Satellite Servicing and Mission Augmentation

Andrew Kwas (1), Anthony DeCicco(2)

(1) Northrop Grumman Space Systems, 2309 Renard Place, S.E., Albuquerque, New Mexico, USA, 90278, 505-603-3672, Andrew.Kwas@ngc.com
(2) Northrop Grumman Space Systems, 1 Space Park Dr, Redondo Beach, California, USA, 90278, 310-813-0969, Anthony.DeCicco@ngc.com

PAPER

ABSTRACT

Following the two recent successful launches of Northrop Grumman's SpaceLogistics Mission Extension Vehicle (MEV) and the ongoing operations of these vehicles to extend service of their respective client vehicles (CVs), satellite servicing is now an operational capability. The next generation of servicing is the smallsat class Mission Extension Pod (MEP) and the larger Mission Robotic Vehicle (MRV) which are scheduled to launch in 2024. Combined, these vehicles will usher in a generational shift in mission extension services whereby one vehicle (MRV) will be able to augment many vehicles with individual MEPs, or other attachable systems. In addition to these services, the MRV will introduce a capability to conduct inspections on spacecraft health and augment its own repair abilities with deliveries of tools to perform the operation. In the not too distant future, this platform will evolve to change out other hardware on satellites, perform repairs, and conduct in-space manufacturing and assembly.

Part of this architecture is to introduce an open, prepared servicing interface which will allow direct access for orbital replacement units, or more standalone capable on-orbit attachable components, to integrate with the power, data, and propellant of a client spacecraft.

Together, these systems will provide the potential for 1) enhanced satellite sustainment and resiliency, 2) satellite augmentation, 3) in orbit assembly, 4) extreme mobility, 5) constellation management, and 6) orbital debris management.

1 INTRODUCTION

History will look back at 2020 and identify it as the year when in-space logistics became a reality. Of course, technology enablers such as basic fluid transfers and in space robotic arms had occurred many years before, but 2020 was the first time an operational commercial satellite's pending demise was changed and it returned to service. The successful launch and servicing operation of the MEV-1 with the Intelsat 901 proved convincingly that commercial servicing is a viable business. The potential has been discussed for decades, to extend a satellites mission life in orbit, replace or upgrade its components to more state-of-the-art devices, or even completely change its mission after launch

Game changing questions can now be answered. Why should satellite life be limited by the propulsion stored on board when first put in service? Can future satellites be put in service without carrying a lifetime of fuel? Is satellite solar panel degradation something we just have to live with? When a key spacecraft component breaks down in space, is that satellite's mission over? What role do smallsats play as an augmentation device for larger satellites?

If your automobile breaks down while on a road trip, do you just leave it there and walk away from it? No. You call a servicing vehicle to tow you to a repair shop or in some cases, the servicing company comes to you and provides a replacement part or fixes it on the spot, and you are back on the road. Same should apply for orbiting satellites.

Let’s look back at how we got here to this milestone in history, what we have just accomplished, and where we expect this on orbit servicing to go in the near future.

1.1 Past servicing enablers

Satellite servicing has been a goal of the space industry for many years, but has previously only been accomplished with on-orbit human assistance in servicing assets like the Hubble Space Telescope, or short term technology demonstrations like the Orbital Express mission. Various programs were developed to assess the technical feasibility of robotic servicing that could perform actions such as autonomous on-orbit refueling and reconfiguration of satellites. The goals were to support a broad range of future U.S. national security and commercial space programs by offering a low cost alternative to sending up a replacement satellite. Research was done in the past to develop the ability to refuel satellites, that would enable them to frequently maneuver to improve coverage, improve survivability, as well as extend the satellite lifetime. On-orbit upgrades to components were investigated that would offer recovery from failures, implement technology enhancements and performance improvements, and allow for installing a different sensor to change the spacecraft mission. This need is what drove the early demo missions.

1.1.1 Canadarm (aka Shuttle Remote Manipulator System)

In the early days of the space shuttle program, a Canadian firm named Spar Aerospace developed the first Canadarm [1] and delivered the initial operational system to NASA in 1981 as shown in Figure 1. The configuration consisted of a manipulator arm, a display and control panel, including rotational and translational hand controllers at the orbiter aft flight deck crew station, and a manipulator controller interface unit that interfaced with the orbiter computer. Five units were built and delivered and successfully serviced over 90 missions until it was retired in 2011. The arm required crew member operation and was capable of deploying and retrieving payloads weighing up to 332.5 kg in space. In the mid-1990s the arm control system was redesigned to increase the payload capability to 3,293 kg in order to support the space station assembly operations. The Canadarm was able to retrieve, repair and deploy satellites, provide a mobile extension ladder for extravehicular activity crew members for work stations or foot restraints, and be used as an inspection aid to allow the flight crew members to view the orbiter's or payload's surfaces through a television camera on the arm. Despite the fact that the system was not autonomous, it provided key information in using robotic mechanisms in space, and led to the more capable Canadarm 2 and future Canadarm 3 to follow.

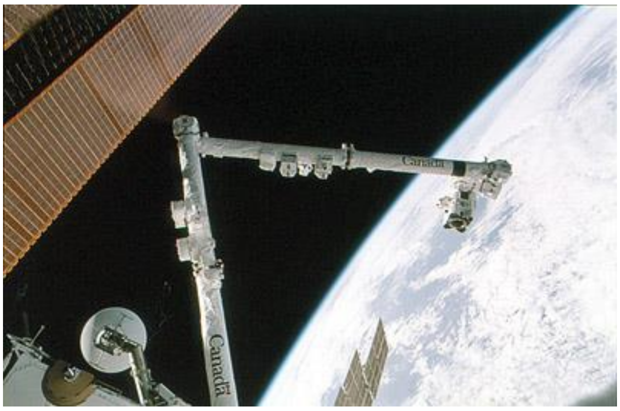


Figure 1. The first Canadarm

Credit: Canadian encyclopedia

1.1.2 Orbital Express

In 2007 the DARPA Orbital Express program was launched to demonstrate “a safe and cost-effective approach to autonomously service satellites in orbit.” The two spacecraft, known as the Autonomous Space Transfer and Robotic Orbiter (ASTRO) and the smallsat, Next Generation Satellite (NextSat) were separated with use of the ASTRO robotic arm. The Orbital Express spacecraft shown in Figure 2, was a three-month mission that demonstrated for the first time fully autonomous rendezvous and capture of a client spacecraft, satellite-to-satellite refueling, and replacement of battery and flight-computer orbital replacement units [2]. For the first time, the Northrop Grumman-provided hardware onboard ASTRO demonstrated autonomous transfer of hydrazine propellant to and from the NextSat spacecraft, in addition to providing the propulsion needed for six-degree-of-freedom vehicle control. The fluid-transfer payload aboard the NextSat spacecraft allowed a variety of client configurations to be simulated over multiple on-orbit fluid-transfer demonstrations. The significance was noted at the time by Tom Romesser, Vice President of Technology Development for Northrop Grumman Space "The ability to refuel and upgrade spacecraft on-orbit, or to move stranded satellites into their correct orbits, could represent a revolutionary change in space operations for both commercial and military users." How right he was.

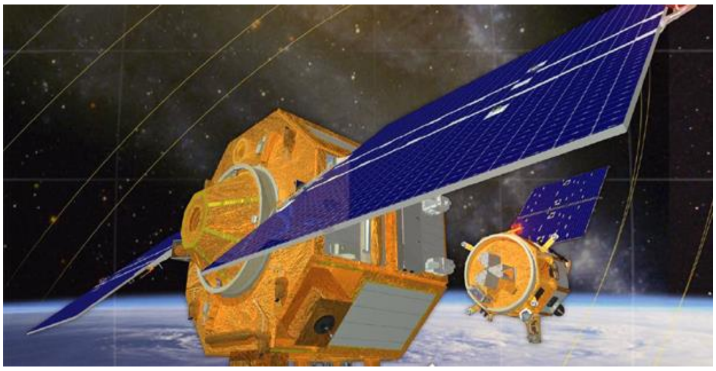
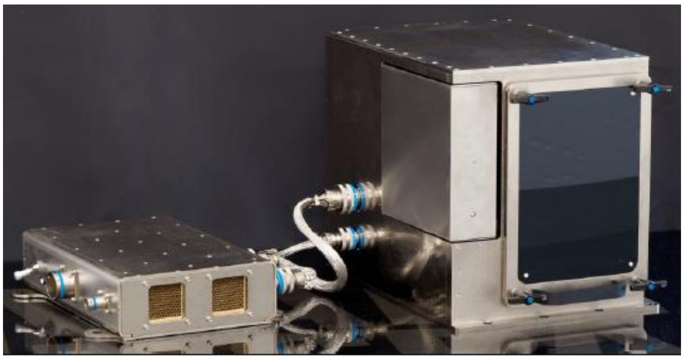


Figure 2. Orbital Express

Credit: DARPA

1.1.3 3D-Printing on the International Space Station

Additive manufacturing is a key enabler for satellite servicing in the future. Several years ago, Made In Space Inc. (now Redwire) was awarded a NASA contract to develop the first series of 3D printers specially designed for use in space [3]. In Figure 3, the first 3D printer aboard the ISS in 2014 was a technology demonstrator, as part of the 3D Printing in Zero-G experiment, to prove the feasibility of additive manufacturing in space. This first generation 3D printer ushered in the era of off-world manufacturing and served as a test bed for understanding the long-term effects of microgravity on 3D printing and how the concept can enable the future of space exploration. The system incorporated three key technology areas, including: environmental control, remote operation and proof of the mission critical design. The ability of the printer to filter toxic gases and nanoparticles was one of the most important technical challenges prior to being approved to operate aboard the ISS.



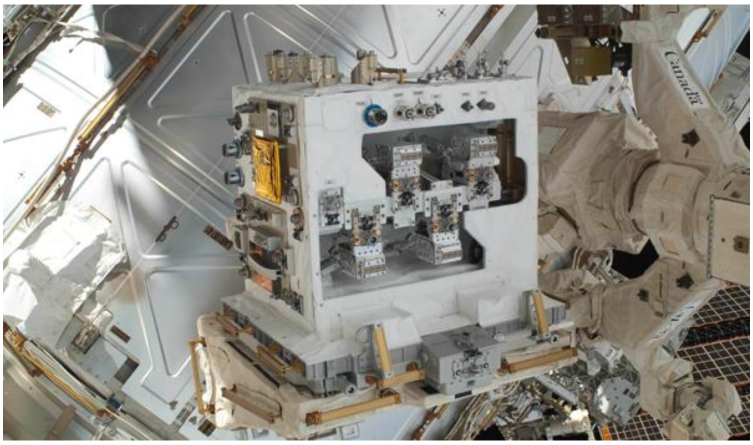
Credit: Redwire

Figure 3. Zero-G 3D Printer Technology Demonstrator

This printer reduced risk and advanced the state-of-the-art in preparation for the company's second generation of in-space 3D printers, the Additive Manufacturing Facility (AMF). The AMF is a permanent manufacturing facility on the ISS and provides increased capability to print with a wide range of materials. AMF is designed to last the entire lifetime of the ISS and is commercially available for any space hardware developer on Earth.

1.1.4 NASA's Robotic Refueling Module (RRM)

The NASA Satellite Servicing Projects Division [4] is actively pursuing satellite-refueling technology. Their Robotic Refueling Mission (RRM), seen in Figure 4, is a multi-phase demonstration on board the International Space Station (ISS), to create a system that can refuel and repair satellites while they are in orbit. RRM is focused on fixing satellites that were not designed to be serviced. Using the robotic ISS Dextre arm to reach into the RRM module and pick up the five RRM tools, it is capable of demonstrating servicing tasks such as cutting and peeling back protective thermal blankets, unscrewing caps, turning valves, transferring fluid, inspection, and intermediary steps leading up to coolant replenishment. It is truly the workhorse of the International Space Station. The module is about the size of a washing machine and weighs approximately 550 pounds, with dimensions of 33" by 43" by 45". RRM includes 0.45 gallon (1.7 liters) of ethanol to demonstrate fluid transfer in orbit. Protective thermal blankets, caps, valves, simulated fuel, and other spacecraft components allow the team to practice a wide range of satellite-servicing tasks. It has been in orbit since 2011, and upgraded in October 2015 and again in December 2018.



Credit: NASA

Figure 4: NASA's Robotic Refueling Mission Module.

1.2 Near term servicing need and solutions

As shown in Figure 5, according to the USC Satellite Database [5], there are 554 satellites in the geosynchronous (GEO) orbit, and many are nearing end of their fuel life. When a satellite reaches the end of its life, it is often boosted to the GEO graveyard orbit, defined typically as 200-300km higher than the GEO orbit. Once there, the satellite is decommissioned to reduce the possibility of future catastrophic failures that could cause additional debris. Placing satellites into this orbit will minimize the chance of interfering with operating satellites in the GEO belt.

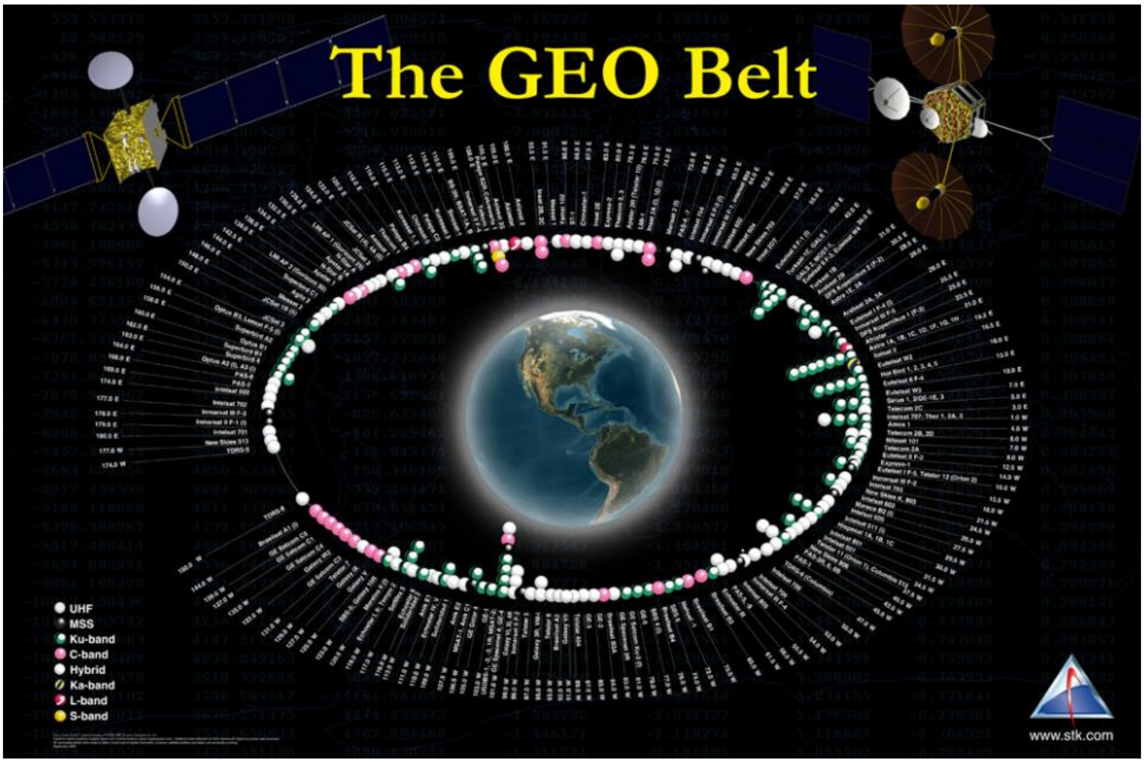


Figure 5. Current Geosynchronous Orbit Satellites

Currently there are more than 2200 satellites in the GEO graveyard orbit [6]. But why are they there? Have they completed the mission they are designed to do and have no future utility? Do they have a failed component/sensor, or are they simply out of propellant to station keep in their operational orbit? What if those satellites had a failed component replaced, or propellant added to stay in their orbit, would they continue in service? The answer to that last question is- likely.

Many satellites are able to far exceed their intended operational life. With the ability to service a satellite on orbit, the satellite designer can reduce redundant components on board, since servicing allows a failed unit to be replaced if the primary component goes bad. Current rationale for completely replacing existing satellites is that their technology has "aged out", so we should send up a new one. That may be valid in the pre-2020 era, but soon we can have a spacecraft decades old technology be upgraded while in space. Or its orbit restored. Or its mission modified. If a satellite is still useful, servicing the satellite is a cost effective alternative to launching a new satellite. On orbit servicing enables that choice.

The sections below discuss the two recent successful MEV missions and path forward for the Mission Extension Pods (MEP), and the Mission Robotics Vehicle (MRV), as well as key features of On-orbit Augmentation Capabilities (OACs), Persistent Platforms, and Orbital replacements units (ORUs) and how they all play into the solution. Plus, a quick look at the status of OSAM 1 and 2.

1.2.1 Mission Extension Vehicle (MEV)

The Mission Extension Vehicle is Space Logistics first in a series of incrementally expanding capabilities providing on-orbit servicing. Built on the Northrop Grumman GEOStar 3 platform, the MEV is a proven spacecraft that can inspect, relocate, and extend the maneuver life of a client satellite. Using only a mechanical interface, the 2600kg MEV docks to the liquid apogee engine and launch adaptor ring on the aft end of its client satellite before taking over the orbit and attitude control functions for the client. Using this technique, the MEV can service existing in-orbit satellites that were not "prepared" for (i.e. designed for) servicing. The high reliability MEV stays attached to the client satellite until service is no longer needed, it then undocks and can proceed to the next client in need. The MEV can perform multiple servicing missions for multiple customers over its projected 15 year life. It is estimated to be compatible with approximately 80% of all operational GEO satellites.

MEV-1's first service was a 5 year life extension of the Intelsat 901 (IS-901). IS-901 was originally launched to geostationary orbit in June 2001 for a planned in-service life of 15 years. The satellite was in good working order. It simply ran out of fuel. Seen in Figure 6, MEV-1 launched Oct 9, 2019, and rendezvoused with the IS-901 in the GEO graveyard orbit drifting westward above the Pacific Ocean. Docking was successfully completed on Feb 25, 2020. Following docking, the MEV increased the altitude of the combined vehicle stack to accelerate the drift rate towards IS-901's new operational location at 332.5 degrees east over the Atlantic Ocean which was achieved in March 30, 2020. On April 2, Intelsat brought the IS-901 satellite back into service by transferring traffic from another satellite. The expected duration of IS-901 life extension service with the MEV-1 staying attached, is 5 years at which point, MEV-1 will take it back to the GEO graveyard orbit, detach, and go on to service other satellites.

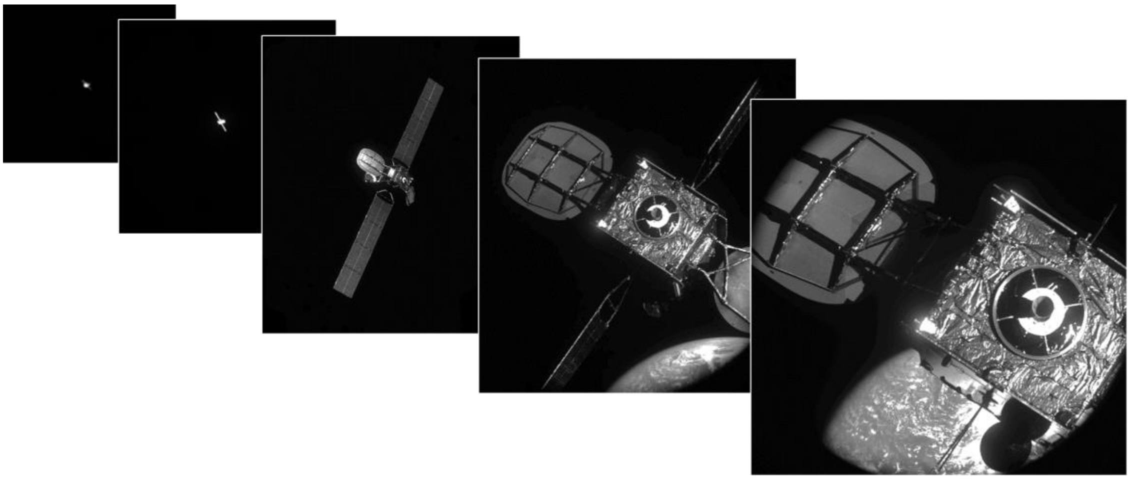


Figure 6. MEV-1 Approaching the Intelsat 901 in GEO Graveyard Orbit

A forward thinking company, Intelsat said it "views life-extension services, like MEV technology, as a cost-effective and efficient way to minimize service disruptions, enhance the overall flexibility of its satellite fleet and better support the evolving needs of its customers." A second MEV (-2) was launched on an Ariane-5 on April 12, 2021 to service another Intelsat satellite (10-02).

The MEV-1 and IS-901 docked in the GEO graveyard orbit out of an abundance of caution for this first ever docking mission. But given the outstanding success and qualification of that mission, the MEV-2 docking took place directly in the IS-10-02's operational geosynchronous orbit, while the satellite was still functioning.

1.2.2 Mission Extension Pod (MEP)

Building off of the success of the MEV missions, SpaceLogistics embarked on a significant cost reduction to develop a comparable servicer that was smaller and more tuned for the life extension mission. The Mission Extension Pod (MEP) which is a smallsat class vehicle, shown in Figure 7, is the next generation life extension system. MEPs are an electric propulsion augmentation device, which provides up to six years of orbit control life extension to a client satellite. The MEP can be installed on existing on-orbit satellites that are not "prepared" for augmentation. It utilizes a docking mechanism very similar to the MEV, clamping the MEP to the liquid apogee engine of the client satellite. The MEP has a self-contained power and telemetry and commanding system (TCS). The flexible frequency TCS can be ordered in C-band or Ku-band and will operate within the clients licensed frequency band utilizing the same TCS uplink/downlink antennas as the client satellite.

One to six MEPs can be launched into a GEO transfer orbit attached to a launch adaptor ring similar to an ESPA Grande. Once separated from the launch vehicle, the MEP will deploy its solar arrays and thruster mechanism then perform its own orbit raising, collocating ("parking") itself near the client vehicle. Once parked in GEO, our Mission Robotic Vehicle (MRV) described below, will retrieve the MEP and install it on the client satellite. After installation, the client satellite operator takes control of the MEP and operates it as another subsystem of its existing satellite.

In March 2022, SpaceLogistics announced a launch agreement for its MRV spacecraft, and the sale of its first MEP. Under the launch agreement, SpaceX will provide launch services for a planned spring 2024 launch of the MRV and several MEPs. Optus, Australia's largest satellite owner and operator, recently completed a purchase agreement with SpaceLogistics for installation of one of the MEPs on its D3 satellite in 2025. Since that time, SpaceLogistics has been in talks with numerous other satellite service providers who also see the benefit of extending their satellite lives. *MEP, a smallsat, performing a key servicing mission – the purpose of the 4S Conference.*

Figure 7. MRV approaching commercial satellite for MEP installation

1.2.3 Mission Robotic Vehicle (MRV)

The Mission Robotic Vehicle (MRV) shown in Figure 8, is SpaceLogistics' next fully operational satellite servicing vehicle, built in partnership with the U.S. Defense Advanced Research Program Agency (DARPA). Through this partnership, DARPA is delivering the Robotic Servicing of Geosynchronous Satellite (RSGS) robotics payload system which will be integrated onto the MRV.

As mentioned above, the initial MRV mission focuses on robotic installation of Mission Extension Pods for asset life extension, but the platform is ready to accept future qualified robotic end effector tools and follow-on missions. The MRV-compatible, standard space-qualified manufacturing end effector kit, with integrated drive control electronics, battery energy storage and power regulation, will enable traditional and non-traditional space companies to quickly and affordably transition new modalities of manufacturing technology to orbit. Suitable technologies include inspection and sensing technologies, laser drilling and trimming technologies, vapor deposition technologies, electrical wire routing tools, thermoplastic material extrusion, various metal additive manufacturing technologies and more. MRV will enable entirely new missions, and open a new market in space logistics to repair and upgrade satellites and perform in-space manufacturing.

Through the course of performing its commercial services, SpaceLogistics will demonstrate several fundamental robotic servicing capabilities of the RSGS robotics system and establish a persistent commercially available robotics servicing system. Initial capabilities of the MRV include detailed robotic inspections, OAC/ORU installations, repairs, and relocations of client satellites.

Figure 8: Mission Robotic Vehicle Approaching a MEP

1.2.4 OSAM-1 (Restore L)

The NASA Goddard Space Flight Center (GSFC) Satellite Servicing Projects Division [7] is leading the On-orbit Servicing, Assembly and Manufacturing (OSAM-1) mission to refuel the Landsat 7 spacecraft in a low earth polar orbit, as shown in Figure 9. Landsat was an Earth observation satellite launched into a sun-synchronous orbit in April 1999. The refueling mission utilizes two robotic arms developed by GSFC to perform the primary mission which is the Landsat 7 refueling demonstration. MAXAR is building the robotic servicing vehicle based on their SSL-1300 bus. The OSAM-1 spacecraft also includes an attached payload called Space Infrastructure Dexterous Robot (SPIDER), which is a lightweight 16-foot (5-meter) robotic arm. With the addition of SPIDER, the OSAM-1 spacecraft with its three robotic arms, will assemble seven elements to form a functional 9-foot (3-meter) communications antenna. The robotically assembled antenna will demonstrate Ka-band transmission with a ground station.

OSAM-1 will be the first of multiple planned missions to bring key OSAM technologies to operational readiness status. This foundational mission will demonstrate various world's firsts from the refueling of a satellite not designed to be serviceable, to in-space robotic precision assembly.

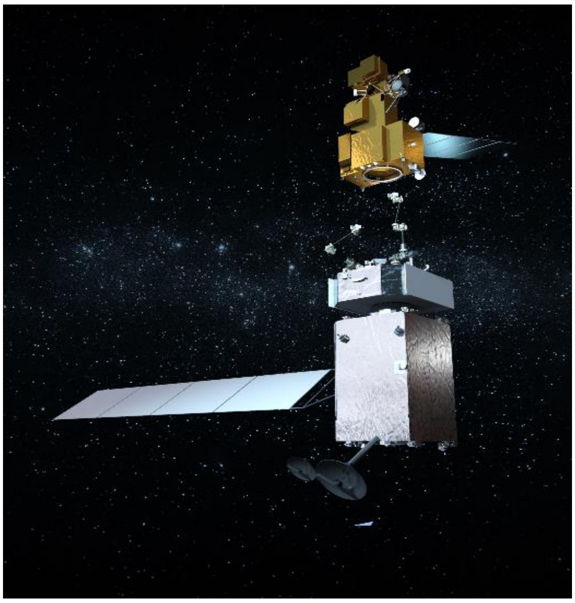


Figure 9: OSAM-1 (Previously Restore L)

Credit: NASA

1.2.5 OSAM -2 (Archinaut)

OSAM-2 (also known as Archinaut) will be the second installment in the series of demonstrations. Leveraging Redwire's successful printing on the International Space Station, the NASA's OSAM 2 program, seen in Figure 10, will demonstrate the ability to print spacecraft elements in free space, which will help enable printing and assembling large space structures in the next decade. Redwire recently completed its Mission Critical Design Review on Archinaut which use additive manufacturing technology and a robotic arm to build and manipulate structures and tools in space, demonstrating critical technologies for producing space infrastructure. After launch, the refrigerator-sized spacecraft will build and deploy a surrogate solar array in orbit. Archinaut will 3D print one beam that extends 10 meters from one side of the spacecraft and a second one that extends six meters from the other side.

Figure 10. Archinaut concept building a large structure

Credit: Redwire

1.3 On-orbit Augmentation Capabilities (OACs)

On-orbit Augmentation Capability (OACs), are hosted payloads that are attached to a client satellite on-orbit. OACs falls into three basic categories, 1) *repair/replace* components of the client satellite, 2) *enhancement* of the satellite mission, or 3) *upgrade* the component of the satellite.

Repair/replacement - OACs are used when something on the client satellite is broke or needs replacement because of impaired operations. Augmenting propulsion systems such as the baseline mission for the MEP, falls into this category because that client satellite propulsion system is either failing or depleting its fuel supply. Failure of on board systems in a client satellite can also be the need for a repair mission. A replacement feature such as adding fuel to the client, or bringing an OAC supply of filament to the Archinaut system would fall into this category as well.

Enhancement - OACs are used to modify or extend the capabilities of the baseline mission. A simple example may be a device to conduct space situational awareness, such as adding surface mounted cameras to provide data needed for space traffic management, a sensor for measuring/ monitoring space weather, or addition of a sensor for scientific research, to name a few. In this scenario an OAC is a standalone device that may utilize a prepared client satellites power, command and data sharing, comm link, etc. to function, or it may have its own subsystems, to operate with un-prepared client satellites.

Upgrade **-**OACs are used to overcome obsolescence. Large satellites which typically include most GEO satellites, often suffer from long technology refresh periods. If an OAC can be delivered to that satellite and replace an existing on board system similar to how we upgrade software now, that satellite can be refreshed with state of the art technologies as they become available. If the satellite is prepared for upgrades, that OAC could be a device to add resiliency, install a more modern battery technology, install higher efficiency solar panels, or utilize a new optical communication system. The original mission may be still valid, but with the upgrade the satellite can continue for years to come.

Sullivan, Parrish, and Roesler [8], proposed the basic characteristics and installation scenario of an OAC as it relates to the GEO mission of the RSGS. They showed a baseline system interface and establish the OACS as devices ranging in the 90-150kg size to provide delivery service of "additional robotic tools, repair hardware, and other as-needed items required to accomplish RSGS servicing missions."

OACs can be delivered to orbit through a variety of means. SpaceLogistics is currently focused on GEO orbits. It is envisioned that OACs can be delivered to GEO as hosted payloads aboard MEPs that are routinely arriving in GEO. In Sullivan, Parrish, and Roesler, they envisioned OACs being delivered using the concept of a payload orbital delivery system (PODS) [9] that act as a delivery medium to get the articles to the right servicing location. MEPs and PODs can carry a series of OACs to be used in single or multiple servicing operation.

1.4 Persistent Platform and ORUs

Orbital persistent platforms for technology demonstrations have traditionally been human-tended stations. The ISS provides a hosting capability for payloads and a robotic system to assist with placement. Next generation commercial destinations will also continue to have capabilities for hosting payloads, albeit these will be restricted to LEO. A nimbler architecture with a capability to operate at multiple orbital regimes would use persistent platforms that are robotically tended and do not have human habitation modules. These platforms could be built around an ESPAStar vehicle, a mature vehicle for hosted payloads, with opportunities for expansion. Starting with a single ESPAStar, equipped with a robotic arm system (RAS), the platform would be able to remove and add payloads to its ports delivered by visiting vehicles. Power, processing, and communications would be provided by the ESPAStar through a common interface to each of the berthed payloads, reducing the complexity of each individual payload.

Orbital replacement units have, to date, been exclusive to such human missions as upgrading the Hubble Space Telescope's (HST) capabilities and life extension and repairs to the International Space Station (ISS). Robotic assistance for both HST servicing and ISS EVAs has been vital to these repairs, but in each of these cases, human dexterity has been utilized for final integration, power and data connections, and on-orbit troubleshooting. With the Mission Robotic Vehicle (MRV) available for in orbit activities in 2024, a capable robotic free-flyer will be able to service future prepared satellites for Earth science, astronomy, and technology demos. Prepared satellites such as persistent platforms would have a common, open interface for power, data, and fluids to enable robotic attachment of ORUs. ORUs for propulsion, edge processing, new instruments, and technology demos for future exploration missions can be developed to be part of this new service ecosystem. These ORUs can follow the same size, weight, and power restrictions that separable payloads do on vehicles such as the ESPAStar. MRV would attach ORUs onto prepared satellites and persistent platforms, integrating them with the spacecraft through a common interface.

GEO is a key commercial opportunity for hosted platforms in the near-term as there is no currently reconfigurable, serviceable platform in this domain. Expansion of this kind of platform may be accomplished using pre-assembled and deployable trusses to connect spacecraft "nodes" together. An interesting expansion of this concept is to utilize a walking robotic arm that uses hard points along the truss structure to move around the entire platform, capturing delivered ORUs and berthing them onto open ports. Coupling this assembly with a refueling capability and swap-out of electric propulsion systems would give the platform an ability for orbital maintenance and/or transfers to other orbital regimes.

A cis-lunar persistent platform would enable a low barrier to entry for commercial partners to test their payloads in providing support to NASA's Lunar exploration objectives. This platform, being only robotically tended, would not have the same crewed safety requirements as NASA's Gateway and will allow commercial providers to integrate a payload rather than having to design either a smallsat or cubesat to accommodate their technology. Each of these payloads may be class C or class D without incurring significant risk to the persistent platform.

Similarly, persistent platforms could be created at Sun-Synchronous (advancing capabilities for Earth science), Earth-Sun L1 (solar observation and space weather early warning system), and GEO (communications). These platforms could be assembled for a relatively low cost and provide commercial companies with a means to operate in each of these domains prior to designing an independent smallsat spacecraft or class A payload that could be a long-term hosted payload on the persistent platform to support NASA's science objectives.

1.5 Space University Research Initiative (SURI)

A team from Carnegie Mellon University in collaboration with Texas A&M and the University of New Mexico, plus Industry partner, Northrop Grumman Corp, recently won a multi-year contract from AFOSR and AFRL called SURI, to develop space rated servicing assets including inspection systems, versatile and flexible robotic devices, and satellite servicing techniques. The effort will focus on cost effective ways to develop future systems that make on orbit modifications to augment or replace mission capabilities on satellites, a common practice by the end of the decade. The results of the SURI is anticipated to feed directly into Industry applications of satellite servicing

2 EXAMPLE MISSIONS

2.1 Replacement of a GEOStar 2 solar panel

In 2021, Northrop Grumman sponsored a student based program at the University of Michigan (UM) to investigate the effort required to replace a hypothetical solar panel that is non-functional in space. Research showed that of the 95 failure incidents reported from 1997-2009, 26% were power problems and 24% of those were caused by solar panel failure and 44% by internal power failure [10]. These power failures have cause approximately $4.4B worth of damages over the last 15 years [11]. It was determined that internal power systems remain farther in the future for servicing opportunities, but solar panel replacement could be accomplished. The method investigated was to slide and clamp a roll-out solar array OAC onto the solar array drive structure, disconnect the bayonet connector of the rigid solar array and connect the bayonet connector of the roll-out solar array, and deploy the roll-out solar array. The clamping mechanism (Figure 11) is engaged using a drive tool on the MRV and is held by a simple latch and magnet. Deployment of the roll-out solar array would be accomplished by heating a breakaway element to failure, allowing the stored strain energy of the array to unfurl itself. The system was scaled for a 5kW array but scaling to larger power generation systems is possible. By targeting a known structure consistent on many satellites, vision system identification for initial placement of the clamp was simplified. This allows some degree of autonomy for servicing to be accomplished with a clear understanding of the expected collision environment. With solar array servicing being external to the spacecraft, this may likely be the next candidate for major subsystem upgrades and repairs after propulsion.

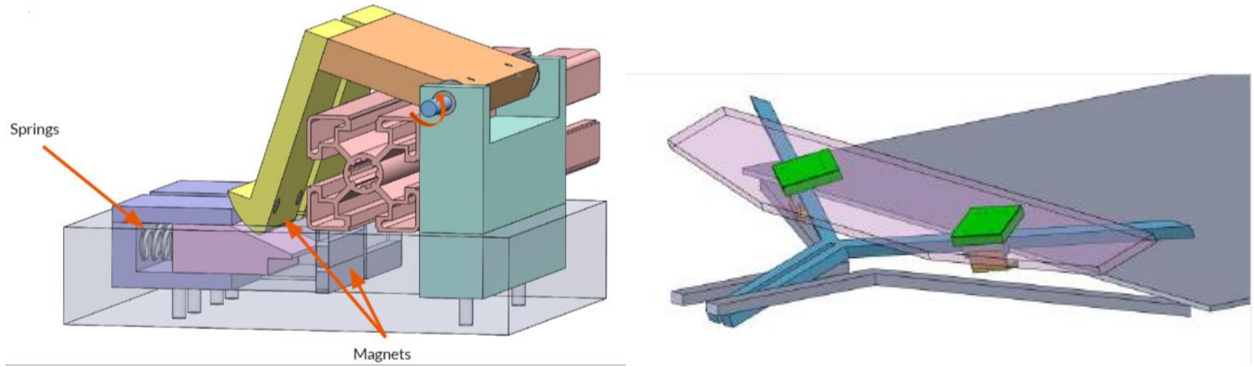


Figure 11 - Clamping mechanism for solar array drive structure

2.2 Chandra

By now you should be thinking about the possibilities for satellite servicing for existing satellites. As shown earlier, data on active GEO Sats [12] indicates that 53% will experience some fuel-related operational impacts. Dozens more are candidates for addition of OACS to change or enhance their post launch mission. One might be Chandra.

A few candidate satellites are large enterprise assets to the science community, such the Chandra X-ray Observatory (CXO) and the Hubble Space Telescope (HST), the remaining operating NASA's Great Observatories, until the addition of the James Webb Space Telescope earlier this year. Northrop Grumman is studying possible life extension missions for these, to assess the science return and cost of various options, to determine if such life extension is a viable option.

The Chandra design, as originally proposed, was an EVA compatible, serviceable LEO mission, including future instruments, similar to the plan for HST. Budget pressures in the early 1990's forced a change in CXO's architecture to a non-EVA compatible design with a highly elliptical orbit, approximately 14,000 km by 130,000 km at launch [13]. The Chandra X-ray Observatory was launched on its 5 year mission in July 1999 into a highly elliptical orbit from the Space Shuttle Columbia as part of STS-93 and achieved first light in August 1999. As a result of its sub-arc second resolution, CXO is a highly successful and singular asset for the worldwide science community [14].

Over twenty years in operation, Chandra is not surprisingly showing signs of wear over its long extended mission which is complicating ground based mission planning. The best known and most fundamental of these wear issues is the long term degradation of the insulation [15]. The degradation has resulted in an overall increase in temperature and increasingly complex operations and scheduling, as CXO cannot dwell on any given attitude, and some attitudes are not permitted at certain times. The implications of the degraded insulation have further resulted in the retirement of the radiation detector, the EIPHIN instrument and increased noise in the aspect camera.

In our study developing life extension mission options for CXO, we investigated options that are cost effective, namely returning a large amount of science capability for the servicing investment. A systems analysis leads to a simple graphic illustrating the range of options is shown as Figure 12. The candidate options, 1-4, return differing amounts of capability at different costs, the zone of acceptability is shown in green. A conceptual set of mission extensions for Chandra are in Table 1.

Recovery of the insulation performance and the restoration of thermal performance on Chandra, can be realized a number of ways; coatings could be reapplied on the existing insulation, a blanket could be replaced or a sunshade similar to that planned for Lynx could be attached (Figure 13). As we begin our study of alternatives, each option is analyzed for independence on the current and unknown integrity of the insulating blankets, demands on robotic assembly, compatibility with other possible life extension options, cost of development and ultimately probability of restoring the BOL thermal condition. We then bundle them into various mission configurations and determine where in the cost effectiveness space they fall.

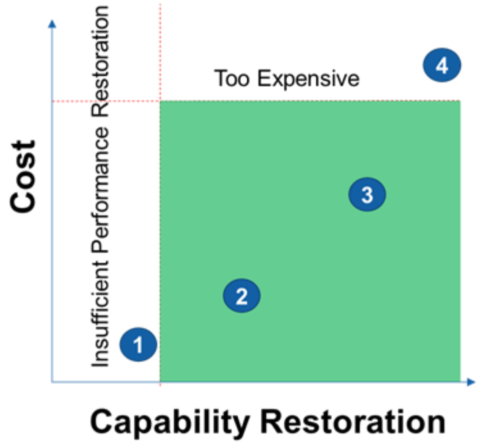


Figure 12: Cost/ Capability Evaluation

Table 1: Potential Life Extension Options for Chandra

Performance Issue	Life Extension Options
Degradation of Insulation	Replace insulation Attach sunshade
Momentum Management	Raise perigee to avoid gravity gradient induced torques
Electrical Power	Solar array replacement
Accumulated Dose in CCD Detector	Local shielding Raise perigee to avoid Van Allen belt transition

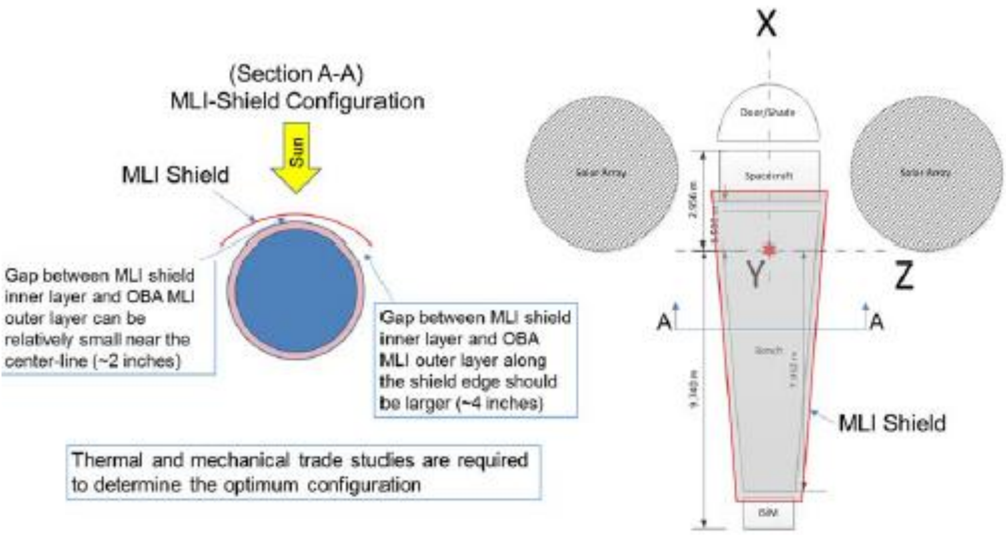


Figure 13 Proposed Lynx Sunshade

It is expected that a life extension mission will add years to the already long-lived Chandra mission, but those years could also be more efficient, further adding to the potential of higher quality scientific return. Our study will help to determine the cost of each of the potential mission and answer the question, what missions lie in the "Green Zone"? Likely a MRV servicing vehicle described above would be called on to perform the on orbit logistics.

3 NEXT STEPS

Now that satellite servicing is a reality and persistent robotic servicing is becoming available in GEO orbit, what should satellite operators being doing next to take advantage of these capabilities? Northrop Grumman and SpaceLogistics are proposing that satellite operators and all Original Equipment and Satellite Manufacturers, begin incorporating satellite servicing features into their next generation satellite designs. The key features proposed are:

- Rendezvous, Proximity Operations and Capture (RPOC) fiducials to assist in precision autonomous RPOC.
- Capture fixtures such as robotic grapple fixtures
- Refueling ports and fixtures for fuel pumping or tank installation
- Power and data ports (similar to a USB port) that can be used to install OACs that connect to the client satellite power, TCS, and data backbone.
- Including terms and conditions in contracts that support the needs for future satellite servicing

Looking further ahead into the future, the current servicing capabilities being commercially deployed together with the technical demonstrations like OSAM-1 and OSAM-2 are demonstrating the fundamentals of in-orbit satellite assembly and manufacturing that will enable a new, more flexible, and cost effective approaches to satellite design and deployment. This future will overcome the tyranny of the launch vehicle that limits the size of the spacecraft being launched and adds tremendous structural and mechanical complexity to the systems.

4 CONCLUSIONS

Satellite servicing is on the cutting edge and will soon transform the way we design satellites of the future. Leveraging off of several key advancements in space logistics, robotics and autonomy of the past, we have shown with the Mission Extension Vehicle and other systems to follow, that repairing, modifying and upgrading satellites while in orbit, is now in our realm of capabilities. Industry and government partners together will continue to develop ways to make this all possible in a cost effective alternative to simply disposing of aging satellites. On orbit servicing will be used in the future for assembling large space structures such as antennas, power grids, and support deep space missions. We have been waiting for years for satellite servicing, and 2020 will be remembered as the year it became an effective tool for satellite and space system developers.

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