The NASA Advanced Exploration Systems Nuclear Thermal Propulsion Project,” Paper Presented at 51st AIAA/SAE/ASEE Joint Propulsion Conference, Orlando, FL, July 27–29, 2015.

Autonomous Mission Operations EXPRESS

Project Manager(s)

Jeremy Frank/Ames Research Center
(650) 604–2524

Angie Haddock/EO40
(256) 544–6285

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

NASA's Advanced Exploration Systems Program-funded Autonomous Systems and Operations (ASO) project conducted an autonomous command and control experiment on board the International Space Station (ISS) that demonstrated single-action intelligent procedures for crew command and control. The experiment enabled crew initialization of a facility-class rack with power and thermal interfaces involving core and payload command and telemetry processing without support from ground controllers. This autonomous operations capability proved such scenarios as the initialization of a medical facility to respond to a crew medical emergency was representative of other spacecraft autonomy challenges. The experiment was conducted using the Expedite the Processing of Experiments for Space Station (EXPRESS) rack 7, which was located in the Port 2 location within the United States laboratory on board ISS. Activation and deactivation of this facility is time consuming and operationally intensive, requiring coordination of three flight control positions, 47 nominal steps, 57 commands, 276 telemetry checks, and coordination of multiple ISS systems (both core and payload). Utilization of Draper Laboratory's Timeliner® software, deployed on board ISS within the command and control computers and the payload computers, allowed the development of automated procedures specific to ISS without having to certify and employ novel software for procedure development and allowed development of the automated procedures specific to ISS without having to certify and employ novel software for procedure development and execution. The procedures contained the ground procedure logic and actions as possible to include fault detection and recovery capabilities. The autonomous operations concept includes a reduction of the amount of data a crew operator is required to verify during activation or deactivation, as well as integration of procedure execution status and relevant data in a single integrated display. During execution, the auto-procedures (via Timeliner) provide a step-by-step messaging paradigm and a high-level status upon termination. This messaging and high-level status are the only data generated for operator display. For this demonstration, the procedure was initiated and monitored from the ground. As the Timeliner sequences executed, their high-level execution status was written to Payload Multiplexer-Demultiplexer (PLMDM) memory. A future demonstration will be performed on board, with ISS astronauts initiating the operations instead of ground controllers. The AMO EXPRESS experiment demonstrated the activation and deactivation of EXPRESS rack 7, providing the capability of future single button activations and deactivations of facility-class racks. The experiment achieved numerous technical and operations 'firsts' for the ISS.

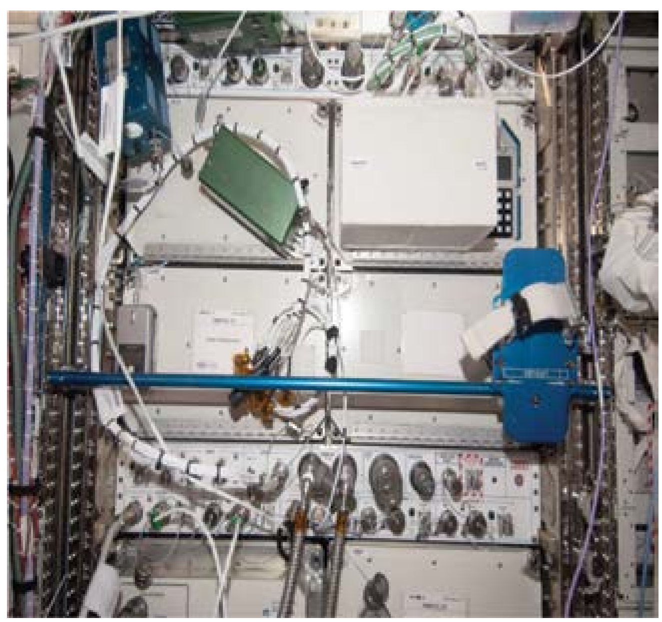


Figure 1: ISS EXPRESS rack 7.

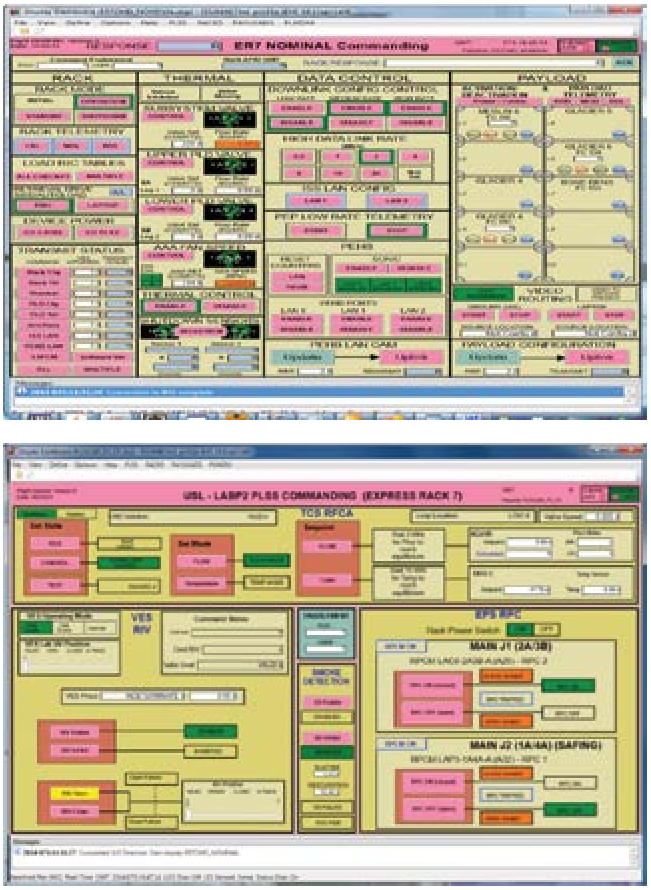


Figure 2: ISS EXPRESS rack ground commanding displays.

Anticipated Benefits

The successful development and implementation of intelligent auto-procedures proved that a significant spacecraft control function could be transferred from ground to onboard. More important, the demonstration showed that this function could be automated without incurring a significant increase of crew-tended manual procedures. The single-action activation and deactivation of the facility EXPRESS rack 7 shows that the current paradigm of console operator command procedures being duplicated by onboard auto-procedures can render the manual procedure obsolete.

Mission Applications

Mission applications include Deep Space Habitat operations, surface operations, and deep space vehicles.

Notable Accomplishments

We demonstrated software for autonomous operations on ISS to reduce the crew's dependence on ground-based mission control.

References

1. Stetson, H.K.; Haddock, A.T.; Frank, J.D.; et al.: "AMO EXPRESS: A Command and Control Experiment for Crew Autonomy Onboard the International Space Station," Paper Presented at AIAA SPACE 2015 Conference and Exposition, Pasadena, CA, August 31–September 2, 2015.

2. Haddock, A.T.; and Stetson, H.K.: "Advancing Autonomous Operations for Deep Space Vehicles," in *Proc. 13th AIAA International Space Operations Conference*, May 5–9, 2014, AIAA, Vol. 3, Pasadena, CA, pp. 2019–2029, AIAA 2014-1782, May 2014.

3. Frank, J.D.; Spirkovska, L.; McCann, R.; et al.: "Autonomous Mission Operations," in *Proc. 2013 IEEE Aerospace Conference*, March 2–9, 2013, IEEE, Big Sky, MT, pp. 3504–3523, doi:10.1109/AERO.2013.6496927, March 2013.

4. Stetson, H.K.; Knickerbocker, G.K.; Cruzen, CA.; and Haddock, A.T.: "The HAL 9000 Space Operating System," in *Proc. 2011 IEEE Aerospace Conference*, March 5–12, 2011, IEEE, Big Sky, MT, pp. 3887–3910, doi:10.1109/AERO.2011.5747602, March 2011.

5. Stetson, H.K.; Deitsch, D.K.; Cruzen, C.A.; and Haddock, A.T.: "Autonomous Payload Operations On Board the International Space Station," in *Proc. 2007 IEEE Aerospace Conference*, March 3–10, 2007, IEEE, Big Sky, MT, pp. 4413–4424, doi:10.1109/AERO.2007.352984, March 2007.

Delay/Disruption Tolerant Network

Project Manager(s)

Kelvin Nichols/EO50
(256) 544–0759

Lee Pitts/COLSA
(256) 544–0666

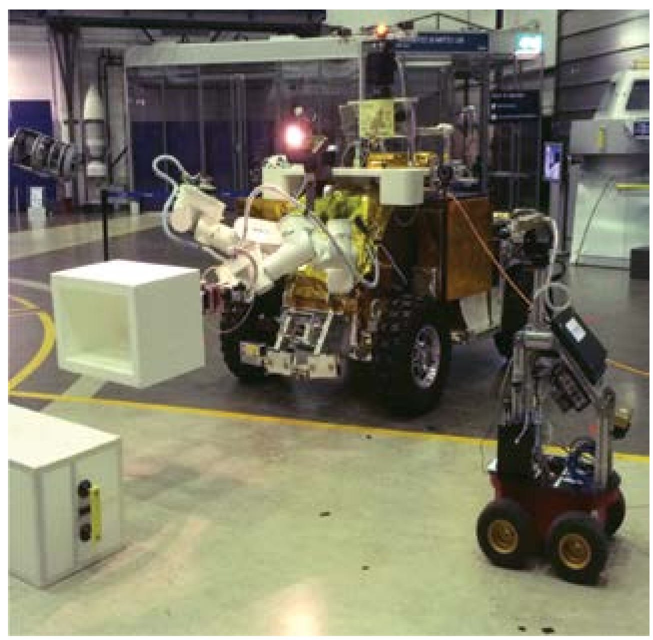
Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

The Delay/Disruption Tolerant Network (DTN) is a combination of protocols that are being developed to extend the terrestrial internet into low-Earth orbit (LEO) and deep space to help form the solar system internet. The ISS Payload Control Center located at the Huntsville Operations Support has been working with NASA Johnson Space Center and the European Space Agency (ESA) to support ESA as they evaluate the performance of DTN technology in their Multipurpose End-to-End Robotic Operation Network (METERON) suite of experiments. This year's METERON experiment was called the supervisory control of Eurobot (SUPVIS-E). During part of ESA astronaut Andreas Mogensen's 10-day stay on the International Space Station (ISS), he was able to conduct the SUPVIS-E experiment where he controlled a Eurobot rover located at the European Space Research and Technology Centre (ESTEC) ground facility from his control console onboard the ISS.

Astronaut controlling a Eurobot from ISS.



Eurobot with a companion rover at ESTEC.

Eurobot and the lunar lander repair mission.

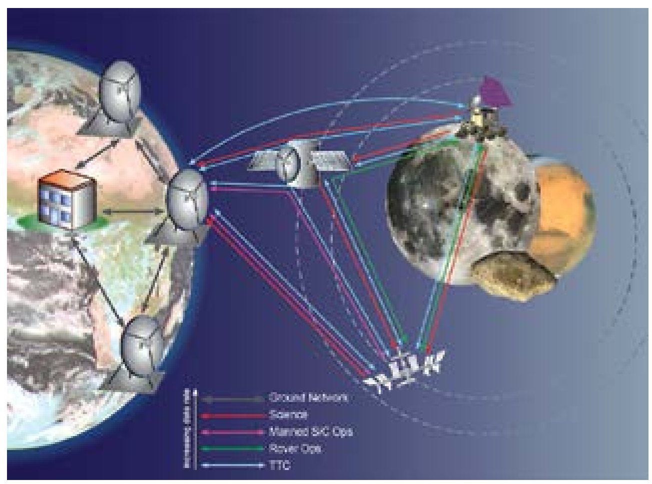
Anticipated Benefits

METERON is studying how astronauts in orbit over another planet or asteroid would respond to controlling robotic assets in a zero-g environment for future missions. Since DTN will be the backbone of the future solar system internet, ESA wants to study how the protocol will help with the low latency links between the orbiting outpost and the surface of the planet or asteroid below.

Notable Accomplishments

The operations had originally been scheduled to take place in three separate activities carried out over the course of two days. Everything ran smoothly during the first activity and ESA was able to execute the entire experiment in only one session.

ESA astronaut Andreas Mogensen was able to command the ESA Eurobot and walk it through a simulated lunar lander repair mission.



METERON operations concept.

References

European Space Agency: "Driving Eurobot from Space," <http://www.esa.int/spaceinvideos/Videos/2015/09/Driving_Eurobot_from_space>**,** August 09, 2015.

Lander Technologies

Project Manager(s)

Greg Chavers/FP30
(256) 544–0494

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

Since 2006, NASA has been formulating robotic missions to the lunar surface through programs and projects like the Robotic Lunar Exploration Program, Lunar Precursor Robotic Program, and the International Lunar Network. All of these efforts were led by NASA Marshall Space Flight Center (MSFC). Due to funding shortfalls, the lunar missions associated with these efforts, the designs, were not completed. From 2010 to 2013, the Robotic Lunar Lander Development Activity was funded by the Science Mission Directorate (SMD) to develop technologies that would enable and enhance robotic lunar surface missions at lower costs. In 2013, a requirements-driven, low-cost robotic lunar lander concept was developed for the Resource Prospector Mission. Beginning in 2014, Advanced Exploration Systems funded the lander team and established the MSFC, NASA's Johnson Space Center (JSC), Applied Physics Laboratory, and the Jet Propulsion Laboratory team, with MSFC leading the project. The lander concept to place a 300-kg rover on the lunar surface has been described in the New Technology Report Case No. MFS-33238-1. A low-cost lander concept for placing a robotic payload on the lunar surface is shown in figures 1 and 2. The NASA lander team has developed several lander concepts using common hardware and software to allow the lander to be configured for a specific mission need.

The Resource Prospector Mission baselined the low-cost lander concept and has sought to develop international partnerships to build and fly the prospector mission. Currently, Taiwan has requested the design drawings and is seeking to partner with NASA and the MSFC/JSC lander team to complete the design, build the lander, and fly to the lunar surface by year 2020.

Figure 1: Lunar lander with solid rocket braking motor and rover.

Figure 2: Lunar pallet lander only.

In addition, the lander technologies project continues to support the United States industry to encourage the commercialization of space, specifically the lunar surface. The Lunar Cargo Transportation and Landing by Soft Touchdown (CATALYST) initiative was started in 2014 with three partners (Moon Express, Astrobotic, and Masten Space Systems) to develop, test, and operate their lunar landers. The companies have three different concepts, shown in figures 3, 4, and 5, respectively.

The project also successfully tested a regenerative cooled chamber, measuring the heat flux of a system that utilizes liquid oxygen (LOX) and liquid methane (LCH_4) propellants. This chamber is the first regenerative cooled chamber using these propellents and is the first step in the development of a LOX/LCH_4 engine that will support multiple engines for future in-space missions that map to the NASA Evolvable Mars Campaign goals and objectives. Figure 6 shows the hot-fire test of the additively manufactured injector and regenerative cooled chamber.

Figure 3: Moon Express lander concept and hot-fire of main propulsion engine.

Figure 4: Astrobotic lander concept.

Figure 5: Masten Space Systems Xeus lander concept.

Figure 6: LOX/LCH$_4$ regenerative cool chamber hot-fire test.

The in-space engine (ISE100) is a 100-lbf thruster that operates using MMH and MON25 (fig. 7). The SMD funded this technology development for use on interplanetary missions (including landers) to reduce the heater requirements for propellants and to allow a high thrust-to-weight engine that requires low volume for packaging. The engine can operate with propellant temperatures as low as –40 °F. Two engines were manufactured during 2015 and delivered to NASA in preparation for qualification.

Figure 7: ISE100 fabricated and delivered in 2015.

Anticipated Benefits

Anticipated benefits of this project include low-cost lunar surface access for multiple missions, which feeds forward to large Mars landers. With the partnership of Taiwan, the Resource Prospector Mission enables a joint venture to design and build the lunar lander to enable the exploration of volatiles on the lunar surface that can be utilized in future in situ resource utilization demonstrators for Mars missions. The regenerative cooled chamber using these propellents is the first step in the development of a LOX/LCH$_4$ engine that will support multiple engines for future in-space missions that map to the NASA Evolvable Mars Campaign goals and objectives.

Mission Applications

Mission applications include lunar landers specifically targeted at exploration and in situ resource utilization demonstrators, Mars landers, and interplanetary missions.

Notable Accomplishments

Some of the notable accomplishments include the design of the low-cost robotic lunar lander with the prototype/engineering unit at the system level. Hot-fire test of the LOX/LCH$_4$ regenerative cooled chamber, Autonomous Landing Hazard Avoidance Technology (ALHAT) closed-loop free flight on Morpheus, and development of subsystems and components for lunar landers with an application for science and exploration missions are also accomplishments.

Near-Earth Asteroid Scout

Project Manager(s)

Leslie McNutt/FP30
(256) 544–1611

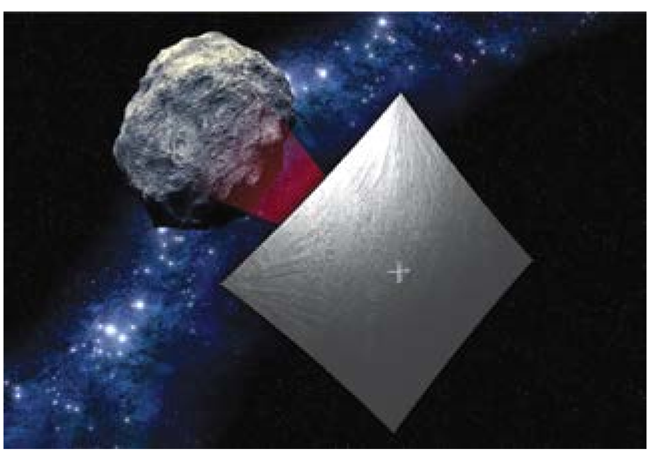
Les Johnson/ED04
(256) 544–7824

Sponsoring Program(s)

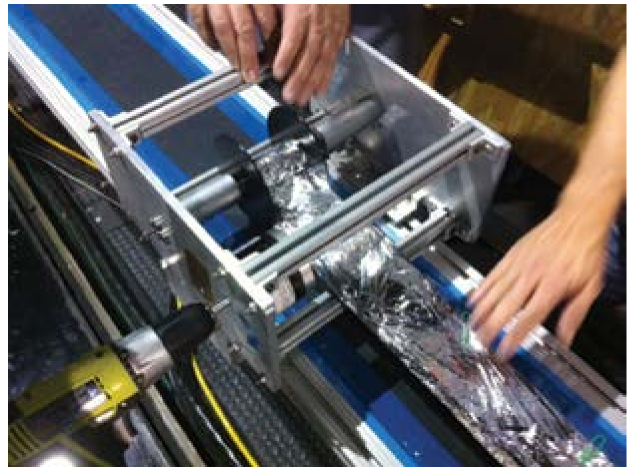
Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

The Near-Earth Asteroid Scout (NEAS) mission will survey and image a near-Earth asteroid (NEA) for possible future human exploration using a small satellite propelled by an 86-m^2 solar sail. NEAs are easily accessible asteroids in Earth's vicinity. As NASA continues to refine its plans to possibly explore these small worlds with human astronauts, initial reconnaissance with comparatively inexpensive robotic precursors is helpful. The NEAS will be secondary payload on Space Launch System (SLS) Exploration Mission-1 (EM-1), the first planned flight of the SLS and the second uncrewed test flight of the Orion Multipurpose Crew Vehicle. EM-1 is scheduled to launch in 2018.



Artist concept of the NEAS sailcraft surveying the target asteroid.



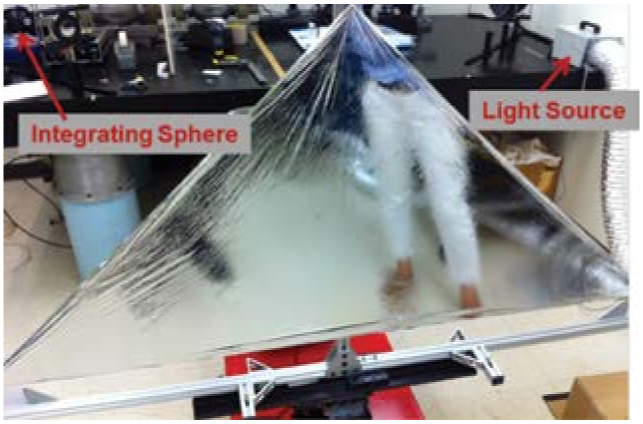
A full-scale solar sail quadrant was folded and rolled to fit on a flight-scale spool to test overall sail packing efficiency.

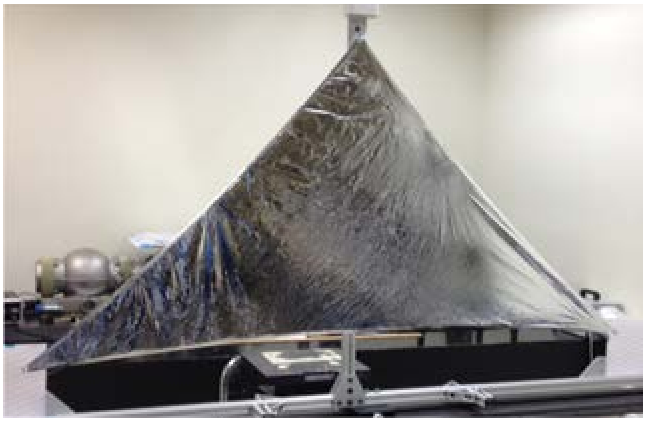
Anticipated Benefits

Obtaining and analyzing relevant data about NEAs via robotic precursors before committing a crew to them will significantly minimize crew and mission risk, as well as maximize exploration return potential. As the technology matures, solar sails will increasingly be used to enable science and exploration missions that are currently impossible or prohibitively expensive using traditional chemical and electric rockets. The NEAS will be NASA's first deep space solar sail mission and one of the least expensive interplanetary missions launched, paving the way for follow-on missions to additional NEAs and other deep space destinations.

Mission Applications

In addition to NEA reconnaissance, solar sail-propelled CubeSats and sail-propelled small spacecraft can be used to meet a host of NASA future mission needs, including missions of interest from the Heliophysics Decadal Survey such as Solar Polar Imager and Interstellar Probe.





Illumination and reflectance testing was conducted of subscale solar sail coupons.

Notable Accomplishments

The NEAS successfully completed its phase 0 and 1 Safety Reviews with the SLS Secondary Payload Safety Panel in January and September 2015, respectively. The phase 1 review was the final step in achieving preliminary design review maturity for the project.

The solar sail Engineering Development Unit design is complete and is being built. A commercialization plan for the solar sail has been developed and a commercial partner will likely be selected in early 2016.

References

Johnson, L.; Castillo-Rogez, J.; Cohen, B.; and McNutt, L.: "Solar Sail Propulsion for Interplanetary CubeSats," Paper Presented at AIAA Propulsion and Energy Conference 2015, Orlando, FL, July 27–29, 2015.

Johnson, L.; Castillo-Rogez, J.; Cohen, B.; and McNutt, L.: "NEA Scout and Lunar Flashlight: Two Near-Term Interplanetary Solar Sail Missions," Paper Presented at 9th AIAA Symposium on the Future of Space Exploration, Torino, Italy, July 7–9, 2015.

Life Support Systems

Project Manager(s)

Walter Schneider/FP10
(256) 544–0557

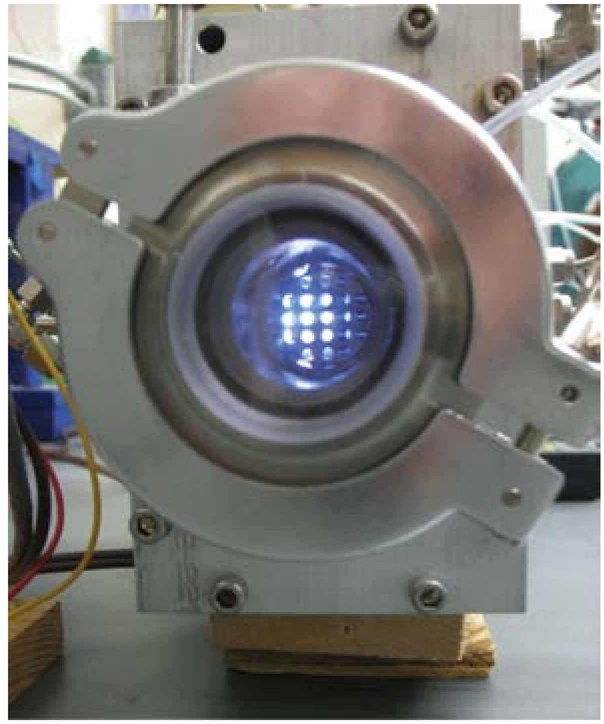
Sarah Shull/Johnson Space Center
(281) 244–6441

Sponsoring Program(s)

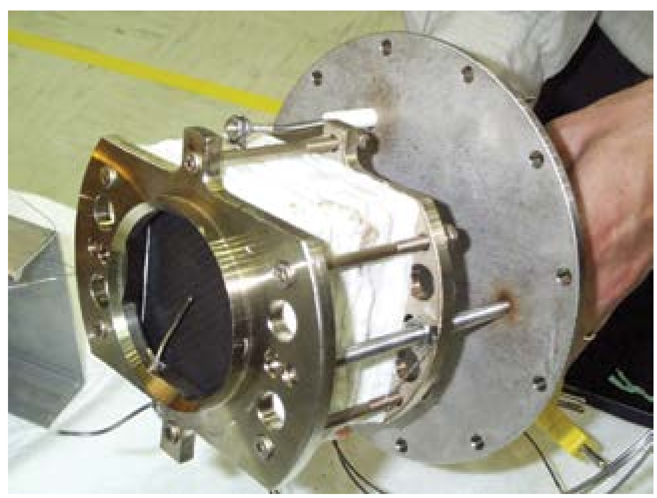
Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

The development of reliable, energy-efficient, and low-mass spacecraft systems to provide environmental control and life support is critical to enabling long-duration human missions beyond low-Earth orbit (LEO). The Human Exploration Framework Team identified high-reliability life support systems as a required technology for destinations beyond cis-lunar space. Highly reliable, closed-loop life support systems are among the capabilities required for the longer duration human space exploration missions assessed by NASA's Habitability Architecture Team. For life support, this means that there is the need for flexibility in enabling a safe, affordable, and sustainable human space exploration program. A strategy to achieve this necessary flexibility is to employ a common core architecture, with modularity as the key building block of human spacecraft and space habitat systems at the lowest functional level possible. Doing so can provide tangible nonrecurring and recurring cost reduction by minimizing destination-specific design development test and evaluation and sustaining infrastructures. The Life Support Systems (LSS) project is charged to advance environmental control and life support system technologies within the framework established by the Advanced Exploration Systems program office. The LSS project is a multi-Center project with project members from NASA's Ames Research Center, Glenn Research Center, Johnson Space Center, Jet Propulsion Laboratory, Marshall Space Flight Center (MSFC), and Kennedy Space Center.



Plasma pyrolysis assembly recovers hydrogen from the methane produced by the carbon dioxide reduction assembly/Sabatier, further enabling the recovery of oxygen from carbon dioxide.



Microlith® catalytic oxidizer is an ultra-compact, lightweight, fast light-off catalytic reactor with resistive heating capability for volatile organic compound trace contaminant control and other applications.

Integrated test chamber enables testing of LSS technologies in an environment that simulates human metabolic activity integrated with functional LSS hardware.

Anticipated Benefits

Because the International Space Station (ISS) resides in LEO, it can depend on consumables resupplies to maintain operations. Technologies being developed by the LSS project will allow deep space exploration without the need for consumables resupplies.

Mission Applications

Technologies developed under LSS support cis-lunar and deep space exploration.

Notable Accomplishments

MSFC accomplishments include a method to screen sorbents and desiccants used for carbon dioxide removal. The project will start screening sorbents and desiccants to determine the best materials to replace the ISS state of the art. Technologies for providing high-pressure and high-purity oxygen have been undergoing testing. A system that provides high-pressure oxygen eliminates the need to stow high-pressure oxygen tanks on the spacecraft. Testing of plasma pyrolysis and Bosch technologies to recover more oxygen continued. Other Centers' accomplishments on the project include design reviews and testing of a cascade distillation system for urine processing. Developments of brine technologies to recover more water were developed to a level where the technologies can be compared for a final technology selection. An aerosol sampler flight demonstration completed design reviews and preliminary testing. This hardware will be flown on the ISS to understand air particulates in spacecraft. The Spacecraft Atmosphere Monitor completed a Systems Requirement Review. This hardware will allow for real-time sampling of the spacecraft atmosphere without the need to return samples to Earth for analysis.

References

Gatens, R.L.; Anderson, M.S.; Broyan, J.L.; et al.: "National Aeronautics and Space Administration Environmental Control and Life Support Technology Development and Maturation for Exploration: 2014 to 2015 Overview," Paper Presented at 45th International Conference on Environmental Systems, Bellevue, WA, July 12–16, 2015.

Exploration Augmentation Module

Project Manager(s)

Lora Bailey/Johnson Space Center
(281) 483–8893

Larry Gagliano/FP50
(256) 684–1887

Sponsoring Program(s)

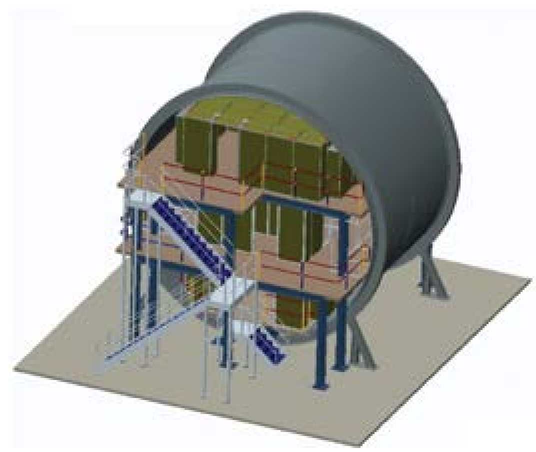
Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

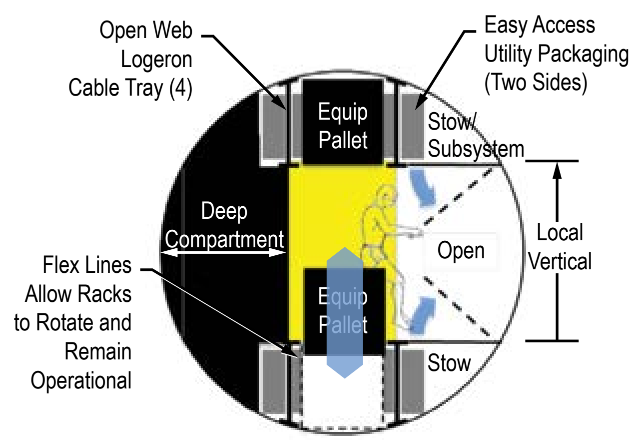
This project focuses on the development of flight-ready elements of a habitation capability to enable extended duration missions for Orion in cis-lunar space with extensibility beyond deep space habitat concept demonstrator development. This project will develop, integrate, and evaluate exploration system technologies needed to advance NASA's understanding of alternative beyond-Earth orbit vehicle architectures, requirements, and Earth-independent operational concepts. The 2015 effort was focused on the construction of an 8.4-m-diameter deep space habitat concept demonstrator developed through Advanced Concept Office trade studies, concentrating on transit and surface habitat commonality assessments. The objectives included construction completion and Human Factors Engineering assessments of the habitat volumes. The demonstrator is used to evaluate and refine the interior layout, subsystem development, and assembly of large-diameter habitat concepts designed to utilize the Space Launch System vehicle.

Large-diameter habitats offer unique opportunities for developing next generation subsystem design and integration, radiation protection studies, logistics stowage trades, and crew habitation assessments. Full-scale concept demonstrators provide a means to showcase design layout and new technologies needed to live and work safely during long-duration exploration missions of cis-lunar space, near-Earth asteroids, and destinations such as Mars. Modular design and construction principles provide flexibility for low-cost reconfiguration of volumes, allowing evaluation of multiple configurations resulting in system and space optimization, increased crew efficiency and safety, and reduced development cost.

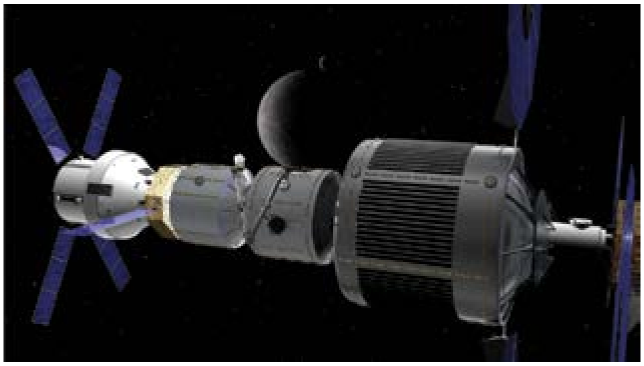
Concept demonstrators also provide a tangible platform for conveying the large-scale habitat architecture approach and fostering collaborative efforts among key stakeholders and engineering disciplines.



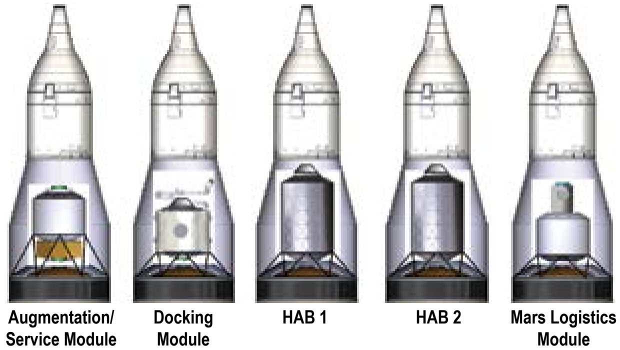
8.4-m-diameter deep space habitat CAD model.



Habitat interior layout configurations.



Conceptual cis-lunar transit architecture.



Habitat configuration studies.

Notable Accomplishments

Some notable accomplishments included the completion of the primary structure and access to all levels. Completion of a baselined layout resulted in the delivery of fabrication and assembly models. Materials needed to complete the physical layout for all levels and work volumes were procured. Several physical volumetric and worksite assessments were conducted. These assessments led to design modifications and layout improvements.

Several habitat design observations have been delivered and are under review. Draft habitat System Requirements Specification and Concept of Operations documents were generated.

A partnership was developed with the High Schools United and NASA to Create Hardware (HUNCH) program to deliver hardware and gain young perspectives regarding actual design projects and inspire future designers/engineers to seek careers in the aerospace industry. The demonstrator provided a tangible platform for conveying a large-scale habitat architecture approach and fostering collaborative efforts among key stakeholders and engineering disciplines.

Automated Propellant Loading

Project Manager(s)

Robert G. Johnson/Kennedy Space Center
(321) 867–7373

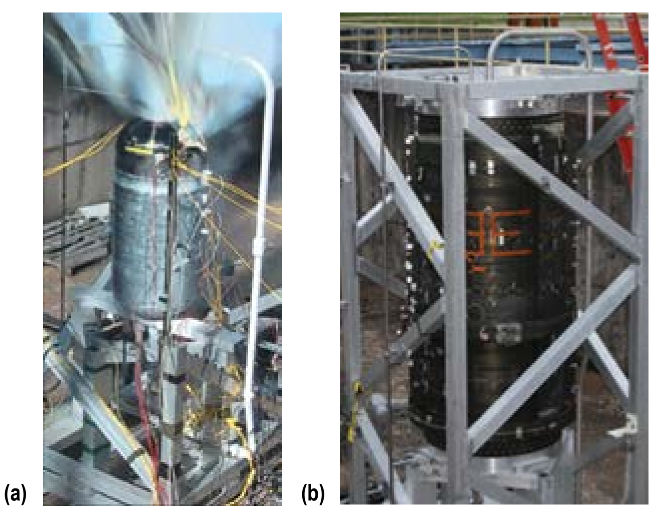
Curtis E. Banks/ES35
(256) 544–4437

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

The objective of the Automated Liquid Hydrogen Liquefaction and Storage effort is twofold. First, it is necessary to evaluate the performance of all composite pressure vessels at liquid nitrogen (LN_2) temperatures while going to failure. The second objective is to develop and apply structural health monitoring (SHM) sensors at LN_2 temperatures to quantify any structural damage while going toward failure or simply to maintain structural integrity prior to use and while in use.



(a) LN_2 spewing out of the dome of an all-composite tank pressure vessel and (b) an Air Force Research fuel tank in a testing frame. The tank has several SHM sensors attached.

Anticipated Benefits

The SHM sensory system is an enabling technology that will allow engineers to monitor the health of carbon composite components and large structures. Composite structures are very important to NASA's future missions because of their weight-saving benefits and very high tensile strength. However, because of the nature of these structures, they are subject to impacts, delamination, and other unintended damages. Any damage to the structure can decrease its loadbearing capability, which may cause a catastrophic or premature failure.

Currently, technicians are required to spend hours inspecting a structure for flaws or mishaps. The state of the art uses flash thermography, laser shearography, or ultrasonic sensing to identify and locate flaws. Each of these techniques can be very time consuming, particularly if the structure is very large.

A composite structure with an SHM sensory system and proper diagnostic software attached to it can identify the location of flaws, quantify the impact energy, and pinpoint an inspector to the location of an incident for further inspection, thus reducing the number of man hours required to properly qualify a structure or component for further use. SHM therefore becomes an enabling technology for safe use of composite as well as maximizing its designed specification.

Mission Applications

Currently, no SHM sensors are applied to composite structures or components. However, it is a technology gap particularly for components such as composite overwrap pressure vessels (COPVs) that are on the International Space Station. These vessels are buried in the station and cannot readily be inspected for damage. Engineers must decrease the operating pressure in order to safely maintain safety and mission assurance. An SHM system applied to these vessels would maximize these components' design specifications.

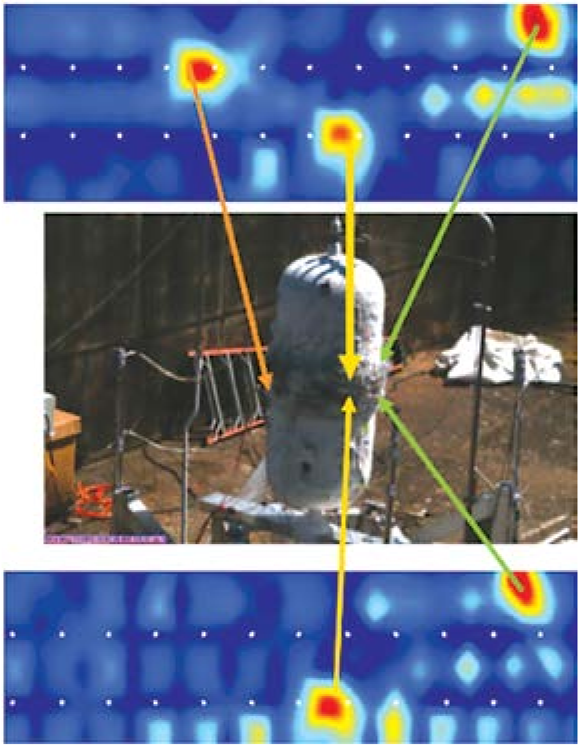
Likewise, SpaceX, which is developing launch capabilities for low-Earth orbit (LEO), has COPV components that can be monitored with SHM sensory technology.

All future deep space manned missions that seek to utilize composite and reinforced composite components will need to apply SHM sensors to safely fly and return crew and cargo to LEO and to Earth.

Notable Accomplishments

NASA's Marshall Space Flight Center (MSFC), Kennedy Space Center, Armstrong Flight Research Center, and Glenn Research Center all worked together across Centers to successfully test three 100-gallon composite tanks. Each Center contributed manpower and expertise to evaluate composite tank performance at LN_2 temperatures and a suite of SHM sensory technology. The testing was performed at MSFC in the East Test Area. MSFC/ES35 was responsible for the test sequence to evaluate the SHM sensor, as well as two of the four sensory technologies: fiber optic strain sensors and Acellent SMART Layer® piezoelectric lamb wave sensors.

Each technology performed well at LN_2 temperatures, but the fiber optics suffered from sensor application. The Acellent detected damage in the composite prior to failure. The finding was validated by the benchmark sensor and acoustic emission.



Acellent SMART Layer responding to damage in the overwrap prior to ultimate failure.

Autonomous Fluid Transfer System

Project Manager(s)

Jeremy Frank/Ames Research Center
(650) 604–2524

Angie Haddock/EO40
(256) 544–6285

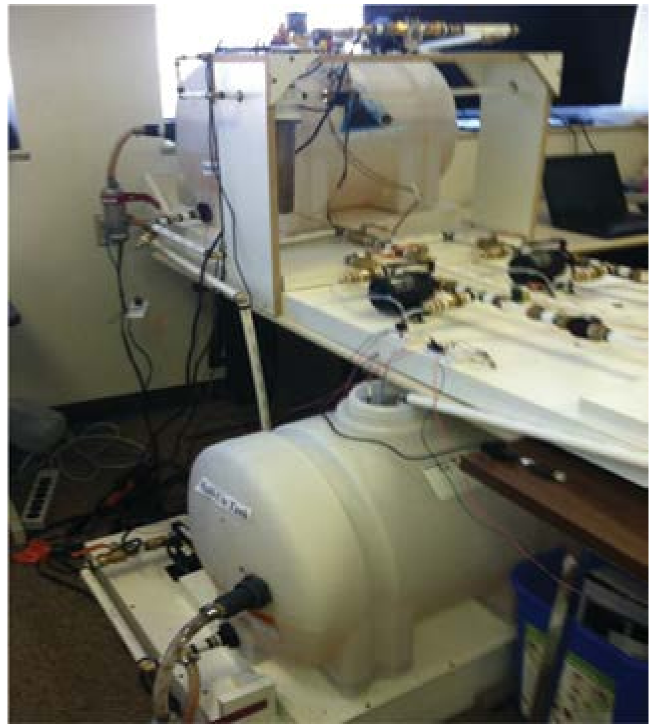
Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

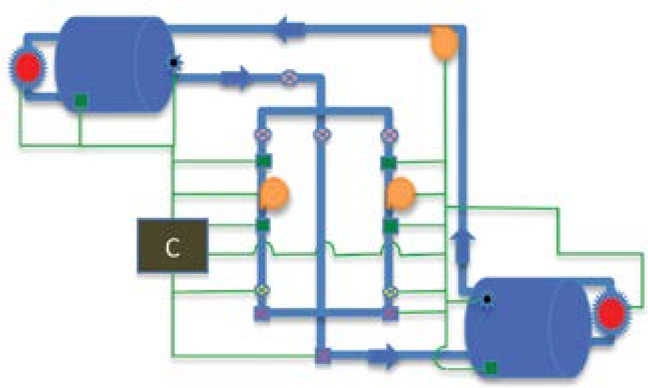
Project Description

The Autonomous Fluid Transfer System (AFTS) consists of two fluid tanks, one for a source of supply connected to one for multi-use. There are two commandable transfer legs, a commandable return transfer leg, and one manual leg for pure manual operations. Each tank contains a pressure sensor at the bottom of the tank, a temperature sensor, and a fluid heater that is interfaced with each tank at approximately the ¾-level up from the bottom. Each commandable transfer leg contains a fluid pump, pressure sensors before and after each pump, and a flow meter after the pump. An additional third flow meter is placed just before the multi-tank for fault tolerance of either transfer leg. The return leg, which transfers fluid from the multi-tank to the supply tank, has a single commandable pump, which is used simply to return fluid back to the supply tank. The return leg is semiautomated since there are no flow meters or pressure sensors in use on this transfer leg. This system architecture allows a single fault tolerance as to transfer leg pump failures and flow meter failures. The manual transfer leg then adds an additional fault tolerance when both the primary and backup transfer legs have been failed.

We desired the crew to operate the AFTS with 'single-button' functions in a 'fire and forget' fashion. The functions must perform the activity, monitor the system during the activity, detect any failures of the subsystem, isolate failures, and recover the original function that was requested by the crew through to completion.



Autonomous Fluid Transfer System.



System layout.

The intelligence of each function or activity was to be embedded within the transfer procedures. Since this was a fluid transfer subsystem, the functions would involve the transference of fluid in preselectable quantities and optional crew input quantities. The operational activities selected were quarter-tank, half-tank, full-tank, and a crew-selectable number of gallons transferred over the primary, backup, and return transfer legs of the AFTS. Since the AFTS contains fluid heaters, a 'set temperature' function was also developed. During nominal space flight operations, flight rules, payload regulations, and safety rules are continually monitored during operations; today, these rules are monitored by the ground, and potential or actual problems are detected and responded to by the ground. We developed an autonomous monitoring system that is employed for flight and safety rule autonomous monitoring and response for further enhancement and demonstration of ground operations movement to onboard capabilities. Further safety controls were created such as single-button AFTS safing, where only one crew action is required to safe the complete testbed.

Anticipated Benefits

The software system design utilizing Timeliner-TLX™ demonstrates the ability to move ground operations to onboard automated and autonomous operations for crew access. This capability will be required for manned deep space missions.

Mission Applications

Mission applications include Deep Space Habitat operations, surface operations, and deep space vehicles.

Notable Accomplishments

The first automated and autonomous procedure system that employs fault detection, isolation, and recovery was created.

References

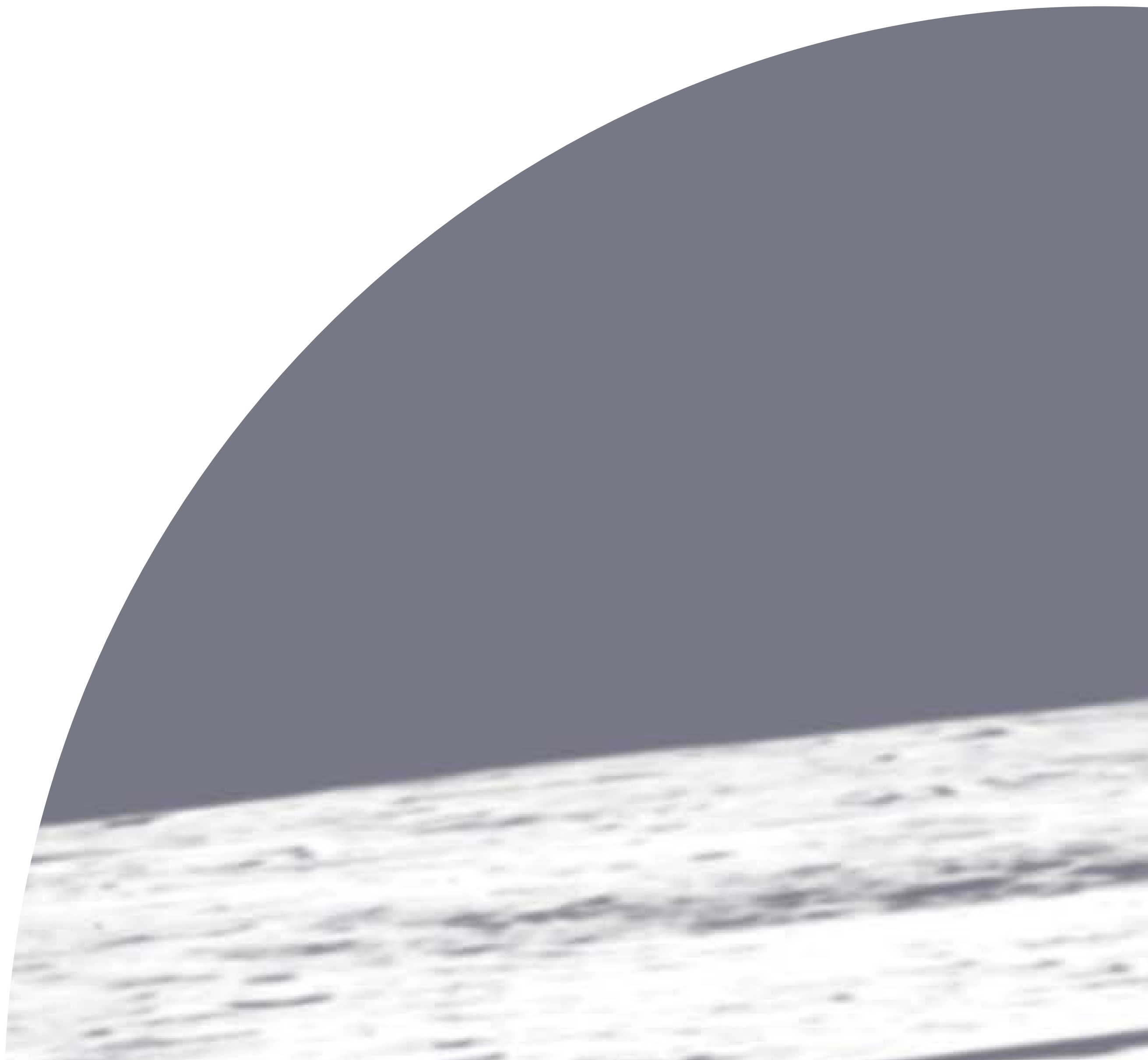
Haddock, A.T.; and Stetson, H.K.: "Advancing Autonomous Operations for Deep Space Vehicles," in *Proc. 13th AIAA International Space Operations Conference*, May 5–9, 2014, AIAA, Vol. 3, Pasadena, CA, pp. 2019–2029, AIAA 2014-1782, May 2014.

Haddock, A.T.; and Stetson, H.K.: "Automated Operations Development for Advanced Exploration Systems," in *Proc. 12th AIAA International Space Operations Conference*, June 11–14, 2012, AIAA, Vol. 1, Stockholm, Sweden, pp. 599–607, June 2012.

Stetson, H.K.; Watson, M.D.; and Shaughnessy, R.: "The HAL 9000 Space Operating System Real-Time Planning Engine Design and Operations Requirements," in *Proc. 12th AIAA International Space Operations Conference*, June 11–14, 2012, AIAA, Vol. 1, Stockholm, Sweden, pp. 586–598, June 2012.

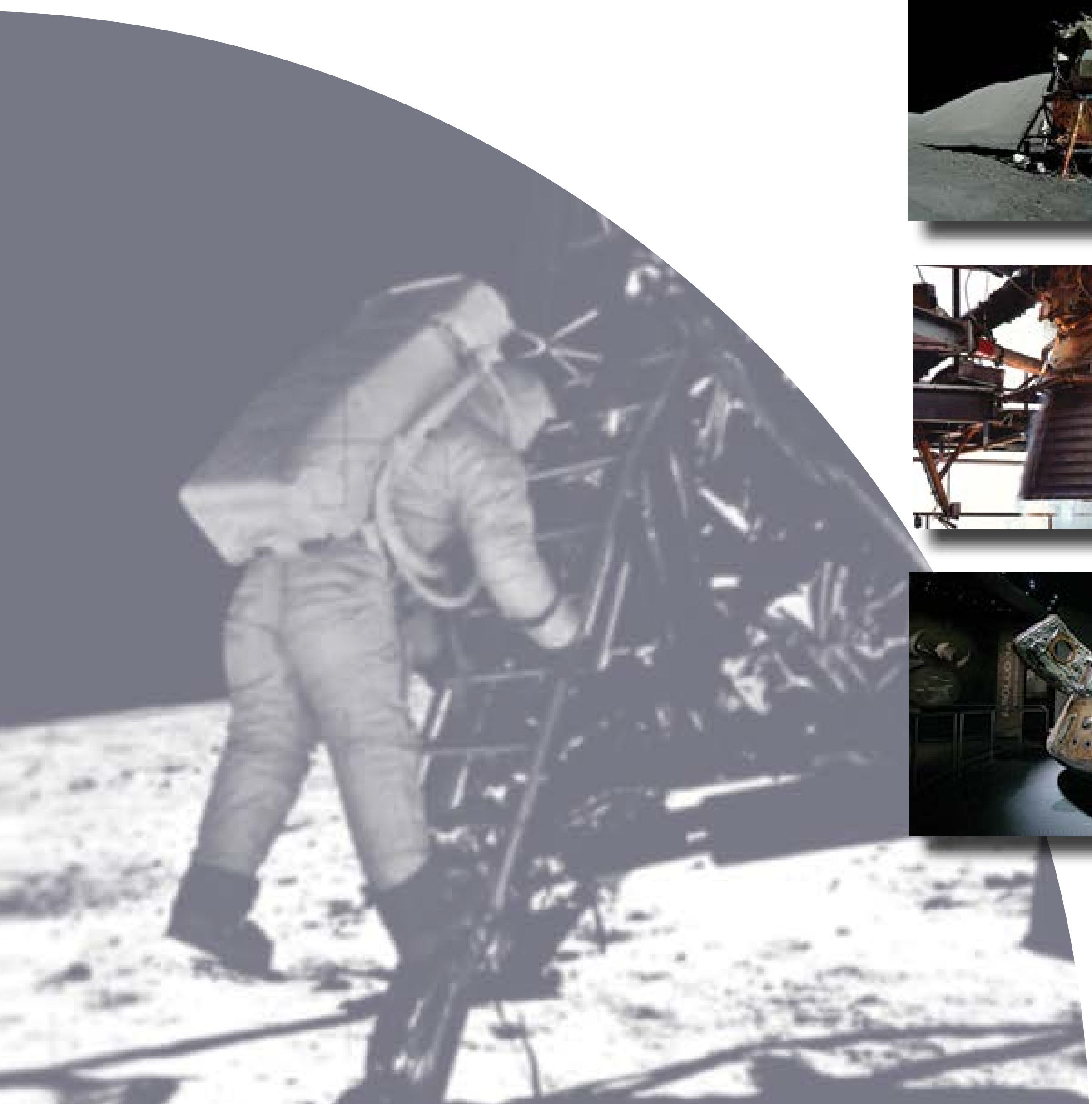
Stetson, H.K.; Knickerbocker, G.K.; Cruzen, CA.; and Haddock, A.T.: "The HAL 9000 Space Operating System," in *Proc. 2011 IEEE Aerospace Conference*, March 5–12, 2011, IEEE, Big Sky, MT, pp. 3887–3910, doi:10.1109/AERO.2011.5747602, March 2011.

Stetson, H.K.; Deitsch, D.K.; Cruzen, C.A.; and Haddock, A.T.: "Autonomous Payload Operations On Board the International Space Station," in *Proc. 2007 IEEE Aerospace Conference*, March 3–10, 2007, IEEE, Big Sky, MT, pp. 4413–4424, doi:10.1109/AERO.2007.352984, March 2007.



Human Exploration and Operations
Mission Directorate

Space Launch System Advanced Development



Additively Manufactured Propellant Ducts and Manifold

Project Manager(s)

Elizabeth Robertson/ER21
(256) 544–9692

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The purpose of this effort was to design, fabricate, and test Inconel® 625 propellant ducts and manifolds. Tasks included using both the selective laser melting (SLM) and laser deposition technology (LDT) fabrication processes, as well as performing weld trials and material testing. Some of the potential benefits from this task were as follows:

- Affordability—Expected cost reduction of 25%, with a 50% reduction in schedule. Reduces touch labor from the traditional bending process.

- Reliability—Increased reliability due to reducing all or most weld joints within a duct or manifold. Fabrication process does not result in wall thinning in a bend section.

- Performance—Reduction in weight based on allowing a variable wall thickness within the duct or manifold. Ability to design in required stiffness or flexibility by varying wall thickness. Ability to include complicated pressure reducing or flow straightening geometry (fins, veins, etc.) within the part during the build.

The technical steps taken are to leverage the first fabrication demonstrator unit built in FY 2013, then design and build two LDT propellant ducts (fig. 1), two SLM propellant ducts, and two LDT main combustion chamber manifolds, and then improve the surface finish of one of each article built using a micropolishing or extrusion honing technique.

Notable Accomplishments

- Completed fabrication and proof pressure tests of fuel and oxidizer turbine bowls:
  - Fuel bowl: 5 cycles at 250 psig (115 psig operating).
  - Liquid oxygen bowl: 5 cycles at 215 psig (110 psig operating).

- Fuel turbopump:
  - Balanced rotor assembly.
  - Passed torque checks.
  - Component testing complete (completed 15 tests).
  - Methane chill test performed.

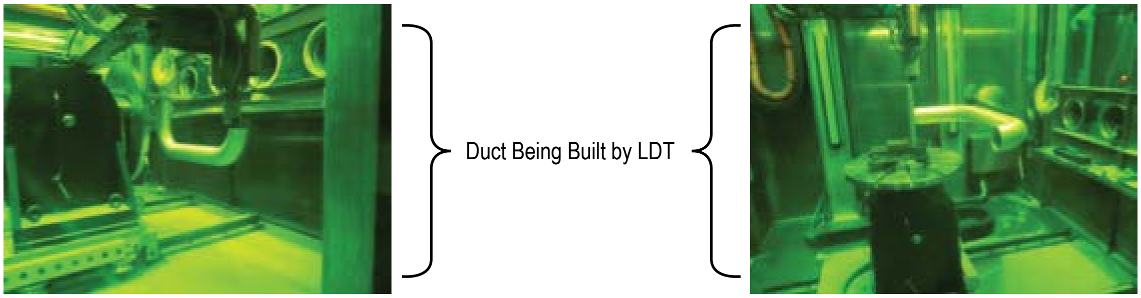


Figure 1: LDT-built propellant ducts.

Advanced Manufacturing of Lightweight Carbon-Carbon Nozzle Extensions for Upper Stage Engines

Project Manager(s)

Pete Valentine/EM41
(256) 544–2837

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task builds upon recent small NASA Marshall Space Flight Center (MSFC) efforts to develop a new type of carbon-carbon composite for upper stage engine nozzle extensions. This technology is also applicable to solid motors and first stages. Some of the potential benefits from this task are:

- Enables mass savings ≥50% (200–300 lb).
- Enables cost savings ≥50% (≥$0.5 million).
- Greatly improves thermal margins (≈1,000 °F).

The technical approach is being taken to partner three MSFC Engineering Directorate labs/departments (EM, ER, and ES) and three small businesses (Materials Research and Design (MR&D), Southern Research Institute (SRI), and Carbon-Carbon Advanced Technologies, Inc. (C-CAT)), each of which is the U.S. leader in their respective technologies. MSFC facilities to be used would include mechanical and thermal testing (EM10), nondestructive evaluation (EM20 and ES43), and microscopy (EM30). The primary effort is the Nozzle Extension Tag-End Ring Mechanical and Thermal Evaluations task and the Fabrication of Lyocell-Based Carbon-Carbon for Material Property Database Development task.

Notable Accomplishments

The specific accomplishments during 2015 were as follows:

- Nozzle Extension Tag-End Ring Mechanical and Thermal Evaluations task:
  - Completed nondestructive evaluations of nozzle extension tag-end rings via five methods.
  - Completed analytical assessment of hoop tension ring specimen design and loading method for testing. (Note: Analysis performed by MR&D.)
  - Completed preparation of cutting plans for carbon-carbon tag-end rings. (Rings were fabricated by C-CAT.)

- Fabrication of Lyocell-Based Carbon-Carbon for Material Property Database Development task:
  - Completed weaving of lyocell fabric at Highland Industries, Inc.
  - Began fabrication of lyocell carbonization oil wringer at Buckeye Machine Fabricators, Inc. (Note: A new oil wringer is being fabricated through collaboration with the U.S. Navy and the Missile Defense Agency.)

Computed Tomography Sensitivity Verification for Selective Laser Melting Space Launch System Engine Components

Project Manager(s)

James Walker/EM20
(256) 961–1784

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task will focus on understanding the detection sensitivity of the computed tomography (CT) system for finding critical defects and also for providing dimensional measurements in additive manufacturing (AM) Space Launch System (SLS) engine components, specifically selective laser melting (SLM) parts. The goal of this task is to provide a quantified assessment of CT nondestructive evaluation (NDE) for AM SLS engine components to help ensure their reliability and affordability.

This task plans to provide the following technical deliverables:

- The determination of the detection sensitivity of CT x-rays for finding critical defects in AM materials and structures.
- Continue mechanical evaluation of defects in Inconel® AM parts.
- Provide the protocol for making dimensional measurements in AM SLS flight-like low-Earth orbit engine components using CT- and SL-rendered software models facilitated by gauge standards.
- Provide 'as-built' renderings to compare to engineering drawings.

Notable Accomplishments

The key conclusions arrived at from this task are:

- The practical CT resolution appears to be at or near 0.010 inches.
  - Tested on aluminum and Inconel.
  - Tested on both high- and low-energy 'micro-focus' systems.
  - Encompasses many SLS engine components.
- The modular reference standard concept works well and provides a lot of flexibility in assessing NDE performance.
  - Will allow testing of a wide range of defect types and orientations for SLS engine components.
  - Next generation 'cylindrical' reference standard will expand on this capability.
- Some of the ideas from the gauge blocks and modular reference standard may work their way into the new ASTM guideline on AM NDE that NASA Marshall Space Flight Center is helping write.
- Many commercially available CT systems exist. The critical factor will be determining the range of part sizes that must be covered, which will drive the amount of x-ray energy required, and critical defect sizes, which will drive the focal spot size.

Solid-State Ultracapacitor to Replace Batteries

Project Manager(s)

Terry Rolin/ES43
(256) 544–5579

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate Space Launch System Advanced Development

Project Description

This task was for research and development activities leading to a solid-state ultracapacitor to replace batteries. The task was focused on internal barrier layer capacitor structures composed of barium titanate (BT) coated with various materials using atomic layer deposition (ALD) techniques. Hybrid approaches using polymer/ceramic mixes as well as material doping were considered. Single-layer ultracapacitor cells were fabricated and tested. The tasks were divided into the following four separate areas:

(1) Evaluate spark plasma sintering at the Oak Ridge National Laboratory (ORNL).
(2) Evaluate zirconia and titania coatings over BT.
(3) Evaluate polyimide/BT hybrid ultracapacitor cells.
(4) Evaluate single-layer ultracapacitor cells.

Notable Accomplishments

The accomplishments were as follows:

- Evaluation of the Spark Plasma Sintering at ORNL task was completed. The team spent a week at ORNL fabricating ultracapacitors from coated BT powders. These were then tested at NASA Marshall Space Flight Center (MSFC) and more thoroughly by Auburn University. The technique shows great promise, as giant permittivity was observed; however, other ultracapacitor properties are not yet desirable, so more experimentation in the future is to be conducted. A spinoff benefit from this research was that the NASA Nuclear Fuel team leveraged the ORNL funding to conduct initial experiments on surrogate nuclear fuel material and had excellent results. This process was pursued so that MSFC may get the capability in-house, which will expedite future densification studies and nuclear propulsion.

- A complete evaluation of zirconia as an alternate coating was conducted. The findings from MSFC and Auburn University show an inconsistent coating from the current coating vendor. To get around this issue, a new ALD vendor at North Carolina State University (VaporPulse) has been contracted so that their process can be evaluated.

- A substantial amount of research in evaluating composite polyimide/BT dielectric materials was carried out. This research also included the development of new 3D printing processes and materials. Another spinoff research benefit is that a new, unique low-temperature silver (Ag) electrode ink was developed that has great potential not only for ultracapacitors, but for all 3D circuit printing in the future (fig. 1). This new ink is expected to solve the problem of coating diffusion into the core. Ultracapacitor samples with ALD-coated BT in solution with the polyimide were constructed and underwent initial testing with promising results.

- Evaluation of many variations of the single-layer ultracapacitor cell was completed with dielectric inks formulated from the various ALD-coated BT and doped perovskite ceramic materials; see figure 2. Some of these showed excellent ultracapacitor properties. A number of new processes to optimize the processing and development of materials for ultracapacitors were also developed, including 3D and additive printing, new low-temperature curing, and submicron powder milling with vibratory mill.

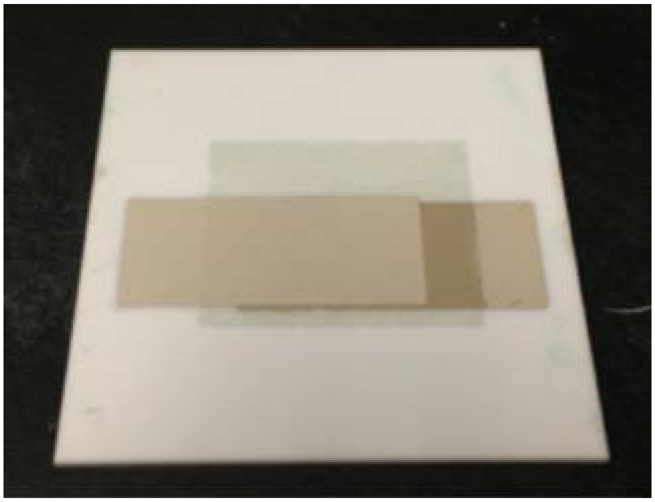


Figure 1: Composite ultracapacitor with new Ag ink.

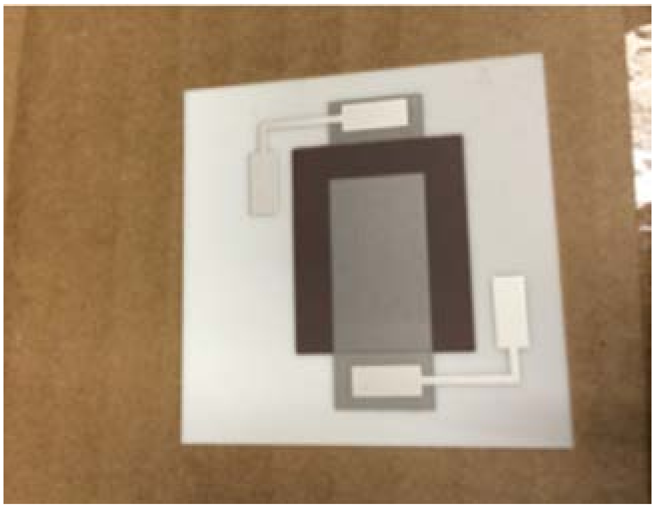


Figure 2: Ultracapacitor device from doped BT materials.

- Titania ALD coatings were evaluated. Ultracapacitor samples with more dielectric formulations were developed. Evaluations of many variations of the single-layer ultracapacitor cell were completed with dielectric inks formulated from the various ALD-coated BT and doped perovskite ceramic materials. Variations of the single-layer ultracapacitor cells with dielectric inks were formulated from the various ALD-coated BT and doped perovskite ceramic materials.

- Ultracapacitors with calculated energy densities exceeding 8 J/cc have been produced. Devices have shown charging times in milliseconds, breakdown voltages as high as 900 V in a 30-µN layer, and demonstrated the ability to activate light-emitting diodes.

- Research in ultracapacitor technology has resulted in the submission of three patent applications and discovery of two spin-off technologies.
  - The spin-offs include creation of a low-temperature conductor ink that was not commercially available and the construction of an ultrasensitive ceramic humidity sensor element that is only 30 µN thick. (This is currently being tested by a commercial humidity sensor vendor to replace their product line with help from MSFC's Technology Transfer Office.)

- Thus far, MSFC has developed many of the sample sets for The University of Alabama Huntsville to begin testing. Early test data are already showing that pretreatment versus post-treatment is one area critical for increasing capacitance.

Lattice Boltzmann Method for Modeling Cryogenic Stage Zero-G Propellant Dynamics

Project Manager(s)

Joseph Powers/EV41
(256) 544–8513

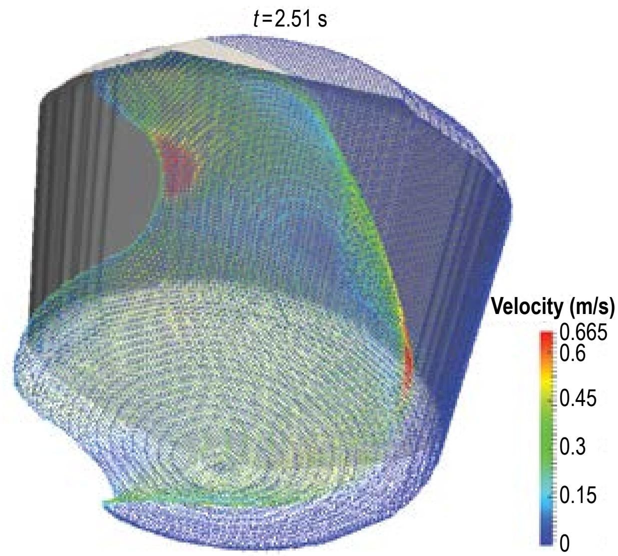
Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

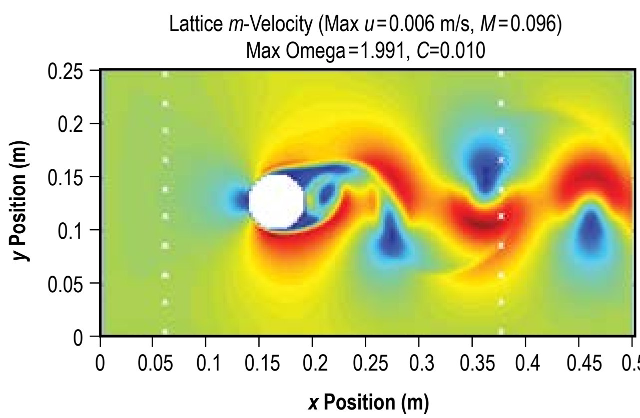
Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task involved developing a new capability to predict liquid propellant sloshing/bulk motion effects on the spacecraft vehicle dynamics in low-g environments associated with flight conditions such as loiter, startup/shutdown transients, and during maneuvering. Accurate modeling of the coupled dynamic behavior of liquid propellants in the low-g environment is crucial to mitigating risks such as undesirable liquid venting and interaction with the spacecraft attitude control system. Nonlinear effects due to a changing acceleration field perturb the integrated spacecraft-liquid dynamics and must be evaluated in flight mechanics simulations. The Lattice Boltzmann method (LBM) has recently emerged as a promising alternative to traditional computational fluid dynamics (CFD) techniques due to its high computational efficiency, which may allow liquid models to be integrated with simulations of spacecraft dynamics rather than run offline. Integration of CFD with guidance, navigation, and control flight mechanics simulations would enable an unprecedented capability for preventing adverse fluid-vehicle interaction. A 2D, two-phase LBM flow solver was developed for a proof-of-concept rapid, parallelizable, coupled vehicle-fluid simulation of free surface flows in spacecraft propellant tanks in microgravity and time-varying acceleration fields.



Zero-g fluid transient response in 0.5-m tank.



Velocity magnitude of unsteady flow over a circular cylinder using the 2D multiple relaxation time formulation at *Re* = 1,000.

Notable Accomplishments

The following have been accomplished for this task:

- A single-component multiphase (SCMP) proof-of-concept flow solver was developed and tested in MATLAB®.
- Explored verification using standard test conditions (e.g., cylinder unsteady flow).
- Implemented the multiple relaxation time turbulence model using D3Q19 lattice.
- Implemented different equations of state to investigate stability properties.
- Conducted additional analysis into acoustic effects (LBM is a compressible flow solver).
- Investigated adaptive time stepping for better run-time.
- Successfully demonstrated stable 3D multiphase flow.
- Activity produced a solid foundation of research data that could facilitate transition of the NASA Marshall Space Flight Center flow solver capability to a production tool using advanced parallel processing hardware and software.

Hot-Fire Test of Liquid Oxygen/Hydrogen Selective Laser Melting Injector Applicable to the Exploration Upper Stage

Project Manager(s)

Elizabeth Robertson/ER21
(256) 544–9692

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task was to hot-fire test an existing selective laser melting (SLM) injector that is applicable for all expander cycle engines being considered for the exploration upper stage. The work leverages investment made in FY 2013 that was used to additively manufacture three injectors (fig. 1), all by different vendors.

Figure 1: Manufactured liquid oxygen/hydrogen SLM injectors.

Notable Accomplishments

Accomplishments include selecting two of the injectors to use for hot-fire testing and completing the following tasks:

- Performed nondestructive evaluation on the original SLM injectors.
- Completed water flow testing (fig. 2).
- Fabricated the ablative chambers used to support testing.
- Test facility buildup, wrote the test requirements document, and successfully completed the test readiness review.
- Completed six hot fire tests (fig. 2).

Figure 2: Water flow and hot-fire testing of two liquid oxygen/hydrogen SLM injectors.

Testing of Selective Laser Melting Turbomachinery Applicable to the Exploration Upper Stage

Project Manager(s)

Elizabeth Robertson/ER21
(256) 544–9692

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task was to design, fabricate, and spin test to failure a Ti6-4 hydrogen turbopump impeller that was built using the selective laser melting (SLM) fabrication process (fig. 1). The impeller is sized around upper stage engine requirements. In addition to the spin burst test, material testing will be performed on coupons that were built with the impeller.

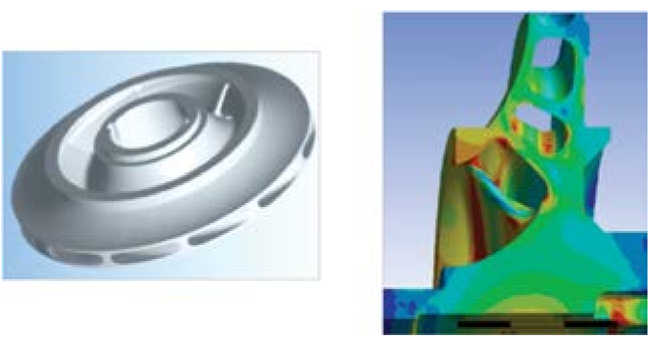


Figure 1: SLM turbopump impeller design.

Notable Accomplishments

Accomplishments for this task include the design of the SLM impeller, impeller and material coupon fabrication, final machining (fig. 2), structured light scanning and inspection, spin burst testing, material strength data development, and data analysis. The spin test was successfully performed and operated up to 147,600 rpm, with the result that the impeller could not be failed with the equipment used.

Figure 2: SLM Ti6-4 manufactured turbopump impeller.

Additive Manufacturing Infrared Inspection

Project Manager(s)

Darrell Gaddy/ER43
(256) 544–0198

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The Additive Manufacturing Infrared Inspection task started the development of a real-time dimensional inspection technique and digital quality record for the additive manufacturing process using infrared camera imaging and processing techniques. The additive manufacturing infrared inspection will benefit additive manufacturing by providing real-time inspection of internal geometry that is not currently possible and will reduce the time and cost of additive manufactured parts with automated real-time dimensional inspections which deletes post-production inspections.

Notable Accomplishments

The task successfully proved the feasibility of infrared hardware detecting additive manufacturing process (fig. 1). Custom software was developed to create 3D geometry files of the additive manufactured part (fig. 2). Specific accomplishment details produced by this task were as follows:

- Orion Delta 3D printer was modified with trigger.
- Moody infrared software was modified to accept trigger for each layer.
- Moody infrared software implemented an algorithm for melted interface.
- Software was modified to create computer aided design (CAD) file (stereo lithography format).
- Software was modified to create CAD file metadata to display temperatures (PLY).

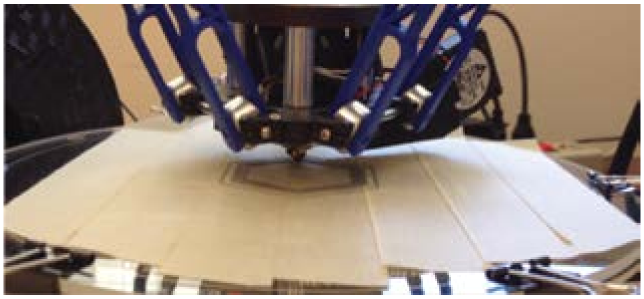
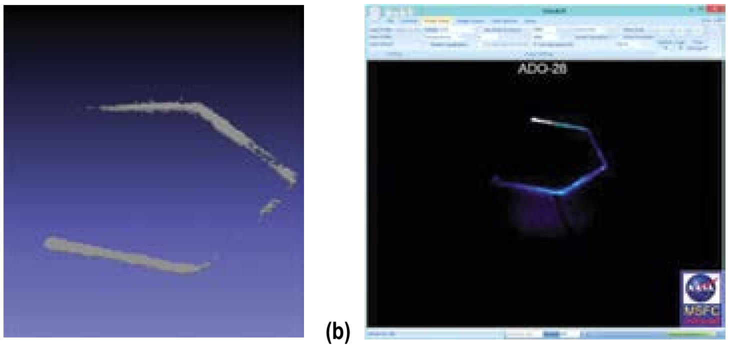


Figure 1: Orion Delta 3D printer and manufactured part.



(a) (b)

Figure 2: Test results of detecting additive manufactured part: (a) CAD image of printed part and (b) software display of infrared temperature of part.

Performance Improvement of Friction Stir Welds by Better Surface Finish

Project Manager(s)

Sam Russell/EM20
(256) 544–4411

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The as-welded friction stir weld (FSW) has a cross section that may act as a stress concentrator. The geometry associated with the stress concentration may reduce the weld strength and makes the weld challenging to inspect with ultrasound. In some cases, the geometry leads to false positive nondestructive evaluation (NDE) indications and, in many cases, it requires manual blending to facilitate the inspection. This study will measure the stress concentration effect and develop an improved phased array ultrasonic testing (PAUT) technique for friction stir welding.

Post-welding, the FSW tool would be fitted with an end mill that would machine the weld smooth, trimmed and shaved. This would eliminate the need for manual weld preparation for ultrasonic inspections. Manual surface preparation is a hand operation that varies widely depending on the person preparing the welds. Shaving is a process that can be automated and tightly controlled.

Anticipated Benefits

Launch vehicle tanks and other structures that use self-reacting friction stir welds (SR-FSWs) can be made lighter and inspected faster and cheaper.

Mission Applications

This project has potential applications in improving fuel and oxidizer tanks, intertanks, and payload fairings.

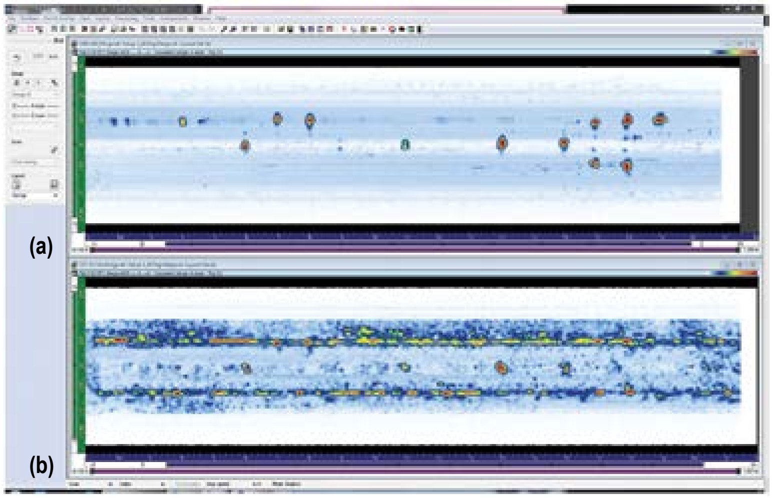
Notable Accomplishments

In FY 2014, the majority of the study on SR-FSWs was concluded. However, the report on SR-FSW was completed in FY 2015. In FY 2015, conventional friction stir welds (C-FSWs) were studied:

- Tensile strengths were measured for baseline welds and smoothed C-FSWs.
- A probability of detection study of the capability of PAUT was started. It is approximately 90% complete.
- Manufacturing of smooth welds was an issue. Bead shaving was pursued to smooth the weld. The bead shaver requires further development. Note this was added to the task approval of the FY 2015 proposal.

The conclusions from this task are as follows:

- For SR-FSW:
  - Smoothed panels exhibit slightly higher average strengths than as-welded panels.
  - Smoothed panels exhibit significantly lower standard deviation in strength and joint efficiency than as-welded panels.
  - Lower standard deviations may translate into higher design allowables.
  - PAUT inspection capability greatly improved by smoothing weld.
  - PAUT analysis much faster with smoothed welds.
  - False positive calls greatly reduced by smoothing weld.
  - Slightly narrower weld land can be inspected.
  - An efficient means of smoothing the weld should be developed.
- For C-FSW:
  - Baseline C-FSW is much smoother than SR-FSW.
  - Strength is slightly better than milled smooth C-FSW.



(a) PAUT scan of notched weld panel with welds smoothed and (b) PAUT notched weld panel with normal surface preparation. Both panels have the same electrical discharge machining notch pattern, seen as the colored spots.

Q2 Inconel 625 Material Properties Development

Project Manager(s)

Kenneth Cooper/EM42
(256) 544–8591

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task involved the development and characterization of selective laser melting (SLM) parameters for additive manufacturing of nickel alloy 625 (a.k.a., Inconel® 625, or In625). SLM is a relatively new manufacturing technology that fabricates complex metal components by fusing thin layers of powder with a high-powered laser beam, utilizing a 3D computer design to direct the energy and form the shape without traditional tools, dies, or molds. There are several metal SLM technologies and materials on the market today and various efforts to quantify the mechanical properties, however, nothing consolidated or formal to date. Meanwhile, SLM material strength properties of Inconel 625 are currently highly sought after by NASA propulsion designers for liquid rocket engine components.

The primary objective of this task was to utilize NASA Marshall Space Flight Center's existing SLM equipment and knowledge base with other metal alloys to generate a reduced design allowables database of expected properties for SLM Inconel 625 parts. This first requires a series of experiments (fig. 1) aimed at optimizing build parameters in the SLM machine to build parts that demonstrate peak properties based on a global energy input probability test matrix. Once a base set of operating parameters were determined, the team built and tested the required number of mechanical coupons to serve as a basis for follow-on allowables development.

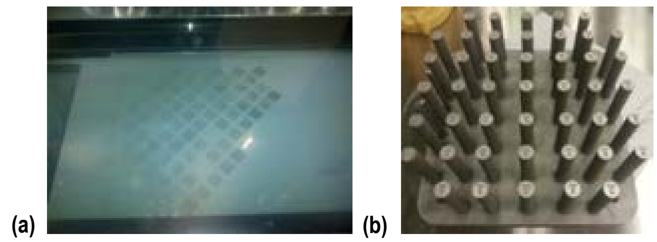


Figure 1: Inconel 625 samples: (a) Samples being built and (b) completed samples ready for testing.

Notable Accomplishments

The following tasks were completed:

- Design of experiments on 100 samples to determine the effects of changes in the global energy input on Rockwell hardness of produced coupons.

- Those test data were then used to build a sample set of 50 coupons to test the resulting tensile strength at room temperature in hopes of selecting one set of parameters to run a larger, 184-coupon sample set of tensile, fracture, and fatigue coupons. The data actually show a large range of acceptable parameters (fig. 2).

- Completed a study of annealing temperatures on mechanical properties and material microstructure. Established heat treatment parameters for future Inconel 625 processing.

- Planned a round robin test series in order to evaluate the state of the industry for SLM Inconel 625 production in terms of quality of material produced and amount of variability between vendors.

- Obtained commitments from three outside vendors to provide two test specimen builds each. Two vendors have delivered the first builds.

- Mechanical testing of the received builds is ongoing.

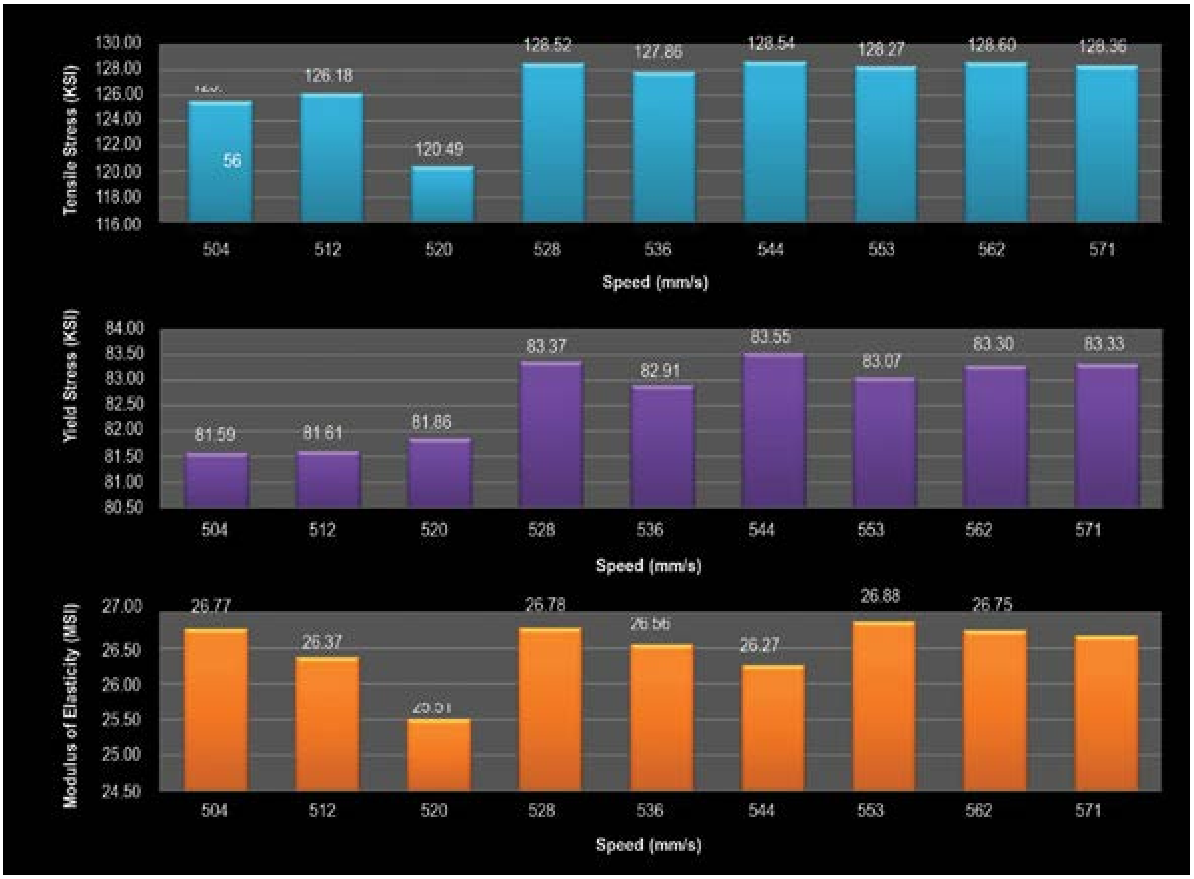


Figure 2: Inconel 625 samples test results.

Q4 Titanium 6-4 Material Properties Development

Project Manager(s)

Kenneth Cooper/EM42
(256) 544–8591

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task involved the development and characterization of selective laser melting (SLM) parameters for additive manufacturing of titanium-6%aluminum-4%vanadium (a.k.a., Ti-6Al-4V, or Ti64). SLM is a relatively new manufacturing technology that fabricates complex metal components by fusing thin layers of powder with a high-powered laser beam, utilizing a 3D computer design to direct the energy and form the shape without traditional tools, dies, or molds. There are several metal SLM technologies and materials on the market today and various efforts to quantify the mechanical properties, however, nothing consolidated or formal to date. Meanwhile, SLM material fatigue properties of Ti64 are currently highly sought after by NASA propulsion designers for rotating turbomachinery components.

The primary objective of this task was to generate a reduced design allowables database of expected properties for SLM Ti64 parts and utilize NASA Marshall Space Flight Center's (MSFC's) existing SLM equipment (fig. 1) and knowledge base with other metal alloys. Unlike Inconel® 625, Ti64 has never been used in MSFC's ConceptLaser SLM machine prior to this development effort. Therefore, the initial build development was done first, followed by parameter optimization. Initial build development entails finding the correct general parameters, build plate materials, and build settings that yield satisfactorily dense (>99.5%) parts. Initial build development also entails maintaining and further honing safety protocols around Ti64. As a reactive powder, it requires vigilant grounding and safety consciousness in order to expose the minimal number of operators to the least risk for the smallest amount of time.

Figure 1: SLM machine with glovebox required for Ti64.

Notable Accomplishments

The first build plate was a set of four small material test samples built on a stainless steel 90-mm×90-mm build plate. Four samples were run at 250 W, 1,600 mm/s with varying spot sizes in an effort to quantify the melt pool size of Ti64 in the SLM. Part parameters were based on parameters successfully used at KU Leuven on a similar laser system. Three of the four samples failed to build due to peeling off the plate due to dissimilar metals. This has been corrected by switching to Ti64 build plates. The surviving part has been sent for sectioning and was used to determine initial density. Parameters were adjusted accordingly to achieve the highest density possible.

Primary accomplishments this year were as follows:

- Developed training and procedures for safe handling of reactive Ti64 powder.
- Developed initial SLM machine parameters to successfully build Ti64 parts. Corrected issues with baseplate materials.
- Evaluated state-of-the-industry for SLM Ti64 development. Provided recommendations for continued development efforts using alternative technologies.

Composite Dry Structure Cost Improvement Approach

Project Manager(s)

Alan Nettles/EM20
(256) 544–6109

Mindy Nettles/XP50
(256) 544–1569

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This effort demonstrates that by focusing only on properties of relevance, composite interstage and shroud structures can be placed on the Space Launch System vehicle that simultaneously reduce cost, improve reliability, and maximize performance, thus providing the Advanced Development Group with a new methodology of how to utilize composites to reduce weight for composite structures on launch vehicles. Interstage and shroud structures were chosen since both of these structures are simple in configuration and do not experience extreme environments (such as cryogenic or hot gas temperatures) and should represent an appropriate starting point for flying composites on a 'human-rated' vehicle. They are used as an example only.

The task consisted of monthly presentations on the subject matter of using polymer matrix composites for launch vehicle structures given from January 2014 through October 2014. A final summary documenting major points is to be done at the conclusion of this task. Each monthly topic presents the logic and rationale behind the proposed new methodology.

Notable Accomplishments

The following eight presentations have addressed the following issues that are barriers to using composites:

(1) Why use composites?
(2) Composites for launch vehicles (how they differ from use in aircraft).
(3) New methodology of generating 'allowables.'
(4) Composites and the use of knockdown factors.
(5) Why fatigue is not an issue in most composite structures…and certainly not launch vehicles.
(6) Mechanical testing of composites.
(7) New methodology of generating allowables for composites used on launch vehicles (updated with Justin Jackson).
(8) Failure of composites.

Some of the conclusions provided in the discussions are as follows: (1) Testing of lamina is not only expensive and difficult but futile since no laminate failure criteria have been shown to be valid for practical use; (2) Undamaged laminate testing is time consuming and costly. This is hard to justify, as these strength numbers will probably never be used since damage must be assumed to exist in the laminate; (3) Undamaged laminate testing is more of a 'test of the test method' rather than a material property test; (4) If a structure has a dominant loading case (such as compression for an interstage structure), then characterizing other strength (such as tension) is of no practical use; (5) Costly fatigue testing is usually not necessary; (6) The statistical significance (the obtaining of which is very costly) of the multitude of undamaged test specimens is lost many times over by the time a final design number for a given piece of hardware is agreed upon; and (7) The final product will have an optimum layup based on undamaged properties that may not result in an optimum layup for damage tolerance considerations. This may contribute to design values that are either too high (poor reliability) or too low (compromised performance) being used.

Pyroshock Characterization of Composite Materials

Project Manager(s)

David Ordway/EV32
(256) 544–8087

Steven Gentz/C105
(256) 544–1642

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development,
NASA Engineering and Safety Center

Project Description

Composite materials are being considered for incorporation into the evolved Space Launch System (SLS) vehicle to improve performance and affordability. The lighter materials increase the vehicle's payload capability.

This task evaluates composite materials to ensure they can withstand the stresses induced into the vehicle during launch and stage separation. Tests are performed where an explosive charge is placed on a metal or composite plate affixed to a composite material panel. The test setup is shown in figure 1. When the charge is initiated, a shockwave is sent through the composite panel. Studying the behavior of composites when the shockwave is transitioning through the material will allow for the creation of a model to predict how it will withstand launch stresses and shock loads.

Anticipated Benefits

Composite materials offer a number of advantages with respect to isotropic materials due to their low density and the possibility of optimizing their strength and stiffness by properly determining the fiber or tape orientation of every layer in the laminate. As a result, the analysis of their static and dynamic behavior is important, especially in the aerospace engineering field, where the minimization of the structural mass is one of the first objectives of the design.

Mission Applications

Use by the launch industry by incorporating composite materials in areas of separation.

Notable Accomplishments

Significant achievements included completing all 28 of the task assessment baseline composite pyroshock tests, which included 10 monolithic composite panel tests (plus four retests) and 18 sandwich composite panel tests. In addition, algorithms were developed to analyze the shock data, and statistical analysis was completed on the output from the algorithms for the monolithic composite panels. Analysis of the sandwich composite panel test data was completed.

In FY 2015, testing of composite panels with and without melamine acoustic dampening foam was completed. The shock data from these tests were qualitatively compared to evaluate the effect the addition of acoustic foam has on shock transmissibility in the composite materials.

References

Gentz, S.J.; Ordway, D.O.; Parsons, D.S.; et al.: "Empirical Model Development for Predicting Shock Response on Composite Materials Subjected to Pyroshock Loading," NASA/TM—2015–218781, NASA Langley Research Center, Hampton, VA, 128 pp., July 2015.

(a) (b)

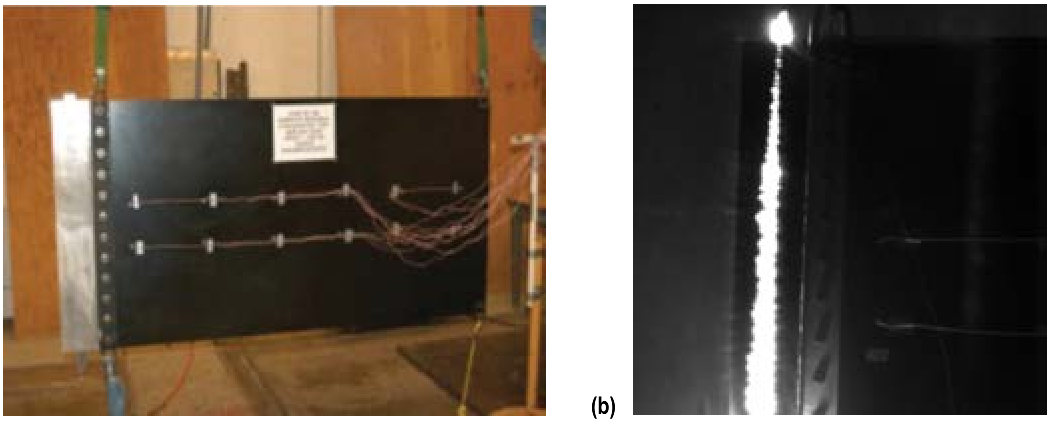


Figure 1: Pyroshock test setup: (a) Test article and (b) test.

Booster Interface Loads

Project Manager(s)

Bill Wood/Langley Research Center
(757) 864–8355

Steven Gentz/C105
(256) 544–1642

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development,
NASA Engineering and Safety Center

Project Description

The interaction between shockwaves and the wake shed from the forward booster/core attach hardware results in unsteady pressure fluctuations, which can lead to large buffeting loads on the vehicle. This task investigates whether computational tools can adequately predict these flows, and whether alternative booster nose shapes can reduce these loads. Results from wind tunnel tests will be used to validate the computations and provide design information for future Space Launch System (SLS) configurations.

The current work combines numerical simulations with wind tunnel testing to predict buffeting loads caused by the boosters. Variations in nose cone shape, similar to the Ariane 5 design (fig. 1), are being evaluated with regard to lowering the buffet loads. The task will provide design information for the mitigation of buffet loads for SLS, along with validated simulation tools to be used to assess future SLS designs.

Notable Accomplishments

The project has completed an initial set of computational fluid dynamics (CFD) cases covering six booster nose configurations for two Mach numbers and two angles of attack. These configurations were tested in NASA Langley Research Center's (LaRC's) 11-ft Transonic Wind Tunnel as part of an SLS aeroacoustic test. Both computationally predicted and measured wind tunnel results indicate that substantial improvement in the booster attach region environments can be achieved (fig. 2).

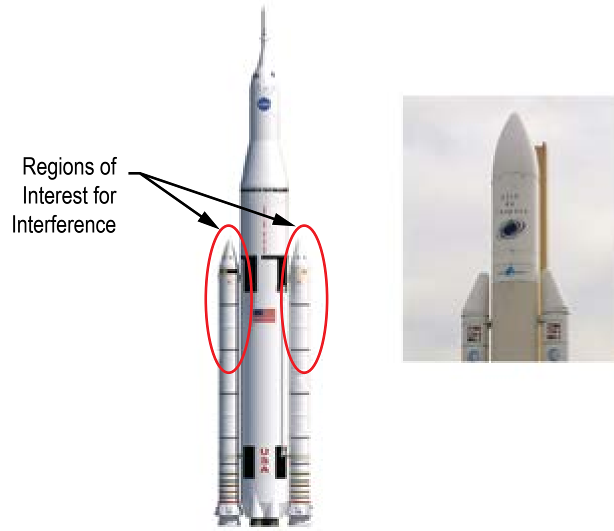


Figure 1: Booster interface loads.

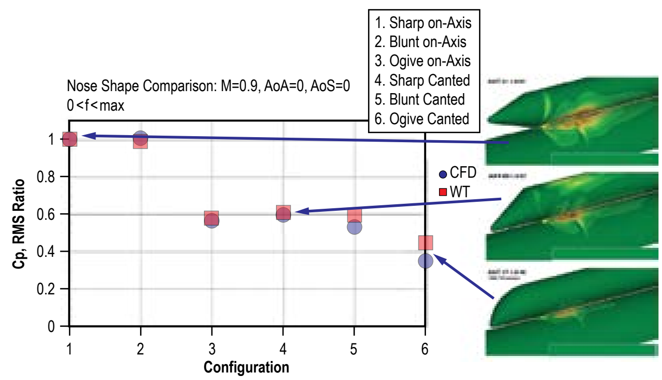


Figure 2: Area-weighted root mean square pressure levels in booster attach region.

While encouraging, overall root mean square pressure levels are a relatively high-level comparison. For combined load analysis, buffet-forcing functions, or integrated loads at a given longitudinal station are needed. Accurate prediction of these buffet-forcing functions requires agreement in both magnitude and frequency. Figure 3(a) shows the computed and measured integrated load over a section of the core downstream of the forward attach point. Figure 3(b) is the corresponding power spectral density (PSD) in the frequency domain. As can be seen, the CFD currently underpredicts the magnitude and shifts the frequency.

A small set of CFD solutions were obtained to complement a recently conducted rigid buffet model test in the LaRC Transonic Wind Tunnel. Lessons learned from the previous CFD efforts were applied that accurately predicted the buffet-forcing functions.

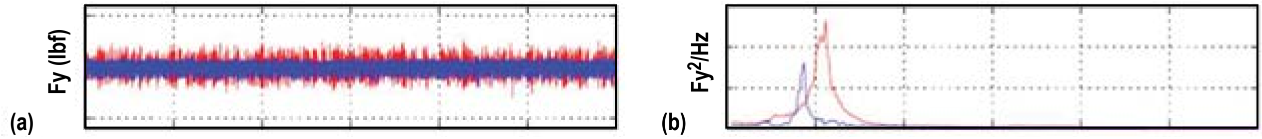


Figure 3: Integrated load and corresponding frequency domain PSD: (a) Integrated force and (b) PSD.

Advanced Booster High-Performance Solid Propellant and Composite Case/ Polybenzimidazole Nitrile Butadiene Rubber Insulation Development

Project Manager(s)

Jessica Chaffin/ER51
(256) 544–5692

Steven Gentz/C105
(256) 544–1642

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development,
NASA Engineering and Safety Center

Project Description

The NASA Engineering and Safety Center (NESC) was requested to examine processing sensitivities (e.g., cure temperature control/variance, debonds, density variations) of polybenzimidazole nitrile butadiene rubber (PBI-NBR) insulation, case fiber, and resin systems and to evaluate nondestructive evaluation (NDE) and damage tolerance methods/models required to support human-rated composite motor cases. The proposed use of composite motor cases in Block 2 is expected to increase performance capability through optimizing operating pressure and increasing propellant mass fraction. This assessment supports the evaluation of risk reduction for large booster component development/fabrication, NDE of low mass-to-strength ratio material structures, and solid booster propellant formulation as requested in the Space Launch System (SLS) NASA Research Announcement for Advanced Booster Engineering Demonstration and/or Risk Reduction. Composite case materials and high-energy propellants represent an enabling capability in the Agency's ability to provide affordable, high-performing advanced booster concepts.

The NESC team was requested to provide an assessment of co- and multiple-cure processing of composite case and PBI-NBR insulation materials and evaluation of high-energy propellant formulations. The assessment objectives included the following:

- Evaluate co- and multiple-cure processing studies through tensile strength, impact peel strength, and water burst testing:
  - Oven cure co-cure prepreg.
  - Oven cure multiple-cure prepreg.
  - Oven cure co-cure wet wind.
  - Oven cure multiple-cure wet wind.
  - Autoclave cure co-cure prepreg.
- Develop NDE damage standards by evaluating the impacts of composite case/PBI-NBR cylinders.
- Evaluate NDE techniques on subscale composite bottles to determine inspection methods best suited to large-scale loaded motors.
- Utilize NDE techniques to evaluate processing studies of composite case and insulation system.
- Evaluate high-energy propellants for burn rate, mechanical properties, and safety requirements for advanced booster concepts at the Army AMRDEC.
- Utilizing AMRDEC, manufacture established liner systems that are compatible with the high-energy propellants that are being evaluated.

Notable Accomplishments

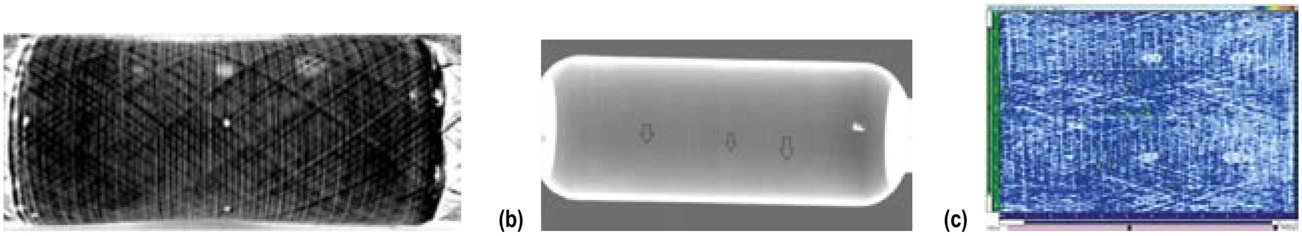
The following accomplishments were made:

- Hydroxyl terminated polybutadiene (HTPB) and hydroxyl terminated polyether (HTPE) propellant mixes (fig. 1) made in 1-pint, 1-gallon, and 5-gallon sizes:
  - Laboratory hazard testing complete and results acceptable.
  - End-of-mix viscosity acceptable.
  - Burning rate and pressure slopes acceptable. Can be modified to meet program requirements.
  - HTPE tensile properties acceptable.
  - HTPB formulation being worked to improve tensile properties.
- Ablative liner mixes made in 1-pint and 1-gallon sizes:
  - End-of-mix viscosities acceptable.
  - Tensile properties acceptable.
- Kevlar®-filled ethylene propylene diene monomer downselected as insulation for bond line evaluations.

Figure 1: Propellant mixing at AMRDEC.

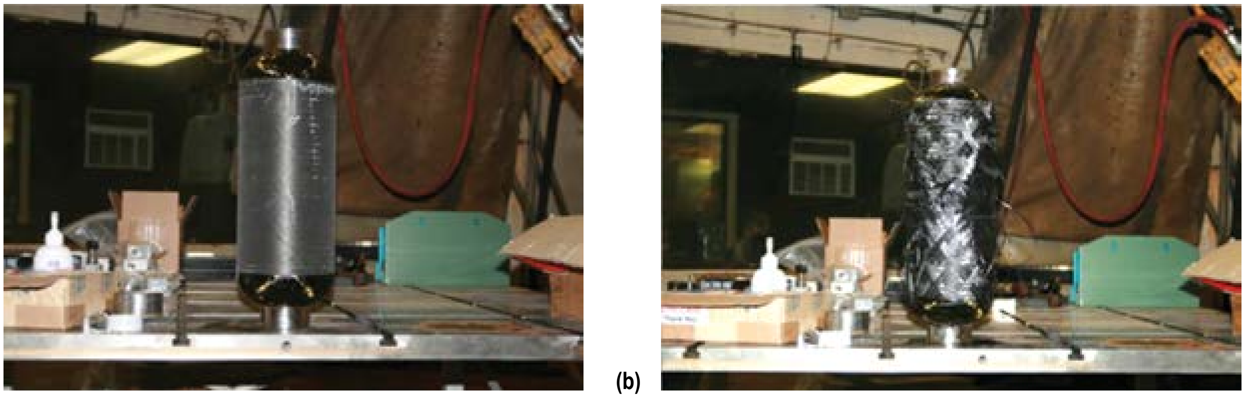
- Accelerated aging of HTPE propellant and its bond line specimens has commenced.
- Forty-five bottles manufactured and NDE complete (fig. 2):
  - Eight test bottles and one defect standard—prepreg co-cure in an oven.
  - Eight test bottles and one defect standard—prepreg multiple-cured in an oven.
  - Eight test bottles and one defect standard bottle—wet wound and co-cured in an oven.
  - Eight test bottles and one defect standard bottle—wet wound multiple-cured in an oven.
  - Eight test bottles and one defect standard bottle—prepreg co-cured in an autoclave.
- Impact trials conducted to determine lower bound on detectable damage via NDE.
- Burst testing of bottles performed (fig. 3) to evaluate possible differences in structural capability of different processing methods. Comparison in burst pressures of the pristine co-cure and pristine multiple-cure bottles do not reveal a visible difference in burst strength.
- NDE techniques evaluated:
  - Infrared flash thermography (IRT) has proved to be an excellent method for finding indications.
  - Radiography has been successful in finding inserts in defect standards.
  - Computed tomography has been unable to find inserts in defect standards or indications found by IRT, but has been excellent in detecting thickness and density changes.

Evaluation of the HTPB formulation for improving mechanical properties at high solids loading (90%) has been completed. Additionally, scale-up optimized HTPB formulation for propellant and bondline accelerated aging and evaluation of burn rates through strands and subscale motors has been finished.



(a) (b) (c)

Figure 2: Defect standard analyzed using various NDE techniques: (a) IRT, (b) radiography, and (c) ultrasonic testing.



(a) (b)

Figure 3: Bottle burst test: (a) Before burst and (b) after burst (failure in hoop).

Advanced Booster Combustion Stability

Project Manager(s)

Kevin Tucker (retired)/ER42

Steven Gentz/C105
(256) 544–1642

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development,
NASA Engineering and Safety Center

Project Description

Combustion instability is a phenomenon in liquid rocket engines caused by complex coupling between the time-varying combustion processes and the fluid dynamics in the combustor. Consequences of the large pressure oscillations associated with combustion instability often cause significant hardware damage and can be catastrophic. The current combustion stability assessment tools are limited by the level of empiricism in many inputs and embedded models. This limited predictive capability creates significant uncertainty in stability assessments. This large uncertainty then increases hardware development costs due to heavy reliance on expensive and time-consuming testing.

The objectives of this task are to advance the predictive capability of state-of-the-practice combustion stability methodologies and tools used for the Space Launch System (SLS) injector combustion stability assessment, facilitate more confident identification and characterization of combustion instabilities and efficient mitigation during SLS propulsion system development, and minimize SLS development costs and improve hardware robustness.

Notable Accomplishments

The following tasks have been accomplished:

- Injector element design, scaling, testing, and computational fluid dynamics (CFD) simulation:
  – Element 1b (baseline element):
    - Testing is complete at both the Air Force Research Laboratory (AFRL) (full-scale at 350–1,100 psia) and Purdue (subscale at 450 psia).
    - CFD analyses of both elements is complete.
    - Testing and CFD analysis at both scales showed a 180-Hz chug instability.
  – Element 1b4:
    - This is a redesign of element 1b to eliminate the chug instability.
    - Testing at AFRL is complete; both testing and CFD analysis indicate chug is still present, but at a considerably lower amplitude.
  – Element 1b5:
    - This redesign of element 1b4 is being fabricated for testing at both AFRL and Purdue.
    - CFD simulations indicate it should be stable.
- Demonstration of new capabilities on SLS Advanced Booster Engineering Design Risk Reduction (ABEDRR) injector:
  – Three-dimensional reacting flow CFD simulations of a seven-element representation of the ABEDRR injector have been completed (figs. 1 and 2).
  – Data extracted from CFD simulations used to augment engineering stability assessment tools see (fig. 3).

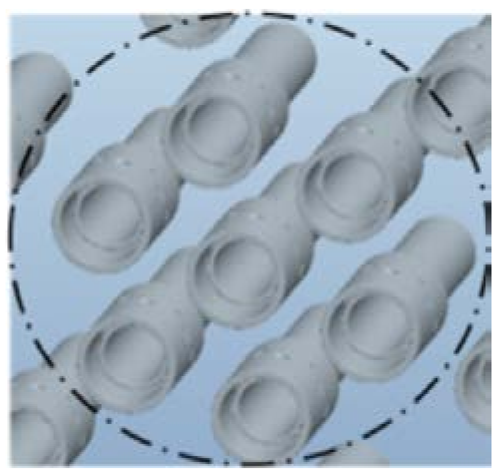


Figure 1: Seven elements from an ABEDRR injector.

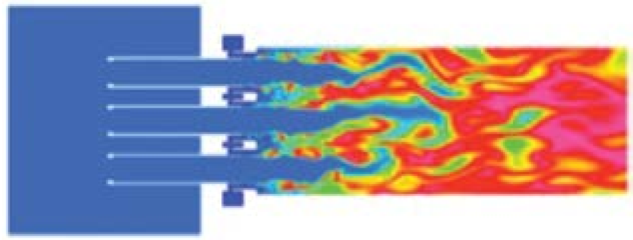
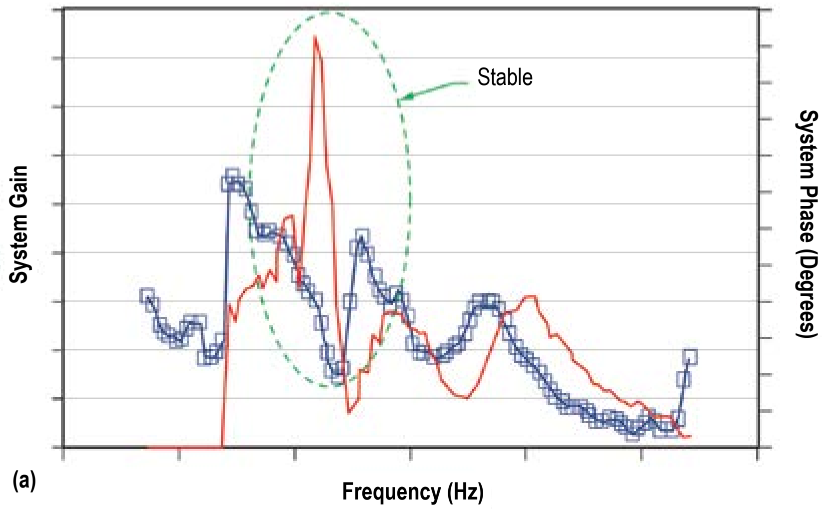


Figure 2: Two-dimensional cut of temperature field of seven-element injector.



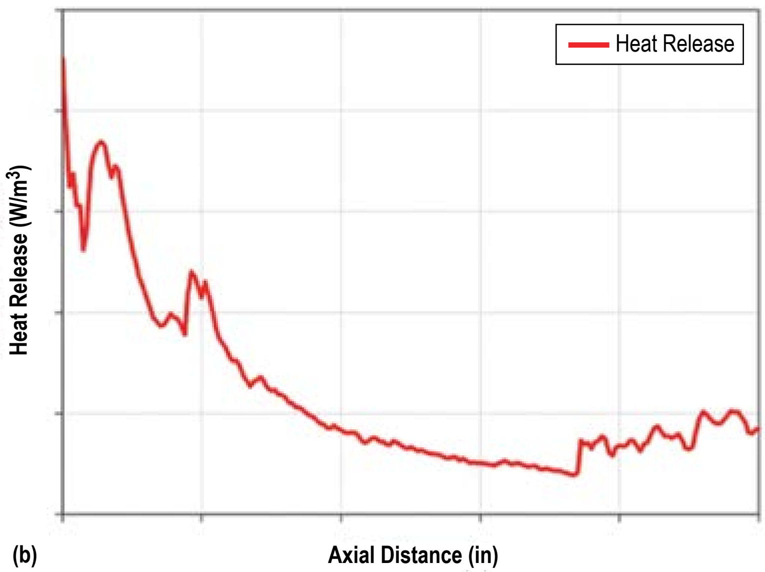
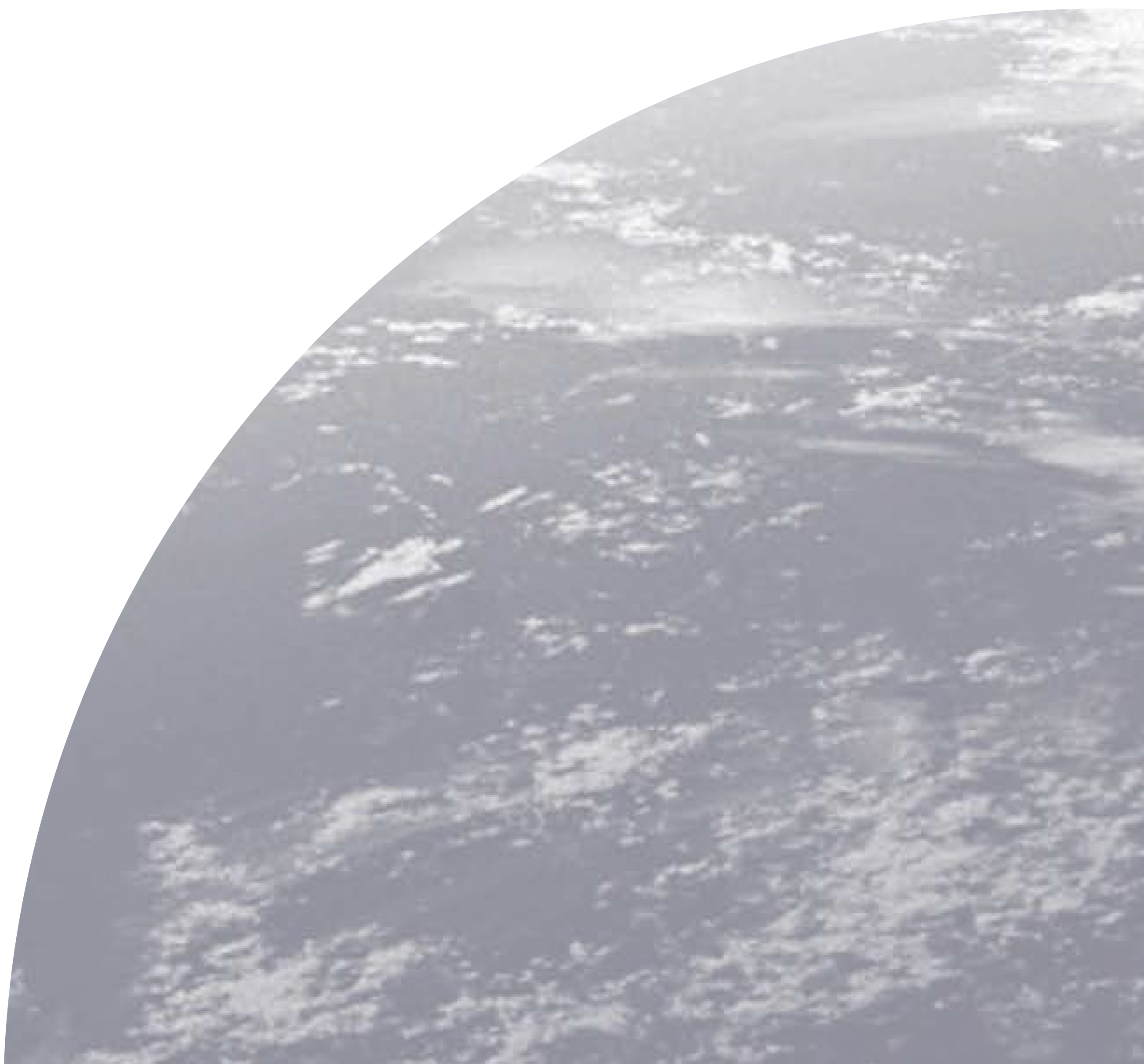
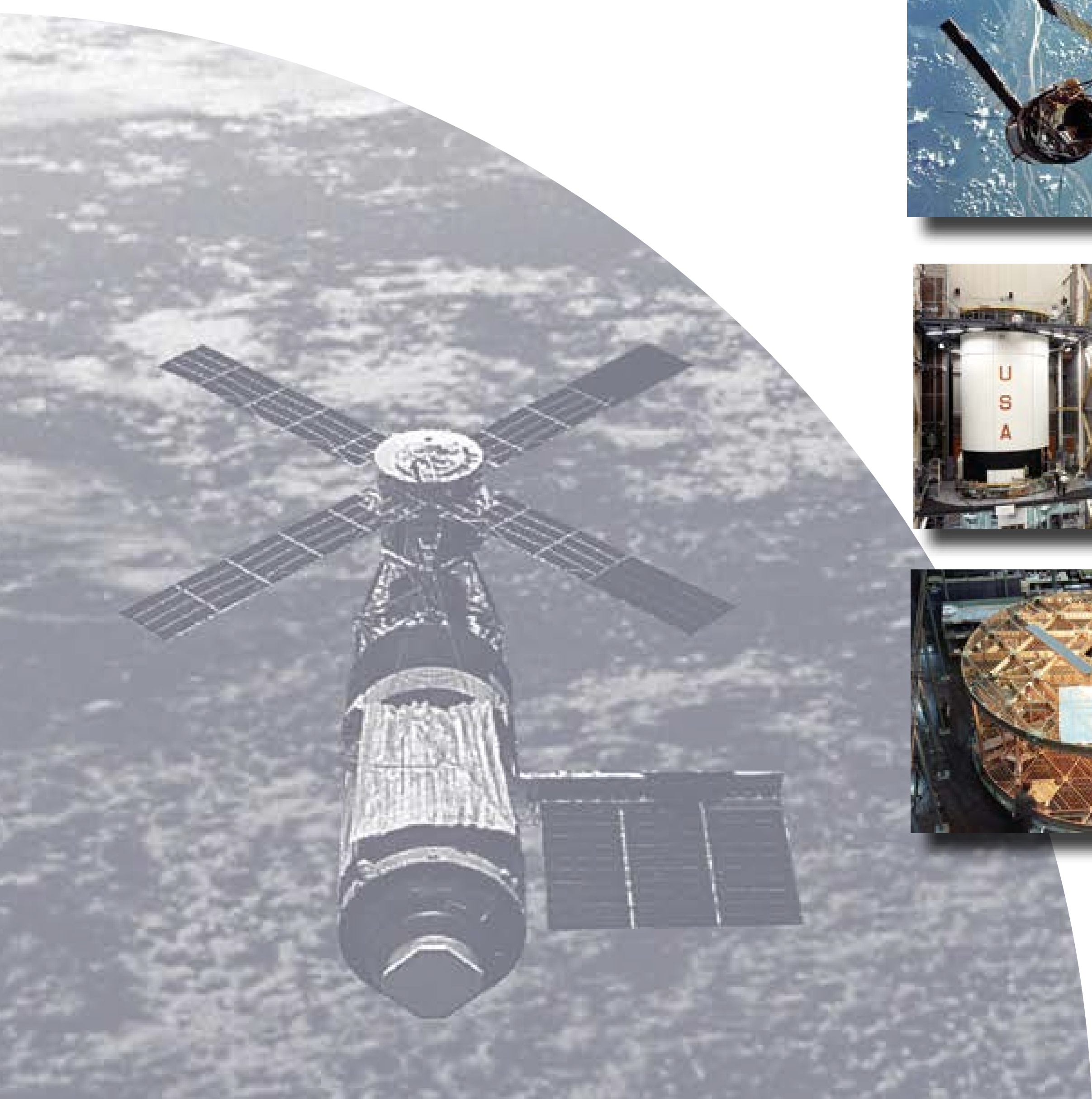


Figure 3: (a) Stability plot generated with input from CFD analysis and (b) heat release profile from CFD simulations.



Human Exploration and Operations Mission Directorate

Space Launch System Academia Contracts/Grants



Academia Contracts/Grants

All eleven academic grants awarded were completed by the end of 2015.

Five of the eleven grants deal with improving or utilizing the Loci family of CFD/finite element modeling codes. Loci is a C++ library and declarative programming framework that efficiently maps numerical algorithms onto parallel architectures. The approach is logic-based so that it allows a description of what the code should accomplish, but it does not dictate how to accomplish it (as in imperative programming). Loci is thus a flexible, rule-based programming model for numerical simulation that allows runtime scheduling of the appropriate subroutine calls required to obtain a user-specified goal.

The Loci family of codes was developed in 1999 by a National Space Foundation funded effort. The architecture was designed at Mississippi State University. The framework and most of the modules are open access; however, there are some modules with ITAR restrictions. These codes are designed such that very large simulations can be run efficiently on multiple processors utilizing supercomputers (e.g., the ARC Pleiades supercomputer). The overall framework is such that the codes are conducive to independent/third party module development resulting in development and implementation of multiple high-fidelity modules.

Loci currently has the following four major areas:

(1) Loci/CHEM (most mature and developed first):
- Advanced turbulence, heat transfer, structural analysis, and droplet models.
- Nonideal equations of states found in high-pressure environments.
- Overset meshes for complex geometry and object-in-motion problems.

(2) Loci/STREAM (originally developed at the University of Florida, funded by MSFC 2004–present):
- Geometric complexity using unstructured or moving grids.
- Real-fluid modeling for cryogenic propellants.
- Unsteady cavitation, multiphase flows, and flamelet models.

(3) Loci/BLAST (relatively new CFD code funded by the U.S. Army):
- Modeled blast-soil interactions (landmines buried in sand).
- Modeled the structural effects of blast on vehicles.
- Validated for blast events that would simulate failed motor ignition on test stand.

(4) Loci/THRUST (research):
- CFD code for acoustic modeling.

Academia contracts/grants for geographical distribution in the United States.

High Electrical Energy Density Devices for Aerospace Applications
Auburn University

Project Manager(s)

Z.Y. Cheng/Auburn University
(334) 844–3419

B.A. Chin/Auburn University
(334) 844–3322

Jeff Brewer/ES44
(256) 544–3345

Terry Rolin/ES43
(256) 544–5579

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This effort was to develop a database of the characteristics and specifications of commercially available electrical energy devices and experimentally determine the characteristics and specifications of these devices. Additional activities included:

- Using different electrical loads to simulate different applications in aerospace environments.
- Identifying the most promising candidates for use on space vehicles.
- Identifying emerging technologies in the energy storage device discipline and their potential applications.

This task was expanded slightly in 2014 to take advantage of a synergistic in-house activity concentrating on ultracapacitors. Working cooperatively and utilizing Auburn's unique material testing capabilities, both efforts benefitted greatly.

Challenges Towards Improved Friction Stir Welds Using Online Sensing of Weld Quality *Louisiana State University*

Project Manager(s)

Muhammad Wahab/Louisiana State University
(225) 578–5823

Arthur Nunes/EM32
(256) 544–2699

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This activity developed an online real-time system to determine weld quality for friction stir welds. The overall effort is depicted in figure 1.

The detection of defects as they form during friction stir welding (FSW) enables online repair and/or avoidance of defects. Four issues have been analyzed, including defect regions, temperature during FSW, fracture surface and systems engineering management (SEM) analysis, and fracture origination detection methods. This tool may ultimately eliminate or reduce unforeseen or sudden failures in lightweight welded structures, increase cost effectiveness, and decrease risk.

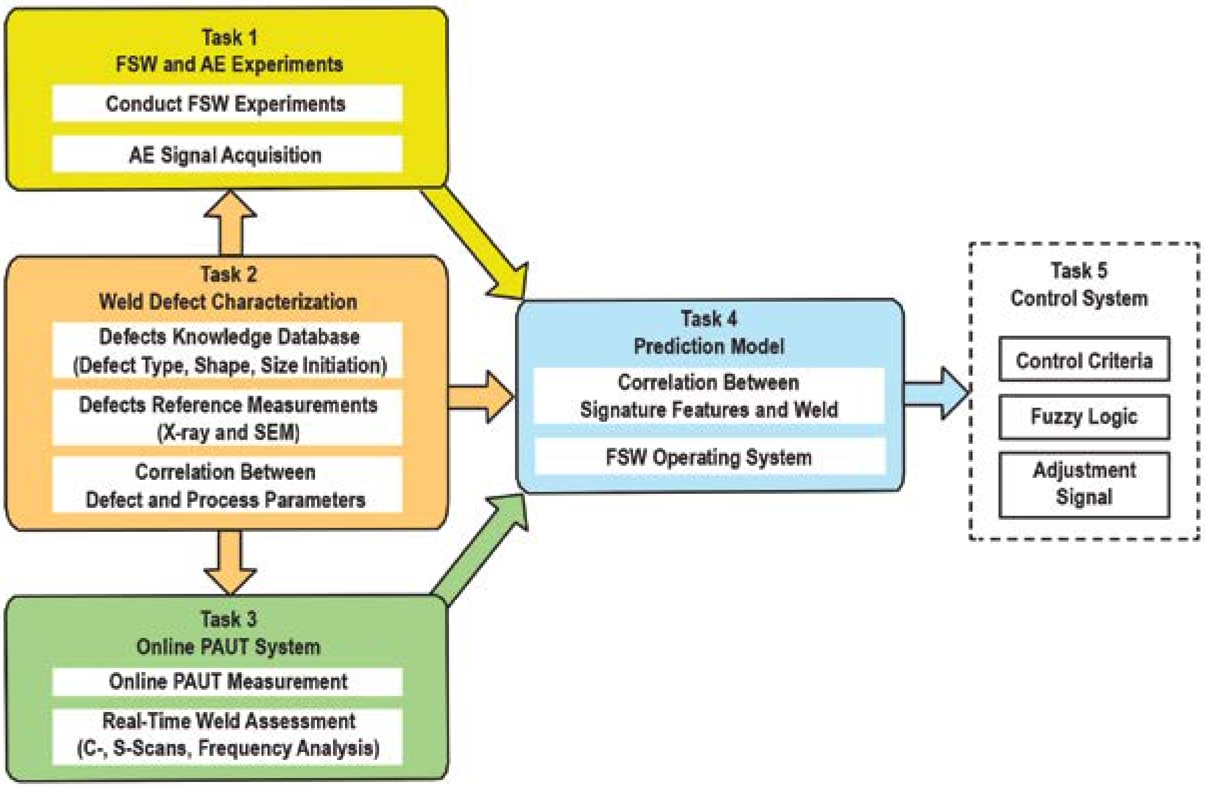


Figure 1: Louisiana State University activity flow chart.

A New Modeling Approach for Rotating Cavitation Instabilities in Rocket Engine Turbopumps *Massachusetts Institute of Technology*

Project Manager(s)

Z. Spakovszky/Massachusetts Institute of Technology
(617) 253–2196

Andrew Mulder/ER42
(256) 544–6750

Thomas Zoladz/ER40
(256) 544–1552

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This project investigates the mechanism of formation and propagation of rotating cavitation in rocket engine turbopump inducers. An open geometry inducer of modern design was developed and tested (fig. 1) to interrogate the path into instability and to lay a foundation for unrestricted research on inducer cavitation. A new modeling approach based on a body force description of the inducer blading and accompanied by two-phase numerical simulations complement the experimental investigations.

This new capability will add fidelity to the inducer design framework and enable advanced inducer and casing treatment configurations to improve performance while reducing development and operating costs. The project directly contributes to NASA's Space Launch System (SLS) program with the aim to improve reliability and performance of the SLS turbomachinery (RS-25 low-pressure oxidizer pump and low-pressure fuel pump, and J2-X liquid oxygen pump).

Figure 1: Inducer rotating cavitation instabilities.

Notable Accomplishments

To date, a new, open geometry, inducer platform for investigating cavitation dynamics was established and experimentally verified (fig. 2), fostering new research and broader dissemination of the results and insight. The hypothesized mechanism responsible for the onset of alternate blade cavitation and rotating cavitation has been identified in the calculations and will be verified with optical measurements.

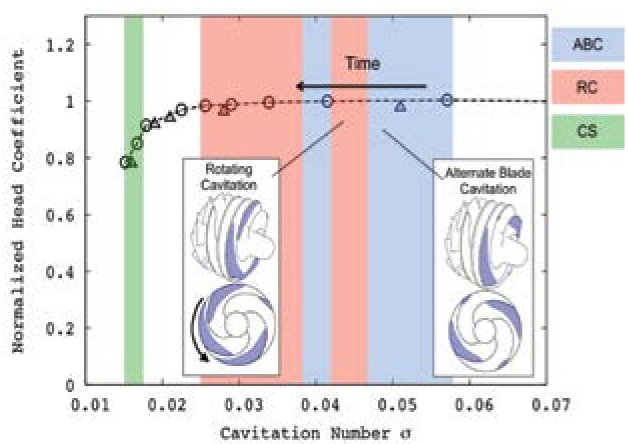


Figure 2: Measured cavitation dynamics of the low-pressure oxidizer pump inducer.

Low Dissipation and High Order Unstructured Computational Fluid Dynamics Algorithms to Complement the Use of Hybrid Reynolds-Averaged Navier Stokes/Large Eddy Simulation Algorithms
Mississippi State University

Project Manager(s)

Keith Walters/Mississippi State University
(662) 325–8231

Ed Luke/Mississippi State University
(662) 325–8424

Chris Morris/EV33
(256) 544–6728

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This activity developed a new methodology to predict loads (steady and unsteady) and heating for the Space Launch System (SLS) vehicle by using a hybrid Reynolds-averaged Navier Stokes (RANS)/large eddy simulation (LES) approach to directly capture turbulent fluid motion in parts of a simulation. This significantly improved computational fluid dynamics predictions (fig. 1) for the following:

- Rocket engine exhaust plumes and associated acoustic noise.
- Vehicle base flows, plume interactions, and recirculation.
- Flow over vehicle protuberances and associated acoustic noise.

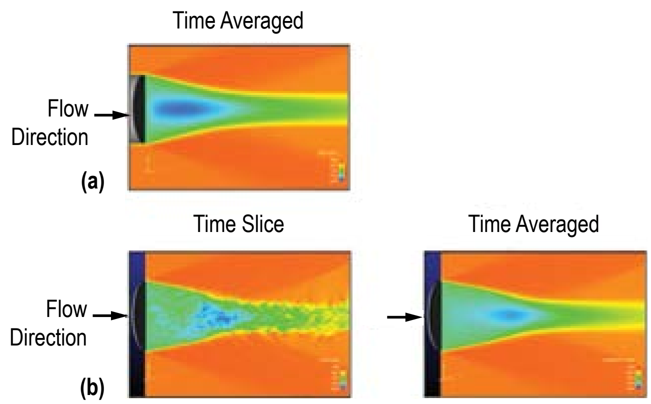


Figure 1: Fluid motion: (a) Current capability versus (b) improved simulation techniques.

The current hybrid RANS/LES capability in the Loci/CHEM code is suboptimal and has been identified for several years as an area that needs improvement. An improved prediction capability of loads on the SLS vehicle and components will enable a higher fidelity environments definition, resulting in a more efficient design.

Notable Accomplishments

Year one of this task focused on initial implementations of two numerical methods in Loci/CHEM that result in improved capturing of unsteady and turbulent flow physics. Work in year two has resulted in stability improvements to these new methods, and development and testing of an improved dynamic hybrid RANS/LES turbulence model was also conducted.

Next Generation Simulation Infrastructure for Large-Scale Multicore Architectures
Mississippi State University

Project Manager(s)

Ed Luke/Mississippi State University
(662) 325–8424

Jeff West/ER42
(256) 544–6309

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

Very large-scale simulations are required to obtain accurate, high-fidelity, physics-based models of the Space Launch System (SLS). These simulations are an integral part of modern engineering and design processes and are important tools for determining risks to design objectives posed by highly complex phenomena associated with vehicle-level concerns (such as launch and flight characterization), as well as component-level concerns (such as modeling rocket combustion chambers and propellant feed systems). The highest fidelity of these models, such as those used for acoustic or large eddy simulations, can require extremely large meshes, which will be run on very large, massively parallel computer systems. The main goal of this project was to significantly advance the already high scalability of the Loci system to facilitate extreme scales that these advanced models will require. The scalability improvements addressed by this project are two-fold:

(1) Next generation systems will be composed of very large numbers of computational cores (100 cores) arranged in high core density nodes composed using large, tightly coupled communication networks. Thus, the next generation of systems will be able to provide 100,000 cores by combination of thousands of nodes with each node consisting of hundreds of cores. For such systems, the use of message passing interface (MPI) alone will not be practical to exploit this parallelism because there are fundamental overheads associated with MPI that, while small, are on the order of the number of cores managed by the MPI system. At 100,000 cores, these costs become significant. To solve this problem, this project created an efficient hybrid thread plus an MPI scheduling approach that can significantly reduce these MPI costs by reducing the number of processes that MPI manages to the number of nodes rather than the number of cores.

(2) The second scaling concern was that such large processing systems would allow for simulations of meshes that are composed of many billions of elements. Unfortunately, the current implementation of Loci utilizes 32-bit integers to index entities that it manages which, unfortunately, limits the number of entities that Loci can manage to 2 billion, consequently limiting mesh sizes to about a half-billion elements (because each element requires many entities to describe). So, the second goal of this task is to raise this limit. A naïve approach to raise this limit would be to uniformly increase the number of bits used for all integers, but this would produce severe performance degradation. Therefore, the approach used was a sophisticated scheduling approach that manages data such that this scale can be increased without imposing performance costs.

Notable Accomplishments

Significant accomplishments have been achieved. A few highlights of these accomplishments are as follows:

- The implementation of a prototype hybrid thread scheduler for Loci is complete.
- A comprehensive characterization of the thread parallelism inherent to the Line Symmetric Gauss-Seidel Linear System Solver (LSGS) used by many Loci codes has been performed.
- A robust vectorization strategy for the LSGS solver has been developed.
- Extension of the scale of entities managed by the Loci system has been increased from 2 billion to 4 billion entities, enabling a doubling of the scale of simulations that can be performed by Loci codes.

Note that the current prototype thread scheduler for Loci is not compatible with the production codes, but is expected to be fully compatible with production codes in the next few months. Some performance degradation has been observed with the thread scheduling compared to MPI scheduling on small numbers of nodes. Optimizing the performance of the thread schedule was one of the second year deliverables of this project.

Development of Subcritical Atomization Models in the Loci Framework for Liquid Rocket Injectors *University of Florida*

Project Manager(s)

Siddharth Thakur/University of Florida
(352) 392–0817

Mrinal Kumar/University of Florida
(352) 392–0886

Jeff West/ER42
(256) 544–6309

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This study is the precursor for advancement in our understanding of combustion instabilities and determination of heat transfer coefficients for two-phase flows of cryogenic propellants during line chilldown and fluid transport. The main objective of this project was to develop primary atomization modeling capability in the Loci-STREAM and Loci/CHEM codes using a computationally tractable phenomenological stochastic model. The primary atomization model was coupled with Lagrangian capability for tracking the droplets along with secondary atomization models. The accurate characterization of primary and secondary atomization in liquid rocket injectors operating under subcritical conditions was the desired goal (fig. 1).

Notable Accomplishments

The Monte Carlo approach was extended to the transient analysis of unsteady atomization. Initial simulation results capturing the time-varying probabilistic distribution of the intact liquid core have been obtained. In addition, the developed unsteady models have been assimilated into the Loci-STREAM framework and coupled with the background flow solver. Time-varying probabilistic models for droplet size, velocity vector at release, and temperature were included. The implementation of the stochastic atomization model in the Loci family of codes (Loci-STREAM and Loci/CHEM), already in use by NASA for supercritical combustion and other applications, was accomplished. Also, five journal and conference publications resulted from this year's work.

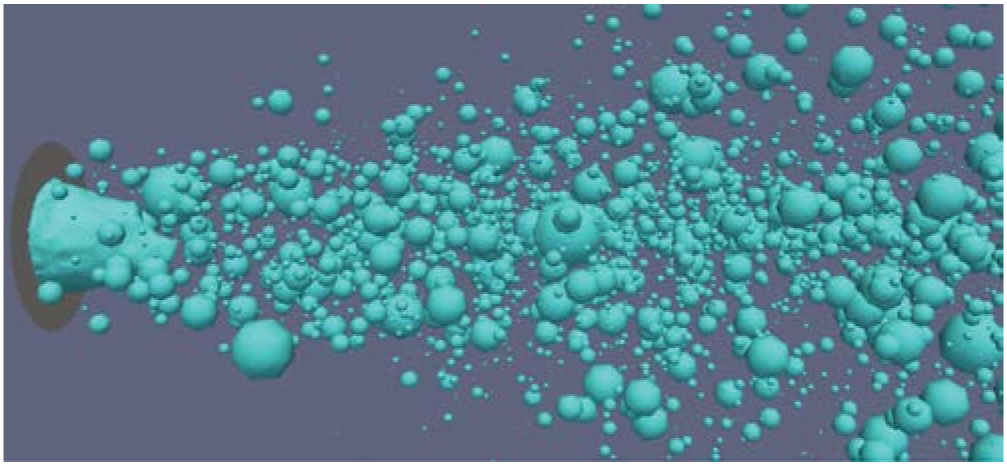


Figure 1: Liquid jet break-up modeled by the stochastic primary atomization model, developed as part of this project and integrated into Loci-STREAM.

Determination of Heat Transfer Coefficients for Two-Phase Flows of Cryogenic Propellants During Line Chilldown and Fluid Transport
University of Florida

Project Manager(s)

J.N. Chung/University of Florida
(352) 392–0886

Alok Majumdar/ER43
(256) 544–8555

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

When any cryogenic system is initially started — this includes rocket thrusters, turbo engines, reciprocating engines, pumps, valves, and transfer lines — it must go through a transient chilldown period prior to steady operation. Chilldown is the process of introducing the cryogenic liquid into the system and allowing the hardware to cool down to several hundred degrees below the ambient temperature. The chilldown process is anything but routine and requires a proper engineering design to chill down a cryogenic system in a safe and efficient manner. The heat transfer characteristics associated with the transfer line chilldown and propellant transfer, loading, and recirculation in feed subsystems of the Space Launch System, are crucial information for the design and proper operation of these cryogenic transport processes.

The general scope of the project was to acquire sufficiently detailed experimental data in both terrestrial and microgravity conditions for characterizing heat transfer coefficients in two-phase flows of cryogenic propellants (using liquid nitrogen as a simulant) with and without ingested helium gases. The heat transfer coefficients in the form of empirical correlations were incorporated in a computer simulation code for the propulsion system model for characterizing the thermal environment in feed systems for chilldown of cryogenic transfer lines and propellant transfer, loading, and recirculation. Tests were conducted over a pressure range from 20 to 70 psia, $2,000 < \text{Reynolds number} < 100,000$, and $1.75 < \text{Prandtl number} < 2.3$. A detailed uncertainty analysis was provided, and the data were presented with appropriate error bars.

Notable Accomplishments

Currently, at the end of seven months in the first year of the project, an experimental database for all the cases without ingested helium has been successfully completed. An experimental system has been modified for the inclusion of helium ingestion effects, and some preliminary runs have been achieved. Correspondingly, data analysis and heat transfer coefficient empirical correlation development proceeded in parallel. Correlation models have been determined and their fittings with the experimental results were evaluated.

Validation of Supersonic Film Cooling Numerical Simulations Using Detailed Measurement and Novel Diagnostics *University of Maryland*

Project Manager(s)

Chris Cadou/University of Maryland
(301) 405–0829

Joe Ruf/ER42
(256) 544–4942

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This activity developed a numerical methodology and experimental data sets to enable validation of fluid dynamics simulations of supersonic film cooling (SSFC). SSFC (fig. 1) is used on the J-2X nozzle extension to protect the extension from the much hotter primary flow. Significant conservatism had to be included in the J-2X nozzle extension design to account for the uncertainty on the effectiveness of the SSFC as calculated with fluid dynamics codes. Improvement in these fluid dynamics codes, ability to define the environments, and effectiveness of SSFC could result in significant savings of resources in the design cycle for the next nozzle that uses SSFC.

Notable Accomplishments

The experiment portion of this effort includes laboratory-scale SSFC experiments that are scaled from the J-2X nozzle extension environments. Detailed measurements of heat flux and pressures have been made for multiple film coolant flow rates. Work continues to implement novel diagnostics such as focused Schlieren imaging, Schlieren image-based particle velocimetry, and automated image interrogation. The fast-acting light source and alignment framework for the focused Schlieren imaging have been constructed. On the numerical methodology portion of the task, many parametric analyses with a high-fidelity large eddy simulation fluid dynamics code have been performed to assess the effects of different boundary conditions and assumptions on the simulation of SSFC. Work has begun to incorporate the lessons learned into fluid dynamic simulations implementing NASA Marshall Space Flight Center's workhouse fluids code, Loci/CHEM.

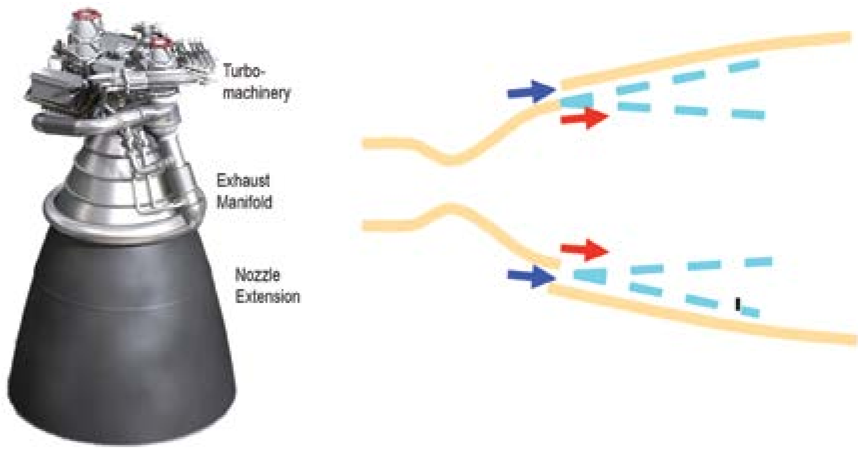


Figure 1: J-2X film-cooled nozzle extension.

Advanced Large Eddy Simulation and Laser Diagnostics to Model Transient Combustion-Dynamical Processes in Rocket Engines: Prediction of Flame Stabilization and Combustion Instabilities

University of Michigan and Stanford University

Project Manager(s)

Jim Driscoll/University of Michigan
(734) 936–0101

Matthias Ihme/Stanford University
(650) 724–3730

Jeff West/ER42
(256) 544–6309

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This activity developed a methodology to enable advanced large eddy simulation (LES) and laser diagnostics to model transient combustion dynamic processes in rocket engines. The objective of this computational and experimental research effort is the development of a fully validated high-fidelity combustion modeling capability to enable the accurate prediction of unstable and combustion dynamical processes involving flame lift-off and flame stabilization in rocket engines. Specifically, the work seeks to develop a fidelity-adaptive combustion model that combines a detailed chemistry description for the accurate characterization of topologically complex combustion regions (associated with flame anchoring, thermoacoustic coupling, and nonequilibrium combustion processes) with a flamelet-based combustion model for the computationally efficient characterization of quasi-one-dimensional, steady, and equilibrated combustion regimes.

This computational effort is complemented by an experimental program to obtain fundamental understanding of instability mechanisms in rocket engines. Measurements will be performed in an existing rocket injector facility. Specific focus is on providing quantitative measurements for velocity, inflow conditions, temperature, hydroxide speciation, flame lift-off, wall heat transfer, and phase-locked measurements of thermoacoustic instabilities. A range of relevant operating conditions (pressure and mass flow rates) and combustion regimes (stable, lifted, and acoustically unstable rocket conditions) will be considered.

Notable Accomplishments

This activity developed a methodology to enable advanced LES and laser diagnostics to model transient combustion dynamic processes in rocket engines. The following specific areas were investigated. One focus of the computation modeling effort has been on the development of a fidelity-adaptive combustion model (FAM) that utilizes a local submodel assignment to predict turbulent combustion in complex flows. The FAM approach utilizes a Pareto efficiency and introduces a manifold drift term as a measure for determining the adequacy of using a particular combustion model to predict specific quantities of interest. The FAM model is self-contained and does not require a priori knowledge about the flame structure. User input to the model consists of selecting a quantity of interest (such as temperature, fuel conversion, or flame stabilization), a threshold value for the departure function to control the accuracy and computational cost, and a set of combustion models that are available to the user. The computational complexity and accuracy of FAM can then be controlled through the selection of the quantity of interest and the threshold on the departure function. As such, FAM can fully accommodate different combustion models and chemical mechanisms of different complexities (including detailed, lumped, and reduced mechanisms) since they are fully characterized by a manifold. To demonstrate the capability of the departure function, we applied FAM to the simulation of a 3D stratified lifted flame, and results are presented in figure 1. In this application, we selected carbon monoxide (CO) as a quantity of interest, with a threshold value corresponding to a maximum allowable error in the CO prediction of 5%, and we considered the following turbulent combustion submodels: inert mixing, premixed FPI, diffusion FPV, equilibrium chemistry, and detailed methane chemistry (with Gas Research Institute 2.11). Turbulence/chemistry interaction was considered using a presumed probability density function-closure for all flamelet models, and a scale reconstruction model was used for the detailed chemistry region. Comparisons against direct numerical simulation (DNS) results (fig. 1(a)) show that single-regime flamelet models only provide insufficient descriptions of this topologically complex flame. In contrast, the departure function identifies specific regions (see fig. 1(b)) in which the fidelity of the combustion model is locally adapted to accurately represent the flame structure. For this specific case, FAM resulted in a reduction in the computational cost by a factor of 25 compared to the DNS with detailed methane chemistry.

Experiments were conducted to investigate the combustion stability characteristics of shear coaxial injectors. We considered a single injector element in a university-scale rocket combustion chamber operated up to 10 bar using gaseous hydrogen/oxygen (with oxygen as the central jet). The system was operated under a range of fueled conditions under which a self-sustained thermoacoustic instability was established. The instability is characterized by a small pressure fluctuation (≈2% of the mean value, with the dominant frequencies on the order of 1 kHz), but which has a significant impact on the flame structure and stability. The flame undergoes a periodic ignition/burn/extinction cycle at about 1 kHz. As a result, unsteady operation of the combustor with large heat transfers to the injector occurs. Furthermore, nonreacting mixing studies are being conducted of the shear coaxial injector under a variety of inner-to-outer velocity and density ratios to investigate the hydrodynamic instabilities characteristics of variable-density, coaxial sheared jets and their link to the observed combustion instabilities.

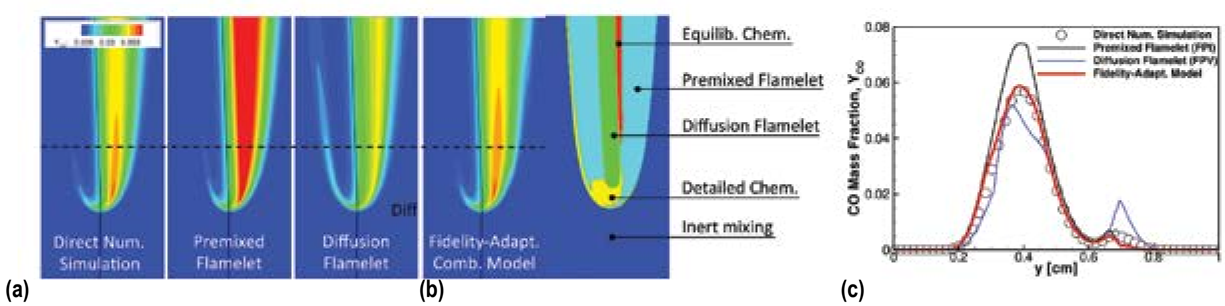


Figure 1: Development of FAM for modeling of multi- and mixed-regime rocket combustion regimes, relevant for predicting blow-out, lift-off, and combustion dynamics: (a) Comparison of CO predictions from DNS, single-regime premixed flamelet and diffusion models, and newly developed FAM model; (b) combustion subzone identification to achieve optimal combustion submodel assignment; and (c) quantitative comparison of CO predictions from DNS, single-regime flamelet models, and FAM.

Characterization of Aluminum/Alumina/ Carbon Interactions Under Simulated Rocket Motor Conditions *Pennsylvania State University*

Project Manager(s)

Kenneth Kuo/Pennsylvania State University
(814) 863–6270

Matthew Cross/ER43
(256) 544–1724

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

Project Description

This activity is investigating the interaction of aluminum (Al) and alumina (Al_2O_3) with carbon in typical solid rocket motor (SRM) environments while considering realistic condensed phase residence times on carbon-containing insulation/nozzle materials surfaces. The primary goal is evaluation of the chemical reaction mechanism and approximate reaction rates between Al_2O_3 and carbon. This effort utilizes multiple test rigs; within the past year, this has included a low-pressure carbon dioxide (CO_2) laser sample heating chamber and a high-pressure induction furnace, which is under development. Some of the highlights from the FY 2014 activities are as follows.

Notable Accomplishments

Laser heating experiments were conducted utilizing an Everlase S48 CO_2 laser capable of delivering 760 W continuously at Penn State's High-Pressure Combustion Lab (HPCL). The beam was augmented using a zinc/selenium lens pair designed to reduce the diameter of the beam and a graphite mask (installed in a water-cooled copper block) to set the final beam diameter and remove the low-power edges of the beam profile. A laser-transparent window assembly, consisting of a purged potassium chloride window within a housing, allowed the augmented laser beam to pass into a low-pressure test chamber. A sample was then placed in the test chamber which was capable of maintaining either subatmospheric or up to 2-atm pressurized gas; either argon (Ar) or carbon monoxide (CO) was used in this test series. The sample consisted of a small graphite 'crucible' containing compressed Al_2O_3 and/or Al powder (1/4-in outer diameter (OD)) mounted on a 1/16-in OD hafnia rod (T_{melt} = 3,031 K). During laser heating, the backside temperature was monitored with an HPCL custom-made, single-bead, 125-µm D-type tungsten-3%/rhenium (W-3%Re/W-25%Re) thermocouple, while the surface temperature was measured by the multicolor pyrometer. The temperature ranges used for these experiments were selected to be consistent with Al/Al_2O_3/carbon reaction onset temperatures and those found on carbon-containing material surfaces inside an SRM.

Over the base year (overlapping with the initial months of FY 2014), 55 laser-heating experiments were conducted. Of those, 29 tests were considered in the nominal configuration with 100% Al_2O_3 in graphite crucible, 23 were conducted with Ar, and six with CO atmospheres. In addition, eight were conducted with various Al_2O_3/Al mixtures. Other testing included graphite heating only, and 100% Al_2O_3 in vacuum. General behavior with temperature was observed with video, along with gas sampling and post-test sample analysis performed on select test samples. For these tests, two heating profiles were utilized: (1) Slow heating (30 to 40 K/s) to a particular temperature and hold for 120 s, and (2) slow ramping up to a high temperature with 5- to 10-s holds at ⊕25- or 50-K increments. Sample temperatures over 2,500 K were examined. X-ray diffraction (XRD) with a microdiffractometer was utilized to examine a select number of post-heated samples. Figure 1 shows extracted video frames of a sample while heating, a photograph of collected particles which ejected from the sample while it was heating, a photograph showing the measurement location for XRD, and the XRD diffraction pattern showing the presence of aluminum carbide (Al_4C_3) post-test. The effect of pressure was examined through a series of thermodynamic calculations for the relevant chemical reactions of interest (see fig. 2). This figure shows the response of three expected reactions; with increased SRM chamber pressure (i.e., higher CO partial pressure), the reaction onset temperatures change significantly and the most likely reactions shift order.

Based upon the initial findings of FY 2014, the remaining portion of the year was dedicated to the development of a unique high-pressure, high-temperature induction furnace (1,000 psia and 2,700 K). This furnace utilized induction heating of larger, well-mixed Al_2O_3/carbon samples within a graphite crucible. In addition to post-test sample analysis, online measurement of sample mass change and temperature was performed. Other Penn State researchers specializing in the development of phase diagrams—and in particular the Al/carbon/oxygen system—were included with the intent of extending the state-of-the-knowledge to pressures significantly higher than atmospheric (current limit of the literature).

In addition to the primary program tasks, support to the NASA Marshall Space Flight Center ER43 technical points of contact on related SRM research has continued, including carbon-cloth phenolic nozzle erosion studies utilizing real-time x-ray radiography, studies of SRM internal insulation, and advanced SRM total and radiative heat transfer diagnostics.

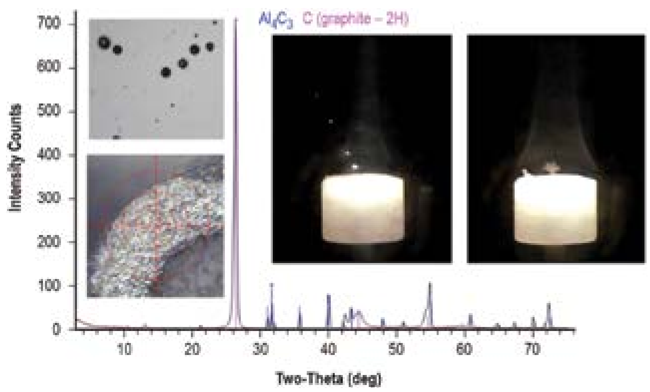


Figure 1: Images of graphite/Al_2O_3 sample heating and XRD diffraction pattern.

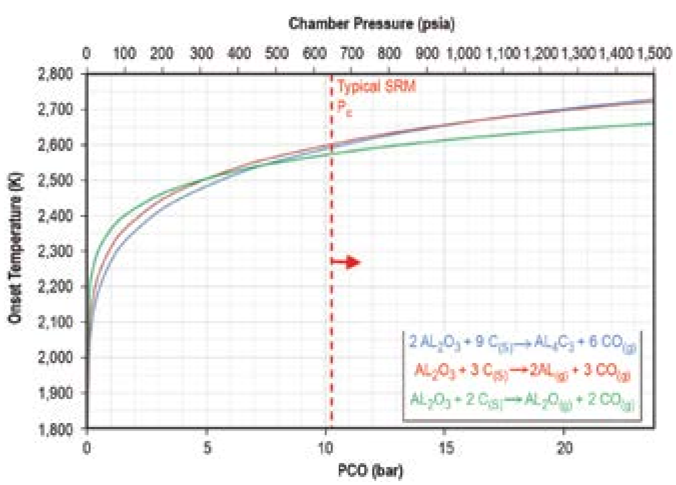


Figure 2: Onset temperature of several Al_2O_3/carbon reactions as functions of CO partial pressure and corresponding SRM chamber pressure.

Acoustic Emission-Based Health Monitoring of Space Launch System Vehicles
University of Utah

Project Manager(s)

V. John Mathews/University of Utah
(814) 863–6270

Daniel Adams/University of Utah
(801) 585–9807

Alan Nettles/EM20
(256) 544–6109

Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
Academia Contracts/Grants

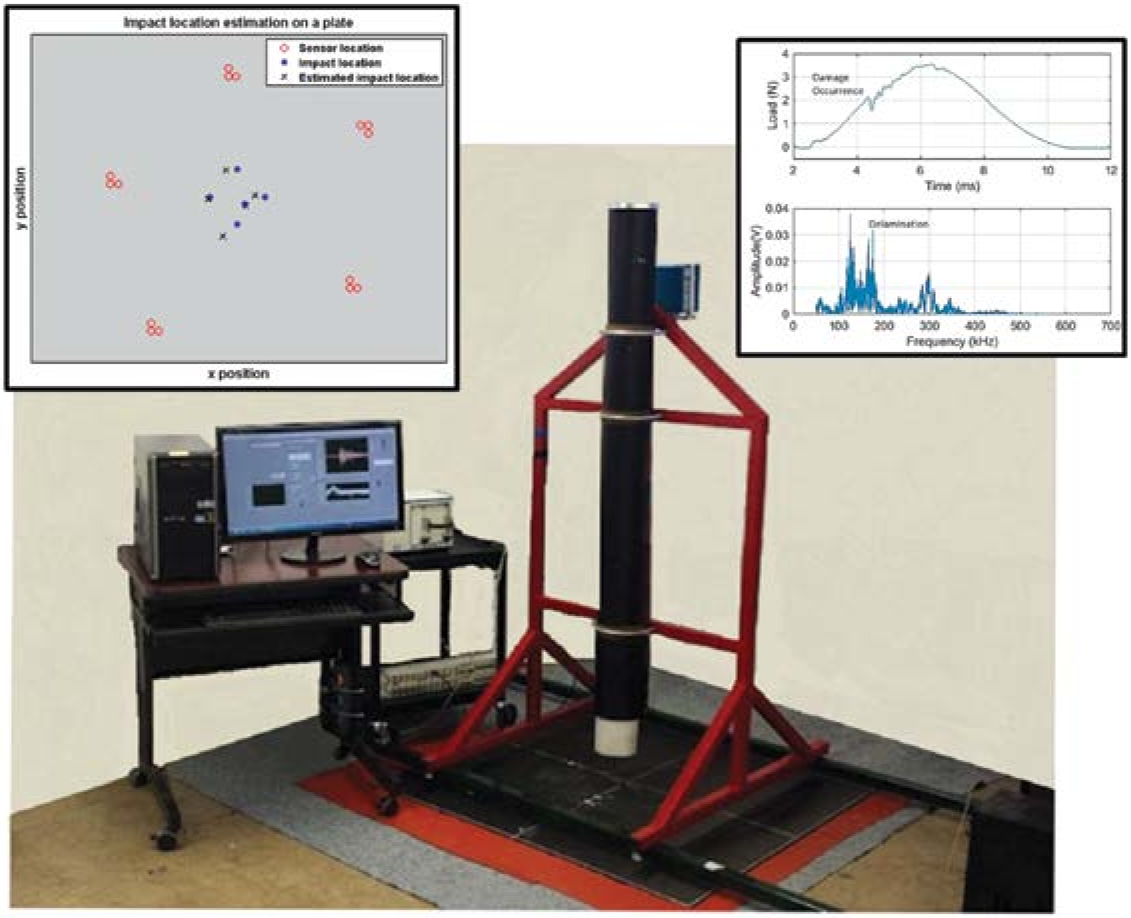
Project Description

An acoustic, emission-based structural health monitoring system is being developed for Space Launch System (SLS) vehicles using a sparse distribution of sensors. In addition to estimating the location of impact events on metallic and composite structures, this system will also determine whether the impact has produced damage in a composite structure and provide an indication of the type of composite damage produced.

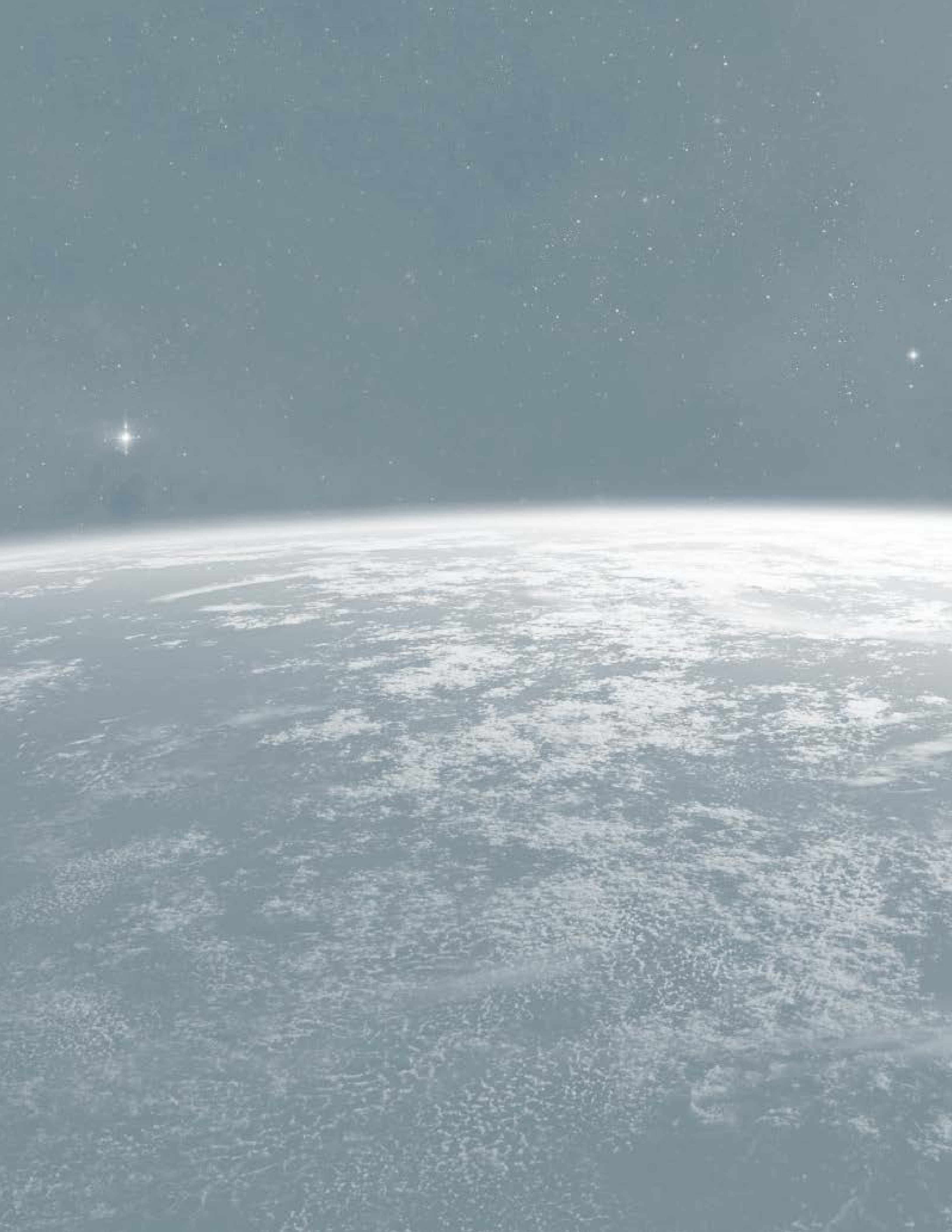
The technical monitor of this activity, Dr. Alan Nettles, worked with the principals to use data collected from ATK on impact testing of composite cases for solid rocket motors (SRMs). These data were used to validate the algorithm and methodology.

Notable Accomplishments

- Developed an automated method for time-of-arrival estimation required for impact location estimation in composite structures.
- Investigation on characteristics of acoustic emission signals associated with the creation of specific types of composite damage.
- Use of acoustic emission signal frequency analysis for impact damage classification in composite panels.
- Developed a modified impact location estimation algorithm for use on composite sandwich structures.
- Developed a method for separating overlapping mode components in sensor signals for active structural health monitoring systems.



Instrumented impact of composite panel with acoustic emission sensor network for location estimation and damage classification. Inserts: (left) Results of location estimation algorithm. Performance analyses have shown that the method works well for composite laminates and sandwich composite structures without prior knowledge of the anisotropic properties of the structure. (Right) Results of acoustic emission signal frequency analysis for impact damage classification. Matrix damage and fiber breakage produce acoustic emission signals with different frequency ranges.



Science Mission Directorate

Mars Ascent Vehicle

Project Manager(s)

John Dankanich/ZP30
(256) 544–3441

Robert Shotwell/Jet Propulsion Laboratory
(256) 544–6562

Sponsoring Program(s)

Science Mission Directorate
Directed Research and Technology, Mars Program

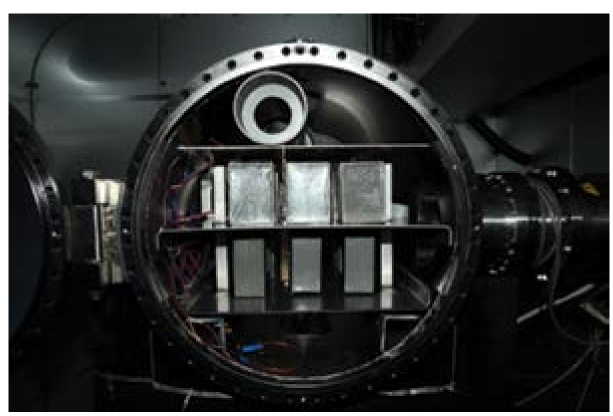
Project Description

Mars Ascent Vehicle (MAV) technology development efforts for 2015 included a wide range of technologies. The scope of 2015 tasks included completion of a third design and analysis cycle (DAC) of a first stage solid motor with industry partner ATK; a fourth DAC in-house led by NASA Marshall Space Flight Center (MSFC); the completion a new propellant formulation project, thrust vector control assessment, concept development, and fuel environmental testing for a hybrid MAV; and assessment of a liquid MAV with potential to freeze and thaw propellants.[1]

First Stage Motor
While anticipated to be a pure engineering development with significant heritage, a first stage solid motor for the MAV based on the ATK STAR™ 15 motor is challenging with the constraints and expected environments for the MAV. The most recent concept includes the MAV carried on 'Mobile MAV,' based on the Curiosity rover. The unique drivers for the solid MAV include the need for long burn times to minimize aero loads and attitude control system (ACS) requirements at burnout, strict limits on volume and length, and exposure to low-temperature thermal cycling. The solid stage motor work included thermal-mechanical design and analyses, ballistics, and computational fluid dynamics. The long-duration, end-burning grain configuration requires significant insulation and low-erosion throat design. The DAC-4 design was capable of meeting the total impulse requirement, but with a length 0.8 inches beyond the requirement.

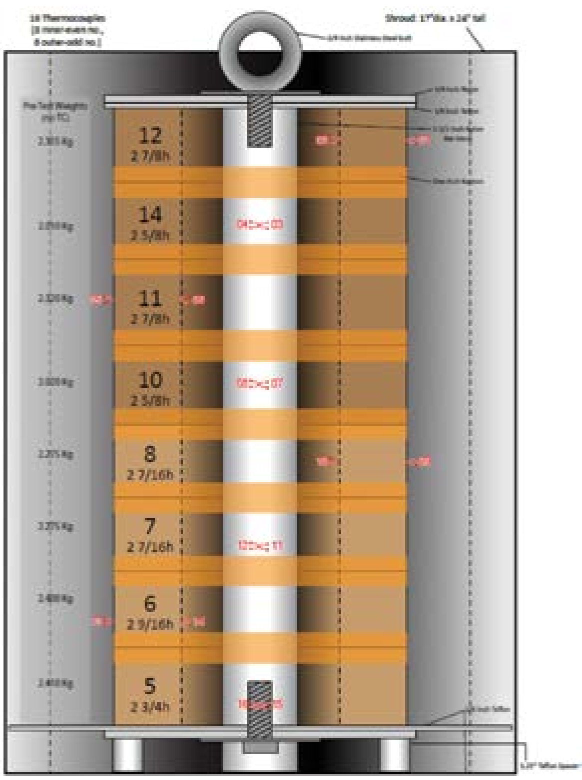
MAV launched from the mobile MAV platform.

Propellant Formulation
Over a two-year effort, ATK and MSFC developed a new propellant formulation specifically for MAV applications. A wide range of propellant blends were evaluated for increasing performance of traditional carboxyl terminated polybutadiene propellants and increasing low-temperature mechanical properties for a hydroxyl terminated polybutadiene (HTPB) propellant. Ultimately, the project selected an HTPB propellant formulation, TP-H-3544, for production and testing. The propellant aged at MSFC first at the Mars transit environment and then for more than one year at the Mars surface conditioned environment. Propellants were removed intermittently from the chamber and tested for mechanical and ballistics performance. The results showed superior tensile properties, outstanding bondline strengths, and no change in properties after aging at the low temperatures of the Mars atmosphere.



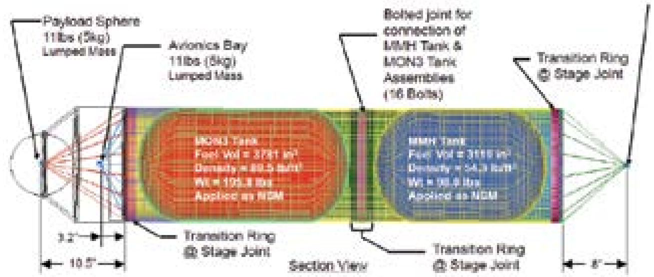
MAV propellant in the test facility.

Hybrid MAV Support
MSFC supported the Jet Propulsion Laboratory program for hybrid motor concept development, ignition recommendation studies, and fuel environmental testing. A hybrid MAV would use a newly developed high regression rate fuel with MON-30 oxidizer. The high regression rate fuel enables the hybrid to be designed with a single cylindrical port in the fuel grain. The concept has the potential to decrease thermal requirements and achieve a gross lift-off mass of 219 kg.[2] One of the key risks includes the new fuel formulation including environmental testing. MSFC is testing the fuel for survivability at low-temperature thermal cycling and assessing fuel-to-case coefficient of thermal expansion mismatch.



Hybrid fuel test configuration.

Liquid—Freeze/Thaw
MSFC also supported an assessment of simply allowing liquid propellant systems to freeze during the Mars surface stay and thaw prior to launch. The system was an MMH/MON-4 concept with a closed-coupled design of components and a propellant management device assessment with provisions to allow for gas to enter and leave as needed during freeze/thaw cycles. Overall, the concept was determined feasible, but would require additional development and testing to sufficiently retire associated risks.



Finite element analysis for freeze/thaw concept.

Anticipated Benefits

All of the FY 2015 efforts focused on technology concepts to enable the MAV to meet the constraints of the robotic Mars Sample Return (MSR) mission and support concept downselect.

Mission Applications

The technologies are focused for the MSR mission; however, they have applicability to other cold environment applications including outer planet/moon missions.

Notable Accomplishments

In FY 2015, the first stage solid motor DAC-4 was complete, meeting nearly all metrics for the two-stage solid MAV; the propellant formulation completed development with superior performance to alternative formulation for the MAV environment, and concepts were developed for reduced mass and resources (heating) required using either liquid or hybrid propulsion systems.

References

1. Shotwell, R.; et al.: "Drivers, Developments, and Options Under Consideration for a Mars Ascent Vehicle," 2016 IEEE Aerospace Conference, Big Sky, MT, March 6–11, 2016.

2. Karp, A.; et al.: "Technology Development and Design of a Hybrid Mars Ascent Vehicle," 2016 IEEE Aerospace Conference, Big Sky, MT, March 6–11, 2016.

Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

Project Manager(s)

H. Philip Stahl/ZP10
(256) 544–0445

Michael Effinger/ZP21
(256) 961–7485

Sponsoring Program(s)

Science Mission Directorate
Astrophysics

Project Description

The Advanced Mirror Technology Development (AMTD) project is in phase 2 of a multiyear effort, initiated in FY 2012, to mature the Technology Readiness Level (TRL) to TRL-6 by 2018 critical technologies required to enable 4-m-or-larger ultraviolet, optical, and infrared (UVOIR) space telescope primary mirror assemblies for general astrophysics and ultra-high contrast observations of exoplanets. AMTD's demonstrated deep core manufacturing method enables 4-m-class mirrors with 20%–30% lower cost and risk. The design tools we have developed increase speed, resulting in a reduced cost for trade studies. In addition, the integrated modeling tools we have developed enable better definition of system and component engineering specifications.

Notable Accomplishments

During FY 2014/15, the advances of AMTD phase 1 were successfully reviewed by the Cosmic Origins Program Office TRL Review Board, and we are progressing in all of our phase 2 technology areas.

Large-Aperture, Low-Areal-Density, High-Stiffness Mirror Substrates

We matured large mirror substrate TRL by quantifying visco-elastic geometric deformations produced during low-temperature fusion, NASA Marshall Space Flight Center (MSFC) performed x-ray tomographic 3D measurements of the 43-cm-diameter, 400-mm-thick, <45 kg/m^2 'deep core' mirror that was successfully fabricated in phase 1 (fig. 1). This mirror was fabricated via a new five-layer 'stack and fuse' process, which is estimated to reduce the cost to fabricate a 4-m-class mirror by ≈30%.

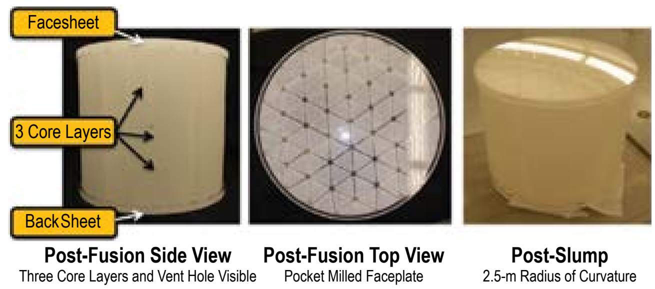


Figure 1: Deep core mirror at different processing stages.

Additionally, Harris performed an A-basis test of the core-to-core low temperature fusion (LTF) bond strength using 60 MOR samples (fig. 2); 30 samples were assembled with nominal alignment and 30 samples were deliberately misaligned. The A-basis Weibull 99% confidence strength allowable based on 49 of the samples was found to be 17.5 MPa, which is ≈50% higher than the strength of core-to-plate LTF bonds.

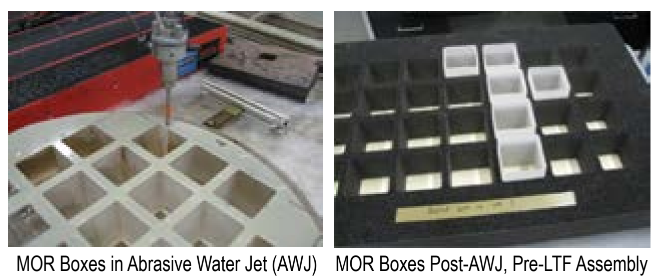


Figure 2: MOR test article fabrication.

Finally, using the data acquired from the x-ray tomography test and A-basis strength test, Harris used a nonlinear visco-elastic tool to design a 4-m-class mirror that could be manufactured via the deep core 'stack and seal' process; then, the mirror was scaled to 1.5 m diameter (fig. 3). The purpose of this mirror is to demonstrate lateral scalability of the fabrication process. It is scheduled for completion in August 2016.

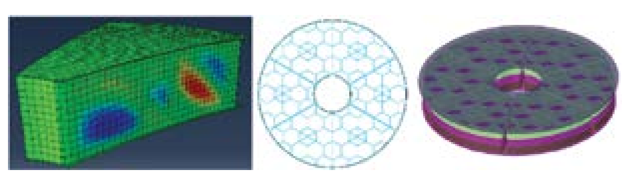


Figure 3: Final design for 1.5-m mirror.

Support System

We continue developing our modeling tool for ANSYS. This tool allows rapid creation and analysis of detailed mirror designs. For example, we studied various mirror support systems integrate to the mirror substrate via kinematic and hexapod mechanisms and their resulting stress distributions (fig. 4), and we evaluated how 100 kg of properly distributed mass can increase the first mode of a 4-m mirror from 50 Hz (725 kg) to 75 Hz (820 kg). Also, we continue to employ undergraduate interns to support these efforts.

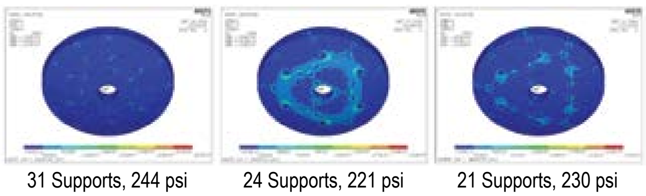


Figure 4: Different support types demonstrated by mirror modeler.

Segment-to-Segment Gap Phasing

We performed an analysis that indicates that 1 nm rms of random segment rigid body motion can produce unwanted speckles at the level of 10^{-8} to 10^{-7} contrast. To get this speckle noise below 10^{-11} requires random rigid body segment motion on the order of 10 pm. Finally, the timeframe for which the primary mirror must be stable (between WFSC cycles) can vary from a few minutes to many tens of minutes depending on the host star's brightness.

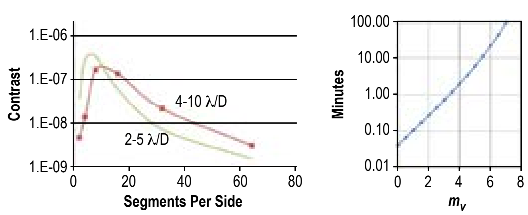


Figure 5: (a) Primary mirror segment motion stability requirement and (b) temporal stability period requirement.

Integrated Model Validation

MSFC developed a new methodology for understanding how mirrors respond to a dynamic thermal environment (fig. 6). Using Fourier theory, any thermal environment can be decomposed into a set of periodic thermal oscillations. These oscillations cause wavefront figure errors with a thermal time constant determined by the mirrors' thermal properties (e.g., mass and conductivity). The amplitude of these errors depends on the amplitude and period of the input thermal oscillation. For the AMTD 4-m point design, the primary mirror wavefront error remains below 10 pm for a 50 mK thermal oscillation of period <140 s. This tool can be used to determine thermal boundary and control conditions for passive and active telescope thermal control.

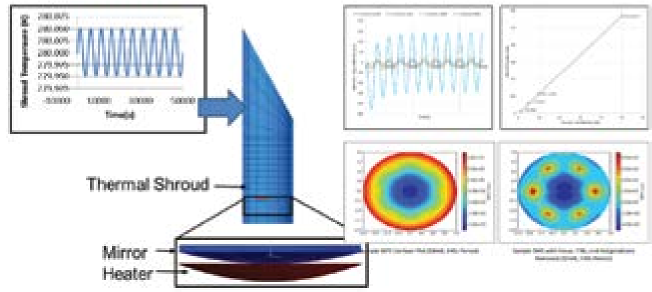


Figure 6: Thermal modulation transfer function for space mirrors.

References

Stahl, H.P.: "Overview and accomplishments of advanced mirror technology development phase 2 (AMTD-2) project," *Proc. SPIE*, Vol. 9602, doi:10.1117/12.2186195, August 2015.

Stahl, M.T.; Shaklan, S.B.; and Stahl, H.P.: "Preliminary analysis of effect of random segment errors on coronagraph performance," *Proc. SPIE*, Vol. 9605, doi:10.1117/12.2190160, August 2015.

Brooks, T.; Stahl, H.P.; and Arnold W.R.: "Advanced Mirror Technology Development (AMTD) thermal trade studies," *Proc. SPIE*, Vol. 9577, doi:10.1117/12.2188371, August 2015.

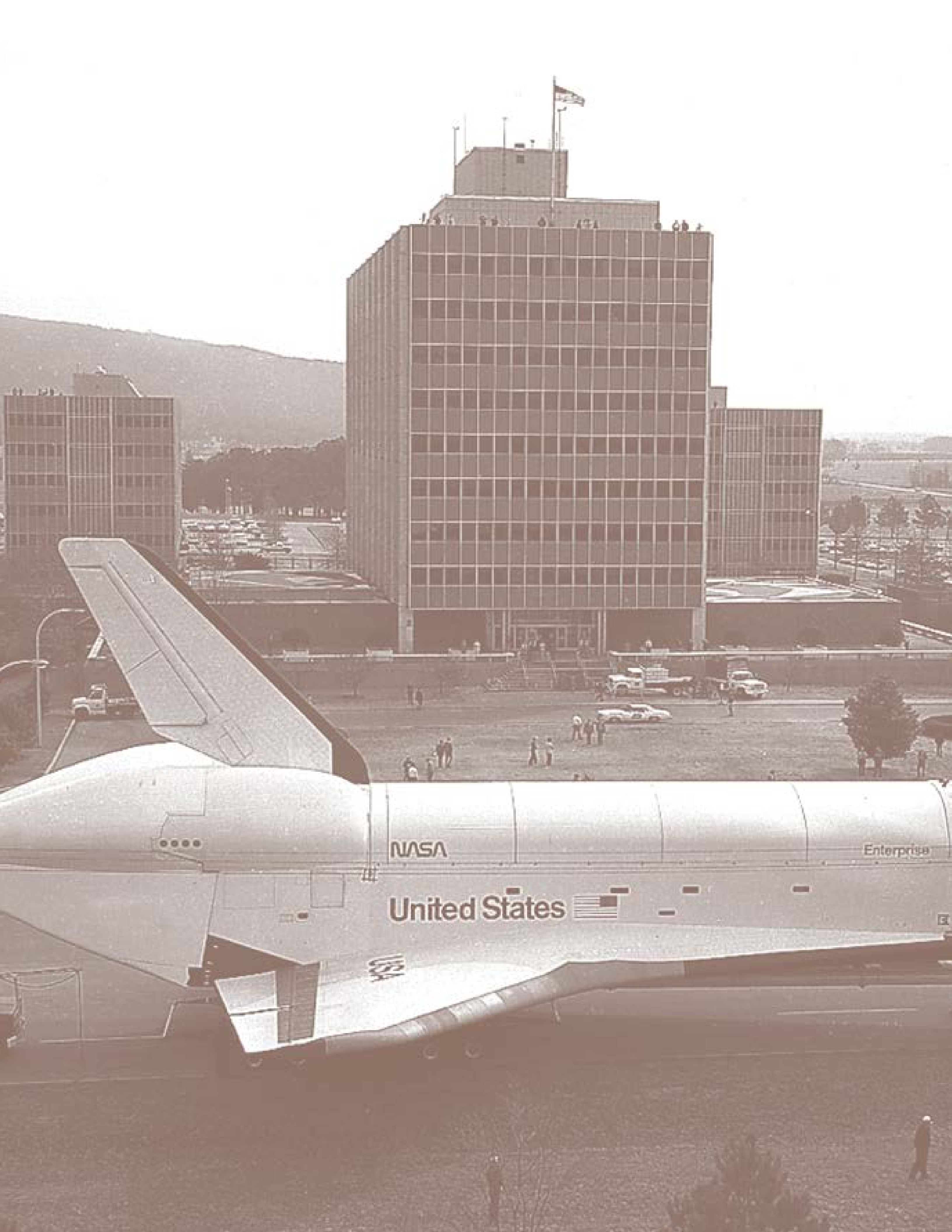
Egerman, R.; et al.: "Status of the Advanced Mirror Technology Development (AMTD) phase 2 1.5m ULE mirror," *Proc. SPIE*, Vol. 9575, doi:10.1117/12.2188566, August 2015.

Gersh-Range, J.; Arnold, W.R.; and Stahl, H.P.: "Edgewise connectivity: an approach to improving segmented primary mirror performance," *J. Ast. Inst. Sys.*, Vol. 1, No. 1, 9 pp., doi:10.1117/1.JATIS.1.1.014002, October 2014.

Stahl, H.P.; et al.: "Advanced mirror technology development (AMTD) project: 2.5 year status," *Proc. SPIE*, Vol. 9143, doi:10.1117/12.2054765, August 2014.

Stahl, H.P.; et al.: "AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes," *Proc. SPIE*, Vol. 9143, doi:10.1117/12.2054766, August 2014.

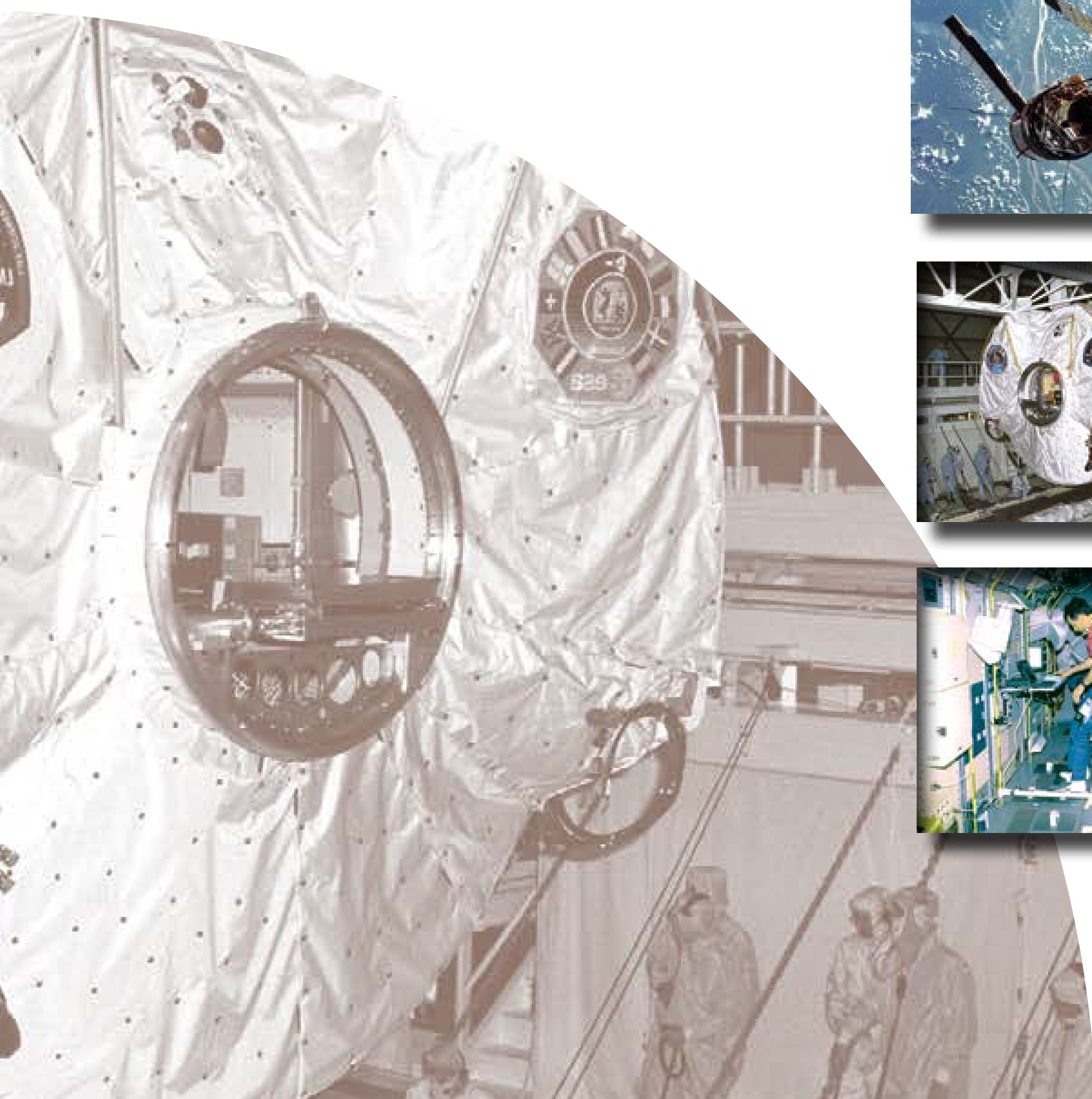
Matthews, G.W.; et al.: "The development of stacked core technology for the fabrication of deep lightweight UV-quality space mirrors," *Proc. SPIE*, Vol. 9143, doi:10.1117/12.2055284, August 2014.


NASA
Enterprise
United States
USA

Space Technology Mission Directorate

Space Technology Mission Directorate

Technology Demonstration Missions



Technology Demonstration Missions Summary

Project Manager(s)

Larry Gagliano/FP50
(256) 544–7175

Danny Harris/FP50
(256) 961–7353

Raymond French/FP50
(256) 961–7642

Sponsoring Program(s)

Space Technology Mission Directorate
Technology Demonstration Missions

Project Description

The Technology Demonstration Missions (TDM) program is completing its fourth year of funding and managing state-of-the-art missions, which align with the strategic goals of NASA and the Space Technology Mission Directorate. During the 2014–2015 year, NASA Marshall Space Flight Center (MSFC) has managed seven projects as part of the TDM program:

- **Low Density Supersonic Decelerator (LDSD)**— This project utilizes balloon-launched supersonic test flights to demonstrate the capabilities of new inflatable decelerators and parachute technologies that will enable Mars landings of larger payloads with even greater precision.

- **Green Propellant Infusion Mission (GPIM)**—The goal of this project is a spaceflight demonstration of a complete propulsion system for spacecraft attitude control and primary propulsion using the 'green propellant' AF-M315E instead of hydrazine.

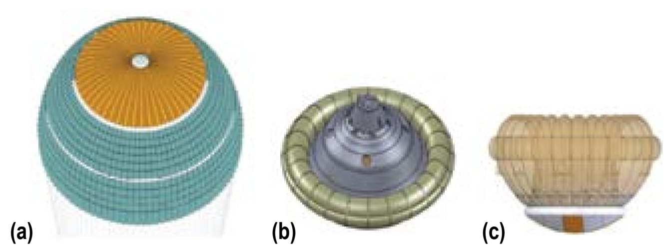
- **Deep Space Atomic Clock (DSAC)**—This project is developing a small, low-mass atomic clock capable of providing unprecedented stability for deep space navigation and radio science.

- **Evolvable Cryogenics (eCryo)**—The eCryo project is developing, integrating, and validating cryogenic fluid management technologies on a scale that is relevant to meet the mission needs for Space Launch System (SLS) upper stages as well as for other exploration missions.

- **Laser Communications Relay Demonstration (LCRD)**—This project is developing and building hardware with the goal of a minimum two-year space flight demonstration to advance optical communications technology. These advanced communications relays would then be infused into deep space and near Earth operational systems.

- **Composites for Exploration Upper Stage (CEUS)**—This project is focused on the fabrication and ground testing of large composite dry structures for future human-rated launch vehicles in an effort to reduce weight, cost, and risk while improving performance.

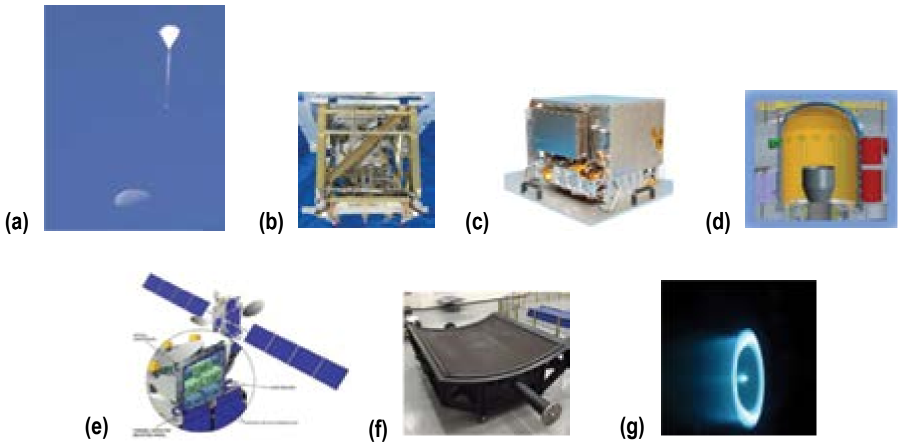
- **Solar Electric Propulsion (SEP)**—The goal of the SEP project is to develop and fly a 50-kW spacecraft that uses flexible blanket solar arrays for power generation and electric propulsion for primary propulsion. This spacecraft will be capable of delivering payload from low-Earth orbit (LEO) to higher orbits and into deep space.



Models of the components of the LDSD hardware: (a) Advanced supersonic parachute, (b) SIAD-R, and (c) SIAD-E.

Anticipated Benefits

All of the TDM projects, including those in which MSFC is involved, are designed to add key capabilities to the suite of technologies available to NASA for future exploration missions, for deep space missions, and for conducting science on the International Space Station and in LEO.



(a) LDSD demonstration, (b) GPIM hardware, (c) DSAC hardware, (d) eCryo test concept, (e) LCRD model, (f) CEUS hardware, and (g) SEP demonstration.

Mission Applications

The technology development being managed by TDM can be used to enhance existing missions or to enable new ones.

Notable Accomplishments

2015 was another year in which TDM projects had many successes. The major accomplishments for the seven projects involving MSFC are as follows:

- **LDSD**—A successful subsonic inflation load test on two 30-m supersonic ring sail parachutes was completed, as well as the integration activities for Test Vehicles 2 and 3. Also, a supersonic flight dynamics test was conducted which yielded profitable data, though the parachute did not survive full inflation.

- **GPIM**—The project completed multiple successful integrations of hardware this year, including five thrusters onto the Green Propellant Propulsion Subsystem (GPPS) and the GPPS onto the BCP-100 spacecraft.

- **DSAC**—Both the flight software and the clock hardware were completed, integrated, and tested this year. Additionally, the whole payload began flight payload testing and integration.

- **eCryo**—This year, the eCryo project successfully completed its formulation review and Key Decision Point-C. Additionally, lessons learned from the Engineering Development Unit tank build and test were shared at a workshop, and a radio frequency mass gauge avionics simulator was designed, built, and delivered to NASA Goddard Space Flight Center for a flight demonstration. Also, phase A testing of a study for an integrated vehicle fluids system was completed.

- **LCRD**—Many necessary components, such as the engineering model space switching unit, two flight controller electronics boxes, and the optical gimbal assemblies were delivered for integration and testing. A successful demonstration of bidirectional communication between the MIT Lincoln Laboratory and the LCRD hardware was also completed.

- **CEUS**—The project successfully completed a System Requirements Review and Key Decision Point-B as well as establishing an Automated Fiber Placement robotic fabrication capability at NASA Langley Research Center and MSFC. Two composite material deliveries were completed, and a trade study to refocus the project scope to the SLS Universal Stage Adapter (USA2) is nearing completion.

- **SEP**—The project completed fabrication and testing of 300- and 120-V power processing units, as well as a HERMeS thruster operating in a vacuum chamber at NASA Glenn Research Center. Subsequently, integration tests were performed demonstrating the HERMeS thruster operation with the 300- and 120-V power processing units. In conjunction with the Asteroid Retrieval Robotic Mission team, an Asteroid Retrieval Vehicle reference configuration was developed for future missions.

Evolvable Cryogenic Project Portfolio

Project Manager(s)

Arthur Werkheiser/ZP30
(256) 544–1269

Sponsoring Program(s)

Space Technology Mission Directorate
Technology Demonstration Missions

Project Description

The evolvable Cryogenic Project (eCryo) is the ground-based version of the Cryogenic Propellant Storage and Transfer project. It is a long-running program in Science and Technology Mission Directorate to enhance the knowledge and technology related to handling cryogenic propellants; specifically liquid hydrogen. eCryo is a multi-Center effort that features NASA Marshall Space Flight Center (MSFC) and NASA Glenn Research Center. In 2015, the eCryo project had several projects running in parallel. The projects that were handled mostly by MSFC were as follows: valve seat leak test (VSLT), high accuracy delta pressure transducer (HADPT), and testing of integrated vehicle fluids (IVFs) (a United Launch Alliance (ULA) patented design) for the benefit of the Space Launch System (SLS) program.

The VSLT was an effort to find a better cryogenic valve seat material that could reduce leakage of cryogenic liquids by at least two magnitudes. Current cryogenic technology is only required to operate for a handful of hours; therefore, the leak rate is not a great concern. VSLT for eCryo is increasing the state of the art for valve technology in order to make the information available industry-wide. The VSLT project was a success and will continue the investigations into 2016 under another name: the Large-Scale Leak Fixture project.

Valve seat leak test element.

The HADPT was a similar effort to VSLT to increase the state of the art for cryogenic pressure transducers. A differential pressure transducer is a sensor that is used to measure flowing cryogens. The focus for HADPT was on repeatability.

Pressure transducer testing.

The largest part of the MSFC eCryo portfolio is the evaluation of ULA's patented integrated vehicle fluids system. The general idea is to use the 'boiled off' vapors from cryogenic propellants to be captured and used to generate useful energy and byproducts. eCryo has teamed with the SLS Advanced Development group to evaluate the system for SLS future configurations. Computer modeling of the system and some cryogenic testing at MSFC's Test Stand 300 will be conducted to generate data for the evaluation.

MSFC's Test Stand 300 during liquid nitrogen testing — Phase A of IVF.

Anticipated Benefits

MSFC has more data on exceptionally low leak-level cryogenic valve seat materials and designs. MSFC continues to catalyze the sensor and cryogenic fluid control industries to provide longer term solutions to measure and control cryogenic liquids. This work is essential on the journey to Mars.

Mission Applications

- Improved manufacturing techniques for propellant tanks and fluid control systems.

- Improved thermal modeling of cryogenic systems.

Notable Accomplishments

MSFC is applying for a patent on the cryogenic valve design.

Composites for Exploration Upper Stage

Project Manager(s)

John Vickers/EM01
(256) 544–3581

John Fikes/ZP30
(256) 544–5570

Sponsoring Program(s)

Space Technology Mission Directorate
Technology Demonstration Missions

Project Description

The Exploration Upper Stage (EUS) and Universal Stage Adapter (USA) are needed for NASA's Space Launch System (SLS) to provide additional capability to travel to deep space. The current state-of-the-art material for structures of this scale is an aluminum alloy that poses significant challenges to further reduce weight while maintaining requisite safety margins. Existing human space flight vehicles do not utilize composites for primary structures since critical technologies have not been validated at such a scale in a relevant environment. The purpose of this project is to design, build, and test composite USA structures on the same scale needed for the EUS to validate manufacturability, structural margins, and weight savings (fig. 1). Also, the project will advance the certification pathway for the inclusion of composites on future large human-rated launch vehicles. The objective is to provide designers a validated alternative structural material candidate in future trade studies for SLS as well as other large booster and space science platform structures.

The need for the Technology Demonstration Missions (TDM) project Composites for Exploration Upper Stage (CEUS) is directly related to the 2014 NASA Strategic Plan:

- Strategic Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space.
  - Objective 1.7: Transform NASA missions and to advance the nation's capabilities by maturing crosscutting and innovative space technologies.
- Strategic Goal 2: Advance understanding of Earth and develop technologies to improve the quality of life on our home planet.
  - Objective 2.3: Optimize Agency technology investments, foster open innovation, and facilitate technology infusion, ensuring the greatest national benefit.

The goal of the TDM CEUS project is to advance the certification pathway for large composite structures and to demonstrate the manufacturability, structural capabilities, and weight savings of using composites in human space flight vehicle primary structure applications over the use of traditional metallic structures. One of the investments that NASA Marshall Space Flight Center (MSFC) has made toward achieving this goal is the automated fiber placement (AFP) capability shown in figure 2.

Figure 1: Technology development for USA risk reduction.

Figure 2: MSFC composites AFP capability.

AFP over core splice and adhesive film. | AFP of localized build-ups. | Vacuum bagged ready for cure. | Removing cured panel from tool.

Figure 3: Manufacturing process development.

The project is a NASA in-house technology project that utilizes skills across multiple NASA Centers. The major focus areas are composites materials led by NASA Glenn Research Center, joints led by NASA Langley Research Center (LaRC), design led by MSFC, manufacturing led by MSFC, and analysis led by LaRC. The project management and the large-scale testing reside at MSFC.

The composite manufacturing processes are key to developing robust, repeatable, and affordable lightweight space structures. The CEUS team has been working on developing the processes required throughout the year, as shown in figure 3. The team is doing material equivalency testing to a known composite material database, evaluating different joint and structural wall designs, and evaluating lessons learned from past composites projects to mature composite technologies and instill confidence in utilizing composites for human space applications.

Anticipated Benefits

In-house investments help develop an expert NASA workforce that are not just smart buyers but also smart doers and innovators. This work will advance the certification pathway for the inclusion of composites on future large human-rated launch vehicles. Large-scale composite structures suitable for future heavy-lift vehicles and other in-space applications will enable future space missions by improving performance and affordability.

Mission Applications

A potential initial target application for the composite technology is an upgrade to the upper stage of SLS.

Notable Accomplishments

A composite tool that will allow for 1/8 arc segments of a 12-ft-tall cylindrical panel to be manufactured at the MSFC Composites Technology Center was designed, built, and delivered to MSFC (fig. 4).

Figure 4: Composite tool manufactured by Janicki Industries.

Space Technology Mission Directorate

Centennial Challenges Program

Centennial Challenges

Program Manager(s)

Monsi Roman/FP30
(256) 544–4071

Eric Eberly/ZP30
(256) 544–2092

Sponsoring Program(s)

Space Technology Mission Directorate
Centennial Challenges Program

Program Description

NASA’s Centennial Challenges Program was initiated in 2005 to directly engage the public in the process of advanced technology development. The program offers incentive prizes to generate revolutionary solutions to problems of interest to NASA and the nation. The program seeks innovations from diverse and nontraditional sources. Competitors are not supported by government funding and awards are only made to successful teams when the challenges are met.

In keeping with the spirit of the Wright Brothers and other American innovators, the Centennial Challenges offer prizes to independent inventors, including small businesses, student groups, and individuals. These independent inventors are sought to generate innovative solutions for technical problems of interest to NASA and the nation, and to stimulate opportunities for creating new industries and new business ventures.

The core of Centennial Challenges: opportunity, innovation, and communication.

The West Virginia University Mountaineers took home a Level 2 prize for $100,000 at the 2015 Sample Return Robot Challenge, which offers a total $1.5 million prize purse.

The Cube Quest Challenge offers a $5.5 million prize purse.

Anticipated Benefits

The Centennial Challenges Program advances technologies that are current barriers to achieving future NASA goals. Challenges conducted address current topics on NASA's technology roadmap that are also beneficial to other technology sectors here on Earth. Teams have a unique opportunity to leverage their ideas whether they win prize money or not. Through the visibility of the challenges, all participants gain the opportunity to be seen by and network with not only one another, but also industries that may be searching for similar solutions, as well as media outlets and with the public at outreach events.

Notable Accomplishments

The fourth year of the Sample Return Robot Challenge was hosted by the nonprofit partner Worcester Polytechnic Institute. The purpose is to demonstrate robots that can locate and retrieve geologic samples from a wide and varied terrain without human control or use of terrestrial navigation aids. Fourteen teams participated in the Level 1 competition; no team qualified to move onto the next level of the challenge. The two teams that previously qualified for Level 2 competed in the 2015 event. West Virginia University met two of the Level 2 requirements and received a $100,000 award. The total prize purse for this challenge is $1.5 million.

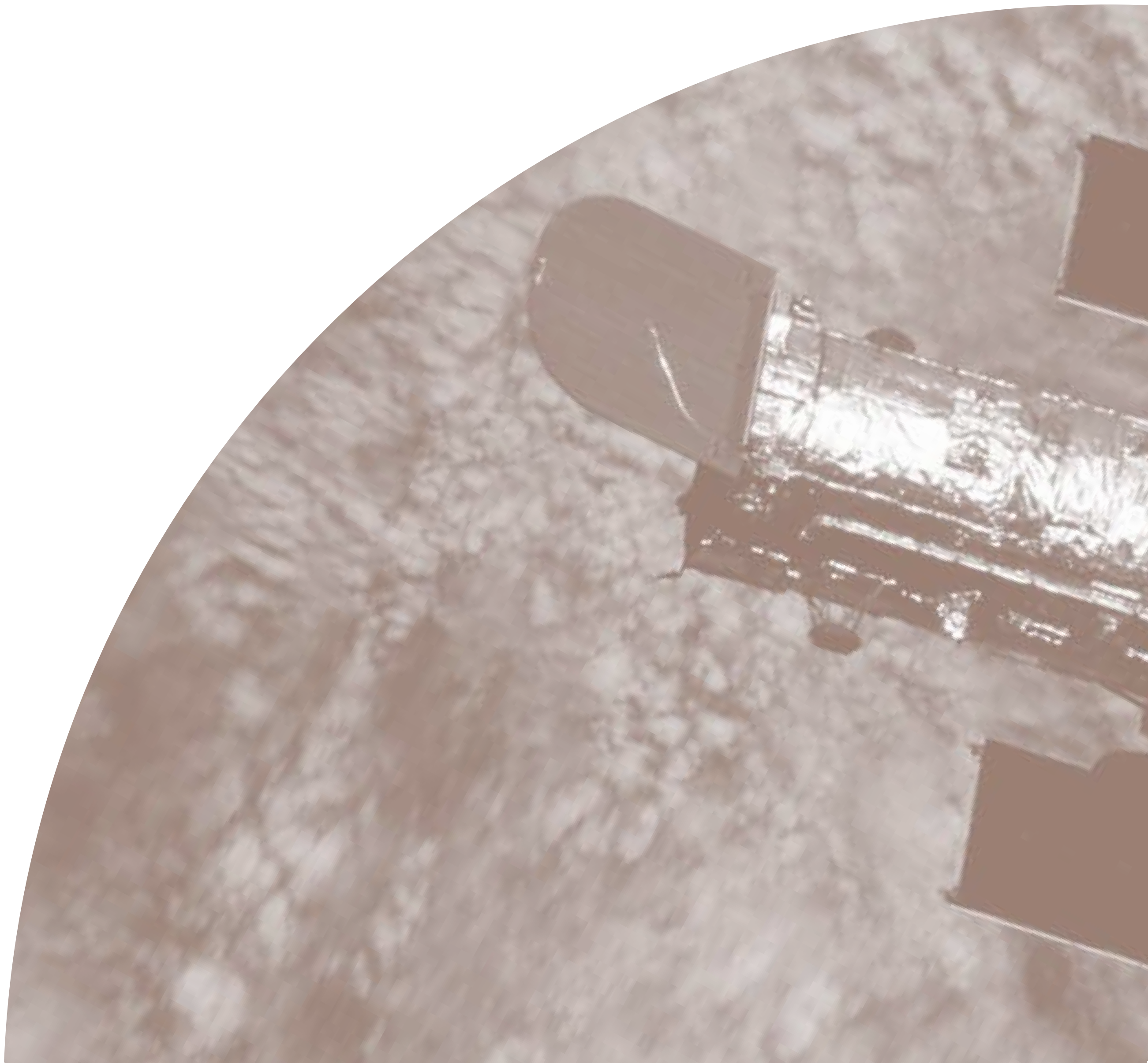
The second year of the Mars Ascent Vehicle Challenge opened for registration in late FY 2015. Teams are challenged to develop an autonomous robotic system that can load a sample into a rocket, launch to a predetermined altitude of 5,280 ft, and safely return the sample container to the Earth's surface. A team from NASA Marshall Space Flight Center is managing the challenge. Fifteen teams participated in the 2015 competition (first year). The winners of the competition were North Carolina State University (first place, $25,000) and Tarleton State University (second place, $15,000). The total prize purse for this challenge is $50,000.

The first year of the Cube Quest Challenge, which included the first of four Ground Tournaments, was executed in FY 2015. The purpose of the challenge is to design, build, and launch flight-qualified small satellites capable of advanced operations near and beyond the Moon to demonstrate communications and propulsion technologies. A team from NASA Ames Research Center, working with San Jose State University, is managing this challenge. Thirteen teams participated in Ground Tournament-1; Ground Tournament-2 and Ground Tournament-3 will be executed in FY 2016, with Ground Tournament-4 taking place in FY 2017. Five teams met Ground Tournament-1 requirements and won $20,000 each. The top three teams that win Ground Tournament-4 will have the opportunity to become secondary payloads on the first integrated flight of NASA's Orion spacecraft and Space Launch System rocket. The total prize purse for this challenge is $5.5 million.

The design challenge of the 3D Printed Habitat Challenge was executed in FY 2015. The purpose of the challenge is to advance the additive construction technology to create sustainable housing on Earth and beyond. NASA has partnered with the nonprofit organization America Makes to manage the challenge. Over 165 entries were received for the design competition; 94 met the minimum requirements. The top 30 competed for the top three places at the Maker Faire in New York. The first-place winner, Team Space Exploration Architecture and Clouds Architecture Office, was awarded $25,000. The second-place winner, Team Gamma (Foster+Partners), was awarded $15,000. The third-place winner, EAS European Astronaut Centre, was not eligible to receive prize money because the team was not from the United States. Level 2 of the challenge will be executed in FY 2016 and FY 2017. The total prize purse for this challenge is $2.25 million.

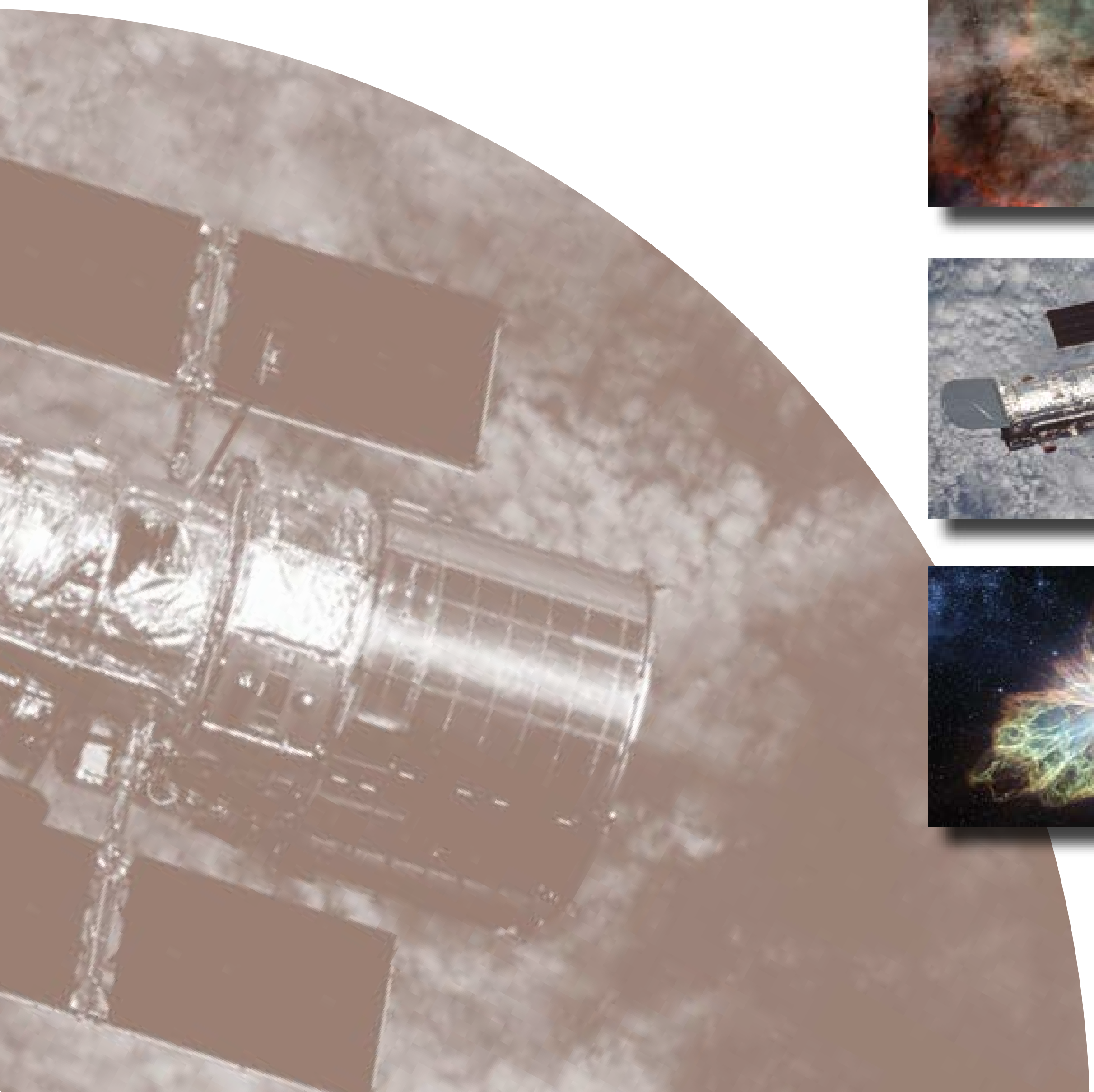
References

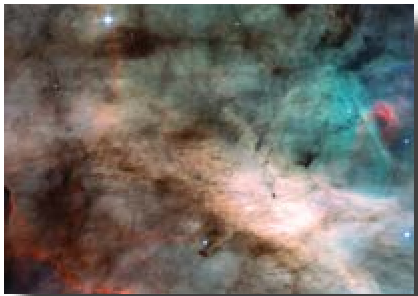
Visit <http://www.nasa.gov/winit> for more information on the program and on active, upcoming, and past challenges.



Space Technology Mission Directorate

Game Changing Development





Fast Light Optical Gyroscopes

Project Manager(s)

David D. Smith/ES34
(256) 544–7778

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

Next generation space missions are currently constrained by existing spacecraft navigation systems, which are not fully autonomous. These systems suffer from accumulated dead-reckoning errors and must therefore rely on periodic corrections provided by supplementary technologies that depend on line-of-sight signals from Earth, satellites, or other celestial bodies for absolute attitude and position determination, which can be spoofed, incorrectly identified, occluded, obscured, attenuated, or insufficiently available. These dead-reckoning errors originate in the ring laser gyros themselves, which constitute inertial measurement units.

Increasing the time for standalone spacecraft navigation therefore requires fundamental improvements in gyroscope technologies. One promising solution to enhance gyro sensitivity is to place an anomalous dispersion or fast light material inside the gyro cavity. The fast light essentially provides a positive feedback to the gyro response, resulting in a larger measured beat frequency for a given rotation rate, as shown in figure 1. Game Changing Development has been investing in this idea through the Fast Light Optical Gyros (FLOG) project, a collaborative effort that began in FY 2013 between NASA Marshall Space Flight Center (MSFC); the U.S. Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC); and Northwestern University. MSFC and AMRDEC are working on the development of a passive FLOG (PFLOG), while Northwestern is developing an active FLOG. The project has demonstrated new benchmarks in the state of the art for scale factor sensitivity enhancement. Recent results show cavity scale factor enhancements of >300 for passive cavities.

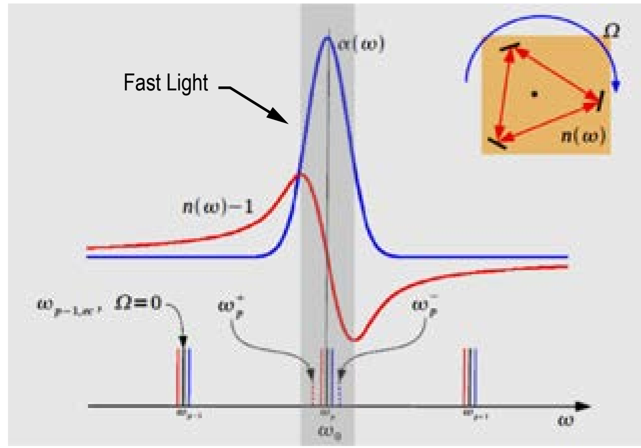


Figure 1: Illustration of how the response of a gyroscope is enhanced by fast light. The cavity modes are split by the rotation of the gyro. In the fast light region, the refractive index, $n(\omega)$, decreases with frequency, ω, which pushes on the modes and further increases the splitting.

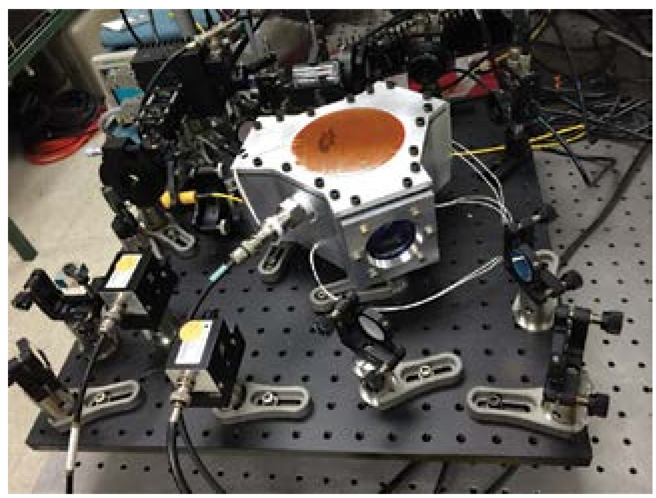


Figure 2: Monolithic, vacuum-enclosed, temperature-stabilized atomic vapor PFLOG cavity on a rotation stage.

Anticipated Benefits

FLOG addresses a critical need for navigation technologies that can meet the complexities of next generation space missions, which will involve a diverse set of navigational challenges that cannot be supported with current methods. The development of onboard autonomous navigation technologies is critical to meeting these challenges, which range from cooperative flight to rendezvous with asteroids and other small bodies. FLOG is an entirely onboard technology that does not rely on the reception of signals external to the spacecraft, extending the time for standalone navigation and reducing the need for updates from startrackers.

Mission Applications

In addition to the benefits for navigation, the improvements in gyro sensitivity open up new science possibilities such as ground-based measurements of the general relativity Lense-Thirring frame dragging effect, tabletop gravitational wave detection, and enhancement of the sensitivity-bandwidth product for interferometric gravitational wave detectors under development by the Laser Interferometric Gravitational-wave Observatory project. The increase in sensitivity can also be traded off against system size, which could benefit other applications that place a premium on compactness, such as pointing and tracking, high-bandwidth satellite and interplanetary laser communications, vehicle motion compensation for synthetic aperture radar, automatic rendezvous and docking systems, and rover/lander localization in non-GPS environments.

Notable Accomplishments

- Achieved largest cavity scale factor enhancement measured in any system (>300) by temperature tuning an atomic vapor in a unidirectional passive cavity, demonstrating possibility for reduction in quantum noise-limited sensitivity.

- Integrated all PFLOG components on a portable breadboard and characterized system on a rotation stage.

- Fabricated and assembled a new monolithic, vacuum-enclosed, magnetically-shielded, temperature-stabilized, high-finesse cavity and integrated the cavity into an atomic vapor PFLOG for testing on a rotation stage (fig. 2).

References

Smith, D.D.; Chang, H.; Myneni, K.; and Rosenberger, A.T.: “Fast-light enhancement of an optical cavity by polarization mode coupling,” *Phys. Rev. A*, Vol. 89, 053804, 2014.

Smith, D.D.; Chang, H.; Myneni, K.; and Rosenberger, A.T.: “Fast light enhancement by polarization mode coupling in a single cavity,” *Proc. SPIE 8998*, in *Advances in Slow and Fast Light VII*, M.S. Shahriar and F.A. Narducci (eds.), 2014.

Myneni, K.; Smith, D.D.; Odutola, J.A.; and Schambeau, C.A.: “Tuning the scale factor and sensitivity of a passive cavity with optical pumping,” *Phys. Rev. A*, Vol. 85, 063813, 2012.

Smith, D.D.; Myneni, K.; Odutola, A.; and Diels, J.C.: “Enhanced sensitivity of a passive optical cavity by an intracavity dispersive medium,” *Phys. Rev. A*, Vol. 80, 011809, 2009.

Pati, G.S.; Tripathi, R.; Gopal, V.; et al.: “Ultrahigh enhancement in absolute and relative rotation sensing using fast and slow light,” *Phys. Rev. A*, Vol. 75, 053807, 2007.

Adjustable Grazing-Incidence X-ray Optics

Project Manager(s)

Stephen L. O'Dell/ZP12
(256) 961–7776

Paul B. Reid/Smithsonian Astrophysical Observatory
(617) 495–7233

Sponsoring Programs(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

With its unique subarcsecond imaging performance, NASA's Chandra X-ray Observatory[1] illustrates the importance of fine angular resolution for x-ray astronomy. Indeed, the future of x-ray astronomy relies upon x-ray telescopes with comparable angular resolution but larger aperture areas. Combined with the special requirements of nested grazing-incidence optics, mass and envelope constraints of spaceborne telescopes render such advances technologically and programmatically challenging.[2]

The goal of this technology research is to enable the cost-effective fabrication of large-area, lightweight grazing-incidence x-ray optics with subarcsecond resolution. Toward this end, the project is developing active x-ray optics[3,4] using slumped-glass mirrors with thin-film piezoelectric arrays (fig. 1) for correction of intrinsic or mount-induced distortions (fig. 2).[5]

Partnering institutions for this project are the Smithsonian Astrophysical Observatory (SAO), Pennsylvania State University (PSU), and NASA Marshall Space Flight Center (MSFC). SAO is responsible for overall direction, mirror substrates, metrology,[6,7] and analyses; PSU, for development of thin-film piezoelectric arrays;[8–10] and MSFC, for coating studies, additional metrology, and x-ray testing (fig. 3).

(a)

(b)

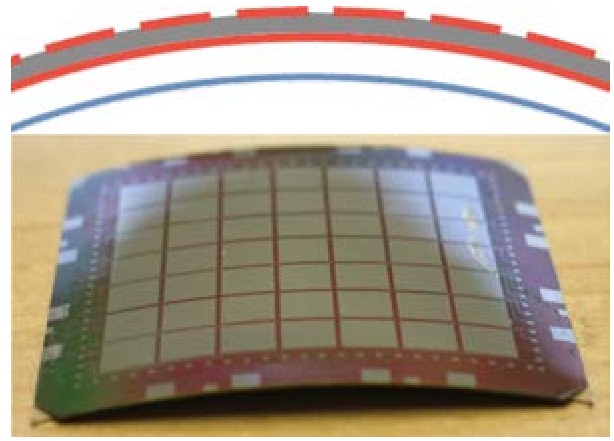


Figure 1: Grazing-incidence conical mirror segment with a backside piezoelectric array for active figure correction through voltage-controlled bimorph deformation. The drawing (a) shows—in cross-section from inner concave surface outward—a thin-film optical coating (blue), the slumped-glass substrate (clear), a thin-film ground electrode (red), a thin-film piezoelectric layer (gray), and a thin-film pixilated electrode (red). The photo (b) displays a fabricated active mirror segment, with a 7×7 array of 1-cm square electrodes.

(a)

(b)

(c)

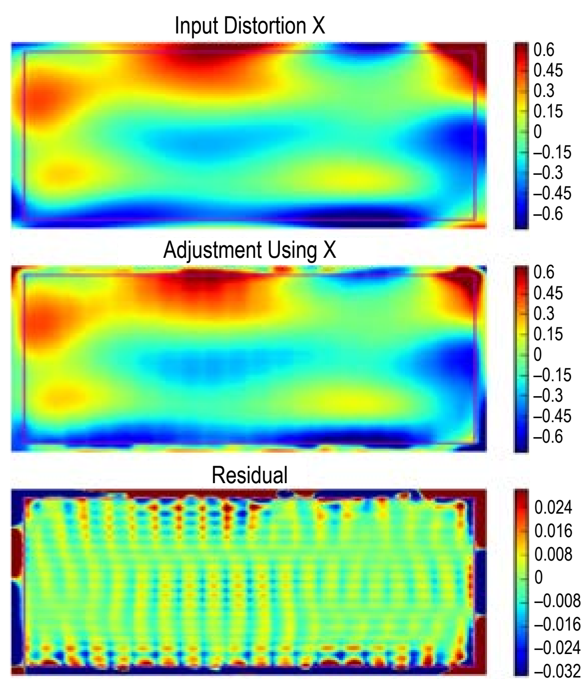


Figure 2: Simulated figure error maps for a segmented mirror showing (a) initial error with respect to the prescribed mirror figure, (b) applied corrective adjustment, and (c) residual figure error after applied correction.

(a) (b) (c)


Figure 3: MSFC capabilities supporting the development of adjustable grazing-incidence optics: (a) Coating chamber used for developing controlled-stress sputtered deposits; (b) a vertical long-trace profilometer, one of multiple metrology instruments for charcterizing x-ray mirror surfaces; and (c) the 3-m-diameter (vacuum) instrument chamber at MSFC's 100-m-long x-ray test facility.

Anticipated Benefits

The primary anticipated benefit is active correction of grazing-incidence x-ray optics for space applications. This technology is equally applicable to normal incidence optics, although existing adaptive optics technologies are adequate in situations where neither mass nor envelope is an issue.

Mission Applications

The mission applications for active grazing-incidence optics are large-area lightweight telescopes for x-ray astronomy. Other potential applications include beam-focusing x-ray mirrors for synchrotron light sources and for x-ray free-electron lasers, although alternative technologies are suitable for these ground-based applications. The underlying thin-film actuator technologies are also applicable to lightweight normal incidence deformable mirrors.

Notable Accomplishments

PSU made significant progress in developing thin-film pixilated piezoelectric devices — over 90% yield[10] in active pixels, on-device thin-film transistors[8] (for row-column addressing) and strain gauges (to monitor deformations), and use of anisotropic conductive films[8] (to simplify electrical connections). MSFC has developed an in situ stress monitor to help accurately control coating stress during deposition[11] and is preparing with SAO for x-ray testing in late 2016.

References

1. Weisskopf, M.C.; et al.: "Chandra X-ray Observatory (CXO): overview," *SPIE*, 4012, 2, 15 pp., 2000.
2. O'Dell, S.L.; et al.: "Toward large-area sub-arcsecond x-ray telescopes," *SPIE*, 9208, 05, 14 pp., 2014.
3. Schwartz, D.A.; et al.: "Technology requirements for a square-meter, arcsecond-resolution telescope for x-rays: the SMART-X mission," *SPIE*, 9208, 06, 8 pp., 2014.
4. O'Dell, S.L.; et al.: "Toward active x-ray telescopes II," *SPIE*, 8503, 07, 15 pp., 2012.
5. Reid, P.B.; et al.: "Development status of adjustable grazing-incidence optics for 0.5-arcsecond x-ray imaging," *SPIE*, 9208, 07, 9 pp., 2014.
6. Allured, R.; et al.: "Measuring the performance of adjustable x-ray optics with wavefront sensing," *SPIE*, 9144, 1D, 8 pp., 2014.
7. Allured, R.; et al.: "Improved control and characterization of adjustable x-ray optics," *SPIE*, 9603, 1M, 10 pp., 2015.
8. Johnson-Wilke, R.L.; et al.: "ZnO thin-film transistors and electronic connections for adjustable x-ray mirrors: SMART-X telescope," *SPIE*, 9208, 09, 9 pp., 2014.
9. Wilke, R.H.; et al.: "Sputter deposition of PZT piezoelectric films on thin glass substrates for adjustable x-ray optics," *ApOpt*, 52, 3412, 8 pp., 2013.
10. Johnson-Wilke, R.L.; et al.: "Improving yield of PZT piezoelectric devices on glass substrates," *SPIE*, 8503, 0A, 9 pp., 2012.
11. Broadway, D.M.; et al.: "Achieving zero stress in iridium, chromium, and nickel thin films," *SPIE*, 9510, 0E, 15 pp., 2015.

Multi-spacecraft Autonomous Positioning System

Project Manager(s)

Dr. Evan Anzalone/EV42
(256) 544–5492

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

As the number of spacecraft in simultaneous operation continues to grow, there is an increased dependency on ground-based navigation support. The current baseline system for deep space navigation utilizes Earth-based radiometric tracking, requiring long-duration observations to perform orbit determination and generate a state update. The age, complexity, and high utilization of the ground assets pose a risk to spacecraft navigation performance. In order to perform complex operations at large distances from Earth, such as extraterrestrial landing and proximity operations, autonomous systems are required. With increasingly complex mission operations, the need for frequent and Earth-independent navigation capabilities is further reinforced.

The Multi-spacecraft Autonomous Positioning System (MAPS) takes advantage of the growing inter-spacecraft communication network and infrastructure to allow for Earth-autonomous state measurements to enable network-based space navigation. A notional concept of operations is given in figure 1. This network is already being implemented and routinely used in Martian communications through the use of the Mars Reconnaissance Orbiter and Mars Odyssey spacecraft as relays for surface assets. The growth of this communications architecture is continued through MAVEN, and future potential commercial Mars telecom orbiters. This growing network provides an initial Mars-local capability for inter-spacecraft communication and navigation. These navigation updates are enabled by cross-communication between assets in the network, coupled with onboard navigation estimation routines to integrate packet travel time to generate ranging measurements and characterization of the onboard platform. Inter-spacecraft communication allows for frequent state broadcasts and time updates from trusted references. The architecture is a software-based solution, enabling implementation on a wide variety of current assets, with the operational constraints and measurement accuracy determined by onboard systems. The Martian communication network, along with deep space network support, provides an initial architecture for simulation and analysis of MAPS, and captures the ideal initial deep space implementation of MAPS.

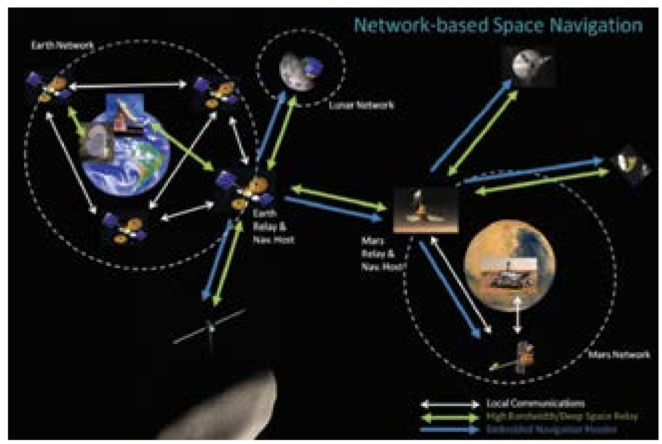


Figure 1: MAPS concept of operations.

To support initial flight validation, a low-Earth orbit (LEO) demonstration mission concept is being developed and analyzed. This mission scenario focuses on capturing the in-flight accuracy of the spacecraft clocks as well as in-flight packet transmission, and state estimation among a limited number of assets. To support this mission, both software and hardware simulation tools have been developed. The simulation architecture allows for analysis of link budgets and estimated performance as a function of individual asset orbits and simulated errors (such as external perturbations and timing uncertainty). To capture the effects of real hardware, a hardware-in-the-loop (HIL) system is being utilized to integrate flight quality radio and clock hardware to capture receiver delays and clock uncertainty to directly model spacecraft behavior. This framework is described in figure 2.

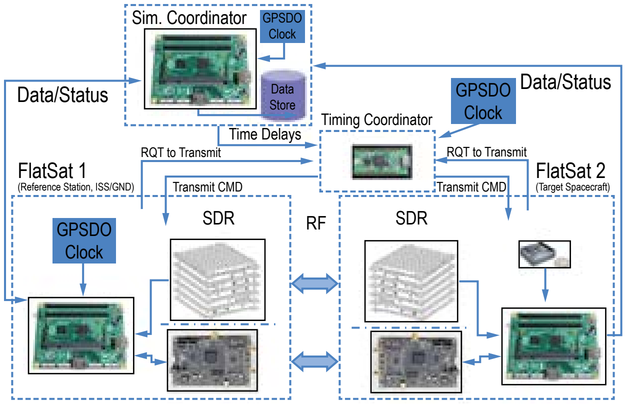


Figure 2: Implemented HIL architecture.

The capability for highly accurate timing measurements and delay modeling is enabled through the use of a truth simulation coordinator and a timing coordinator. These are both synced to high-accuracy network clocks, with the timing coordinator running minimal processing to reduce any timing errors in modeling and controlling communication delays. This architecture will allow for verification and performance analysis of MAPS across a variety of mission scenarios and provides a starting point for a full architecture simulation.

Anticipated Benefits

This technology is well suited to providing navigation capability to spacecraft participating in the communication network. By utilizing this technology, it is possible to turn every communication pass between assets into a real-time autonomous navigation pass as well, supplementing and enhancing traditional state determination methods. This reduces the reliance and load on ground-based assets while also increasing onboard state estimation capability.

Mission Applications

This architecture is designed to support in-space navigation for robotic and human missions. It can also serve as a backup navigation method for cases with limited ground support availability. As onboard clocks improve in capability and multiple spacecraft implement these algorithms, MAPS can be used as a primary navigation source. Additionally, this architecture can be used to develop high-accuracy navigation references throughout our solar system, integrating with interplanetary communication relays.

Notable Accomplishments

- Demonstrated HIL architecture using multiple FlatSats communicating via commercial radios simulating LEO missions.
- Implementation of MAPS navigation algorithms into FlatSat flight software stack using libSprite.
- Integration and demonstration of MAPS packet definitions with standard Consultative Committee for Space Data Systems (CCSDS) protocols.
- Initial sizing and design of flight platform for MAPS demonstration and implementation.

References

1. Anzalone, E.: “Agent and Model-Based Simulation Framework for Deep Space Navigation Design and Analysis,” Ph.D. Thesis, Georgia Institute of Technology, August 2013.

2. Anzalone, E.: “Unified Simulation and Analysis Framework for Deep Space Navigation Design,” in *Proc. 37th Annual AAS Guidance and Control Conference*, J. Alexander (ed.), Univelt, Breckenridge, CO, January 31–February 5, 2014.

3. Anzalone, E.; and Chuang, C.H.: “Conceptual Design of a Communication-based Deep Space Navigation Network,” Paper Presented at AIAA Space 2012 Conference & Exposition, Pasadena, CA, September 11–13, 2012.

4. Anzalone, E.; Becker, C.; Crump, D.; and Heater, D.: “Multi-spacecraft Autonomous Positioning System: LEO Demo Development (SSC15-IV-4),” Paper Presented at 29th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 8–13, 2015.

NanoLaunch

Project Manager(s)

Jonathan Jones/ER50
(256) 544–1043

Lawanna Harris/EV32 (detailed to ZP30)
(256) 544–9592

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

NASA's NanoLaunch effort seeks to mature both Earth-to-orbit and on-orbit propulsion and avionics technologies, leading to affordable, dedicated access to low-Earth orbit for CubeSat-class payloads. The project also serves as early career personnel training opportunity with mentors to gain hands-on project experience.

NanoLaunch is a three-phase, high-risk research and technology development project focused on developing the insertion stages needed to place a nanoclass payload (1–10kg) in orbit. Successes in phase I (FY 2013) included the development and static fire test of a fully printed solid rocket motor, avionics flight test, control systems testing, and hands-on training in rocket assembly and integration (fig. 1).

Figure 1: Hands-on training building and troubleshooting rockets in the field.

Phase 2 (FY 2014/2015) focused on the development, assembly, and integration of a two-stage, 9-in-diameter reusable test vehicle that included a full-scale insertion stage, avionics, reaction control system, and separation system. The phase 2 scope for the two-staged vehicle was modified to a single stage due to complications in developing the insertion motor for the upper stage. Phase 3 plans to utilize the phase 2 vehicle (two-stage) as the upper stage on top of a heritage sounding rocket configuration, which provides a testbed for suborbital and orbital capability for this class of payloads.

Figure 2: NL2A single-stage vehicle configuration.

A modified phase 2 vehicle, the single-stage NL2A (fig. 2), was manifested and included payloads from NASA Ames Research Center (ARC), NASA Kennedy Space Center, and ATK, but the flight was postponed in March due to inclement weather (ice storm). In preparation for the flight, the team was able to successfully complete a series of ground tests and a test flight of the vehicle, avionics, and recovery systems. The single-stage NL2A vehicle (13 ft in length) successfully demonstrated the new flight separation system and vehicle avionics in December 2014. Payload integration and testing for the ARC payload was completed; the other two payloads were delayed due to inclement weather and Center shutdown. Later, integrated ground testing was performed and data provided to the respective customers. Figure 3 documents the avionics bay and payload hardware.

The aforementioned project was unsuccessful in demonstrating the design of a low-cost, fully printed, upper stage motor using electron beam melting technology. Printing the motor, designated PSRM 30, pushed the build volume limits of the Arcam A2X printer. The cylinder walls near the edges of the build volume were porous and attempts to correct the porosity issue were unsuccessful. At this point, the project chose and completed an alternate joint design that would allow for cartridge loading of the motor, designated the 9M motor.

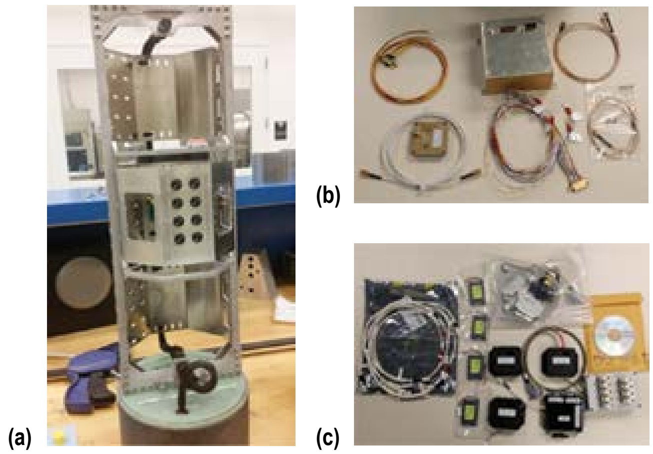


Figure 3: (a) Avionics bay, (b) ARC affordable vehicle avionics, and (c) ATK wireless sensors.

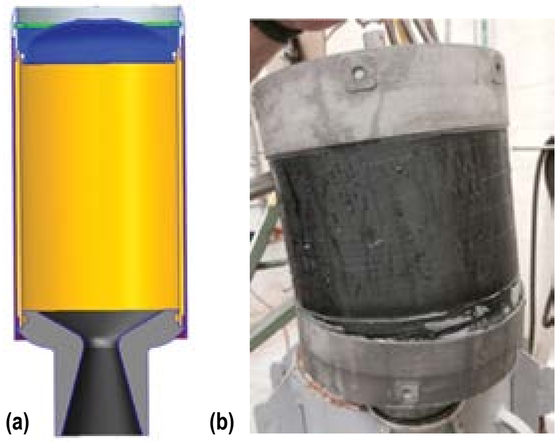


Figure 4: (a) 9M motor computer aided design and (b) full-scale PSRM 30 after hydroburst test.

Personnel Training

The personnel training aspect was a success. The experience gained by many of those involved resulted in them moving into leadership positions as chief engineers, task team leads, and lead systems engineers. For others, this was the catalyst for them to apply for and receive Center/Agency funding for projects within their chosen discipline. These changes promote the type of growth and excitement that will continually benefit the individual and the Agency.

Anticipated Benefits

- Low-cost flight opportunities for potential high-payoff technologies.
- Dedicated, low-cost, orbital access for CubeSat-class payloads.
- Training for the next generation of engineers, project managers, and chief engineers.

Mission Applications

The desire for dedicated low cost orbital access continues to grow. NanoLaunch seeks to aid our Agency/industry partners through maturing promising technologies and manufacturing techniques. By using a phased approach, it is hoped that a higher number of promising options can be effectively vetted through robust ground and flight testing, helping focus resources on critical needs through early testing.

Notable Accomplishments

The NanoLaunch project was able to design, build, test, and launch a high-powered rocket and avionics suite successfully four times.

In preparation for the March 7, 2015, launch attempt from Phoenix Missile Works, a significant effort was undertaken to write a Mishap Preparation and Contingency Plan, which was approved by NASA Headquarters. Of particular note was that this effort initiated an essential discussion on ‘right sizing’ the NASA procedural requirements for flight testing this class of vehicles.

Lawanna Harris, project manager, and Brent Cobb, chief engineer, concluded their one-year detail by presenting a Lessons Learned briefing to the NASA Marshall Space Flight Center Engineering Management Council/Safety Mission Assurance Council in April 2015. Key lessons learned included uncertainty in project definition and structure, overly ambitious goals, and managing a team of fractional full-time employee personnel.

The NanoLaunch Small Business Technology Transfer subtopic saw continued activity with four new phase I awards and one phase II award. The NanoLaunch project continues to work with the Flight Opportunities Program to provide a path to bridge the ‘Valley of Death’ for technology.

Magnetogram Forecast: An All-Clear Space-Weather Forecasting System

Project Manager(s)

Nasser Barghouty/ZP12
(256) 961–7600

David Falconer/ZP12
University of Alabama Huntsville/CSPAR
(256) 961–7616

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development, Advance Radiation Protection

Project Description

Solar flares and coronal mass ejections (CMEs) are the drivers of severe space weather. Forecasting the probability of their occurrence is critical in improving space weather forecasts. The National Oceanic and Atmospheric Administration (NOAA) currently uses the McIntosh active region category system, in which each active region on the disk is assigned to one of 60 categories, and uses the historical flare rates of that category to make an initial forecast that can then be adjusted by the NOAA forecaster.

Flares and CMEs are caused by the sudden release of energy from the coronal magnetic field by magnetic reconnection. It is believed that the rate of flare and CME occurrence in an active region is correlated with the free energy of an active region. While the free energy cannot be measured directly with present observations, proxies of the free energy can instead be used to characterize the relative free energy of an active region. The Magnetogram Forecast (MAG4) (output is available at the Community Coordinated Modeling Center) was conceived and designed to be a data-based, all-clear forecasting system to support the operational goals of NASA's Space Radiation Analysis Group.

The MAG4 system automatically downloads near-real-time line-of-sight (LOS) and vector Helioseismic and Magnetic Imager (HMI) magnetograms on the Solar Dynamics Observatory (SDO) satellite, identifies active regions on the solar disk, measures a free-energy proxy, and then applies forecasting curves to convert the free-energy proxy into predicted event rates for X-class flares, M- and X- class flares, CMEs, fast CMEs, and solar energetic particle events (SPEs). The forecast curves themselves are derived from a sample of 40,000 magnetograms from 1,300 active region samples observed by the Solar and Heliospheric Observatory Michelson Doppler Imager. Figure 1 is an example of MAG4 visual output.

Each strong magnetic field area is outlined by a polygon. The polygon is color coded by threat level (green, yellow, and red, with blue showing strong magnetic field areas that do not belong to an active region). The full disk forecast with confidence levels (yellow bar) is shown graphically in the lower-left. The particular date shown in figure 1 is a 'high threat day.' Figure 2 shows the same flare as seen by SDO/Atmospheric Imaging Assembly, the CME as seen by STEREO-B, and the resulting SPE that the active region in the red box produced hours after the forecast. MAG4 also creates datasets that are used to further research and analysis, and to improve the forecast curves.

In FY 2015, we began the transition from forecasting from LOS HMI to vector HMI. Figure 2 (left) shows the LOS HMI magnetograms from a three-day composite of active region 11944 as it transits the disk. Figure 2 (right) shows the deprojected vector magnetograms, which is what would approximately be seen had the active region been at disk center. Deprojection allows for more accurate measurement of the free-energy proxies as currently used by MAG4, especially further from the disk center, hence more accurate forecasts. This improvement has been incorporated into the most recent version MAG4.

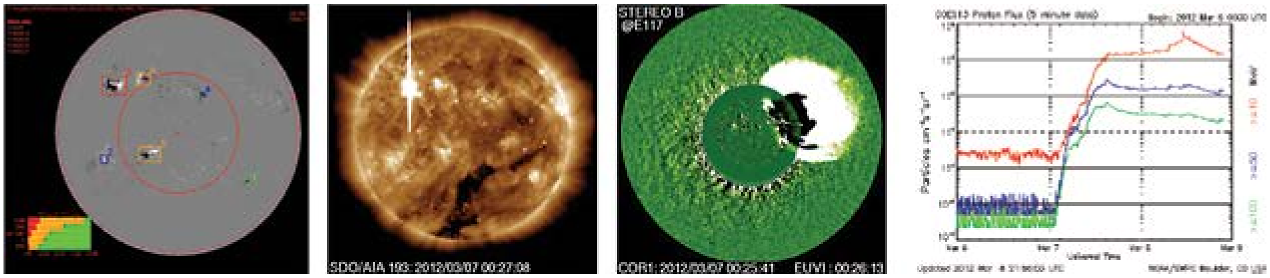


Figure 1: On the left is seen a graphical display of MAG4 forecast for March 6, 2012, followed by the flare and CME as observed by SDO and STEREO B, respectively, and on the right, the SPE event as measured by GOES13.

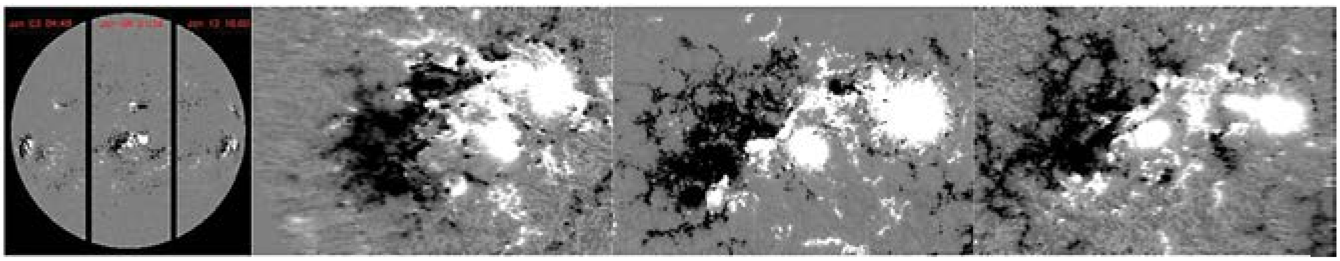


Figure 2: Comparison of LOS and deprojected vector magnetograms. On the left, a composite of three LOS magnetograms from January 3, 8, and 12, 2014. The large active region that crosses the disk has been deprojected on the right. MAG4 began making forecasts from vector magnetograms in the summer of 2015.

Anticipated Benefits

The deprojected vector magnetograms will improve the measurement of free-energy proxy and thus the accuracy of MAG4 forecasts far from the disk center. Further improvements are expected by correcting for systematic radial projection effects.

Mission Applications

MAG4 can be incorporated into any operational forecasts to supplement or replace the McIntosh forecasts.

Notable Accomplishments

- During FY 2015, we enabled MAG4 to use vector magnetograms.
- We conducted a pilot study that suggests the possibility of forecasting event rates from far-side coronal imagers by estimating the total magnetic flux of far-side active regions using their coronal luminosity, thus potentially being able to predict event rates of active regions before they rotate onto the disk.

References

Falconer, D.A.; Barghouty, A.F.; Khazanov, I.; and Moore, R.L.: "A tool for empirical forecasting of major flares, coronal mass ejections, and solar particle events from a proxy of active-region free magnetic energy," *Space Weather,* Vol. 9, No. 4, 2011.

Falconer, D.A.; Moore, R.L.; Barghouty, A.F.; and Khazanov, I.: "Prior flaring as a complement to free magnetic energy for forecasting solar eruptions," *Astrophys. J.*, Vol. 757, No. 1, pp. 32, 2012.

Falconer, D.A.; Moore, R.L.; Barghouty, A.F.; and Khazanov, I.: "MAG4 versus alternative techniques for forecasting active region flare productivity," *Space Weather*, Vol. 12, No. 5, pp. 306–317, 2014.

McIntosh, P.S.: "The classification of sunspot groups," *Sol. Phys.*, Vol. 125, pp. 251–267, 1990.

Programmable Ultra-Lightweight System Adaptable Radio

Project Manager(s)

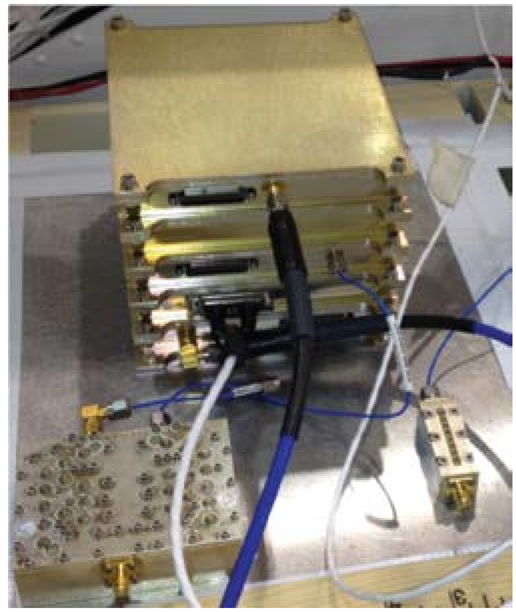
Arthur Werkheiser/ZP30
(256) 544–1269

Sponsoring Program(s)

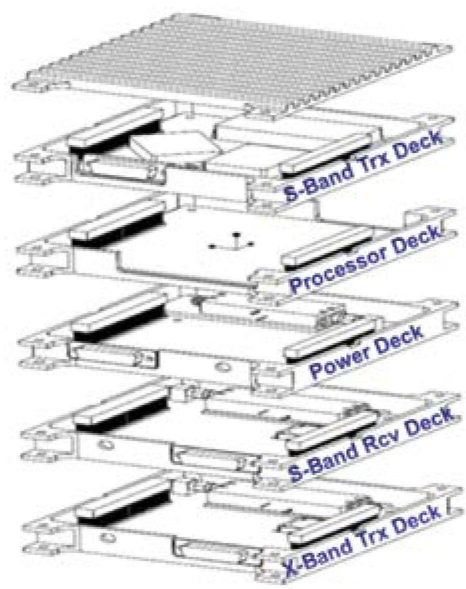
Science and Technology Mission Directorate
Game Changing Development

Project Description

The programmable ultra-lightweight system adaptable radio (PULSAR) is a NASA Marshall Space Flight Center (MSFC) transceiver designed for the CubeSat market, but has the potential for other markets. The PULSAR project aims to reduce size, weight, and power while increasing telemetry data rate. The current version of the PULSAR has a mass of 2.2 kg and a footprint of 10.8 cm^2. The height depends on the specific configuration. The PULSAR S-Band Communications Subsystem is an S- and X-band transponder system comprised of a receiver/detector (receiver) element, a transmitter element(s), and related power distribution, command, control, and telemetry element for operation and information interfaces. It is capable of receiving commands and encoding and transmitting telemetry in a manner compatible with Earth-based ground stations, near-Earth network, and deep space network station resources. The software-defined radio's (SDR's) data format characteristics can be defined and reconfigured during spaceflight or prior to launch. The PULSAR team continues to evolve the SDR to improve the performance and form factor to meet the requirements that the CubeSat market space requires. One of the unique features is that the actual radio design can change (somewhat) without requiring any hardware modifications due to the use of field programmable gate arrays.

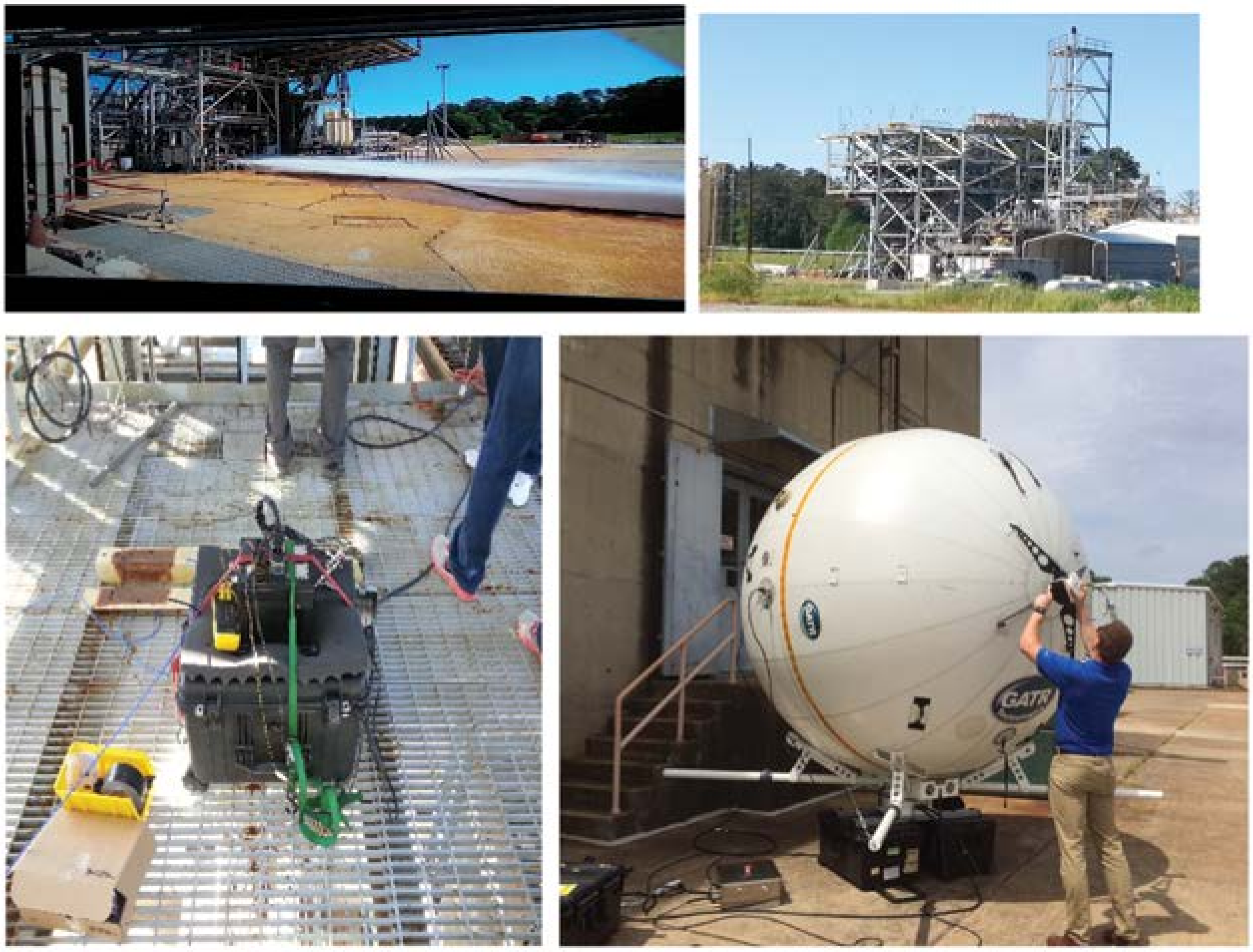


PULSAR unit.



PULSAR expanded view.

PULSAR 2.2A model radios have been delivered to NASA Johnson Space Center iPASS Lab and to the High-rate Data Acquisition (HiDAq) project to support



PULSAR 2.2A (embedded in HiDaq) demonstrated during engine test.

an engine test. The PULSAR 2.2A radio is the part of HiDAq that actually transmits the data. The rest of HiDaq collects and stores data at a high rate and wide bandwidth. The HiDaq (and embedded PULSAR) were successfully demonstrated in spring of 2015 by collecting and transmitting test engine data (and was received) over a significant distance (≈300 m). The subscale engine is shown during one of the tests at MSFC Test Stand 116.

In FY 2016, the PULSAR 2.3 model will undergo environmental testing, fly a high-altitude balloon flight, and also fly on an UP Aerospace, Inc., sounding rocket as a payload. After the 2.3 model is refined and flight-proven, development is expected to continue into smaller form factors and X-band reception (not just transmit).

Anticipated Benefits

The PULSAR radio has the benefit of providing a CubeSat radio at a high data rate and a cost that is significantly lower than any other commercially available S- and X-band frequencies.

Mission Applications

Potential mission applications include CubeSats, unmanned aerial vehicles, and portable ground stations for satellite communication.

Notable Accomplishments

PULSAR has been demonstrated during engine hot-fire testing as part of HiDaq. PULSAR has strong industry ties with GATR antennas, Miltec, and Orbital Telemetry.

Propulsion Descent Technologies

Project Manager(s)

Francisco Canabal/EV33
(256) 544–3053

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

Advanced robotic and human missions to Mars require the landing of payloads with larger mass than current capabilities. A variety of potential solutions exist to extend current capabilities to land payloads with larger mass. Supersonic Retro-Propulsion (SRP) is one such critical technology on the road to human Mars exploration. In an SRP descent architecture, rocket engines are used to decelerate a lander from supersonic to subsonic conditions. This poses challenges that need to be addressed.

In this project, some of the aerothermodynamic challenges are investigated. A study is carried out with the human architecture concept for a Mars lander V1 operating in retro-propulsion mode during its descent into the Mars atmosphere. The V1 concept design consists of a vertically stacked configuration with a nested ascent module mounted on a landing module, as shown in figure 1. There are two engine clusters mounted on the landing module, each containing six methane (CH_4)/ oxygen (O_2) liquid engines.

A computational fluid dynamics calculation was performed using the Loci/CHEM™ solver. The calculation required 40,000 CPU-hours at the NASA Advanced Supercomputing Division. Figure 2 shows the mean flow field distribution in terms of Mach number and plane-projected flow traces at a plane bisecting both engine clusters.

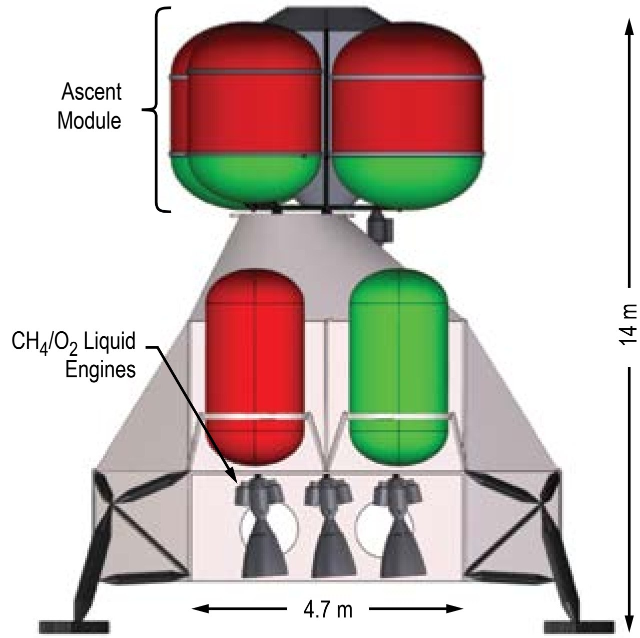


Figure 1: Mars lander concept V1.

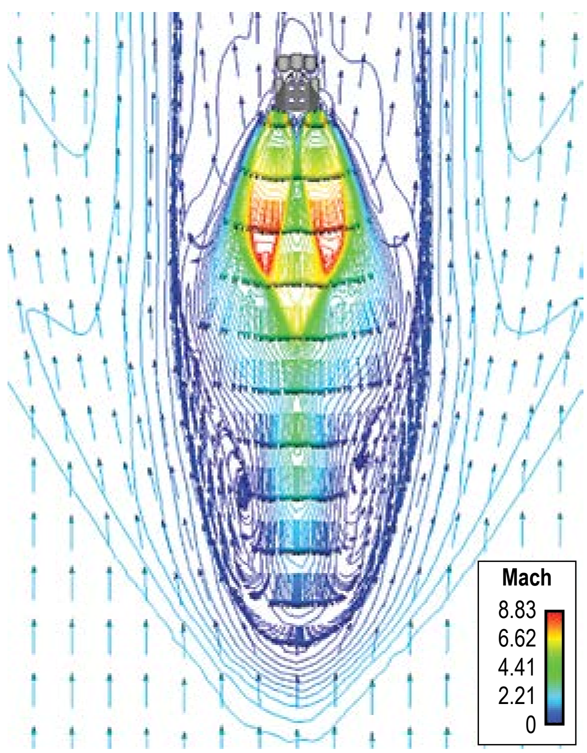


Figure 2: Mean Mach number distribution.

The flow field is characterized by an expanding core of exhaust gases embedding a complex system of oblique shocks induced by plume/plume interactions. As the core expands away from the vehicle, it transitions into an unsteady mixing zone while interacting with the upcoming freestream. The resulting mixture of exhaust gases and ambient gas (i.e., mostly carbon dioxide in the Mars atmosphere) is deflected back toward the vehicle, as shown in figures 2 and 3. The total enthalpy of this mixture is considerably higher than the freestream, as shown in terms of temperature in figure 3. The resulting surface heat flux distribution is shown in figure 4. For this particular lander design, the higher values of surface heat flux are observed at the outboard regions of the tanks. The vents at the landing module base allow the entrainment of ambient gas into the base region, resulting in relatively lower base heating, as shown in figures 3 and 4.

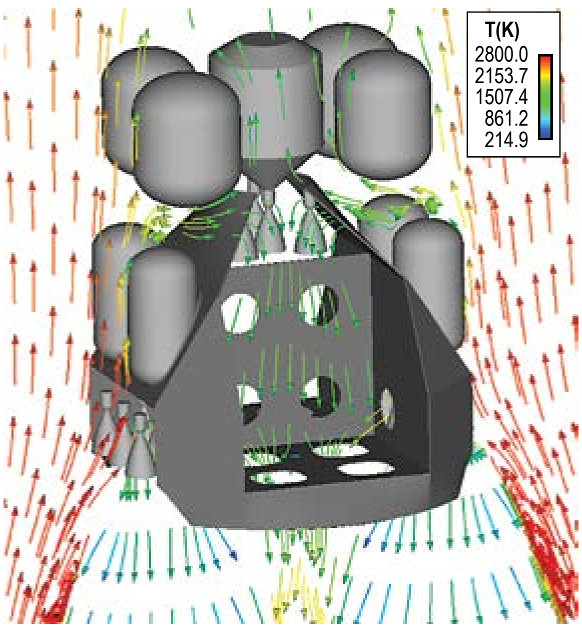


Figure 3: Flow traces colored by mean static temperature.

Anticipated Benefits

The characterization of the flow field distribution and the aerothermodynamics environment provides valuable insights for further redesigns and/or for the development of new Mars lander concepts.

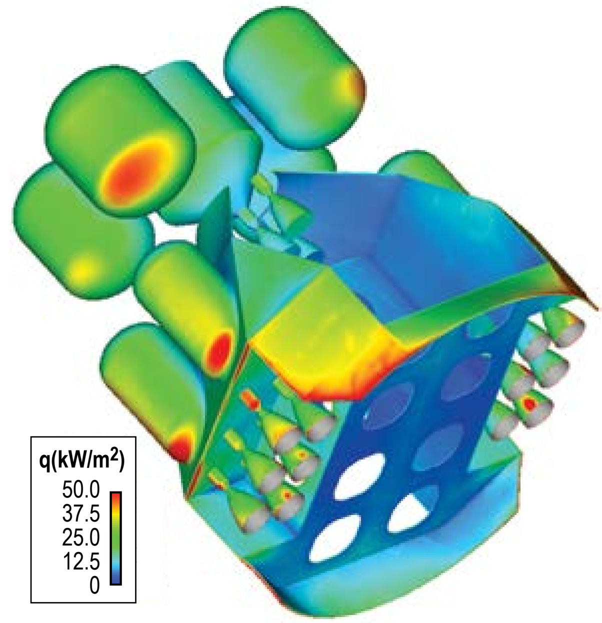


Figure 4: Mean surface heat flux distribution.

Mission Applications

This effort directly supports human missions to Mars as well as robotic missions to Mars requiring a payload with a mass of over 50 metric tons.

Notable Accomplishments

The main accomplishment of this task is the prediction of the aerothermodynamics environment of a 12-engine Mars lander concept operating in SRP mode. The complexity of the plume/plume, plumes/vehicle, and plumes/freestream interactions represents a challenge to any flow field prediction technique.

References

Luke, E.: "A Rule-Based Specification System for Computational Fluid Dynamics," Ph.D. Dissertation, Mississippi State University, December 1999.

Materials Genome Initiative

Project Manager(s)

John Vickers/EM01
(256) 544–3581

John Fikes/ZP30
(256) 544–5570

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

The Materials Genome Initiative (MGI) project element is a cross-Center effort that is focused on the integration of computational tools to simulate manufacturing processes and materials behavior. These computational simulations will be utilized to gain understanding of processes and materials behavior to accelerate process development and certification to more efficiently integrate new materials in existing NASA projects and to lead to the design of new materials for improved performance. This NASA effort looks to collaborate with efforts at other government agencies and universities working under the national MGI.

MGI plans to develop integrated computational/experimental/processing methodologies for accelerating discovery and insertion of materials to satisfy NASA's unique mission demands.

The challenges include validated design tools that incorporate materials properties, processes, and design requirements; and materials process control to rapidly mature emerging manufacturing methods and develop certified manufacturing processes.

The approach includes physics-based modeling to guide material design (e.g., composition, grain size, and texture); multiscale modeling to predict the influence of materials design on mechanical properties and durability; process modeling to determine optimal processing parameters to reliably produce as-designed material nano-/microstructures and enable advanced manufacturing methods; and material data management to support robust material design methodology

Capabilities provided by this technology include: (1) Develop reliable process control and certification methods for the manufacture of engine components for the Space Launch System (SLS) by selective laser manufacturing (SLM), (2) computational tools to enable process control with a reduced reliance on trial-and-error approaches will accelerate the development cycle, and (3) simulation of the behavior of components manufactured through the SLM process will be used to inform the certification process to reduce the testing burden and the associated time and cost for future additively manufactured components.

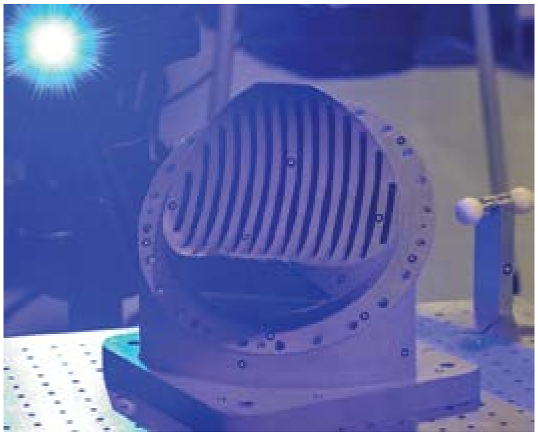
Anticipated Benefits

Synergistic efforts in multiscale modeling, information management, experimental characterization, and materials processing will accelerate design, development, and sustainment of ultra-durable material systems.

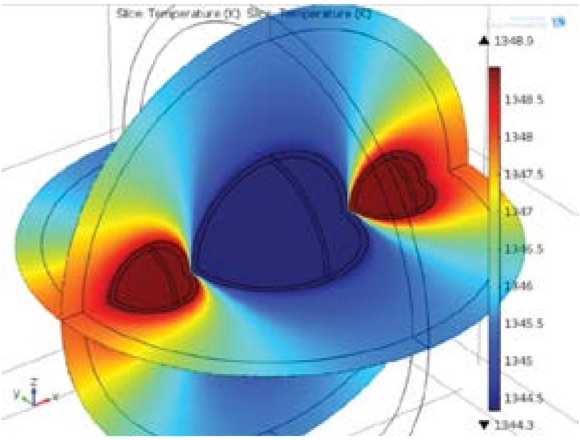
Quantitative impact includes the reduced time between discovery and technology insertion by at least half relative to current practice; shorter maturation and insertion period can translate to lower costs, greater affordability, and lower risk of failure; and integration of materials certification within a comprehensive computational approach will reduce time and cost to certify new flight hardware.

Mission Applications

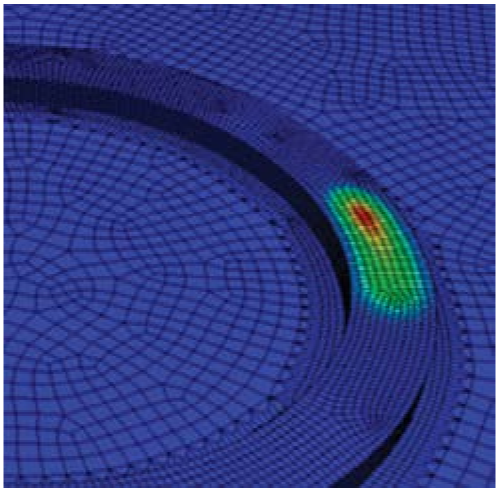
Computational materials tools will be developed in close collaboration with existing projects. These tools will be applied to improve manufacturing processes and materials performance while also reducing the cost and time to insert new materials and processes into NASA applications. For the SLS project, computational tools will focus on reducing manufacturing variability and part certification to reduce cost and time to infuse new parts.



Pogo Z-baffle additively manufactured for use in SLS.



Physics-based model of powder bed heating for SLM.



Three-dimensional finite element method model of thermal profile for cylindrical additive manufacturing build.

Notable Accomplishments

A near-infrared camera system has been developed and calibrated to monitor the melt pool for metallic additive manufacturing systems. Thermal maps of the melt pool and semi-solidus areas have been analyzed to develop algorithms to track and quantify the melt pool area. These algorithms have been used to create closed-loop control for an additive manufacturing system to improve manufacturing quality and to demonstrate improved process reliability.

Thermal models of the of the melt pool for two SLM systems being used by the SLS program have been developed to modify processing parameters to improve reproducibility of the SLM process. These models can be used to reduce development time and to reduce component variability for parts manufactured on different systems.

Low Cost, Upper Stage-Class Propulsion

Project Manager(s)

John Vickers/EM01
(256) 544–3581

John Fikes/ZP30
(256) 544-5570

Tony Kim/ZP30
(256) 544-6217

Sponsoring Program(s)

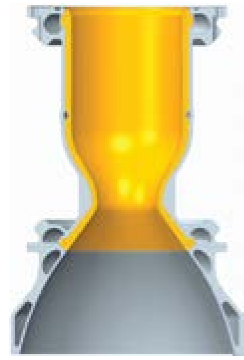
Space Technology Mission Directorate
Game Changing Development

Project Description

The low cost, upper stage-class propulsion (LCUSP) element will develop processes to additively manufacture critical components for an upper stage-class propulsion system that will be demonstrated with testing. A process for selective laser melting (SLM) of a high-conductivity/high-strength copper alloy and a process for deposition of high-strength nickel onto the copper alloy will be developed and characterized through materials test specimens.

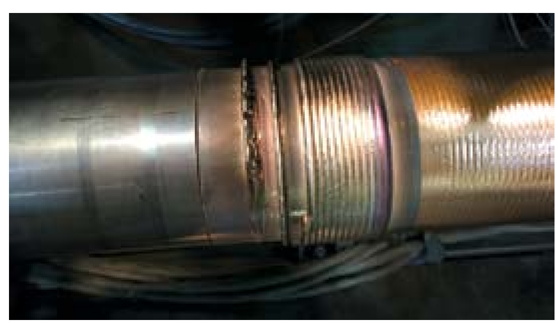
As manufacturing technologies have matured, it now appears possible to build all the major components and subsystems of an upper stage-class rocket engine for substantially less money and much faster than traditionally done. However, several enabling technologies must be developed before that can happen. This activity will address these technologies and demonstrate the concept by designing, manufacturing, and testing the critical components of a rocket engine. The processes developed and materials' property data will be transitioned to industry upon completion of the activity.

Technologies to enable the concept are additive manufacturing (AM) copper alloy process development, AM post-processing finishing to enable parts exceeding the build box dimensions, AM material deposition on existing copper alloy substrate, and materials characterization.



Chamber cross sections illustrating the copper alloy liner with built-in coolant passages and the deposited nickel alloy jacket and manifolds.

Throat section of combustion chamber fabricated utilizing SLM of high-strength copper alloy powder.



EBF3 of Inconel® 625 nickel alloy on copper substrate.

Specifically, the LCUSP project element will (1) develop materials properties and characterization for SLM-manufactured GRCop, (2) develop and optimize SLM manufacturing process for a full component GRCop chamber and nozzle, (3) develop and optimize the electron beam freeform fabrication (EBF3) manufacturing process to directly deposit a nickel alloy structural jacket and manifolds onto an SLM-manufactured GRCop chamber, and (4) demonstrate the process for integrating the engine combustion chamber system by performing a hot-fire resistance test.

Example of a previous engine component testing at MSFC's Test Stand 116. LCUSP combustion chamber will be tested at similar liquid hydrogen and liquid oxygen flow rates and thrust levels.

Anticipated Benefits

Existing AM equipment combined with new, enabling processes and manufacturing 'best practices' will make it possible for more companies to build high-quality rocket propulsion hardware at a lower cost and faster delivery than previously possible. These cost and schedule savings will be passed along to NASA when a new rocket engine is competed. Additive manufacturing can potentially offer an order of magnitude savings of cost and schedule for complex rocket propulsion hardware. The AM process development for copper alloy, materials characterization, and technology transfer to industry will open new competitive markets that may reach beyond the space flight industry.

While this project is focused on thrust chamber components, AM of copper alloys is applicable to a variety of applications, including igniters, injector faceplates, and injector baffle elements.

Another benefit will be to provide space industry with a new material property database and proven techniques for implementing AM in their manufacturing processes.

Mission Applications

The LCUSP element is complimentary and directly relevant to the continued development of the SLS capability by pursuing affordability improvements for engines and stages.

Notable Accomplishments

NASA Marshall Space Flight Center (MSFC) is partnering with NASA's Langley Research Center (LaRC) (for the EBF3 jacket/manifold deposition) and Glenn Research Center (GRC) (for materials properties determination).

A solid monolithic part with relevant feature sizes has been demonstrated. Additionally, a process to join two parts that when combined exceed the dimensions of the SLM machine build box has been successfully demonstrated through electron beam welding. MSFC EM42 has printed a small chamber demonstration article utilizing an available nickel-silicon-bronze powder and one using copper alloy C18150, which is used in some commercial, conventionally manufactured chamber applications. LaRC has completed initial successful trial depositions of Inconel 625 onto copper alloy and has further developed techniques for EBF3 deposition of Inconel 625 jacket onto GrCop-84 liner. Microscopy of SLM trials by GRC have shown a process set that produces highly dense parts that can be almost completely densified in the standard post-SLM build hot isostatic press cycle. Initial materials properties tests indicate both copper alloy and nickel alloy processes produce parts that meet the expected strengths needed for a rocket engine combustion chamber.

References

Protz, C.; et al.: "Development of Additive Manufactured Low Cost Upper Stage Propulsion Components," *JANNAF*, Huntsville, AL, September 2014.

Taminger, K.; and Hagen, R.: "Electron Beam Freeform Fabrication (EBF3) Applications and Research at NASA." Deep Space Deep Oceans Forum," Woodlands, TX, April 2015.

Carter, B.; et al.: "Material Characterization of Additively Manufactured Components for Rocket Propulsion," International Astronautical Congress (IAC), Jerusalem, Israel, October 2015.

Additive Construction With Mobile Emplacement

Project Manager(s)

Niki Werkheiser/ZP30
(256) 544–8406

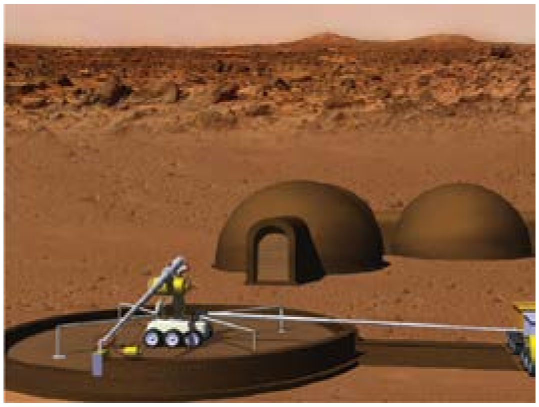
Robert Mueller/Kennedy Space Center
(321) 867–2557

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

The Additive Construction with Mobile Emplacement (ACME) project is developing technology to build structures on planetary surfaces using in situ resources. The project focuses on the construction of both 2D (landing pads, roads, and structure foundations) and 3D (habitats, garages, radiation shelters, and other structures) infrastructure needs for planetary surface missions. The ACME project seeks to raise the Technology Readiness Level (TRL) of two components needed for planetary surface habitation and exploration: 3D additive construction (e.g., contour crafting) and excavation and handling technologies (to effectively and continuously produce in situ feedstock). The TRL increase in additive construction technology is possible by combining the expertise, technologies, and goals of NASA Marshall Space Flight Center (MSFC), NASA Kennedy Space Center (KSC), the United States Army Corps of Engineers (USACE), the Contour Crafting Corporation, and the Pacific International Space Center for Exploration Systems.



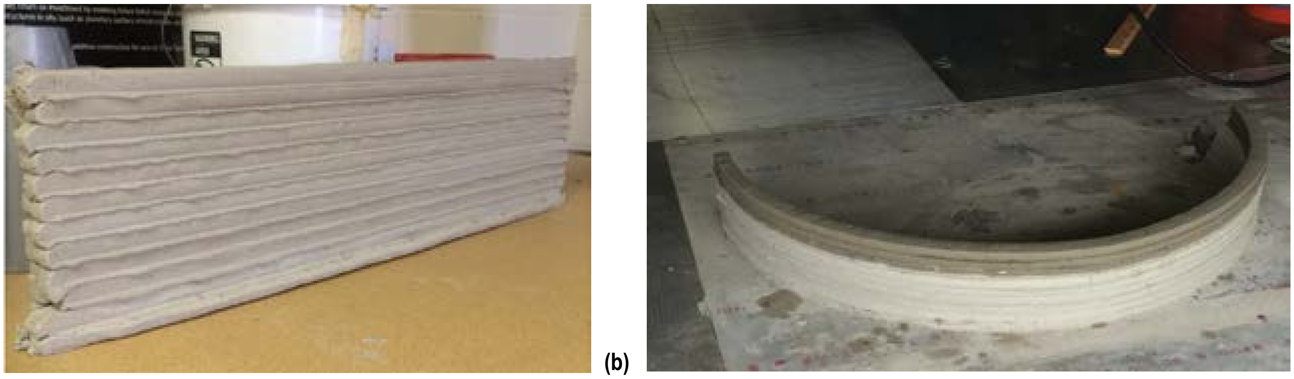
Planetary contour crafting concept.

Contour crafting nozzle.

Concept of potential emplacement devices.

Anticipated Benefits

Multiple advancements in technology will be made during the ACME project and are applicable to both NASA and USACE goals:



(a) (b)

(a) Completed contour-crafted subscale straight wall segment and (b) subscale curved wall segment.

- A continuous feedstock excavation, size sorting, and delivery system will be designed, fabricated, and tested to allow continuous construction capabilities. This is opposed to the current 'batch mixing' of concrete and 'assemble one piece at a time' processes in construction. The feedstock will be delivered continuously to a mixing or emplacement implement, which will in turn continuously fabricate a structure.

- A continuous mixing system, where a binder will be mixed with excavated regolith to produce construction materials.

- An emplacement nozzle, with shutters to cut off deposition as needed and specifically designed to accommodate planetary regolith feedstock (or other similar terrestrial aggregates), will be designed and fabricated through ACME.

- A focus on construction materials produced from in situ materials. This work is intended to reduce the mass launched from Earth, and thus cost, for planetary surface missions. It is also directly applicable to terrestrial locations, such as the islands of Hawaii, where it is extremely expensive to import building materials.

The USACE is interested in the additive construction technology as a means to build Army structures to enable field operations. The ACME project will help the USACE minimize the number of people and the amount of time it takes to build a structure, allow digital design and the 3D printing of structures to resemble local buildings, and reduce the amount of material brought into the field and waste produced by the construction process.

Mission Applications

The project plans to (1) be the first demonstration of additive construction using planetary analog materials; (2) investigate binder and regolith mixtures, as well as construction materials made only from regolith, to identify optimal planetary construction materials; (3) provide a detailed analysis of materials for additive construction on different planets, including radiation shielding potential; (4) advance the TRL of additive construction hardware and processes to provide risk reduction and capabilities to future missions; (5) provide the gateway to fabricating structures on demand in space with in situ resources, thereby reducing the need for sizeable structure up-mass; (6) provide a significant return on investment by enabling future NASA missions not feasible without the capability to manufacture structures in situ (such as planetary surface infrastructure) and doing so with significant external leverage; and (7) provide a first step towards evolving additive construction for use on deep space missions.

Notable Accomplishments

- Performed a hypervelocity impact test of Martian simulant concrete at White Sands on August 19, 2015.

- Completed construction of a straight wall segment from Martian simulant concrete at MSFC on September 25, 2015.

- Demonstrated a regolith feedstock delivery/size sorting system at KSC on September 28, 2015.

- Completed construction of a curved wall segment from Martian simulant concrete at MSFC on November 4, 2015.

Microelectrospray Thrusters

Project Manager(s)

John Dankanich/ZP30
(256) 544–3441

Nate Demmons/Busek Co., Inc.
(508) 655–5565

Colleen Marrese-Reading/Jet Propulsion Laboratory
(818) 354–8179

Paulo Lozano/Massachusetts Institute of Technology
(617) 258–0741

Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

Propulsion technology is often a critical enabling technology for space missions. NASA is investing in technologies to enable high-value missions with very small spacecraft, even CubeSats. However, these nanosatellites currently lack any appreciable propulsion capability. CubeSats are typically deployed and tumble or drift without any ability to transfer to higher value orbits, perform orbit maintenance, or perform deorbit. Larger spacecraft can also benefit from high-precision attitude control systems. Existing practices include reaction wheels with lifetime concerns and system-level complexity. Microelectrospray thrusters will provide new propulsion capabilities to address these mission needs.

Electric propulsion is an approach to accelerate propellant to very high exhaust velocities through the use of electrical power. Typical propulsion systems are limited to the combustion energy available in the chemical bonds of the fuel and then acceleration through a converging diverging nozzle. However, electric propulsion can accelerate propellant to ten times higher velocities and therefore increase momentum transfer efficiency or essentially increasing the fuel economy. Fuel efficiency of thrusters is proportional to the exhaust velocity and referred to as specific impulse (I_{sp}). The state of the art for CubeSats is cold gas propulsion with specific impulse of 50–80 s. The space shuttle main engine demonstrated a specific impulse of 450 s. The target I_{sp} for the Mars Exploration Program (MEP) systems is >1,500 s. This propellant efficiency can enable a 1-kg, 10-cm cube to transfer from low-Earth orbit to interplanetary space with only 200 g of propellant.

In September 2013, NASA's Game Changing Technology Development program competitively awarded three teams with contracts to develop MEP systems from Technology Readiness Level-3 (TRL-3), experimental concept, to TRL-5, system validation in a relevant environment. The project was planned for 18 months of system development. The target objectives of the project are provided in table 1.

Table 1: MEP phase 1 project objectives.

Metric	Goal
I_{sp}	≥1,500 s
Thrust	≥100 µN
Power	≤10 W
System Efficiency	≥70%
Mass	≤100 g
Volume	≤100 cm^3
Demonstrated Life	≥200 hr
Predicted Life	≥500 hr

Due to the ambitious project goals, NASA awarded contracts to mature three unique methods to achieve the desired goals. Some of the MEP concepts have been developed for more than a decade at the component level and were deemed ready for system maturation. The three concepts included the high aspect ratio porous surface (HARPS) microthruster system, the scalable ion electrospray propulsion system (S-iEPS), and an indium microfluidic electrospray propulsion system.

The HARPS system was developed by Busek Co. The HARPS thruster is an electrospray thruster that relies on surface emission of a porous metal with a passive capillary wicking system for propellant management. The HARPS thruster is expected to provide a simple, high-ΔV and low-cost solution. The HARPS thruster concept is shown in figure 1. Figure 1 includes the thruster and integrated power processing unit and propellant reservoir.

Figure 1: Busek HARPS delivered system.

The S-iEPS development was led by the Massachusetts Institute of Technology (MIT). The MIT S-iEPS benefits from many years of component-level development and experimentation. The S-iEPS is a microelectromechanical system based on ionic liquid emission. An electrostatic field is used to extract and accelerate both positive and negative ions from a conductive salt that remains liquid over the operational temperature range. The concept is scalable in that the thrusters can produce flat panel thrusters. Thruster pairs are used emitting the positive and negative ions to maintain charge balance. The delivered system of S-iEPS is shown in figure 2.

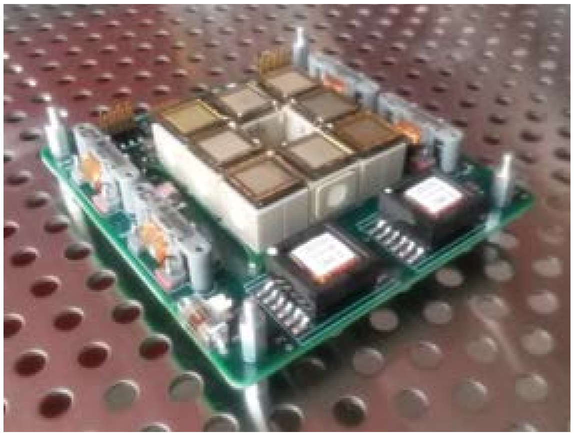


Figure 2: MIT S-iEPS delivered system.

The Jet Propulsion Laboratory (JPL) was leading a liquid metal, indium, propellant-based microfabricated thruster relying on a capillary force-driven propellant management system with no pressurization, no valves, and no moving parts. The indium thruster concept will push the limits of microfabrication techniques to produce a compact and scalable thruster. The JPL thruster is targeting 200 μN of thrust and 5,000 s I_{sp} at <10 W and 80 g. Figure 3 illustrates the JPL indium thruster concept.

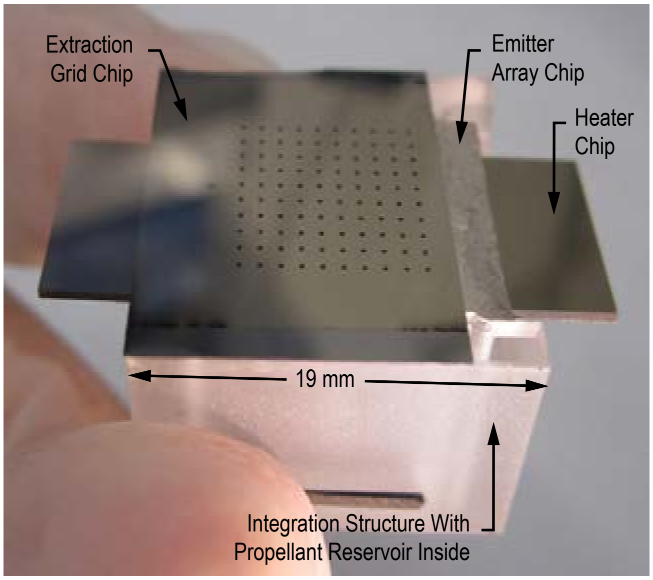


Figure 3: JPL indium thruster.

Anticipated Benefits

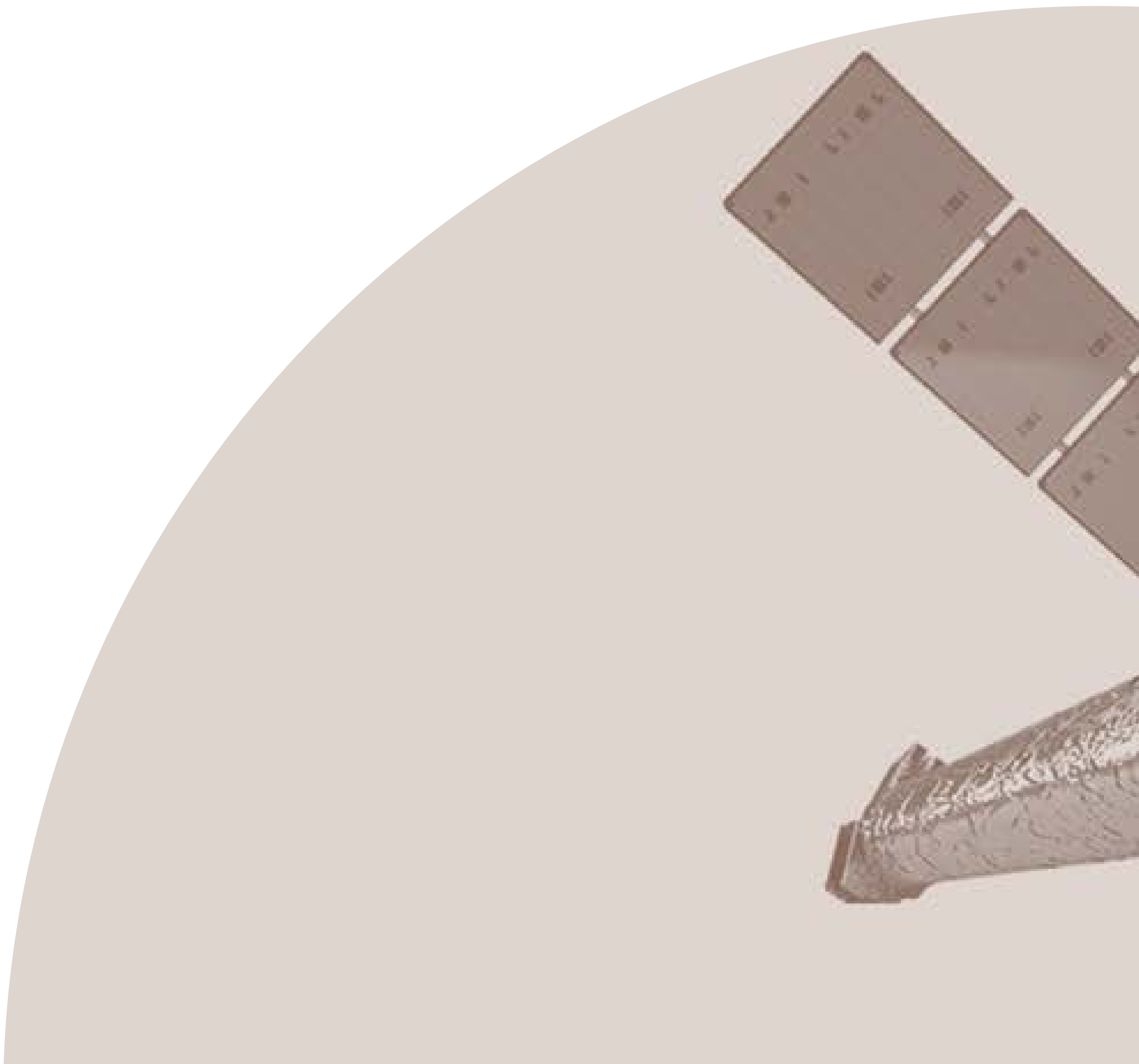
The benefits of MEP technology include significant improvement in low-power electric propulsion efficiency, high-ΔV capability for CubeSats, and I_{sp} density over alternatives.

Mission Applications

The application targets for the MEP systems include primary propulsion for small spacecraft, attitude control, and precision propulsion for future missions.

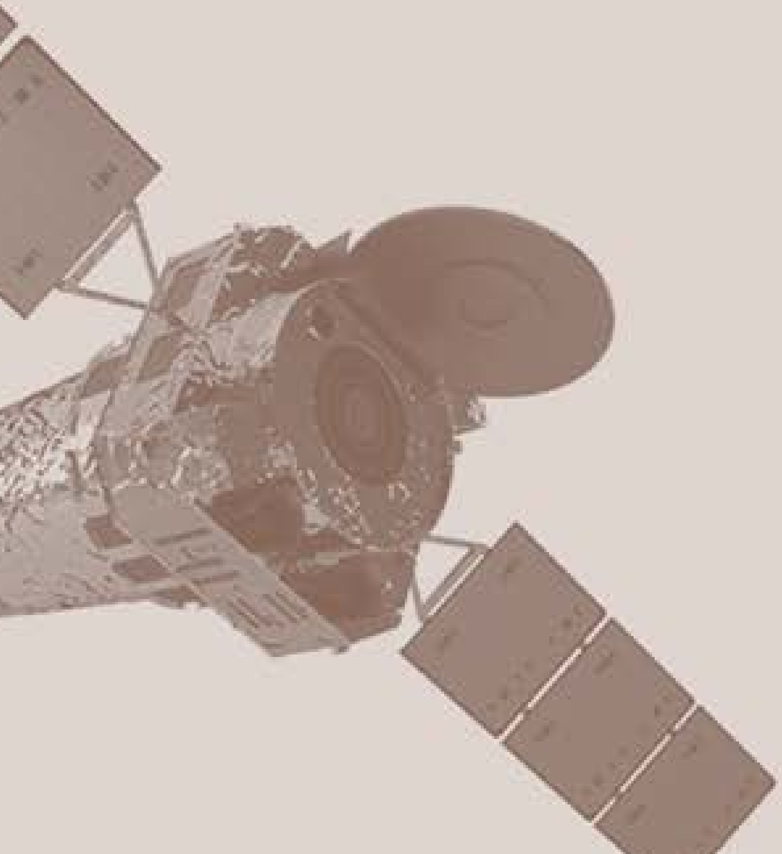
Notable Accomplishments

This project completed its contracts in 2015. The project included the delivery and long-duration testing of systems from both Busek and MIT, though neither set met the full life or performance requirements within the contracted efforts. Busek has since been selected for a flight demonstration of their system and transitioned to the Small Spacecraft Technology Program, and MIT has received follow-on efforts, completed additional long-duration testing, and also performed a flight demonstration in 2015.



Space Technology Mission Directorate

Small Business Innovation Research



Small Business Innovation Research and Small Business Technology Transfer Programs

Project Manager(s)

Lynn Garrison/ZP30
(256) 544–6719

Gwen Jasper/ZP30
(256) 544–1666

Sponsoring Program(s)

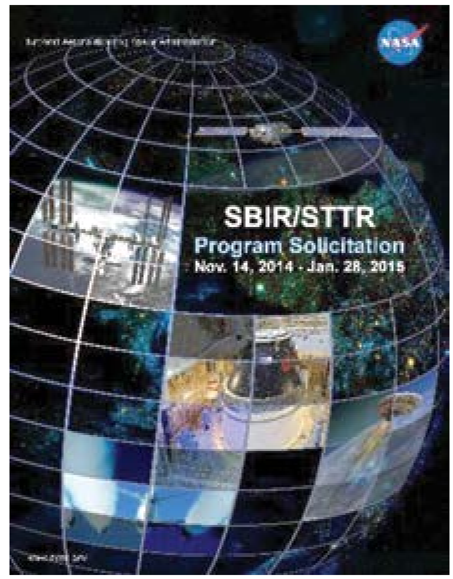
Space Technology Mission Directorate
Small Business Innovation Research/Small Business Technology Transfer Program Office

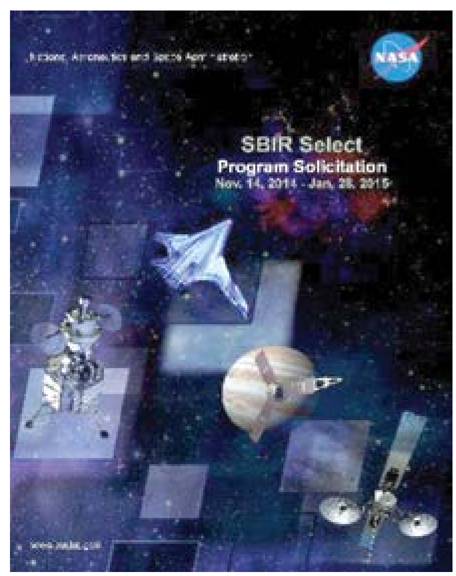
Project Description

The Small Business Innovation Research (SBIR)/ Small Business Technology Transfer (STTR) programs fund the research, development, and demonstration of innovative technologies that fulfill NASA's needs as described in the annual Solicitations and have significant potential for successful commercialization. The only eligible participants are small business concern (SBC) with 500 or fewer employees or a nonprofit research institute such as a university or a research laboratory with ties to an SBC. These programs are potential sources of seed funding for the development of small business innovations.

Notable Accomplishments

The PY 2015 SBIR/STTR phase I feasibility studies were completed. For Human Exploration and Operations Mission Directorate subtopics, NASA Marshall Space Flight Center (MSFC) was lead Center on four subtopics: Nuclear Thermal Propulsion, Extreme Temperature Structures, Spacecraft Cabin Atmosphere Quality and Thermal Management, Recycling Reclamation of 3D Printer Plastic, and participating Center in eight subtopics.





For the Science Mission Directorate (SMD), MSFC was lead Center for two subtopics: Advanced Optical Systems and Slow and Fast Light, and participating Center for 12 subtopics.

For the Space Technology Mission Directorate (STMD), MSFC was lead Center for two subtopics: Large-Scale Polymer Matrix Composites Structures, Materials and Manufacturing Processes; and Advanced Metallic Materials and Processes Innovation, and participating Center on one subtopic.

For the SBIR SELECT Solicitation: MSFC was lead Center for one SMD subtopic: Advanced Technology Telescope for Balloon and Sub-Orbital Missions, and participating Center in 17 subtopics.

For STTR solicitation, MSFC was lead Center for two subtopics: Affordable Nano/Micro Launch Propulsion Stages and Experimental and Analytical Technologies for Additive Manufacturing, and participating Center on one subtopic.

MSFC received 44 PY 2015 phase I awards and 18 phase II awards.

ZP30 developed briefing charts for SBIR/STTR technical monitor's (TM's) and contracting officer's (COR's) technical reps and conducted these briefings on April 1 and 23, 2015. The MSFC SBIR Office along with the Center New Technology Representative and NASA Shared Services Center provided valuable information to assist the TMs and CORs in the successful execution of phase I and II contracts.

MSFC SBIR phase III contracts will continue the development of the SBIR/STTR innovation with funding from NASA programs/projects and/or external funding sources.

International Space Station Commander "Butch" Wilmore holding a 3D-printed sample container.

The SBIR program has funded In-Space Manufacturing Project activities that will result in the technologies and capabilities required for sustainable, on-demand manufacturing and repair during Exploration missions.

Several SBIRs have been awarded with the purpose of demonstrating the ability to recycle obsolete or damaged 3D-printed parts into feedstock for the on-orbit 3D printing of new items.

Space Technology Mission Directorate

Small Spacecraft Technology Program

Iodine Satellite

Project Manager(s)

John Dankanich/ZP30
(256) 544–3441

Hani Kamhawi/Glenn Research Center
(216) 977–7435

James Szabo/Busek Co., Inc.
(508) 655–5565

Sponsoring Program(s)

Space Technology Mission Directorate
Small Spacecraft Technology Program

Project Description

This project is a collaborative effort to mature an iodine propulsion system while reducing risk and increasing fidelity of a technology demonstration mission concept.[1] In FY 2015, the project was formally approved for the technology demonstration mission phase A through the end of phase D.

Propulsion technology is often a critical enabling technology for space missions. NASA is investing in technologies to enable high-value missions with very small and low-cost spacecraft, even CubeSats. However, these small spacecraft currently lack any appreciable propulsion capability. CubeSats are typically deployed and drift without any ability to transfer to higher value orbits, perform orbit maintenance, or deorbit. However, the iodine Hall system can allow the spacecraft to transfer into a higher value science orbit. The iodine satellite (iSAT) will be able to achieve a ΔV of >500 m/s with <1 kg of solid iodine propellant, which can be stored in an unpressurized benign state prior to launch.

The iSAT propulsion system consists of the 200-W Hall thruster, solid iodine propellant tank, a power processing unit (PPU), and the necessary valves and tubing to route the iodine vapor. The propulsion system is led by NASA Glenn Research Center, with critical hardware provided by Busek Co.

The propellant tank begins with solid iodine unpressurized on the ground and in flight before operations, which is then heated via tank heaters to a temperature at which solid iodine sublimates to iodine vapor. The vapor is then routed through tubing and custom valves to control mass flow to the thruster and cathode assembly.[2] The thruster then ionizes the vapor and accelerates it via magnetic and electrostatic fields, resulting in thrust with a specific impulse >1,300 s.

The iSAT spacecraft, illustrated in figure 1, is currently a 12U CubeSat. The spacecraft chassis will be constructed from aluminum with a finish to prevent iodine-driven corrosion. The iSAT spacecraft includes full three-axis control using wheels, magnetic torque rods, inertial management unit, and a suite of sensors and optics. The spacecraft will leverage heat generated by spacecraft components and radiators for a passive thermal control system.

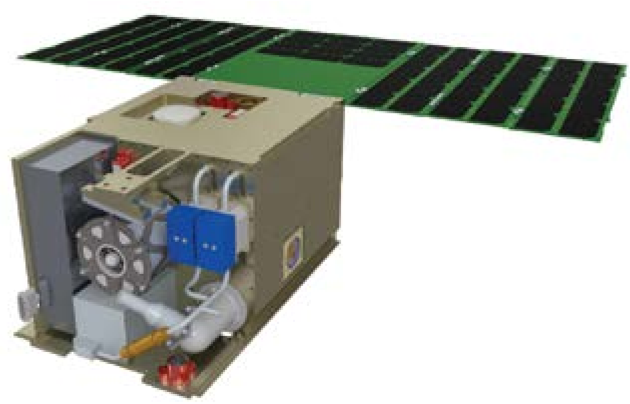


Figure 1: Interim concept design as of October 2015.

Anticipated Benefits

The benefits of the iodine Hall technology and iSAT demonstration include enabling significant small spacecraft maneuverability with a propulsion system viable with secondary payload launch opportunities.[3] Most of the technology benefits are derived from the unpressurized storage, low pressure operation, and high density. The storage and operating pressures allow for additive manufacturing of the propellant tank and shapes to maximum volume. Also, the iodine density of components

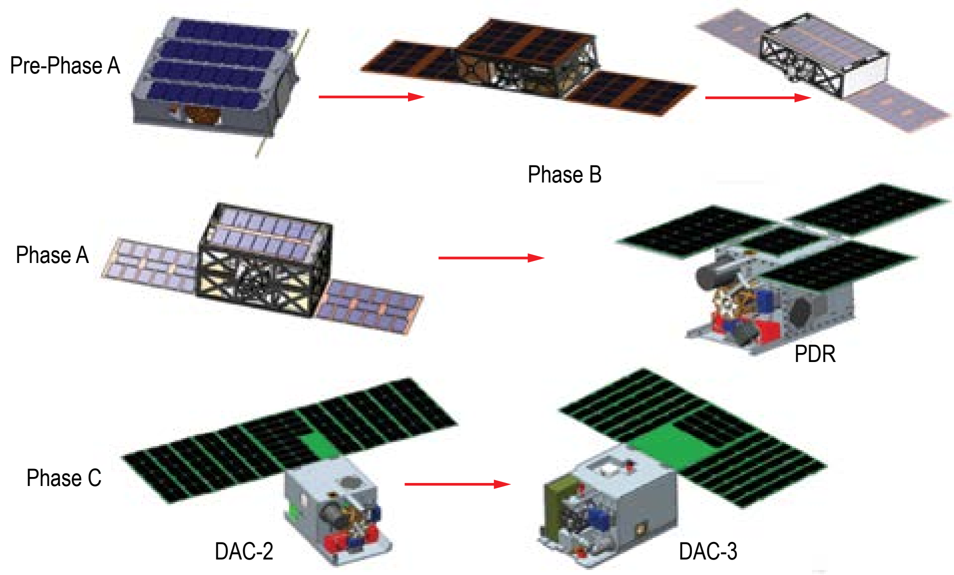


Figure 2: Design evolution of the iodine demonstration spacecraft.

with the Hall thrusters results in more than an order of magnitude improvement in ΔV per unit volume of small satellite state of the art.

Mission Applications

The primary applications are geocentric maneuverability and interplanetary transit for small spacecraft. The technology enables cost-effective geocentric constellation deployment, orbit maintenance, and deorbit. The technology can also enable EELV Secondary Payload Adapter-class small satellites to depart from geosynchronous transfer orbit and go to the Moon, asteroids, Mars, and Venus, saving potentially upwards of $100 million in launch costs to interplanetary destinations. Higher power systems can also be used for orbit transfer vehicles and eventually have potential for human exploration activities with ground test and propellant packaging advantages.

Notable Accomplishments

The spacecraft design has evolved significantly throughout FY 2015, from phase A to the preliminary design review (PDR) and through the DAC-2 and 3, as shown in figure 2.

The iSat project successfully passed the project PDR in December of 2014.

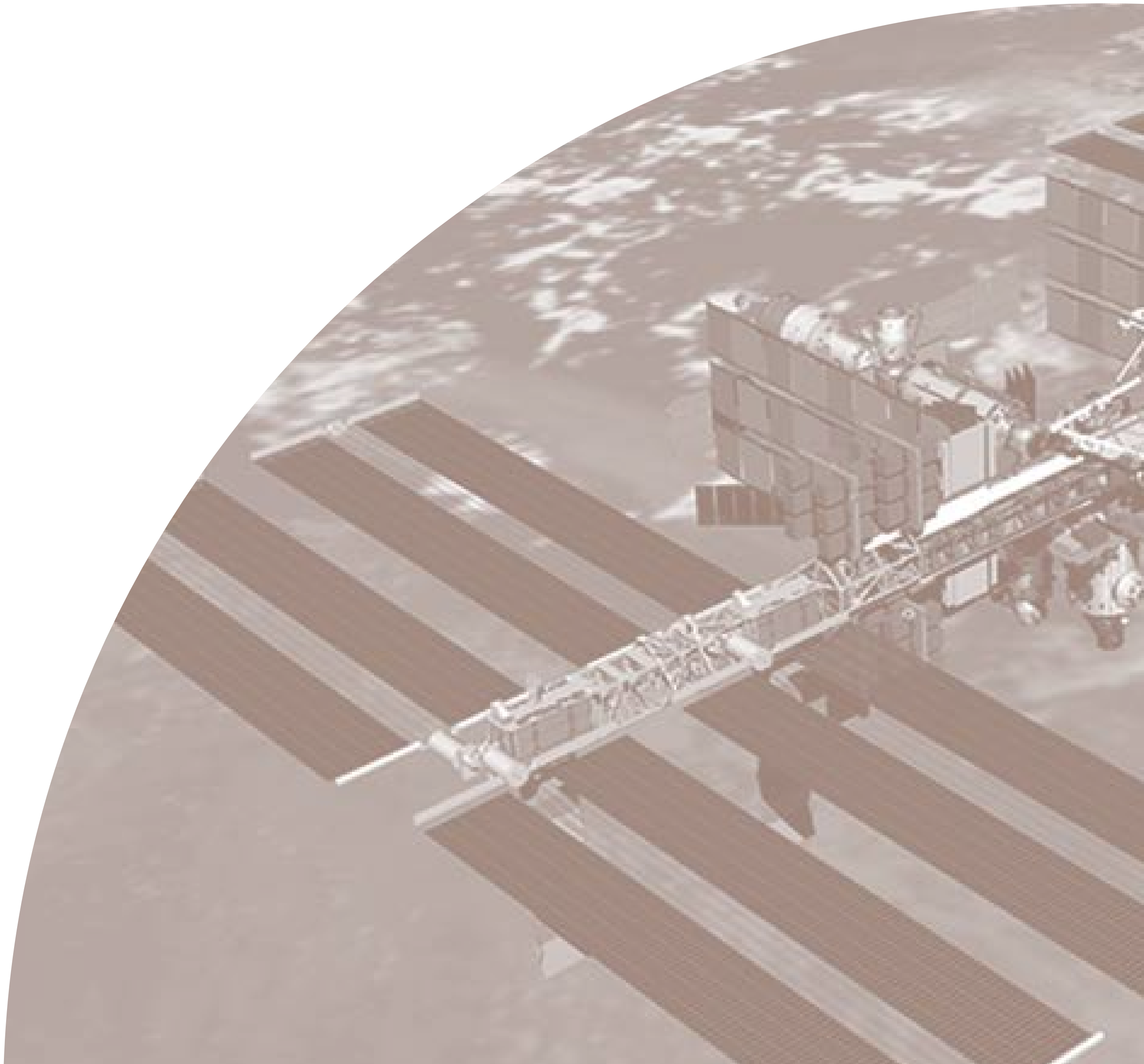
This iSat project went through another Space Technology Mission Directorate program management council and was approved through phase F, including all required operations costs. The launch costs are assumed contributed from a Department of Defense partner.

References

1. Dankanich, J.W.; Polzin, K.A.; Calvert, D.; and Kamhawi, H.: "The iodine Satellite (iSAT) Hall Thruster Demonstration Mission Concept and Development," Paper Presented at 50th Joint Propulsion Conference, Cleveland, OH, July 28–30, 2014.

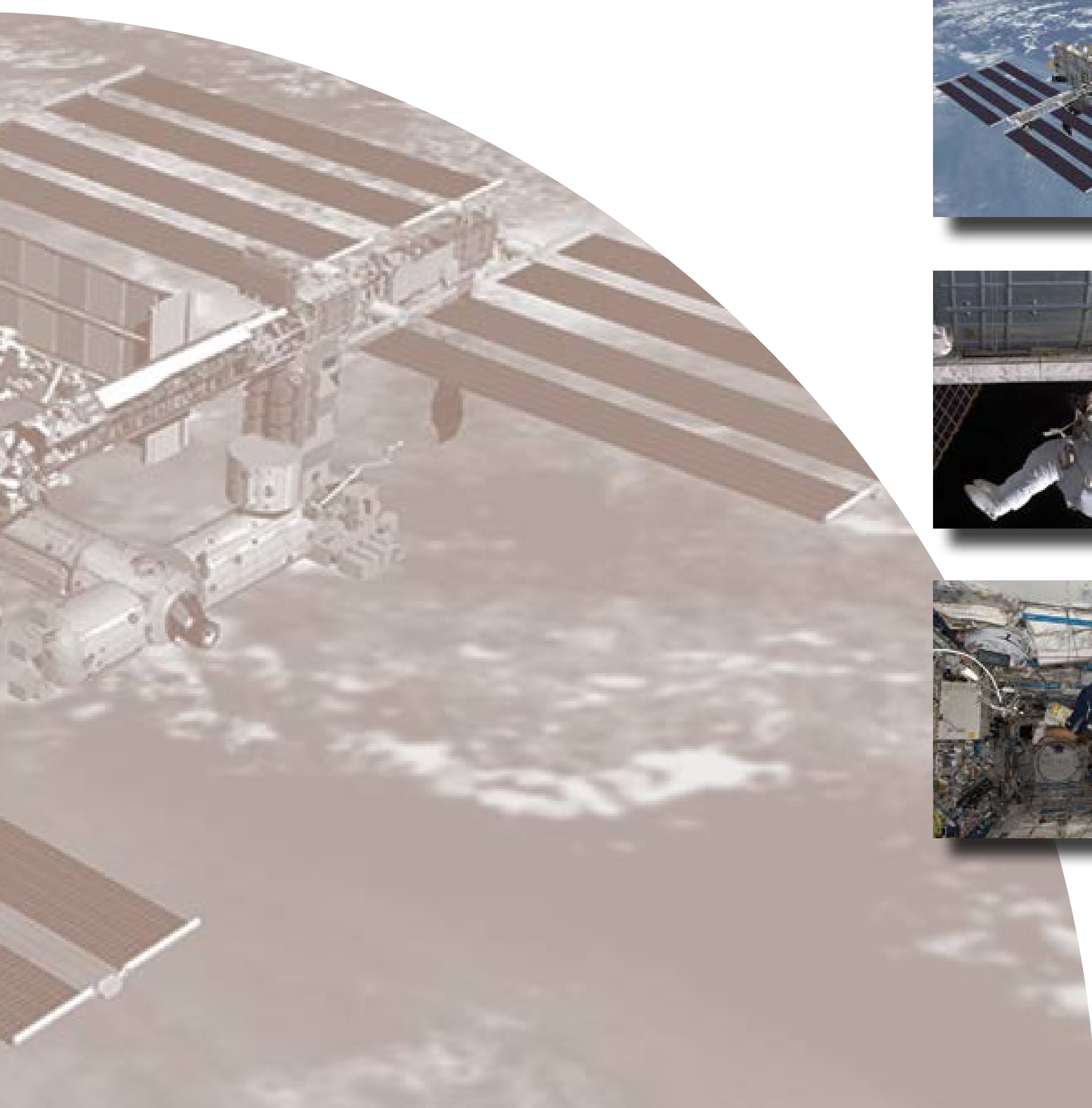
2. Dankanich, J.W.; Szabo, J.; Pote, B.; et al.: "Mission and System Advantages of Iodine Hall Thrusters," Paper Presented at 50th Joint Propulsion Conference, July 28–30, 2014.

3. Polzin, K.A.; and Peeples, S.: "Iodine Hall Thruster Propellant Feed System for a CubeSat," Paper Presented at 50th Joint Propulsion Conference, Cleveland, OH, July 28–30, 2014.



Space Technology Mission Directorate

Center Innovation Fund



Flexible Hybrid Battery/Pseudocapacitor Using Carbon Nanotube Electrodes

Project Manager(s)

Dr. Dennis S. Tucker/EM32
(256) 544–7022

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

The purpose of this project was to develop a flexible hybrid battery/pseudocapacitor in one unit. The approach was to coat carbon nanotube sheets with titanium dioxide to act as a capacitor electrode. Carbon nanotube sheets were coated with silicon to act as a battery electrode. The electrolyte was an ionic liquid doped with lithium ions. When packaged in a pouch cell, this would lead to a flexible hybrid device that is environmentally green, since no acids are used as the electrolyte fluid. Figure 1 shows a cyclic voltammetry curve of a test sample. This is a curve of voltage versus current. On the left side of the curve, one notes the classic capacitor effect, while on the right side of the figure, a charge/discharge occurs (battery effect). This sample was charged and discharged 60 cycles and showed no degradation. The electrochemical window is >2V for this arrangement.

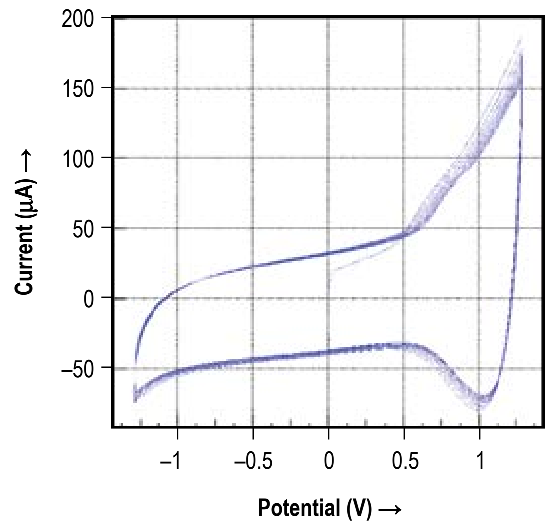


Figure 1: Cyclic voltammetry curve showing hybrid effect.

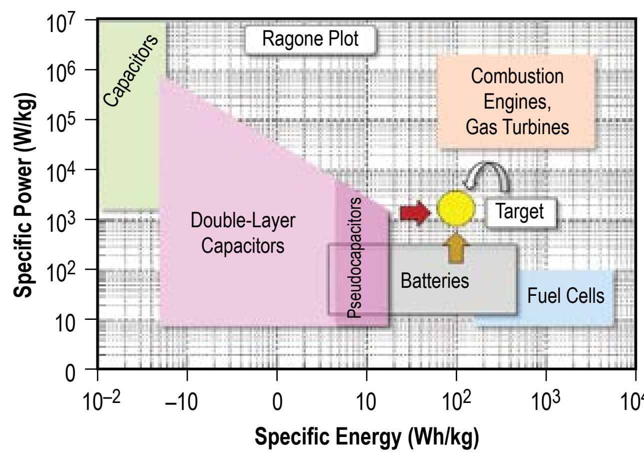


Figure 2: Ragone chart showing target for specific power versus specific energy.

Anticipated Benefits

It is anticipated that this technology can be used where a flexible energy storage device will be advantageous and also provides an environmentally friendly package.

Applications include:

- Nanosatellites
- Missiles
- Laptops
- Smartphones

Mission Applications

This technology can be used in support of Space Launch System, lunar and Martian colonies, as well as nanosatellite deployments.

Notable Accomplishments

We demonstrated a pure capacitor effect using titanium oxide-coated carbon nanotube sheets as the capacitor electrodes and a pure battery effect using silicon-coated carbon nanotube sheets as battery electrodes. We were able to produce a real hybrid effect in a single device which had a better than 2-V electrochemical window and could be cycled with no degradation. This device is also environmentally friendly due to the use of low vapor pressure ionic liquids doped with lithium ions as the electrolyte.

High-Fidelity Design Tools and a New Hydrogen Containment Process for Nuclear Thermal Engine Ground Testing

Project Manager(s)

Ten-See Wang/EV33
(256) 544–0503

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

This project developed a total hydrogen containment process (fig. 1) to enable the testing required for nuclear thermal propulsion (NTP) engine development. This hydrogen removal process is comprised of two unit operations: an oxygen-rich burner and a shell-and-tube heat exchanger. The goals were assumed for the burner to remove the majority of the hydrogen through oxygen-rich combustion reactions, and the remaining hydrogen is cooled and removed in the heat exchanger with the recombination reactions. A burner was drafted with parametric studies using a multidimensional, pressure-based, multiphase computational fluid dynamics (CFD) methodology, while the heat exchanger (fig. 2) was sized with the assistance of a one-dimensional thermal system model. The entire hydrogen removal process was simulated with the aforementioned CFD methodology on a three-dimensional computational domain (fig. 3) using flammability as the measure for total hydrogen containment.

Anticipated Benefits

A total hydrogen containment process is needed to enable the testing required for NTP engine development. This effort developed such a process using high-fidelity design and analysis tools. The anticipated benefits are as follows:

- A safe, robust, and affordable process that meets the goals of total hydrogen containment was developed and demonstrated.

- This process does not involve nuclear reactor modeling and therefore is not tied to NTP engine testing, and can potentially be applied to many industrial waste gas safety applications.

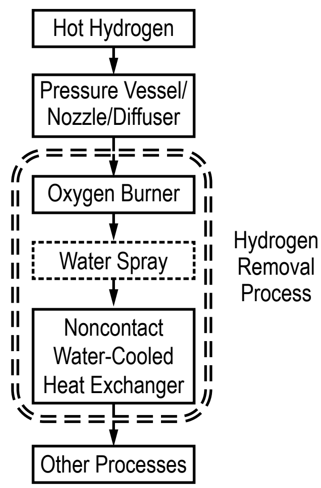


Figure 1: A new hydrogen containment process.

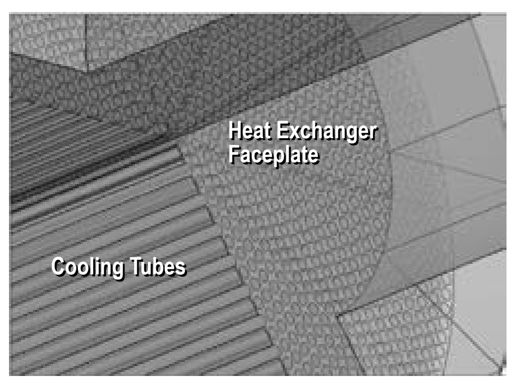


Figure 2: A 240° view of the cooling tubes layout.

Mission Applications

This effort aligns directly with the NASA Technology Area 2: In-Space Propulsion Technologies, with emphasis on nuclear propulsion, specifically, NTP. NTP is an enabling technology for delivering large payloads to Mars with reasonable transit time because of its high thrust and high specific impulse. Safe, robust, and cost-efficient ground testing of NTP is a critical part of the development of NTP systems. This effort developed and demonstrated a new process for NTP engine ground testing that achieves the goals of total containment of the hydrogen exhaust and safety of the operation in a cost-effective manner.

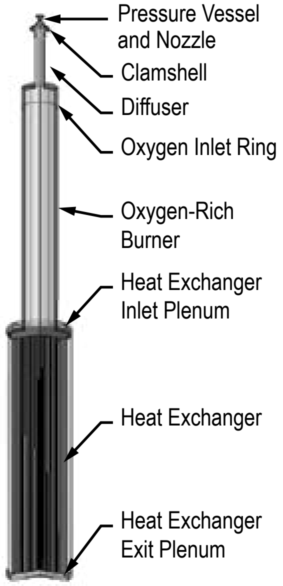


Figure 3: Layout of computational domain.

Notable Accomplishments

A new hydrogen containment process was developed for ground testing of an NTP engine with a high-fidelity, multidimensional, pressure-based, multiphase CFD methodology. Two unit operations were drafted: an oxygen-rich burner and a shell-and-tube heat exchanger. A steady-state operation of the new hydrogen removal process from pressure vessel and nozzle, diffuser, through burner and heat exchanger (figs. 2 and 3), with full details of the flow physics, was simulated computationally. The computed results (figs. 4 and 5) show that the hydrogen is significantly reduced at the end of the heat exchanger. The flammability computed at the exit of the heat exchanger is less than the lower flammability limit, demonstrating the exhaust hydrogen from the test is totally contained with the proposed process.

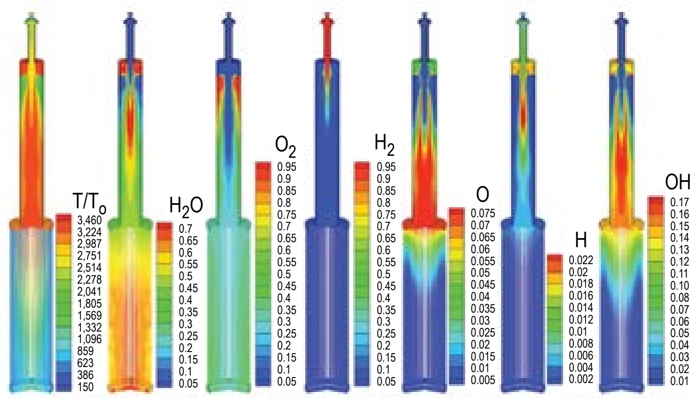


Figure 4: Computed temperature and species mass fraction contours.

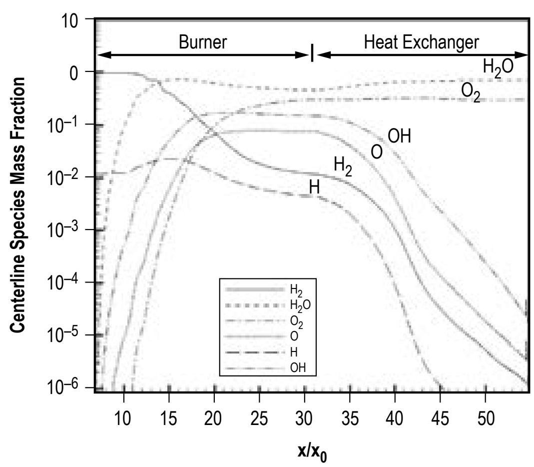


Figure 5: Computed centerline species mass fraction profiles.

Novel Aerogel-Based Catalysts for Spacecraft Life Support Application

Project Manager(s)

Matt Mansell/ES62
(256) 544–8297

Walter Schneider/FP10
(256) 544–0557

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Funds

Project Description

Efficient conversion of metabolic carbon dioxide (CO_2) into mission-essential products (generally water (H_2O) and oxygen (O_2)) is a critical enabling capability for sustainable long-duration human exploration of space. Reduction to elemental carbon (C) via reactions giving the net result $CO_2 + 2H_2 \rightarrow C + 2H_2O$ recovers 75% of the reactant mass as highly valuable H_2O, with the remaining mass consisting of elemental carbon, for which various applications have been proposed, including as a component of construction materials.[1] Two major obstacles to implementation of such processes are the payload mass and volume required to replace the catalyst, which becomes homogeneously dispersed within the solid product, and the large reactor volume required to maximize the operating time before the reactor becomes clogged with product.

The objective of this project was to demonstrate the feasibility of using aerogel-supported metals as catalysts for CO_2 reduction or any other life support processes identified as likely to benefit from this technology. Such catalysts could greatly reduce the expendable mass required to operate a CO_2 reduction reactor and even substantially reduce the volume of those expendables if the catalysts could be produced in space from dense, nonporous precursors. See figures 1–3 for images of results of the effort.

Figure 1: Carbon formed from the reduction of CO by hydrogen on (and within) an iron-impregnated silica gel particle. Particle mean diameter is approximately 8 mm.

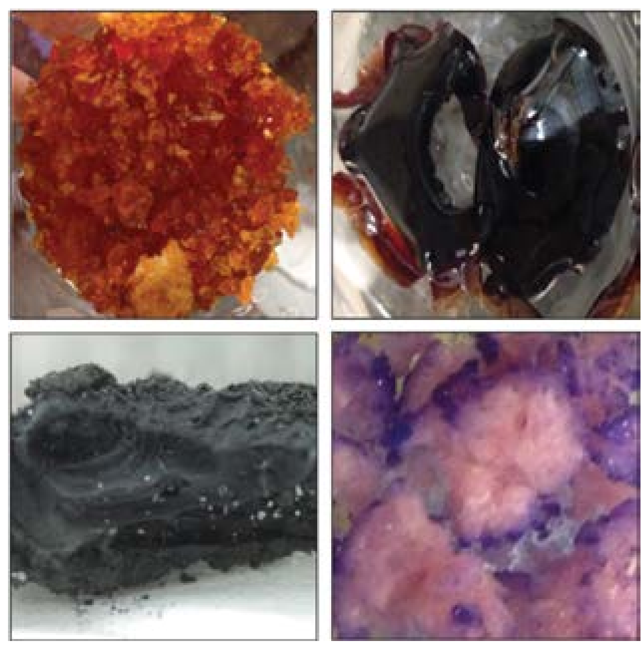


Figure 2: From top right, clockwise: (1) Fe-C gel, pre-test; (2) Co-SiO_2 gel, pre-test; (3) Fe-C gel, post-test; (4) Fe-SiO_2 gel, pre-test.

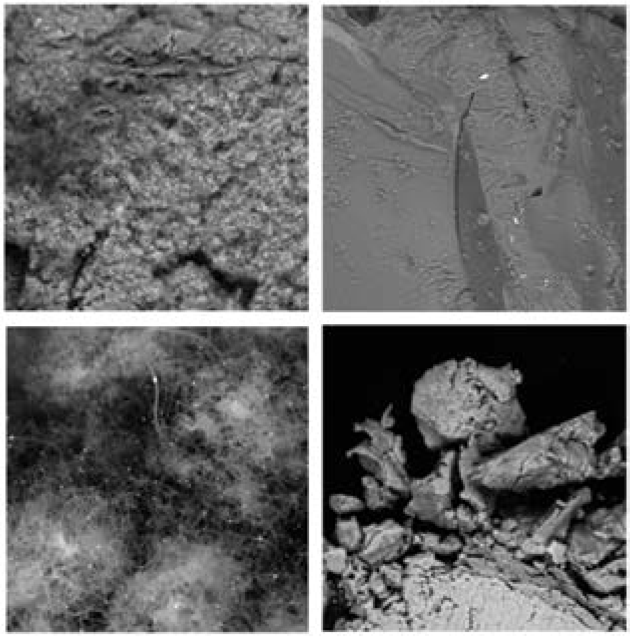


Figure 3: Scanning electron microscopy images. Clockwise from top right: (1) Fe-SiO_2 gel, pre-test (no carbon); (2) Ni-SiO_2 gel, pre-test; (3) Fe-C gel, post-test; (4) Fe-SiO_2 gel, post-test (95 at.% carbon).

Anticipated Benefits

- Decrease payload mass required for life support catalysts.
- Potential additional decreases in payload mass and volume if materials can be manufactured in space.

Mission Applications

- Sustainable long-duration human space exploration (deep space habitat, Lunar base, Mars missions, etc.).

Notable Accomplishments

- Demonstrated significant carbon deposition on external and internal surfaces of two iron-containing gel materials: Fe-SiO_2 and Fe-C.
- Synthesized various gel-based catalyst samples:
  – Supports: SiO_2, C
  – Doping: Fe, Ni, Co
- Tested the following material combinations for qualitative catalytic performance ($CO + H_2 \rightarrow C + H_2O$):
  – Fe/SiO_2 (high relative active)
  – Fe/C (moderate relative active)
- Conducted materials characterization (scanning electron microscopy with image analysis techniques), providing evidence for dispersion of catalytic centers, solid product morphology, and pore size distribution.

References

1. Abney, M.; et al.: "Series-Bosch Technology for Oxygen Recovery During Lunar or Martian Surface Missions," Paper Presented at 44th International Conference on Environmental Systems, Tucson, AZ, July 13, 2014.

Deployable Nozzle Extension

Project Manager(s)

Joseph Ruf/ER42
(256) 544–4942

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

A deployable nozzle extension (DNE) concept was developed and tested by Orbital ATK, Inc., to demonstrate its basic functionality. This nozzle extension concept is innovative in that it requires no mechanical actuation to deploy and could be retrofitted to many existing rocket nozzles used in space. (Further description of the forum is not possible due to the proprietary nature of the technology).

There are multiple possible DNE applications that would benefit the United States launcher industry, including the Space Launch System's (SLS's) Exploration Upper Stage (EUS). This task's objective was to obtain sufficient technical understanding of the DNE's capabilities such that an investment of significant funds for further development could be made with a high level of confidence. To develop this technical understanding, a specific design point (i.e., a DNE on an RL10 A) was evaluated. The RL10 is the baseline engine for the SLS EUS.

An RL10B2 is shown in figure 1. The engine can be flown without the B- and C-cones as the RL10 A.

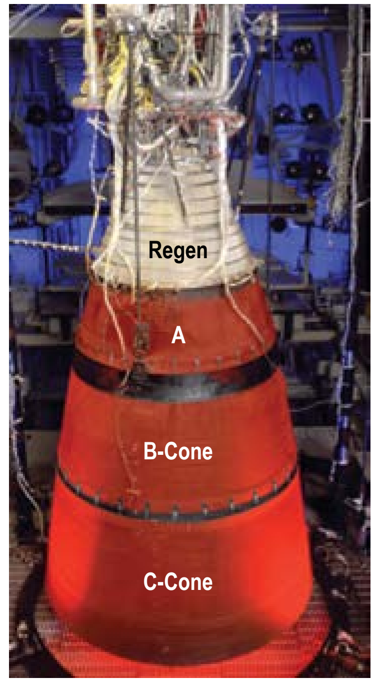


Figure 1: RL10 with B- and C-cones in flight position (Photo: Pratt & Whitney).

This evaluation addressed three key questions to assess a DNE's viability as a nozzle extension for an RL10 A:

(1) What specific impulse (I_{sp}) can it deliver?
(2) How hot will it get and how long will it survive?
(3) How will a DNE be mounted on the base nozzle?

Anticipated Benefits

The primary benefit of a DNE is increased payload capability for existing and new launcher systems. This requires almost no additional volume of the launch vehicle to accommodate a stowed DNE, nor does it require significant modifications to the engine's nozzle. The payload benefit could be had on NASA, for-profit, and other noncommercial launcher services. Table 1 lists the potential I_{sp} gain with a DNE added to different locations on an RL10.

Table 1: Specific impulse gain with addition of DNE to RL10 engine.

Location DNE is Attached	I_{sp} (s) is added by DNE
Exit of regen nozzle	16.6
Exit of regen with A-cone	11.1
Exit of regen with A- and B-cone	5.8

Mission Applications

The DNE concept is applicable to almost all liquid rocket engines that operate in vacuum. Because in-space nozzles are usually length-limited by a launch vehicle volume constraint (i.e., the interstage length or diameter), their performance would be significantly enhanced by the larger area ratio nozzles that a DNE enables. This includes smaller thrust systems such as reaction control thrusters and orbital maneuvering engines, as well as the main propulsion engines such as the RL10.

DNE should work for solid rocket motors (in vacuum) as well.

Notable Accomplishments

Within this task, the DNE configuration that best satisfies the needs of and fits within the constraints of the SLS EUS was determined. The nozzle performance for the RL10 with DNE was then optimized through a sizing and performance trade. Mechanical design concepts were developed for the chosen DNE and the base nozzle-to-DNE joint. The effect on nozzle performance of the three-dimensional features of the DNE was assessed with computational fluid dynamics (CFD). CFD and thermal analyses were used to determine operational thermal and pressure loads on the DNE. These environments were used in structural analyses of the DNE and joint.

The team has concluded that the DNE concept should work on an RL10, and the concept is worth investing in to further its development.

A development plan has been laid out and funding is currently being sought.

Novel Metrology Concept for High-Resolution Grazing Incidence Optics

Project Manager(s)

Mikhail Gubarev/ZP12
(256) 544–7816

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

With the recent introduction of optical surface error correction methods, such as differential deposition[1] and smart optics,[2] the availability of in situ surface figure metrology methods become crucial for development of the high-resolution, high-effective-area x-ray optics needed for future NASA astrophysics missions. One promising alternative for these methods is the use of phase measuring deflectometry (PMD). The concept here is as follows: a perfect fringe pattern displayed by a monitor is observed after refection from the surface under the test by a camera. Deviations from perfect spacing of the observed fringe pattern measured at multiple phases would provide unambiguous measurement of deviations in the slopes of the mirror surface from its ideal shape.

Deflectometry displays several advantageous properties for in situ measurements of the optical surfaces. It is relatively insensitive to vibrations, and immune to trace errors and to coherent noise. It is fast, so many data sets can be averaged to reduce any random noise. It has been demonstrated that the PMD method is capable of nanometer resolution[3,4] using small samples, the level adequate for subarcsecond x-ray optics if the same accuracy level can be achieved for larger aspheric surfaces. In addition, it does not require the observation angle to be normal for the measurements and does not require perfect positioning of the surface under test in the measuring system, so it can be adapted for in situ measurements in a manufacturing environment. As always, advantages come with a price. The deflectometry methods measure the surface slope, so they are prone to calibration errors for larger samples because of the need to convert the surface slope into the surface height. Recent developments in the ultra-high-definition imaging instrumentation and novel calibration techniques provide an opportunity to develop the high-resolution, in situ PMD method for the surface figure metrology of large grazing incidence optics.

Anticipated Benefits

Based on the Chandra optics fabrication history, about one third of the manufacturing time is spent on moving a mirror between fabrication and metrology sites, reinstallation, and alignment with either the metrology or fabrication instruments. Also, the accuracy of the alignment significantly affects the ultimate accuracy of the resulting mirrors. In order to achieve higher convergence rates, it is highly desirable to have a metrology technique capable of in situ surface figure measurements of the optics under fabrication, so the overall fabrication costs would be greatly reduced while removing the surface errors due to the realignment necessary after each metrology cycle during the fabrication. Moreover, the metrology will be performed for the mirror in the exact fabrication configuration, so the working precision of the metrology will be improved and the possibility of damaging the delicate mirror during the transfer, installation, and realignment process is removed.

Mission Applications

Availability of fast and accurate in situ surface figure metrology during x-ray optics fabrication would allow a significant reduction in manufacturing costs, making high-resolution x-ray optics more affordable for future NASA astrophysical and heliophysical missions.

Notable Accomplishments

- Deflectometer breadboard built (fig. 1).
- Fringe pattern generation software developed (fig. 2).
- Software code for grayscale offset calibration (monitor calibration) developed. Figure 3 shows the map of the grayscale offset measured for the

ultra-high-definition monitor used for the deflectomenter breadboard.
- Software code for fringe pattern distortion correction (camera calibration) developed.
- Software for all necessary fringe data manipulations procured.
- Surface data analysis in progress.

References

1. Gubarev, M.V.; Kilaru, K.; and Ramsey, B.D.: "An investigation of differential deposition for figure corrections in full-shell grazing-incidence X-ray optics," *Nucl. Instrum. Meth. A*, Vol. 616, pp. 273–276, May 2010.

2. Reid, P.B.; et al.: "Technology development of adjustable grazing incidence x-ray optics for sub-arc second imaging," *Proc. SPIE*, Vol. 8433, No. 84330T, 8 pp., September 2012.

3. Jüptner, W.; and Bothe, T.: "Sub-nanometer resolution for the inspection of reflective surfaces using white light," *Proc. SPIE*, Vol. 7405, No. 740502, August 2009.

4. Su, P.; et al.: "Non-null full field X-ray mirror metrology using SCOTS: a reflection deflectometry approach," *Opt. Express*, Vol. 20, No. 11, May 2012.

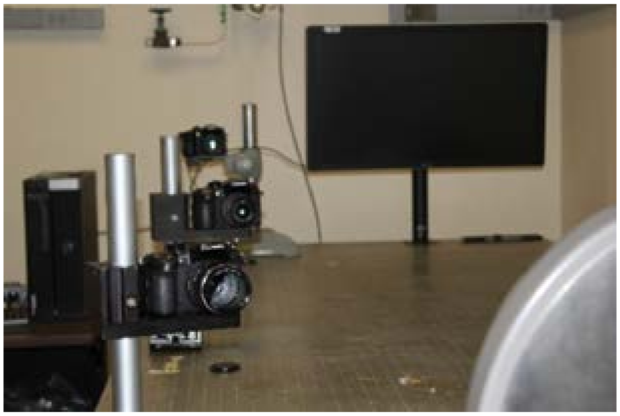


Figure 1: Breadboard setup for PMD experiments.

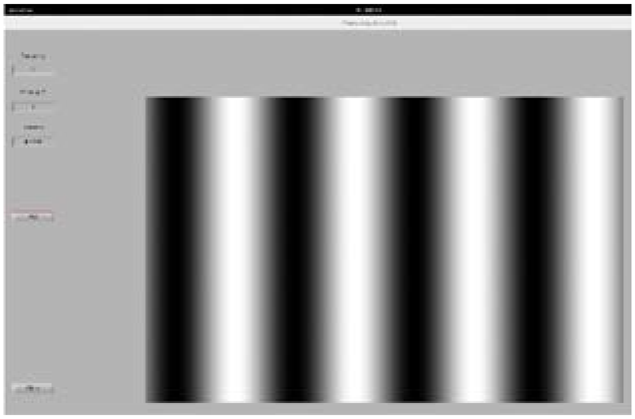


Figure 2: Screenshot of the fringe generation software developed.

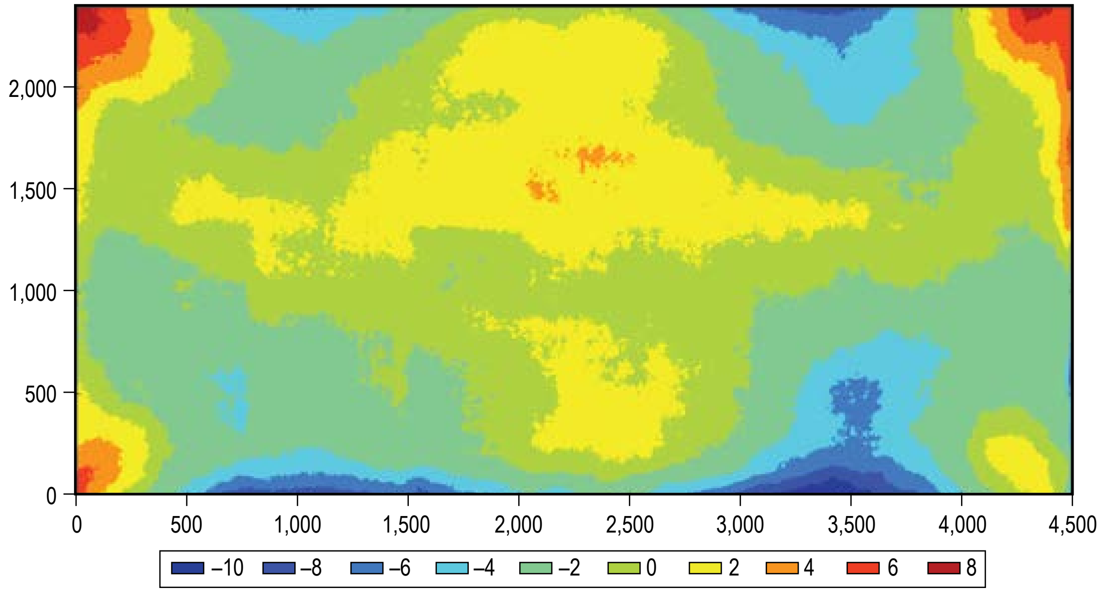


Figure 3: The measured map of the grayscale offset at the monitor. The map was used for the monitor calibration.

Correlated Electromagnetic Levitation Actuator

Project Manager(s)

Sarah Triana/EV42
(256) 544–6042

Paul Britton/QD33
(256) 544–8301

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

With this project, we seek to prove we can create an efficient frictionless reaction wheel using correlated electromagnets by levitating and rotating one above the other and changing the levitation height and rotation by actuation. A correlated electromagnet would have many tiny dipoles that can be individually controlled to gain desired behavior. Correlated permanent magnets do exist and have proven the theory of magnetic correlation, but because they are permanent, they cannot be changed, controlled, or actuated. The capability to electrically control the individual dipoles of correlated electromagnets would greatly advance the current applicability of magnets to technology challenges of interest. With the added capability of being turned on or off, reversing polarity, reprogramming, or even preprogramming to induce a sequence of events, correlated electromagnets would produce even more complex, dynamic, and useful behaviors in comparison to their permanent counterparts. We propose to first characterize the capabilities of correlated electromagnets by developing a prototype with readily available materials and manufacturing techniques. To show that this technology is feasible for a frictionless reaction wheel, we will demonstrate that one correlated electromagnet can be levitated above another correlated electromagnet at various controllable heights and then rotated at that levitation height. This will demonstrate that the change in levitation height and rotation can be actuated through controlling the individual dipoles of the correlated electromagnets. The following is a summary of the benefits from this project: (1) A single pair of correlated electromagnets could exhibit the behavior of several correlated patterns (in sequence); (2) the process for designing correlated patterns will be made accessible to a broader set of engineers; (3) initial characterization of the properties and performance parameters of correlated electromagnets will be made; (4) a focal point is created for microelectromechanical systems and other advanced manufacturing techniques, and advanced materials development, leading to external leveraging; and (5) we can create a frictionless reaction wheel.

Anticipated Benefits

An array of electromagnetic maxels (e-maxels) would be capable of being turned on or off, reprogrammed, or even preprogrammed to induce a sequence of magnetic topologies. They have the potential to be made stronger than permanent magnets. Various coil designs can yield a wide array of field shapes, resulting in a theoretically larger space of correlated patterns. An array of e-maxels would have the ability to induce a sequence of complex magnetic field topologies and the ability to change the strength of the individual e-maxels, giving more complex behavior which would produce even more multifaceted and useful behaviors in comparison to their permanent counterparts. This also means that instead of having static fields and fixed behavior, whereas a new magnet has to be printed every time a new behavior is desired, only the code in a correlated electromagnet has to be updated to create the new desired dynamic or static behavior by changing the individual dipoles of the e-maxels. This project focuses on a single application, which is levitation and rotation that proves the concept of reaction wheels without ball bearings. This is important because ball bearings are a major failure point for reaction wheels. It also means that there is no friction from the bearings, and hence, efficiency and lifespan will be increased.

Other potential future uses and applications:

- Electric propulsion.
- Separation systems.
- Autonomous rendezvous/docking.

Mission Applications

This prototype being developed is to demonstrate the use of a frictionless reaction wheel that can be used on satellites.

Notable Accomplishments

Prototype Development
The initial design was a 14×14 matrix of electromagnets. Each e-maxel independently changes polarity and intensity when commanded via the graphical user interface.

Controller Design
A controller was designed to control each individual e-maxel's polarity and intensity.

Modeling
Modeling was done to show that we can match the test data (fig. 2). If the model matches the test data, then we can use the model to predict future characteristics and behavior.

Testing Structure/Interfaces
The test setup is shown in figure 3.

Test Results
The following shows the temperature of the array during operation (fig. 1) and the magnetic field (fig. 4). Initial testing shows that each electromagnet can be controlled individually and can produce a north or south polarity at full intensity.

Future Design
The dipole pattern and printed circuit board (PCB) layout to be used for the levitation is shown in figure 5.

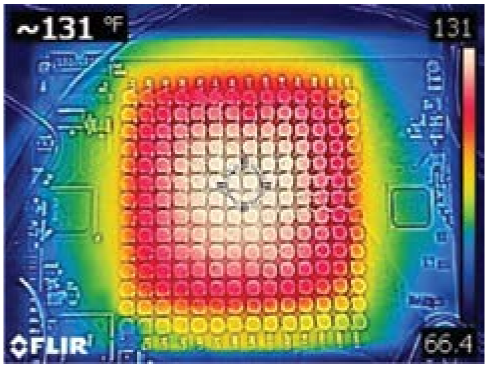


Figure 1: Temperature.

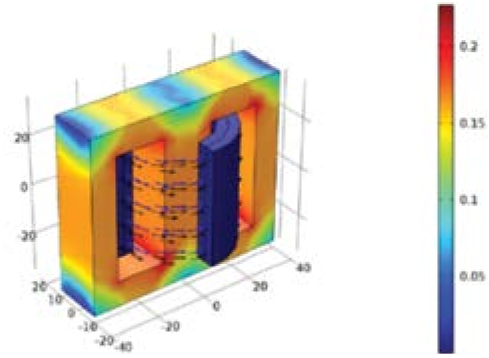


Figure 2: Magnetic field model.

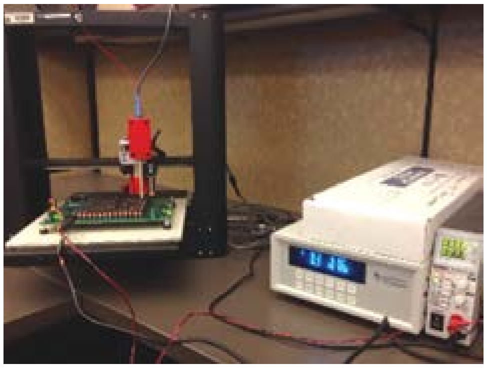


Figure 3: Test setup.

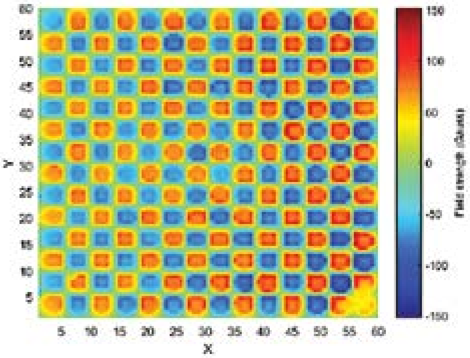


Figure 4: Magnetic field at surface.

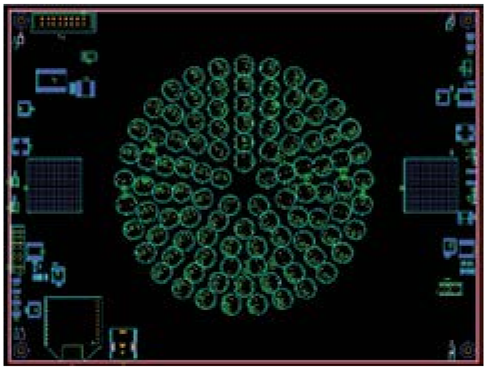


Figure 5: PCB design for levitation.

Flexible Electrostatic Tools for Capture and Handling

Project Manager(s)

Tom Bryan/ES35
(256) 653–5990

Sponsoring Program(s)

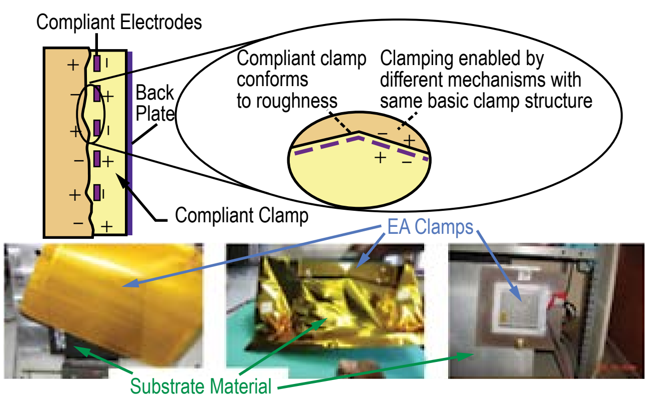
Space Technology Mission Directorate
Center Innovation Fund

Project Description

Innovative Electrostatic Gripper Capabilities

Current robotic arms and docking mechanisms have difficulties with spacecraft without suitable capture structures or docking ports. However, flexible electrostatic (ES) gripper tools have the following capabilities for capturing spacecraft:

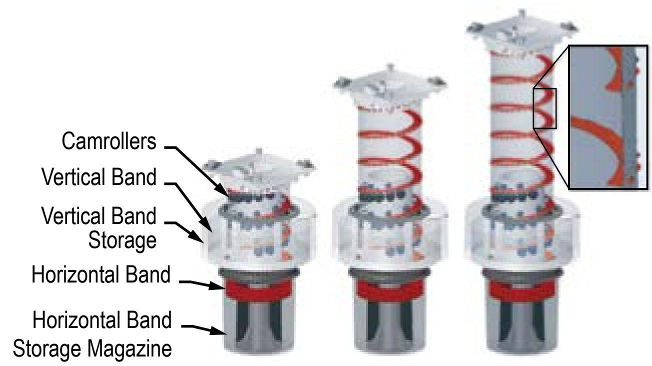
(1) Able to grip and release various materials on command.
(2) Able to conform to different surfaces due to flexibility.
(3) Fewer moving parts, potential to be more reliable.



FETCH Development

To use the innovative gripping capability of ES adhesion to capture unstable satellites and orbital objects, we need a retractable boom that allows the retrieval vehicle to observe from a safe stand-off distance and extend and synchronize the flexible ES gripper with the unstable object's center of rotation to grip with minimal impact and use its grip to de-spin before moving the object toward the retrieval vehicle by boom or releasing and recapturing it.

The I-Lock 75



<u>Breadboard ES Gripper Positioner Arm</u>: Using a heavy-duty pan and tilt unit as the shoulder joint, a retractable mechanism (using aforementioned boom) with a continuous spin table is being built to spin and lower the ES gripper to capture the simulator.

<u>Reactive (Unstable) Satellite Simulator</u>: To evaluate Flexible Electrostatic Technologies for space Capture and Handling (FETCH) and methodology, a 5-axis air-bearing simulator was assembled to support various simulated spacecraft surfaces and spun up by decoupled air jets. Misalignments at capture will result in relative motion or gripping failure.

Anticipated Benefits

Changing the Physics of Docking and Capture

When we change the joining of two spacecraft from a mechanical jousting event into an electronic 'reach out and touch it' grappling, the physics of the process change for both vehicles:

(1) Docking requires the 'chase' vehicle to use a complex thruster system to move into the docking port envelope (controlled collision) while controlling position and velocity in six axes simultaneously.

(2) Thruster; sensor; center of gravity; guidance, navigation, and control (GN&C); and velocity errors in docking must be minimized or absorbed during docking contact dynamics.
(3) Docking contact dynamics can excite 'water hammer' in chase vehicle and target vehicle tanks, which may require additional baffling.
(4) Berthing requires a multijoint mechanism to capture and move the incoming vehicle from station-keeping into the capture latch envelope, baseline for Japanese and U.S. resupply for the International Space Station (ISS) (mechanism can be on incoming vehicle for dexterous docking).
(5) Station-keeping is less demanding on attitude control systems and GN&C; slower approach requires fewer thrusters, simpler abort and collision avoidance maneuvers and operations, and less plume and contamination.
(6) Relative motion control is simplified between capture vehicle and target vehicle by building a 'spin' table into the capture boom.
(7) Electrostatic grippers work with various shapes, materials, and finishes for capture (aluminum, multilayer insulation, foam, composites, etc.).
(8) Zero-velocity vehicle capture enables scaling up to 'exploration-sized' assembly and down to servicer vehicle for satellite capture, sample capsule return, or other activities.
(9) Small ES grippers can allow CubeSats to capture low-Earth orbit spacecraft and then deploy drag augmentation devices for deorbit missions.

Mission Applications

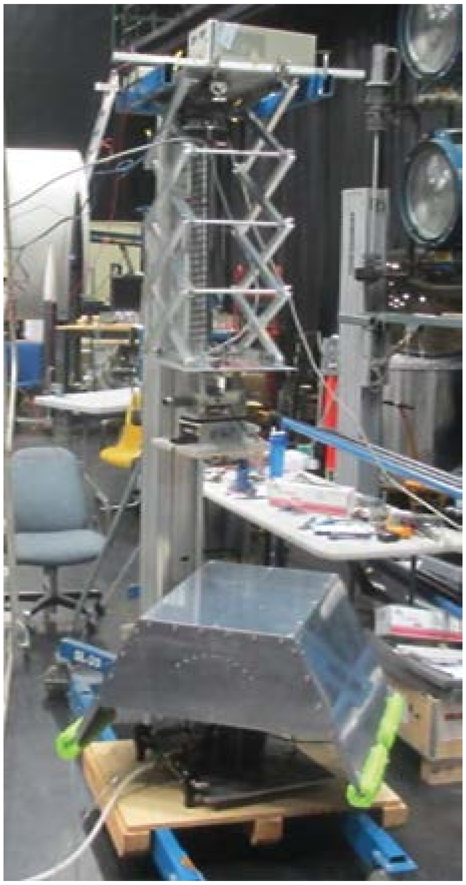
- Spacecraft capture and deorbit.
- Satellite servicing.
- Sample capsule capture and return.
- Exploration vehicle orbital assembly.
- Asteroid attachment and handling.

Notable Accomplishments

- Assembled a reactive 5-axis spacecraft air-bearing reconfigurable simulator (air-jet spun).
- Fabricated a 4-jointed retractable capture boom with spin table and compliant ES gripper mount.
- Purchased 'smart video' sensor and LED light detection and ranging sensors for automated alignment to spinning target.
- Refurbishing of first generation ES gripper with new pads.
- Reconfiguring of vacuum pass-through for new tests.
- White paper and poster for Advanced Maui Optical and Surveillance Conference with Stanford Research Institute.
- Two NASA Robotics Intern Teams and two reapplicants.
- New technology report pending.

Forward Plans

- Complete next round of flat floor demos and vacuum chamber tests of refurbished gripper.
- Evaluate sensor suite for align and capture
- Pursue proposals, partnerships, and intern projects.
- Continue evolution of FETCH concept.



Intern-assembled retractable ES capture boom.

Superior Epoxies for Cryogenic Composite Tank Fabrication

Project Manager(s)

Richard Grugel/EM31
(256) 544–9165

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

In terms of 'innovation,' this is a unique epoxy with unique properties, and NASA co-holds the patent.[1] Furthermore, this epoxy is being exclusively formulated for cryogenic use. The intent of the work proposed here is to ascertain the viability of ionic liquid (IL) epoxy-based carbon fiber composites for use as storage tanks at cryogenic temperatures. This IL epoxy has been specifically developed to address composite cryogenic tank challenges associated with achieving NASA's in-space propulsion and exploration goals. Our initial work showed that an unadulterated IL carbon fiber composite exhibited improved properties over an optimized commercial product at cryogenic temperatures. Subsequent investigative work[2] has significantly improved the IL epoxy, and our first carbon fiber composite overwrap pressure vessel (COPV) was successfully fabricated (fig. 1).

Anticipated Benefits

It is anticipated that lower weight tanks are to contain cryogenic fluids and gases both in space and for getting to space.

Mission Applications

In addition to applications for Moon/Mars mission cryogenic fuel tanks, the strong epoxy/metal bonding can be used to join components, and its low vapor pressure makes it an ideal candidate for in-space repairs.

Figure 1: COPV fabricated using the IL-based epoxy.

Notable Accomplishments

Sample sections from a fabricated, liner-less composite cylinder were subjected to direct quenching into liquid oxygen (LOX) and liquid hydrogen (LH_2). No cracking of the matrix or debonding from the fibers were seen (fig. 2).

We examined IL epoxy samples that spent 2+ years of continual exposure outside of the International Space Station on the MISSE-8 sample rack. Here, they experienced some 12,500 thermal cycles (–40 °C and 40 °C). The four flight samples exhibited insignificant weight variances, a slight ultraviolet (UV) darkening of the surface was seen, and there was no cracking or debonding from the aluminum sample substrate, (fig. 3(a)). Microscopic examination of the exposed surface (fig. 3(b)) revealed submicron (nanoscale) dimpling.

References

1. Paley, M.S.; Libb, R.S.; Grugel, R.N.; and Boothe, R.E.: "Ionic Liquid Epoxide Resins," U.S. Patent No. 8,193,280, June 5, 2012.

2. Grugel, R.N.; Kaukler, W.F.; Paley, M.S.; et al.: "Development of Ionic Liquid Based Epoxies for Carbon Fiber Composite Cryogenic Tanks," in *Proc. 2014 NSMMS Symposium*, June 23–26, 2014, Huntsville, AL, 15 pp., 2014.

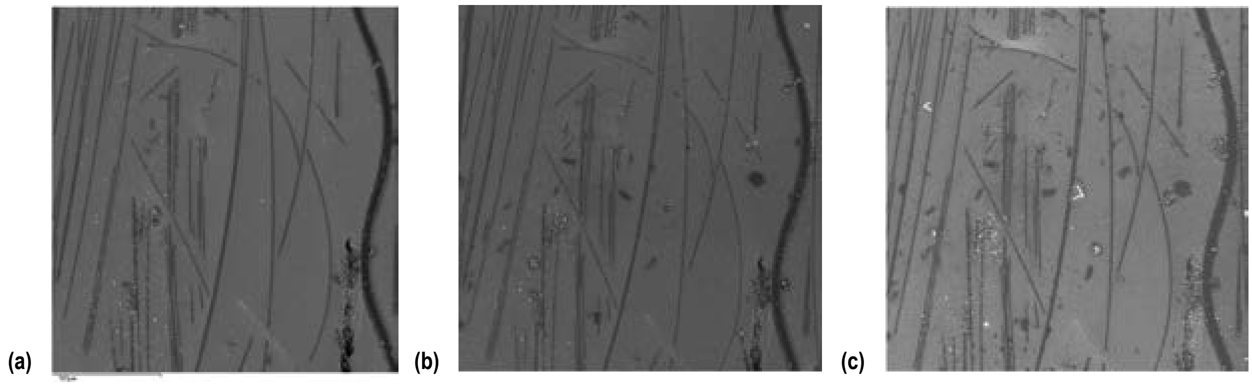


Figure 2: Comparison of an IL epoxy carbon composite section before and after cryogenic submersions: (a) As-made, (b) post-LOX, and (c) post-LOX and LH_2 submersion. Scanning electron microscopy micrographs show maintained fiber/epoxy integrity.

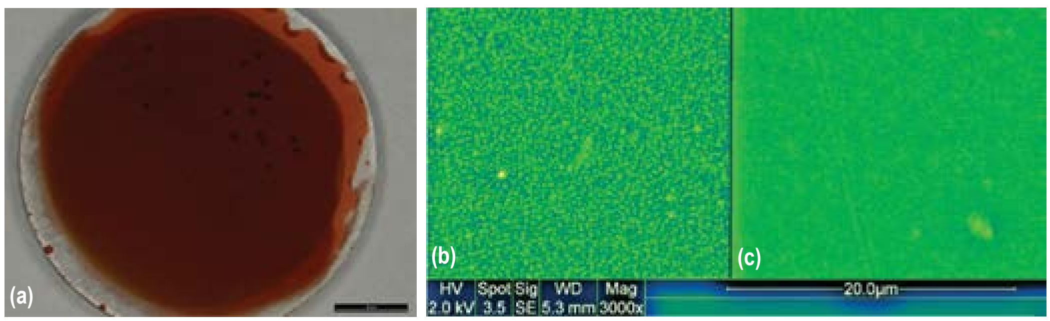


Figure 3: (a) Ionic liquid sample returned from MISSE-8. The lighter orange color indicates where the sample was covered and not exposed to the space environment. (b) High magnification (3000×) of the surface of figure 3(a) for comparison to figure 3(c), the ground sample.

Radar Hazard Identification for Planetary Landers

Project Manager(s)

Paul Meyer/ZP11
(256) 961–7892

Mike Hannan/EV41
(256) 544–1403

Sponsoring Program(s)

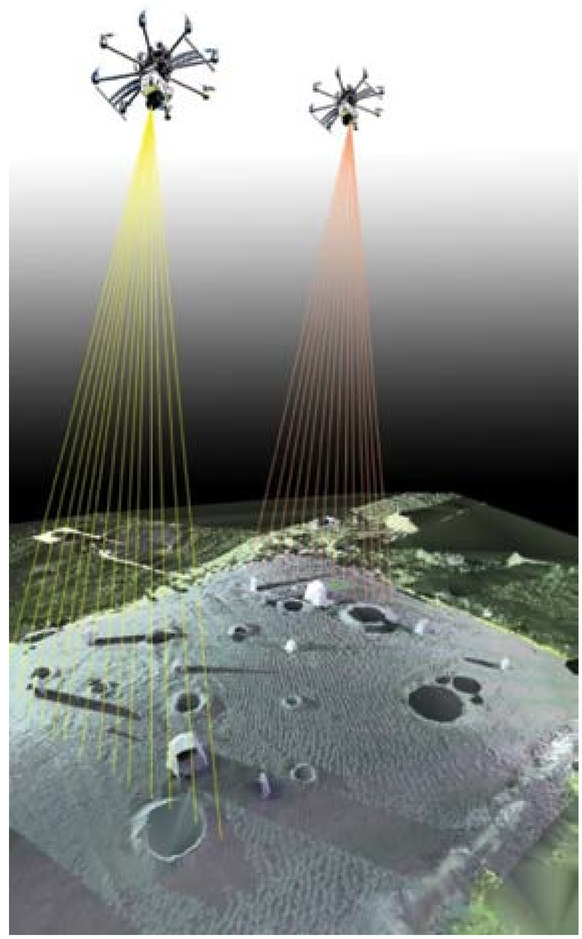
Space Technology Mission Directorate
Center Innovation Fund

Project Description

This project endeavors to see if low-cost automotive sensors being developed for autonomous cars can be used on NASA landers. Developing sensors is expensive, and if NASA can leverage the large investments being made by the auto industry, some missions will become significantly more affordable. Hazard identification and avoidance is a critical technology for NASA's exploration mission. For unmanned scientific missions to scientifically interesting locations, such as inside of craters or near outcrops, mission success will depend on the ability to identify and avoid hazards (boulders, craters, and steep slopes). For manned missions, these sensors could be used to assist a human pilot. We believe that an investigation into the application of automotive sensors for landers is an effort that should continue because of the large potential return on investment.

Anticipated Benefits

Use of sensors developed by the automobile industry has the potential to significantly reduce the cost of sensors needed for hazard identification and avoidance. Industry investment in these sensors is ongoing, so significant advances in sensors and software are to be expected.



Visualization of radar scanning the surface.

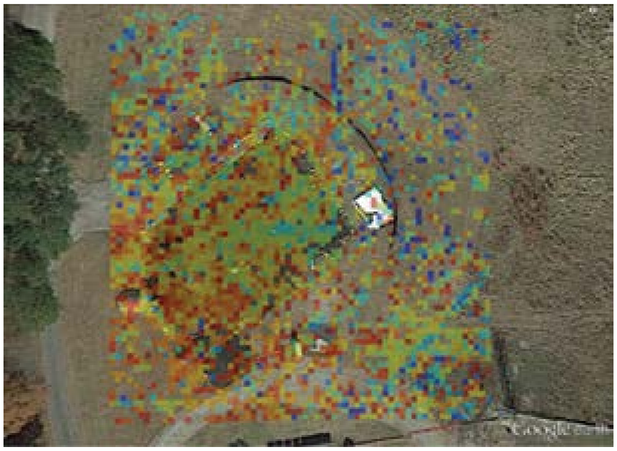
Mission Applications

- Hazard avoidance for autonomous scientific missions.
- Pilot assist for manned landers.
- Precision navigation for resupply missions.
- Autonomous rendezvous and docking.

Octocopter flying over the terrain field carrying the radar.

Notable Accomplishments

- Assembled the radar, power interface, data acquisition, GPS, and IMU into a flight system.
- Flight-tested a low-cost auto radar for use as a hazard identification sensor.
- Extracted needed range and reflectivity data from automobile data bus.
- Established valuable relationship with the navigation team at Auburn University.
- Acquired preliminary radar data and developed the software to process it with adjustments made using GPS and IMU measurements.



Radar range and reflectivity.

References

Hannan, M.; Rickman, D.; Chavers, G.; et al.: "Flight Testing of Guidance, Navigation and Control Systems on the Mighty Eagle Robotic Lander Testbed," Paper Presented at AIAA SciTech 2015, Kissimmee, FL, January 5–9, 2015.

Linear Transformer Driver Development

Project Manager(s)

Robert Adams/ER24
(256) 544–3464

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

The Linear Transformer Driver (LTD) is a revolutionary new technology that has applications in propulsion and power. Pulsed power systems generally store energy in capacitors and release that energy in a short burst. Adequate time compression of the burst is essential to raise the temperatures of operating plasmas and to encourage compression of the plasma. The LTD can compress an electrical current by a high factor, replacing a traditional Marx bank in a pulsed power application. LTDs can reach efficiencies of near 80% with a required mass potentially a factor of 10 lower than a comparable Marx bank. LTDs can revolutionize the size of fusion and other pulsed power applications. Additionally, LTDs scale well from tabletop to terawatt applications. This technology has broad applications, and its development can be done incrementally.

The objective of this project is to construct a first and second generation LTD capable of producing a 100-ns signal at roughly hundreds of joules per pulse. As will be shown in the discussion, this energy level would demonstrate the building blocks for a much larger system capable of pulsing several pulsed electric propulsion systems, or could be applied to a rail gun/launch assist application. The eventual goal is to implode a fusion target. LTDs are a new technology, first developed in the Russian Federation. Several LTDs were purchased from Russia and are either at Sandia National Labs or The University of Michigan (UM). The authors of this proposal have been in contact with the Sandia and UM and are discussing possibilities to reverse engineer LTDs and adapt them for applications for space propulsion and ground power systems. The greater efficiency and lighter weight of LTDs relative to existing high-discharge capacitor systems means more effective propulsion and power systems and simpler operations for ground-based facilities.

The LTD is basically a special inductive transformer whose primary inductor consists of a number of moderate-voltage, low-inductance, self-powered, ultra-fast switched loops, called ***cavities***. Each cavity is a flat torus with a conductor looped around the center hole. The cavities induce a current in a long conductive bar that serves as a secondary (output) electrode. This bar runs through the center holes of the cavities (fig. 1). Since the cavities are self-powered and have the same voltage (V), the voltage in the secondary is $N \times V$, where N is the number of cavities enclosing the secondary. The set of cavities enclosing a single secondary is called a ***stack***.

Each cavity is powered by a number of parallel circuits, each consisting of a pair of low-valued (≈40 nF) capacitors charged to moderate voltage (5–100 kV), referred to as ***bricks***. These bricks are switched to the cavity conductor simultaneously to induce a pulsed current in the secondary. Because each circuit has very low inductance, the pulse width is very short (≈100 ns). This eliminates the need for pulse shaping diodes and the associated power loss.

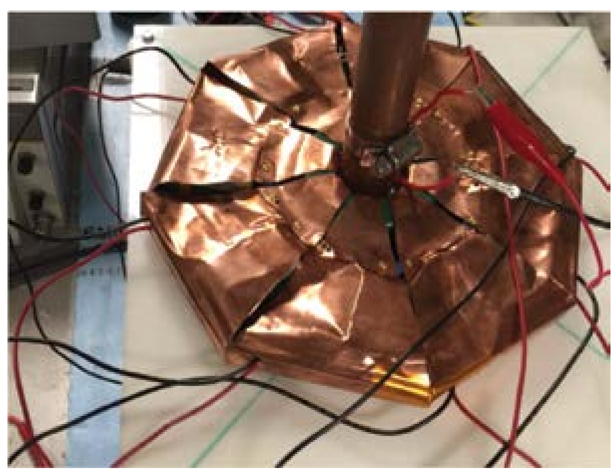


Figure 1: LTD cavity latest version.

Anticipated Benefits/Mission Applications

Eventually, the LTD system will be used in a variety of pulsed power applications. At NASA Marshall Space Flight Center, there are two propulsion applications that have been identified: the pulsed plasma thrusters for CubeSats and pulsed fission-fusion hybrid propulsion.

Notable Accomplishments

When charged to 2 kV, the cavity can store 0.81 J of energy in its capacitors. When the cavity is fired, it transfers the energy to its load via mutual inductance with its stalk (the copper pipe extending through the center of the cavity). If the impedance of the load is the same as the impedance of the LTD, then this energy (less core and other losses) is transferred to the load in a single pulse (half cycle). If the impedance is not the same, then only a portion of the energy is transferred, and the rest is dumped back into the capacitors (with polarity reversed) and the LTD drives the current through its inductor again in the opposite direction. This continues until all of the energy has been dissipated into the load. This cyclic behavior is known as ringing, and can be seen most clearly in figure 2. Note that the wave repeats, with each cycle having lower amplitude (voltage and current) than the previous one.

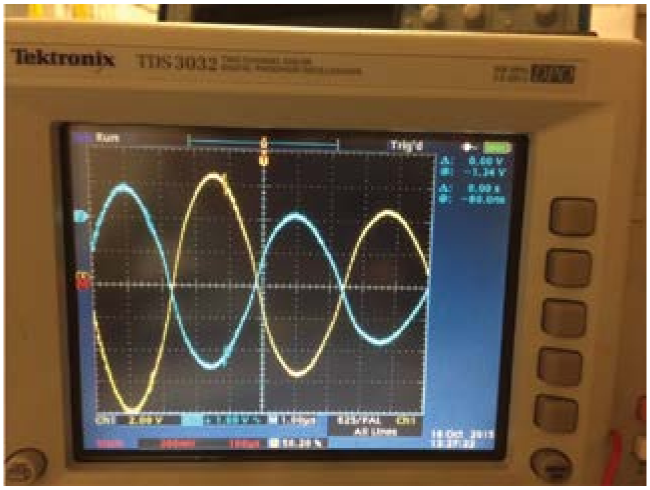


Figure 2: Test results using the latest version of the LTD.

Most of the inefficiency is due to impedance mismatch; the actual core and inductive losses appear to be very small. One of the future goals of our experimentation is to quantify those losses.

Second Generation QUATARA Flight Computer

Project Manager(s)

Jose Carlos Molina Fraticelli/ES53
(256) 544–0328

Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

The QUATARA computer enables a CubeSat to manage more data, process more sensors, and control multiple actuators without compromising the computational capabilities of any single microprocessor.[1]

The QUATARA computer is fault tolerant by means of software voting using a scheme leveraged from the Space Launch System's flight software. As part of the iodine satellite project, the principal investigators had the opportunity to develop the first generation of the QUATARA computers. This first generation was connected using the internal communication ports of the processors. This is not optimal as it reduces the computer's capability of interfacing with additional sensors and effectors. For that reason, the second generation QUATARA computer (fig. 1) uses a custom field programmable gate array (FPGA) high-speed communication interface (fig. 2) to increase the data transfer rate between the processors and additionally free up the processors' own communication interfaces so that they can be used to connect additional sensors and effectors.

Why Is This Innovative?

- Fault tolerance provided through software voting scheme with no need for radiation-hardened components.

- High-speed microprocessors able to process large algorithms much faster than microcontrollers.

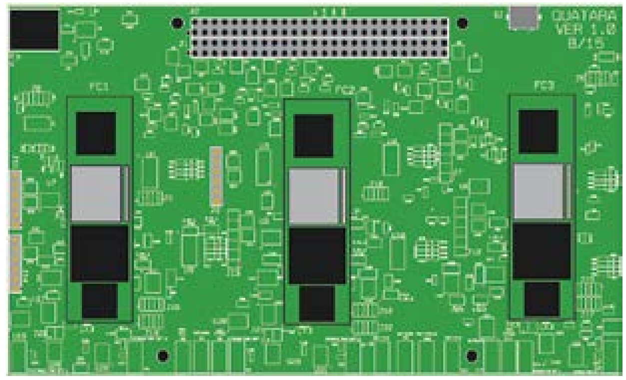


Figure 1: QUATARA prototype printed circuit board.

Anticipated Benefits

The use of multiple nodes allows the computer to have redundancy through software and some level of tolerance against single event upsets and other such events. There is also a possibility of bringing back a downed node by restarting it.

Having Linux running on each processor node allows for the use of powerful open source libraries such as OpenCV for image processing.[2]

Mission Applications

Developing the fault tolerant capability of the second generation QUATARA enables new missions such as sample return, debris removal, satellite inspection, peer-to-peer refueling, and formation flying, which are not currently possible due to the lack of CubeSat flight computers with a sufficiently high level of fault tolerance that would be required for these types of missions.

Potential Future Uses

By changing the computer nodes to multicore microprocessors, internode parallel processing capabilities could be added by using industry-standard specifications such as OpenMP®.[3]

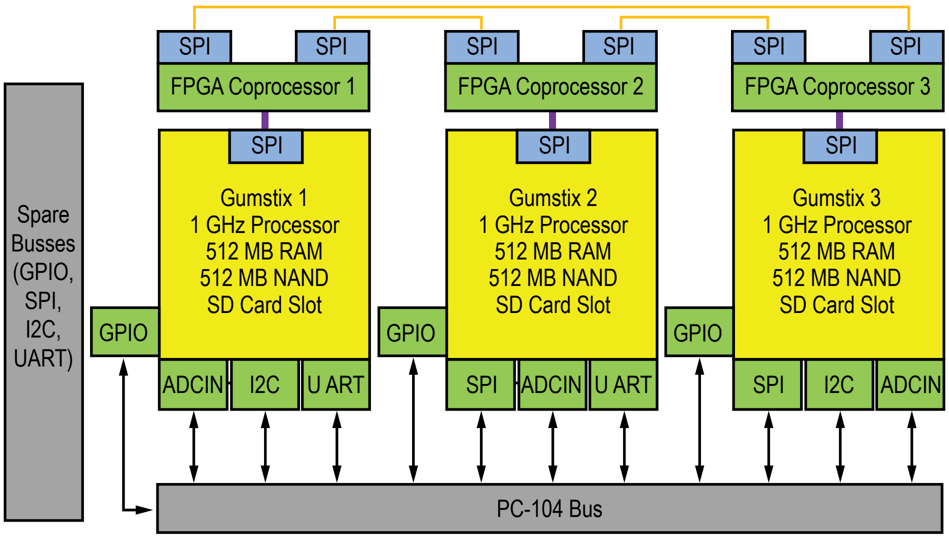


Figure 2: Hardware block diagram and FPGA communication interface.

A third generation of the board could support additional interfaces and act as the processing unit of a science payload for a CubeSat mission.

Notable Accomplishments

A custom FPGA communication interface has been developed to pass data between the flight computer nodes at high speeds. Custom software was developed and installed on the nodes to test the interface.

A prototype printed circuit board was designed and manufactured (fig. 1).

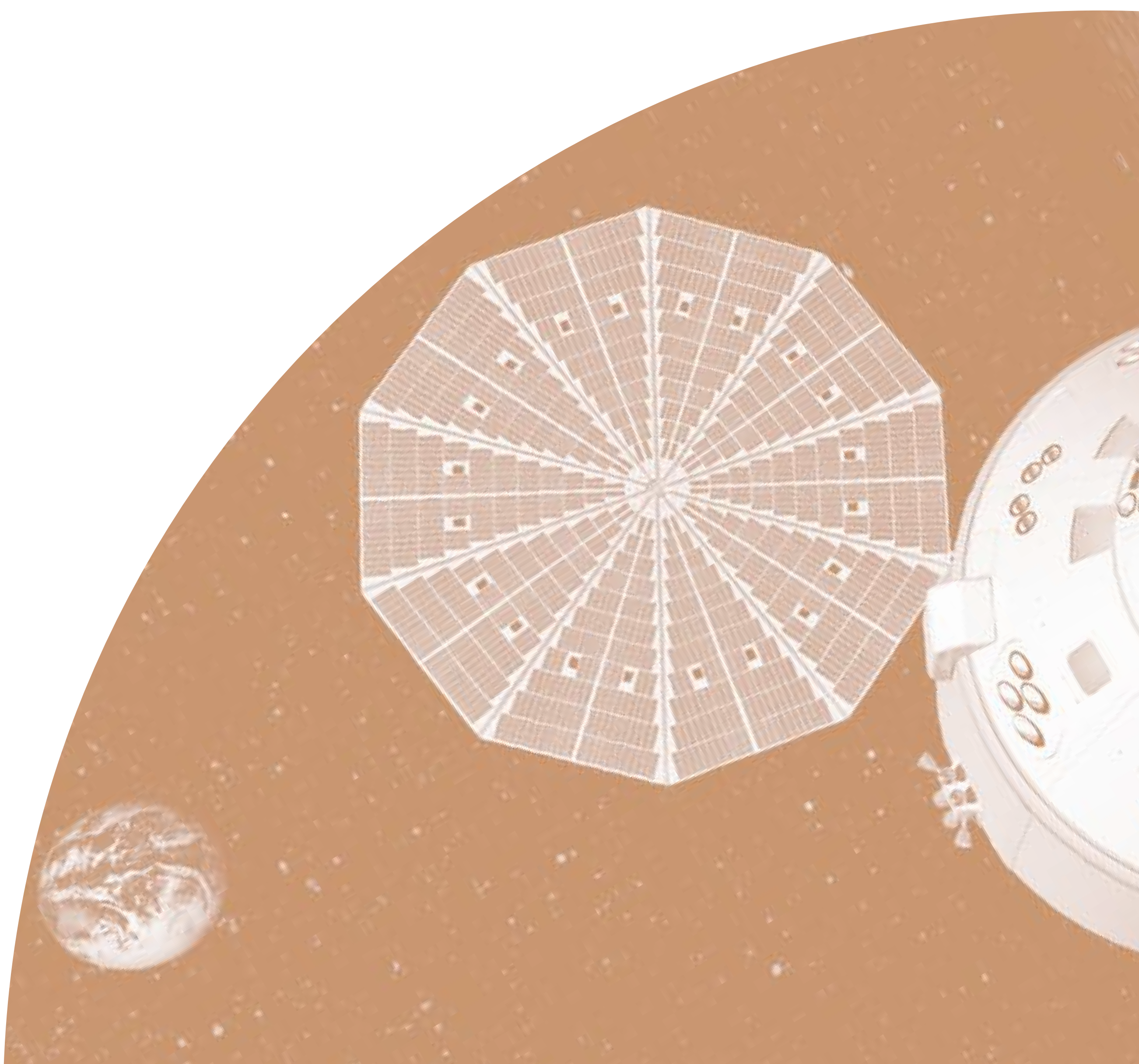
References

1. "CubeSat Design Specification," Rev. 13, <http://cubesat.calpoly.edu/images/developers/cds_rev13_final.pdf>, February 2014.

2. OpenCV, <http://opencv.org/>, 2015.

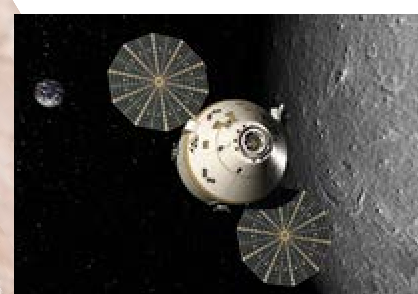
3. OpenMP API Specification for Parallel Programming, <http://openmp.org/wp/>, 2015.

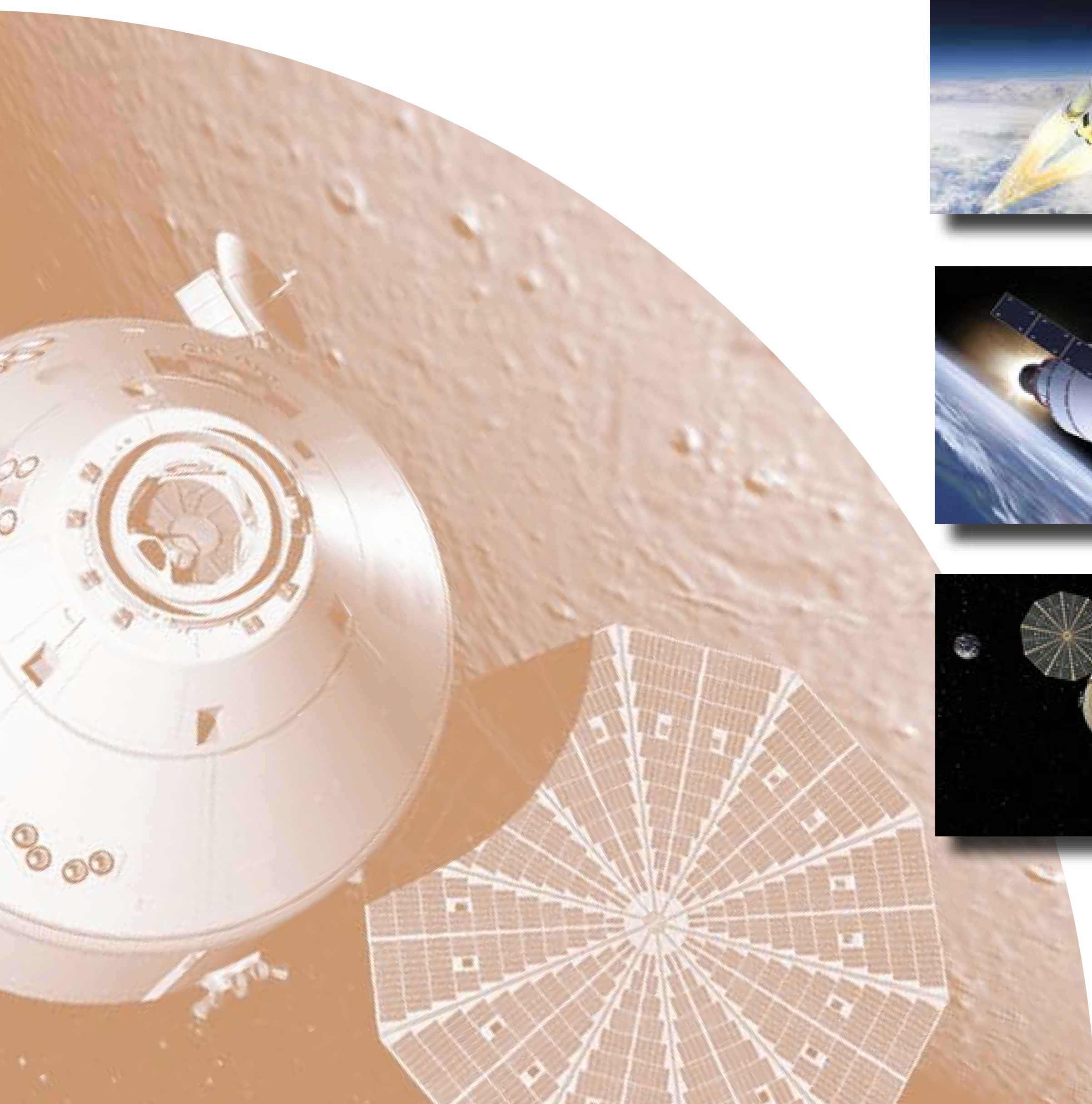
Marshall Space Flight Center/ Center Management and Operations



Marshall Space Flight Center/ Center Management and Operations

Technology Investment Program





Common Data System Architecture for Earth and Space Science Instruments

Project Manager(s)

Timothy Lang/ZP11
(256) 961–7861

Anthony Guillory/ZP21
(256) 961–7441

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

The objective of this project was to develop and test a compact common data system architecture for use in Earth and space science instruments. This architecture is called NASA Marshall Space Flight Center (MSFC) Instrument Data Architecture for Science (MIDAS). We performed a trade study to identify common characteristics between data systems for a broad range of instruments, including those commonly flown on aircraft, balloons, and sounding rockets. We then designed MIDAS and produced technical documentation for it. Finally, we are building, testing, and demonstrating a prototype MIDAS data system by integrating it with MSFC's own Advanced Microwave Precipitation Radiometer (AMPR). The testing and demonstration will occur within the MSFC thermal altitude chamber to reproduce common flight conditions.

Common components of a MIDAS data system are as follows (see also fig. 1):

<u>Hardware</u>
- Central processing unit (CPU).
- Power supply.
- Field programmable gate array (FPGA) for instrument-specific tasks (e.g., motor control).
- Compact peripheral component interconnect (cPCI) back plane.
- Analog-to-digital conversion (ADC) cards (medium data rate).
- Custom instrument-specific card(s).
- Data storage (<1 TB onboard).
- Enclosure to withstand corrosion.
- Slots for additional instrument-specific cards, and/or upgrade cards as needed.

<u>Software</u>
- Linux operating system.
- Common software drivers for card components.

Technical requirements for each component were developed. Each MIDAS data system component has a range of requirements (e.g., for temperature) that will not need to be met by each individual MIDAS data system. Rather, the specific components for that data system must overlap with MIDAS requirements. For example, a specific brand of FPGA card's specifications must at least partially overlap with MIDAS requirements (e.g., for temperature), but they do not need to overlap the entire range of MIDAS requirements. In addition, the specific role of the FPGA card may vary between individual MIDAS data systems. In this way, MIDAS can be used to identify a population of potential data system components, from which specific parts (e.g., a specific make and model of FPGA card) can be selected. In a sense, MIDAS provides a catalog for building a data system.

Anticipated Benefits

The purpose of a common data system architecture is to drive down costs and development time required for both new and existing scientific instruments at MSFC. This will make MSFC more capable of obtaining both competed and directed work for its instruments. Furthermore, the analysis, design, and implementation of the newest data system technologies are needed to ready MSFC to develop next generation instrumentation for scientific missions. Having a common data system architecture also will create overlapping capabilities of personnel and hardware, removing single points of failure that reduce MSFC competitiveness in the scientific instruments arena.

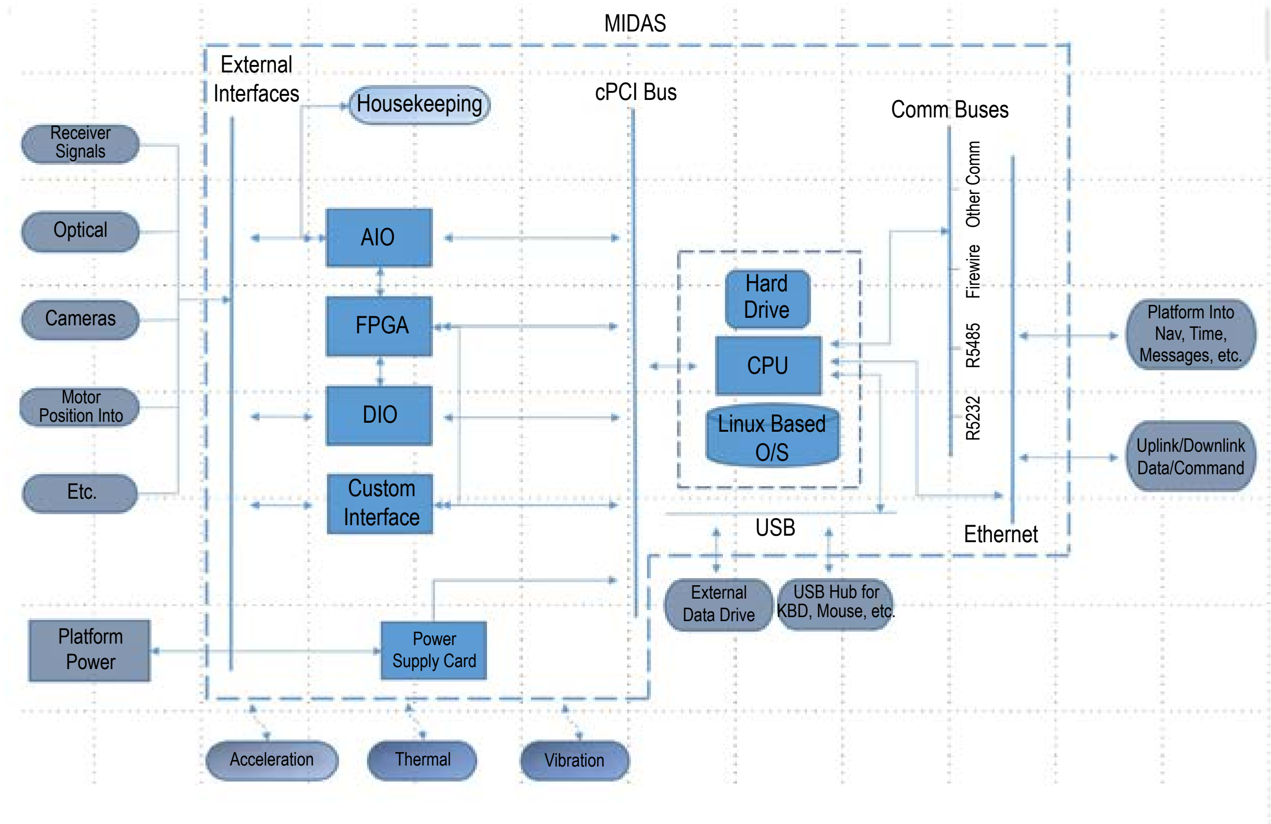


Figure 1: Functional block diagram for MIDAS.

Mission Applications

MIDAS will serve as a guide for building future MSFC Earth and space science instrument data systems, including those built for high-altitude or space environments (e.g., sounding rockets). In particular, the new MIDAS-AMPR data system will enable the AMPR airborne instrument to continue addressing multiple NASA airborne mission needs, including global precipitation measurement ground validation and Earth Venture Suborbital missions.

Notable Accomplishments

- Trade study of existing data system architectures to identify common characteristics.
- MIDAS design and technical documentation reviewed and completed.
- MIDAS-AMPR designed and under construction.
- Schedule for remaining work developed.

Lightweight Integrated Solar Array and Transceivers

Project Manager(s)

Les Johnson/ED04
(256) 544–7824

John Carr/ES44
(256) 544–7114

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

The use of thin-film-based solar arrays for spacecraft applications has long been recognized as an advantageous power generation option.[1] Thinner materials yield a mass savings, equating to lighter launch loads or more payload allocation. Furthermore, their mechanical flexibility lends well to stowage and deployment schemes. Both make thin-film arrays an exciting prospect for small-scale satellites.[2] However, a gap in thin-film array development exists, leaving very few choices for available array structures. The Lightweight Integrated Solar Array and Transceiver (LISA-T) seeks to address this, building upon NASA Marshall Space Flight Center's (MSFC's) experience in space-deployed structures such as NanoSail-D,[3] enabling higher power generation in small-scale satellites at low weights and high stowage efficiency without the need for solar tracking.

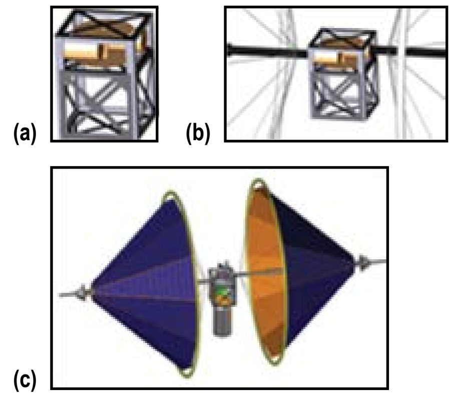


Figure 1: Conceptual rendering of LISA-T (a) stowed, and (b) and (c) deployed.

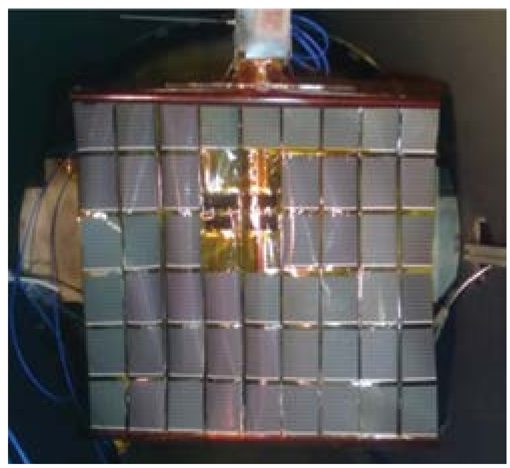


Figure 2: Pathfinder flat-panel LISA-T array. 1U CubeSat with antennas shown at the top.

Anticipated Benefits

LISA-T is a tunable, launch-stowed, orbit-deployed array on which thin-film solar power and communication devices are embedded (fig. 1). Initial estimates indicate upwards of 200 W of power generation can be packaged into and deployed from 1U craft and nearly 500 W from 2U craft. Furthermore, the system can also leverage high-volume terrestrial market photovoltaics (PVs), lowering module costs ($/W). The integration of thin-film antennas allows multiple communication

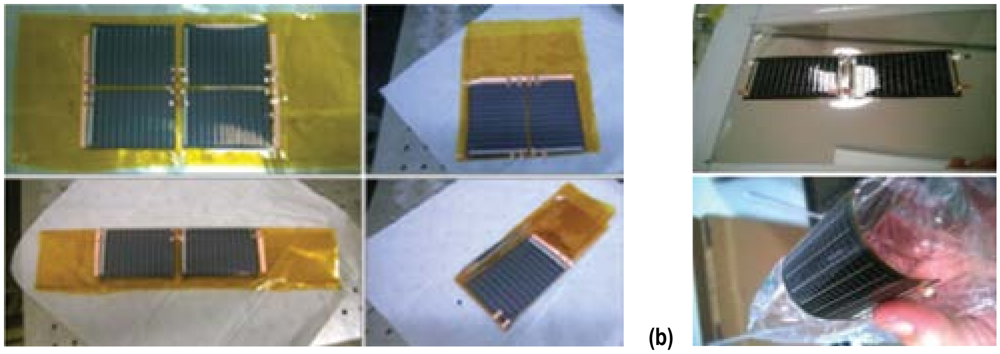
(a)

(b)

Figure 3: (a) Pathfinder PV assembly. Uncovered thin-film PV bonded to 25 µm Kapton with 12-µm copper ribbon interconnects. (b) Second generation PV assembly. Covered thin-film PV adhesivelessly bonded to TCP1.

arrays to be simultaneously deployed. An option for 'three-dimensional deployment' eliminates the need for solar tracking and allows for stronger omnidirectional communications.

Mission Applications

The trend of satellite miniaturization continues to enable lower-cost alternatives to the traditional large-scale spacecraft, opening a door to space for many research and commercial payloads. These small-scale satellites, however, are inherently plagued by limited surface area, volume, and mass allocation, limiting solar array real estate and electrical power generation. Solar array deployment options exist, but are still limited in size, and some require solar tracking. Though a lower cost vehicle to space exists, capabilities remain choked by the small power systems. LISA-T will directly address this problem, enabling higher-power — but still low-cost — small spacecraft missions.

Notable Accomplishments

A pathfinder flat-panel LISA-T array (fig. 2) was successfully deployed and illuminated in the MSFC High Intensity Solar Environment Test (HISET) test chamber, taking the system to Technology Readiness Level-5. The HISET combines the elements of the solar wind environment with a high-intensity, high-power solar radiation source to simulate the environment LISA-T will experience in space.

An environmental effects test plan was developed based on a tailoring of the American Institute of Aeronautics and Astronautics standards for space solar cell/panels testing.

Thin-film protective covers and adhesiveless bonding techniques have also been matured for LISA-T PV (fig. 3). Cells are fully covered and bonded to <5 µm toughened colorless polyimide 1 (TCP1) without the use of adhesive.

References

1. Bailey, S.; McNatt, J.; Raffaelle, R.; et al.: "The Future of Space Photovoltaics," Paper Presented at Photovoltaic Specialists Conference, 2009 34th IEEE, Philadelphia, PA, June 7–12, 2009.

2. Adler, A.L.; Engberg, B.; Hague, N.; et al.: "AFRL PowerSail Structure for Large Solar Arrays," Paper Presented at Space 2003 Conference and Exposition, AIAA 2003-6356, Long Beach, CA, September 23–25, 2003.

3. Alhorn D.C.; Casas, J.P.; Agasid, E.F.; et al.: "NanoSail-D: The Small Satellite That Could!" Paper Presented at 25th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 8–11, 2011.

High Thermal Conductivity NARloy-Z-Diamond Composite Combustion Chamber Liner for Advanced Rocket Engines

Project Manager(s)

Biliyar Bhat/EM31
(256) 544–2596

Sandra Greene/ER32
(256) 544–8902

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

NARloy-Z (Cu-3Ag-0.5Zr) alloy is state-of-the-art combustion chamber liner material used in liquid propulsion engines such as the RS-68 and RS-25. The performance of future liquid propulsion systems can be improved significantly by increasing the heat transfer through the combustion chamber liner. Prior work done at NASA Marshall Space Flight Center (MSFC) has shown that the thermal conductivity of NARloy-Z alloy can be improved significantly by embedding high thermal conductivity diamond particles in the alloy matrix to form NARloy-Z-diamond composite, up to 69% at 40vol% diamond.[1] It is also 24% lighter than NARloy-Z. These attributes will improve the performance and life of the advanced rocket engines significantly.

Research work this year showed that it is necessary to coat the diamonds with copper for better mixing with NARloy-Z powder and better properties. A transition layer of molybdenum carbide on diamonds is required to provide a high contact thermal conductance between diamond and copper. The copper-coated powder is designated as Cu-D. A typical microstructure of NARloy-Z-Cu-D composite is shown in figure 1.

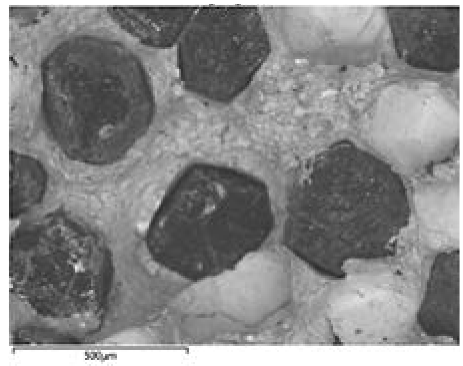


Figure 1: NARloy-Z-Cu-diamond composite microstructure (diamond particles shown in black).

The technology work consists of (1) developing design properties (thermal and mechanical) of NARloy-Z-Cu-D composite, (2) fabrication of near net shape subscale combustion chamber liner, and (3) hot-fire testing of the liner to test performance. Initially, a cylindrical ring (fig. 2) was fabricated using Field Assisted Sintering Technology (FAST) (fig. 3) to demonstrate feasibility. The material from this ring was evaluated for thermal and tensile properties. The liner will be made from eight rings, which are sintered separately by FAST and then stacked and diffusion bonded to make the liner (fig. 4). The cooling channels will be machined by water jet grinding. The liner will be assembled to form a combustion chamber which will be hot-fire tested in the MSFC Test Stand 115 (TS 115) to determine performance (fig. 5).

Figure 2: Combustion chamber liner ring (2.5 in inner diameter, 2.75 in outer diameter, 1 ft long) made from NARloy-Z-Cu-D composite.

Figure 3: Sintering at high temperature using FAST at Applied Research Laboratory, Pennsylvania State University.

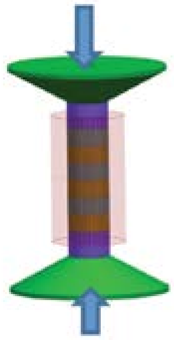


Figure 4: Fabrication of combustion chamber liner by diffusion bonding eight rings by FAST (shown schematically).

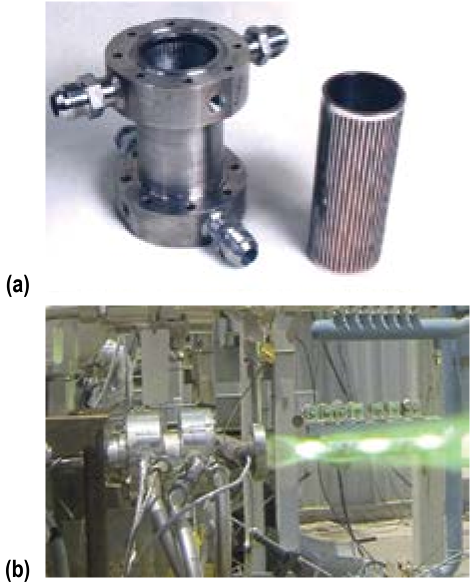


Figure 5: (a) Combustion chamber assembly and chamber liner showing machined channels, and (b) hot-fire testing.

Anticipated Benefits

This project will demonstrate the capability to make our future propulsion systems lighter and higher performing using a high thermal conductivity material for the combustion chamber liner. Turbopump power is expected to increase up to 2×. Increased heat transfer will directly result in increased thrust. There is potential for increased specific impulse for regeneratively cooled rocket engines such as the RL-10/NGE, RL-25E/F, and J-2X. Significant weight savings are possible due to the use of lightweight and higher thermal conductivity material. System-level trades need to be conducted to determine the overall weight savings, but as one example, it may be possible to maintain the current performance and reduce the engine mass.

Mission Applications

This project addresses an important material technology area that has high payoff in terms of affordability and performance of rocket propulsion systems. It will advance the Technology Readiness Level (TRL) from current TRL-3 to TRL-5, at which point it will be ready for implementation in an engine program such as the RL-10/NGE, RL-25E/F, and/or J-2X. Furthermore, the high thermal conductivity NARloy-Z-Cu-D composite material developed in this program will have many applications in the industry, e.g., thermal management for computer hardware (heat sinks), heat exchangers, etc.

Notable Accomplishments

NARloy-Z-28vol%Cu-D cylinders have been successfully sintered using the FAST process (fig. 2). Thermal conductivity and tensile properties are excellent. Preparations are being made to diffusion bond rings to make the liner. A technical paper on this project has been accepted for presentation in the SciTech 2016 57th Structures, Structural Dynamics, and Materials Conference.[2]

References

1. Bhat, B.N.; Ellis, D.; and Singh, J.: “High Thermal Conductivity NARloy-Z-Diamond Composite Combustion Chamber Liner for Advanced Rocket Engines,” Paper Presented at 2014 National Space and Missile Materials Symposium, Huntsville, AL, June 23–26, 2014.

2. Bhat, B.N.; Greene, S.; and Singh, J.: “Fabrication of High Thermal Conductivity NARloy-Z-Diamond Composite Combustion Chamber Liner for Advanced Rocket Engines,” Paper Presented at SciTech 2016 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, San Diego, CA, January 4–8, 2016.

Oxygen-Rich Material Testing

Project Manager(s)

William Greene/XP20
(256) 544–1038

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

In support of the United States (U.S.) Air Force, NASA Marshall Space Flight Center (MSFC) is helping to develop and demonstrate technology that may be required for a future high-pressure, oxygen-rich, RP-1-fueled engine. Demonstrating potential oxygen-rich materials in appropriate high-pressure environments is critical to optimizing such an engine design.

MSFC's efforts to support the U.S. Air Force include hot-fire testing an MSFC-owned, oxygen-rich/RP-1 preburner. This preburner will eventually be used to support further testing of subscale staged combustion hardware. The environment produced in the preburner testing is also ideal for initial screening of new materials. The design of MSFC's preburner hardware assembly allows it to be easily modified to allow a spool section that holds material samples in the hot gas stream of the preburner environment.

MSFC discretionary funds in FY 2015 were used to design the material sample spool section and prepare appropriate drawings for its fabrication. The first samples to be tested in this arrangement will be fabricated with Mondaloy™, an oxygen-resistant material developed by personnel at Aerojet-Rocketdyne. It offers high strength compared to traditional alloys used in specific engine components, allowing a potential weight savings and/or less risk in new engine designs. Its oxygen resistance could also eliminate the need for coatings in some engine components.

Funds to fabricate and test the hardware and the Mondaloy samples from Aerojet-Rocketdyne are being provided by the U.S. Air Force. The samples are expected to be delivered before the end of 2015, and hot-fire testing will be performed at MSFC before the end of 2015 or early in 2016.

Anticipated Benefits

The spool section designed to hold the material samples in this effort is not limited to Mondaloy material samples. It can be used to test similar samples of other oxygen-rich materials offered by industry or other government agencies. So, the hardware designed in this task is expected to enhance MSFC's test capabilities by offering a convenient way to test a variety of materials that could benefit future oxygen-rich, staged combustion engines.

Notable Accomplishments

Figure 1 shows one of MSFC's previous tests with the oxygen-rich preburner hardware in 2015. Figure 2 shows an image of the current assembly. The new spool section that will be used to hold the material samples is imaged in figure 3, while figure 4 depicts the spool section assembled in the preburner hardware. The spool section accommodates two material samples at a time.

When the initial preburner testing at MSFC is completed, the results will provide an assessment of the Mondaloy alloy in a high-pressure, oxygen-rich environment. The samples and required spool section will then be removed and the original preburner assembly will be used to support MSFC's testing of new subscale staged combustion hardware.

The spool section to hold the material samples will remain available at MSFC for future testing, however, in case other entities have additional materials to evaluate in the available oxygen-rich environment. MSFC also prepared the drawing of the material sample required to mate with the spool section. The drawing of the sample can be made available to those interested in testing other material options.

Figure 1: Oxygen-rich/RP-1 preburner testing at MSFC.

Figure 2: MSFC's oxygen-rich/RP-1 preburner assembly.

Figure 3: Spool section to hold material samples.

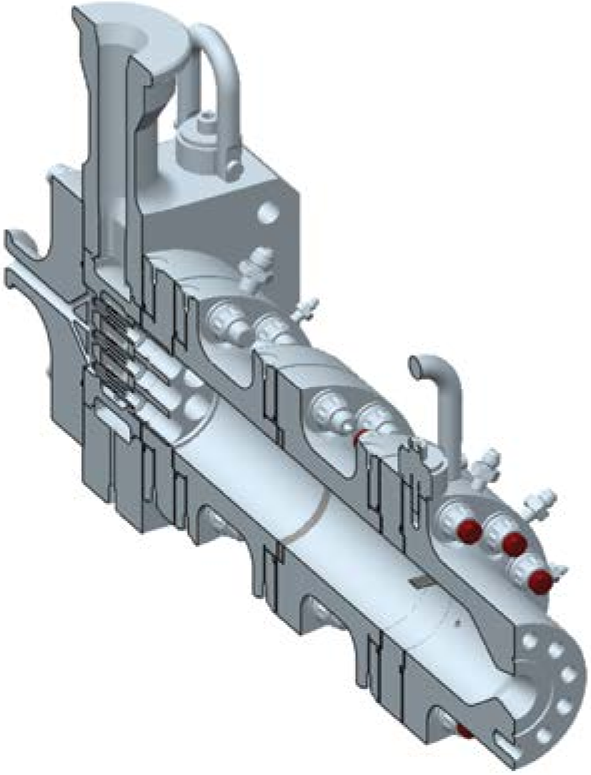


Figure 4: Depiction of material sample installed in MSFC's preburner assembly.

Radio Frequency Identification for Automated Inventory Management

Project Manager(s)

Carole Wagner/EO40
(256) 544–2719

Shawn Hicks/Teledyne Brown Engineering
(256) 544–1628

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

This effort has utilized radio frequency identification (RFID) technologies to help reduce the real-time errors that occur as a result of improper location callout for equipment/items. To date, the most extensive space-based inventory management operation has been the International Space Station (ISS). Approximately 20,000 items are tracked in a database using the Inventory Management System software application, which requires both flight and ground crews to update daily. This process is manually intensive and laborious, requiring the crew to open cargo transfer bags (CTBs) and then multiple Ziplock® bags therein to retrieve individual items. This mundane but required inventory process contributes greatly to the time allocated for general crew activities. To date, RFID technology and a next generation handheld barcode reader have been certified for use on ISS. Although the current handheld reader has resulted in significant savings in crew time, it falls far short of a fully-automated inventory management and tracking system that would save time currently spent by the crew in tracking inventory, resulting in more time for science operations.

In 2014, the NASA Technology Investment Program (TIP) enabled NASA Marshall Space Flight Center's (MSFC's) Mission Operations Laboratory to develop and integrate RFID technologies at the component level and demonstrate a modified application for spaceflight use. The 2015 effort continued to refine in-house RFID innovations and provided the basis for collaboration with another NASA Center, Johnson Space Center. During MSFC demonstration and testing of the RFID CTB and International Subrack Interface Standards (ISIS) drawer, initial detailed testing/feasibility studies showed significant potential for dense zone RFID applications.

The project, aligned with NASA Agency long-term habitat systems goals, involves the use of RFID readers, compartmentalized passive sensors, and RFID sensor-activated tags. The passive sensors and RFID reader have been integrated into a CTB and ISIS drawer. Both the CTB and ISIS drawer are capable of reading the RFID tagged contents in their respective containers.

The RFID for the Automated Inventory Management project had three main objectives in FY 2015. The following objectives apply to automating the inventory audit process using RFID tags for space applications while also enhancing ground operations for ISS inventory management applications:

(1) Demonstrate RFID technology by building and using an automated Wi-Fi-enabled CTB to autonomously self-report contents scanned over Wi-Fi/Ethernet (see figs. 1 and 2).

(2) Demonstrate RFID technology by building, in collaboration with the RFID-Enabled Autonomous Logistics Management-1 (REALM-1) project, an RFID-enabled ISIS drawer (see fig. 3). (Used in ISS Microgravity Science Glovebox and Expedite the Processing of Experiments to Space Station (EXPRESS) racks — a network capability to locate science samples.)

(3) Use the CTB and ISIS drawer RFID tag data collected via Wi-Fi/Ethernet to demonstrate a completely automated process to conduct audits and tool gathering activities, reporting the contents of the CTB or ISIS drawer to an inventory database.

Figure 1: RFID-enabled CTB.

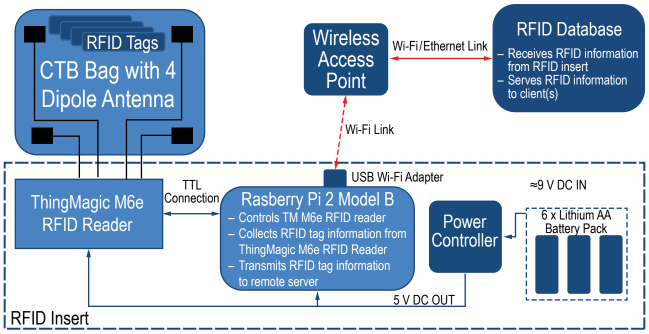


Figure 2: RFID CTB system block diagram.

Figure 3: RFID-enabled ISIS drawer.

Notable Accomplishments/Anticipated Benefits

Testing of both the RFID-enabled CTB and RFID-enabled ISIS drawer showed that the technology is feasible for both ISS and deep space habitat system applications. This RFID technology provides for an autonomously operating spacecraft, resulting in a reduction of required ISS and ground crew maintenance and servicing while optimizing resource utilization. A significant increase is expected in crew well-being and productivity due to the minimized number of crew hours required to operate and maintain a spacecraft or habitat logistics system while also making more efficient use of spacecraft resources. If the system is made truly autonomous, the space-based logistics ‘Smart Habitat’ system could be operated with or without the flight crew present by a ground crew. A Smart Habitat system could also significantly reduce ground crew hours required for logistics planning and situational awareness to increase real-time productivity by employing what the NASA Agency roadmap refers to as “…exploration habitat performance monitoring using embedded sensors.”

Mission Applications

The TIP RFID technology aligns with NASA Agency roadmap areas Human Habitation Elements and Life Support Systems Technologies for Space Situational Awareness, and Space Object Interactions.

Formation Flying for Satellites and Unmanned Aerial Vehicles

Project Manager(s)

Garrick Merrill/ES36
(256) 544–4409

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

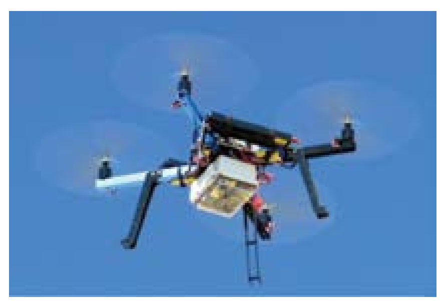
The shrinking size of satellites and unmanned aerial vehicles (UAVs) is enabling lower cost missions. As sensors and electronics continue to downsize, the next step is multiple vehicles providing different perspectives or variations for more precise measurements. While flying a single satellite or UAV autonomously is a challenge, flying multiple vehicles in a precise formation is even more so.

The goal of this project is to develop a scalable mesh network between vehicles to share real-time position data and maintain formations autonomously. The second generation design employs a hardware independent design and implementation of a software-based Time Division Multiplex Architecture mesh network with low latency and multihop capability. Small UAVs and simulated satellites were used to demonstrate the system in flight conditions. UAVs built by the Aero-M team will be used to demonstrate the formation flying in the West Test Area of NASA Marshall Space Flight Center (MSFC).

The ability to test in flight on NASA-owned UAVs allows this technology to achieve a high Technology Readiness Level (TRL) (TRL-4 for satellites and TRL-7 for UAVs). The low cost of small UAVs and the availability of a large test range (West Test Area) dramatically reduces the expense of testing. The end goal for this technology is to be ready for use on any multiple-satellite or UAV mission.

Formation node.

Eight nodes.



Quadcopter UAV with payload.

Anticipated Benefits

Demonstrating the concept on small, inexpensive UAVs provides a unique testing platform and a way to raise the TRL before taking on a multiple-satellite mission. In addition, the same technology can be directly applied to UAVs in the rapidly expanding small UAV market.

Quadcopter UAVs in formation.

The Federal Aviation Administration is starting to allow commercial UAVs in United States (U.S.) airspace. The formation flying system can not only be directly applied to a multiple-vehicle formation, but also as a method of avoiding collisions between all small UAVs in the area. Being at the forefront of formation flying for satellites and UAVs not only allows leveraging across platforms, but keeps MSFC at the forefront of autonomous flight control in unmanned systems.

Mission Applications

There are many applications for satellites in a cluster formation that provide benefits over a single larger platform. The Space Launch System/Interim Cryogenic Propulsion System will be deploying CubeSats in deep space on Exploration Mission-1 that could use this technology. A follow-on mission to the Edison Demonstration of SmallSat Networks CubeSat mission could utilize this technology to enhance the intervehicle communication and provide a more robust network topology.

Notable Accomplishments

Six formation nodes were assembled, tested, and used using Xbee radios. Six formation nodes were assembled, tested, and used using Astrodev radios. UAV flight tests included up to five UAVs with formation nodes and demonstrated autonomous formation flying and the various operating modes. Satellite orbital simulations with up to four nodes configured as satellites and durations up to three days were completed. The code that was developed for the formation nodes, controls the mesh network, and enables formation maneuvers was made available to U.S. citizens through the NASA software catalog.

Solar Sail Attitude Control Capability

Project Manager(s)

Tiffany Russell Lockett/ED04
(256) 961–1304

Dr. Jeremy Munday/University of Maryland
(301) 405–4960

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

Solar sail technology has been included in the NASA Technology Roadmap, Technical Area 2: In-Space Propulsion Technologies, Section 2.2.2 Solar and Drag Sail Propulsion, and NASA Marshall Space Flight Center (MSFC) has listed solar sails as a Tier 3 Propulsion Systems Technology investment. Deployment of sails in low-Earth orbit (LEO) has become well understood in recent years. Understanding the dynamics of a sail in flight has led to the conclusion that a sail would need to be accompanied by an attitude control system during the lifetime of its mission. However, a traditional chemical propulsion attitude control system is not the only option. The purpose of this project is to investigate attitude control capabilities for solar sailing and endorse the best concept for future solar sail missions without the reliance on propellant-based systems.

The research produced an integrated concept that focused on adjusting the center of pressure and center of mass in relation to each other. The alignment of the center of mass and pressure ensures stability of the sail. The reflective control devices (see fig. 1) would control the amount of solar pressure applied to the sail by either reflecting photons or allowing them to pass through. To affect the motion of the sail, the devices are placed along the edge of the sail. This technique and similar devices were flown on the Japanese Space Agency (JAXA) flight called Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS). The technology was successfully demonstrated during a flight in 2010 to Venus.

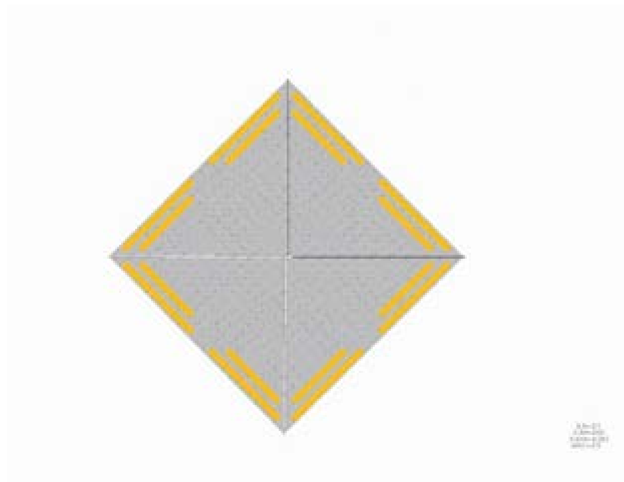


Figure 1: Conceptual render of reflective control devices along the edge of a solar sail (Source: NASA).

The University of Maryland has been developing reflective control devices and has demonstrated their functionality in the lab, bringing the technology to a Technology Readiness Level (TRL) of TRL-3. The technology difference between the JAXA and University of Maryland designs is in the reflection. IKAROS utilizes specular and diffuse reflection to achieve a momentum change, whereas The University of Maryland design employs direct transmission and diffuse reflection (see fig. 2).

The second element of the integrated concept focuses on the center of mass. The translation stage is a system that moves in the *x*-*y*-axis, splitting the spacecraft into two elements and moving them in relation each other (see fig. 3). The translation table is an effective method of modifying the center of mass of the spacecraft. Performance is bounded by the amount of mass that can be moved and the distance it can move.

Various concepts exist for moving the mass and the amount of mass that can be moved. At one end of the extreme, a small amount of mass can be moved along the booms of the sailcraft, which maximizes the amount of travel of the mass and minimizes the amount of mass moved. This concept was explored in some detail by Dr. Bong Wie for the ATK In-Space S4 sail.[1]

Figure 2: A functioning prototype of The University of Maryland reflective control devices. The material becomes transmissive when a voltage is applied, allowing photons to pass through in the on state (Source: The University of Maryland).

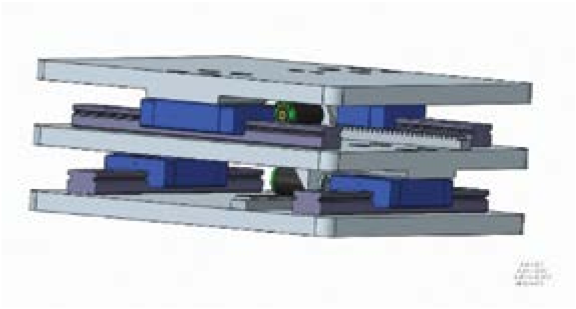


Figure 3: Conceptual render of a translation table for a 3U CubeSat (Source: NASA).

Mission Applications and Anticipated Benefits

The integrated reflective control devices and translation table could replace the traditional gas thruster attitude control system for future solar sailing missions. This advancement would reduce the mass and volume allocated for attitude control and thus improve mission lifetime.

Notable Accomplishments

The translation table concept is currently incorporated into the flight design of the Near Earth Asteroid Scout mission for additional attitude control support for the spacecraft. The translation table will help align the center of mass and center of pressure to minimize the disturbance torques produced by the sail.

The reflective control devices have been awarded funding for further research and development through the Small Spacecraft Technology Program within the Space Technology Mission Directorate. The two-year collaborative agreement between NASA and The University of Maryland will enhance the technology readiness level to TRL-5+.

References

1. Wie, B.; Murphy, D.; Paluszek, M.; and Thomas, S.: “Robust Attitude Control Systems for a Solar Sail Flight Validation Mission,” Paper Presented at AIAA GNC Conference and Exhibit, Providence, RI, August 16–19, 2004.

CubeSat Demonstration Mission

Project Manager(s)

Jeremy Rousseau/ER52
(256) 544–7331

Sponsoring Program(s)

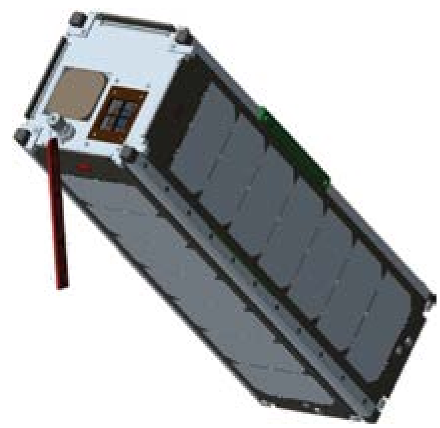
Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

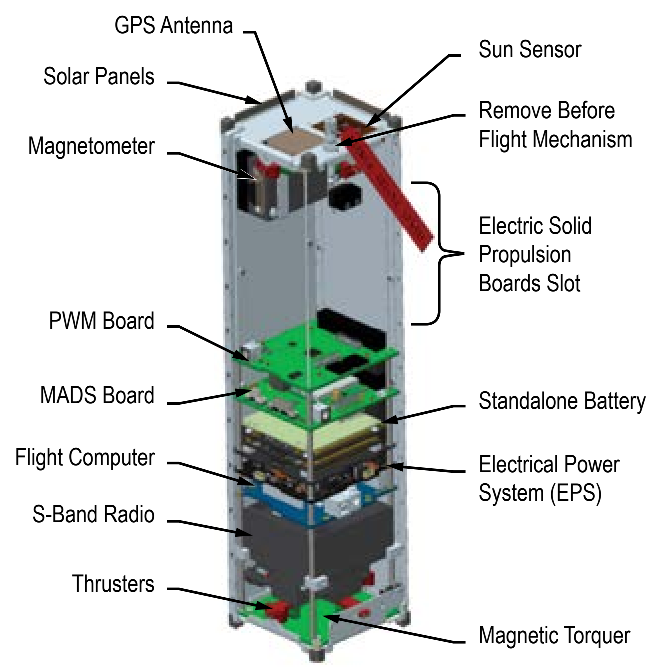
The primary technical objective of this project was to provide a low-cost CubeSat for a demonstration mission that demonstrates three-axis fine attitude control using electrically controllable solid propellant thrusters while increasing the Technology Readiness Level (TRL) of TRL-2 for other NASA Marshall Space Flight Center- (MSFC-) developed technologies: CubeSat attitude determination system and magnetic torquers.

The satellite will utilize well-characterized, commercially available CubeSat components in order to maintain a reasonable expectation of mission success. The project's budget was an order of magnitude less than previously considered possible at MSFC.

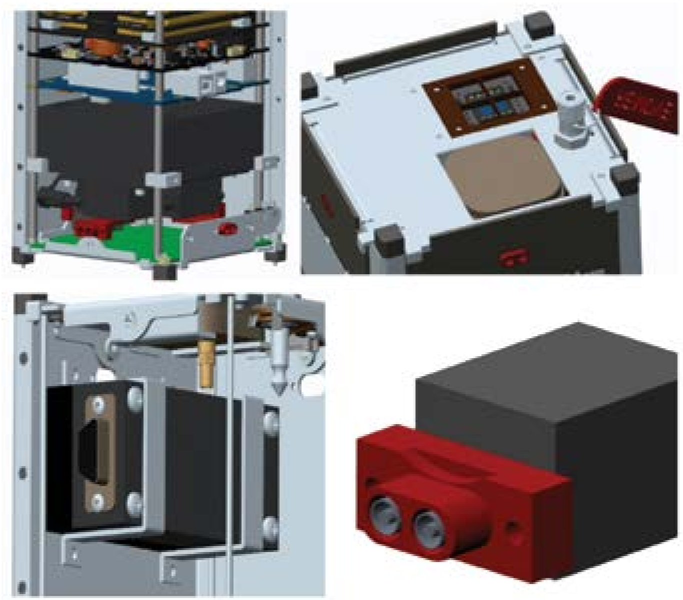
MSFC utilized multidisciplined engineers for the tasks in order to reduce the labor loading associated with traditional projects.



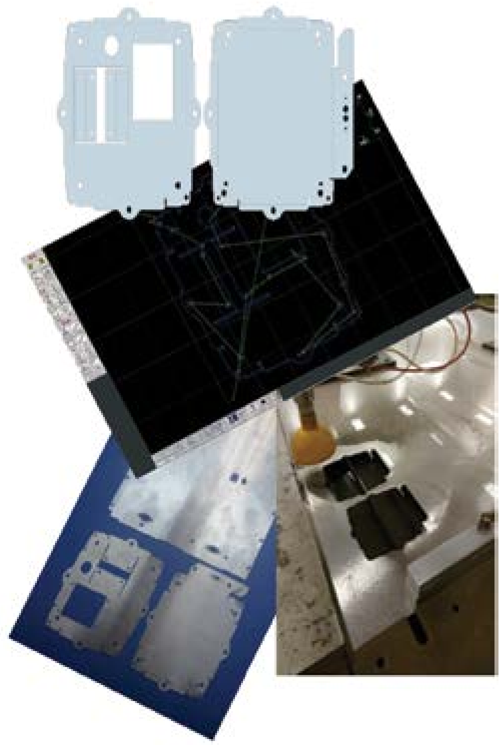
Assembled satellite.



Satellite cutaway.



Satellite details.



In-house chassis manufacturing.

Anticipated Benefits

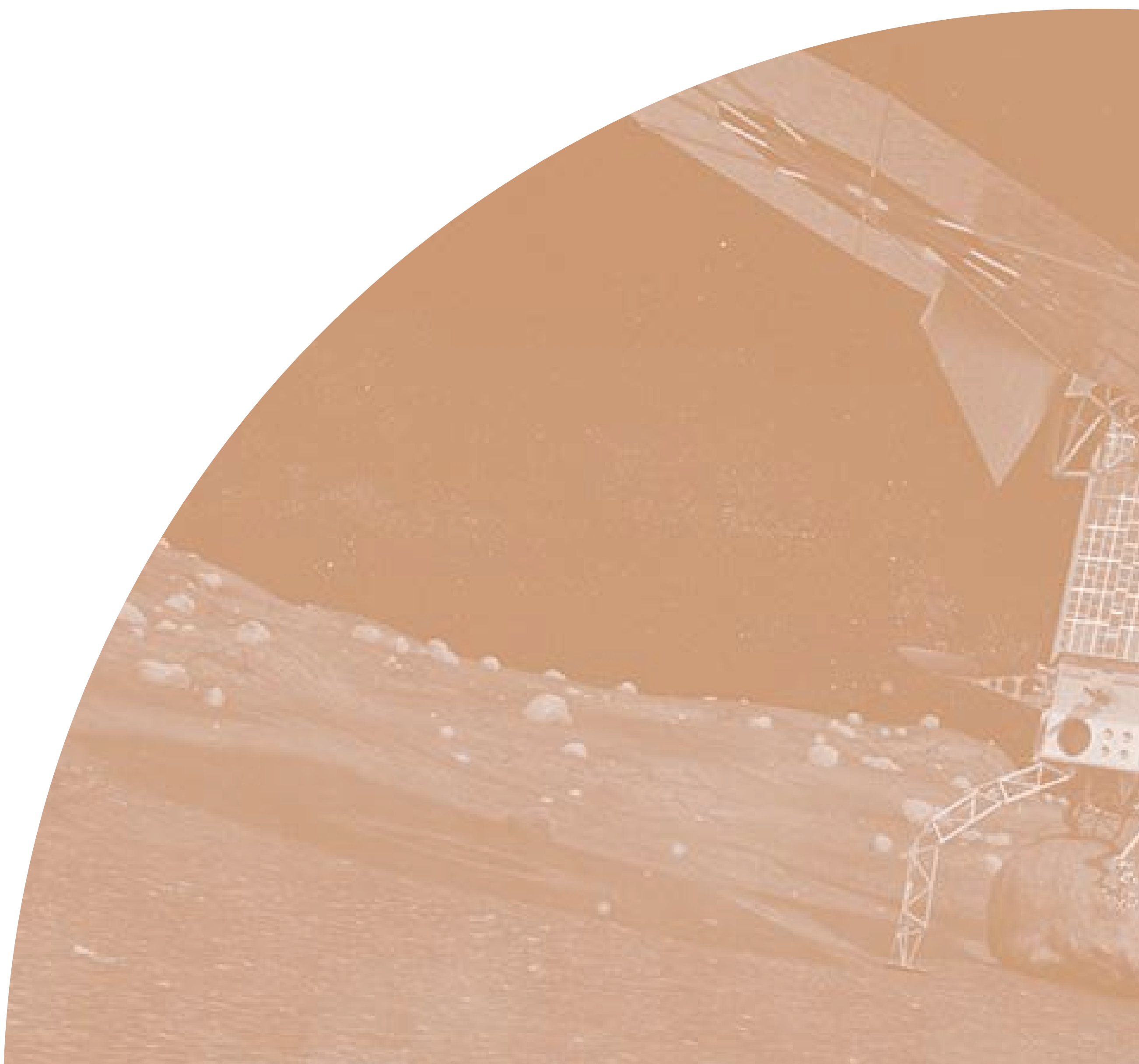
The low resource level this project utilized should bring a paradigm shift to the small satellite community at MSFC while providing a platform for other small projects to leverage and build from.

Mission Applications

With tighter budgets across the government comes the need for more affordable in-space science. With more in-space science comes a need for small, safe, green satellite propulsion and attitude control systems. The subject project helps in providing said capability.

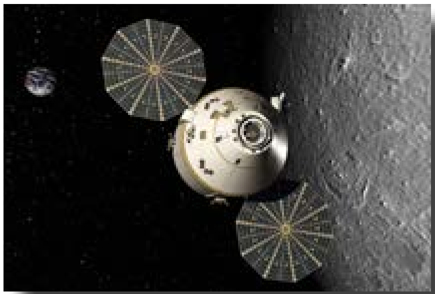
Notable Accomplishments

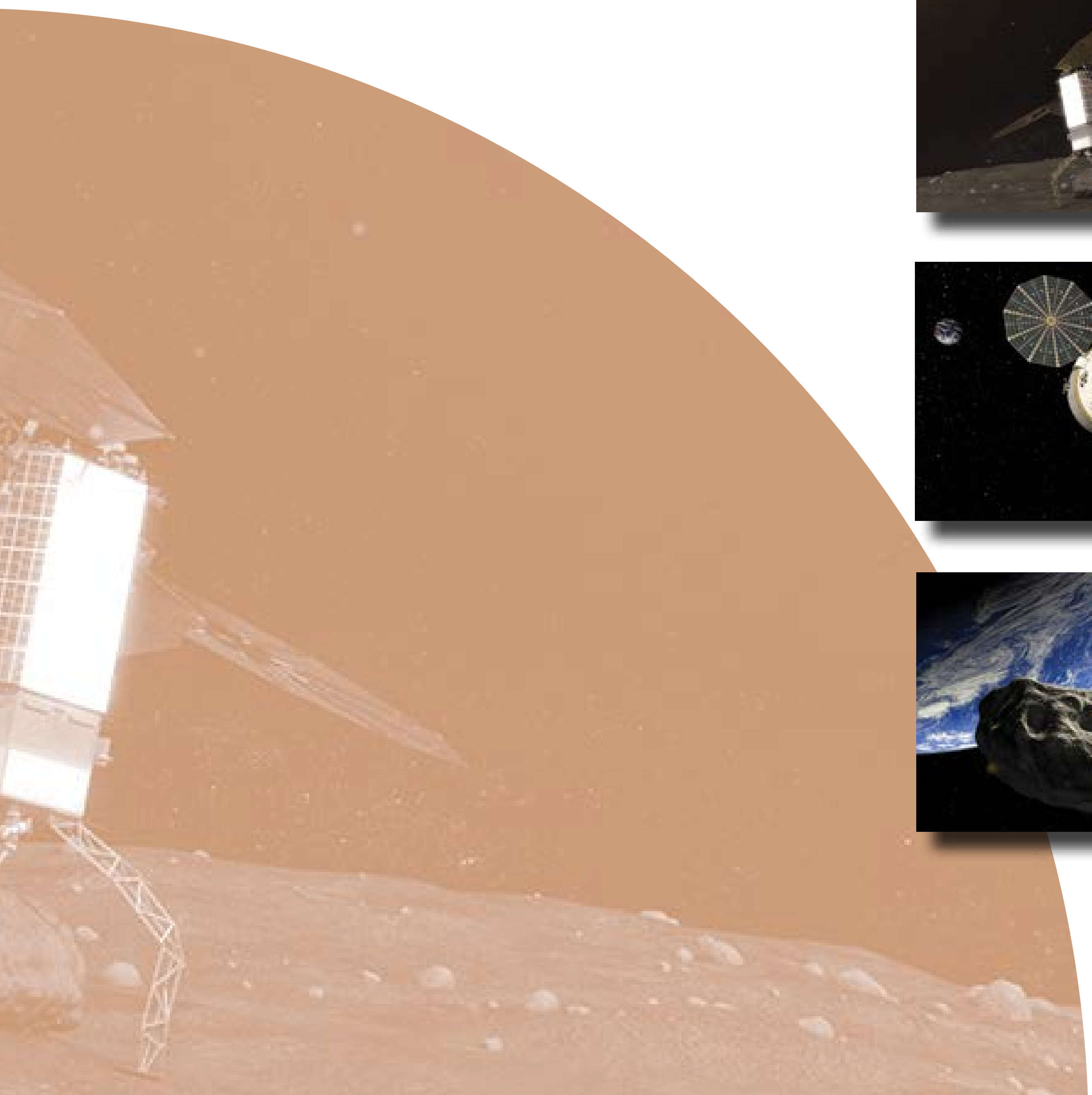
- Utilized intern labor to develop and test low-cost alternative propulsion system prototypes and vehicle chassis. Estimated vehicle cost savings are 80% and 95%, respectively.
- Provided a flight-ready revision for the Modular Attitude Determination System (MADS) 2.0.
- Provided a system design with hardware costs within the allocated project budget.



Marshall Space Flight Center/
Center Management and Operations

Center Strategic Development Steering Group





Chromospheric Lyman-Alpha Spectropolarimeter

Project Manager(s)

Dr. Amy Winebarger/ZP13
(256) 961–7509

Todd Holloway/ZP21
(256) 961–7581

Ryouhei Kano/National Astronomical Observatory of Japan

Javier Trujillo Bueno/Instituto de Astrofísica de Canarias

Frédéric Auchère/Institut d'Astrophysique Spatiale

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

The aim of the Chromospheric Lyman-Alpha Spectropolarimeter (CLASP) is to achieve the first measurement of magnetic field in the upper chromosphere and transition region of the Sun through the detection and measurement of Hanle effect polarization of the Lyman-alpha line. The Hanle effect (i.e., the magnetic field-induced modification of the linear polarization due to scattering processes in spectral lines) is believed to be a powerful tool for measuring the magnetic field in the upper chromosphere, as it is more sensitive to weaker magnetic fields than the Zeeman effect and also sensitive to magnetic fields tangled at spatial scales too small to be resolved. The Lyman-alpha (121.567 nm) spectral line has been chosen because it is a chromospheric/transition region line, and because the Hanle effect polarization of the Lyman-alpha line is predicted to be sensitive to 10–250 gauss.

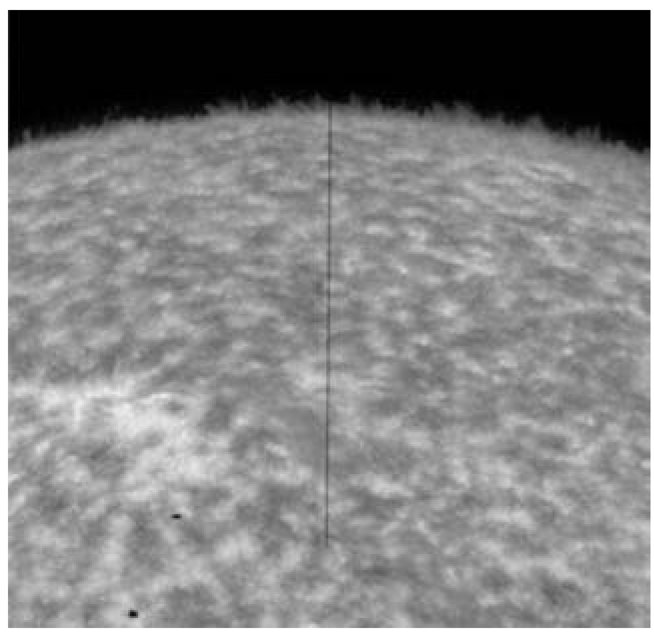
The CLASP instrument is a partnership between NASA Marshall Space Flight Center (MSFC), the Japan Aerospace Exploration Agency (JAXA), the National Astronomical Observatory of Japan (NAOJ), the Instituto de Astrofísica de Canarias in Santa Cruz de Tenerife, Spain (IAC), and the Institut d'Astrophysique Spatiale in Paris (IAS).

Anticipated Benefits and Mission Applications

The MSFC CLASP team developed a low-noise camera system, which achieved a six-electron rms noise during flight. Additionally, they developed an accompanying flexible avionics package that can be modified to accommodate other suborbital missions.

Notable Accomplishments

CLASP was launched from White Sands Missile Range on September 3, 2015. The initial data indicate that CLASP detected scattering polarization in Lyman-alpha. Additional analysis is underway to infer the chromospheric magnetic field from the CLASP data.



The quiet sun region observed by CLASP. This image is taken with the slitjaw camera with a broadband filter centered on the Lyman-alpha spectral line. The black line in the image is the slit.

The experiment team attending the launch of the CLASP instrument (inside white box) mounted on the launch rail. Team members attending launch include (bottom row) Ken Kobayashi (MSFC), Yukio Katsukawa (NAOJ), Patrick Champey (University of Alabama Huntsville), Brent Beabout (MSFC), Dyana Beabout (MSFC), Takamasa Bando (NAOJ), Gabriel Giono (NAOJ), Masahito Kubo (NAOJ), Shin-nosuke Ishikawa (JAXA ISAS), (top row) Ryouhei Kano (NAOJ), Amy Winebarger (MSFC), Noriyuki Narukage (NAOJ), Javier Trujillo Bueno (IAC), Ryoko Ishikawa (NAOJ), and Harlan Haight (MSFC).

International Space Station Agricultural Camera Reutilization for Earth Observation

Project Manager(s)

Burgess Howell/Universities Space Research Association
(256) 961–7908

Jeff McCracken/ZP21
(256) 961–7457

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

We propose to reutilize the International Space Station Agricultural Camera (ISSAC) by adapting it to external use on the Multiple User System for Earth Sensing (MUSES). This reutilization will provide a low-cost mechanism for the collection of data and information to serve a variety of scientific, humanitarian, and technical purposes, and provide both tangible and intangible benefits in varying degrees to several entities and groups. ISSAC is an Earth observing instrument developed by the University of North Dakota and operated in the Window Observational Research Facility (WORF), part of the Destiny science module aboard the International Space Station (ISS), for approximately 12 months during 2011 and 2012 (fig. 1). ISSAC was intended primarily to provide timely information for agricultural land use analyses over the northern Great Plains of North America. ISSAC's sensor system consists of a telephoto lens mounted ahead of a three-way beam splitter that directs electromagnetic radiation (EMR) to three charge-coupled device (CCD) arrays. The CCD's response is fully calibrated and characterized. The camera records EMR in three bands (green, red, and near-infrared), which closely correspond to Landsat bands 2, 3, and 4. These bands were chosen for their value in various vegetation indices, land cover characterizations, and species identification. On February 10, 2015, the ISSAC camera, a spare lens, and power and data cables were returned to Earth via the SpaceX-5 Dragon capsule. Those components have been transported to NASA Marshall Space Flight Center (MSFC) to undergo an assessment to determine the suitability of the instrument to perform a new mission aboard the ISS via the platform. MUSES is an external, Earth-facing pointing platform, the result of a cooperative agreement between NASA and Teledyne Brown Engineering (TBE), scheduled for deployment aboard the ISS. MUSES is designed to accommodate up to four instruments concurrently on large- and small-hosted payload sites (two each), and provides a mechanical interface for securing a payload to the mount, as well as standardized connections for payload power and data needs. The ISSAC instrument will be repurposed for a new mission, called CLEO (Camera for Low Earth Orbit) and will be designed to fly by early 2017. In Greek mythology, Clio was one of the Seven Muses.

Figure 1: ISSAC camera recently returned from ISS on SpaceX-5.

Anticipated Benefits

Humanitarian Organizations—As a project envisioned essentially as a follow-on instrument to the ISS SERVIR Environmental Research and Visualization System (ISERV) pathfinder instrument, CLEO will provide Earth observation (EO) imagery to the same customer groups as those associated with ISERV's original parent project, SERVIR (primarily the United States Agency for International Development (USAID)), and serviced by ISERV. ISERV developed an excellent working relationship with USAID over its operational life and still maintains a backlog of unfulfilled USAID image requests. Provision of data to satisfy these requests would be a prime objective of the CLEO project.

Disaster Response, Monitoring, and Assessment Entities—CLEO would honor the existing ISERV mandate to respond to activations of the International Disasters Charter (IDC), providing EO data of disaster-stricken areas to IDC managers around the world. Additionally, CLEO would continue ISERV's practice of providing EO data for U.S. domestic disasters, as well as requests for disaster-related imagery from management agencies anywhere in the world.

Science Investigations—ISERV data has proven to be useful in a variety of scientific studies, such as mapping the probability of malaria incidence in Zanzibar and the validation of flood extent modeling in the lower Mekong. These studies and others will receive data from CLEO operations. They will benefit significantly more than they have from ISERV data because of the increased information content in CLEO visible/near-infrared (VNIR) spectral range. This VNIR capability will allow provision of data to a much broader range of inquiries, spanning both scientific and humanitarian concerns such as climate change (e.g., small-scale forest canopy inventory), food security (e.g., agricultural biomass and crop vigor estimates), and water security (e.g., monitoring surface water extent and turbidity).

Concurrently, NASA will also realize intangible benefits accruing from the successful operation of CLEO and the public dissemination of CLEO image data sets.

Subsequent MUSES Payloads—While all subsequent MUSES-located payloads will benefit from CLEO's role in the on-orbit characterization of MUSES pointing performance, the first commercial MUSES payload in particular will benefit by being relieved of the requirement to use any of its operational life for the pointing characterization task.

Mission Applications

CLEO will leverage the success of the ISERV mission, including use of the knowledge gained from ISERV mission planning, ISS operations, data acquisition and data processing, and archiving.

Notable Accomplishments

A study to investigate the possible use of ISSAC as an external ISS payload on the MUSES platform was completed in 2015. A thermal model was developed using available hardware information and was correlated to the 'observed' thermal behavior during WORF installation on ISS. The correlated thermal model was used to investigate the thermal environments to be expected when installed on the MUSES platform. A thermal control system will be defined to attain compatible temperature results for all low-Earth orbit mission phases. This study was considered to be a 'quick look' feasibility study. The goal was to determine if the payload would survive outside ISS. The study concluded that the ISSAC hardware would survive outside the ISS, but with operational caveats. This thermal study raised the project Technology Readiness Level (TRL) from TRL-2 to TRL-3.

Direct Fabrication of Grazing Incidence Optics

Project Manager(s)

Mikhail Gubarev/ZP12
(256) 544–7816

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

The Chandra Observatory demonstrated that modern fabrication techniques can provide subarcsecond resolution grazing incidence optics if thick mirror substrates are used. Other approaches such as electroformed nickel, slumped glass,[1] and silicon pore optics[2] aim to decrease the mirror thickness to permit dense nesting of lightweighted mirrors and, hence, to increase the effective area of the telescope. The low specific stiffness of these thinner mirrors makes them more susceptible to replication- or other fabrication-induced figure errors and to mounting errors, all of which result in angular resolutions over an order of magnitude worse than Chandra. The challenge therefore is to develop the optical fabrication technology capable of producing Chandra-like full-shell optics but with an order of magnitude lighter mirror shells and at an affordable price.

Lightweight stiff materials and advanced fabrication and metrology fixtures offer the potential for a significant reduction of x-ray mirror thickness. However, for thin-shell fabrication, a major challenge is to support the shell during processing so that at one extreme it cannot fracture or microyield, but also cannot deflect enough to affect the polishing itself.

Our overall approach is based on the use of metal mirror substrates. The metal substrate materials will be diamond turned and heat treated to relieve residual stresses, then machined to the final form and thickness. After this, the electroless nickel plating will be done in two stages. In order to compensate for plating stresses, first the minimum thickness will be plated on the back surface with the front surface masked. Then, the rear surface will be masked and the front surface will be plated with thicker material to account for optical processing. Now, the mirror surface is single-point diamond turned. The result will be a surface with a 1- to 2-µm surface error, and a few tens of nanometers surface finish as a starting point for polishing using the computer-controlled machine (fig. 1) to achieve sub arcsecond slope error surface.

Figure 1: Computer-controlled polishing machine with the mandrel used for the validation of the developed polishing techniques installed.

Anticipated Benefits

The use of a computer-controlled deterministic polishing machine, in situ metrology, and utilization of novel fabrication approaches and materials will lower the fabrication costs and make direct fabrication of x-ray mirrors competitive with replication techniques while preserving high angular resolution. These techniques also open the opportunity of making the process fully automated and potentially expanding astronomical x-ray optics fabrication to medium and small optics fabrication companies, in turn increasing competition and lowering prices.

Mission Applications

The few-arcsecond, full-shell optics are well suited for a wide variety of applications from future small explorers to probe-class missions. For the latter, mission design studies[3] have shown that full-shell optics of minimum shell thickness equivalent to that proposed here can provide for scientifically compelling missions that satisfy the medium-term needs of x-ray astronomy. A goal of the program is to advance the technique to subarcsecond optics, suitable for future flagship missions.

Notable Accomplishments

- Inner (fig. 2) and outer diameter diamond turning mounts and polishing fixture (fig. 3) have been developed and fabricated.
- Metrology mounts for the direct fabrication of high-resolution x-ray optics designed to minimize the shell distortions have also been completed.
- The polishing routine software has been written.
- The metrology and polishing techniques have been validated using an x-ray mandrel.
- Original slope errors: 6.6 arcsec rms.
- Measured slope errors after correction: 0.7 arcsec rms.

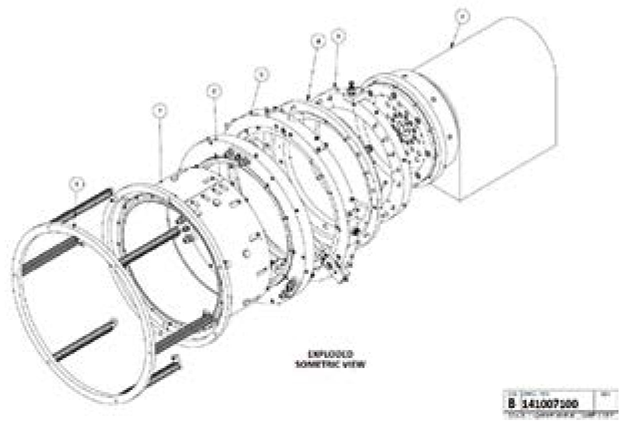


Figure 2: Inner diameter diamond turning mount developed for the project.

Figure 3: Full-shell polishing mount developed for the project.

References

1. Zhang, W.W.; Biskach, M.P.; Blake, P.N.; et al.: "Lightweight and high angular resolution x-ray optics for astronomical missions," *Proc. SPIE 8147*: *Optics for EUV*, *X-Ray*, *and Gamma-Ray Astronomy*, SPIE, Bellingham, WA, p. 81470K, doi:10.1117/12.893697, September 2011.

2. Collon, M.J.; Günther, R.; Ackermann, M.; et al.: "Silicon pore x-ray optics for IXO," *Proc. SPIE Space Telescopes and Instrumentation 2010*: *Ultraviolet to Gamma Ray*, SPIE, Bellingham, WA, p. 77321F, doi:10.1117/12.858166, July 27, 2010.

3. "X-ray Mission Concepts Study Report," <http://pcos.gsfc.nasa.gov/physpag/X-ray_Mission_Concepts_Study_Report-Final.pdf>, August 2012.

Regenerable Catalyst From In Situ Resources for Life Support Using Ionic Liquids

Project Manager(s)

Morgan Abney/ES62
(256) 961–4758

Laurel Karr/EM10
(256) 544–7817

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

Advanced life support systems for deep space missions, including a lunar outpost, Mars transit, and Martian surface missions, will require maximum resource recovery to limit resupplies from Earth. Of the oxygen respired by the crew in the form of carbon dioxide (CO_2) on the International Space Station, only 50% is recovered using state-of-the-art life support systems. Technology has been proposed since the late 1950s to achieve 100% oxygen recovery by decomposing CO_2 into its elemental components: oxygen and solid carbon. The formation of carbon occurs over an iron or nickel catalyst and results in carbon nanofibers (as seen in fig. 1), nanotubes, microfibers, microtubes, and amorphous carbon. The product carbon 'grows' from single crystals of the catalyst metal and can physically modify the catalyst material by chemically extracting the crystalline material from the bulk surface and dispersing it throughout the product carbon.[1] As carbon mass increases, pressure drop across the reactor increases until the process must be discontinued. The resulting product, as shown in figure 2, is a mass of carbon with well-dispersed iron or nickel crystals. Historically, this carbon/catalyst mass was disposed of and fresh catalyst resupplied to continue oxygen recovery. In an effort to reduce the total system mass (including resupply mass) of an oxygen recovery technology capable of 100% recovery, a method of regenerating catalyst dispersed in carbon was proposed.

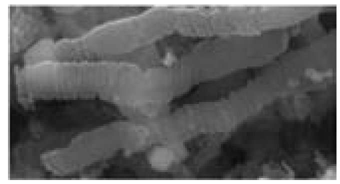


Figure 1: Carbon fibers generated from CO_2 over an iron catalyst (5,000×).

Figure 2: High-density carbon product containing dispersed iron catalyst.

Ionic liquids are molten organic salts that have almost no vapor pressure, are stable liquids at room temperatures or slightly above, are environmentally safe, and are recyclable. Studies have shown that ionic liquids can be used to extract specific metals such as iron from multimetal compounds such as ore, with great selectivity for the targeted metal.[2] The isolated metal can then be electroplated onto surfaces for a variety of applications and the ionic liquid regenerated to repeat the process.

This project proposed to demonstrate the use of ionic liquids to recover catalyst metal from carbon waste products in a life support architecture, to deposit the extracted metal onto a substrate, and to demonstrate the catalytic activity of the resulting substrate/catalyst material.

Anticipated Benefits

The primary benefit of this technology is in the area of life support technology. A system designed to achieve 100% oxygen recovery was developed in the late 1980s. The system required catalyst cartridges weighing ≈50 lb to be resupplied every 19 days. For a 1,000-day Martian surface mission, this would require a total catalyst cartridge resupply of ≈2,632 lb. The capability to regenerate the catalyst in these cartridges instead of replacing them would dramatically improve the overall technology trade with competing options. Additionally, in emergency situations, the use of ionic liquids provides the capability to extract iron from the Martian surface regolith, thereby resupplying iron from an in situ resource.

Mission Applications

The proposed application for this technology is in oxygen recovery life support systems for long-duration manned space flight.

Notable Accomplishments

Four tasks were accomplished during the project. First, the catalytic activity of iron on a copper support was demonstrated using traditional electroplating methods (no ionic liquids used). This was done to prove the feasibility of electroplating a catalytic iron surface. The copper substrate is shown before and after plating in figure 3. The plated 'puck' was exposed to reactant gases at targeted temperatures and showed significant carbon formation.

The second task was to demonstrate extraction of iron from an iron catalyst that had produced a large quantity of carbon using an ionic liquid. Carbon-covered iron was available from previous testing. An ionic liquid was used to extract iron from the carbon. The remaining carbon and the ionic liquid with bound iron is shown in figure 4. Carbon was separated from the ionic liquid via centrifugation.

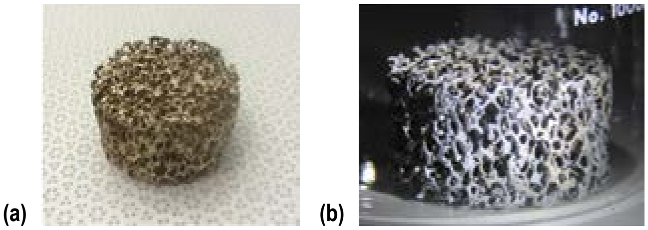


Figure 3: Copper substrate (a) before and (b) after plating with iron using a traditional electroplating technique.

Figure 4: Carbon remaining after ionic liquid extraction (left) and ionic liquid containing iron (right).

The third task was to demonstrate plating of iron on a copper support using an ionic liquid. Figure 5 shows a copper support after plating using an ionic liquid. Iron was observed over the surface, though in less than complete coverage.

Figure 5: Iron coated on copper substrate using an ionic liquid.

The fourth accomplished task was to demonstrate catalytic activity of the iron plated from the ionic liquid. Figure 6 shows a copper substrate plated with iron from an ionic liquid before and after carbon formation. Although it is difficult to see in the photographs, handling the material after carbon formation yielded considerable carbon residue on gloves and Kimwipes. There was low carbon yield, but this was likely due to the relatively low surface area of the catalyst material.

This project has demonstrated four key aspects to an ionic liquids-based regenerative catalyst system for achieving 100% oxygen recovery for long-duration manned space flight. Continued efforts in this area will result in the data necessary to design and scale a system based on a regenerable approach. Additionally, continued efforts will result an architecture concept surrounding the ionic liquids approach that will be reviewed by experts in the area of life support.

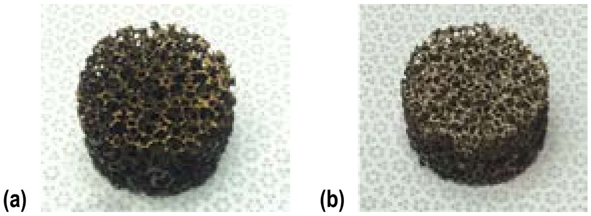


Figure 6: Copper substrate plated with iron using an ionic liquid (a) before and (b) after carbon formation.

References

1. Abney, M.B.; and Mansell, J.M.: "The Bosch Process - Performance of a Developmental Reactor and Experimental Evaluation of Alternative Catalysts," Paper Presented at 40th International Conference on Environmental Systems, Barcelona, Spain, July 11–15, 2010.

2. Karr, L.J.; et al.: "Metals and Oxygen Mining from Meteorites, Asteroids and Planets using Reusable Ionic Liquids," Paper Presented at 2012 PISCES Conference, Waikoloa, HI, November 11–15, 2012.

X-ray Surveyor Strawman Payload Definition

Project Manager(s)

Martin Weisskopf/ZP12
(256) 961–7798

Jessica Gaskin/ZP12
(256) 961–7818

A. Vikhlinin/Smithsonian Astrophysics Observatory

H. Tananbaum/Smithsonian Astrophysics Observatory

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

The X-ray Surveyor is one of the large astrophysics mission concepts that may be studied by NASA in preparation for the 2020 United States Decadal Survey.[1] Consistent with the 2013 Astrophysics Roadmap,[2] the goals for the observatory are as follows: excellent (at least Chandra-like) angular resolution while providing a factor of 30–100 higher throughput; significantly larger field of view than Chandra for subarcsec imaging; and a suite of next generation science instruments, including a microcalorimeter, a high-definition imager, and high-efficiency gratings for spectroscopy in the soft x-ray band. With these capabilities, the X-ray Surveyor will be able to detect and characterize extremely faint objects and study physical processes in a very wide range of astrophysical settings.

The strawman X-ray Surveyor mission concept was developed in response to the "Planning for the 2020 Decadal Survey: An Astrophysics Division White Paper," presented to the community by the NASA astrophysics director in January of 2015.[1] In this white paper, the astrophysics community was asked to comment on a small list of candidate missions to NASA Program Analysis Groups (PAGs). The report(s) generated by the PAGs, with a favorable recommendation concerning X-ray Surveyor, has been submitted to the NASA Advisory Council Astrophysics Subcommittee, who will report to the Astrophysics Division for selection of the mission concepts to study as input for the 2020 Decadal Survey. These more formal studies will be carried out by appointed Science and Technology Definition Teams, and will be assigned to NASA Centers to manage.

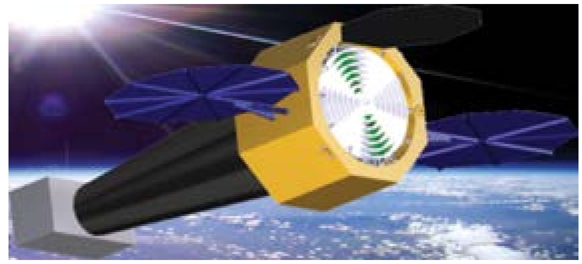


Figure 1: X-ray Surveyor strawman concept.

This initial concept study for the X-ray Surveyor mission was carried out by the Advanced Concept Office at NASA Marshall Space Flight Center (MSFC), with a strawman payload and related requirements that were provided by an Informal Mission Concept Team comprised of MSFC and Smithsonian Astrophysics Observatory (SAO) scientists, plus a diverse cross section of the x-ray community. The study included a detailed assessment of the requirements, a preliminary design (fig. 1), a mission analysis, and a preliminary cost estimate. It leveraged relevant concept definitions for other large area missions carried out over the past two decades, such as Con-X, AXSIO, and IXO.

In many areas, the X-ray Surveyor mission requirements are no more stringent than those of Chandra, and so heritage systems and design features were utilized when possible. The X-ray Surveyor focal length, for example, is approximately the same as Chandra's, which limits the spacecraft requirements and results in a Chandra-like cost.

With its half-arcsecond angular resolution, Chandra has provided an unparalleled means for exploring the high-energy universe; deepening our understanding of astronomical systems as diverse as galaxy clusters, active galaxies, normal and starburst galaxies, supernova remnants, normal stars, planets, and solar system objects.[3,4,5] As we look beyond Chandra, it is clear that comparable angular resolution combined with greatly increased photon throughput is essential for addressing the key science questions. As a first step at defining this frontier science, MSFC and SAO co-hosted the "X-ray Vision Workshop: Probing the Universe in Depth and Detail with the X-Ray Surveyor" in October 2015.

Anticipated Benefits

The X-ray Surveyor mission concept is designed to make dramatic increases in discovery space and science capabilities for x-ray astronomy. These would be accomplished through orders of magnitude improvements over Chandra in sensitivity, field of view for subarcsec imaging, effective area

(a)


Figure 2: Simulated 2′-by-2′ region of (a) a James Webb Space Telescope deep survey (reproduced from Windhorst et al. (2002)), (b) 4-Ms exposures with X-ray Surveyor, and (c) Athena. The x-ray log N – log S model is from Lehmer et al. (2012). Active galactic nuclei and normal galaxies are shown in magenta and green, respectively (Gaskin, Tananbaum, Vikhlinin, Weisskopf).

for grating spectroscopy, and by providing high spectral resolution capabilities for extended objects on 1-arcsec angular scales. An x-ray observatory with such capabilities, operating in concert with other major astronomical facilities of the 2020–2030s, is required to address and solve some of the greatest challenges in modern astrophysics. The X-ray Surveyor will shed light on the formation of supermassive black holes by being able to detect x-rays from these objects as they grow beyond their seed state in the first galaxies. Direct data on the nature and operating modes of feedback will be provided by characterizing hot gas in galaxies and groups on scales from the very near vicinity of the central black out to the virial radius. A new era in our understanding of the plasma physics effects on astrophysical scales will be opened, for example, by resolving the detailed structure of relativistic shocks in pulsar wind nebulae and the gas turbulence in galaxy clusters. The detailed structure of the Cosmic Web will be exposed for the first time by mapping x-ray emission from hot gas in its filaments. The outstanding capabilities of X-ray Surveyor will make it an indispensable research tool in nearly every area of astrophysics.

Substantial gains in the detection sensitivity limit for X-ray Surveyor requires x-ray mirrors, which combine large throughput with high angular resolution to avoid x-ray source confusion and background contamination. High angular resolution is also critical for providing unique identifications of faint x-ray sources with the high-redshift James Webb Space Telescope (JWST) galaxies. Figure 2 illustrates this situation with a simulated 2′-by-2′-deep field observed with JWST (fig. 2(a)), along with 4-Ms exposures with X-ray Surveyor (fig. 2(b)), and the European Space Agency's Athena mission (fig. 2(c)). With its 0.5″ angular resolution, X-ray Surveyor sees substantially deeper than Chandra and Athena and is well matched for unique identifications of faint x-ray sources with JWST galaxies (0.03 JWST galaxies per 0.5″ X-ray Surveyor beam).

Notable Accomplishments

The X-ray Surveyor strawman concept study and science workshop summarized here is a first step towards proving feasibility of such a mission. All crucial technologies for the telescope and focal plane instrumentation are actively being developed. Designing the focal length to be approximately that of Chandra and utilizing Chandra heritage systems for the spacecraft results in a Chandra-like cost.

References

1. Hertz, P.: "Planning for the 2020 Decadal Survey: An Astrophysics Division White Paper," *NASA Science*: *Astrophysics*, <http://science.nasa.gov/media/medialibrary/2015/01/02/White_Paper_-_Planning_for_the_2020_Decadal_Survey.pdf>, 2015.

2. Kouveliotou, C.; Centrella, J.; Agol, E.; et al.: "2013 Astrophysics Roadmap," *NASA Science*: *Astrophysics*, <http://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap/>, 2013.

3. Santos-Lleo, M.; Schartel, N.; Tananbaum, H.; et al.: "The first decade of science with Chandra and XMM-Newton," *Nature*, Vol. 462 No. 7276, pp. 997–1004, doi:10.1038/nature08690, December 2009.

4. Weisskopf, M.C.: "The Chandra X-Ray Observatory: Progress Report and Highlights," *Proc. SPIE*, Vol. 8443, No. 84430Y, 9 pp., doi:10.1117/12.929670, September 2012.

5. Tananbaum, H.; Weisskopf, M.C.; Tucker, W.; et al.: "Highlights and discoveries from the Chandra X-ray Observatory," *Reports on Progress in Physics*, Vol. 77 No. 6, 74 pp., doi:10.1088/0034-4885/77/6/066902, June 2014.

GreenSat

Project Manager(s)

Joel Robinson/CS10
(256) 544–3513

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

During the spring of 2014, the Swedish company ECAPS offered NASA Marshall Space Flight Center (MSFC) the opportunity to fly contributed hardware. Residual hardware that had been flown on the PRISMA mission was offered along with a 50-N thruster. MSFC surveyed existing NASA missions that could be enabled by use of this system, but unfortunately did not locate any near-term applications. Given existing contacts, MSFC reached out to the United States Air Force (USAF) Space Test Program (STP) and they had a small spacecraft to consider. Through the use of FY 2014 funds, MSFC conducted a 45-day trade study looking at the combination of the 50-N system with this small spacecraft. Further trade study analysis revealed that the contributed thruster system was too powerful for the 100-kg spacecraft. The concern was that buildup of angular momentum due to off-axis thrusting could not be dissipated with nonpropulsive reaction control systems (RCSs) (reaction wheels, torque rod, etc.), so MSFC kept on the lookout for another opportunity.

While attending the 2014 Department of Defense (DoD) Space Experiments Review Board (SERB), MSFC became aware through discussions with STP of a larger spacecraft application with the USAF Operationally Responsive Space (ORS) program. The Compact Ocean Wind Vector Radiometer (COWVR) instrument was funded by the USAF Space and Missiles System Center (SMC), but the design and fabrication was led by NASA's Jet Propulsion Laboratory. It was anticipated that the COWVR instrument would rank highly at the SERB and therefore gain advocacy for flight. SMC and ORS had been looking at the combination of the existing Modular Space Vehicle (MSV) bus with the COWVR instrument. The MSV was not delivered with a propulsion system, and with new mission requirements, ORS agreed to consider use of the MSFC/ECAPS contributed system.

FY 2015 resources were used to have continued discussions with ORS about integrating the propulsion system to enhance spacecraft capabilities. The spacecraft control authority, as experienced with the previous STP option, was less of a problem as this spacecraft is 350+ kg in size. Operational constraints (continuous thruster duration limits) may still need to be developed since the spacecraft has larger but limited reaction wheels and torque rods to dissipate angular momentum buildup.

The majority of FY 2015 was needed to develop and route a nonreimburseable Space Act Agreement between NASA and ECAPS. All international agreements have to be negotiated out of NASA Headquarters, so various questions and concerns had to be addressed prior to proceeding with the agreement. On August 21, a presentation was made at the Partnerships Council facilitated by Deputy Administrator Dr. Dava Newman. Approval came a couple of weeks later to proceed with negotiation of the agreement. Those discussions are still in work with the vendor and separately with ORS.

Figure 1: ORS modular space vehicle.

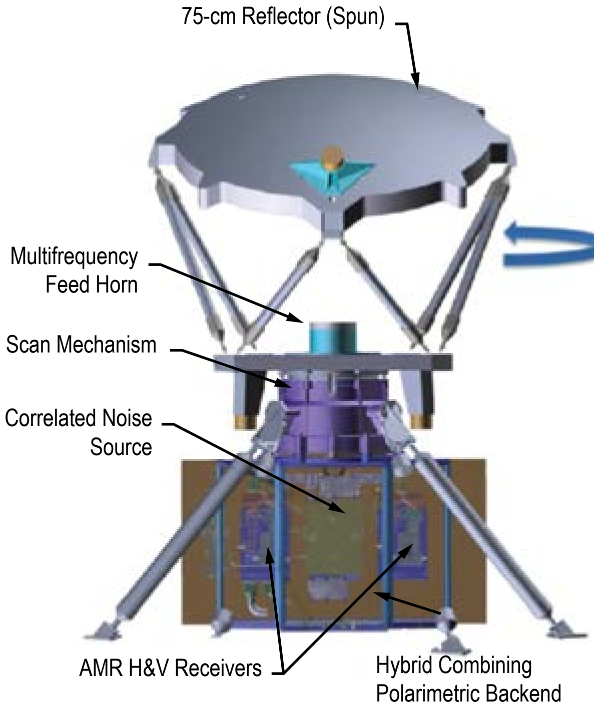


Figure 2: Compact Ocean Wind Vector Radiometer.

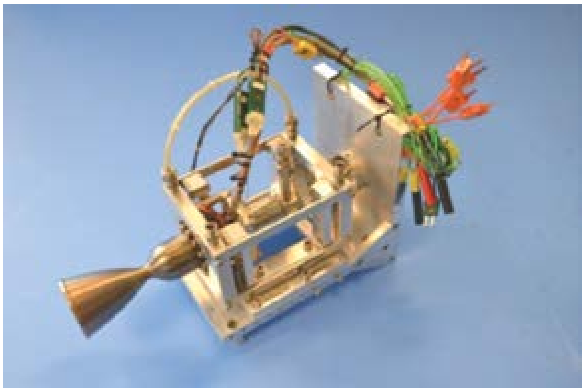


Figure 3: ECAPS 50-N thruster hardware.

Anticipated Benefits

Current demonstrations of green propulsion have focused on smaller thrust classes for application to small spacecraft attitude control or RCS as the technology matures. MSFC developed a green propulsion roadmap is focused on (1) scale-up of the thruster hardware and (2) the potential application for auxiliary power units. ECAPS has fabricated over 80 different thrusters since 1998 and range from 0.5 N up to 220 N thruster sizes. Since the NASA Technology Demonstration Mission-funded Green Propellant Infusion Mission was scheduled to fly a 22-N thruster, ECAPS offered the next size up for flight or the 50-N. Demonstration at this size and for the ORS mission in particular will showcase the larger delta velocity maneuvers required for spacecraft (otherwise known as apogee thruster operations). Transitioning from the RCS to apogee operations will demonstrate to the larger NASA, DoD, and commercial applications of the increased safety and performance green propellant has over hydrazine.

Mission Applications

There have been a variety of past NASA, DoD, and commercial missions that have used hydrazine propellant for apogee and RCS. These thrust classes range from 1 N to 3,500 N for some Mars applications. The ideal thrust class that benefits the Agency is the 440-N thruster size. This class would be used as an apogee thruster for SMD missions and would be used as an RCS thruster for Human Exploration and Operations Mission Directorate missions. Previous MSFC Center Innovation Funds have shown how green propellant can also be used for auxiliary power units as demonstrated by testing in FY 2014 using the F-16 emergency power unit as surrogate hardware. By not requiring SCAPE suits and providing between a 25% and 40% increase in density impulse, green propulsion can help replace hydrazine with these improvements.

Notable Accomplishments

- Participated in DoD SERB, January 6, 2015.
- Approval from export control, January 25, 2015.
- Partnership working group approval, February 12, 2015.
- Center Strategic Development Steering Group approval to proceed, March 2, 2015.
- SAA abstract to NASA Headquarters, March 10, 2015.
- NASA Headquarters approval to proceed, September 7, 2015.

Oxygen-Rich Assessment of Mondaloy Alloy

Project Manager(s)

William Greene/XP20
(256) 544–1038

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

Mondaloy™ is a high-pressure, oxygen-resistant material developed by personnel at Aerojet Rocketdyne. It offers high strength compared to traditional alloys used in specific engine components, allowing a potential weight savings and/or less risk in new engine designs. Its oxygen resistance could also eliminate the need for coatings in some engine components. In support of the United States (U.S.) Air Force, NASA Marshall Space Flight Center (MSFC) is helping to develop and demonstrate technology that will be required for a high-pressure, oxygen-rich, RP-1-fueled engine. Demonstrating Mondaloy in a high-pressure, oxygen-rich environment will help confirm its application in this new engine development program.

MSFC's efforts to support the U.S. Air Force include hot-fire testing an oxygen-rich/RP-1 preburner. This preburner will eventually be used to support further testing of subscale staged combustion hardware. The environment produced in the preburner testing is ideal for initial screening of Mondaloy samples; therefore, MSFC's preburner hardware assembly will be modified to allow a spool section that holds material samples in the hot gas stream of the preburner environment.

MSFC discretionary funds in FY 2015 were used to design the material sample spool section and prepare appropriate drawings for its fabrication. Funds to fabricate and test the hardware and the Mondaloy samples from Aerojet Rocketdyne are being provided by the U.S. Air Force. The samples are expected to be delivered before the end of 2015, and hot-fire testing will be performed at MSFC before the end of 2015 or early in 2016.

Anticipated Benefits

The spool section designed to hold the material samples in this effort is not limited to Mondaloy material samples. It can be used to test similar samples of other oxygen-rich materials offered by industry or other government agencies. Thus, the hardware designed in this task is expected to enhance MSFC's test capabilities by offering a convenient way to test a variety of materials that could benefit oxygen-rich staged combustion engines.

Notable Accomplishments

Figure 1 shows one of MSFC's previous tests with the oxygen-rich preburner hardware in 2015. Figure 2 shows an image of the current assembly. The new spool section that will be used to hold the material samples is imaged in figure 3, while figure 4 depicts the spool section assembled in the preburner hardware. The spool section accommodates two material samples at a time.

When the preburner testing at MSFC is completed, the results will provide an assessment of the Mondaloy alloy in a high-pressure, oxygen-rich environment. The samples and required spool section will then be removed and the original preburner assembly will be used to support MSFC's testing of new subscale staged combustion hardware. The spool section to hold the material samples will remain available at MSFC for future testing, however, in case other entities have additional materials to evaluate in the preburner environment.

MSFC also prepared the drawing of the material sample required to mate with the spool section. The drawings of the sample and spool section can be made available to those interested in testing other material options.

Figure 1: Oxygen-rich/RP-1 preburner testing at MSFC.

Figure 2: MSFC's oxygen-rich/RP-1 preburner assembly.

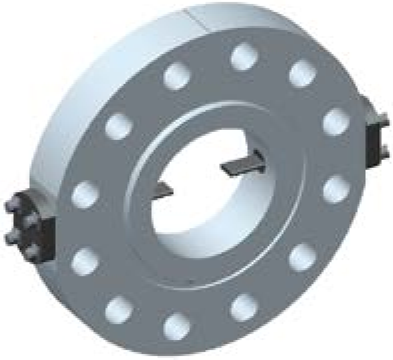


Figure 3: Spool section to hold Mondaloy.

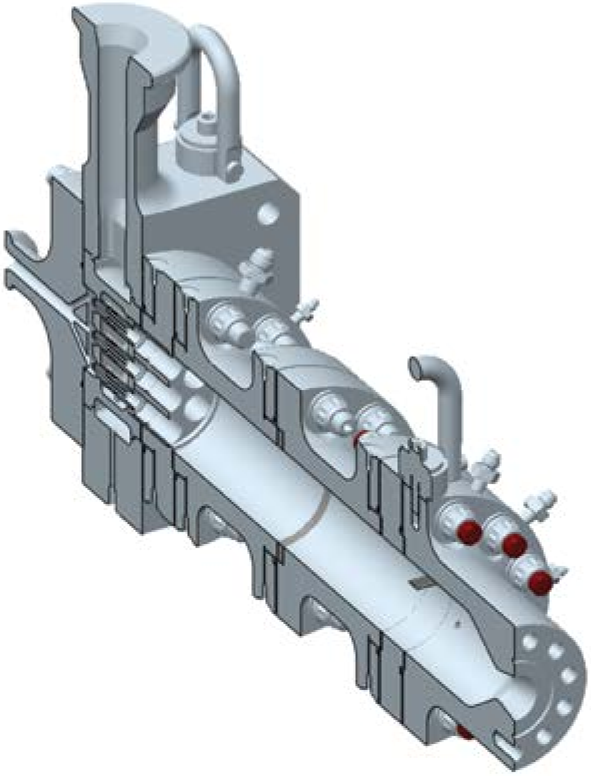


Figure 4: Depiction of material sample installed in MSFC's preburner assembly.

Marshall Grazing Incidence X-ray Spectrometer

Project Manager(s)

Dr. Amy Winebarger/ZP13
(256) 961–7509

Jeff McCracken/ZP21
(256) 961–7457

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

For over four decades, x-ray, extreme ultraviolet (EUV), and ultraviolet (UV) spectral observations have been used to measure physical properties of the solar atmosphere. During this time, there has been substantial improvement in the spectral, spatial, and temporal resolution of the observations in the EUV and UV wavelength ranges. At wavelengths below 10 nm, however, observations of the solar corona with simultaneous spatial and spectral resolution are limited, and not since the late 1970s have spatially resolved solar x-ray spectra been measured. X-ray spectroscopy provides unique capabilities for answering fundamental questions in solar physics. Because emission lines formed at high temperatures dominate the soft x-ray regime, x-ray spectroscopic techniques yield insights to fundamental physical processes that are not accessible by any other means.

The culmination of technological advances in grating lithography, mirror fabrication techniques, and camera efficiencies can now be leveraged to build imaging spectrometers similar to world-class x-ray observatories such as the Chandra X-ray Observatory, but at a far more reasonable cost. Using a novel implementation of corrective optics, the Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) will measure, for the first time, the solar spectrum from 0.6 to 2.4 nm with a 6-arcsec resolution over an 8-arcmin slit. Earlier investments in this technology have improved the MaGIXS design and reduced risk for the upcoming mission.

Anticipated Benefits and Mission Applications

NASA Marshall Space Flight Center (MSFC) will fabricate the MaGIXS mirrors using an electroformed nickel replication process. The MaGIXS cameras will be made at MSFC and are based on the successful design of the Chromospheric Lyman-Alpha Spectropolarimeter (CLASP) cameras. MaGIXS alignment and testing will occur at the Stray Light Facility. MaGIXS is a pathfinder for future satellite missions that utilize grazing incidence spectrometers.

Notable Accomplishments

MaGIXS was selected in 2014 and will launch on a sounding rocket from White Sands Missile Range in the summer of 2018 or 2019.

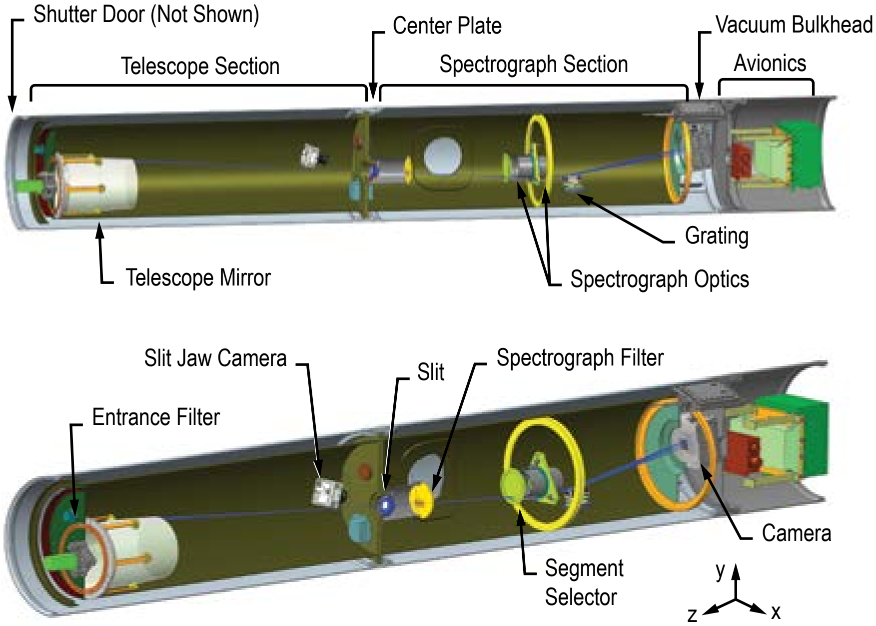


Figure 1: A schematic of the MaGIXS instrument concept.

Methane Pump Test

Project Manager(s)

T. Derek O'Neal/ER31
(256) 544–2543

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

Current architectures for missions to Mars note the use of pump-fed, liquid oxygen (LOX)/liquid methane (LCH_4) propulsion systems for in-space and lander applications. The technical goal of this project was to obtain early turbopump test data with LCH_4 to support the development of this propulsion system technology. The approach was to use the fuel pump developed as part of the Additive Manufacturing Demonstrator Engine (AMDE) for an LCH_4 test series. This pump was designed for operation in liquid hydrogen (LH_2), but its characteristics allow operation in LCH_4 at points that are close to those desired for current LCH_4 lander engine concepts. These early test data are valuable for anchoring future LCH_4 turbopump designs that would need to be developed for Mars missions.

Figure 1: Turbopump LCH_4 chill testing.

Early evaluations of test stand capability found that a new low-pressure tank would be needed for LCH_4 at Test Stand 116 (TS 116) in the East Test Area of NASA Marshall Space Flight Center (MSFC). The existing tanks were unable to be certified for LCH_4 use due to a number of technical reasons. A 10,000-gallon tank from the West Test Area was relocated to TS 116 to support turbopump testing (see fig. 2). Relocating the tank required design, fabrication, and installation of low-pressure LCH_4 run lines, valves, instrumentation, and supports at the existing AMDE test position.

Figure 2: Relocating 10,000-gallon tank to TS 116.

The original turbopump testing task was split into two parts: turbopump chill testing and performance testing. The separate pump chill test in LCH_4 was completed on September 29, 2015. Information from this test was requested by the Office of Strategic Analysis and Communication for the Von Braun Symposium. The turbopump performance testing is scheduled for FY 2016. It is currently only partially funded.

Anticipated Benefits

Collecting early turbopump test data in LCH_4 will give engineers a head start on LCH_4 pump-fed engine development. The collected data will be used to anchor the LCH_4 turbopump designs required for Mars lander applications. Bringing LCH_4 capability to TS 116 allows for component- and system-level testing during development. These test data can be used to refine designs, which in turn leads to more robust LCH_4 propulsion systems.

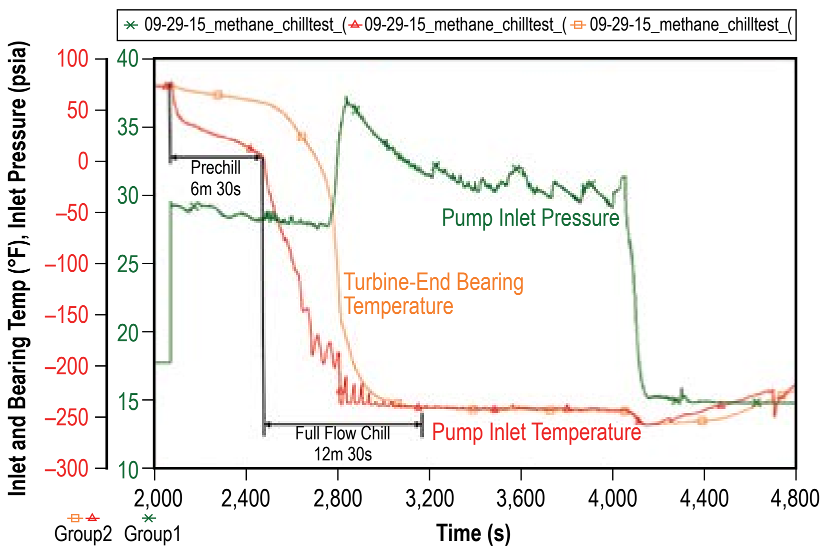


Figure 3: Turbopump chill test data.

Mission Applications

Pump-fed LOX/LCH_4 propulsion system technology is being developed for human exploration missions to Mars. These systems are in the current plans for in-space and lander applications.

Figure 4: Test Stand 116 pump-fed position (AMDE setup).

Notable Accomplishments

The turbopump chill test yielded baseline data for conditioning turbomachinery in LCH_4. Saturated LCH_4 conditions were reached after 19 minutes of chill, including 6.5 minutes of low flow prechill and 12.5 minutes of full flow chill (see fig. 3). These data verify turbopump conditioning methods and stand operation during chill.

The current pump-fed test position at TS 116 is being configured to run LCH_4. The new tank has been inspected and installed. Plumbing the position is in work (roughly 40% complete). Once complete, TS 116 will have the capability to test engine components in relevant LCH_4 environments, which is critical for engine system development. Figure 4 shows the pump-fed position at TS 116 during the turbopump chill test. It is currently built up for AMDE system testing. After AMDE testing in LOX/LH_2, the turbopump will be performance tested in LCH_4. Conducting pump-fed tests in relevant LCH_4 environments will keep MSFC at the forefront of pump-fed engine technology development.

Marshall Space Flight Center/
Center Management and Operations

Dual-Use Technology Cooperative Agreement Notice

Optimization of Ultracapacitors

Project Manager(s)

Dr. Terry D. Rolin/ES43
(256) 544–5579

Dr. Fat Duen Ho/University of Alabama Huntsville
(256) 824–6126

Caroline John/University of Alabama Huntsville
csj005@uah.edu

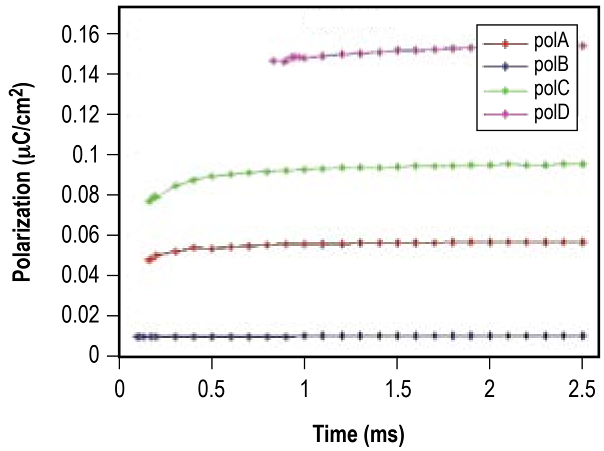
Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

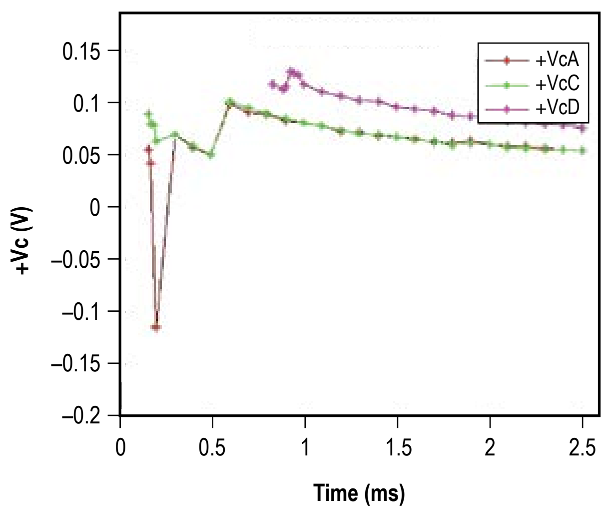
Project Description

NASA analyzes, tests, packages, and fabricates electrical, electronic, and electromechanical (EEE) parts used in space vehicles. One area that NASA wishes to advance is energy storage and delivery. Currently, space vehicles use rechargeable batteries that utilize silver-zinc or lithium-ion electrochemical processes. These current state-of-the-art rechargeable batteries cannot be rapidly charged, contain harmful chemicals, and suffer from early wear-out mechanisms. A solid-state ultracapacitor is an EEE part that offers significant advantages over current electrochemical and electrolytic devices.

The objective of this research is to develop critical design parameters that will aid in the design of ferroelectric ultracapacitors for optimal energy storage. This project was established to further the research and development activities of the Solid-State Ultracapacitor project. Currently, the list of variables that can be implemented to build an ultracapacitor is extremely large and complex. The University of Alabama Huntsville (UAH) has unique expertise and modeling capabilities to minimize variables in complex ferroelectrics. The process has begun to determine which parameters are important, that is, the ones that have the greatest effect on energy storage, capacitance, voltage breakdown, etc. Those parameters that have little to no impact can be ignored, thus reducing processing time and costs while still maintaining the functionality desired.



These data are measures of polarization with respect to frequency. Capacitor B has minimal polarization, thus ideally making it nonferroelectric. On the other hand, Capacitor A exhibits a higher polarization, with Capacitor D exhibiting the highest. This can be translated to the different amounts of energy stored in each of these capacitors based on the physical changes of their molecular structures.



Coercive voltages can be translated to the hysteresis measurements of the ferroelectric capacitors from which the energy storage capabilities of each ultracapacitor can be derived.

Anticipated Benefits

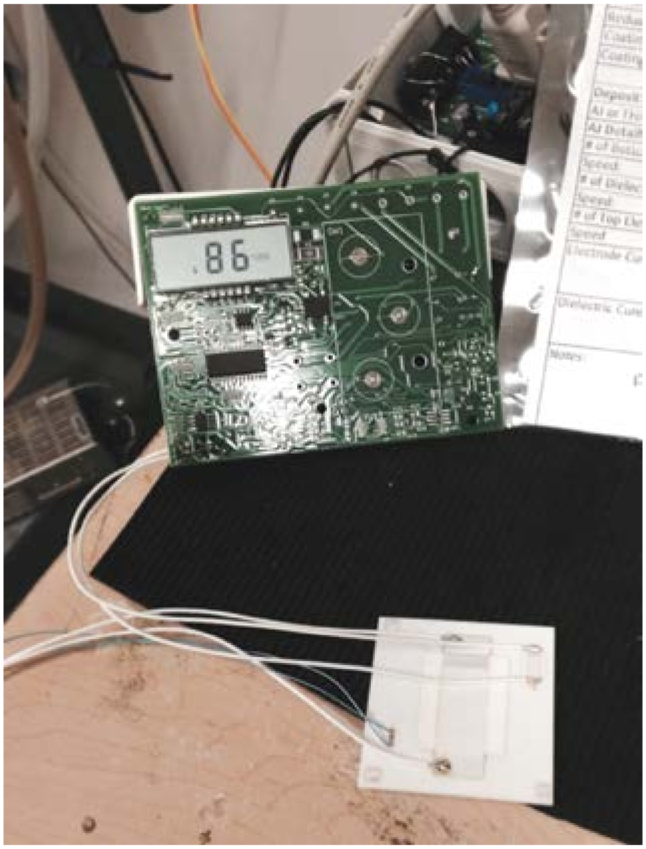
By minimizing unnecessary variables, the time from design to optimized device will be decreased considerably. This will save cost of manufacturing the devices, thereby making them more attractive for commercialization. The outcome and deliverable, a parametric model, can be used for other ferroelectric devices as well. For example, manufacturers in the ferroelectric transistor area could benefit from utilization of the model. If the model can predict the parameter necessary to increase energy density by an order of magnitude, it could point the way to a device that could replace lithium ion batteries with a more reliable, longer lasting, and safer alternative.

Mission Applications

The Propulsion Research Center at NASA Marshall Space Flight Center (MSFC) is already considering ultracapacitor technology for their electric propulsion systems in order to replace wet tantalum capacitors. The CubeSat community is also looking at ultracapacitors to provide emergency supplemental power as primary power systems drain below required operating levels.

Notable Accomplishments

Ultracapacitors with calculated energy densities exceeding 8 J/cc have been produced. Devices have shown charging times in milliseconds, breakdown voltages as high as 900 V in a 30-µm layer, and demonstrated the ability to activate light emitting diodes. Past research in ultracapacitor technology has resulted in the submission of three patent applications and discovery of two spin-off technologies. The spin-offs include creation of a low-temperature conductor ink that was not commercially available and the construction of an ultrasensitive ceramic humidity sensor element that is only 30 µm thick. The latter is currently being tested by a commercial humidity sensor vendor to replace their product line with help from MSFC's Technology Transfer Office. Thus far, MSFC has developed many of the sample sets for UAH to begin testing. Early test data are already showing that pretreatment versus post-treatment is one area critical for increasing capacitance.



Test data from a commercial vendor testing the humidity response of ceramic humidity sensor built at MSFC. This material was a spin-off discovery from the ultracapacitor research and development project.

Low-Cost Plasma Micropropulsion Using 3D Printing and Off-the-Shelf Components

Project Manager(s)

Kunning G. Xu/University of Alabama Huntsville
(256) 824–5083

Kurt Polzin/ER24
(256) 544–5513

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

This project seeks to develop and study a new low-cost micropropulsion concept for satellite propulsion called the Microwave Microplasma Micro-Thruster (3MT). The thruster utilizes microwave resonators to generate a microplasma. The project takes advantage of additive manufacturing and circuit fabrication techniques to build the major components. The thruster is designed to operate with microwave power at standard communications frequencies (e.g., 2.45 GHz) and at low power (<10 W) to directly tap into the existing communications equipment on satellites, eliminating the need for a dedicated power processing unit (PPU). The thruster can operate on a range of gaseous and condensable solid propellants, such as iodine.

The specific microplasma device developed here is called the split-ring resonator (SRR), which is shown in figure 1. The ring circumference is sized to be half the wavelength of the driving signal. A 2.45-GHz device would have a mean diameter of ≈1.22 cm. A small gap (≈500 µm) in the ring creates large amplitude electric fields between the two ends of the gap to ionize the surrounding gas to create a microplasma.

The thruster body is built with additive manufacturing, either from acrylonitrile butadiene styrene (ABS) plastic using fused deposition modeling, or Inconel® using electron beam sintering as shown in figure 2. Performance testing has begun at NASA Marshall Space Flight Center to measure thrust, specific impulse, and efficiency.

Figure 1: An SRR fabricated with photolithography. The SMA connector supplies the driving microwave power. The unseen backside of the white substrate is fully clad in copper and acts as the ground plane.

Anticipated Benefits

Microwave resonators can produce plasmas with low power requirements and can be easily scaled to multiple emitters for large plasma volume. A single 3MT with a single SRR is expected produce 0.1–0.5 mN of thrust at 10 W of power using the current electrothermal design. Multiple SRRs in a single unit can be used to increase thrust, and the units can easily be arrayed as well to produce larger thrust levels. The low cost, fast fabrication, and lack of a dedicated PPU makes the 3MT attractive for small satellite missions where cost, mass, and power are very limited.

Mission Applications

The primary application of the 3MT is for CubeSat or other small satellite propulsion. Missions such as the Lunar Flashlight, Lunar IceCube, and Near Earth Asteroid Scout can benefit from this technology. The additive manufacturing nature of the thruster also opens the potential for it to be built directly in space from raw materials. This can enable future on-demand construction and launch of small satellites.

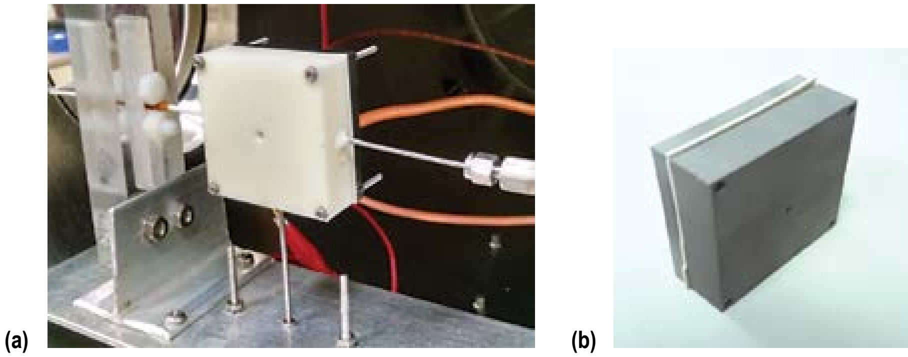


Figure 2: (a) The ABS prototype made with fused deposition modeling mounted in the vacuum chamber and (b) an Inconel version made with electron beam sintering.

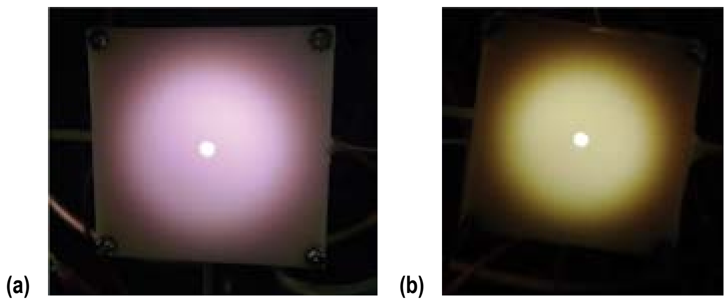


Figure 3: The 3MT operating on (a) argon and (b) air.

Notable Accomplishments

The 3MT has been tested with both argon and air as a propellant at 10–100 torr and has little difficulty sustaining the plasma with as little as 1 W of microwave power, as seen in fig. 3. The thruster body has been fabricated from ABS plastic and Inconel with additive manufacturing methods. An alternative SRR fabrication method was successfully tested using iron-on masks that greatly reduced the time from 4 hours in a clean room for photolithograph to just 30 minutes in a simple fume hood. The total cost per ABS unit is <$200, the majority of which is the cost of the substrate. From design to assembly, the ABS unit takes less than two days to produce, largely depending on the speed of the 3D printer. A wide-range torsional thrust stand is being designed and built by a University of Alabama Huntsville (UAH) senior design class as part of educational outreach. The thrust stand will be able to measure thrust levels from 10 μN to 1 N. Three conference papers on the project have been or will be presented at the 2015 American Institute of Aeronautics and Astronautics (AIAA) Propulsion and Energy and 2016 AIAA SciTech Forums.[1–3]

References

1. Dextre, R.A.; and Xu, K.G.: “Status of the Development and Measurement of a Microwave Microplasma Source for Micropropulsion,” Paper Presented at 51st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Orlando, FL, July 27–29, 2015.

2. Dextre, R.A.; Searcy, B.; and Xu, K.G.: “Confined versus Unconfined Analysis of Split Ring Resonator Microplasma Source in a Microwave Electrothermal Thruster,” Paper Presented at 2016 AIAA SciTech Forum, San Diego, CA, January 4–6, 2016.

3. Searcy, B.; Dextre, R.A.; and Xu, K.G.: “Performance Analysis of a Microwave Electrothermal Thruster Using a Split Ring Resonator Microplasma Source,” Paper Presented at AIAA 2016 SciTech Forum, San Diego, CA, January 4–6, 2016.

Liquid Oxygen Expansion Cycle— A Dual-Cooled Expander Cycle Engine Using Hydrogen and Oxygen

Project Manager(s)

Joe Leahy/ER21
(256) 544–9202

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

The liquid oxygen expansion cycle (LEC) engine, also referred to as the dual-cooled expander cycle (DCEC) rocket engine concept, employs two expander cycles within a single engine, one each to pump the fuel and oxidizer. The LEC engine will serve as an orbit transfer engine to propel a payload from low-Earth orbit (LEO) to geosynchronous orbit and to achieve escape velocity for interplanetary missions. This research will employ industry-standard design tools to create a model of an upper stage engine and then operate that engine in a simulation to optimize performance. The two key parameters used in this research of rocket engine performance were thrust-to-weight ratios and specific impulse (I_{sp}). The overall objective for the LEC is to double the current United States capability for orbit transfer by increasing thrust-to-weight while maximizing performance (I_{sp}).

The primary objective was to develop a power balance model of a high-performance DCEC engine using liquid oxygen (LOX) to cool the engine to validate the performance benefits and feasibility of the concept.

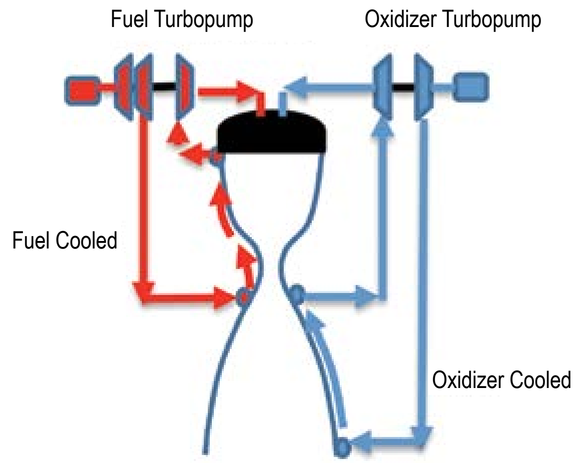


Figure 1: DCEC concept.

Anticipated Benefits

Determining the feasibility of this enabling technology will allow the removal of the number one catastrophic failure mode in current liquid rocket engines (the interpropellant seal package) and provide a higher performing cycle for use in upper stage applications. Deliverables will be a validated power balance model utilizing the DCEC engine.

Mission Applications

All upper stage and orbit transfer of payloads are currently limited to 7,000 kg into LEO. Replacing the RL-10 with a dual expander engine has the potential to increase payload by hundreds if not thousands of kilograms.

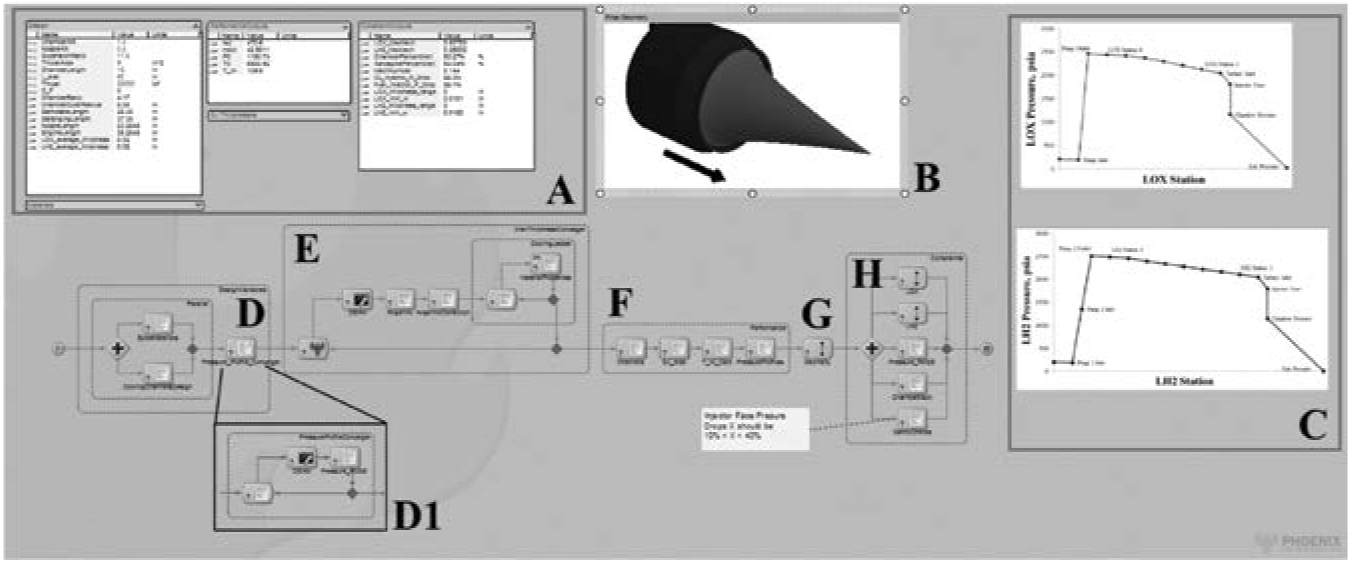


Figure 2: DCEC with aerospike nozzle option.

Notable Accomplishments

This research effort has benefited from previous efforts modeling a dual expander aerospike engine (fig. 2). Notably, the power balance model using NASA's Numerical Propulsion System Simulation (NPSS) was incorporated into an optimization code known as ModelCenter®.[4] The power balance model was simplified for robust operation but successfully captured the physics of the engine cycle.[1–3]

The model has been adapted to the DCEC engine and efforts to verify the modeling approach are underway. The RL-10a-3-3a is modeled and will be compared with experimental results to validate the tool.

Additionally, the DCEC engine cycle preliminary results are promising but need to be better grounded in the physical constraints.[4] Design parameters have been chosen for minimum pressure loss and maximum performance (chamber pressure). The results from the validated RL-10 modeling effort will provide the needed grounding for this model.

Several key features of the ModelCenter optimization scheme have been incorporated into the DCEC engine model.

References

1. Simmons III, J.R.: "Design and Evaluation of Dual-Expander Aerospike Nozzle Upper Stage Engine," Ph.D. Dissertation, AFIT-ENY-DS-14-S-06, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, 376 pp., September 2014.

2. Martin, D.F.: "Computational Design of Upper-stage Chamber, Aerospike, & Cooling Jacket of Dual-Expander Rocket Engine," Master's Thesis, AFIT/GAE/ENY/08-M20, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, 135 pp., March 2008.

3. Simmons, J.; and Branam, R.: "Parametric Study of Dual-Expander Aerospike Nozzle Upper-Stage Rocket Engine," *J. Spacecraft Rockets*, Vol. 48, No. 2, pp. 355–367, doi: 10.2514/1.51534, April 2011.

4. *ModelCenter 10.2 User Manual*, Phoenix Integration, Blacksburg, VA, 2013.

Enabling Fast-Responding Pressure-Sensitive Paint Systems in Blowdown Wind Tunnels

Project Manager(s)

James Aaron/ET20
(256) 544–9098

Dr. Jim Crafton/Innovative Scientific Solutions, Inc.
(937) 630–3012

Dr. Paul Hubner/The University of Alabama
(205) 348–1617

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

Fast-responding pressure-sensitive paint (PSP), which offers a means of acquiring unsteady pressure data at millions of locations on a wind tunnel model surface, has long been viewed as a disruptive technology. The overall objective of this project is to develop and demonstrate a fast PSP system (fig. 1) for use in a blowdown wind tunnel such as the NASA Marshall Space Flight Center Aerodynamic Research Facility (ARF). The proposed fast PSP technology is based on several proven pieces of hardware, such as fast cameras and ultra-bright lighting, and has been demonstrated in similar-scale transonic wind tunnels. Data shown in figure 2 establish the technical readiness of the fast PSP hardware; however, it is noted that the ARF is a blowdown tunnel rather than a closed-loop tunnel. This means that the stagnation temperature of the flow is dropping during the run. Temperature sensitivity is a well-documented issue for PSP technology, and therefore will be addressed if a fast PSP system is to be deployed in any blowdown wind tunnel.[1]

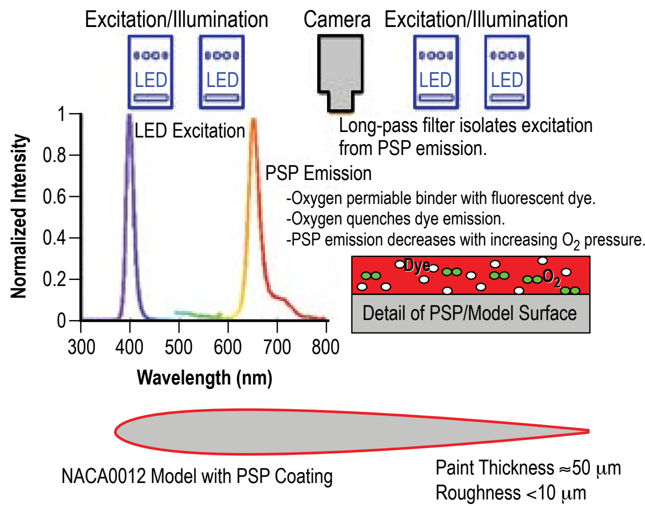


Figure 1: Basic PSP system.

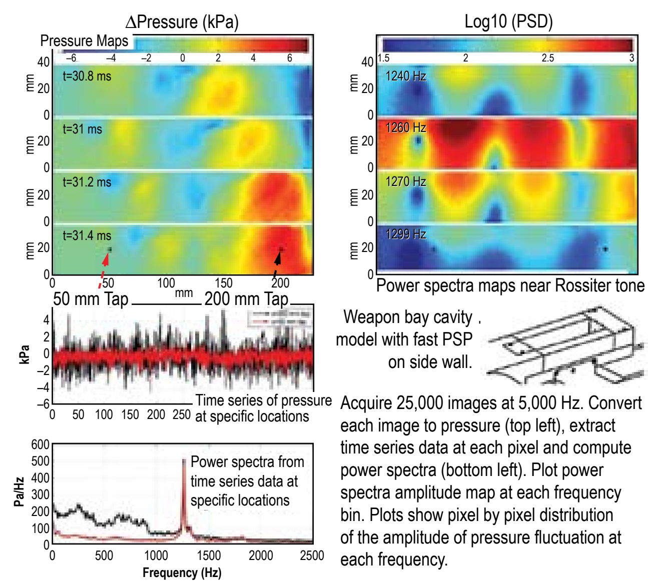


Figure 2: Unsteady pressure measurements on the wall of a supersonic cavity model using fast PSP.[2]

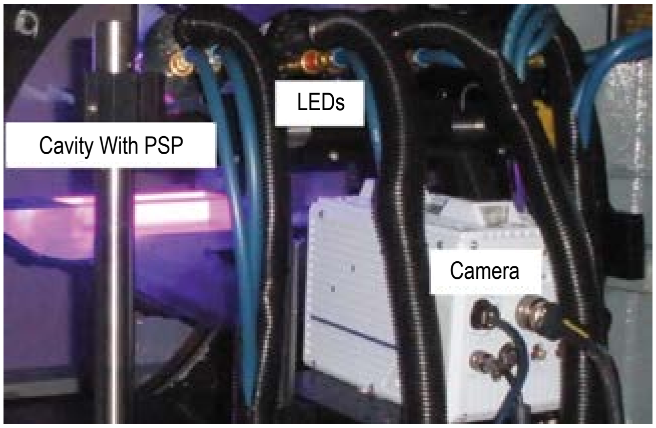


Figure 3: Wind tunnel setup for fast PSP.

Anticipated Benefits

The ARF has a 14-in test section, which restricts the size of the models being tested. Conventional methods of pressure measurements on the models require the installation of very small pressure ports. Due to the model sizes, there can only be a very limited number of these ports, and therefore a limited number of pressure measurements. The PSP system (fig. 3) will allow pressure measurements at thousands of locations. Photographs of models with PSP over their entire surfaces allow each pixel of a photo to measure pressure. In addition to higher fidelity pressure measurements, the PSP system's data processing will allow the measurement of unsteady pressures, which is critical to assessing the aerodynamics of an aerospace vehicle.

Mission Applications

The PSP system will provide extensive unsteady pressure measurements for any flight vehicle very early in the design phase and at a lower cost compared to larger wind tunnels. Both large programs (such as the Space Launch System) and smaller programs (such commercial launch vehicles) can benefit from the unsteady pressure measurements that are used to assess the performance of their vehicles. Having this capability will allow programs to have an early assessment of their vehicle's performance, which in turn can reduce the time and costs for conducting both additional analyses and testing at larger wind tunnels that would be needed for continued vehicle development.

Notable Accomplishments

The principal investigators have completed plans for the first wind tunnel tests at The University of Alabama using the PSP on a cone cavity model supplied by Dr. Semih Ölçmen's research team. These tests will provide the first set of data to determine the performance of PSP with improved paint chemistry for mitigating temperature sensitivity and data processing for measurement of unsteady pressures. Also, they will lay the groundwork for tests to be conducted at the ARF.

References

1. Crafton, J.W.; Forlines, A.; Palluconi, S.; et al.: "Investigation of Transverse Jet Injections in a Supersonic Crossflow Using Fast Responding Pressure-Sensitive Paint," Paper Presented at 29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, June 27–30, 2011.

2. Flaherty, W.; Reedy, T.M.; Elliot, G.S.; et al.: "Investigation of Cavity Flow Using Fast-Response Pressure Sensitive Paint," Paper Presented at 51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Dallas/Ft. Worth, TX, January 7–10, 2013.

Multi-Mode Micropropulsion for Small Spacecraft

Project Manager(s)

Kurt Polzin/ER24
(256) 544–5513

Joshua L. Rovey/Missouri University of Science and Technology
(573) 341–4613

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

The Missouri University of Science and Technology in partnership with NASA Marshall Space Flight Center is developing multi-mode micropropulsion for small spacecraft. The main benefit of a multi-mode system is increased mission flexibility through the use of both a high-thrust chemical thruster and a high-specific impulse electric thruster. By utilizing both thrust modes, the mission design space is much larger.[1] Missions not normally accessible by a single type of thruster are possible since both are available. The system is a single-propulsion system (i.e., one propellant tank, one set of feed lines/valves, one thruster) that can be operated in either high-thrust, low-specific impulse chemical mode or low-thrust, high-specific impulse electric mode. We have already demonstrated operation of this multi-mode propulsion concept using our custom propellant in separate chemical and electric modes using identical thruster hardware but separate propellant feed systems. Through this project, we are combining the feed systems and thruster hardware and creating an integrated multi-mode propulsion system.

The goal of the project is to experimentally quantify the performance of a multi-mode micropropulsion system for small spacecraft. Current efforts are focused on (1) fundamental burn rate measurements of our novel multi-mode propellant and (2) optimizing chemical mode operation, shown in figure 1.

Anticipated Benefits

Multi-mode micropropulsion significantly enhances the flexibility of small spacecraft. Our results (fig. 2) show a factor of 3 increase in small satellite mission flexibility with multi-mode micropropulsion.[2] We have also compared five different propulsion system combinations and showed that a 40% wider range in spacecraft delta-v is possible with the proposed multi-mode system, as compared to state-of-the-art hydrazine and xenon Hall thruster propulsion.[3] We have also compared six different multi-mode micropropulsion configurations and found that our system has the highest mission capability in terms of delta-v for missions lasting shorter than 150 days due to the combination of a single propellant for both propulsive modes, low inert mass, and high electric thrust.[2] Additionally, our work has compared spacecraft mass and volume requirements for lunar and Jupiter missions using different types of propulsion (fig. 3). The spacecraft with our multi-mode propulsion has lower mass and volume than separate thruster systems using the same AF-M315E propellant. This mass savings can be used for extra payload. Additionally, smaller mass and volume enables the spacecraft to be launched from an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) while still having enhanced capability.

Mission Applications

Multi-mode micropropulsion has applications relevant to numerous small satellite missions being investigated by NASA. In fact, NASA personnel have investigated small satellite multi-mode micropropulsion and found it to be a hugely beneficial and enabling technology. Lee and Hwang[3] showed that the multi-mode approach is more fuel-efficient than conventional two impulsive high-thrust maneuvers for formation flight. Oland et al.[4] showed that the multi-mode thrust history is a favorable solution for attitude control using chemical thrusters for slew maneuvers, while using the electric thruster for fine attitude pointing. Kemble and Taylor[5] compared thrust approaches for small satellite missions to Jupiter. The best result was a combined solar-electric and chemical propulsion system. Trawny et al.[6] showed that electric propulsion followed by a chemical impulse for a final aposelene boost yields much more favorable impact conditions for impacting a small satellite into the lunar surface.

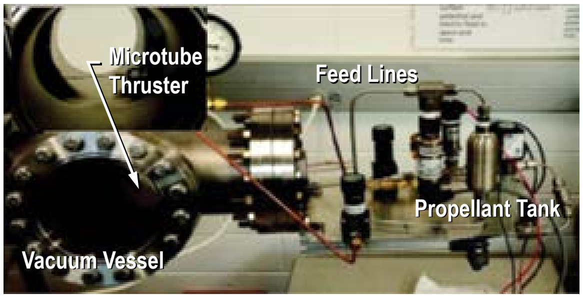


Figure 1: Experimental setup being used to test the chemical operating mode of the micropropulsion system.

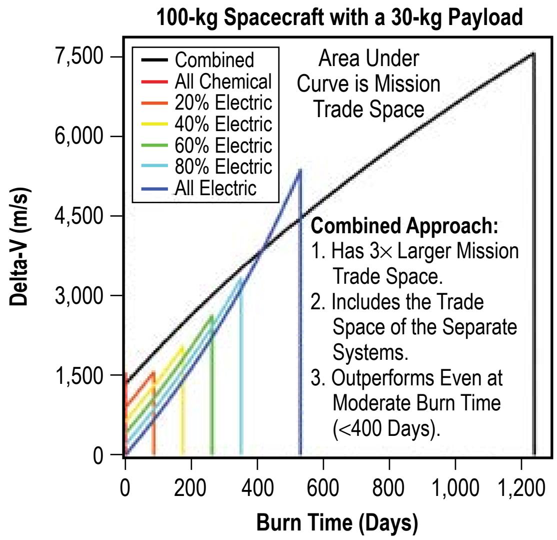


Figure 2: Flexibility provided by a multi-mode (combined) propulsion system on a small spacecraft.

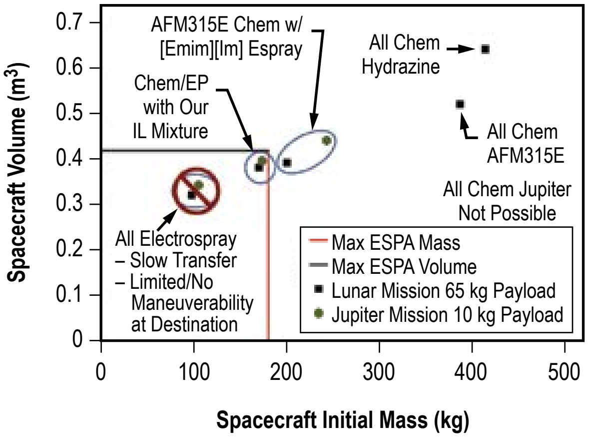


Figure 3: Comparison of spacecraft mass and volume for lunar and Jupiter missions using multi-mode, separate chemical and electric, all electric, or all chemical propulsion. A spacecraft with our multi-mode propulsion enhances small satellite capabilities and can fit within ESPA ring mass/volume constraints.

Notable Accomplishments

We have synthesized and demonstrated chemical reactivity of our novel multi-mode propellant. We have demonstrated chemical mode operation and electric mode operation of the multi-mode microthruster in separate test setups, with identical hardware. We have designed the integrated multi-mode microthruster. Upcoming activities will determine optimized operation of the chemical and electric thruster modes, fabricate an integrated multi-mode thruster, and measure performance.

References

1. Dextre, R.A.; and Xu, K.G.: “Status of the Development and Measurement of a Microwave Microplasma Source for Micropropulsion,” Paper Presented at 51st AIAA/SAE/ASEE Joint Propulsion Conference, Orlando, FL, July 27–29, 2015.

2. Dextre, R.A.; Searcy, B.; and Xu, K.G.: “Confined versus Unconfined Analysis of Split Ring Resonator Microplasma Source in a Microwave Electrothermal Thruster,” Paper Presented at 54th AIAA Aerospace Sciences Meeting, Cleveland, OH, January 4–8, 2016.

3. Lee, S.; and Hwang, I.: “Hybrid High- and Low-Thrust Optimal Path Planning for Satellite Formation Flying,” Paper Presented at AIAA Guidance, Navigation, and Control Conference, Minneapolis, MN, August 13–16, 2012.

4. Oland, E.; Kristiansen, R.; and Nicklasson, P.J.: “Combined chemical and electric thruster solution for attitude control,” Paper Presented at 4th International Conference on Recent Advances in Space Technologies, Istanbul, Turkey, June 11–13, 2009.

5. Kemble, S.; and Taylor, M.J.: “Mission Design Options for a Small Satellite Mission to Jupiter,” Paper Presented at 54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, Bremen, Germany, September 29–October 3, 2003.

6. Trawny, N.; Graesslin, M.; Laufer, R.; and Roeser, H.-P.: “Mission Scenarios for a Controlled Lunar Impact of a Small Satellite,” Paper Presented at 55th International Astronautical Congress, Vancouver, Canada, October 4–8, 2004.

Topic Mapping

Project Manager(s)

Mark Rogers/ED04
(256) 544–6969

Pat Hunt/ED04
(256) 544–2297

Gregory Funaro/ED04
(256) 544–3747

Thomas Marsh/ai-one, inc.
(858) 531–0674

Jeremy Toor/ISC Consulting Group
(520) 508–8501

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

The Advanced Concepts Office (ACO) performs conceptual design and analysis on many far-reaching missions, which requires significant technology development. The intent is to help guide NASA's technology development programs and to quantify through analysis the benefits of those technologies. The Agency's programs and projects, by their very nature, frequently require the development and infusion of new technological advances to meet mission goals, objectives, and resulting requirements. Figure 1 depicts the relationship between architectural studies and technology assessments.

Key to the technology assessment process is an understanding of program and Agency goals, technology capabilities, the collection of the technology data, and the actual technology assessments. The process requires significant input in the form of interviews with technologists throughout the industry/government/academia. Technology assessments also require the input from multiple discipline analysts.

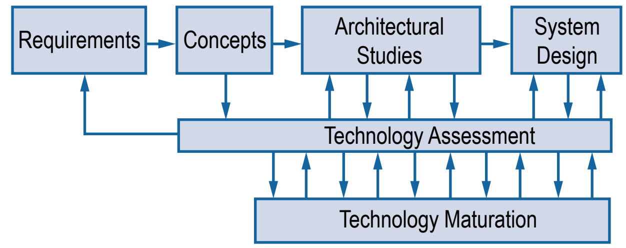


Figure 1: Relationship between concepts, architectural studies, and technology assessments.

The technology assessment process is laborious and time intensive due to the nature of assembling and obtaining input from multiple discipline experts. ACO is attempting to improve the process by using state-of-the-art technology in computer text and content analytics. ACO is collaborating with two leading experts in this field: ai-one™ and ISC Consulting Group.

ai-one is a recognized Who's Who in text analytics technology, which will enable ACO to obtain information from almost any digital source, in any language, regardless of its structure (or lack of structure). ISC Consulting Group has experience working with the ai-one technology to obtain and classify information for the United States Army Intelligence Center.

ACO is testing the ai-one technology by performing a technology assessment of wireless sensors. ACO collected data on wireless sensors from the NASA Technical Reports Service repository, which returned 230 documents, which amounts to approximately 10,000 paragraphs, or 3,000 pages, of technical information from all NASA Centers from the years 2000–2015.

With the help of the ai-one technology and support from ISC Consulting Group, ACO created 45 agents to represent various avionics system designs. This was done not through programming, but by providing each agent a few paragraphs describing each avionic system. The 10,000 paragraphs were then evaluated by each agent and scored on how well the wireless sensor paragraphs matched the capabilities described by the avionics system. That amounts to 450,000 assessments.

Figure 2: Technology assessment of wireless sensors using text analytics.

The next step was to organize the data for analysis. This step was done by using a statistical method for clustering data into a hierarchical group of systems, subsystems, and components. With the data organized into groups, the information was summarized using text summarization algorithms.

The final result was impressive. The groups fell into three primary elements: landers, habitats, and Mars concepts (fig. 2). Normally, a task like this could take six months. Using this process, ACO put together a wireless technology roadmap in about two weeks that NASA Marshall Space Flight Center's (MSFC's) Engineering Directorate will use to plan future developments in wireless sensors.

Anticipated Benefits

ACO identified three goals with regard to expanding our current technology assessment methodologies:

(1) Improve stakeholders ability to make decisions regarding technology.
(2) Enable 'information-based decisions.'
(3) Lead the effort to align MSFC's organizational posture toward its corporate business objectives.

These activities represent the vision of future technology assessments and portfolio planning for ACO. In this effort, a computer, instead of a team of discipline analysts, extracted from a multitude of documents the degree of alignment between work being done and technological needs. The information was mapped across mission systems to shape a strategy for wireless sensor development.

Mission Applications

Utilizing robust software platforms to conduct technology assessments and assist in technology roadmap development will have a cross-cutting impact on future NASA missions. By being able to effectively match technology development efforts with researchers, programs, funding, and missions, time and expense can be saved while hopefully improving the available technologies for each mission.

Printing Outside the Box: Additive Manufacturing Processes for Fabrication of Large Aerospace Structures

Project Manager(s)

Gregg Jones/ER32
(256) 544–2225

Majid Babai/EM42
(256) 544–2795

Judy Schnieder/Mississippi State University
(256) 824–5186

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

To achieve NASA's mission of space exploration, new innovative additive manufacturing processes are needed to reduce the cost and fabrication time of large propulsion components like a liquid rocket engine (LRE) nozzle (fig. 1). These structures are much larger than current capabilities with selective laser melting (SLM) in powder beds. Metal direct deposit manufacturing (MDDM) with a robotic pulsed source has the capability to build large structures like an LRE nozzle.

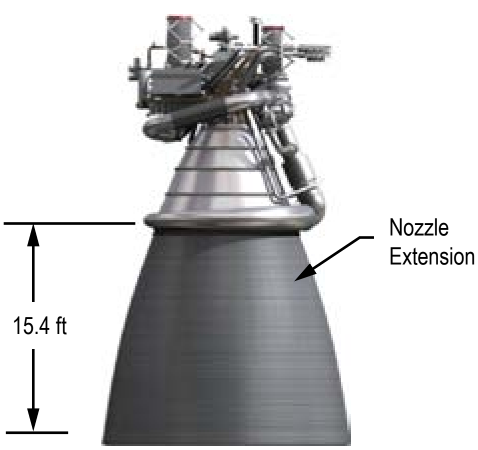


Figure 1: Nozzle extension for the J2X LRE.

The MDDM process uses a robotic arc welder to build up materials a layer at a time similar to how the SLM process builds. Since it is not confined to a powder bed, the SLM size restrictions do not apply.

This program explored material properties of samples built with the MDDM process and with a powder bed. Figure 2 shows a typical build from the MDDM process. Material samples were taken from MDDM builds and from SLM powder bed build (fig. 3), and their material characteristics were compared (fig. 4). Properties were slightly lower than wrought and powder bed strengths, but were better than cast properties.

Figure 2: Typical MDDM Inconel® 718 build-up.

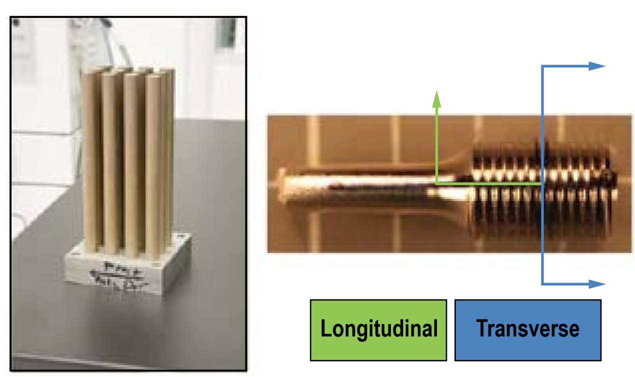


Figure 3: SLM tensile samples.

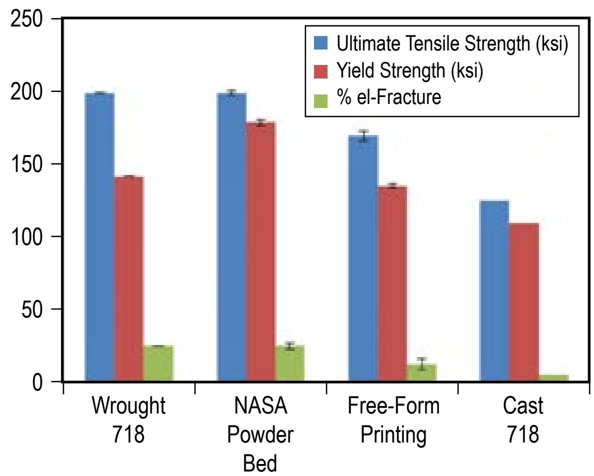


Figure 4: Comparison of properties obtained using powder bed process versus free-form printing.

Controlling temperatures is critical for the MDDM processes to avoid slumping during the build process. As part of this program, new predictive thermal models of the MDDM build process were developed (fig. 5). The modeling effort builds on an analytical solution for a moving heat source.[1] Thermocouple data from an MDDM build using a metal inert gas source were used to adjust and validate the model.

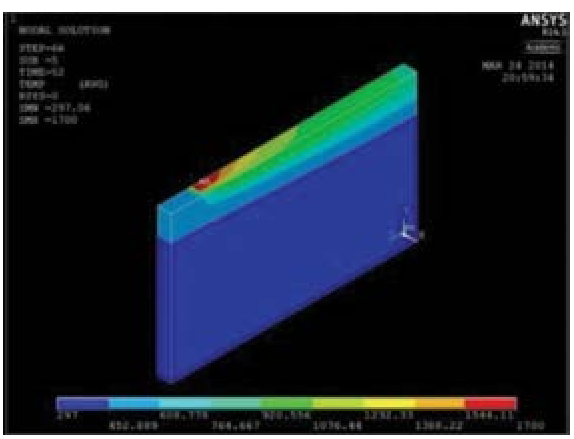


Figure 5: ANSYS transient heat analysis for specimen shown in figure 2 (temperature = °C).

In addition to the thermal condition during the build, post-build heat treatment is also important.

Anticipated Benefits

This program demonstrated that the MDDM process with a robotic arc can produce the high-strength materials properties needed for LRE applications. The MDDM process has the potential to greatly reduce the cost and fabrication time of constructing large rocket engine parts like rocket nozzles.

Mission Applications

Large additively manufactured nozzles are needed for upper stages and in-space propulsion.

Notable Accomplishments

- Demonstrated high strength and ductility for samples created with a robotic arc and the MDDM process.
- Demonstrated a new thermal model of the build process which can be used to model and optimize the MDDM process.

References

1. Rosenthal, D.: "The Theory of Moving Sources of Heat and Its Applications to Metal Treatments," *Transactions of the American Society of Engineers*, Vol. 68, pp. 849–866, 1946.

Improving the Interlaminar Shear Strength of Out-of-Autocave Composites

Project Manager(s)

Justin Jackson/EM42
(256) 961–2215

Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

To achieve NASA's mission of space exploration, innovative manufacturing processes are being applied to the fabrication of complex propulsion elements.[1] Use of fiber-reinforced, polymeric composite tanks are known to reduce weight while increasing performance of propulsion vehicles. Maximizing the performance of these materials is needed to reduce the hardware weight to result in increased performance in support of NASA missions. From July 2014 to August 2015, NASA partnered with Mississippi State University (MSU) in a cooperative agreement project to utilize a unique scalable approach of locally improving the critical properties needed for composite structures. MSU was responsible for the primary development of the concept with material and engineering support provided by the NASA Marshall Space Flight Center (MSFC).

The all-composite tank, shown in figure 1, is fabricated using a prepreg system of IM7 carbon fiber/CYCOM 5320-1 epoxy resin. This is a resin system developed for out-of-autoclave (OoA) applications. This new technology is needed to support the fabrication of large, all-composite structures, and was evaluated on a joint project between the NASA and Boeing for the Space Launch System (SLS) program. Figure 2 shows the all-composite tank being installed on the test facility at MSFC.

Figure 1: Fabrication of the 18-ft- (5.5-m-) diameter, all-composite tank at the Boeing facility.

Figure 2: All-composite tank being tested at MSFC.

In initial efforts to form the all-composite pressure vessel using this prepreg system, a 60% decrease in properties was observed in scarf joint regions. Inspection of these areas identified interlaminar failure in the adjacent laminated structure as the main failure mechanism. This project considered methods to improve the interlaminar shear strength (ILSS) within the prepreg layup by locally modifying the interply region.[2] This approach would be readily scalable for use in a production environment.

Status

MSU explored methods to embed reinforcing nanoparticles in the resin-rich regions between plies to strengthen and toughen the matrix. Short beam shear tests were conducted at room temperature and in liquid nitrogen (LN_2) to evaluate the energy absorbed. Figure 3 shows the testing apparatus. Test specimens were fabricated using a 24-ply layup.

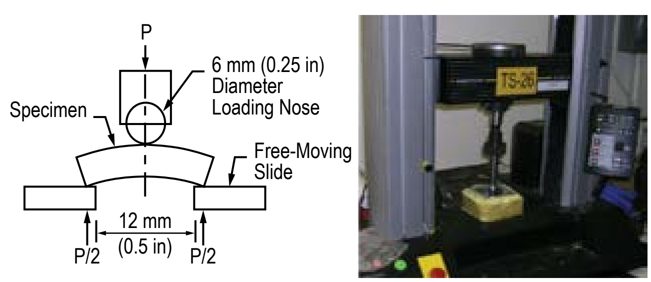


Figure 3: Short beam shear tests were conducted on an Instron® load frame.

Initial results on this project showed promise in improving shear strength, as shown in figure 4. Based on initial results and the potential for sizing to improve bonding with the resin system, multiwalled carbon nanotubes (MWCNTs) were selected as the most promising additive to carry forward in the study.

Testing was conducted to evaluate the ability of various dispersants to suspend MWCNTs for up to two hours. Figure 5 shows that slightly improved suspension results were obtained utilizing isopropanol (fig. 5(b)) with different loading of MWCNTs. This has implications in working time during fabrication as well as uniformity of deposition.

Utilizing a spray gun, the suspended MWCNTs were applied to the plies during fabrication. To further eliminate voids observed in the initial test specimens shown in figure 4, a slight dead weight was applied to provide a loading of 15.9 kPa.

Testing of these specimens using 0.17 wt% MWCNT dispersed between plies obtained more consistent and higher values of energy absorbed, as shown in figure 6.

Figure 7 shows the probability of failure using a normal distribution for the flexural strain (fig. 7(a)) versus the flexural stress (fig. 7(b)). The modified composite specimens showed an increased strain to failure over the unmodified control specimens.

Further improvements could be made utilizing functionalized MWCNT. Once proven, this concept could be readily implemented into current fabrication schemes.

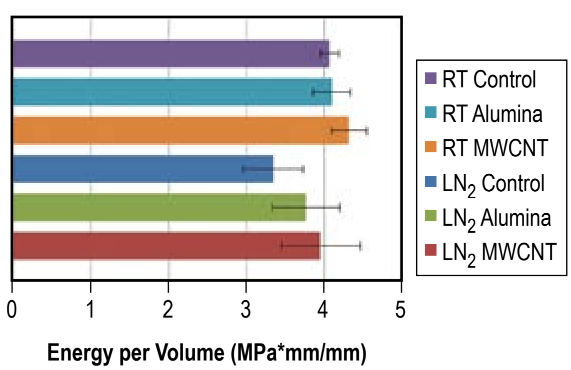


Figure 4: Improved energy absorbed was demonstrated using a local modification of nanoparticles. Intial studies on a woven prepreg showed MWCNT to be most effective.

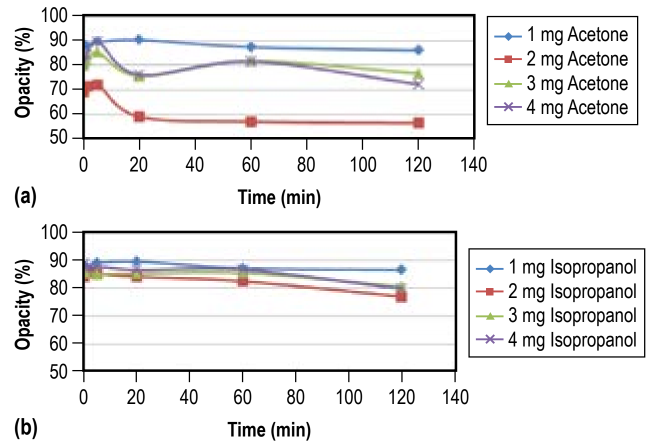


Figure 5: Variation in suspension times for varying loading of MWCNT in (a) acetone and (b) isopropanol.

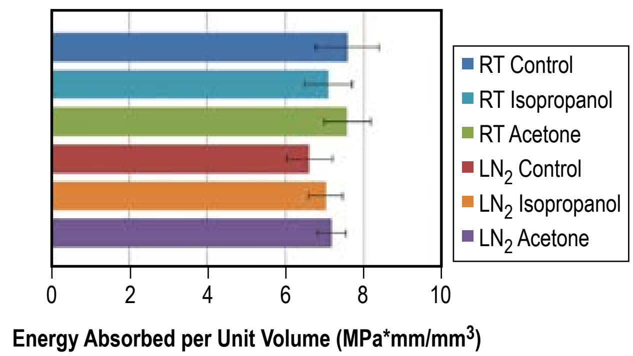


Figure 6: Further increases in energy absorption during a short beam shear tests were obtained by process modification during curing of the woven prepreg system.

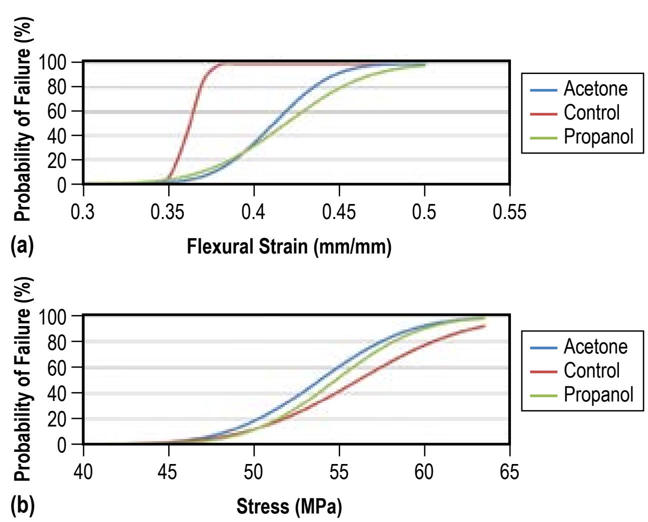


Figure 7: LN_2 temperature failure probabilities with respect to (a) flexural strain and (b) flexural stress.

Anticipated Benefits

The prepreg system uses a continuous carbon fiber to realize the overall global strength of the part. This approach can also be applied locally by use of reinforcing additives, such as carbon nanotubes (CNTs) within the epoxy resin. In studies on neat resins using various additives, an increase was shown both in strength and toughness.[3] As ILSS is reported to be matrix-driven, methods to improve the strength and toughness of the resin are of interest. However, these types of modifications cannot be applied to an existing prepreg system without extensive development costs. This study evaluated the local modification of a prepreg system in increasing the ILSS using methods that could be easily scaled for production environments.

Mission Applications

Methodology being developed in this project can immediately benefit current production of an OoA fabricated fuel tank for the SLS program, as well as have commercial interests in transportation usage of alternative cryogenic fuels and for use of in-field repair of polymeric composite structures.

Use of CNTs as piezoelectric sensors is also being pursued on other studies at NASA.[4] Proving CNTs' effectiveness in locally modifying joint properties may make it possible to provide local monitoring for structural health.

Notable Accomplishments

Use of short beam shear tests on coupon specimens indicated that both the shear strength and energy absorption were improved at both room and cryogenic temperatures. The most noticeable improvement was in the flexural strain to failure, which indicated increased resistance to debonding.

Both acetone and isopropanol appear to be suitable suspension and dispersion agents. No degradation of properties was observed with either dispersant.

This study was presented at the SAMPE/CAMX Conference in Baltimore, MD, in October 2014.[5]

References

1. Fikes, J.; and Vickers, J.: "Composite Cryotank Technologies and Demonstration Project," Paper Presented at JANNAF Liquid Propulsion Subcommittee Meeting, Huntsville, AL, December 7, 2011.

2. Myers, Z.A.; Schneider, J.: "Methods to improve interlaminar shear strength in out of autoclave composites," Paper Presented at SAMPE/CAMX Conference, Orlando, FL, October 13–16, 2014.

3. Brown, H.R.; Schneider, J.A.; and Murphy, T.L.: "Experimental studies of the deformation mechanisms of core-shell rubber-modified diglycidyl ether of bisphenol-A epoxy at cryogenic temperatures," *J. Compos. Mater.*, Vol. 48, No. 11, pp. 1279–1296, doi:10:1177/0021998313485262, May 2013.

4. Wang, X.; Yong, Z.Z.; Li, Q.W.; et al.: "Ultrastrong, Stiff and Multifunctional Carbon Nanotube Composites," *Materials Research Letters*, Vol. 1, No. 1, 8 pp., doi:10.1080/21663831.2012.686586, October 2012.

5. Myers, Z.; and Schneider, J.: "Improving Interlaminar Shear Strength of Carbon Fiber Composites Using Nano-Additives for Use in Cryogenic Applications," Paper Presented at SAMPE/CAMX Conference, Orlando, FL, October 13–16, 2014.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01–04–2016

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*
October 2014–September 2015

4. TITLE AND SUBTITLE
Marshall Space Flight Center Research and Technology Report 2015

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A.S. Keys, M.L. Tinker, A.D. Sivak, and H.C. Morris, Compilers

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Huntsville, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–1411

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM—2016–218221

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 12
Availability: NASA STI Information Desk (757–864–9658)

13. SUPPLEMENTARY NOTES
Prepared by the Office of the Director, Center Chief Technologist

14. ABSTRACT

Many of NASA's missions would not be possible if it were not for the investments made in research advancements and technology development efforts. The technologies developed at Marshall Space Flight Center contribute to NASA's strategic array of missions through technology development and accomplishments. The scientists, researchers, and technologists of Marshall Space Flight Center who are working these enabling technology efforts are facilitating NASA's ability to fulfill the ambitious goals of innovation, exploration, and discovery.

15. SUBJECT TERMS
MSFC Research and Technology Report 2015, engineering, science, technology

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk at email: help@sti.nasa.gov
U	U	U	UU	222	19b. TELEPHONE NUMBER *(Include area code)* STI Help Desk at: 757–864–9658

National Aeronautics and Space Administration

George C. Marshall Space Flight Center
Huntsville, AL 35812
www.nasa.gov/marshall

www.nasa.gov