Near-term Persistent Platform Orbital Testbed: Three Candidate Architecture Options

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On-orbit Servicing, Assembly, and Manufacturing (OSAM) will revolutionize the space industry by transforming the concept of operations of space systems and enabling new, radically different system implementations. These new implementations will benefit from a novel persistent asset design paradigm which focuses on evolvable designs that are tailored to the operational environment, not the launch environment. In addition, the ability to launch sub-systems independently enable future persistent assets to economically expand in capability and size, achieving cost effective and productive operations lasting for decades like terrestrial observatories. With few exceptions (International Space Station, Hubble Space Telescope, Mission Extension Vehicle customers), current space systems are not visited once they are operational. Leveraging emerging low cost commercial launch provides the ability to repeatedly and routinely revisit space systems. Thus, revolutionary new approaches for space system design are possible, creating completely new opportunities for small businesses and accelerating the growth of already established space industries.

To usher in the revolutionary new operational paradigm, two things are needed. First, to build confidence in the technology and new paradigm, there must be a leading example, a bellwether persistent asset, that demonstrates the reliability and maturity of the new persistent asset paradigm (where repeated visits are common). Second, in order to rapidly advance and

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validate OSAM capabilities, an efficient means is required to conduct tests in the space environment. A persistent platform testbed satisfies both these needs.

The space environment exhibits a plethora of characteristics that are difficult and costly to accurately simulate for a full system in a terrestrial laboratory, such as near zero gravity, a wide range of ionizing radiation types, atomic oxygen, and micro-meteoroids and space debris traveling at high velocity. In addition, since persistent assets range in mass from a few grams to several metric tons, it is difficult to accurately simulate interactions between these systems and visiting vehicles (that also exhibit a wide range of varying masses and capabilities). These interactions include the transmission of forces and/or exchanging mass (in the form of instruments, fuel, robotic assets, etc.). Thus, a rapid, versatile and cost efficient in-space testing capability that includes a persistent test platform and a surrounding in-space test zone is needed to mature technologies through experimentation. The testbed can provide common services, such as: power, thermal control, vibration isolation, data transmission between experiments and terrestrial experimenters, station-keeping, pointing, and robotic agents that can be leveraged by customer experiments. The onboard robotic agents can be used to provide payload handling services, such as: assembly, change out or upgrade, relocation, connecting/disconnecting utilities, inspection, repair or servicing, etc. Since the persistent platform cost will be amortized over many hosted payloads, its services can eventually be offered at a price much lower than if one were to design a unique and dedicated spacecraft and mission for those few experiments.

The key to achieving an effective testbed is providing efficient cost effective access and infrastructure to a variety of commercial, academic and government customers coupled with extensibility, in the capability of an individual persistent platform test bed or replication of the test bed in a different operational regime. Three potential options for implementing a test bed were developed and evaluated in this study.

Nomenclature and Acronyms

ACCESS	Assembly Concept for Construction of Erectable Space Structures
ADAM	Able Deployable Articulated Mast
ASEM	Assembly of Station by EVA Methods
AR&D	Autonomous Rendezvous and Docking
DARPA	Defense Advanced Research Projects Agency
EASE	Experimental Assembly of Structures in EVA
EELV	Evolved Expendable Launch Vehicle
ESn	ESPAStar launch here n = 1, 2, 3…
ESPA	EELV Secondary Payload Adapter
ESPAStar	ESPA with GNC capability, GEO compatible
EVA	Extravehicular Activity
GEO	Geosynchronous Orbit
GNC	Guidance Navigation and Control
HISAT	Hierarchical Indexing for Spliced Alignment of Transcripts
IOC	Initial Operating Capability
IRMA	In-Space Robotic Manufacturing and Assembly
ISA	In-Space Assembly
ISDT	In-Space Developmental Testbed
LEO	Low Earth Orbit
MakerSat	CubeSat additive manufacturing.
MiS	Made-in-Space, Inc.
NASA	National Aeronautics and Space Administration
OSAM	On-orbit Servicing, Assembly, and Manufacturing
OSAM-1	First servicing, assembly, and manufacturing mission, formally Restore-L
OSAM-2	Second servicing, assembly, and manufacturing mission, with Made In Space, Inc. on-orbit manufacture beams to support and deploy solar arrays.
PA	Persistent Asset
PP	Persistent Platform
PPE	Power Propulsion Element
Raven	Relative Navigation test mission.
RRM	Robotic Refueling Mission
RSGS	Robotic Servicing of Geosynchronous Satellites
RSV	Robotic Service Vehicle
SMC	Air Force Space and Missile Systems Center
SPIDER	Space Infrastructure Dexterous Robot
T&E	Testing and Evaluation
TBD	To Be Determined
TRL	Technology Readiness Level
XST	eXperimental Space Testbed
UDA	Universal Device Adapter

I Introduction

Several United States government agencies have identified the need for a capability to perform rapid, low cost test and evaluation (T&E) in the space environment in order to more rapidly insert new technologies into their space missions.[1] One method of achieving this capability in the near term is by embracing the capabilities of Orbital Servicing, Assembly and Manufacturing (OSAM) to develop and provide an unmanned persistent test platform in space. Such a persistent platform has been referred to as the Edwards of Space or eXperimental Space Testbed (XST) and more recently as the In-Space Developmental Testbed (ISDT) by the Air Force Space and Missile Systems Center (SMC).[2] Implementation of the persistent test platform has two major goals. **First, in order to build confidence in the technology and new paradigm, there must be a leading example, a bellwether persistent asset, that demonstrates** OSAM technology benefits including those provided by multiple routine visits to the persistent asset using emerging low cost commercial launch services and space tugs. Second, the persistent asset must provide a location within the relevant space environment where new technologies can be rapidly tested and validated, enabling rapid Technology Readiness Level (TRL) advancement. This would, in turn, allow rapid insertion of these technologies into spaceflight systems. Such a platform, or group of platforms, will mature critical technologies with broad applicability to many different missions and system implementations, as depicted in the middle and right of Fig. 1. These missions range from lunar surface applications to low Earth orbit applications for commercial, government and university experimenters. The majority of the technologies necessary for such a platform have been developed under foundational missions and programs (including on-going efforts) as indicated on the left of the figure, but many technologies have not been automated, nor integrated into a cohesive operational platform with the following attributes:

- Be available to commercial, university and government agencies.
- Be autonomously assembled, expanded, serviced and operated in space.
- Be able to operate in a variety of orbits, trading ease of access versus operations in relevant environments. Note: Low/medium Earth orbit altitudes minimize launch costs and allow a variety of commercial launch providers to bid on launch opportunities, while higher orbits expose systems to harsher radiation environments. The final orbit for first platform(s) has not been chosen.
- Be robust, likely with core functionality for station keeping along with rendezvous and proximity operations that are highly redundant.
- Be instrumented to enable effective model correlation.
- Provide common and comprehensive set of services to payloads and experiments, including:
  - power,
  - data transmission,
  - robotic agents to maneuver, inspect and interact with the payloads,
  - thermal control,
  - space weather monitoring,
  - station keeping and platform pointing.

Key capabilities enabled by an orbital persistent test platform include:

- long term exposure to and evaluation of experiments in the space environment,
- on-demand inspection of the experiment using resident robotics in a pay-as-you-need model,
- experimenters focus development on the experiment, not a host spacecraft, simplifying experiment design,
- rapid technology iteration because of the ability to frequently visit the platform,
- a variety of experiments ranging from hosted experiments on the platform to non-resident and swarm experiments in the vicinity of the platform,
- potential to return experiments for detailed inspection and evaluation.

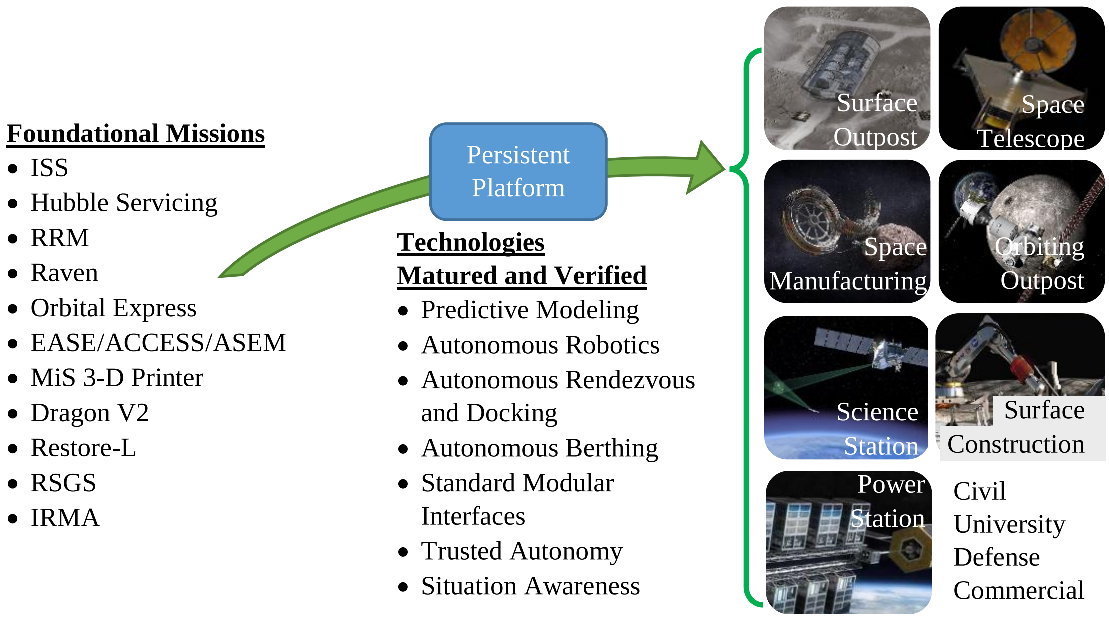


Figure 1. Leveraging past investments, broad applicability of technologies matured on a persistent test platform to future mission needs.

The persistent test platform also has the potential to drastically reduce costs to experimenters. Unfortunately, this benefit has been difficult to quantify because existing cost models are largely based on mass and are not able to capture and quantify the benefits incurred by adopting the OSAM paradigm. Potential cost benefits that may be realized by a persistent platform that adopts the OSAM paradigm would include:

- ability to use routine rideshare (i.e. low cost transportation) opportunities for transporting payloads/experiments to and from the platform,
- the payload uses standard interfaces for integration and test with the spacecraft bus,
- the ability to exploit low cost commercial launch to transfer the experiment, with the entire launch vehicle payload dedicated to the experiment, not associated support systems provided by the platform,
- common ground test environments and open simulations to verify experiments before they are launched,
- common "designs of reference" and modular components/systems which have been flown previously and validated and can be exploited for future experiments,
- common services, including power, thermal control, communications, etc. are provided in a pay-as-you-need model, reducing the burden on experiments.

Alternative to the benefits discussed, there are also potential compromises for payloads/experiments that are located on a persistent platform such as:

- operational orbits that may not be optimal for a given experiment,
- disturbances from other experiments and robotic operations might be detrimental, however this might be mitigated with:
  - novel solutions are available including the ability to have robotically tended formation flying experiments enabling complete isolation from the platform or "coasting" in a defined capture box/net near the platform,
  - platform operations tailored to accommodate sensitive experiments,
  - a custom isolation interface leveraging the measured and well known operational environment,
- failures on the platform may affect multiple experiments: this could be mitigated by ensuring critical capabilities, such as station keeping, communication, power generation, will be redundant and thus likely far more robust than on a standalone spacecraft.

Three different test bed implementation options are described in this report. These options exploit newly available in-space assembly technologies including: autonomous robotic operations, component assembly (including fastening technology), and assembly of modular elements that have been built on the Earth. Modular interfaces and connectors are an example of a technology that could immediately benefit from test and evaluation on the test bed where a variety of competing interfaces could be implemented and assessed. This rapid evaluation capability would be enabled using task boards that can rapidly be exchanged to evaluate new options or improve maturity of existing approaches. Government agencies have been investing in a variety of modular interfaces, such as DARPA's SATLETS or NovaWurk's HiSATs.[3, 4] In addition, the US government has funded an activity to create a universal device adaptor (UDA) that is also compatible with the HiSATs and would be made available for use. Over 30 companies contributed to the UDA Interface Control Document and user guide during interactions with the DARPA F6 and Phoenix programs.[5] All of these modular interface options can be tested and evaluated "apples-to-apples" in a relevant environment on the platform. The task boards provide a versatile and cost effective means to develop, test and rapidly evolve modular interface standards which could then form the basis of a modular persistent asset.

The three implementation options selected for the test bed were chosen to span a wide range of possible architectures. The three options are:

1. Servicer based persistent platform as depicted in Fig. 2, detailed in section III.A on page 8.
2. Bus based platform as depicted in Fig. 3, detailed in section III.B on page 12.
3. Small satellite based platform as depicted in Fig. 4, detailed in section III.C on page 15.

This paper begins by describing and summarizing the set of customer requirements that were solicited and received for the testbed. It will then summarize a set of representative payloads (solicited from the SMC and the NASA Earth Science Office and detailed in Appendices B and C) and the consolidated set of specifications (total number, average mass, average volume, average power requirements) derived from this set to define an average payload. Then the three platform architectures will be described, beginning with each platform's unique initial operating condition (IOC) state, followed by a description of the particular concept of operations required for each concept to achieve an identical baseline capability. At baseline capability, all three implementations had to host and support 35 of the averaged payloads. Finally, the three architecture implementation options will be compared, contrasted and evaluated to determine the pros and cons of each, including a notional expectation of operational costs.

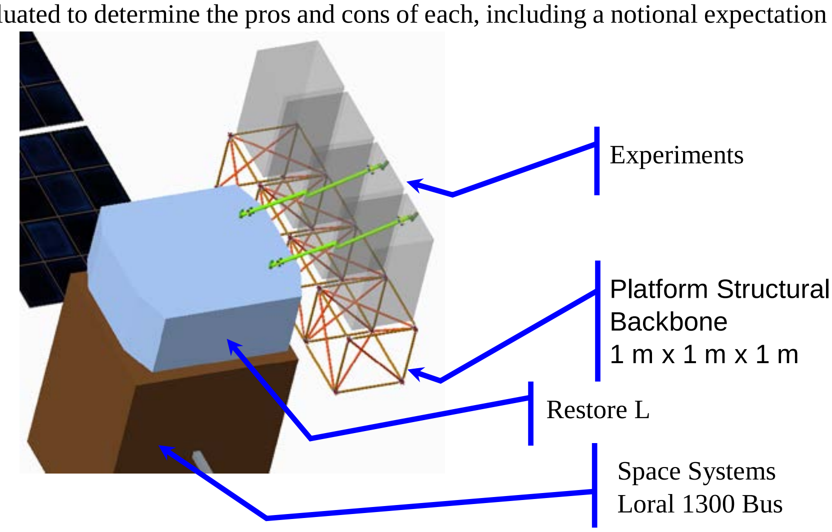


Figure 2. Servicer based test platform.

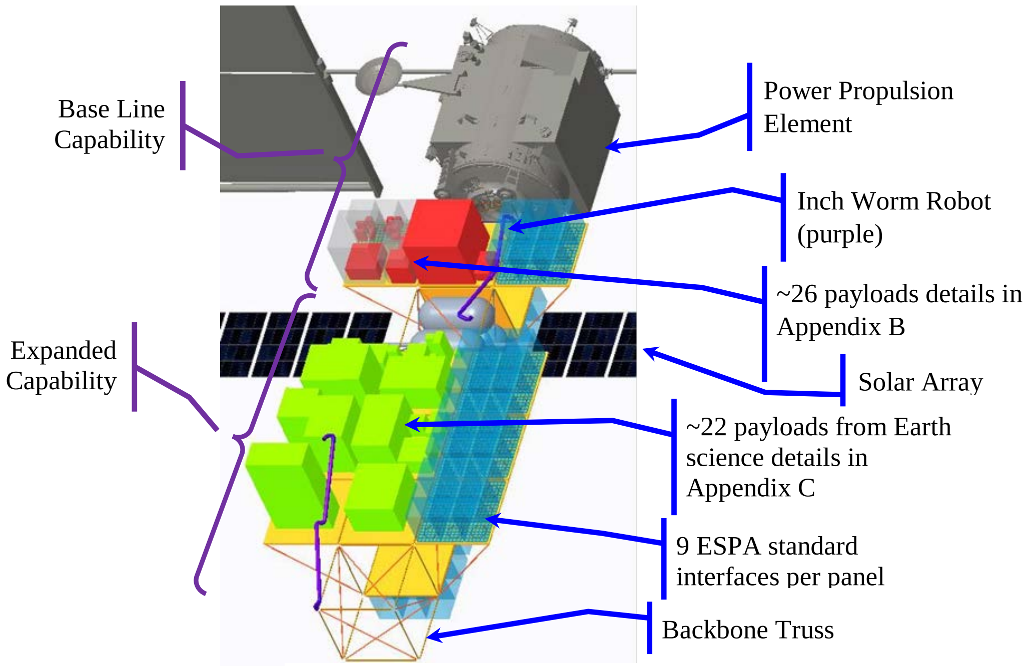


Figure 3. Bus based test platform.

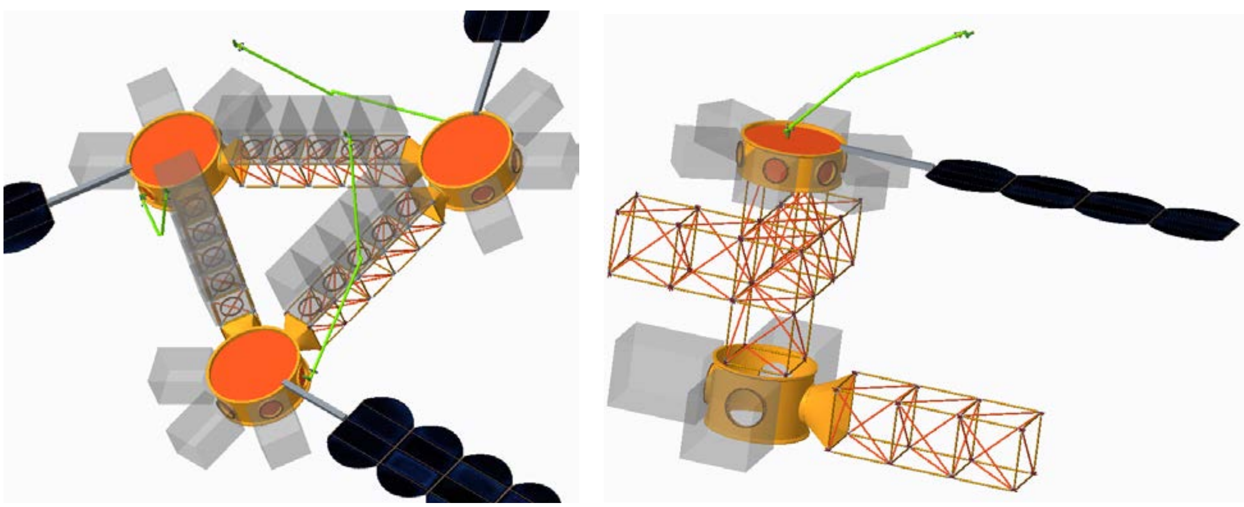


Figure 4. Small satellite based test platform.

II Customer Requirements, Reference Data and Assumptions

The objectives of implementing the persistent platform orbital testbed are to:

1) **Be the first instance of a robotically tended persistent platform to demonstrate the reliability and maturity of the persistent asset paradigm where repeated visits are common, and**
2) **Validate on-orbit servicing, assembly and manufacturing (OSAM) capabilities and technologies while providing rapid TRL advancement of a variety of hosted experiments which are frequently exchanged during repeated visits.**

II. A Customer requirements.

The top-level customer requirements for the persistent platform orbital testbed are:

1. Demonstrate OSAM capabilities,
2. Provide services (structural, power, thermal, data, etc.) to payloads,
3. Provide in-situ robotics capabilities.

The SMC has expressed needs similar to those in the NASA community for a capability to perform rapid, low cost and standardized T&E in the space environment. Attributes for this platform include:

- Be used as a developmental lab bench for in-space testing,
- Be used by civilian and military government agencies and their contractors,
- Be autonomously assembled, serviced and operated in space,
- Exist in a low/medium Earth orbit altitude (final orbit for first platform has not been chosen).

In addition, the Air Force developed a set of preliminary functional and operational requirements for a T&E platform, which are detailed in Appendix A and the OSAM requirements are summarized as:

Design - The XST system shall enable design for serviceability by visiting vehicles.
Orbit - The XST space segment orbit shall be at low Earth orbit (LEO).
Structure Assembly and Integration - The XST system shall be capable of adding and removing components.
Common Interface - The XST system shall be capable of robotically attaching and detaching payload units.
In-Space Assembly - The XST space segment shall be capable of evolving its structure.

II. B Reference data: potential experiments/payloads and their characteristics.

The SMC solicited (across their organization) potential payloads for a test platform, resulting in an extensive list which is summarized in Table 1 (detailed data is included in Appendix B).

Table 1. Summary of Potential SMC Payloads

ID	Category	Number of experiments/payloads
1	Instruments, Sensors, Electronics, Software	22
2	CubeSats	7
3	Modular Connectors	3
4	Spacecraft/Bus Components	4
5	Miscellaneous Modules/Components/Systems or Unknown	5

Information was also compiled for NASA Earth science payloads, in particular instrument sets that might benefit from flying together on a persistent platform instead of individually on a customized spacecraft bus. The list of these instruments as well as data on their mass, volume and power requirements are summarized in the table in Appendix B. This data represents a total of 81 payloads, including those of both the Air Force (46 payloads) and NASA (35 payloads). This data, summarized with the results in Appendix D, was used to inform the following assumptions.

II. C Payload assumptions: based on statistics from appendix D.

In order to be able to develop the platform implementation concepts and to evaluate and compare them on an equal basis, the team developed a set of definitions and assumptions:

- Initial Operational Capability (IOC) is the configuration and capabilities achievable after the first flight and hosting a minimum of 4 standard payloads. The number of hosted payloads is not required to be equal across the different concepts.
- Baseline Capability (BC) is the configuration and capabilities necessary to support 35 standard payloads.
- Standard Payload is referenced to a standard EELV Secondary Payload Adapter (ESPA) based unit which has a rectangular interface (payload to ring) size/dimensions of:
    - Width is 28 inches (0.71 meters)
    - Height is 24 inches (0.61 meters)
    - Based on the mean payload volume of 0.48 cubic meters (Appendix D, Figure 2), the resulting payload height is: 1.11 meters
- Standard Payload Mass = 118 kg (Appendix D, Figure 1)
- Standard Payload Power Requirement = 170 Watts (Appendix D, Figure 4)
- Payload Pointing: based on Appendix D, Figure 5, half (17 or 18) of the payloads must point in the Nadir direction and half (18 or 17) can be located and point in any direction.

Payload Separation: Payloads may need to be separated based on thermal, radio interference and other considerations. Although no requirements exist for a generic/standard payload, this study assumed that the separation distance was included in the 24-inch by 28-inch footprint.

III Architecture Descriptions Including Concept of Operations for Three Different Implementations

III.A **Servicer Based Persistent Platform**

<u>Concept Overview</u>

The Servicer Based Persistent Platform (PP) concept uses a robotic servicing vehicle to perform autonomous rendezvous and capture, robotic manipulation, and hosting an initial set of payloads for a persistent platform that can expand over several missions. Payloads are launched and transported to the platform using rideshare opportunities, such as ESPA rings, or as dedicated payloads on smaller launch vehicles.[6] Using separate launch opportunities, this concept expands and evolves into a self-sustaining persistent platform over multiple missions. This option benefits greatly when it can leverage capabilities (communications, station keeping, etc.) provided by an existing robotic servicing vehicle such as included in the OSAM-1 or Robotic Servicing of Geosynchronous Satellites (RSGS) missions; as well as commercial transport vehicles and space-tugs such as the Momentus' Vigoride or Atomos space tugs.[7, 8, 9]

This implementation option develops a concept of operations based on augmentation to an OSAM-1 like mission. The OSAM-1 primary mission is to refuel and relocate Landsat 7, use Space Infrastructure Dexterous Robot (SPIDER) to assemble a 3-meter-diameter antenna, and manufacture the MakerSat 10-meter-beam.[10] Other robotic servicing vehicles may provide similar capabilities, and other servicing vehicle options should be included in a more detailed future trade. OSAM-1's primary mission demonstrates rendezvous, inspection, autonomous capture, tele-robotic servicing, refueling, relocation, and release of spacecraft in Low Earth Orbit. OSAM-1 is a valuable asset which includes OSAM-1 dual arm robotic capabilities, SPIDER payload's robotic assembly and manufacturing capabilities coupled with the residual fuel remaining at the end of its primary mission create an asset that could be used to initiate a persistent platform concept.[7] Figure 5 provides an overview of the in-space services that OSAM-1 can provide to a persistent platform.

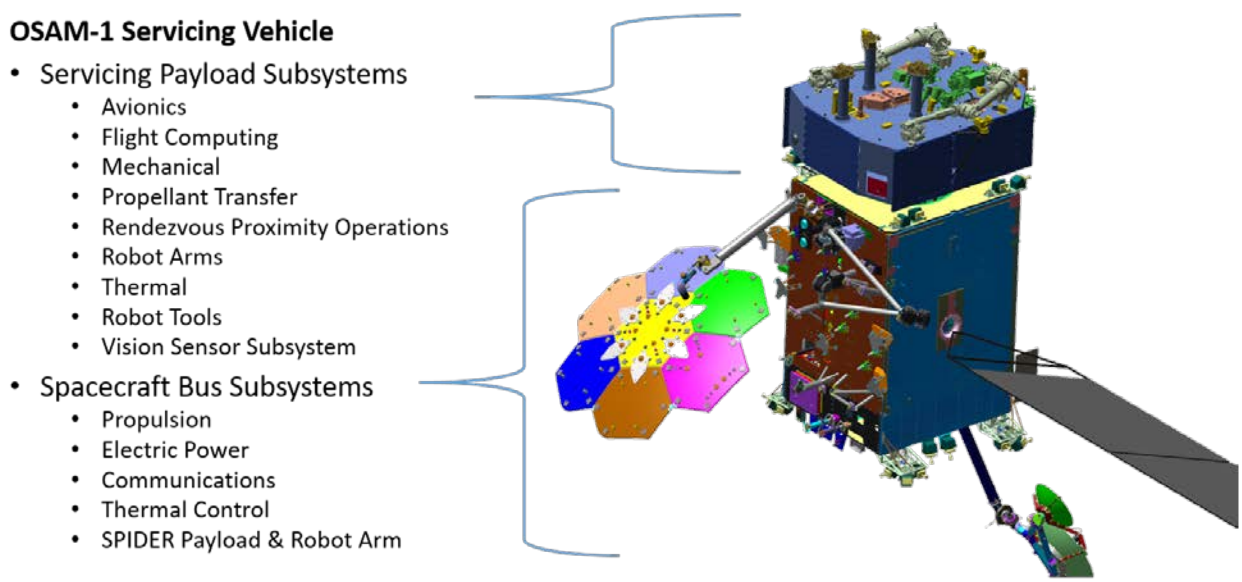


Figure 5: OSAM-1 servicing vehicle has substantial remaining capability after executing its primary mission.

After completing the OSAM-1 primary mission, the OSAM-1 servicing vehicle is available to support a persistent platform. OSAM-1 can be used as a servicing vehicle to provide power, communications, pointing, maneuvering, and robotic assembly services to the evolving platform.

This platform can evolve over time as new payloads arrive by ride share opportunities or direct launch and are added. These additional payloads might include deployable structures to link modules and provide hosting locations for payloads, science instruments, and robotic agents to manage the evolving platform. Figure 6 provides an example of an ESPAStar spacecraft capable of providing six payloads of up to 181 kilograms each, and 950 watts total power available for payloads [11]. Examples of options for direct payload delivery to the platform include Rocket Lab's Electron small launch vehicles [12] (Figure 7), which can launch 150 kilogram payloads to 500 km SSO, and Virgin Orbit's LauncherOne [13] (Figure 8), which can launch 300 kg payloads to 500 km SSO.

Figure 6. ESPAStar platform: example of delivering multiple payloads on rideshare mission.

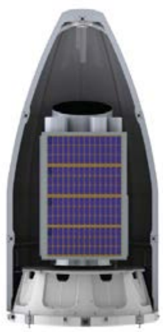


Figure 7: Rocket Lab example of delivering single payload on Electron small launch vehicle.

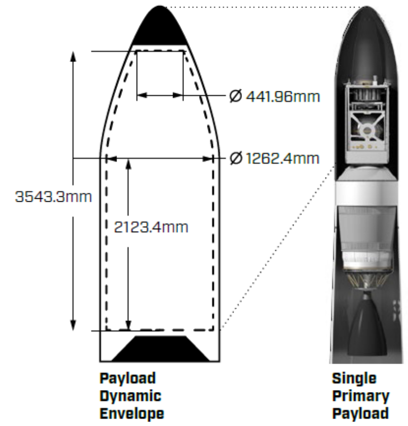


Figure 8: Virgin Orbit example of delivering single payload on LauncherOne small launch vehicle.

Concept of Operations

The Servicer Based PP concept of operations depicted in Figure 9 leverages a proven robotic servicing vehicle and variety of payload delivery capabilities to provide rapid IOC for a persistent platform. The OSAM-1 primary mission will demonstrate the autonomous rendezvous and proximity operations and robotic operations necessary to reduce risk for assembling a persistent platform on orbit. Given that there are commercial spacecraft available, such as those demonstrated on Air Force Long Duration Propulsive ESPA missions, the risk of assuming ride share payload delivery methods in this implementation option is low. ESPA payload delivery is an attractive option for missions to polar Sun-synchronous orbit because ESPA rings are required to be included on future NASA science missions. Leveraging proven capabilities for the servicer and ride share allows the focus to be on demonstrating lower TRL OSAM experiments and payloads on the persistent platform.

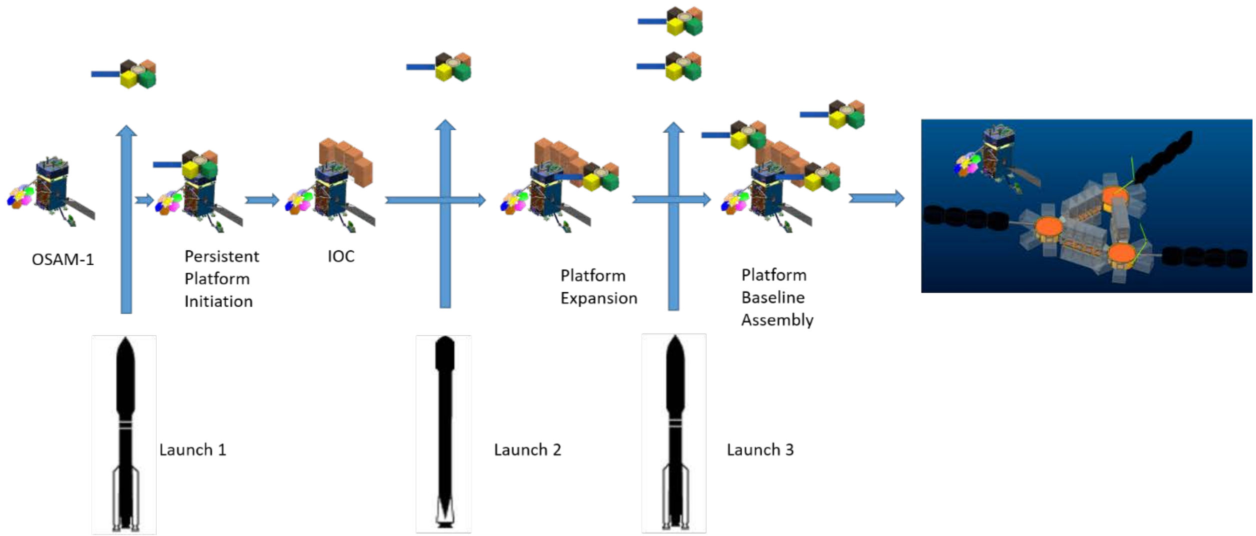


Figure 9: Servicer based platform concept leverages OSAM-1, after it has completed its primary mission, to capture, assemble, and host the persistent platform IOC and support growth to the baseline capability.

Initial Operating Capability

The IOC for this PP implementation incorporates four payloads. IOC is achieved by launching an initial experiment carrier to the vicinity of the servicer, and using the servicer to perform the necessary maneuvers to autonomously grapple, berth, and assemble the platform. One realization of the initial set of payloads consists of a deployable structure and several modules/instruments mounted on a powered ESPA, which has a standardized Marman ring interface. This initial payload does not need to have propulsive capability since the servicer (such as OSAM-1) will perform necessary rendezvous and capture operations, thus allowing more mass and volume for experiments. OSAM-1 is designed to autonomously capture Landsat 7 at its 1194 mm Marman ring launch interface using robotic arms and specialized grapple tools. Once captured, the OSAM-1 seven degree-of-freedom, 2.3 meter long, robotic arms berth and lock the initial ESPA to OSAM-1's three servicing payload client berthing system pedestals in a process similar to Landsat 7 berthing operations.

Once the ESPA spacecraft is berthed to the servicing vehicle, as shown in Figure 10, OSAM-1 assembles the platform and makes connections to the applicable OSAM-1 spacecraft bus functions using its three on-board robotic arms. Initial plans are to assemble and install a deployable truss structure on the expansion port interface of the OSAM-1 servicing payload. Additional OSAM-1 interfaces are available to provide additional payload hosting or power if required. After the deployable truss is connected to OSAM-1, payloads are added to the truss using modular connectors, expected to be similar to the connectors used to host the payloads on the ESPA rideshare. The modular connectors and robotic arm interfaces can also be used to provide power and data connections for the payloads. Figure 11 illustrates the initial operating capability for the persistent platform.

If each of the four payloads is assumed to use full power, resulting in a total usage of 680 watts, the IOC is achievable using OSAM-1 onboard capabilities and the initial powered ESPA. With OSAM-1 supporting the IOC version of the platform, connections can be tested and validated before future segments of the platform are delivered.

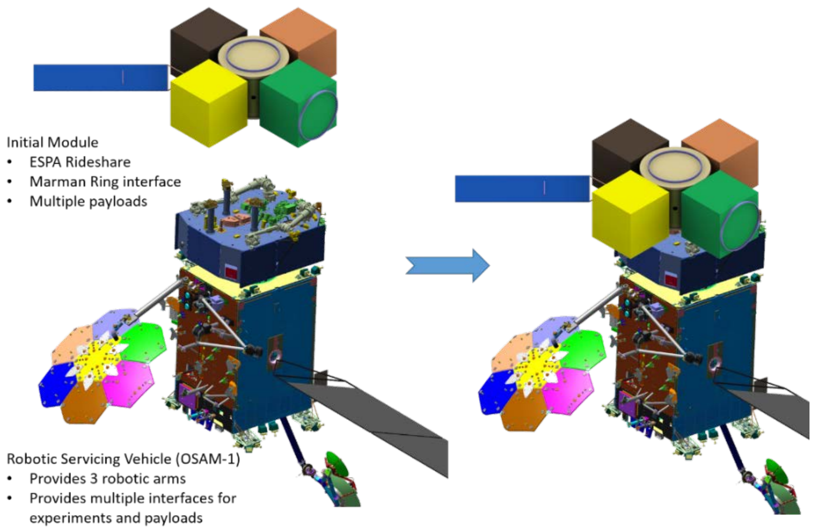


Figure 10: OSAM-1 rendezvous, capture, and berthing with multiple payloads using ESPA with standardized Marman ring and cooperative servicing features.

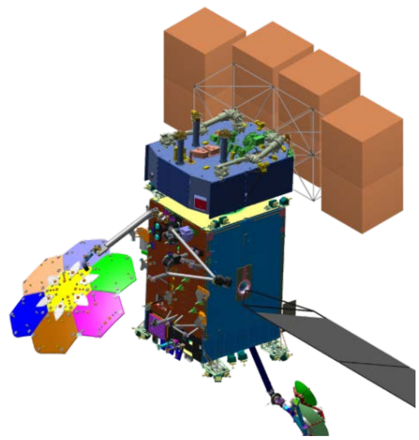


Figure 11: Initial operating capability for servicer based persistent platform consists of OSAM-1 robotic servicing vehicle, deployable truss structure, and four payloads.

Platform Expansion

The Servicer Based Persistent Platform can expand its capabilities by adding payloads that arrive on small launch vehicles, such as Rocket Labs Electron or Virgin Orbit Launcher One, or on rideshare missions. Small launch vehicle delivery benefits include more frequent launch opportunities and lower launch costs, but at reduced mass and volume to the platform orbital location (compared to standard EELVs). Although ride share based missions offer benefits that include larger number of payloads, additional platform structure, and increased platform power, they are constrained by fewer launch opportunities and higher cost. As additional payloads are delivered to the platform, power, mass, and volume capacities are all expected to increase. Figure 12 summarizes the number of powered ESPA's, in addition to the OSAM-1 servicer that are required to support the additional payloads power needs. Another option to consider for increasing the power available to the payloads is to install power modules, such as deployable solar arrays, which can be added using on-orbit assembly.

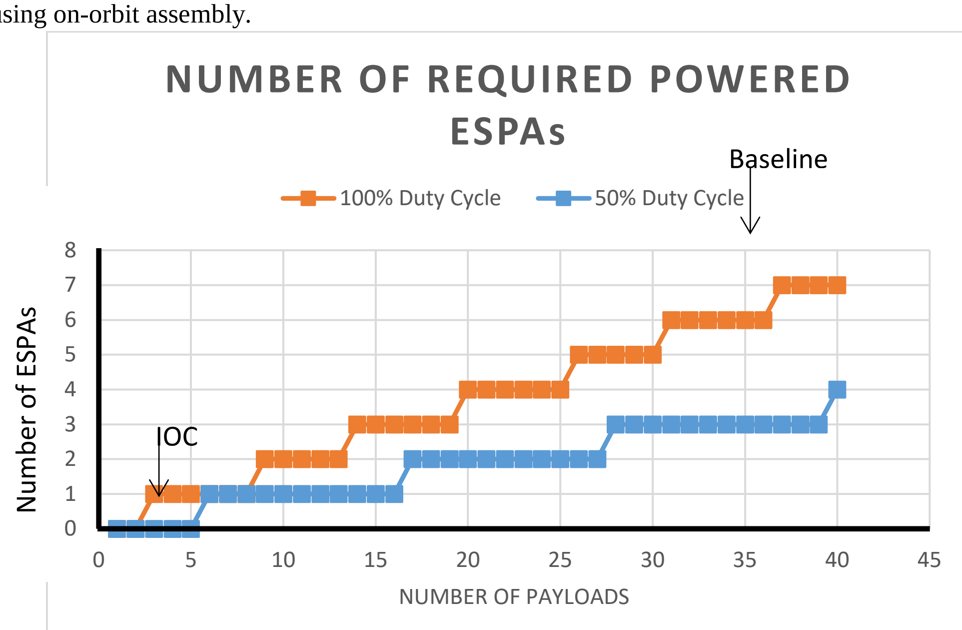


Figure 12: Servicer based persistent platform can use powered ESPA modules to provide the majority of power for the expanding platform.

Both growth of platform power and physical size are required to evolve from the IOC to the baseline persistent platform configurations, with the final baseline persistent platform payload capability being defined to accommodate 35 payloads. In order to support 35 payloads operating at 100 percent duty cycle, the equivalent of seven powered ESPAs need to be delivered to support power requirements. If a 50 percent duty cycle is assumed, three powered ESPAs could support payload power requirements. This does not address additional requirements for surface area, thermal rejection, or satisfying field-of-view needs. Missions have already been flown with single or multiple ESPA spacecraft, so platform expansion could occur quickly or more slowly, to fit within any budget constraints. Figure 9 depicts an expansion scenario that requires multiple launches to reach the baseline persistent platform configuration.

In this concept of operations, the baseline persistent platform becomes independent, replacing OSAM-1 capabilities with ESPA based spacecraft bus functionality. When the persistent platform becomes self-sufficient and no longer relies on OSAM-1, OSAM-1can transition back to a servicing vehicle supporting this platform as well as other missions. Figure 13 is a representation of the baseline platform, with OSAM-1 shown as a servicing vehicle in the upper left. A servicer could be used to assist with capturing and adding payloads to the platform. In order to operate independently of a servicing vehicle, the platform will need berthing or docking capabilities as well as robotics to facilitate payload installation and platform evolution.

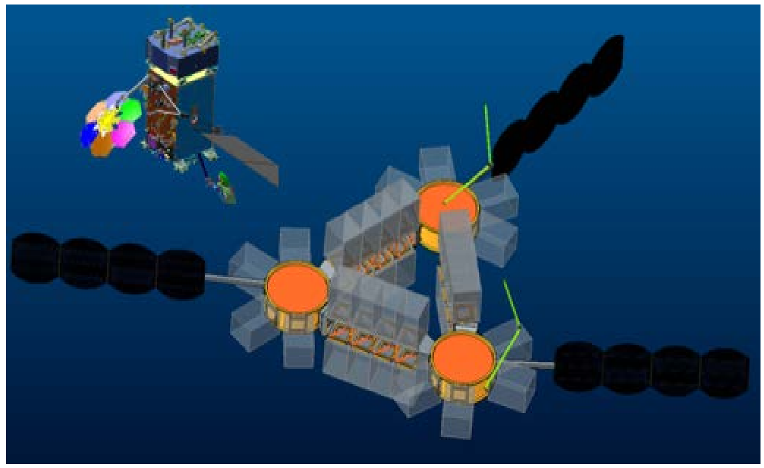


Figure 13: Baseline configuration for servicer based persistent platform consists of OSAM-1 robotic servicing vehicle, a free-flying ESPA spacecraft and structure assembly.

Summary of Servicer Based Persistent Platform

A Servicer Persistent Platform can enable rapid experimentation by civilian and military customers by supporting routine revisit through rideshare missions or small launch vehicle missions. This platform is evolvable and affordable and leverages existing high TRL space assets to provide an initial capability. As the platform evolves and becomes self-sufficient, the robotic servicing vehicle can detach from the platform and provide services to new customers.

III.B Bus based platform description and concept of operation.

In this PP implementation option a generic bus, represented by the Power and Propulsion Element (PPE) of Fig. 3, supports the persistent platform. The bus provides an interface for an integrated cubic truss that serves as the backbone of the persistent platform. The backbone truss structure provides a variety of options to:

a) route utilities (for example, power, data, and thermal energy),
b) provide grapple points for visiting servicers,
c) provide hard points for mobile robotic devices,
d) provide and support expansion interfaces.

Figure 3 that depicts the system in the deployed operational state, illustrates a 2m x 2m x 6 m backbone truss that supports integrated panels which can host a variety of modular interfaces for attaching payloads and experiments. The two-meter square backbone truss was selected because it packages readily into a 5-meter-diameter launch shroud, a standard in the commercial launch industry as depicted by the Falcon 9 vehicle in Figure 14 [14]. The panels are arranged perpendicular to the primary truss axis, with three panels spanning the truss as shown in Figure 3. This arrangement is chosen because the panels can be efficiently packaged and deployed to provide significant Earth or anti-Earth surface area while also directly supporting the payloads during launch, as depicted in Fig. 14. The included robotic systems are immediately available once on orbit allowing a wide variety of advanced payload packaging schemes to be considered. For example, large payloads may be launched while attached along the spacecraft centerline, as depicted in Fig. 14b, and relocated on-orbit to satisfy operational objectives. In this scenario, the entire panel initially located at the top of the launch stack (as shown in Fig. 14a and identified in Fig. 14b) is relocated to the truss face resulting in the layout that achieves the baseline capability depicted in Fig. 3. In Fig. 3, the 26 payloads corresponding to the set provided by SMC, shown in red, are mounted to two of three deployed panels adjacent to the PPE. The boxes shown on the panels represent the bounding volumes that were derived in Appendix B. The Earth science payloads, depicted as green boxes and identified in Appendix C, are also shown mounted to 6 panels that are attached to truss bays just outboard of the solar arrays. The backbone truss incorporates modular connectors (at the truss nodal locations) that provide significant versatility for expanding the persistent platform and can be configured to support expansion in any direction. The resident robotic capability is depicted by the purple robotic arm in Fig. 3. Included on the platform is ample room for robotic tool storage, either within a truss bay or along one of the truss sides. In this implementation, the robotic arm is assumed to be capable of inch worm mobility so that it may assemble, exchange, service and inspect all payloads.

The IOC and base-line capability are expected to be the same for the bus-based platform. The backbone truss modularity ensures straight forward platform expansion beyond the baseline capability. As indicated in Fig. 3, the expanded capability can support the full suite of Earth science payloads while also adding a solar array module to provide power for the new payloads if additional power (though likely not required if the PPE is used to host the mission) is required beyond that provided by the baseline configuration. Given the appropriate launch vehicle, it would be possible to include the expanded capability module on the same launch as with the baseline capability module. This may be desirable to allow the two systems to be separated and reconnected on-orbit to exercise and verify the truss-to-truss interface using the onboard robotic capability. As an alternative, the expanded capability could be launched independently of the baseline capability and assembled on orbit as depicted in Fig. 15. In the Fig. 15 scenario, a space tug is used to bring the new module (on the left of the figure) within the reach envelope of the robotic arm on the baseline bus-based platform (depicted on the right of the figure). The platform robotic arm carefully guides and berths the arriving module to complete the assembly.

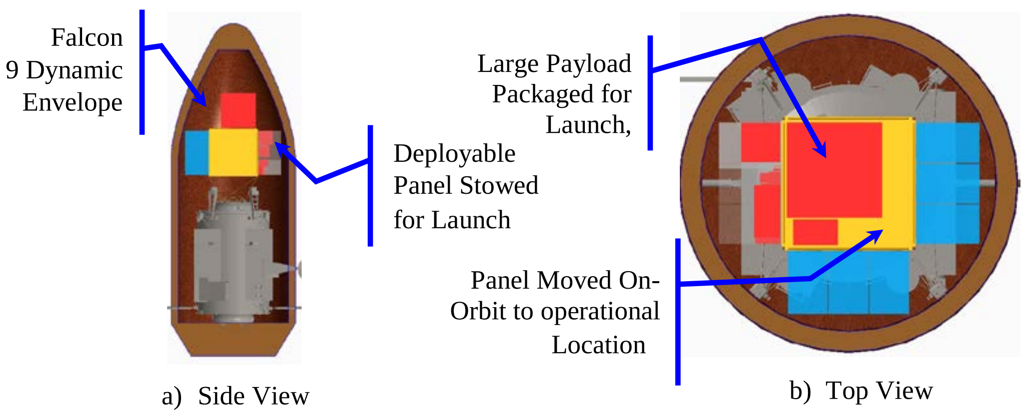


Figure 14. Initial operating condition for bus based options package in a Falcon 9.

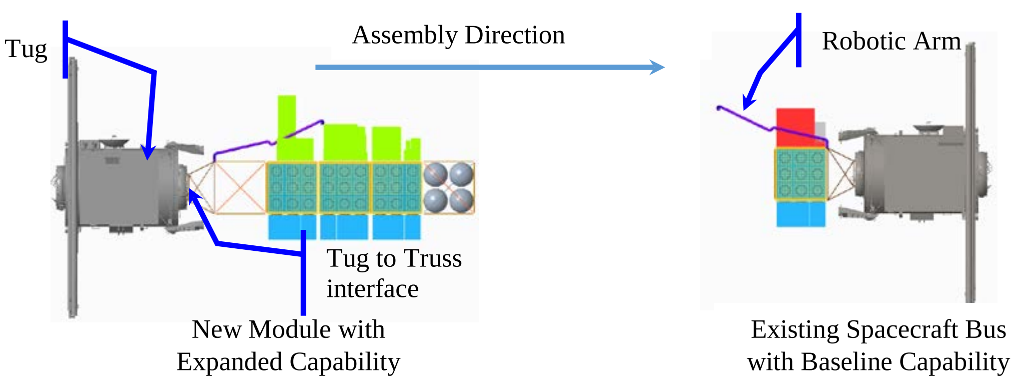
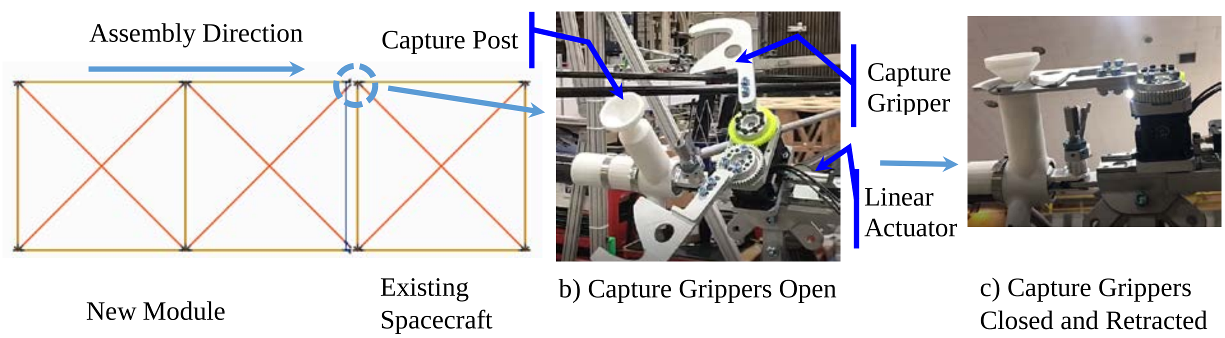


Figure 15. Modular expansion of the bus based platform via berthing.

Once assembled, the resulting system represents the configuration shown in Fig. 3. Although the assembly scenario shown here has been performed axially along the truss, a significant advantage of having the truss backbone in the bus based solution is that expansion can proceed from any of the 4 exposed faces of the individual cubic elements, as well as from the end of the truss (as illustrated in Fig. 15).

Launching the modules that provide expanded capability at the same time as the modules that provide baseline capability enables rapid low risk evaluation of the capture and assembly interfaces. Multiple tool options may be evaluated and their performance evaluated by interchanging the tools and repeating the assembly operations. A laboratory prototype interface capture tool is depicted in Fig. 16 where it is located at one of the truss corners. For assembly, three of these tools would be affixed to three of the cubic truss's four corners and the two truss modules assembled as shown in Figure 16a. Figure 16b shows a prototype tool, one tool of the three tools on three truss corners which are used during module assembly. In Figure 16b the capture grippers are opened and in the extended position, providing a large capture envelope. When the capture grippers initially close, the truss modules are still sufficiently separated to prevent collision. Once the capture post is captured by the three capture grippers, linear actuators on each tool retract to pull the two modules together into precise alignment allowing the joint to be locked, Fig. 16c. A key feature and benefit of this approach is that the capture system (i.e. three tools) is removable and can then be reused by attaching the system to the end of the backbone truss in preparation for assembly of additional modules. This approach improves the reliability of the system and a single backup module can be stored to provide redundancy for the three capture system. In addition, the majority of the parasitic mass needed for assembly is removed from the interface between modules and reused resulting in a more efficient and robust overall operational system. The system is more robust, because tools can be verified prior to their use and easily replaced if necessary. Finally, multiple tool sets may be evaluated (as discussed above) and in an operational system the capture tool set may be upgraded independently of the assembly system to provide a larger capture envelope or more force authority if requirements change over time.

Figures 17 and 18 show two options for the payload/experiment-support panel design. Two panels are needed to provide enough surface area to support the list of 26 payloads identified in Appendix B (shown in red near the PPE in Fig. 3). An additional seven panels are needed to support the 22 Earth science payloads, identified in Appendix C, and shown in green in Fig. 3. A key benefit of the bus-based solution is the versatility enabled by having exchangeable panels which allows different interface solutions to be easily evaluated. Conceptually, each panel can provide a different type of modular payload interface or a single panel could have several different interface concepts which are located in different test areas. The panels themselves are also designed to be modular and can be exchanged on-orbit to test different interface options and allow future expansion to evaluate and support emerging capabilities. In one option, depicted in Fig. 17, the panel interfaces support standard 15-inch ESPA ports as well as 18-inch ESPA grande ports. In another option, the panel layout could support 36 cubesat standard unit groups as illustrated in Fig. 18. Using payload/instrument panels attached to the truss bays provides a high degree of versatility for payload mounting options.



a) Truss Modules b) Capture Grippers Open c) Capture Grippers Closed and Retracted

Figure 16. Truss to truss modular connections.

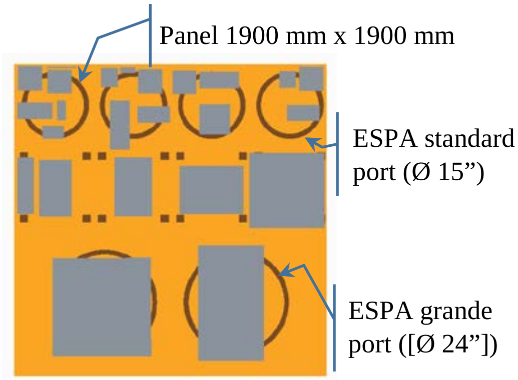


Figure 17. Panel option for bus based solution.

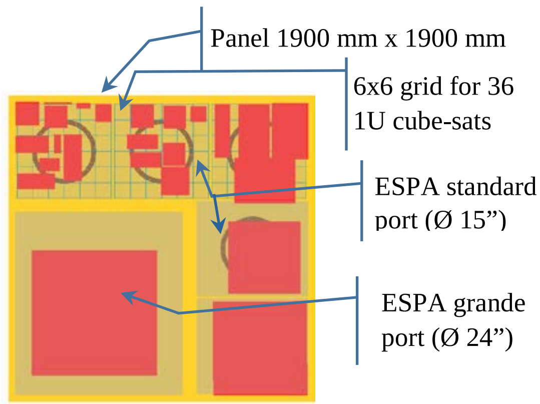


Figure 18. Panel option B for bus based solution.

III.C Small satellite based platform

This platform implementation option is based on using and aggregating (Evolved Expendable Launch Vehicle) EELV Secondary Payload Adapter Star (ESPAStar) units, one of which is shown in Figure 6. ESPAStar is a self-contained spacecraft that can serve as a platform and host up to 6 payloads for a mission lifetime of up to 5 years. Each payload can have a mass of up to 181 kg and the total power available to the payloads is 950 watts.

For this implementation option, the XST platform IOC is achieved using a single ESPAStar (ES1) platform as a ride share on a launch. The IOC XST platform will use an ESPA ring that has six standard 4-Point Mounts, with the mounts having a 15-inch high by 15-inch wide (circumferential direction) footprint on the ring. A standard ESPAStar ring is assumed, which has a height of 24 inches and a ring diameter of 62 inches. At launch, the following are integrated with each of the six ESPA ports (see figure 19):

1. Port 1 – Ring-mounted deployable truss modular interface
2. Port 2 – Standard payload 1
3. Port 3 – Standard payload 2
4. Port 4 – Standard payload 3
5. Port 5 – Standard payload 4
6. Port 6 – Ring-mounted deployable truss modular interface with connected (truss-to-mount modular interface) stowed deployable truss.

The mass of each standard payload (118 kg) is well within each port's payload capacity of 181 kg. This gives a total payload mass (Ports 2 – 5) of 472 kg and allows the mass of the deployable truss and its ring-mounted modular interface on Port 6 and the ring-mounted deployable truss modular interface on Port 1 to have masses up to the maximum of 181 kg. The total power required for the four payloads is 680 watts, which is well within the ESPAStar capacity of 950 watts. A serial robotic arm, with length to-be-determined, is also included in this repeating unit. The length of the robotic arm is governed by the concept of operations. Although a robotic arm that supports inch worm walking does not need to be as long as a fixed arm, enabling a walking robot adds complexity in terms of operations and the need to have appropriate grapple locations to serve as base locations. Since each robotic arm launched on subsequent repeating units does not have to be identical to the initial arm, alternate robotic and manipulation strategies can be evaluated and tested as the platform evolves.

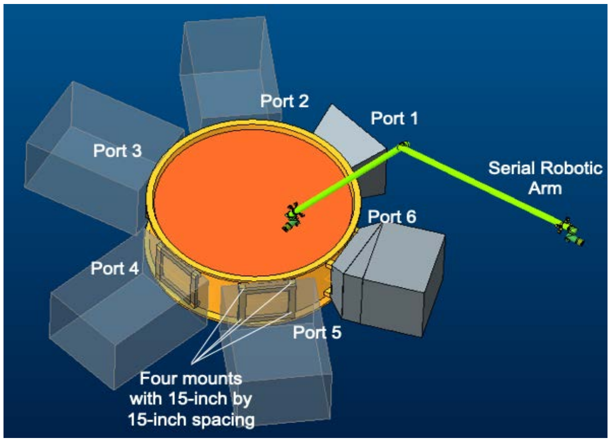


Figure 19. ESPA-based XST IOC platform, also the repeating unit.

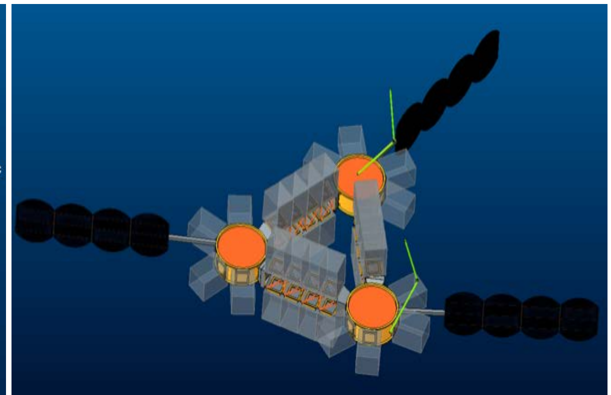
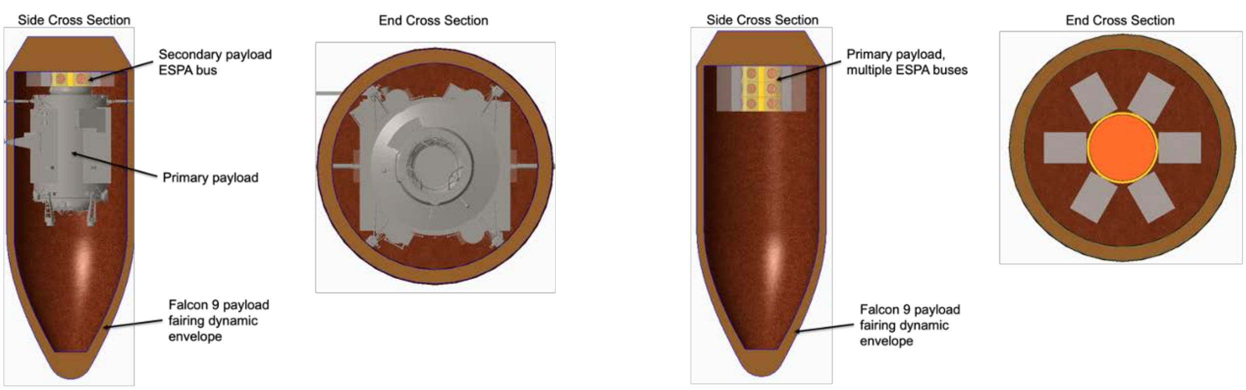


Figure 20. Baseline platform configuration based on ESPAStar repeating units.

Achieving the Baseline Capability requires launching two more duplicates of the IOC platform (ES1) repeating unit (except for the payloads) and 23 additional payloads. The resulting Baseline Platform configuration is shown in Figure 20. While all ports are shown populated, expansion is possible by moving appropriate payloads from the ESPA ring to the truss.

The ESPAStar repeating units package very efficiently into a five meter diameter standard launch vehicle payload shroud, allowing for many implementation options. For example, a single repeating unit could be launched as a ride-share, as shown in Figure 21a, resulting in IOC being achieved. Baseline capability could easily be achieved on a single launch, as either a dedicated launch (as shown in Figure 21b), or as a rideshare, where the excess space and mass is occupied by other payloads.



a. Single repeating unit packaged as a secondary payload. b. Three repeating units packaged as primary payload.

Figure 21. Launch packaging options for ESPAStar repeating units.

The Baseline platform can be aggregated and assembled using a number of different approaches that depend on the number of launches desired and individual payload availability. The general steps needed to achieve the baseline capability are:

1. Launch second ESPAStar (ES2) and maneuver to approach point of IOC platform.
2. ES1 platform deploys its truss using on-board robotic arm, Figure 22.
3. ES2 maneuvers to approach point with its truss-to-mount modular interface aligned with the deployed truss from ES1.

4. ES1 platform robotic arm grapples ES2, and guides ES2 truss-to-mount modular interface into truss-end interface engaging a capture mechanism.
5. ES1 platform robotic arm releases ES2 and engages truss locking mechanism, securing interface.

At this point, the platform would appear as in Figure 24 and two scenarios are possible going forward. If the third ESPAStar (ES3) was launched with ES2, then the next stage of assembly takes place:

1. ES2 uses its onboard robotic arm to deploy its on-board truss.
2. The third ESPAStar (ES3) maneuvers to approach point at free end of deployed truss with its truss-to-mount modular interface aligned with the deployed truss.
3. ES2 robotic arm grapples ES3 and guides ES3 truss-to-mount modular interface into truss-end interface engaging a capture mechanism.
4. ES2 platform robotic arm releases ES3 and engages truss locking mechanism, securing interface resulting in the configuration shown in Figure 24.
5. ES1 robotic arm grapples and deploys the ES3 on-board truss.
6. ES1 robotic arm guides free end of ES3 on-board truss, and guides its truss-end interface into the ES1 truss-to-mount modular interface engaging a capture mechanism.
7. ES1 platform robotic arm releases free end of ES3 on-board truss and engages truss locking mechanism, securing interface, as shown in Figure 25.

At this point, the platform structure is complete, but the testbed has not achieved Baseline Capability because there are only 12 of the 35 payloads on board. Thus, one or more additional cargo/servicing flights would be required to deliver the additional 23 payloads to the platform. The two on-board serial robotic arms could be used to berth visiting cargo/servicing vehicles as well as remove the payloads from the delivery vehicle and install them on the deployable trusses to achieve the Baseline Capability illustrated in Figure 20.

If there is a lapse in time between launching ES2 and ES3, the ES1/2 combination can function as an enhanced platform. Another option before adding ES3 would be to launch and integrate additional payloads which would be installed on the connector truss:

1. Cargo/servicing vehicle is launched with up to eight additional payloads.
2. Cargo/servicing vehicle maneuvers to approach point for the platform.
3. ES2 uses its onboard robotic arm to grapple cargo/servicing vehicle and positions approximately halfway along connecting truss at TBD separation distance and holds in place.
4. ES1 arm unloads each payload and installs onto appropriate truss location.

In order to keep the deployable truss as simple and representative of heritage hardware as possible (which has flown in space such as the truss shown in Figure 26 [15]), it is desirable to include the payload-to-truss modular connector on the payloads. Thus, the concept of operations for installing payloads on the truss may include the need to deploy (if necessary) the payload-to-truss modular connector before the payload installation step, i.e. step 4 described previously.

Growth beyond the Baseline Capability is also possible by adding new repeating ESPA units to the platform: adding two more repeating units gives a double-triangular platform configuration if appropriate Ports (2-5) are replaced with modular truss interface connectors.

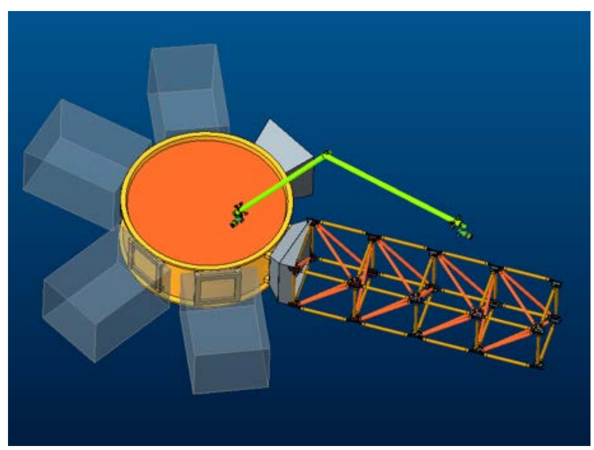


Figure 22. ES1 platform deploys onboard truss using robotic arm.

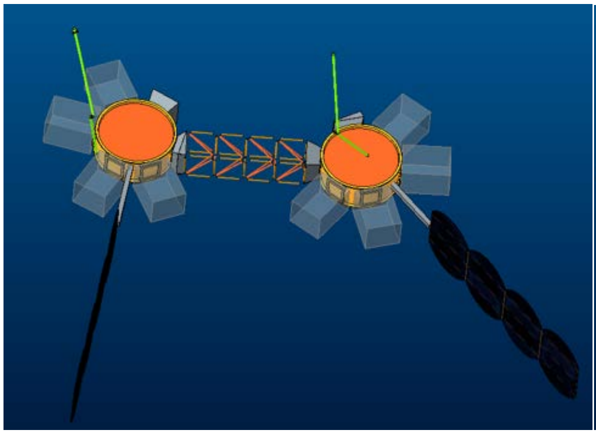


Figure 23. Second ESPAStar repeating unit added to testbed platform.

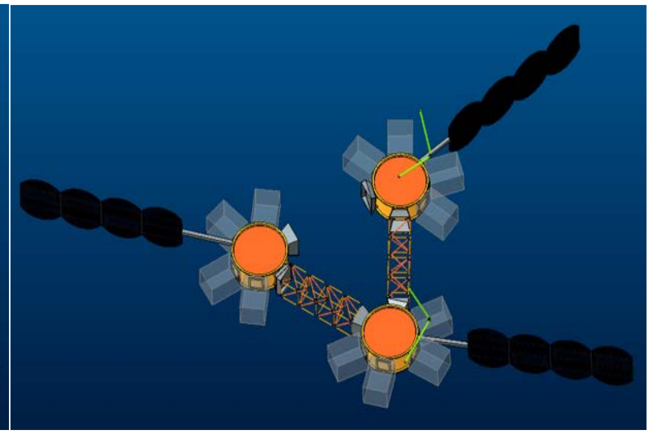


Figure 24. Third ESPAStar repeating unit added to testbed platform.

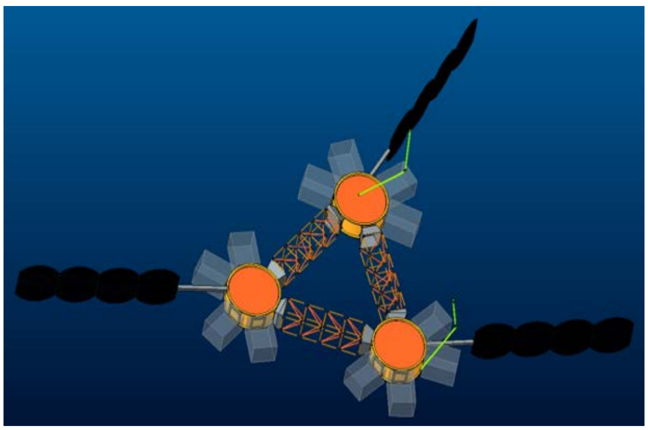


Figure 25. Truss connection completed between first and third ESPAStar repeating units.

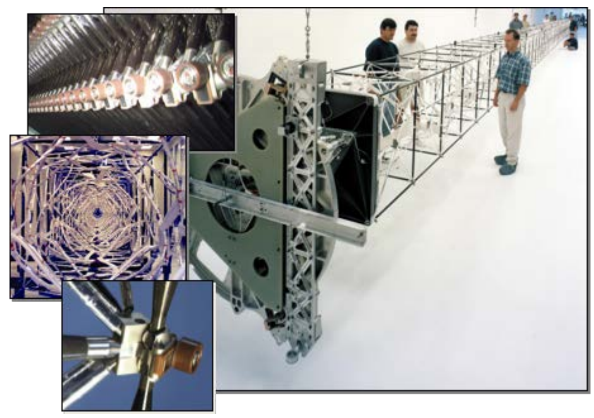


Figure 26. Heritage ADAM – flew on two Space Shuttle flights.

IV. Discussing the Potential Cost of Implementing the Persistent Platform Architectures

All three of the persistent platform implementations described in this paper embrace and benefit from the persistent asset paradigm. Ultimately, potential customers for a platform would benefit from understanding the relative levels of performance, risks and costs for each option before choosing one to implement. However, cost modelling tools that can be applied to missions using persistent assets (assets that benefit from multiple visits and evolve over time, as well as assets that are assembled in space from modules transported on multiple launches) do not exist and this lack of an accurate cost estimating capability is impeding the implementation of OSAM for future missions. This lack of accurate cost modeling tools also precludes a cost comparison being performed and reported in this paper. Rather, this section summarizes suggestions on cost estimation and includes a description of the developments needed for next generation cost models that can capture and quantify the benefits accrued in assets that embrace OSAM.

The recent in-Space Assembled Telescope (iSAT) study was chartered to answer the question: "When is it worth assembling space telescopes in space rather than building them on the Earth and deploying them autonomously from single launch vehicles?"[16] As part of that assessment, the iSAT team attempted to develop cost estimates for implementing a large astronomical observatory that embraced persistent platform and OSAM principles. When attempting to apply legacy models to the in-space assembly (ISA)/OSAM approach, the study found that existing cost models are inadequate for estimating the cost benefits accrued by the new approach. The traditional models are largely mass-based driven, relying on legacy data for missions which are constrained by a single launch vehicle's capacity, thus, do not consider many of the features unique to ISA. For example, from a costing point of view, they do not:

- take into account that, for a given total mass, the total cost to put that mass in orbit can be considerably less using inexpensive multiple launches rather than a single large expensive launch vehicle;

- reflect (in fact they penalize) the benefit that added mass can have in reducing module/system cost and risk;
- reflect the ability to change launch vehicles late in the project, to take advantage of cost reductions or respond to launch system failures;
- account for the fact that assembly inherently makes the system easy to service and repair at no extra cost to the mission;
- account for the fact that as subsystem modules (for power generation, attitude control, etc.) are commoditized, they can be incorporated into new mission designs and the costs to the mission for those capabilities will drop considerably.

From the iSAT study, the key cost benefits enabled by OSAM were (quoted here from reference 16);

- Relaxes mass and volume constraints,
  - Reduces engineering design complexity and time (i.e. cost),
  - Eliminates complex folding/deployable mechanism designs, reduces mass iterations, less need for complex modeling (kinematics for example);
- Allows for more versatile scheduling,
  - More work can be conducted in parallel,
  - Allows systems with schedule slips to be integrated in-situ using a subsequent launch. Naturally parallelizes development as well as assembly integration and test;
- Modules with standardized interfaces help speed up assembly integration and test, especially during anomaly resolution;
- Eliminates costly systems-level testing activities: enabled by greater degrees of designed on-orbit adjustability and correctability to meet system tolerance requirements;
- Reduces need for ruggedizing subsystems/modules and their interfaces to survive launch;
- Mitigates need for new and larger ground test facilities;
- Spread the wealth: can distribute and compete module development work across NASA and industrial base to the most cost-efficient vendors and facilities;
- Share the wealth: well defined interfaces enhances international contributions and partnerships;
- More readily enables project to be responsive to changing funding profiles. Can launch what is ready and expand capability once the persistent asset is on-orbit. (i.e. pay as you go)

A fundamental effort is needed to develop new and improved cost models that begin with a list of Persistent Asset/OSAM beneficial attributes and compiles the potential cost benefits (compared to conventional system implementation options) attributed to each. The method must also include and take advantage of: 1) the long life offered by a persistent asset and the ease at which servicing, upgrading, etc. can be performed; 2) the benefits of upgrading (especially for scientific instruments), compared to buying a completely new spacecraft and mission; 3) the benefits of rapid access to the asset for repair/servicing to reduce risk, and the reduced cost of system design and testing that take advantage of this risk reduction; 4) the reduced cost in transportation services for launch as well as orbital transfer as commercial services are developed and competition reduces their costs.

There are many other attributes that must be included and characterized in the cost model, such as the following:

1) OSAM provides rapid emplacement of capabilities (and associated rapid return on investment, for example rapid science return) followed by planned upgrades and enhancements: A mission system can be designed such that it achieves initial operational capability quickly, potentially with the first launch. Subsequent visits to the asset enhance mission performance using new or advancing technology.
2) Persistent assets benefit from multiple visits: The initial system design assumes there will be multiple visits that will occur; on a defined schedule (for servicing or upgrading operations), or on an unscheduled basis (when critical repair is needed for example). Multiple visits may also be used to assemble the system to achieve its initial operating capability, and provide redundancy of deteriorating components. The multiple visit approach can ensure that one launch failure does not result in mission failure.
3) Persistent assets incorporate modular subsystems and connections: Modules can be developed for structures (backbone trusses for example), power, propulsion, etc. In general, any spacecraft system that will be assembled, serviced, repaired, upgraded or expanded in capability should be modularized. As modules become standardized, they become commodities that can be used in subsequent missions and the costs associated with module design, development and manufacturing will reduce drastically.

4) Modules are fully integrated and tested on the ground before launch: A risk is that for some persistent assets, the full system cannot be tested as an integrated system before launch. The system could be: 1) too large, 2) planned for periodic updates, or 3) be designed solely for its operational (zero-g) environment and thus unable to be tested in 1-g. To mitigate this risk, individual modules designed to be assembled in space using modular interfaces can be tested and integrated on the ground before launch and the entire PA validated through analysis. However, confidence in such an approach must be matured through correlation with flight data.
5) Modules have the ability to be assembled, serviced, repaired, and exchanged; features that are inherent in the system design. The term "in-space assembly" has been used extensively as a paradigm for increasing the performance and lifetime of space systems. The term Persistent Asset (PA) recognizes that there can be missions that do not require in-space assembly, but will still be modular and benefit from the PA paradigm. Assets can be put in service using a single launch, but be designed to be serviced, upgraded and evolve to achieve their persistence.
6) Modular components are launch-vehicle agnostic allowing launch competition. Avoids need for large capacity vehicles to launch fully integrated large PA. For example, there are a large number of launch vehicles that have 5-meter diameter fairings and a payload mass in the 10-metric-ton class, such as the Falcon 9, Atlas 5, Antares, and New Glenn. Thus, modular components can take advantage of lowest launch cost or ride sharing opportunities. This capability has the potential to drastically reduce the costs associated with any mission designed under the PA paradigm and provide alternatives if a particular launch vehicle is retired or ceases operations (the Space Shuttle and Hubble Space Telescope Servicing being a prime example of a detrimental linkage).
7) Orbital operations emphasize cost effective supervised robotics, as opposed to crew interactions: Space robotic capabilities are advancing under a variety of programs for both LEO [17], and Geosynchronous Orbit (GEO) [18], whereas crewed operations remain limited to LEO and the International Space Station (ISS). Multiple commercial vendors are investing in robotic capabilities and associated support systems, such as space tugs.
8) OSAM will make use of a standard toolbox of technologies, capabilities and infrastructure: As more systems are designed for and implement the Persistent Asset paradigm, there will naturally evolve standards for modules and connectors, standards for operations, and a standard set of robotic capabilities, etc. Ultimately permanent infrastructure will evolve (space dock, space tug, servicing vehicles, etc.) to support mission operations creating an evolving toolbox of capabilities that mission planners are able to leverage to reduce the cost, risk and schedule for missions.

V Comparison of Architectures

Appendix E contains a table describing the qualitative comparison between the three persistent platform architecture concepts. Characteristics identified as differentiators are highlighted by a green background in Appendix E and discussed in the following paragraphs. A critical assumption in the responses tabulated in Appendix E is that the servicer is assumed to exist, be in the correct orbit, and have existing robotic capability. Several servicing vehicles are under development, both directly funded by the government and in the commercial section. The servicer based concept can leverage anyone of these systems.

Time to initial deployment (item 6). The servicer based solution led this characteristic because of the assumption that the servicer is available and in the correct orbit, followed by the small sat solution ahead of the bus based solution. The consensus was that a bus based solution likely would need a larger, potentially dedicated launch and require longer to fully assemble. It is important to note, however, that the bus based solution when launched achieves the baseline configuration, without additional launches. The consensus was that the small sat-based solution could be deployed more rapidly than the bus based solution, because the small sat-based solution exploits existing hardware which can be configured quickly and then launched via a ride share opportunity or an appropriate direct launch. Further, the robotic system for the small sat-based solution was viewed as smaller, with need for fewer hard-points and thus less associated development and integration time than the servicer. In the servicer based solution, robotic mobility is provided by servicer, potentially at the expense of propellant. Exploring the robotic capability trade space and how it affects the persistent platform is a key factor in a future, more detailed investigation.

Extensibility and expansion potential (item 11). A major feature of the bus based solution is a capable backbone structural truss, specifically designed to support extensive expansion and extension in three dimensions. For this reason, the bus based solution was preferred over the small sat solution. Further the availability of a common interface for deployment panels, enabled significant versatility in the bus based solution. Both the servicer and small sat-based solutions adopted the ability to use interface panels to improve versatility between the backbone system and the payloads. Panels can be preinstalled and provide a direct payload interface, or arrive with the payload and provide a customizable interface to the backbone structures. Use of panels to connect payloads and experiments to the structural truss allows several interface concepts to be traded and evaluated without being constrained in the initial design and enables future interface development.

Risk: Payload failure leads to platform failure (item 14). It is expected that safeguards will be included within the platform to enable isolation of payloads. However, because the servicer is independent of the platform, platform payloads are inherently isolated from the servicer and failure of a platform payload is less likely to affect the servicer. In the case of the small sat platform, it is acknowledged that because the platform is made of multiple copies of a common module, a design flaw can affect all units.

Terrestrial test environment (item 22). In the case of OSAM-1 (Restore-L) and ESPAStar, significant investment has been made in existing test hardware to immediately allow detailed terrestrial testing. This terrestrial test environment for the extensible bus based solution would have to be created.

VI Technology Development

A key technology driver is the robotic approach for the overall architecture of the platform. The team viewed a walking robot as a key technology, but the length of the robot and the robot's ability to access all locations affects the number of hard-points (stepping locations) and associated harnessing complexity which are key cost drivers to creation of the platform. Such a detailed study was beyond the scope of the current activity. A walking robot needs to be traded against a servicing robotic system. A servicing robot with multiple arms can likely maneuver around the platform, potentially in a "hand over hand" manner, without the need for power to be supplied at the hard-points (grasp locations). Further, the robotic capability can be expanded over time. Servicing robot arms have matured over the last decade, and multiple options exist that could be used to realize any of the persistent platform architectures presented here in the near-term. These include the main OSAM-1 robot arm [19], the robot developed for DARPA's RSGS project and the SPIDER that will be carried as an attached payload on the OSAM-1 spacecraft [20]. Figure 27 depicts an OSAM-1 robot arm packaged on an ESPA Grande as one example of a way to bring additional robotic capability to a platform.

A second technology driver concerns the long term use of small sat systems. Long term use of powered ESPAs in a platform configuration where payloads are interchanged and platform resources are shared among several powered ESPAs is not well understood. The data provided by powered ESPA manufacturers is tailored to a use case where the powered ESPA is serving as a spacecraft bus to payloads permanently attached to the ports.

Since the mass properties (distribution and geometry) of an in-space assembled spacecraft are constantly changing, guidance, navigation, and control (GNC) systems must be constantly reconfigured to remain adequate and be capable of adapting to the growing and evolving spacecraft and structure. An intelligent, autonomous system could be used to allocate the usage and placement of control hardware such as reaction wheels, control moment gyroscopes, or propulsors. Control gains could also be capable of being updated autonomously using real-time system identification techniques to maintain nominal performance in spite of changing mass properties. This technology has already been developed under a NASA aeronautics project [21]. The core concepts and algorithms can readily be adapted for spacecraft control. As the spacecraft is assembled by robotic agents, the motion of the robots will impart torques to the spacecraft. These constitute disturbances that the control system must reject. The spacecraft GNC should be able to coordinate multi-agent systems

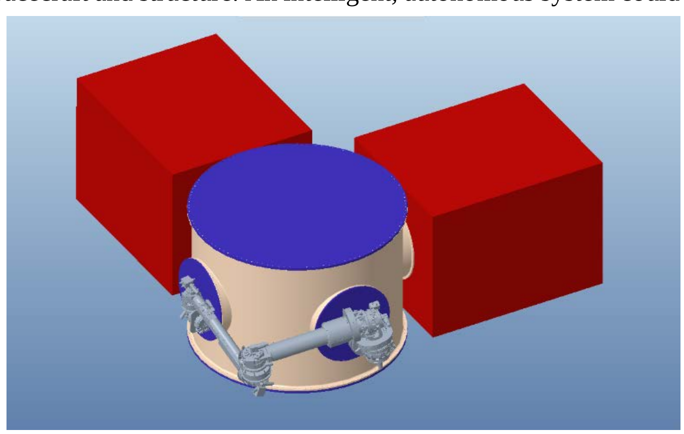


Figure 27: ESPA Grande with OSAM-1 robot arm. Feasibility for expansion capability requires additional evaluation in robot arm trade space.

for tasks such as formation flying of sub-platforms with a main platform. This may be required for vibration isolation of certain payloads.

Common needs of all architectures include:

- Reversible modular connectors (including mechanical, electrical, fluid, etc.) that enable structure expansion, reconfiguration, and interfacing to module transportation systems such as space tugs. In the small sat-based solution, a truss-to-small sat modular interface is required.
- New strategies for deployment that leverage available robotic systems. For example the trusses of the small sat-based approach may be deployed using the robotic agents.
- Supervisory automation technologies that support a well-defined suite of untended operations, with any deviation requiring operator approval. For example, periodic payload inspection may be desirable to support experimental measurements.
- Adaptive guidance, navigation, and control systems that are robust to robotic systems moving around the platform, can adapt to the addition of defined modules, and are capable of integrating new capabilities as they are delivered (additional reaction control wheels for example).

A future, more detailed design study will yield a roadmap for rapid development and near-term deployment of a persistent platform system using mature existing key technologies.

VII Concluding Remarks and Recommendations

The persistent asset paradigm represents a radical, revolutionary shift in our approach to orbital systems through leveraging multiple visits to persistent assets. This shift will enable assets that can be rapidly modified to respond to changes in the operational environment, and are not burdened by the constraints of the launch environment. These persistent space assets will be more timely and cost effective by providing a rapid return on initial investment through a modest initial orbital capability that grows, evolves and leverages existing orbital systems, leveraging multiple Orbital Servicing Assembly and Manufacturing (OSAM) capabilities. This shift has far reaching implications for the design of these systems, their concept of operations, operational support, and asset evolution. **In order to build confidence in the technology and new paradigm, there must be a leading example, a bellwether persistent asset that demonstrates OSAM technology benefits.** The persistent test platform can be this leading example.

This study demonstrated the versatility available via OSAM. Three completely different architectures were evaluated and all found to satisfy the requirements. The study objective was to develop a platform that could serve as an orbital testbed and allow new technologies to rapidly advance from development into operation/service (i.e. advance from Technology Readiness Level (TRL) 6 to TRL 9). The testbed could host payloads and experiments which could be updated and refreshed on a regular schedule. The OSAM paradigm provides many different technologies and options to choose from, there is no single best implementation that is obvious as a result of this study. Rather, the value of applying the OSAM paradigm to a persistent asset lies in the many existing technology, launch, assembly, servicing, etc. options that are available to choose from and can be leveraged to customize each mission. The value of this study was to illustrate three very distinct architectures for implementing different OSAM options and capabilities that all resulted in platforms meeting the payload and operational requirements. All of these architectures could be deployed within a few years using existing technologies.

A framework for comparing options has been developed and discussed. This framework can be used as a basis for more detailed design trades of specific implementation options. The framework identifies many critical requirement categories which can form the basis of metrics for quantitative comparison of different implementations.

Now is the time to act, i.e. to commit to an orbital testbed. Through presidential directive there has been a renewed focus on OSAM activities, including a multi-agency working group. There are many customers from science, military, and commercial domains who all recognize the benefit of a paradigm shift to persistent assets leveraging OSAM technologies. In addition the availability of several low cost commercial launch systems makes quickly revisiting assets not only possible, but also more cost effective than it has ever been.

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Appendix A. Excerpt of Air Force XST Mission/Architecture - Level Requirements.

The Air Force developed a set of preliminary functional and operational requirements for a T&E platform described in this appendix. This includes a description of design objectives followed by a more detailed requirements.

Design - The XST system shall enable design for serviceability.

Common Interface - The XST system shall be capable of robotically attaching and detaching XST bus and XST payload units and assemblies, docking stations, and user payloads to and from XST common interfaces over TBD cycles. The XST space segment common interface shall accommodate robotic arms, docking stations, user payloads, XST bus units and assemblies, and XST payload units and assemblies, in accordance with TBD standard defining mechanical, electrical, thermal, and fluid connections. The XST system shall have the ability to safely mate and demate electrical connections. The XST system shall have means of verifying the continuity of interface connections/ disconnections.
Note 1: The definition of "safely" is causing no damage to the XST system or degradation of XST system capabilities.
Note 2: The electrical connections include but are not limited to data connections, power connections, grounding connections, fiber optical connections, etc.

Orbit - The XST space segment orbit shall be at Low Earth Orbit (LEO) at To Be Determined (TBD) miles ± TBD miles from the surface of the Earth.
Note: The altitude is TBD but it will be at LEO (Alt. 300 – 1000 km) in general; and if at LEO Sun-synchronous orbit (SSO) (Alt. < 2000 km) (~700 – 1000 km) in particular.
(TBD's to be developed in more detailed follow-on study)

Structure Assembly and Integration - The XST system shall be capable of adding and removing XST bus, XST payload, and user payload units and assemblies on the XST structure while in the XST space segment orbit.
Note: Units and assemblies will need to be replaced due to failure, performance degradation, near end-of-life, the need to upgrade to a new version, etc.
The XST system shall be capable of replacing XST bus, XST payload, and user payload units and assemblies on the XST structure while in the XST space segment orbit.
Note: Units and assemblies will need to be replaced due to failure, performance degradation, near end-of-life, the need to upgrade to a new version, etc.
The XST space segment structure shall be robotically assembled and incorporate modular joining.
The XST system shall have the ability to safely assemble and disassemble structural connections.
Note: The definition of "safely" is causing no damage to the XST system or degradation of XST system capabilities.

In-Space Assembly - The XST space segment shall be capable of changing its structural shape and size by employing ISA techniques and procedures in accordance with the XST ISA/manufacturing procedure.

<u>*On-Board Robotics*</u> - The XST space segment robotic arm shall have long-reach manipulation of (TBD) meters, with full-operations and services provided to all areas of the XST structure.
Note: robotic arm refers to both stationary robotic arm and mobile robotic arm types.
The XST space segment robotic arm shall be able to transfer, grasp, and manipulate objects without damage or degradation to the XST space segment, or to other objects that it transfers, grasps, or manipulates, including:
1) Grasping and manipulating objects less than or equal to TBD in size,
2) Grasping and manipulating objects less than or equal to TBD in mass,
3) Transferring objects to and from the delivery service, robotic service vehicle (RSV), inspector vehicles, and other user spacecraft.

Delivery Service (Experiments/Payloads) - The XST system shall be capable of receiving delivery of XST and user units and assemblies performed in accordance with the XST delivery service procedure while in the XST space segment orbit.

Note 1: the delivery service will be able to hand over units and assemblies to the RSV, which will in turn deliver to the XST space segment.

Note 2: the delivery service will also be able to dock with the XST space segment, and an XST robotic arm will receive units and assemblies from the delivery service.

Visiting Vehicles Accommodations - The XST space segment shall have soft docking/berthing of modules in accordance with the XST spacecraft docking procedure. The XST space segment shall have standard docking protocols and ports to accommodate visiting vehicles and communication traffic in accordance with the XST spacecraft docking procedure.

Fault Protection /State of Health - The XST system shall monitor spacecraft state of health.

Note: Spacecraft state-of-health analysis typically consists of limit-checking to compare incoming measured values against their predetermined limits. A preferred approach is to apply data mining techniques to uncover hidden trends and patterns as well as interaction among groups of “measure and fail” responses. The XST system shall have fault management software that will identify errors/interconnection failures.

Note: The XST sensors will support detection of failures and/or unacceptable quality of the assembly process after it has been completed. Upon identification of errors/interconnection failures, the XST system shall execute fault protection procedures.

Propulsion Subsystem - The XST space segment shall have a propulsion subsystem that provide adequate propulsion for guidance navigation and control (GNC) in order to maintain the XST space segment orbit.

Identifier	**Level**	**Value Package**	**Section Title**	**Requirement**
AF2.2	L1	VP1	Common Interface	The XST system shall be capable of robotically attaching and detaching XST bus and XST payload units and assemblies, docking stations, and user payloads to and from XST common interface over TBD cycles.
AF27.3	L1	VP1	Design	The XST system shall enable design for serviceability.
AF1	L2	VP1	Orbit	The XST space segment orbit shall be at Low Earth Orbit (LEO) at TBD miles ± TBD miles from the surface of the Earth. Note: The altitude is TBD but it will be at LEO (Alt. 300 – 1000 km) in general; and if at LEO Sun-synchronous orbit (SSO) (Alt. < 2000 km) (~700 – 1000 km) in particular.
AF22	L1	VP1	Sensing, Modeling and Simulation	The XST system shall have means of verifying the continuity of interface connections/ disconnections.
AF26	L2	VP2	Adaptive Correction	The XST space segment shall enable tools and approaches to alter a build-up in progress to correct build-up errors.
AF2	L2	VP2	Common Interface	The XST space segment common interface shall accommodate robotic arms, docking stations, user payloads, XST bus units and assemblies, and XST payload units and assemblies, in accordance with TBD standard defining mechanical, electrical, thermal, and fluid connections. Note: This TBD standard is developed by the DARPA CONFERS Program.

Identifier	Level	Value Package	Section Title	Requirement
AF11	L1	VP2	Common Interface	The XST system shall have the ability to safely de-mate electrical connections. Note: The definition of "safely" is causing no damage to the XST system or degradation of XST system capabilities. Note 2: The electrical connections include but are not limited to data connections, power connections, ground connections, fiber optical connections, etc.
AF10.2	L1	VP2	Common Interface	The XST system shall have the ability to safely mate electrical connections. Note 1: The definition of "safely" is causing no damage to the XST system or degradation of XST system capabilities. Note 2: The electrical connections include but are not limited to data connections, power connections, ground connections, fiber optical connections, etc.
AF15	L1	VP2	Fault Protection	State of health: Upon identification of errors/interconnection failures, the XST system shall execute fault protection procedures.
AF14	L1	VP2	Fault Protection / State of Health	The XST system shall have fault management software that will identify errors/ interconnection failures. Note: The XST sensors will support detection of failures and/or unacceptable quality of the assembly process after it has been completed.
	L1	VP2	Fault Protection / State of Health	The XST system shall monitor spacecraft State of Health. Note: spacecraft state-of-health analysis typically consists of limit-checking to compare incoming measured values against their predetermined limits. A preferred approach is to apply data mining techniques to uncover hidden trends and patterns as well as interaction among groups of measure and fail.
AF16	L2	VP2	Propulsion Subsystem	The XST Space Segment shall have a Propulsion Subsystem that provide adequate propulsion for Guidance Navigation and Control (GNC) in order to maintain the XST Space Segment Orbit.
	L1	VP2	Structure Assembly and Integration	The XST system shall be capable of adding XST Bus, XST Payload, and User Payload units and assemblies on the XST structure while in the XST Space Segment Orbit. Note: Units and assemblies will need to be replaced due to failure, performance degradation, near end-of-life, the need to upgrade to a new version, etc.
	L1	VP2	Structure Assembly and Integration	The XST system shall be capable of removing XST bus, XST payload, and user payload units and assemblies on the XST structure while in the XST space segment orbit. Note: Units and assemblies will need to be replaced due to failure, performance degradation, near end-of-life, the need to upgrade to a new version, etc.
	L1	VP2	Structure Assembly and Integration	The XST system shall be capable of replacing XST bus, XST payload, and user payload units and assemblies on the XST structure while in the XST space segment orbit. Note: Units and assemblies will need to be replaced due to failure, performance degradation, near end-of-life, the need to upgrade to a new version, etc.

Identifier	Level	Value Package	Section Title	Requirement
	L2	VP2	Structure Assembly and Integration	The XST space segment structure shall robotically assembly with joining.
AF10.1	L1	VP2	Structure Assembly and Integration	The XST system shall have the ability to safely assemble structural connections. Note: The definition of "safely" is causing no damage to the XST system or degradation of XST system capabilities.
AF11.1	L1	VP2	Structure Assembly and Integration	The XST system shall have the ability to safely disassemble structural connections. Note: The definition of "safely" is causing no damage to the XST system or degradation of XST system capabilities.
	L1	VP3	Delivery Service	The XST system shall be capable of receiving delivery of XST and user units and assemblies while in the XST space segment orbit performed in accordance with the XST delivery service procedure. Note 1: the delivery service will be able to hand over units and assemblies to the RSV, which will in turn deliver to the XST space segment. Note 2: the delivery service will also be able to dock with the XST space segment, and an XST robotic arm will receive units and assemblies from the delivery service.
	L2	VP4	Isa	The XST space segment shall be capable of changing its structural shape by employing ISA techniques and procedures in accordance with the XST ISA/manufacturing procedure.
	L2	VP4	Isa	The XST space segment shall be capable of changing its structural size by employing ISA techniques and procedures in accordance with the XST ISA/manufacturing procedure.
AF3.2	L2	VP4	Robotic Arm	The XST space segment robotic arm shall have long-reach manipulation of TBD meters, with full-operations and services provided to all areas of the XST structure. Note: robotic arm refers to both stationary robotic arm and articulating robotic arm types.
AF3.4	L2	VP4	Robotic Arm	The XST space segment robotic arm shall perform transferring, grasping, and manipulating objects without damage or degradation to the XST space segment, or to other objects that it transfers, grasps, or manipulates, including: 1) Grasping & manipulating objects less than or equal to TBD in size, 2) Grasping & manipulating objects less than or equal to TBD in mass, 3) Transferring objects to and from the delivery service, RSV, inspector vehicles, and other user spacecraft. Note: robotic arm refers to both stationary robotic arm and articulating robotic arm types.
AF30	L2	VP5	Docking	The XST space segment shall have soft docking/berthing of modules in accordance with the XST spacecraft docking procedure.
AF23	L2	VP5	Docking	The XST space segment shall have standard docking protocols and ports to accommodate visiting vehicles and communication traffic in accordance with the XST spacecraft docking procedure.

Appendix B. SMC payload list

Several members of the team reviewed a very detailed and extensive payloads/experiments table (maintained by SMC) and developed a summary of those payloads which were organized into the following categories:

1. Instruments, Sensors, Electronics, Software

Number of Payloads in this category and Payload Names

- Star Tracker
- 3 Types of Zero Volt Batteries
- Earth Science Instruments
- Mapping and Ocean Color Imager (MOCI): Control System Electronic Box
- CASPR: Sensor/Electronics Box
- SPADES: Sensor/Electronics Box
- COPS-D: Sensors/Instrument
- Agile Space Radio: No information, is it a physical object or just software
- ASHI (22): Instrument/Imager
- WSCE-T (25): Hosted payload/instrument
- ELROI (26): Space Beacon
- PIANO (28): Imager/Camera
- FLYSEY2 (33): Sensor/Camera
- LASSO (34): Camera/Sensor (hosted payload)
- SIAMSS (37): Flight Software, what hardware is it being tested on?
- DSXCHADS (38): Flight Software for Cybersecurity
- MBFII for MOSA (40): Flight Software (needs telemetry, data handling, hardware to run on?)
- DRAGSTER (41): Ground Software, drag forecast tool
- OCEANA (42): Software, Processing on ground
- Secure IP Payload Accommodation (43)

2. CubeSats

Number of Payloads in this category and Payload Names

- GLADOS: a Satellite – 6U CubeSat, docking experiment with XST
- RECONSO: 6U CubeSat, Sensor: is this a free-flying spacecraft, is it attached to XST permanently or deploys and returns for rendezvous/berthing/docking?
- M-SAT?? Is this a CubeSat: has dimensions, mass, power requirements but no description.
- MAXWELL (23): 6U CubeSat, communications technology
- TREND (27): Two 1.5U CubeSats – Hosted payload
- SPARC-1 (31): Reconfigurable Radio Frequency/Radio Beacon CubeSat
- ODE (35): 1U(?) CubeSat, deploys and tracks targets

3. Modular Connectors

Number of Payloads in this category and Payload Names

- NovaWurks HiSAT: Delivery System
- FuseBlox/Jumbo
- MagTags

4. Spacecraft/Bus Components

Number of Payloads in this category and Payload Names

- NTS-3 (20): Large Scale Deployable Antenna Experiment
- ROSA (24): Solar Array
- CMGSS (29): Miniature CMG Package (requires 50 – 100 kg class satellite)
- RESIST (32): Resilient Solar Array, drop in replacement

5. Miscellaneous Modules/Components/Systems or Unknown

Number of Payloads in this category and Payload Names

- PRECISE (21): Plasma generator, assess impact on operational systems
- VPM (30): Free flying satellite payload
- SPHINX (36): Everything in spreadsheet TBD, no real data
- Low Cost DeOrbit System (39): no data
- Orbital Transfer Technique (44):

Appendix C. Potential NASA Science Payloads

This appendix catalogs missions. The data was taken from an excel spread sheet provided by Dale Arney, one of the co-authors. For completeness, the columns have been included in this appendix in several groups, repeating the "Instrument Name Short" column for a reference. In the current study, the mass, power and volume columns were used to inform the baseline configuration of the PP.

Instrument Name Short	Instrument Name Full	Instrument Agencies	Instrument Status
A-DCS3	A-DCS3	CNES (NASA)	Operational
AIRS	Atmospheric Infra-red Sounder	NASA	Operational
AMR	Advanced Microwave Radiometer	NASA	Operational
AMSU-A	Advanced Microwave Sounding Unit-A	NASA	Operational
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer	METI (NASA)	Operational
ATMS	Advanced Technology Microwave Sounder	NASA (NOAA)	Operational
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization	NASA	Operational
CATS	Cloud-Aerosol Transport System	NASA	Operational
CERES	Cloud and the Earth's Radiant Energy System	NASA	Operational
CPR (CloudSat)	Cloud Profiling Radar	NASA	Operational
ETM+	Enhanced Thematic Mapper Plus	USGS (NASA)	Operational
FC	Faraday Cup	NASA	Operational
GOX	Global Positioning Satellite Occultation Experiment (GOX)	NASA, NSPO (JPL)	Operational
GPSP	Global Positioning System Payload	NASA	Operational
GPSRO (Oersted)	GPS Radio Occultation System	NASA	Operational
GPSRO (Terra-SAR)	GPS Radio Occultation System	NASA	Operational
GRACE instrument	GRACE instrument	NASA (DLR, GFZ, ESA)	Operational
HiRDLS	High Resolution Dynamics Limb Sounder	NASA (UKSA)	Operational
LRA	Laser Retroreflector Array	NASA (ASI)	Operational
MISR	Multi-angle Imaging SpectroRadiometer	NASA	Operational
MLS (EOS-Aura)	Microwave Limb Sounder (EOS-Aura)	NASA	Operational
MODIS	MODerate-Resolution Imaging Spectroradiometer	NASA	Operational
MOPITT	Measurements Of Pollution In The Troposphere	CSA (NASA)	Operational
OLI	Operational Land Imager	USGS (NASA)	Operational
OMI	Ozone Measuring Instrument	NSO (NASA)	Operational
OMPS-L	Ozone Mapping and Profiler Suite Limb Profiler	NASA (NOAA)	Operational
SeaWinds	SeaWinds	NASA	Operational
SIM	Spectral Irradiance Monitor	NASA	Operational
SOLSTICE	SOLar STellar Irradiance Comparison Experiment	NASA	Operational
TES	Tropospheric Emission Spectrometer	NASA	Operational
TIM	Total Irradiance Monitor	NASA	Operational
TIRS	Thermal Infrared Sensor	USGS (NASA)	Operational
VIIRS	Visible/Infrared Imager Radiometer Suite	NOAA (NASA)	Operational
WFC	Wide Field Camera	NASA	Operational
XPS	XUV Photometer System	NASA	Operational

Instrument Name Short	Measurements and applications
A-DCS3	Location data by Doppler measurements.
AIRS	High spectral resolution measurement of temperature and humidity profiles in the atmosphere. Long-wave Earth surface emissivity. Cloud diagnostics. Trace gas profiles. Surface temperatures.
AMR	Altimeter data to correct for errors caused by water vapour and cloud-cover. Also measures total water vapour and brightness temperature.
AMSU-A	All-weather night-day temperature sounding to an altitude of 45 km.
ASTER	Surface and cloud imaging with high spatial resolution, stereoscopic observation of local topography, cloud heights, volcanic plumes, and generation of local surface digital elevation maps. Surface temperature and emissivity. ASTER SWIR detectors are no longer functioning due to anomalously high SWIR detector temperatures. ASTER SWIR data acquired since April 2008 are not useable, and show saturation of values and severe striping. All attempts to bring the SWIR bands back to life have failed, and no further action is envisioned.
ATMS	Collects microwave radiance data that when combined with the CrIS data will permit calculation of atmospheric temperature and water vapour profiles.
CALIOP	Two-wavelength, polarisation lidar capable of providing aerosol and cloud profiles and properties.
CATS	Cloud and aerosol lidar profiling
CERES	Long term measurement of the Earth's radiation budget and atmospheric radiation from the top of the atmosphere to the surface; provision of an accurate and self-consistent cloud and radiation database.
CPR (CloudSat)	Primary goal to provide data needed to evaluate and improve the way clouds are represented in global climate models. Measures vertical profile of clouds.
ETM+	Measures surface radiance and emittance, land cover state and change (eg vegetation type). Used as multi-purpose imagery for land applications.
FC	The Faraday Cup is a retarding potential particle detector that provides high time resolution solar wind proton bulk properties (wind speed, density and temperature)
GOX	Each instrument equipped with 4 GPS antennas to receive the L1 and L2 radio wave signals transmitted from the 24 US GPS satellites. Based on the signal transmission delay caused by the electric density, temperature, pressure, and water content in the ionosphere and atmosphere, information about ionosphere and atmosphere can be derived.
GPSP	Precision orbit determination.
GPSRO (Oersted)	Measurements of atmospheric temperature, pressure and water vapour content.
GPSRO (Terra-SAR)	Measurements of atmospheric temperature, pressure and water vapour content.
GRACE instrument	Includes BlackJack Global Positioning System (Turbo Rogue Space Receiver) and High Accuracy Inter-satellite Ranging System (aka K-band Ranging System) for Inter-satellite ranging system estimates for global models of the mean and time variable Earth gravity field.
HiRDLS	Measures atmospheric temperature, concentrations of ozone, water vapour, methane, NOx, N2O, CFCs and other minor species, aerosol concentration, location of polar stratospheric clouds and cloud tops. Currently not collecting data on Aqua.
LRA	Baseline tracking data for precision orbit determination and/or geodesy. Also for calibration of radar altimeter bias. Several types used on various missions. (ASI involved in LAGEOS 2 development).
MISR	Measurements of global surface albedo, aerosol and vegetation properties. Also provides multi-angle bidirectional data (1% angle-to-angle accuracy) for cloud cover and reflectances at the surface and aerosol opacities. Global and local modes.
MLS (EOS-Aura)	Measures lower stratospheric temperature and concentration of H2O, O3, ClO, HCl, OH, HNO3, N2O and SO2.

Instrument Name Short	Measurements and applications
MOPITT	Measurements of CO in the troposphere.
OLI	Measures surface radiance, land cover state and change (eg vegetation type). Used as multi-purpose imagery for land applications.
OMI	Mapping of ozone columns, key air quality components (NO2, SO2, BrO, OClO and aerosols), measurements of cloud pressure and coverage, global distribution and trends in UV-B radiation.
OMPS-L	Measures high resolution vertical distribution of ozone and aerosols.
SeaWinds	Measurement of surface wind speed and direction. The SeaWinds antenna on QuikSCAT stopped rotating in November 2009, and the instrument no longer collects ocean wind vector data. However it still provides calibration data for other on-orbit scatterometers, which enables the continuation of a climate-quality wind vector dataset.
SIM	Measures solar spectral irradiance in the 200 - 2000 nm range.
SOLSTICE	Measures solar UV spectral irradiance (115 - 310 nm) with resolution of 0.1 nm and with an absolute accuracy of 2% and relative stability of 0.3% per year. Compares solar UV output with UV radiation of stable bright blue stars.
TES	3D profiles on a global scale of all infra-red active species from surface to lower stratosphere. Measures greenhouse gas concentrations, tropospheric ozone, acid rain precursors, gas exchange leading to stratospheric ozone depletion.
TIM	Measurement of total solar irradiance directly traceable to SI units with an absolute accuracy of 0.03% and relative accuracy of 0.001% per year.
TIRS	Measures surface emittance, lands cover state and change). Used as multipurpose imagery for land applications.
VIIRS	Global observations of land, ocean, and atmosphere parameters: cloud/weather imagery, sea-surface temperature, ocean color, land surface vegetation indices.
WFC	Scene Context
XPS	Measure the extreme UV solar irradiance from 1 - 35 nm with absolute accuracy of 20% and relative stability of 1% per year.

Instrument Name Short	Wavebands	Beginning of Ops	Mass	Volume	Power Required	Missions
A-DCS3	UHF: 401 MHz, 467 MHz	1984	16 kg + 8 kg = 24 kg	.0460 m^3	62 W	
AIRS	VIS - TIR: 0.4 - 1.7 µm, 3.4 - 15.4 µm, Has approximately 2382 bands from VIS to TIR	2002	177 kg		220 W	
AMR	Microwave: 18.7 GHz, 23.8 GHz, 34 GHz	2008				OSTM, Jason-3
AMSU-A	Microwave: 15 channels, 23.8 - 89.0 GHz	2002	49 kg + 42 kg	.72 x .34 . x .59 m(A1) + .73 x .61 x .68 m(A2)	72W	Aqua
ASTER	VIS and NIR: 3 bands in 0.52 - 0.86 µm, SWIR: 6 bands in 1.6 - 2.43 µm, TIR: 5 bands in 8.125 - 11.65 µm	1999	421 kg		463 W avg., 646 W peak	Terra
ATMS	Microwave: 22 bands, 23-184 GHz	2011	75 kg	.7 x .6 x .4 m	100 W	Suomi NPP, NPOESS-(1,5,3), JPSS-(1-4)
CALIOP	532 nm (polarization-sensitive), 1064 nm, VIS - NIR	2006	156 kg		124 W	CALIPSO
CATS	532 and 1064 nm (polarization sensing at both)	2015	500 kg	1.5 x 1.0 x .8 m		CATS-on-ISS
CERES	3 channels: 0.3-5 µm, 0.3 - 100 µm, 8 - 12 µm	1997	114 kg	.6 x .6 x .576 m	100 W	TRMM, Terra, Aqua, Suomi NPP, NPOESS(1,5), JPSS-1
CPR (CloudSat)	Microwave: 94 GHz	2006	230 kg		270 W (1700 peak power)	CloudSat
ETM+	VIS - TIR: 8 bands: 0.45 - 12.5 µm	1999	scanner =298 kg, AEM = 103 kg, cable harness = 20 kg	scanner = 1.5 x .7 x 2.5 m, electronics assembly = .4 x .7 x .9 m	590 W avg.	Landsat 7
FC		2015	27.5 (sensors) + 15.7 kg (electronics)	.0598 m^3	2.4 W	DSCOVR

Instrument Name Short	**Wavebands**	**Beginning of Ops**	**Mass**	**Volume**	**Power Required**	**Missions**
GOX	L1/L2	2006	4.6 kg	.2 x .24 x .105 m	16 W nominal, 23 W peak	COSMIC-1 FM (1-6)
GPSP		2008	10 kg		17.5 kg	OSTM, Jason-3, SWOT
GPSRO (Oersted)		1999	4 kg		7-15 W	Oersted (TRSR??)
GPSRO (Terra-SAR)		2007				TerraSAR-X
GRACE instrument	Microwave: 24 GHz and 32 GHz	2002	487 kg (x2)	1.3175 x 3.123 x .720 m, V = 2.96 m^3 (x2)	150-210 W	GRACE, GRACE-FO, GRACE-II
HiRDLS	TIR: 6.12 - 17.76 µm (21 channels)	2002	220 kg	1.545 x 1.1135 x 1.30 m	220 - 239 (avg. to peak)	Aqua, Aura
LRA		1992	2.2 kg			Topex-Poseidon, Jason-1, OSTM, Jason-3, SWOT
MISR	VIS: 0.44 µm, 0.56 µm, 0.67 µm, NIR: 0.86 µm	1999	148 kg	.9 x .9 x 1.3 m	131 W peak, 83 W avg.	Terra
MLS (EOS-Aura)	Microwave: 118 GHz, 190 GHz, 240 GHz, 640 GHz and 2.5 THz	2004	490 kg		550 W	Aura
MODIS	VIS - TIR: 36 bands in range 0.4 - 14.4 µm	1999	220 kg	1.0 x 1.6 x 1.0 m	160 W	Terra, Aqua
MOPITT	SWIR-MWIR: 2.3 µm, 2.4 µm and 4.7 µm	1999	182 kg		243 W	Terra
OLI	VIS - SWIR: 9 bands: 0.43 - 2.3 µm	2013				Landat 8
OMI	UV: 270 - 314 nm and 306 - 380 nm, VIS: 350 - 500 nm	2004	65 kg	.5 x .4 x .35 m	66 W	Aura
OMPS-L	280 - 1020 nm	2011	22 kg	.254 x .178 x .762 m	25.3 W avg, 35.4 W peak	Suomi NPP, JPSS-(2-4)
SeaWinds	Microwave: 13.402 GHz	1999	205 kg	250 W avg	250 W avg	QuikSCAT, ADEOS-II
SIM	UV - SWIR: 200 - 2490 nm	2003	22 kg	.254 x .178 x .762 m	25.3 W avg, 35.4 W peak	SORCE

Instrument Name Short	Wavebands	Beginning of Ops	Mass	Volume	Power Required	Missions
SOLSTICE	UV: 115 - 310 nm	1991	36 kg (x2?)	.183 x .387 x .846 m (x2)	33.2 W (x2?)	UARS, SORCE
TES	SWIR-TIR: 3.2 - 15.4 µm	2004	385 kg	1.0 x 1.3 x 1.4 m	334 W(ave), 361 W(peak)	Aura
TIM		2003	7.9 kg	.177 x .279 x .272 m	14 W avg	SORCE, Glory, TCTE
TIRS	TIR 10.5 µm and 12 µm	2013	236 kg	.8 x .76 x. 43 m	380 W	Landsat 8
VIIRS	VIS - TIR: 0.4 - 12.5 µm (22 channels)	2011	252 kg	1.34 x 1.41 x .85 m	191 W	Suomi NPP, NPOESS-(1-6), JPSS-(1-4), DWSS
WFC	VIS: 620 to 670 nm	2006				CALIPSO
XPS	UV: 1 - 35 nm	2003	2.6 kg	.156 x .187 x .172 m	8.6 W	SORCE

Appendix D. Summary of NASA and SMC Experiment/Payload Data

Note that data for each performance category was not given for all of the payloads, so only the subset of payloads that provided data are presented, which is noted in each figure.

Figure D1 shows the mass distribution for the 57 (of the 81 total) payloads where a mass was provided. In some cases, the payloads had zero mass (if they were software for example), and for others, no mass data was given. Half of the payloads have mass of 24 kg or less while 90% of the payloads have mass less than 360 kg. The minimum payload mass is just 0.05 kg while the maximum is 974kg. A single persistent platform that could accommodate all of the payloads would need to support approximately 6500 kg.

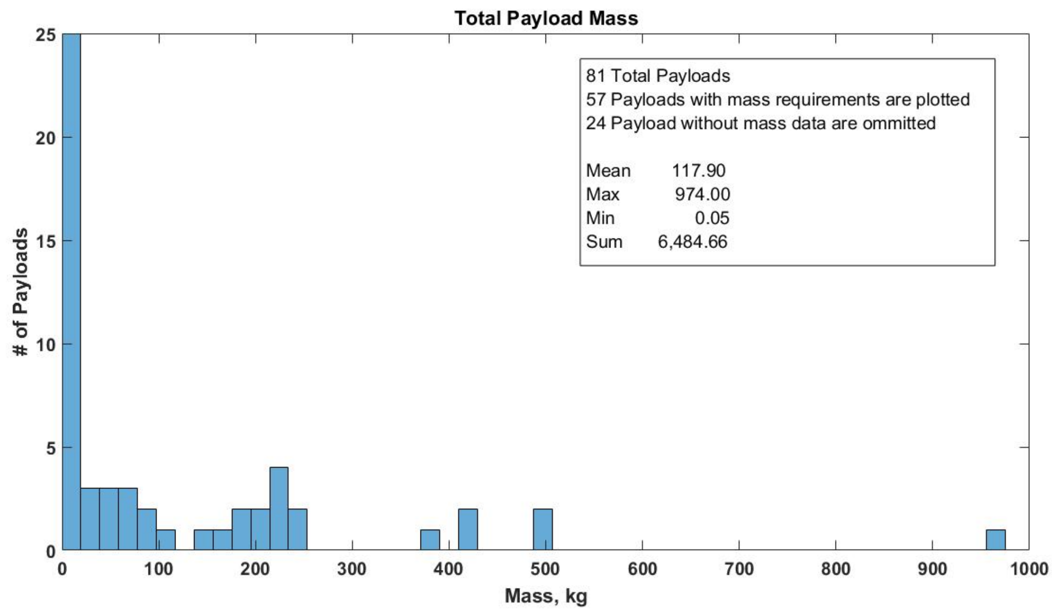


Figure D1. Potential payloads: mass distribution.

In Figure D2, the volume each payload occupies is plotted for 47 (of the 81 total) payloads. The distribution shows that almost all of the payloads (75%) require a volume of less than or equal to a half of a cubic meter with the mean volume for all payloads being 0.48 cubic meters. The largest payload occupies a volume of 4.62 cubic meters. The base area, or footprint the payload would occupy on the platform was provided for the Air Force payloads. However, only the total volume was given for the NASA payloads, so a base area was estimated by squaring the cube root of the payload's total volume. The corresponding base area distribution of the payloads are shown in Figure D3. Half of the payloads require a small footprint on the platform, less than or equal to 0.106 square meters. The total cumulative footprint area for all of the payloads is 20.1 square meters, which assumes no spacing between any of the payloads.

The maximum power a payload would require for operations and to perform its mission was also requested and the corresponding data is summarized for the 50 payloads that responded in Figure D4. Half of the payloads require 56 Watts or less each and 90 percent of the payloads require less than 570 Watts each. If all payloads were drawing their maximum power, they would require approximately 8.34 kilowatts from the platform.

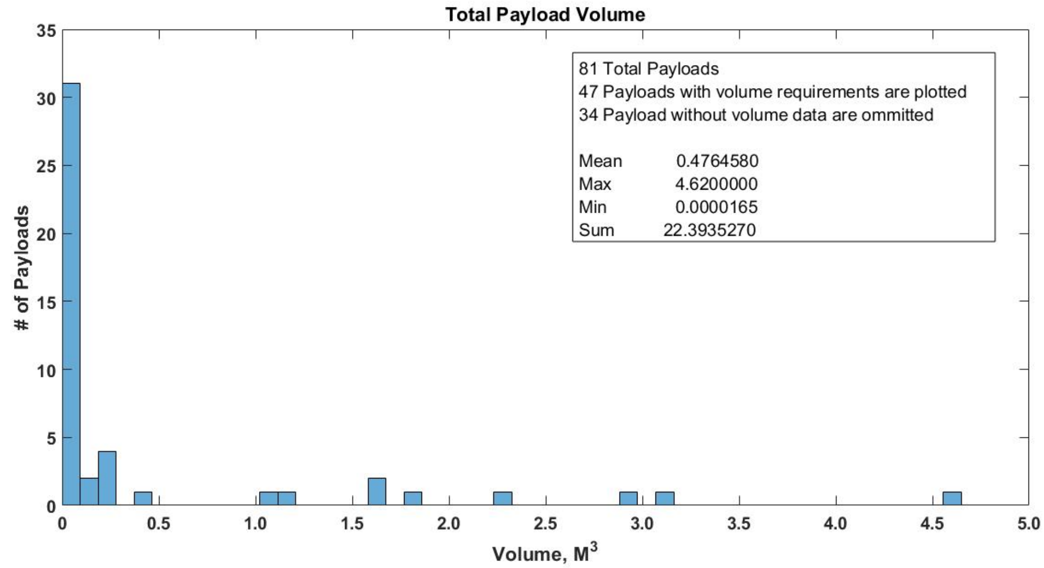


Figure **D**2. Potential payloads: volume distribution.

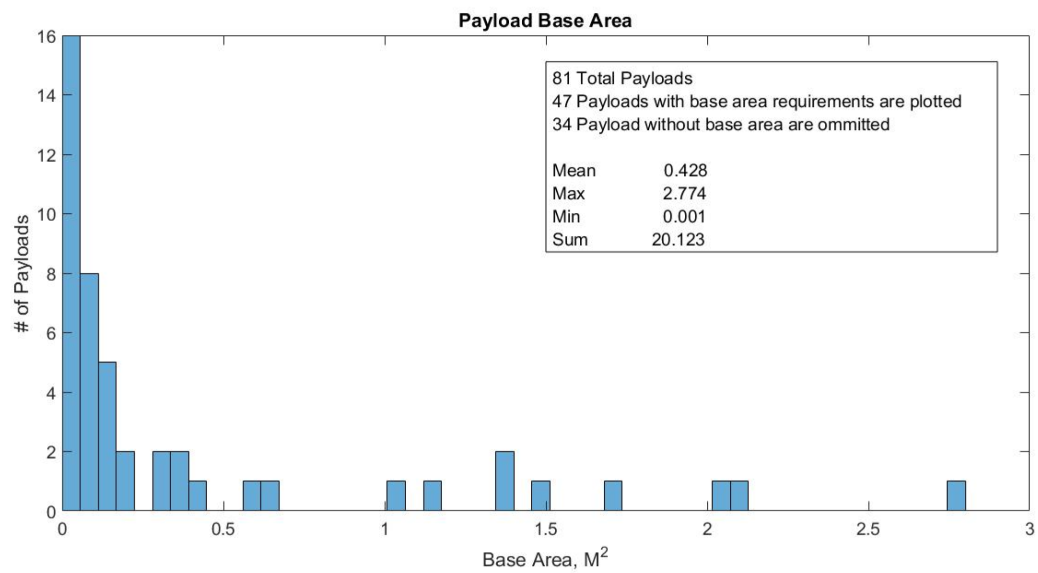


Figure D3. Potential payload base areas (based on assuming cube for volume).

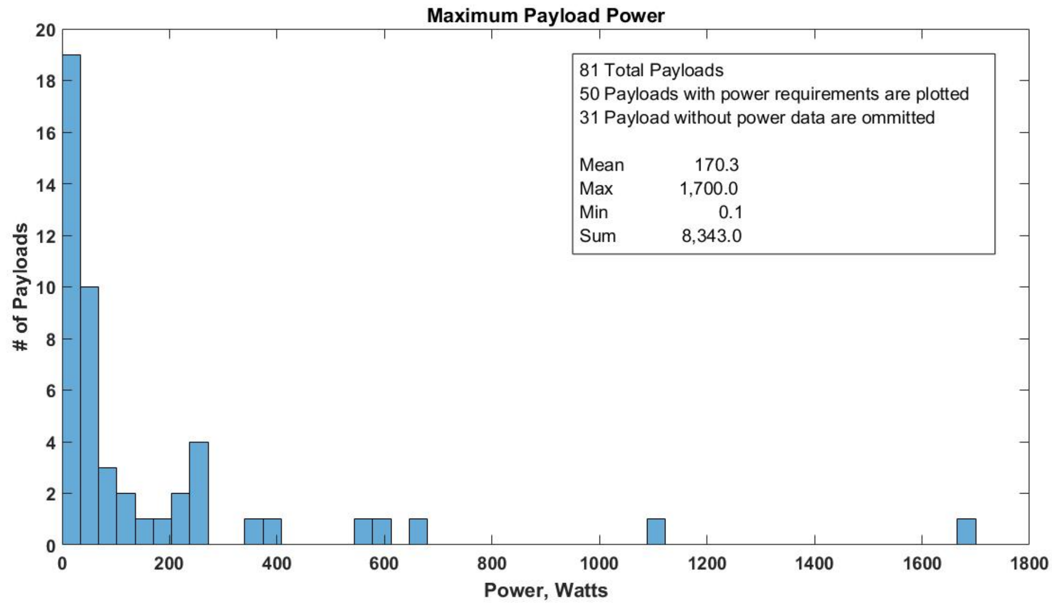


Figure D4. Potential payload power requirements.

As a final set of data, the payload proposers were asked to specify a preferential viewing direction for their payload (if one was required) and that data is summarized in Figure D5. Approximately 45 percent of the payloads did not specify a viewing direction and would be free to be placed anywhere on the platform. Another 41 percent required a Nadir view, indicating the need for many payloads, predominantly Earth Science, to be Earth viewing.

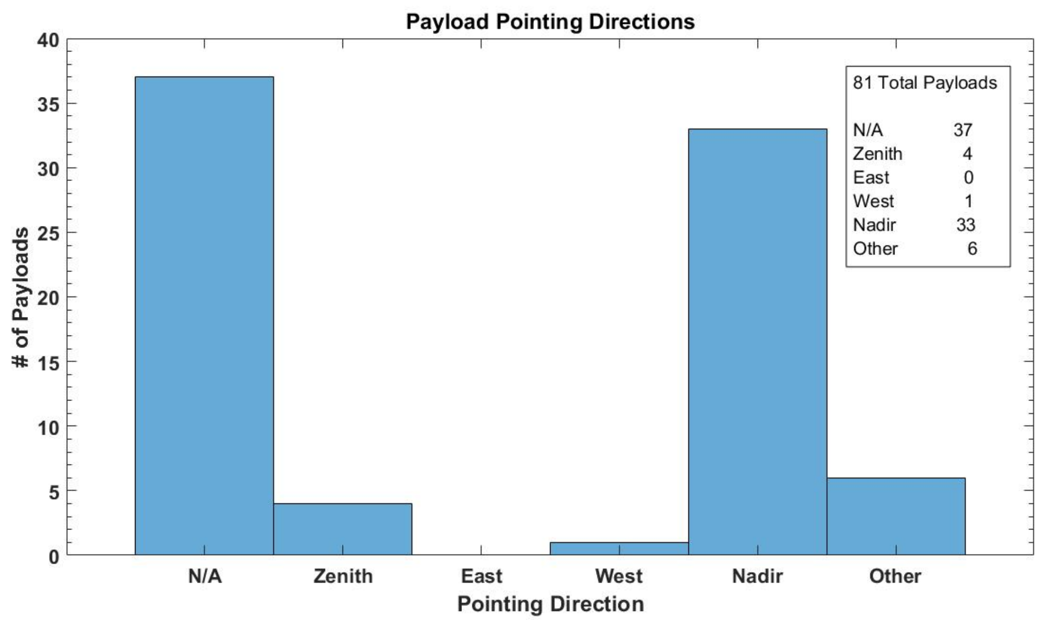
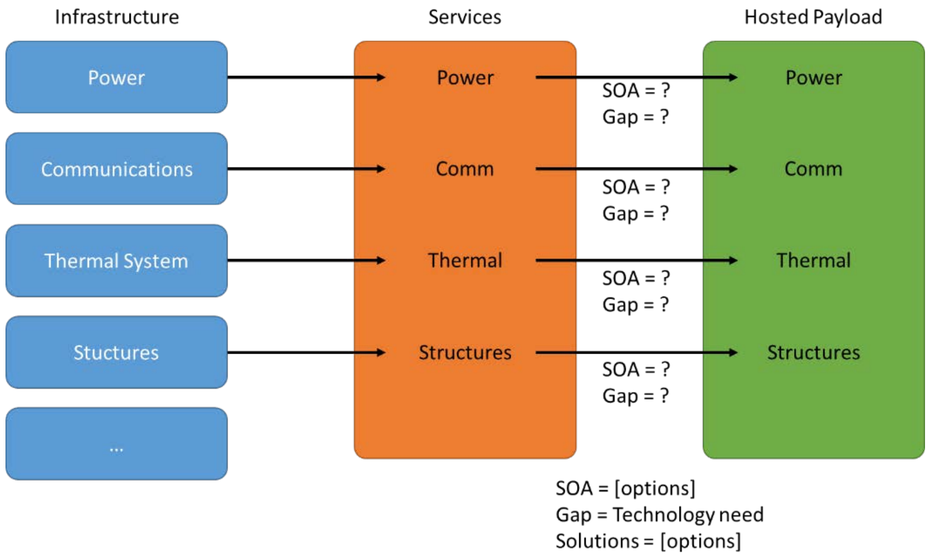


Figure D5. Payload pointing direction preferences.

Three different implementations have been studied and are described in this report. These implementations could consist of one or more of the following attributes: in-space manufactured elements, component assembly (including fastening technology), and attachment of modular elements that have been built on the Earth. The Air Force is also interested in exploring the use of DARPA Phoenix SATLETS to interface test items to the platform: the DARPA developed HiSAT along with its universal device adaptor (UDA) already have an ICD (interface control document) and user guide and hardware available for use. Over 30 companies contributed to this ICD and user guide during interactions with the DARPA F6 and Phoenix programs. There is also a desire to use the platform as a means to develop, test and incorporate additional interface standards for use in modular space systems.

1. Payloads and Services
2. Include a functional/services diagram like below
3. Compare the IOC with the future capability



The architecture-level platform options define the physical and functional form of the platform itself. Decisions made in this trade space define the size, scope, and evolution of the persistent demonstration platform. These decisions along with a list of reasonable alternatives are listed in Table 2. Alternatives to the LEO bus include GEO bus, custom built bus, modular bus, decentralized bus approach (i.e. multiple independent modular units).

Table 2. High level design decisions and alternatives.

Decision	**Alternatives**			
Bus options	Small sat	Powered ESPA	Cubesat	LEO Bus
Platform Primary Structure	Deployable	Assembled (truss modules or piece-parts)	Monolithic	In-space Manufactured (link)
Agent options	Resident Robotics	Servicer	None	
Expansion Strategy	Expand	Replace	Combo	
Modularization Strategy	Component level (e.g. arrays, batteries)	Subsystem level (e.g. power module)	System level (e.g. bus)	Subcomponent level (e.g. memory, cards)
Payload location possibilities	External to truss	Internal to the truss	Deployable surfaces/panel	Stacked payloads
Platform lifetime	5 year	10 year	15 year	Indefinite

Decision	Alternatives			
Orbit Selection	SSO (a) dawn-dusk; b) morning; c) afternoon; d) noon-midnight (what MLT?)	LEO	GEO	
Launch of platform	Small launcher (500 kg class, <2 m)	Rideshare (ESPA class)	Dedicated launch (Falcon 9 class, 5 m)	Dedicated launch (Antares class)
Platform growth	Add modules to the side	Add modules to length	Add modules to top/bottom	
Pressurized Volume	Yes	No		
Pointing approach (platform vs pointing package/disturbance rejection system)	Platform LVLH Pointing	Platform Inertial pointing	Payload pointing mechanism	Payload Disturbance rejection system

D.A Operations Options

The architecture-level operations options define how the functions of the platform are instantiated once on orbit. Decisions made in this trade space define agents that operate around the platform, payload accessibility, and ground operations of the persistent demonstration platform. These decisions along with a list of reasonable alternatives are listed in Table 3.

Table 3. High level driving operational decisions.

Decision	Alternatives				
Delivery Agent	Reusable tug or tender	Disposable vehicle (e.g. SmallSat)	Cargo module	Multifunction (delivery agent and platform module)	Delivery and Disposal
Cargo capture agent	Robotic (e.g. long reach manipulator) w/o berthing	Docking	Robotic and Berthing	Formation fly and pull payloads off	
Assembly agent	Resident robot	Free flying servicer	Direct docking of modules		
Servicing agent	Resident robot	Free flying servicer			
Launch of payloads	Same as above (platform launch)?	Single payload per launch	Multiple payloads per launch		
Ground support/operations	DOD	NASA	Inter-government	Private	Distributed (Cal Poly, Amazon, etc.)
Enable human visitation	Yes	No			
Ownership	Public	Private	Partnership	NASA	DOD

D.B Payload Support Options

The architecture-level payload support options define the interactions between hosted payloads and the platform itself. Decisions made in this trade space define the services that the platform will provide and how those services will be executed. These decisions along with a list of reasonable alternatives are listed in Table 4. There are many alternatives that could be considered beyond those listed in Table 4 including: inspection, testing, diagnostic approach, repair vs. replace, dexterity of robotic manipulation provided, return to Earth or disposal/burn up service, etc.

Table 4. High level design decisions for payload utility services.

Decision	**Alternatives**						
List of Services (on orbit)	Mechanical Interface	Power	Data Storage	Data Transfer	Computer (hardware and software)	Thermal Control	Fluid Transfer
Electric/power/data infrastructure	Pre-installed	Robotically installed	wireless	Payload provides service			
Thermal management	Conductive I/F to payloads	Coolant supplied to payload I/F	Isolate payloads (they control)	Sun Shades			
Fluid transfer	Hydrazine	Xenon	Water	Cryogenic propellants	oxidizer	ammonia	Green propella nt
Payload refueling architecture	Fill empty tanks	Launch new tanks	None				
Platform Refueling agent	Dedicated refueler	Cargo Delivery Agent excess propellant	Tanks delivered				
Propellant transfer strategy	Robot w/ hose	Interface supports prop xfer	Tank swap	Centralized depot	None		
Payload lifetime	<1 year	1-2 years	>2 years	~5 years (Earth science)	Indefinite		
Payload Physical Isolation Strategy	Free flyer	Tethers	Booms				
Payload Vibration Isolation	Active isolation	Passive damping	Free flyer	Tethers	Booms		
Payload EM Isolation	Impose requirements on the payload	Shielding on platform	Physical isolation (e.g. tethers, free flyers)				
Payload class	Operational (A-D)	Experimental					
Security Rating	Commercial	Public	Classified				
Encryption implementation	Ground	In-space local	In-space remote	Customer defined	NASA Level 1		

Decision	Alternatives			
List of services (ground, customer support)	Offload data	Health monitoring	Failure recovery	"Parking lot"/storage
Payload (size and mass) class	Small (e.g. CubeSat (~10 cm))	Medium (e.g. ESPA payloads)	Large (e.g. Lidar, 2+ m diameter)	Aggregation of small payloads
Payload quantity (simultaneous)	1	10	50	100

Appendix E. Qualitative Comparison of Three Architecture Options

In the comparison below, it is assumed the servicer system is available. These factors should be used to form a foundation for a quantitative comparison of options in future studies. Here they are used to introduce concepts that must be traded for different options.

Scoring: 1 good, 3 neutral, 5 poor

Table 5. Comparison factors. (Green: indicates items discussed in main body of paper, yellow: team results).

Item	Description	Bus Based	Servicer Based	Small Sat	notes
1	Cost: Initial Operating Capability	5	1	3	Delta from nothing to IOC assuming servicers exist, Cost of Robotics for Small Sat
2	Cost: Baseline Capability	1	5	3	Delta from IOC to Baseline
3	Cost: Operation for 10 year after baseline	3	3	3	
3.5	Cost: To customer (smaller sizes)	3	3	3	Similar resupply mission possible
4	Cost: Robotic system	5	1	5	
5	Cost: To duplicate platform	3	1	1	Assume only one servicer
6	Schedule: time to initial deployment (to IOC)	5	1	3	Assume servicer available, may take longer to add robotics to small Sat, interaction between robot and spacecraft will take time
7	Schedule: payload refresh time (potentially diff in delivery options, limited by space on platform,)	3	3	3	
8	Performance: Payload Accommodations	1	5	5	
9	Performance: Size, power, data, thermal, etc. (power enabling for a LIDAR mission)	1	5	5	
10	Performance: Science Metrics (pointing, ability to support different orbits, support decadal survey characteristics (stability, jitter, pointing control and knowledge))	1	1	1	OSAM-1 is in LEO, RSGS in GEO so potential to support variety of orbits with servicers. ESPAStar can support GEO
11	Performance: Extensibility and expansion potential	1	3	3	
12	Performance: Lifetime (50 yr. … vs. 10 yr., then launch another (payload yrs./$))	3	3	3	
13	Risk: External dependence (e.g. servicer needs)	1	5	1	
14	Risk: Payload failure spreads or leads to platform failure	3	1	3	Bus, because of the panels, maybe difficult to isolate a single payload. This is a design task. Independent servicer mitigates platform failures because it can stabilize platform.

Item	Description	Bus Based	Servicer Based	Small Sat	notes
15	Risk: Technology development	3	3	3	
16	Risk: Ability to jettison platform portion	3	1	1	
17	Robotic versatility (exchangeability, number, etc.)	3	3	3	
18	Payload/mission operation center	5	1	5	
19	% of launch (launch availability) to baseline capability	5	1	1	
20	Payload delivery costs – likely payloads are assumed to be three axis stabilized	5	1	3	
21	Payload return capability (return to Earth)	3	3	3	
22	Terrestrial test environment (HW in loop) Believe restore L system can be used for all	5	1	1	
23	Range of delivery options supported of payloads (likely not a discriminator)	3	3	3	
24	Ability to for different orbits (different. customers, etc.)	1	5	1	