Application of Solar Electric Propulsion in the Emerging Satellite Servicing Industry

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Michael J. Glogowski[1], Joe D. Anderson[2], Gregg A. Herbert[3], Andrea D. Kodys[4], and Will A. Llorens[5]
Northrop Grumman Innovations Systems, Space Systems Division, Dulles, Virginia, 20166, USA

Abstract: Solar electric propulsion has fundamentally changed the design and economics of communications satellites, starting with its initial use for station keeping operations of geostationary satellites to its widespread adoption for orbit raising, either alone or in conjunction with a chemical propulsion system. In low earth orbit, the ability of electric propulsion to reduce the mass to orbit and correspondingly increase the number of satellites carried during a single launch has made low power electric propulsion systems a key element in the realization of large satellite constellations in low earth orbit. Beyond these missions, the next evolutionary step for electric propulsion lies within the emerging satellite servicing industry as evidenced by Northrop Grumman's Mission Extension Vehicle slated for launch in 2019. This paper provides an overview of the satellite servicing ecosystem, the market potential, and mission requirements as they relate to the sizing of the electric propulsion system. The paper includes a description of the first Mission Extension Vehicle, it electric propulsion system, which is based on Northrop Grumman' flight proven GEOStar-3 system, and its concept of operations for satellite servicing. The paper also provides a preview of the next generation systems under development at Northrop Grumman to enable more services beyond mission lifetime extension.

Nomenclature

g	=	gravity constant
Isp	=	specific impulse
P_T	=	total power
T	=	thrust
η_T	=	thruster total efficiency

I. Introduction

SOLAR electric propulsion has changed fundamentally the design and economics of communications satellites, starting with its initial use for station keeping operations of geostationary satellites to its widespread adoption for orbit raising, either in conjunction with a chemical propulsion system or exclusively by electric means. Furthermore, given its ability to reduce the mass to orbit and correspondingly increase the number of satellites

[1] Senior Director, Advanced Product Development, Space Systems Division, michael.glogowski@ngc.com
[2] Vice President, Business Development and Operations, Space Systems Division, joseph.anderson@ngc.com
[3] Chief Engineer, Mission Extension Vehicle, Civil and Commercial Satellites, gregg.herbert@ngc.com
[4] Senior Principal Mechanical Engineer, Propulsion Engineering Department, andrea.kodys@ngc.com
[5] Systems Consulting Engineer, Systems Engineering Department, william.llorens@ngc.com

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carried during a single launch, solar electric propulsion has become a key element in the deployment of large satellite constellations into low earth orbit. Beyond these applications, the next evolutionary step lies within the emerging satellite servicing industry as evidenced by Northrop Grumman's Mission Extension Vehicle (MEV™) slated for launch in 2019. This vehicle (Fig. 1) will rendezvous with a communications satellite near its end of life (EOL) in geostationary (GEO) orbit, dock with the vehicle, and then take over both attitude control and orbit maintenance functions. This first-of-its-kind mission represents one of numerous potential on-orbit services, such as inspection, repair, refueling, and assembly, which would benefit commercial, civil, and defense customers. In view of the high delta-V associated with these missions, in particular those beyond LEO, these missions are only made possible by the high propellant utilization efficiency offered by solar electric propulsion.

II. Background

Up until this year, on-orbit servicing has been exclusively the purview of human-based operations and government research and development projects. Early examples of on-orbit servicing by humans go as far back as the Gemini and Apollo missions where rendezvous, proximity operations and docking (RPOD) were realized to the benefit of human exploration of the moon. On-orbit repairs were first demonstrated on Skylab and the Solar Maximum Mission, leading up to routine servicing of the Hubble Space Telescope starting in 1993 with the replacement of its optics package and numerous other components. Subsequently, the International Space Station (ISS) demonstrated on-orbit assembly, replenishment of consumables, and payload augmentation. In terms of robotics-based servicing, the Defense Advanced Research Projects Agency (DARPA) successfully led a demonstration of end-to-end robotic servicing through its Orbital Express (OE) program[1]. In 2007, the OE program demonstrated autonomous docking, liquid propellant transfer, and transfer of a battery and flight computer, referred to as Orbital Replacement Units (ORU), between a client vehicle (NextSat) and a servicing vehicle, known as the Autonomous Space Transport Robotic Orbiter (ASTRO). NASA's Demonstration of Autonomous Rendezvous Technology (DART) program[2] preceded the OE program by two years but ended prematurely after encountering a collision with its client vehicle, the MUltipaths Beyond Line-of-sight COMmunications satellite (MUBLCOM), due to inaccurate navigational data.

Figure 1. The Mission Extension Vehicle.

DARPA and NASA continue to promote, and serve as catalysts for, robotics-based on-orbit servicing. At NASA Goddard's Satellite Servicing Capability Office (SSCO), the agency is developing the technology that will enable refueling of spacecraft not designed to be serviced on orbit. NASA's Restore-L mission[3] will demonstrate this capability starting in 2020 by rendezvousing, grasping and refueling a government-owned satellite in Low Earth Orbit (LEO). DARPA is pursuing the Robotic Servicing of Geosynchronous Satellites (RSGS) program to "demonstrate in or near GEO that a robotic servicing vehicle can perform safe, reliable, useful, and efficient operations, with the flexibility to adapt to a variety of on-orbit missions and conditions.[4]" Both government agencies are pursuing their programs with industry support with the goal of ultimately creating a new domestic, commercial satellite servicing industry.

Northrop Grumman (NG) is positioned to be a leader within this new industry and has created a wholly-owned subsidiary, known as SpaceLogistics LLC, to promote the development and commercialization of NG satellite servicing vehicles. The following sections provide an overview of the on-orbit servicing ecosystem, the market potential, and the enabling role of electric propulsion for these services. Section IV provides a description of the first vehicle, MEV-1, while Section V provides a preview of the future systems under development at NG.

A. On-Orbit Servicing Ecosystem

On-orbit servicing (OOS) refers to activities performed in orbit by one space vehicle on another space vehicle for the purpose of providing some beneficial service for the serviced space vehicle. The space vehicle designed for servicing operations is known as the *servicer* or *servicing vehicle*, while the space vehicle receiving the service is known as the *client* or *client vehicle* (CV). The CV can be either prepared or non-prepared, meaning that the CV possesses or does not possess features that help facilitate the servicing operation. These features include, but are not limited to, grappling fixtures that aid in robotic capture by the servicer, positional targets that aid in rendezvous with the CV, and quick disconnect vales that simplify refueling operations by the servicer. NG's Commercial Resupply Vehicle, known as Cygnus, is an example of a prepared client having been designed in advance to mate with the ISS. The numerous operational satellites in LEO, MEO, and GEO are examples of non-prepared CVs as they have been designed and built without the forethought of being serviced on-orbit. However, these vehicles do possess features, such as separation clamp bands, liquid apogee engines, and external valves, which can be utilized for servicing operations. These non-prepared clients constitute the largest market for near term servicing missions until on-orbit servicing becomes a norm within the industry and is accounted for in the spacecraft design process.

Satellite servicing activities cover a wide range of operations without a common set of terms used to describe the different categories of operations. The Consortium for Execution of Rendezvous, and Servicing Operations (CONFERS)[5] with support from NASA, DOD, the AIAA, and industry members like SpaceLogistics are working on standardizing these activities as the industry continues to grow and become a part of future space systems. For this paper, the categories for on-orbit servicing as defined by The Aerospace Corporation[6] are used as follows:

- **Inspections (non-contact support).** Inspections occur near the CV and help facilitate determination of the failure mechanism and degree of damage due to an on-orbit anomaly. It also aids in determining the best course of action to recover from the anomaly.
- **Orbit Modification and Maintenance.** This service requires mating of the servicer to the client vehicle in order to provide the propulsion and possibly the attitude control functions for these services. Orbit modification refers to moving the CV between two orbital positions by the servicer. This action covers the full spectrum of servicer assisted maneuvers, from end of life disposal to orbit transfer (space tug) from an intermediary transfer orbit to a final operational orbit. It also includes repositioning between orbit longitudes, inclination reduction, and orbital node rotation. Orbit maintenance covers primarily station keeping but can also include CV attitude control and/or momentum control. Orbit modification is a one-time service completed over days, weeks, or months, while orbit maintenance occurs over an extended period of time expressed in terms of years of service.
- **Refueling and Commodities Replenishment**. Both of these services refer mostly to fluids that are depleted over the course of CV operations, such as liquid propellant and pressurant gas. It can also include other objects with limited service life due to known wear out and aging mechanisms, like propulsion thrusters (degradation in catalyst bed, wear-out of nozzle, erosion of ion thruster grids, etc.) and batteries.
- **Upgrades.** This service results in enhancements of the CV's capability through replacement of existing components with more capable components or addition of new components with new capabilities. Examples of replacement components include a new imaging sensor for greater resolution or a new flight computer with more processing power. Examples of new components could be a new communications payload that expands the market potential of the CV or a sensor suite for situational awareness of the CV's immediate space.
- **Repair.** This service entails the correction or replacement of a component or subassembly that has encountered a failure during operations. Examples over the past 20 years that would have benefited from on-orbit repair include: releasing a stuck solar array or reflector; adjusting or removing thermal blankets that are interfering with another system; and repositioning of coordination cables on the solar array guide tracks.
- **Assembly.** As the name indicates, this operation combines two or more objects to form a new object in space. It could also include the addition of a new object to an existing in-space asset, which overlaps with the Upgrade service discussed above. The best example of a recent in-space assembly operation is the ISS. Examples of future missions requiring in-orbit assembly include the lunar Gateway, the next generation of very large space telescopes, like Star Shade, in-space power generation towers, and modular, high power communications arrays.

- **Debris Mitigation.** Similar to orbit modification, debris mitigation targets in-space objects that are no longer operational and pose a threat to its surrounding environment and moves the object to an orbit where it is safe (GEO graveyard orbit) or can be de-orbited entirely (LEO objects). Examples include 'zombiesats' that drift within the GEO belt, launch vehicle upper stages, and satellite fragments from an ASAT event.

The tools required to perform these services can vary widely, but typically fall into the category of sensors for rendezvous and proximity operations (RPO), mechanisms for docking, and robotics for grappling and manipulation. In addition to these tools is the spacecraft bus, which provides the necessary power, propulsion, data, guidance, navigation, and control for these operations.

B. Satellite Servicing Market

The Aerospace Corporation conducted a study[7] in 2011 to understand the potential demand for on-orbit servicing of spacecraft in geosynchronous orbit. The study focused on spacecraft in GEO, rather than other orbits like LEO or MEO, since a servicer would have access to numerous spacecraft within a relatively narrow orbital regime, thereby reducing the delta-V requirements needed to service multiple spacecraft. The data for the study originated from the Space Systems Engineering Database (SSED) maintained at The Aerospace Corporation. While the database contained at that time approximately 30,000 records of anomalies, only those anomalies occurring on spacecraft intended for GEO launched between January 1990 and August 2010 were included in the study. Furthermore, the anomalies were limited to unclassified missions, meaning it was limited to U.S commercial and civil vehicles as well as foreign commercial, civil, and military spacecraft. Of the missions with an end of life event, 92% were communications satellites. Over the 20 year period, 556 satellites were launched, and 128 encountered an anomaly that was evaluated for its serviceability. Of this total number of satellites, 47 would have been candidates for life extension and 38 would have been candidates for repair.

Intelsat[8] studied the implication of these on-orbit anomalies to the probability that a satellite within their fleet would benefit from servicing, if it were readily available on orbit. At the time of the study (2013), Intelsat had 50 satellites in GEO and was launching approximately 3 satellites per year to replenish their fleet. Based on the failure statistics compiled by Intelsat, they forecasted that one serviceable beginning of life (BOL) anomaly would occur every 7 years. Extending this argument to all of the unclassified satellites in GEO, for which there were over 400 in 2013, indicates that, statistically, one GEO satellite would require servicing every year. For a satellite that encountered a BOL anomaly, the ability to inspect and rescue the on-orbit asset, whose cost could be between $200M to $400M (including spacecraft, launch, and insurance, but not return on investment), would provide considerable value to the satellite operator, spacecraft manufacturer, and the insurance company. In turn, it would produce a huge wind-fall for the satellite servicing company capable of rescuing the mission.

In addition to BOL anomalies, the satellite servicing market potential is much bigger when including the opportunity to extend the mission lifetime of satellites reaching the end of their propellant life. Based on Ref [9], the number of satellites retiring per year was approximately 8 in the early 2000's and is expected to increase to about 10 - 15 by the end of this decade. Looking forward, Northrop Grumman estimates that over 230 satellites will reach the end of their design life between 2020 and 2030 as shown in Fig. 2. While historically GEO comsats tend to exceed their design life by several years, this number conveys a very large potential of serviceable satellites.

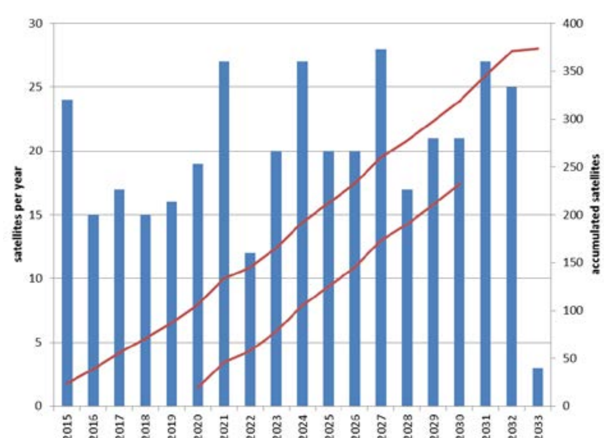

Figure 2. Satellites reaching end of design life from 2015 through 2033.

The direct benefit of extending the mission life of a GEO satellite is to prolong the revenue generating potential of the on-orbit asset. In the early 2010's, it was estimated[8,9] that the average communications satellite with 24 transponders earns roughly $2M/year/transponder, equating to $48M of annual revenue from that satellite. Larger spacecraft may have 48 to 100 transponders, yielding even higher earnings and the associated return on investment. While the earnings per transponder have decreased recently due to the oversupply of capacity in traditional areas, like C- and Ku-band Fixed Satellite Services (FSS), and to the roll-out of High Throughput Satellite (HTS) systems offering much higher capacity per transponder, this change in the market landscape could further increase the interest in on-orbit satellite servicing by providing the satellite operator with a means to achieve a return on their original investment by extending the satellite mission lifetime. It also permits the satellite operator to delay the capital expenditure for a replacement satellite as market conditions evolve. According to Ref [8], the savings associated with the 'cost of funding' the construction and launch of a new satellite could be as much as $18M per year. In view of this amount, the authors argue that it sets the annual cost of the mission lifetime extension service. However, this argument does not reflect certain realities, such as tight capital markets and uncertainty about the GEO communications market, which could create a stronger demand for the mission lifetime extension service.

In short, while the satellite servicing market holds enormous potential as reflected in the roughly 20 satellites per year reaching their end of design life in the next decade, the business economics must be factored into the engineering design process to ensure that the final system is not just technically viable, but commercially as well.

III. Application of Solar Electric Propulsion

Electric propulsion (EP) enables satellite servicing missions in GEO by reducing the amount of propellant required to deliver the service to the client vehicle. Whether the service involves refueling, robotic operations, orbit maintenance, or orbit modification, there is an associated delta-V for bringing the service to the client and performing the service for the client. To make the satellite servicing economically viable, multiple servicing operations should be performed over multiple clients, whether the service is a single operation, like orbit modification, or an extended operation, like orbit maintenance. Combined with the delta-V required to reach GEO from a geostationary transfer orbit on an affordable, medium class launch vehicle, the total delta-V for the servicer can be significant, and in most cases, higher than the delta-V budget of a GEO communications satellite. Table 1 illustrates a notional delta-V budget of a multi-purpose servicer, where the servicer completes 15 years of orbit maintenance, one to three inclination pull-downs to zero inclination depending on the CV' initial inclination, three CV relocations, and three CV EOL disposals. Typically, more services are required to maximize the utilization of the servicer and reduce the cost of the service, driving the total delta V above 4,000 m/s. For comparison, a typical GEO satellite would require approximately 2,350 m/s of propulsive maneuvering.

Table 1. Example of Delta-V Budget for an EP Enabled Servicing Vehicle

Propulsive Maneuver	Delta-V (m/s)
Low Thrust GTO-to-GEO Transfer (Impulse Equivalent)	2,520 (1,800)
Inclination Adjustment	420
Station Keeping (15 years)	825
Station Reposition	60
EOL Disposal	65
Total DV	3,890

Through the rocket equation, the delta-V translates into propellant requirements for the total mass of the servicing vehicle and the propellant consumption efficiency of the vehicle propulsion system. For orbit transfer between GTO and GEO, the total mass is the combined mass of the servicer dry mass, the propellant mass for on-orbit operations and servicing (i.e., payload), and the propellant mass for the GTO-to-GEO transfer maneuver. As a result, the total mass of the servicer and the associated launch cost will increase as the propellant mass for on-orbit servicing increases. Since launch cost plays a significant factor in determining the price per year of service, it is important to minimize the total mass of the servicing vehicle.

For a CV refueling service, the propellant mass allocated to on-orbit servicing can be significant since the servicing vehicle must carry enough chemical propellant to refuel multiple CVs, transport this heavy propellant from GTO to GEO and between CVs, and control its orbital inclination relative to the CVs over its servicing lifetime. According to Ref [9], the liquid propellant mass needed to refuel a CV can be as high as 50 kg per year of extended lifetime. If the refueler intends to provide 40 years of total mission lifetime extension, then the total 'payload' equates to 2,000 kg of propellant. However, the penalty to boost this propellant from GTO to GEO, transport it from one CV to the next, and maintain the servicer orbital inclination in line with the CV's can be as high as 1,400 kg assuming that 8 refueling operations are performed over a servicer mission lifetime of 15 years. In this example, the total mass becomes 3,400 kg, or 85 kg per year of mission lifetime extension. EP can help reduce this propellant mass by providing a more efficient means to transport the chemical propellant and service the clients.

For a CV 'tugging' service, the propellant requirements can be reduced significantly by using an electric propulsion system with its higher fuel utilization efficiency over chemical propulsion. Combined with its use for orbital transport from GTO to GEO, the mass savings can be significant over an all-chemical, refueling approach. At a conservative 4X improvement in fuel efficiency (when accounting for the higher cosine losses associated with EP usage for orbit maintenance), the total required propellant load may only be 21 kg per year for mission lifetime extension. However, this approach carries its own penalty in that the servicer mass remains attached to the CV during servicing operations. In this case, it is essential that the servicer bus be optimized around the specific service(s) it is intended to provide. This optimization includes the electric propulsion system, as discussed in the following section.

A. EP System Sizing

Between the large total delta-V requirements and the range of potential client vehicle masses, the sole method for reducing the propellant load is through higher propellant utilization efficiencies characterized by the 'specific impulse' (Isp) of the servicer propulsion device. Electric propulsion enables the higher specific impulse and, as a consequence, becomes an economic necessity for satellite servicing. At a minimum, it can reduce the propellant mass penalty to transport the servicing propellant to GEO. At its best, it can reduce the total propellant demand for the complete satellite servicing mission. To that end, EP has been adopted on NG's first generation Mission Extension Vehicle and is planned for its next generation of satellite servicing spacecraft as discussed in Section V.

However, having a system with the highest, available Isp is not necessarily the right system solution. Per the relationship,

$$\frac{T}{P_T} = \frac{2\eta_T}{g\mathrm{Isp}},$$

increasing the Isp equates to lower thrust at fixed power and efficiency, which in turn equates to longer maneuver durations and the associated impact to spacecraft system sizing and mission operations. While not universal, the Hall thruster tends to trade more favorably over other electric thrusters, like the arcjet or gridded ion thruster, when used on Earth-orbiting satellites. The reason lies in the combination of higher thrust relative to the ion thruster and higher specific impulse relative to the arcjet thruster. At these conditions, the Hall thruster can propel the host spacecraft to its intended orbit in less time than an ion thruster at an equivalent spacecraft power level and can yield much less propellant and total spacecraft mass than the arcjet thruster.

The benefits of Hall thrusters for orbit raising have been reported elsewhere[10,11] and realized through their wide spread use on the all-electric communications satellites offered by the majority of satellite manufacturers, including Northrop Grumman. For CV servicing, several factors come into play that determine the optimal selection and sizing of the EP system. When the servicer is required to perform orbit modification maneuvers, such as relocation, inclination reduction, or even orbit circularization of a stranded CV, then maneuver duration becomes a major factor in establishing the EP power level and performance. For example, if an average sized GEO satellite (e.g., 2000 kg) requires reduction of its inclination to restore full communications services, then the maneuver duration for one degree of inclination could last less than a couple of weeks using a medium power Hall thruster system versus a couple of months using a low power system. The maneuver duration becomes even longer as the inclination reduction requirement becomes larger, as could be the case for a CV in free drift.

These considerations drive the system design to higher operating power levels, which in turn can drive the servicer solar array into a non-standard orientation to avoid CV shadowing during servicing operations. For this reason, the solar array on MEV (see Fig. 1) is oriented in the East-West direction as opposed to the nominal North-South direction (orbit normal) used by all GEO satellites. In the East-West orientation, the solar array cannot track the sun continuously throughout the day and, in fact, can encounter partial shadowing by the CV at certain points in the orbit. This condition produces the power availability profile shown in Fig. 3, which the servicing vehicle must account for, when developing a burn plan for CV orbit maintenance. This profile imposes constraints on EP firing and adds complexity to the orbit maintenance algorithm. However, to the first order, it does not drive the EP system size for a vehicle that must use its EP system for other functions, like orbit raising and orbit modification, where higher power and thrust are important.

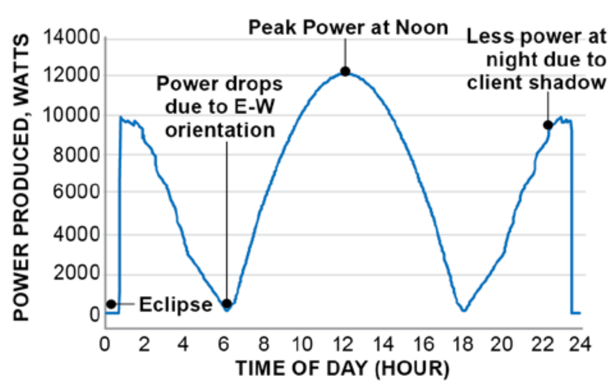

Figure 3. Power during equinox season for solar arrays oriented in E-W direction on servicing vehicle.

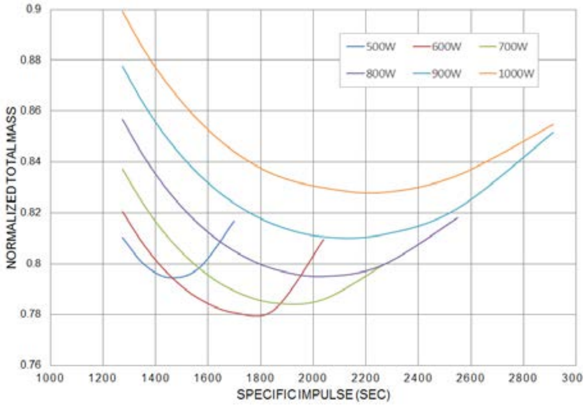

Figure 4. Electric propulsion system sizing results for client vehicle orbit maintenance only.

For a servicer that is optimized around a single function, such as orbit maintenance, a smaller solar array would be preferred for reasons of lower total system mass and cost. However, this configuration could lead to longer periods without solar array power due to CV shadowing, leading to larger batteries required to maintain power and propulsion during CV operations. To that end, a study was conducted to identify the ideal EP system operating point (specific impulse and thrust) and power system size for a servicer whose sole function was CV orbit maintenance. Fig. 4 presents the idealized results from this study for a heavy client vehicle. The normalized mass on the y-axis represents the relative change in the combined mass of the battery, solar array, EP system hardware, and propellant load, and therefore, provides a reasonable metric for the sizing of the system as each element will vary by power, Isp and thrust. The figure indicates that the optimal point for the propulsion system is neither higher Isp nor higher thrust, but rather somewhere in between. For a fixed EP power level, the normalized mass decreases with increasing Isp until it reaches a minimum, beyond which the normalized mass increases. The trend reflects the inherent trade between propellant mass and power system mass, which also translates into total system cost. At lower Isp, the increase in propellant mass is higher than the decrease in power system (battery) mass that comes with the higher thrust per the equation above. At higher Isp, the decrease in propellant mass is offset by a larger increase in power system mass as well as a decrease in maneuver efficiency due to the lower thrust. For different EP power levels, a similar trend is observed with the added influence of the mass of the solar array and power distribution electronics. For this particular example, the preferred operating point would be around 1800 seconds and 600 W. However, at this value, the servicer may not be capable of servicing a spacecraft heavier than the design reference point or may have difficulty in controlling CV momentum simultaneous with orbit maintenance. As a result, operation at a lower Isp and/or higher power to achieve higher thrust would provide a more robust system solution. Also, worth noting is that the chart does not reflect the realities of an actual system design. Solar arrays, battery, and even electric propulsion hardware will have step function changes in their hardware size and not smoothly varying as implied by the figure. Thruster power and Isp may also not be variable for the unit used in this application.

Table 2 captures the top level EP requirements for a multi-purpose vehicle, like MEV, and for a single purpose vehicle, like the Mission Extension Pod (MEP) as discussed in Section V. For MEV, Northrop Grumman employs Aerojet Rocketdyne's XR-5 Hall thruster system in a similar manner as on its GEOStar-3 spacecraft. A description of this system is provided in Section IV. For the MEP, a low power EP system is more suitable, but with its high propellant throughput requirement, it greatly restricts the type of thruster that can be used for the mission. Regardless, several low power Hall thrusters[12,13,14] are currently under development with the goal of reaching a propellant throughput that could ultimately support the MEP mission requirements.

Table 2: Electric Propulsion Requirements for Satellite Servicing

Parameter	Multi-Purpose Vehicle	Single* Purpose Vehicle
Orbit Delivery Method	Self-Propelled from GTO to GEO	Direct-to-GEO or Self-Propelled from GTO to GEO
On-Orbit Maneuvering	Inclination Reduction, Station Keeping, Satellite Relocation, and EOL Disposal	Station Keeping (with momentum adjustment)
Anode Power (W)	3000 - 4500	600 - 900
Specific Impulse (sec)	> 1600	> 1600
Thrust to Power (mN/kW)	>58	>58
Throughput / thruster (kg)	> 400	> 100

* Single purpose indicates an optimization of the system design around a single service and does not preclude other services, like station relocation and end-of-life satellite disposal.

B. EP System Compatibility Considerations

Development of a system for satellite servicing introduces several compatibility issues between the servicing vehicle and client vehicle, which must be addressed in order to ensure a safe and reliable service. In addition to client vehicle shadowing as discussed in the previous section, the issues include, but are not limited to, such matters as electromagnetic interference (EMI), electrostatic discharge (ESD), attitude transients, and momentum growth. The issues introduced by using electric propulsion relate to the unique plasma plume environment produced the electric thruster. This environment is characterized by high-energy xenon ions of different charge states, high-energy xenon neutrals formed through a charge exchange process, free electrons, and physical material sputtered from the body of the thruster. This plume can impact the CV attitude control system through torques induced by plume impingement on the CV solar array or the swirling motion of the ionized gas emitted by the thruster. It can affect the CV solar array efficiency and, in some limited cases, the solar array lifetime through erosion of the anti-reflective coatings and solar array interconnects. It could also lead to contamination of the spacecraft thermal control surface and optical sensors from the back-sputtered material from the solar array. Related to the plume are the radiated emission produced by the thruster. These emissions can occur in the communications bands of commercial satellites (mostly L and S-band) and could lead to interference with the telemetry, command, and ranging (TCR) subsystem or payload of the client vehicle.

However, these interactions are well understood and are evaluated for compatibility with the other satellites systems using sophisticated numerical models and simulation tools backed up with experimental test data. Northrop Grumman' uses AFRL's COLISUEM software suite to provide a realistic 3D framework for modeling the dynamics of the Hall thruster plasma plume and its interactions with the spacecraft surfaces[15]. These tools are applied as part of the verification and validation process for CV compatibility with the XR-5 plasma plume environment. An example of the results are shown in Fig. 5 for the integrated vehicle.

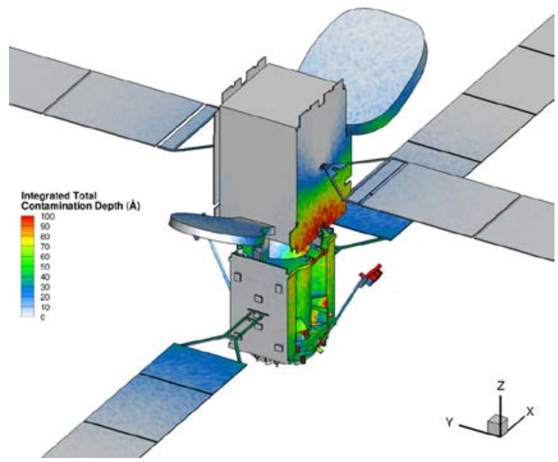

Figure 5. Integrated MEV/Client Vehicle plume compatibility analysis.

IV. Mission Extension Vehicle – First Commercial Satellite Servicing Mission

SpaceLogistics LLC provides on-orbit satellite servicing to geosynchronous satellite operators using a fleet of commercial servicing vehicles developed and built by Northrop Grumman. The initial servicing vehicle is MEV, which docks with any spacecraft equipped with a standard liquid apogee engine and launch separation ring and then takes over its guidance, navigation, and control for accurate pointing and station-keeping within its nominal orbit control box. This service maintains a 'keep-it-simple' approach and enables satellite operators to significantly extend satellite mission life, activate new markets, drive asset value, and protect finances.

In 2016, SpaceLogistics received contracts from Intelsat, the world's second-largest satellite fleet operator by revenue, for two MEVs. The first MEV is slated to fly in the autumn of 2019, as one of two payloads on a Russian Proton rocket. Once in orbit, MEV-1 will dock with the Intelsat-901 satellite in a rendezvous orbit outside of the nominal operational orbit of the client satellite. After the two vehicles mate, Intelsat will bring the stack to the operational orbit where it will continue to provide communications services under full control by MEV-1. The second MEV will launch in 2020 for rendezvous with another Intelsat satellite. In this case, the RPOD operations will be done in the geostationary belt leveraging the lessons learned from the RPOD operations on the first MEV. For the MEV-2 mission, Intelsat plans to dock and undock several times over the MEV-2 contract period for management of their fleet.

A. Space Vehicle Overview

MEV is a three-axis stabilized spacecraft based on the flight-proven GEOStar-3 platform. It consists of a central core structure, two bus avionics panels, two thruster pointing assemblies (TPAs), a communications boom, two articulating solar arrays, a rendezvous, proximity operations and docking (RPOD) sensor suite, and a mechanical docking system (MDS). It is designed for 15 years of mission life, taking into account the radiation environment of the geosynchronous orbit and the longer geostationary transfer orbits associated with electric orbit raising. It is also compatible with the electromagnetic interference (EMI) and electrostatic discharge (ESD) requirements associated with client vehicle servicing.

The central core structure is a modified GEOStar-3 structure that is compatible with all commercially available launch vehicles and capable of launching in tandem with a second satellite for greater flexibility and lower launch cost. It supports a single hydrazine tank for a monopropellant propulsion system and four xenon tanks for an electric (Hall) propulsion system as shown in Fig. 6. The monopropellant propulsion system is used for RPOD operations with the CV in addition to early orbit operations, as needed. The electric propulsion system uses the flight-proven Aerojet Rocketdyne XR-5 Hall thruster system and a modified version of the GEOStar-3 TPA, as discussed in more detail in the following section. The EP system performs a majority of the orbit raising and rendezvous operations to reach the client vehicle and then after docking is complete, it performs all station keeping and momentum management functions of the combined stack of MEV and CV. Given the large delta V requirements and multiple thruster pointing orientations, the MEV service can only be accomplished through the use of this technology. In particular, the XR-5 Hall thrusters provide the specific impulse and thrust-to-power needed for minimal fuel usage and acceptable maneuver burn durations during orbit modification operations. The TPA facilitates the use of the EP thrusters in an optimal manner by adjusting their thrust vector depending on the maneuver and center of gravity (C.G.) of the combined vehicle. Each TPA supports operation of one thruster at a time and deploys away from the spacecraft for greater maneuverability and plume separation distance from critical systems on the MEV and CV.

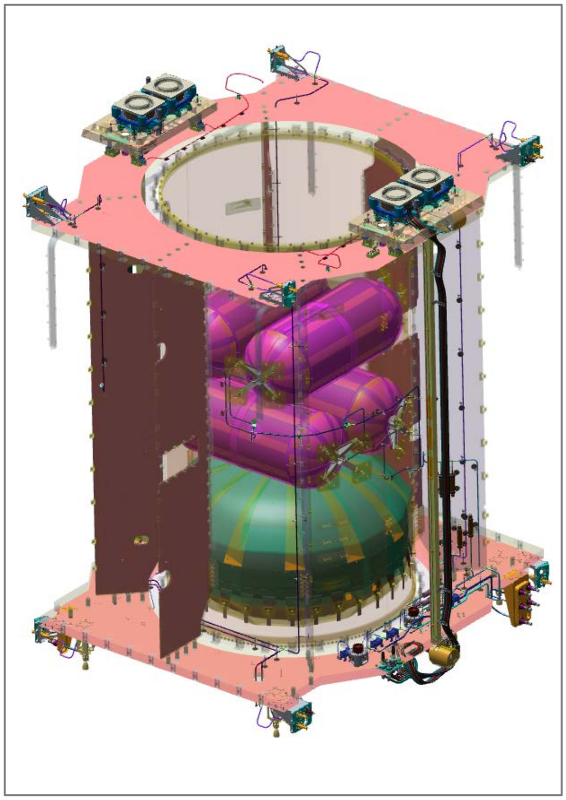

Figure 6. MEV hybrid monopropellant chemical and electric propulsion system.

The power system uses two solar array wings sized for 10 kW at end of design life and oriented in the East-West direction to limit CV shadowing. It uses solar array drive assemblies (SADA) with 360° articulation and lithium ion batteries to support on-orbit operation during shadowing events. The telemetry, control and ranging (TCR) system consists of two sets of flexible frequency receivers and transmitters, one set operating in C-band and the other in Ku-band. The communications boom has four TCR antennae, one receiving and one transmitting for both Ku- and C-band communications, as well as two actuators for azimuth and elevation control of the boom. This configuration allows the antenna arrays to be moved according to client vehicle (CV) geometry to maximize ground coverage during RPOD operations. The guidance, navigation, and control (GN&C system) includes all equipment needed to maneuver and control the attitude of the stand-alone MEV during orbit raising and RPOD operations and of the combined vehicle during CV servicing. This includes the ability to point the CV antennae within a tight pointing error required by GEO communications satellites. The RPOD sensor suite consists of visible cameras, infrared cameras, and LIDAR in addition to the avionics boxes that control the sensors and navigation software. The capture mechanism system consists of stanchions used to provide a docking interface between MEV and the CV, a probe used to capture the CV's liquid apogee engine (LAE), and a lance used to deploy and retract the probe.

B. MEV Electric Propulsion System

The EP system consists of two Hall thruster strings, each having one power processing unit (PPU), two XR-5 Hall (current) thrusters (HCT), and two xenon flow controllers (XFCs). Each string is fed by an independent xenon pressure regulation branch within the propellant management assembly (PMA). Xenon is stored in four composite overwrapped tanks at a total load required for the MEV mission. One pair of thrusters (from separate strings) is mounted onto each TPA. The key elements of the Hall thruster string are shown in Fig. 7 and discussed as follows.

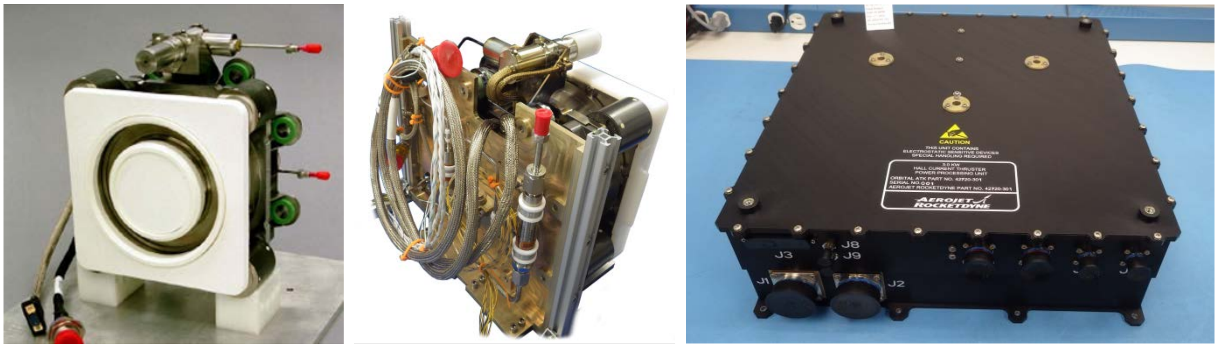

Figure 7. The XR-5 Hall thruster string (HCT, XFC, and PPU).

1. XR-5 Hall Thruster

The XR-5 is a medium power Hall thruster designed for high performance operation and throughput. On MEV, it operates at an anode discharge power level of 3 kW and discharge voltage of 400 V. The thruster consists of two major subassemblies, the accelerator subassembly and hollow cathode subassembly. The accelerator subassembly includes the xenon gas flow distributor, anode plate, insulator rings, and magnetic circuit, all of which are required to maintain a stable plasma discharge for production of xenon ions and generation of thrust. The hollow cathode subassembly contains a thermionic emitter material, which generates the electrons required to sustain the plasma discharge and neutralize the ion beam. A cathode heater and keeper circuit within the cathode subassembly help facilitate the generation of electrons and extend the lifetime of the cathode emitter. Details of the XR-5 design can be found in Ref. [16]. For the MEV, minor design updates were made to the heritage design and verified under the GEOStar-3 program[17]. To date, Northrop Grumman has launched eight XR-5 Hall thrusters on two GEOStar-3 satellites. The first system on Al Yah-3 completed extensive orbit raising as a result of a launch error that placed the satellite into an incorrect geostationary transfer orbit[18]. The thrusters were successful in recovering the mission and have now completed over one year of station keeping operations. All eight thrusters are performing nominally.

2. Xenon Flow Controller

The xenon flow controller delivers xenon flow to the XR-5 thruster at a rate in the range of 6 – 20 mg/s. One XFC is required for each XR-5 and is mounted directly behind the XR-5 on the TPA pallet. The XFC consists of one normally-closed Moog proportional flow control valve (PFCV), two flow control orifices (gas flow restrictors), and one cathode in-line filter. Regulated xenon pressure (34 – 40 psi) from the propellant management assembly (PMA) is provided to the inlet of the XFC. The PFCV provides positive isolation when closed, providing an additional seal in series with the PMA seals to minimize xenon propellant leakage during non-operational periods. During operation, the PFCV regulates the xenon flow to the XR-5 via closed loop control of the poppet location using a proportional-integral-derivative (PID) control circuit within the PPU. The PPU senses the HCT discharge current and opens or closes the poppet valve to achieve the commanded discharge power level (for a fixed voltage). The PFCV can also be commanded open loop via the PPU for venting xenon, as required, to test the propulsion system or control the upstream pressure. Gas flow restrictors on the anode and cathode lines provide the required cathode to anode flow split. The cathode inline filter provides additional protection to the cathode against micron-scale particles which may cause flow restriction or chemical contamination of the cathode.

3. Power Processing Unit

The PPU provides all power conditioning, command, and telemetry interfaces from the MEV spacecraft to the HCT and XFC. It provides regulated discharge power to the HCT for both start-up and steady-state operation as well as commandable currents to the HCT magnets and cathode heater. The PPU includes an integral thruster output selection module that enables the PPU to switch between two HCTs, operating one at a time. The PPU also provides closed-loop control of the XFC. The PPU directly interfaces with the regulated 36V spacecraft bus and operates with a total efficiency greater than 90%. Commands and telemetry are communicated over a MIL-STD-1553B data link. Radiation hardened components are utilized to meet the MEV mission requirements.

4. Thruster Pointing Assembly

MEV uses a patented, multi-axis thruster pointing mechanism for steering the electric thrusters for a wide range of maneuvers, either in the MEV only configuration or the MEV/CV stacked configuration. Shown in Fig. 8, the TPA employs four Moog rotary actuators with two mounted to the spacecraft body for deployment and delta-V steering of the HCT pallet and two mounted onto the pallet for two-axis thrust vector control. In between the

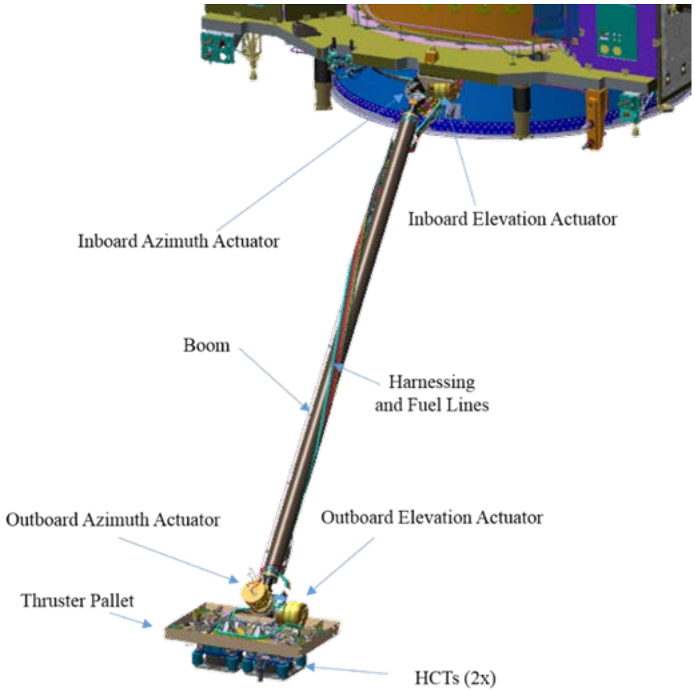

Figure 8. Thruster Pointing Assembly on MEV-1.

spacecraft-mounted actuator and thruster pallet is a single boom. The thruster pallet provides a mounting interface for two Hall thrusters and their xenon flow controllers and can support the operation of one Hall thruster at power levels greater than the nominal operating point of 3 kW for the XR-5 Hall thruster.

Salient features include a low-shock launch lock configuration, a nested coil assembly for a wide range of travel with primary and redundant feed lines, and a harness routing configuration that minimizes both resistive torque and packaging volume. Coarse position is provided by potentiometers within each actuator for general state of health of the TPA. Fine position knowledge is accomplished by counting the individual step command pulses delivered by the C&DH subsystem to the actuator.

The harnessing consists of two pairs of primary and redundant bundles for the HCT, XFC, and TPA control function (actuator windings, potentiometer, heaters and temperature sensors). The harness construction was selected such that it provided EMI shielding, radiation protection, and increased robustness to handling and articulation. The routing of the harnessing across the rotational axes was designed to minimize resistive torque in the operational position while achieving a compact and stiff configuration in the stowed configuration.

5. Propellant Management Assembly

The PMA is a passive pressure-regulated system designed for simplicity and reliability. A Moog mechanical regulator reduces the xenon pressure from storage tank pressure to the narrower pressure range required by the XFC. The PMA is configured with two redundant branches that are separated from each other to prevent failure propagation between strings. Isolation is provided by Moog latching solenoid valves, which when combined with the PFCV, provide the required number of barriers for leakage and range safety. All components within the PMA have flight heritage. In view of the higher shock levels associated with the mounting location on the GEOStar-3/MEV structure, the pressure regulator includes a shock isolation system developed by Moog to maintain the shock levels imparted to the regulator within its qualified range. This shock isolation system successfully underwent qualification testing prior to its implementation. As with the xenon tank at high pressures, the PMA includes active thermal control of the high pressure section in order to maintain xenon in the supercritical state. Special provisions were also adopted on the pressure regulator to address the additional cooling caused by the Joule-Thompson effect.

6. Xenon Storage Tanks

Xenon propellant is stored in four tanks to support the full xenon load required of electric orbit raising and satellite servicing operations of the combined stack. The xenon tank is manufactured by Northrop Grumman at its Commerce, CA, facility and uses a commercially pure titanium liner constructed of a center cylinder welded to end domes and overwrapped with carbon fiber. Each tank provides a minimum internal volume of 7300 in3, which allows for storing up to 229 kg of xenon at 2700 psig pressure. At these pressures, the tank temperature must be controlled with heaters to maintain the xenon in a supercritical state at launch.

C. MEV Concept of Operations

MEV-1 will be launched directly into a Geosynchronous Transfer Orbit (GTO) and transferred to GEO over a 3 month period using its low thrust electric propulsion system. Once in GEO, it will rendezvous with the Intelsat-901 spacecraft, dock to its LAE, and take over all propulsion and attitude control functions. Fig. 9 illustrates the sequence of events, while the subsequent sections provide more detail on the mission concept of operations.

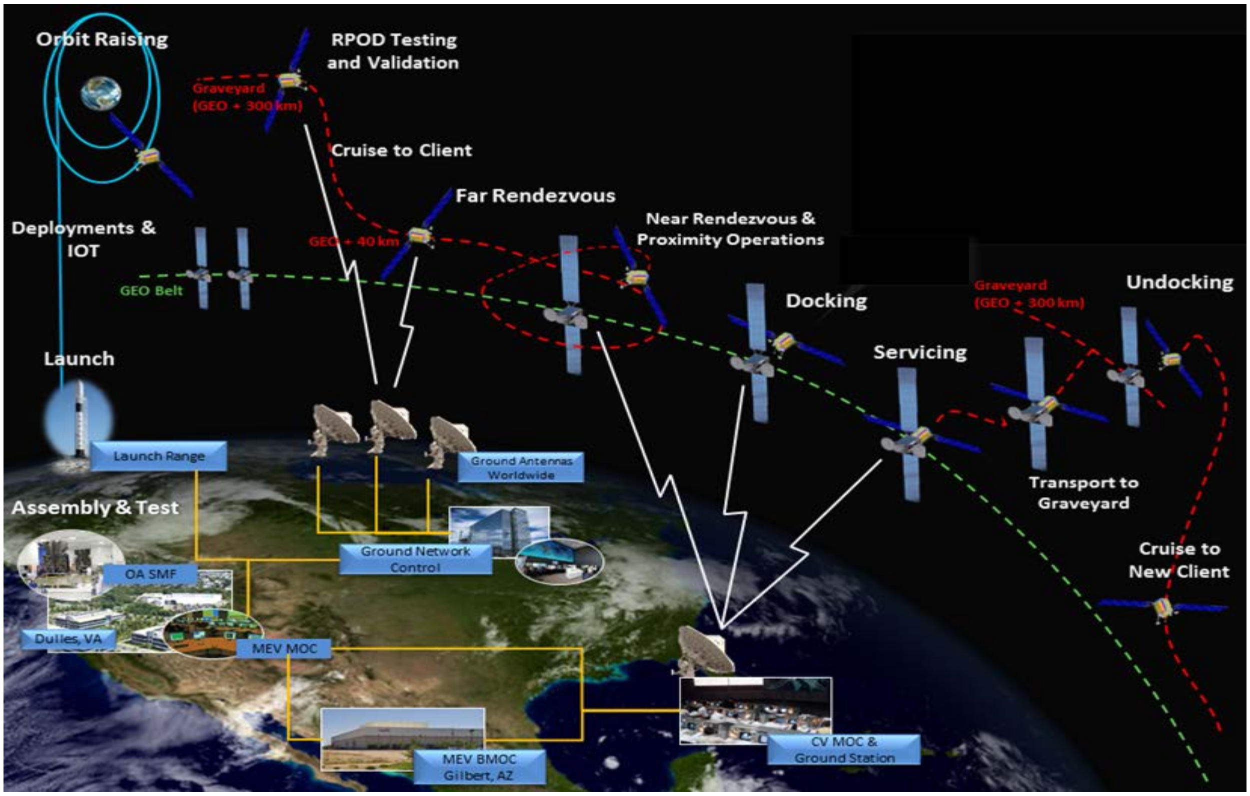

Figure 9. MEV concept of operations.

1. Launch and Transfer Orbit Operations

This phase begins with launch vehicle ground operations leading up to launch and powered flight. After separation from the launch vehicle, the MEV ground operations team performs a series of procedures to deploy the solar array, transition into a safe hold attitude, perform system wide check-outs, and condition the chemical and electric propulsion systems. At this point, the vehicle is ready for orbit raising maneuvers using initially its mono-propellant thrusters to raise the perigee and then its electric thrusters to circularize the orbit. The electric propulsion burn plan utilizes a low thrust trajectory optimizer for minimal time to orbit. The optimization process produces a set of thrust steering profiles that are uploaded for one segment of the orbit raising phase at a time. Each segment can vary in duration, ranging from several days to a couple of weeks. Multiple segments are executed over the course of the orbit raising phase. During this phase, orbit determination is performed by using ranging data from multiple earth stations. The Hall thrusters are fired continuously in pairs, except during eclipses, while the solar arrays are continuously oriented towards the sun. The steering profile is achieved using reaction wheels that are commanded through a flight software generated profile. Momentum management is provided by adjusting the orientation of the gimbal angles of the thruster pointing assembly. At the conclusion of the orbit raising phase, the MEV is moved to rendezvous with a satellite in a "grave-yard orbit" to demonstrate RPOD operations with a test satellite.

2. Rendezvous & Docking

The MEV rendezvous and proximity operations (RPO) phase is comprised of several sub-phases, which correspond with range and RPO sensor utility. Prior to undertaking a rendezvous mission, the spacecraft is brought into the same orbit regime as the target object. After adjustment to co-elliptic conditions, deterministic maneuvers using electric propulsion are sized for the initial transfer from the GEO drift altitude to the client altitude. In general, this mission phase makes use of absolute orbit knowledge of the spacecraft and target object from whatever traditional sources are available. For most GEO-communication satellite operators, this knowledge is provided through ranging measurements. Attitude control is 3-axis stabilized and only offset from nominal Local Vertical, Local Horizontal (LVLH) reference frame as necessary for delta-V maneuvers.

- **Far Rendezvous.** This phase begins after the spacecraft is approximately 2,000 km from the CV but too far from the CV to obtain target information with on-board sensors. The objective of this phase is to drift to a specific relative orbit state goal, as opposed to an absolute state, from the client vehicle within a prescribed distance. Sensors and critical hardware are tested during this phase. Attitude control during this phase is 3-axis stabilized and is offset from nominal LVLH as necessary for delta-V maneuvers and testing.
- **Near Rendezvous.** The near rendezvous phase begins when the spacecraft is close enough to the CV to acquire bearings information from on-board, long range instrumentation and ends when the spacecraft is close enough to acquire bearing and range information from the mid-range imaging system. The on-orbit measurement information is included in the input to the ground based relative orbit estimation tools to refine planning of the remaining electric propulsion maneuvers. These maneuvers bring the spacecraft to the nearby natural motion ellipsoid referred to as the "approach ellipsoid" (AE), which can be used to pause the approach, if needed. Upon reaching the AE, the spacecraft is commanded to point the mid-range sensors at the expected target location using continuously updated measurements from these sensors. From this point forward all maneuvers are accomplished using the 6-DoF hydrazine propulsion system where individual thruster firing times are calculated by a fuel optimal logic in the GN&C part of the flight software.
- **Proximity Operations.** While in the Proximity Operations mission phase, the spacecraft is always pointed at the CV. A waypoint trajectory plan defines a fixed relative position and velocity trajectory that enacts movement of the spacecraft relative to the target object in a prescribed manner.
- **Docking Operations**. The docking is executed in two steps. In the first step, the MEV is commanded to approach the client vehicle up to a near-hold position. The MEV uses its on-board sensors to generate 6-DoF information to move the satellite to this near-hold position. During this phase, collision avoidance maneuvers are available to let the MEV to move away from a keep-out sphere. In the second step, the MEV is commanded to approach the client to a short distance from the CV before a docking mechanism is commanded to initiate docking. The docking mechanism is extended through the LAE nozzle into the throat and locks onto the inside of the LAE. Then, the docking mechanism retracts until the MEV stanchions on the nadir deck establish a contact with the LV adapter ring, thereby establishing a rigid connectivity between the MEV and the CV.

3. Integrated Client Vehicle Operations.

The transition from docking and checkout of the integrated MEV/CV is termed 'handover.' At handover, the integrated vehicle is declared operational, and control is transitioned to the satellite operations center at Northrop Grumman using the client's ground stations. The client continues to operate and control the payload, while also monitoring the operation and health of the integrated satellite.

- **Inclination Pull-Down.** MEV can perform a maneuver to reduce the inclination of the CV that has allowed its inclination to drift to reduce on-board propellant consumption. This maneuver is similar to North/South station keeping except that it requires longer burn durations in view of the amount of delta-V required to restore the orbit to a nominal inclination control box.
- **Station-Keeping.** Station-keeping is required to maintain the integrated MEV/CV within its orbital slot and avoid other spacecraft. The nominal approach calls for two station-keeping maneuvers every twenty-four hours with the first one between 1 and 2 hours in duration and the second, of a similar duration, approximately twelve hours after the first one in the opposite direction. The Station keeping maneuvers are loaded in the on-board scheduler and executed on a weekly basis. Maneuver planning is performed with the help of the flight dynamics ground software.
- **Station Relocation.** The orbital location of the CV satellite may be changed by MEV over the duration of the servicing mission for the purpose of changing the CV longitude and likewise coverage area as well as removing the CV from its operational orbit into a disposal orbit at end of life.

4. Multi-Client Servicing

MEV is capable of docking and undocking with multiple CVs over the course of its satellite servicing lifetime. This capability ensures that MEV can be utilized beyond its initial mission and become an on-orbit asset for unexpected servicing requirements**.**

V. Next Generation Satellite Servicing Systems

Northrop Grumman continues to invest in on-orbit servicing and through close collaboration with U.S. Government agencies plans to establish a fleet of commercial servicing vehicles, primarily in GEO, for various servicing needs. These future services are expected to include:

- Propellant augmentation
- Inspection and repair
- Replacement or enhancement of components and systems, such as propulsion, guidance, navigation and control, power, and communications
- In-orbit robotic assembly of space structures
- Cargo and payload transportation

In March 2018, Northrop Grumman through its subsidiary, SpaceLogistics LLC, announced plans for its next generation of satellite servicing vehicles, the Mission Robotics Vehicle and the Mission Extension Pod. Combined with other efforts in advanced robotic assembly of in-orbit structures, Northrop Grumman is preparing for the eventuality of wide scale adoption of on-orbit servicing.

A. Mission Robotics Vehicle

The MRV (Fig. 10) leverages the heritage RPOD system of MEV and adds the incremental capability of a robotics module. This unique spacecraft represents an evolution of the MEV product line, which expands and addresses new space logistics markets. The primary application of the MRV is to transport and install MEPs or other augmentation payloads to client vehicles. Utilizing its space robotics system, the MRV can perform this operation under near transient free conditions, thereby allowing the client to continue normal operations during the installation process. Additional applications cover the full spectrum of potential robotics-based services, such as detailed inspection and repair of a crippled spacecraft. While basic tools reside on the MRV for these operations, the MRV robotics system can be fitted in-space with additional tools delivered by the MEP or any other vehicle that provides payload ride share service. In this way, a client can develop bespoke tools for a specific operation, have the tools delivered into GEO, and then transferred to the MRV for use on their in-orbit asset. Northrop Grumman's robotics laboratory in Dulles, VA, allows development and testing of these tools prior to delivery into space.

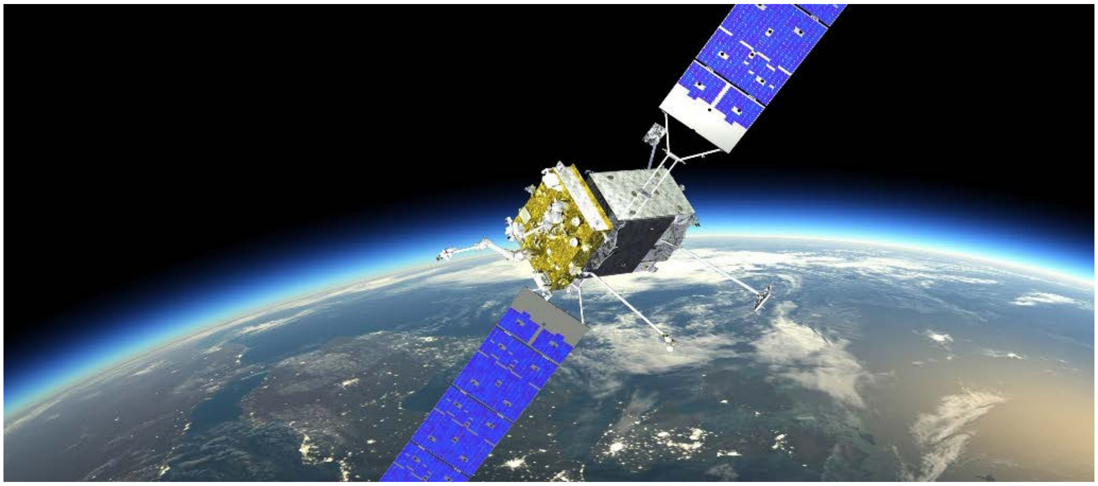

Figure 10. The Mission Robotics Vehicle.

Furthermore, MRV incorporates all of the orbit maintenance and modification capabilities of MEV with greater flexibility in the docking interface through the use of its space robotics system. These delta-V maneuvers will complement the MEP by providing higher power and thrust for one-off services that would benefit from shorter maneuver durations. In turn, the MEP would provide the extended CV services, such as station keeping and momentum management. To maintain commonality, the MRV core bus, structure and propulsion system are the same as MEV. The key difference lies in the maneuvering requirements. Where MEV performs mission lifetime extension on one CV at a time, the MRV/MEP system can provide this service to multiple CVs at a time. This means that the MRV will be required to rendezvous and dock with more CVs over its lifetime, including the additional dockings for the MEV-like services and the unique robotics-enabled services.

B. Mission Extension Pod

Figure 11. Mission Extension Pod.

The MEP is nearly 1/10th the size of an MEV, enabling multiple MEPs to be delivered into GEO for servicing multiple client vehicles in parallel. Like the MEV, the MEP carries power and an electric propulsion system for CV station keeping. It also enables CV momentum management by means of off-pointing the thrust vector from the C.G. of the combined stack using a patent-pending algorithm. It is designed nominally for a 6 year mission life, but can carry a xenon load that permits even longer servicing lifetimes depending on the CV mass and the orbit delivery method. To optimize the overall on-orbit servicing architecture, the MEP uses the same EP system for CV servicing to propel itself from a LV injection orbit into an orbit near the CV, where the MRV rendezvous with, and captures the MEP, for installation onto the CV. By using the MRV, the MEP does not require its own RPOD sensor suite, thereby reducing its system complexity, mass, and cost. Furthermore, the MRV can leverage the RPOD operations demonstrated on MEV-1 and achieve a near transient-free condition during MEP installation using its compliant space robotics system.

After evaluating the performance capability of different EP systems and their impact on power system sizing and cost for the range of client vehicle masses and maneuvering requirements, a low power Hall thruster was selected for use on MEP. For redundancy, the system consists of two Hall thruster strings with both thrusters mounted on a steering mechanism as shown in Fig. 11. This configuration and the corresponding station keeping concept of operations are very similar to the implementation of the medium power Hall thruster system on MEV with one notable difference. On the MEP, the steering mechanism articulates between both sides of the CV allowing one EP string and one mechanism to perform all orbit maintenance operations. Furthermore, the communications antennae are mounted on this mechanism, thereby further reducing the overall system complexity.

First launch of the MEP with the MRV is expected before the end of 2023. Multiple MEPs will be deployed at that time to provide mission extension to several customers at once. Additional MEPs will be delivered to orbit afterwards on a dedicated dispenser or as a ride-share on a commercial launch vehicle. By taking this approach, an entirely new ecosystem will be created for satellite servicing, offering services well beyond the immediate CV mission lifetime extension.

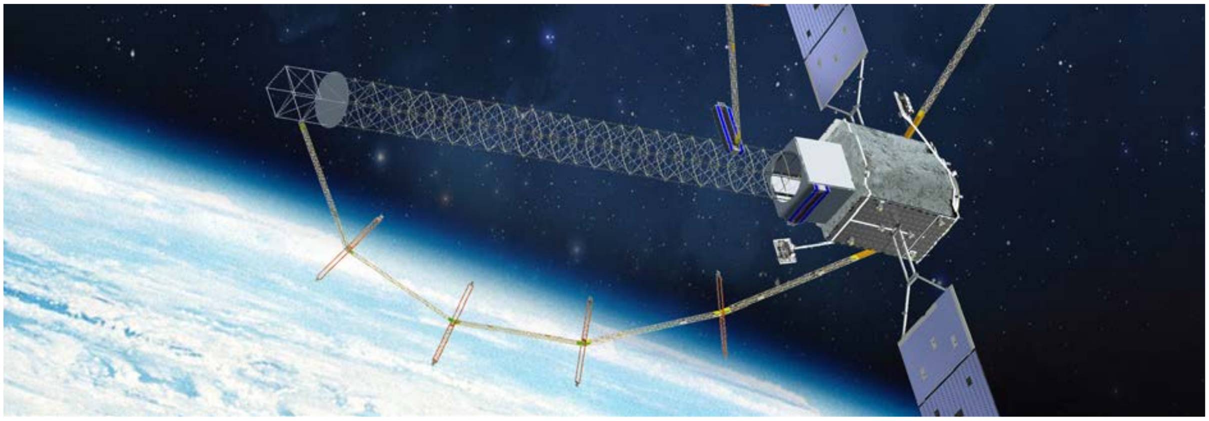

Figure 12. On-orbit manufacturing and assembly.

C. On-Orbit Manufacturing and Assembly

On-orbit manufacturing and assembly of large space vehicles (Fig. 12) was the focus of the Commercial Infrastructure for Robotic Assembly and Services (CIRAS) program, which was awarded to Northrop Grumman under a public-private partnership between Northrop Grumman and NASA's Space Technology

Mission Directorate (STMD) through STMD's "Utilizing Public-Private Partnerships to Advance Tipping Point Technologies" solicitation. Our teammates included NASA Langley Research Center, NASA Glenn Research Center, and the Naval Research Lab.

During phase 1, the CIRAS program successfully completed a ground demonstration of the technologies required for robotic assembly of large space structures, such as next-generation telescoped, solar-powered structures for transport, and communications platforms. These technologies included reversible joints on a structure and addressing precision measurement and alignment through a 20-meter robotic arm and a precision robot. CIRAS builds upon the existing capabilities of MEV, such as its RPOD capability and electric propulsion system. While Northrop Grumman did not receive a follow-on contract, NG remains committed to advancing the key technologies for in-orbit manufacturing and assembly to meet the goals for robotic and human exploration of the solar system.

D. Mission Transport Vehicle

Building off of the success with the commercial resupply service to ISS, Northrop Grumman continues to evaluate and develop systems that can transport cargo into Cislunar space and beyond. One system, known as the Mission Transport Vehicle (MTV), is an extended version of the Cygnus spacecraft and utilizes Megaflex solar arrays and four high power Advanced Electric Propulsion System (AEPS) thrusters to achieve a total orbital maneuvering power of up to 56 kW. Other variants operating at lower total power levels have also been developed through concept design to support transportation of cargo, primary payload, and secondary payload between any orbits within the orbital space defined by LEO and GEO.

VI. Conclusion

Satellite servicing is an emerging new industry with large market potential. In view of the large number of GEO satellites close to the end of their propellant lifetime, the near term services are focused on providing mission lifetime extension through tugging or refueling methods. MEV represents the first step in the commercialization of on-orbit servicing and paves the way for additional services beyond mission lifetime extension. An enabling technology for these services is solar electric propulsion as it reduces the propellant requirements for maneuvering into and throughout the GEO belt. As a result, each MEV can perform multiple orbit modification and lifetime extension services, making the service economically viable and attractive to both Northrop Grumman and its customers. This capability will be demonstrated in early 2020 after the launch of MEV-1 in the fall of 2019. Future satellite servicing systems are planned at Northrop Grumman and expected to rely further on electric propulsion with the system sizing being dictated by the specific mission needs. The follow-on mission lifetime extension vehicle, known as the MEP, will be supported by low power Hall thrusters with high throughput capability and power levels less than 1 kW. The MRV, which facilitates the installation of the MEP and adds robotic servicing on top of the MEV-like services, will continue to be supported by medium power Hall thrusters, while even higher power Hall thrusters are envisioned for SEP space tugs transporting cargo and payload over very large delta-Vs.

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