National Aeronautics and Space Administration
Goddard Space Flight Center

On-Orbit Satellite Servicing Study
Project Report

October 2010

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“Energy and persistence conquer all things.”

Benjamin Franklin

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Executive Summary

In the past two decades, some of the most extraordinary successes in space exploration have emphasized the growing importance of on-orbit servicing. As space explorers, our challenges have moved beyond simply launching complex spacecraft and systems. We are faced with the need to more fully exploit the flight systems already launched, to construct large structures *in situ* to enable new scientific ventures, and to provide systems that reliably and cost-effectively support the next steps in space exploration. A more refined consciousness of the need to reduce, reuse, and recycle here on Earth drives towards a similar awareness of these needs beyond our planet. The proliferation of abandoned satellites poses known hazards to newer members of the constellation, and may occupy unique and economically valuable orbital real estate that could be recycled for other uses. With the successful completion of a series of Hubble Space Telescope repairs, as well as the assembly of the International Space Station, we can look forward with confidence to plan such a future. Satellite servicing is a tool—a tool that can serve as the “master enabler” to create the architectures needed to conquer the next frontiers in space.

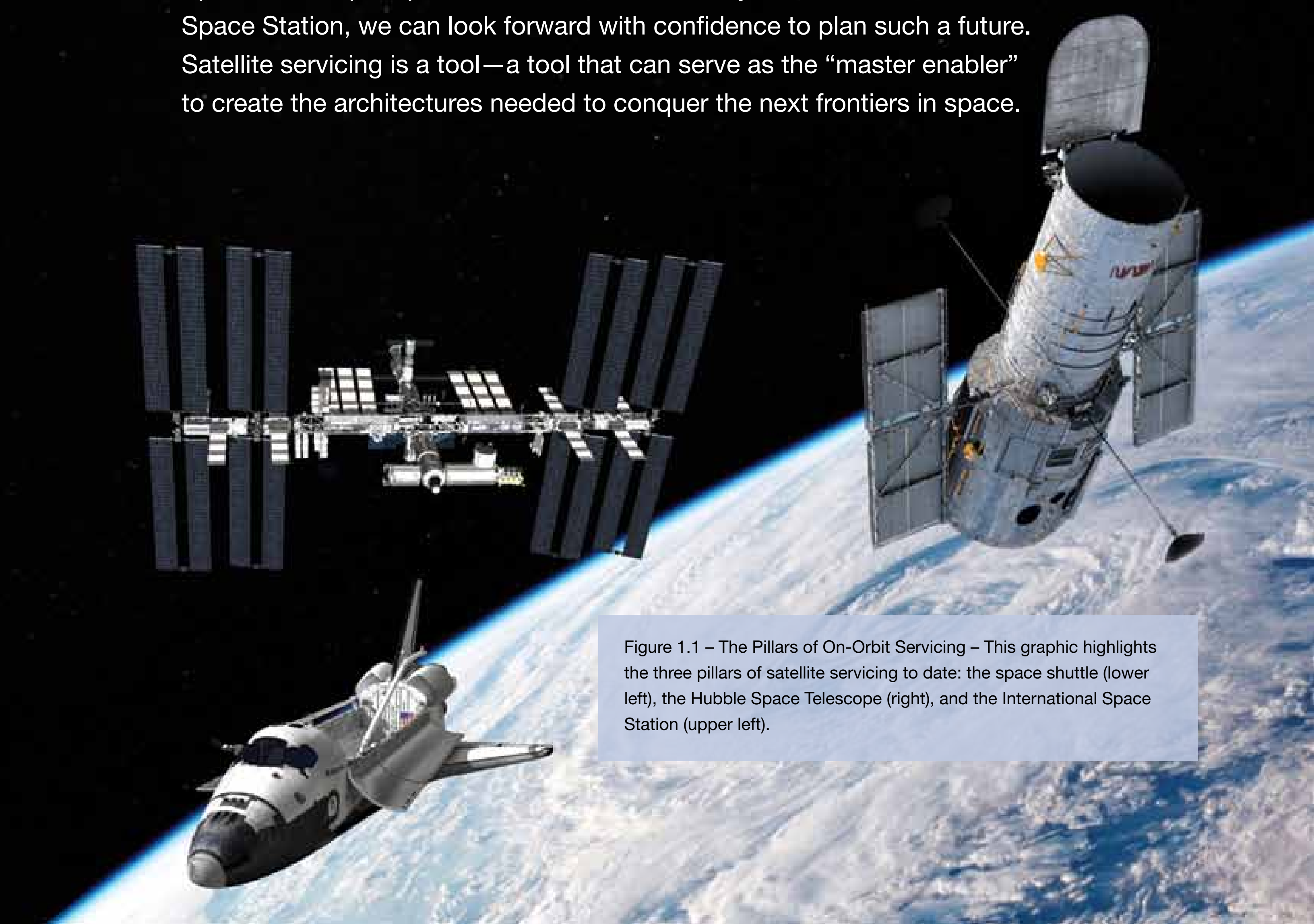

Figure 1.1 – The Pillars of On-Orbit Servicing – This graphic highlights the three pillars of satellite servicing to date: the space shuttle (lower left), the Hubble Space Telescope (right), and the International Space Station (upper left).

The NASA On-Orbit Satellite Servicing Study, mandated by Congress and supported by the NASA Advisory Council (NAC), investigates what our future may hold. This document, an internal report by the Space Servicing Capabilities Project at the NASA Goddard Space Flight Center that performed the study, captures the work performed under this Congressional mandate. Its conclusion is unequivocal. Viable plans can be put into place to develop a meaningful on-orbit satellite servicing capability, allowing us to achieve our key ambitions in space using today's technology and with current and projected launch systems. These plans would advance our presence in space by enabling more effective use of assets at near-Earth locations and by supporting future ventures to more distant destinations. This report discusses such an initiative.

This study incorporates the results from the following major activities: 1) conduct an industry-wide *Request For Information* (RFI) to notify the satellite servicing community of an opportunity for discussion, 2) conduct the *International Workshop on On-Orbit Satellite Servicing* in March 2010 to engage the community, 3) examine *notional missions* to bracket the trades involved for possible servicing customers, 4) examine near-term *in-space hardware demonstrations* to provide relevant and immediate results, and 5) develop and validate *ground simulator and test bed* capabilities that can be used to verify satellite servicing flight hardware and software. From these results, we suggest a possible *mission sequence* and also identify *technology gaps* that need to be closed for the more ambitious future activities.

The 2009 Congressional mandate for this study specifically refers to the Constellation architecture that was being implemented at that time. The human spaceflight architecture has since evolved into a new architecture reflected in the NASA Authorization Act of 2010. While this report does not assess using the now defunct Constellation architecture, we believe that it has met the intent of the Congressional direction.

One use of this study will be to inform the NASA-wide Human Exploration Framework Team (HEFT) that is charged with developing the new space exploration plans. The comprehensive HEFT study is in keeping with the will of the Congress and the Administration as expressed in the recently signed multiyear 2010 NASA Authorization Bill. It will include a study of the development of an in-space servicing capability and identify those areas where human participation in servicing is required or beneficial.

Our introduction dissects some common myths about satellite servicing. The main points fall into two general categories: "There is nothing to service" and "It is too costly to service." Superficially, these statements appear plausible. However, by studying the end-to-end life cycle costs of a wide variety of missions, it becomes apparent that these myths are incorrect except for limited or unlikely situations.

There are constellations of satellites that would benefit from refueling and/or orbit modifications. These were not designed to be serviceable, although current technology could enable such servicing. Moreover, the business cases are sound for those applications that have a commercial component, thus refuting the statement that servicing is too costly.

Even for those applications that do not have a commercial business case, the systems engineering rigor of designing a serviceable system improves the robustness of the Integration and Test (I&T) flow of a project so that this phase takes less time. Since I&T is a very high-cost phase of any program, these savings should offset the initial systems design work that would permit servicing. This is one potential paradigm shift in the development and operations of space missions that is enabled by satellite servicing. Servicing expands the options for mission design, providing a potentially cost-effective path for more sophisticated and capable systems.

There is general confusion about servicing with astronauts. It is more expensive to human-rate flight components, and rightly so. However, with new servicing architectures, most of the equipment does not need to be transported on human-rated vehicles, thus avoiding some of this complexity and cost. We also separate the categories of servicing to examine the roles of human, robotic, and combined servicing modes. The most routine servicing activities (e.g., refueling, orbit modification, and perhaps simple repairs) can be accomplished with robotic servicing alone. Astronaut involvement would be reserved for those tasks that provide sufficient benefits to justify the cost and risk.

Our second chapter, "Satellite Servicing: The Vision," shows how an advanced servicing infrastructure enables the next generation of space architectures. This infrastructure provides unique capabilities such as the ability to construct extremely large space telescopes. Such telescopes (e.g., the Thirty-Meter Space Telescope study[1]) would reach beyond the realms explored by the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST) to significantly advance our understanding of the Universe. The extremely large apertures involved will require shifting to a "born-in-space" architecture, in contrast to the current practice of assembly and test on Earth.

An advanced servicing infrastructure also enables longer-range transportation capabilities. It would provide fuel depots and other services required by missions going to destinations far beyond the Earth. Even basic servicing capabilities would provide refueling, repair, and refurbishment for operating satellites, an important means to extend mission life and to improve the cost-benefits ratio. In many cases, these operations can even be performed on legacy satellites that may not have been designed with servicing in mind.

The third chapter, "Satellite Servicing: The Benefits," describes broad categories of benefits and how these benefits might be quantified. Those applications with commercial potential require sound business cases. The business cases have been made for satellites that support the infrastructure of modern society, and in particular, communication services. Those applications that are purely scientific or exploratory require a rationale that they enable extraordinary advancements that are commensurate with the cost. Among the key benefits of satellite servicing are the refueling, repair, and refurbishment capabilities that it provides. These benefits increase overall mission reliability and, where applicable, economic value. For extremely high-value assets used for scientific or strategic purposes, a repair and refurbishment capability provides an extension of functionality and utility without the associated costs and risks of a new build and launch. In the strategic domain, orbital modification through satellite servicing provides powerful capabilities that could be central to maintaining our national security. Conversely, this technical capability would become a threat if implemented by unfriendly entities. Finally, previous experience shows that successful servicing activities on highly visible satellites can act as a strong catalyst for intense public interest.

The fourth chapter, "Satellite Servicing: The Implementation," discusses more concrete issues. It summarizes the technical content of the study and charts a technically sound implementation path. We first identify and define an appropriate "parameter space" for discussing satellite servicing capabilities. A set of "notional missions" then examine the commonalities and unique capabilities for representative parameter choices. An important observation is that most of the satellite-servicing activities or tasks required have already been demonstrated in low Earth orbit with humans. The challenges lie in extending that capability to robots and more autonomous operations at more distant locations where communication latency impedes direct ground control for detailed or critical operations. These notional missions provided the building blocks that the study team then used to construct an executable mission sequence, from which technology gaps were identified.

The final chapter, "Satellite Servicing: The Challenges," focuses on key areas that require additional work. Here we argue that the technology is ready, and that some of the key issues that remain are in other realms such as perceived risks and economic motivation. It describes these challenges and provides a methodology for addressing them.

During our study, several high-level recurring themes emerged.

1. *In examining the range of tasks required for servicing, the tasks themselves (and the hardware to support them) do not appear to be the limiting factors.* Extremely complex servicing tasks have already been successfully performed in orbit, including operations on legacy satellite customers as well as repairs on hardware not originally intended for on-orbit servicing. Advanced robotic analogues of these tasks are routinely demonstrated on the ground. The advancements needed are mostly in the areas of increased autonomy to support such tasks farther from Earth and the systems engineering to create sufficiently robust servicing architectures. While all the technologies and techniques are available, their application in a mission require maturation. For this, we recommend a robust in-orbit verification program using accessible platforms such as the International Space Station in combination with vetted ground simulators and test beds.
2. *Legacy satellites can be successfully serviced.* In fact, much of the servicing performed to date has been on legacy hardware never intended for on-orbit servicing. The range of applicable servicing activities includes repair, refurbishment, refueling, and orbit modification. Successful implementation requires identifying the correct interfaces, developing the appropriate tools, and executing a well-planned mission, all of which have been demonstrated. Servicing these legacy satellites provides an immediate customer base on which to build a future satellite-servicing infrastructure. The business case for commercial satellites is favorable if the capability is available and well understood. The first step of the proposed mission sequence is to realize this capability for satellites in Geostationary Earth Orbit (GEO).
3. *Modular, reconfigurable robotic architectures that are mobile around large structures are important to provide a cost-effective and upgradeable servicing infrastructure.* Part of the initial technology assessment would be to further develop these systems and demonstrate their adaptability.
4. *Launch mass and orbit modification capacity drive servicing mission design.* Here, the available launch vehicles could impact the architecture and even the feasibility and cost effectiveness of satellite servicing. For example, for reaching distant destinations, there is a trade between heavy-lift rockets with refueling depots and multiple small launches with on-orbit assembly of small modules. These trades could also be affected by advanced propulsion systems. Our technology gap assessment identifies other investment goals.
5. *Astrodynamics is a major factor in mission design, especially when there is human presence.* We paid close attention to this aspect for the satellite servicing locations that we considered. Interesting results include useful orbits that support satellite servicing.
6. *Satellite servicing is critical to our national interests.* As a nation, we need to develop this capability in order to maintain our leadership in space for scientific, commercial, and strategic reasons.

We have the technologies today to implement a useful, cost-effective, and exciting program that incorporates satellite servicing into humankind's portfolio of spaceflight capabilities. This implementation needs to be a partnership of government agencies, industry, and academia, as satellite servicing has implications and benefits in economic, legal, and scientific arenas. Such a program would take advantage of near-term, economically viable commercial applications as a stepping-stone to more ambitious activities. Table 1.1, discussed further in "Satellite Servicing: The Implementation," describes a set of near-term recommended actions and their expected results.

Table 1.1 – Table of Recommended Actions

Recommended Action	Result
Optimize engineering design and trade studies for the identified mission sequence.	Refined technical and cost assessments.
Invest in key enabling technologies such as 1) increased autonomy for robotic systems, 2) improved systems for rendezvous/docking/refueling, 3) advanced tools and end-effectors for astronauts and robots, 4) modular, self-reconfigurable, and mobile robotic architectures and systems that can move around large structures in space, and 5) advanced imaging/pose-estimating capabilities.	Proven technologies that will serve as the basic building blocks for complex servicing activities to allow future missions to focus on mission-specific challenges and solutions.
Assess a range of customers for satellite servicing.	Defined benefits for a suite of executable missions.
Create design recommendations for future spacecraft.	Accepted standards for spacecraft design that improve serviceability.
Establish customer/provider working groups.	A routine venue for discussion and feedback to implement lessons learned and best practices.
Integrate a satellite-servicing infrastructure with NASA program architectures and priorities.	The benefits of satellite servicing will be exploited where available and appropriate.
Initiate plans for executing the missions described in the Mission Sequence section (Chapter 4).	Immediate benefits provided by satellite servicing while refining the technologies needed for further advances.

Chapter 1

Introduction

Every new frontier brings new challenges and new rewards. Regardless of the ultimate motivation for conquering a new frontier, the process takes on a familiar cadence. At first, recognition of the frontier and learning how to deal with its environment lead to early exploratory missions that come at great cost and often with great sacrifice. Next comes the attempt to reap economic or other benefits. Finally, as the new frontier becomes more familiar, infrastructure development provides the backbone for a continued presence that enables using its unique characteristics and provides a springboard to the next frontiers. So it is for space.

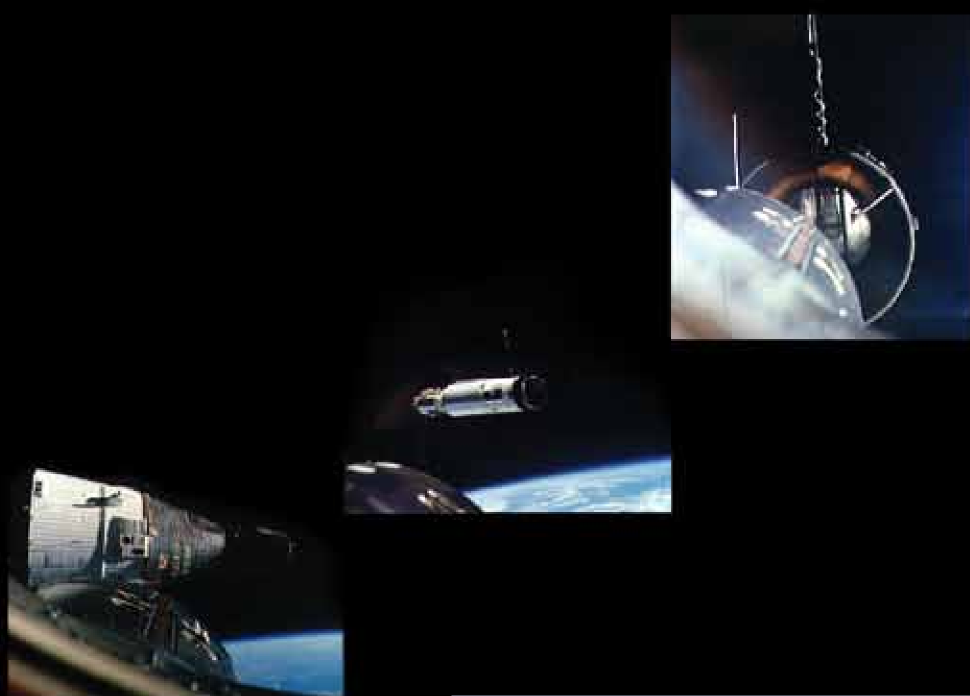

Figure 1.2 – The Gemini Rendezvous and Docking Experiments – The Gemini program in the mid-1960s had to validate, among other things, the rendezvous and docking techniques that would be required for the Apollo program. The photograph on the left was taken on the Gemini 76 mission, where Gemini 6 maneuvered to and kept station within 30 cm of its sister ship, Gemini 7. Subsequent Gemini missions successfully validated rendezvous and docking with used Agena second stages (center and right photographs), which were then used to boost the docked spacecraft into higher orbits that broke human altitude records. This was the beginning of rendezvous and docking technology on-orbit, which is a basic capability required for satellite servicing.

On-orbit repair and refurbishment have matured to the point where they can be applied to fairly complex satellite systems. This is evident in the remarkable successes enjoyed by the five servicing missions for the Hubble Space Telescope. The tools and methodologies developed to enable these successes apply equally well to a broad range of customer satellites. On-orbit repair and refurbishment directly improves overall mission reliability and helps to ensure mission success. These benefits will become increasingly important as our ambitions in space increase and the cost and feasibility of major projects become commensurately more challenging.

We now have a long-term human outpost in space, the International Space Station, that provides an unprecedented platform for developing satellite servicing technologies and techniques. It is only the beginning of humankind's infrastructure in space, and not surprisingly, it has not yet addressed every issue. Significant resources are still expended to simply ensure basic needs. Nevertheless, it can serve as a significant springboard to more distant destinations through enabling essential technology development.

These potential benefits have not escaped Congress and the NASA Advisory Council (NAC). Their desire to realize these benefits led to the mandate for this study. The results from this study are clear:

1. *We have the technologies today to realize a viable satellite servicing program.* Such a program can respond to a wide range of foreseeable requirements for routine maintenance, refueling, and the assembly of large structures.
2. *We can articulate a concrete series of actions to execute this program*. The program is consistent with current NASA plans for human and robotic exploration and is sufficiently robust that it can evolve with NASA's plans.

Study Mandate

For the past several years, NASA has received formal advice, recommendations, and, more recently, appropriated funding to develop concepts for satellite servicing and assess their values. In 2007, the NASA Advisory Council Astrophysics Subcommittee recommended that NASA carry out trade studies on "in-space operations (and their) potential for assembly, servicing, and deployment."

A year later in NASA's FY 2008 Authorization, Congress also became interested in the importance of spacecraft servicing:

> The Administrator shall take all necessary steps to ensure that provision is made in the design and construction of all future observatory-class scientific spacecraft intended to be deployed in Earth orbit or at a Lagrangian point in space for robotic or human servicing and repair to the extent practicable and appropriate.[2]

Congress provided further guidance in NASA's FY 2009 and FY 2010 appropriations bills. Specifically, it linked the servicing of scientific spacecraft with the future human spaceflight architecture, *viz.*,

> Therefore, it will be critical that the Constellation program demonstrate unique capabilities to maintain synergies between free-flying scientific spacecraft and human spaceflight endeavors. Accordingly, the bill provides $20,000,000 for NASA to undertake an assessment of the feasibility of using the Constellation architecture to service existing and future observatory-class scientific spacecraft, fully utilizing the unique, core expertise and competencies for in-space servicing developed by the Goddard Space Flight Center and its private sector partners for the Hubble Space Telescope.[3]

This document is the internal Project report for the required assessment. More complete references related to this mandate are provided in Appendix A.

The 2009 Congressional mandate specifically refers to the Constellation architecture that was being implemented at that time. The human spaceflight architecture has since evolved into a new architecture reflected in the NASA Authorization Act of 2010. While this report does not assess using the now defunct Constellation architecture, we believe that the study has met the intent of the Congressional direction.

What Will This Study Contribute?

Our study provides a balanced assessment of the state of satellite servicing and charts a path toward a future where the benefits of satellite servicing will be realized and become routine. The resulting paradigm changes could result in new space architectures to enable otherwise impossible applications. By charter, our study provides the following results.

1. Data-based assessments on the feasibility and practicality of satellite servicing.
2. Definition of common design choices and interfaces that make a satellite more serviceable, and a description of the benefits of doing so.
3. Assessment of key technologies that enable satellite servicing using any architecture envisioned today, and identifying gaps in what will be needed for future servicing.
4. The basis for decisions about ground and flight demonstrations of satellite servicing technologies and techniques.

Our study intends to bring up-to-date the understanding of the potential of satellite servicing and to contribute to future design work and investments. The past two decades have seen extensive research in academia and industry, along with significant demonstrated interest in spacecraft upgrading and servicing. There have also been some widely quoted myths about the value of this capability. Nevertheless, there has been no relevant wide-ranging systematic NASA study of this activity since the series of satellite servicing workshops that ended in 1989.

Our study identifies design choices and capabilities that are common among many different servicing scenarios. This is intended to guide future mission concepts to make them more accessible to potential servicing systems. Examples include a high degree of modularity, standardized interfaces, common electrical and fueling connectors, common fasteners, accessibility of key spacecraft systems, etc. These types of design requirements also tend to make spacecraft Integration and Test (I&T) substantially less expensive. This is discussed under Chapter 5, "Satellite Servicing: The Challenges."

More specifically, our study makes available designs and operational scenarios of sufficient fidelity to permit on-orbit servicing discussions based on data, rather than anecdote and mythology. Similarly, our results enable identification of servicing scenarios that are more—or less—implausible, unaffordable, or too complex to carry out (e.g., require too many elements to be launched, require human spaceflight capabilities that are not planned). These are investigated in detail, along with their technology requirements, in a set of notional missions and are summarized under Chapter 4, "Satellite Servicing: The Implementation."

Finally, our study identifies precursor and demonstration programs that should be carried out over the next few years to verify key capabilities in advance of more ambitious servicing missions. The beginnings of this program are the International Space Station-based demonstration experiments being developed by NASA's Goddard Space Flight Center (GSFC) Satellite Servicing Capabilities Project. These experiments are also discussed further in Chapter 4, "Satellite Servicing: The Implementation."

Study Methodology

This internal project report provides the detailed results of the NASA On-Orbit Satellite Servicing Study, which includes five major activities.

1. Conduct an industry-wide Request for Information (RFI) to notify the satellite servicing community of an opportunity for discussion.
2. Conduct the International Workshop on On-Orbit Satellite Servicing in March 2010 to engage the community.
3. Examine notional missions to bracket the trades involved for possible servicing customers.
4. Examine near-term in-space hardware demonstrations to provide relevant and immediate results.
5. Develop and validate ground simulator and test bed capabilities that can be used to verify satellite servicing flight hardware and software.

From these, we develop implementable recommendations for a mission sequence and identify gaps in the technology required for more ambitious future elements. A core team at NASA's Goddard Space Flight Center (GSFC) performed the day-to-day work for the study.

The industry-wide RFI was intended to gather information from the providers and customers of servicing-related technologies to supplement the knowledge base of our core team. A total of 70 RFI responses (plus 22 workshop abstracts) were received and are summarized in Appendix B. Of these RFI responses, 12 were from academia, 42 from industry, 14 from government organizations, and 2 from foreign organizations.

The workshop gathered together experts in satellite servicing for a three-day event to share information. This event drew over 250 participants (234 in person and 20 to 30 through the web) and 58 presentations. Some of these participants were invited speakers because of their RFI responses. The workshop summary is provided in Appendix C.

The notional mission studies used the Integrated Design Center (IDC) at NASA GSFC to investigate the major trades for various servicing scenarios. A total of six notional mission studies were completed in seven weeks of IDC time. The results are discussed in Chapter 4, "Satellite Servicing: The Implementation" and also presented in detail in Appendix F.

The near-term hardware demonstrations started the implementation of some technologies that could benefit from demonstrations using the International Space Station (ISS). These are also discussed in Chapter 4.

The team reviewed past literature while conducting this study. These works are listed in the References and Related Historical Materials sections.

All of these activities were completed prior to the end of FY 2010.

Assumptions

In any study of this scope, interactions with external elements cannot be ignored. Specific discussions demand assumptions about the external environment that may or may not turn out to be correct. This is especially the case for forward-looking studies. In this section, we attempt to highlight some of these basic assumptions in five areas so that the results can be interpreted in the appropriate context.

1. Our selection of potential customers.
2. The agency-wide paradigms that existed and were changed during the study.
3. How we evaluated launch vehicle considerations.
4. The human/robotic servicing paradigm.
5. Customer satellite cooperation levels.

The intent of the notional missions is to explore the most revealing areas of the satellite servicing trade space rather than to find specific solutions for flight projects. In other words, the notional missions enabled the team to identify successful engineering solutions that can be treated as "existence proofs" in subsequent analyses, rather than to produce optimized designs for a real mission. The notional missions were each developed in a one-week, intensive, and extremely challenging exercise called a design charrette.

Designing a multi-vehicle servicing mission within the normal constraints of a one-week charrette is particularly challenging given the many inter-vehicle interfaces. Mechanical interfaces are obvious, but every subsystem must be considered and addressed. For example, if one is to transfer power from a servicer vehicle to a customer vehicle after the two are physically mated, one must first define the duty cycle, the average and peak loads, and the durations. These are either negotiated between the two vehicles if the customer is designed to accommodate servicing, or dictated to the servicer by a legacy customer. This is but one example of the choreography that must be crafted for any servicing mission. Therefore, where possible, existing satellites and launch vehicles were used in the notional mission study process.

This is an important point, as it would be easy to misread the intent behind the choice of customer satellites in the notional mission suite. Customer satellites were chosen solely to facilitate the design charrettes and not to favor one particular mission over another. For any servicing configuration, the interfaces must be understood. In the absence of well-defined customer interfaces, valuable time would have to be spent considering details such as solar array shadowing, communication system relaying, mass properties, etc., and this time would be taken away from studying the more generally applicable aspects of servicing. For example, the Hubble Space Telescope (HST) was the customer satellite in Notional Mission 3 because it is an existing low Earth orbiting satellite that was designed to be serviced. Accordingly, its interfaces exist and are well known, which allowed the study team to develop well-defined requirements for those interfaces on the notional servicer (dimensions, power, data, etc.).

The launch system infrastructure assumptions also deserve explicit clarification. The Congressional language that enabled this study focused on identifying elements of the Constellation architecture that enable satellite servicing, such as an airlock for the Orion spacecraft. However, as the study progressed, NASA shifted focus toward the "Flexible Path" and the Commercial Orbital Transportation Services (COTS) concepts discussed by the White House Augustine Committee.[4] Since the notional missions were intended to identify commonalities and technologies that enable multiple future architectures, we deliberately constructed these notional missions to be independent of specific Constellation elements. As a result, some of the notional missions involve Constellation elements, some involve COTS, and some involve sending humans to ever-greater distances from the Earth. The interfaces provided by these elements allowed us to proceed with the study, but these interfaces should be viewed as example "boundary conditions." We expect that a different set of boundary conditions (for missions with comparable objectives) would lead to largely the same conclusions.

The study team also deliberately chose not to perform any launch vehicle trade studies. Often during the charrettes we would discover that the particular launch vehicle chosen was too limiting in launch mass, fairing length, or fairing total volume. These design obstacles were not resolved with a launch vehicle trade. Instead, a larger fairing, more capable vehicle, or multiple launches were assumed so that the design of that notional mission's servicer could continue. Therefore, we caution the reader against drawing conclusions from our use of any particular launch vehicle.

The study team discussed the potential servicing customers at length as we developed the notional mission suite. Existing satellites were selected to define reasonable interfaces for designing the servicer. Given the diversity of existing and planned satellites, every choice involved considerable discussion. For example, some members proposed studying a cryogenic tank depot instead of a large-aperture telescope mission. Intense discussion followed, centered around what servicing elements of a tank farm in LEO were unique and therefore deserving of one of the design charrettes and what elements were already covered. In the end, we concluded that Notional Mission 1 (orbit modification) and Notional Mission 3 (LEO Autonomous Rendezvous and Capture [AR&C], communication coverage, and battery cycling) explored the general servicing elements well enough to eliminate the need for a separate charrette.

The decision to use human-robotic scenarios for some missions and not others was dictated by the desire to explore the unique areas of the satellite servicing trade space. Additionally, the Flexible Path concept of sending humans to ever-greater distances did influence some of the notional mission choices. If humans travel beyond LEO, our studies explain how satellite servicing is a meaningful activity that exploits the unique capabilities brought by a human presence.

Lastly, we define our convention for classifying customer satellites from the perspective of satellite servicing cooperation. All spacecraft servicing activities begin with an approach, rendezvous, proximity operations, and capture sequence that brings the servicer and customer spacecraft together. The servicer spacecraft is typically the active vehicle during the AR&C sequence and the customer vehicle is generally passive (i.e., not maneuvering to translate towards the servicer). Where possible, the servicer vehicle will always be designed to take advantage of any cooperative features offered by a customer vehicle. Some of our notional mission servicers were designed to conduct successful AR&C with partially cooperative or even non-cooperative customers when necessary.

A cooperative rendezvous customer is one that offers features that make the AR&C sequence easier in various ways that will discussed later. By contrast, a *non*-cooperative vehicle does not offer such features and may instead have characteristics that are hindrances. For completeness, we define an *un*cooperative vehicle as one that is actively and deliberately attempting to foil AR&C in one or more ways (e.g., evasive maneuvers). The active and deliberate nature of the lack of cooperation here is what sets an *un*cooperative vehicle apart from a *non*-cooperative vehicle. Note that uncooperative vehicles are beyond the scope of this study. In the sections that follow, most legacy satellites would fall into the non-cooperative category. Our goal is to help ensure that future satellites are cooperative to the degree practical for their mission objectives.

Why Is Satellite Servicing Important?

At the most general level, the answer to this question is simple. In order to push the boundaries of our ventures into space, we must advance beyond visiting destinations in space with sophisticated systems that allow no room for failure, and beyond bringing everything we need with us. Closer to Earth, we must be able to "pack out our trash" and extract the most utility from expensive space assets. All of these activities require some aspect of what satellite servicing capabilities offer.

There are clearly many applications for satellite servicing, each with its own definition of "importance" based on the scientific, economic, strategic, and societal benefits it offers. For instance, if the goal is to travel to distant destinations, depots are a potential enabling infrastructure and satellite servicing capabilities are required to construct and stock such depots.

Another important service that satellite servicing can offer is the orbital manipulation of existing objects, a capacity that enables the removal of debris and the reuse of unique orbital real estate. The debris issue is a serious one even today in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). In February 2009, an Iridium satellite collided with a spent Russian military satellite.[5] Today, events where two satellites come within several kilometers of each other occur numerous times each day. As time progresses, these unintended orbital intersections could lead to catastrophic debris generation in an "ablation cascade" or Kessler Syndrome.[6] In addition to the dangers of space collisions, the orbital real estate at Geostationary Earth Orbit (GEO) is a limited resource that is in high demand for communications satellites. Thus, strong business and national security cases can be made for clearing failed satellites at GEO to reuse their orbital slots.

Repair and refurbishment are the most visible successes of satellite servicing because of the remarkable missions to service the Hubble Space Telescope (HST). The life of valuable assets could be extended through maintenance and upgrade, but there is a more important related point. As our ambitions in space increase, the systems required to support these ambitions will become increasingly more sophisticated. One could argue that such systems would fail if satellite servicing were not an integral part of the infrastructure. As an analogy, consider operating an automobile in an environment where no repair facilities were available. No matter how well designed the automobile might be, it would eventually fail. Without the infrastructure and capabilities of "repair shops," automobiles and satellites are only useful until the first major failure.

To better understand the issues surrounding servicing activities with existing customer satellites, we can use an intuitive categorization developed by Henshaw[7] that clarifies their dynamics. Suppose that all satellites are placed into one of these analogous categories for cars:

1. **Fleet** – a workhorse car used in car rental fleets. It is sturdy, high utility, and very basic in terms of technology. Its main utility is in providing the ability to get reliably from one place to another. Such a car is probably not sufficiently valuable to warrant significant repair, and once it reaches a certain mileage or age, it is removed from service and replaced by a newer model. Its spacecraft counterpart would be the commercial satellite fleet that provides communications services as a commodity. Servicing activities for this class of spacecraft would center around basic maintenance and refueling. If something

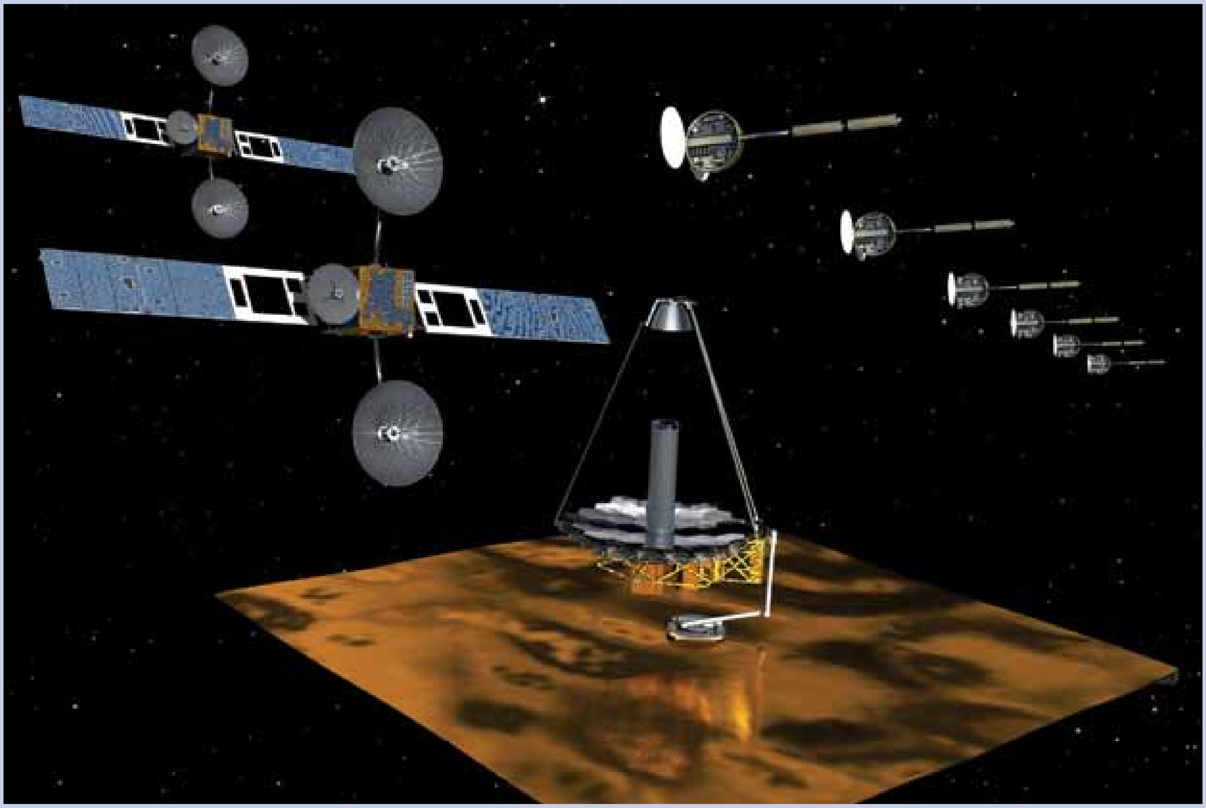

Figure 1.3 – Classes of Spacecraft for Servicing – Just as different cars receive different levels of maintenance, different spacecraft fall into different categories of servicing needs based upon their application. At the top right is a “fleet” of commodity communications spacecraft (based on the Orbcomm satellites). These could be compared to a fleet car for a rental company and would receive minimal maintenance during their profit-generating lifetime. The two spacecraft at the top left (based on the NASA Tracking and Data Relay Satellites) would be used for a more specific application such as surveillance or private communications, and would be maintained more extensively like a family car. The bottom spacecraft (based on the ATLAST observatory concept) represents a one-of-a-kind observatory, which would be compared to an exotic car and is a potential candidate for extensive servicing.

should go wrong, the spacecraft would simply and most cost- effectively be replaced.

2. **Family** – a car that is more likely to be privately owned. It provides special features to support the daily transportation needs of a family. If such a car should break, it would make sense for the family to repair it until such time that major overhauls are required. Its spacecraft counterpart would be the government spacecraft constellation that provides a variety of communications and surveillance services, but only to restricted customers. Servicing activities here would include basic maintenance and refueling, but because these are not commodity satellites, some level of repair may also be justified to maintain strategic capability or service, or to “buy time” to allow new technologies to be incorporated into their replacements.
3. **Exotic** – a state-of-the-art car that is made in limited numbers. It provides special capabilities that are unique and deemed rewarding to the owner. In the case of such a car, even a complete refurbishment may be justified when it becomes necessary. For space missions, these would be the occasional cases like the Hubble Space Telescope, other astronomical observatories, or reconnaissance

spacecraft. These spacecraft are sufficiently high-value and unique that great effort may be justified in repairing and maintaining their capabilities.

This classification is illustrated in Figure 1.3. Our first observation is that there are many more "fleet" than "exotic" cars. The benefits of servicing will be very different for these cases.

The ability to refuel commodity communications satellites would likely need to be a commodity itself. In general, a refueling spacecraft would need to service multiple customers in order to be economically viable. Such a spacecraft would give the customer satellite extended life, providing a continuing revenue stream from an already depreciated satellite. To be viable, the cost of refueling must be less than this additional profit. If something serious were broken on one of these commodity satellites, it is not likely that mounting a special campaign to repair it would make more economic sense than simply launching a replacement.

For the family car, however, the application may be sufficiently specific that replacements may not be readily available. More extensive repairs may therefore be desirable if the satellite's function is required. An example would be strategic communication services for NASA or the Department of Defense.

The exotic car clearly serves a specific purpose that is hard (if even possible) to replace. In this event, extensive repairs may be warranted. The gain in these cases is almost certainly realized by extending, restoring, or improving function.

Clearly, the definition of "importance" depends on the application, and each application will impose a set of standards against which to gauge that importance. This will be discussed more in Chapter 3, "Satellite Servicing: The Benefits."

What Has Been Done Before?

Figure 1.4 – The Repaired Skylab – Launched in 1973, Skylab was not only NASA's first space station, it was also the Agency's first human satellite servicing endeavor. A successfully deployed parasol (seen on the top of the central cylinder of the spacecraft, nearer to the viewer) restored an acceptable thermal configuration and saved the mission.

This section reviews some of the seminal missions that have helped to define satellite servicing. This is not intended to be an exhaustive list, and the reader is referred to other published works for this information.[8,9,10] Throughout this discussion, it becomes apparent that, until recently, satellite servicing has developed as specific critical needs arose. That is, a problem would present itself and, if the necessary technology existed, the problem would be resolved—and usually resolved successfully. This is a technology "pull" situation, or a "necessity is the mother of invention" strategy. There is now sufficient experience with these sorts of situations, both planned and unplanned, that we understand the challenges for a wide range of servicing activities. There are also a wide range of technologies waiting to be applied to this problem. Thus, we are now in more of a "push" situation. Once we establish the vision of what we need to do, we have a clear technology path for realizing that vision.

The Dawn of Satellite Servicing

Skylab

In the mid-to-late 1960s, even as the Apollo program was in full swing, space visionaries were planning the follow-on programs that would eventually lead to launching Skylab on May 14, 1973 (Figure 1.4). At launch, NASA's first space station had already faced a tumultuous history. It then immediately developed some serious technical problems. These problems resulted in a delay of the second launch that would bring up the first Skylab crew. The two most pressing problems were the failures of the micrometeoroid shield and the solar arrays to deploy as planned. Micrometeoroid protection was not the main issue with the shield as the risk was small and not immediate. However, the shield also served a more critical thermal management role. Without it, the Skylab overheated and its cold-bias configuration could not be maintained, threatening its contents as well as human habitability and structural integrity. These problems aggravated each other because any attitude adjustments to maximize solar array output would also increase the solar impingement on the Skylab and further warm it up. These problems had the potential to threaten mission success and consequently NASA's future in human spaceflight and space stations.

On May 25, just 10 days after the initial launch of the Skylab, the crew launched with some ingenious hardware on board, designed to provide a replacement thermal shield. After a series of heroic Extravehicular Activities (EVAs), Skylab was restored to acceptable performance limits on June 8, moving on to complete its amazingly diverse mission as NASA's first space station. Despite the formidable challenges, the ingenuity of the Skylab team also led to the first successful demonstration of on-orbit repair.

The anomalies resulted in an Investigation Board that attempted to determine their causes. Among the many technical and managerial conclusions reached by the Board, several were to have a lasting impact on NASA's ability to ensure mission success. These words are no less relevant today than they were when they were written almost four decades ago and should be applied when planning a successful servicing mission.

> One recommendation called for the appointment of a project engineer on complex items that involved more than one engineering discipline. A second warned against undue emphasis on documentation and formal details: "Positive steps must always be taken to assure that engineers become familiar with actual hardware, develop an intuitive understanding of computer-developed results, and make productive use of flight data in this learning process." Finally, the Board encouraged the assignment of an experienced chief engineer to major projects such as the Workshop or Airlock. Freed from administrative and managerial duties, he would 'spend most of his time in the subtle integration of all elements of the system under his purview.'"[11,12]

Figure 1.5 – Solar Maximum Mission in the Space Shuttle Bay – The Solar Maximum Mission was one of the first orbiting spacecraft to be retrieved, repaired, and redeployed using satellite servicing. This photograph from 1984 shows the spacecraft being repaired by astronauts in the payload bay of the space shuttle Challenger.

Solar Maximum Mission Repair

As spacecraft technology became more refined, so did the architectural designs that enabled more efficient mission execution. One such early design was the Multimission Modular Spacecraft (MMS). This design emphasizes a basic tenet: make the standard spacecraft parts modular so that 1) they can be repaired and/or replaced in space, and 2) ground integration and test costs are reduced. That same modularity that allows for on-orbit replacement also enables straightforward replacement on the ground. We note, however, that designing modular spacecraft remains the exception rather than the rule, as modularity in spacecraft design remains controversial.

The first spacecraft to make use of this architecture was the Solar Maximum Mission (SMM), launched in February 1980 to investigate solar phenomena during an active part of the solar cycle. It operated until January 1981 when a failure in the attitude control system truncated the mission.

Making full use of the MMS design, NASA launched an ambitious recovery mission in April 1984 that fully restored SMM operation until it reentered in December 1989 (Figure 1.5). During this repair mission, STS-41C, the space shuttle Challenger maneuvered close to the MMS and successfully captured it. Astronaut EVAs replaced the failed parts, and the SMM was redeployed from the Challenger payload bay.

This successful first use of the space shuttle to repair a valuable asset set the stage for the more ambitious undertakings that would follow.

Palapa B2 and Westar 6

Almost immediately after the SMM success, the space shuttle was called upon for yet another on-orbit servicing challenge. As reported on August 23, 1984 in *New Scientist*:[13]

> America's space shuttle may make its second salvage run into space on 2 November. Encouraged by the rescue and repair of the Solar Maximum Mission Satellite by shuttle astronauts on 10 April, NASA is planning a similar attempt.

Figure 1.6 – Palapa B2 Recovery – Palapa B2 being manipulated by an astronaut in a free-flying Manned Maneuvering Unit. Palapa B2 was returned to Earth for refurbishment and eventual reflight.

> This time, astronauts would hook on to at least one of the two malfunctioning communications satellites now drifting uselessly...
>
> The satellites are Palapa B2, owned by the Indonesian government, and Westar 6, owned by Western Union. Last February, shortly after the two craft were released from the cargo bay of the shuttle, Challenger, both of their upper-stage rockets misfired. Neither satellite has functioned since.

On November 8, 1984, Discovery's STS-51A mission launched and deployed two new satellites as planned. Subsequently, it successfully retrieved the two errant spacecraft through daring and dramatic EVAs that saw the use of the astronauts' free-flying Manned Maneuvering Units (MMUs, see Figure 1.6). Discovery then returned these satellites to Earth for refurbishment and reflight. This dramatic recovery of two satellites that had never been intended for on-orbit servicing led to the headline, "Insuror Delighted By Space Rescue And Implications," with the quote, "What's happened here goes beyond any commercial results and in our judgment ushers in a new era of insurance practice in space programs."[14]

This is an early example of an on-orbit servicing activity resulting in commercial benefit. The insurers paid the owners of the satellites a total of $180 million for the initial loss, and were planning on recouping $50 million of those costs after the failed satellites were retrieved and resold.[15] This plan ultimately returned both spacecraft to space in April 1990, as Palapa B2P and AsiaSat 1.[16]

This interest from the satellite insurance industry continues to be relevant today: "Adam Sturmer, vice president at Marsh Space Projects, one of the world's three principal space-insurance brokers, said that in the last four years, insurance underwriters have paid out some $700 million in claims for satellite failures caused by propulsion-leak issues or due to the satellites being placed into too-low orbits. In either case, on-orbit servicing could have sizable appeal to operators or underwriters."[17]

Figure 1.7 – HST First Servicing Mission: COSTAR Installation – The first Hubble Space Telescope Servicing Mission restored the observatory by replacing the High Speed Photometer instrument with the new COSTAR corrective optics, designed to correct Hubble's faulty vision. Both of these modular, telephone-booth sized instruments were designed to be replaced in-orbit.

Satellite Servicing Gets Its Challenge

Hubble Space Telescope

The challenges and successes in the early days of satellite servicing would presage the maturation of this discipline in the 1990s. This was the start of the Hubble Space Telescope (HST) era. HST was designed specifically to support on-orbit servicing and evolved the entire discipline in major ways (Figure 1.7). It defined the methodologies of crew training, coupled with tool design and procedure, testing, and verification, to support complex servicing missions. "Test, test, and retest" and "train, train, and retrain" became the mantras that led to success. Orbital Replacement Unit (ORU) and Orbital Replacement Instrument (ORI) design improved as the project developed experience through the servicing missions, ranging from "simple" box removals and replacements in the beginning to very intricate board-level repairs at the end. These missions also demonstrated how to successfully use nominal mission planning, preplanning for contingencies, *in situ* contingency assessment, and detailed simulation tools to help ensure success.

Deployed by the space shuttle Discovery on April 25, 1990, HST suffered international notoriety when initial checkout found an optical flaw (spherical aberration) in its primary mirror. The HST also experienced thermally induced "jitter" or shaking from its solar arrays during orbital sunrise and sunset. Both of these anomalies blurred the images from an otherwise functional observatory. This was the first of NASA's Great Observatories, and, once again, the reputation of the agency was at stake. As HST targeted those scientific topics that could tolerate the imperfect images, NASA initiated an ambitious program to restore the capabilities of the observatory through astronaut servicing. A servicing mission had already been planned to support repair and refurbishment, but not to resolve such a major and unexpected problem.

A series of corrective optics were designed, built, and tested as the centerpiece for this task. The Corrective Optics Space Telescope Axial Replacement (COSTAR) housed one set of optics in an axial instrument enclosure that replaced the High Speed Photometer, a relatively underutilized instrument in the original complement. This innovative optical system deployed by internal mechanisms and corrected the telescope beam for the remaining three axial instruments. The Wide Field and Planetary Camera 2 (WFPC2), which contained a second set of corrective optics internal to the instrument, replaced the original Wide Field/Planetary Camera. NASA's European partner, the European Space Agency (ESA), had provided the original solar arrays. ESA successfully rebuilt a set of improved solar arrays to minimize the thermal sensitivity. Several other spacecraft components were also flown to replace/augment the original set.

On December 2, 1993, after a rapid-development program of only three years, the First Servicing Mission (FSM) was ready and launched on the space shuttle Endeavour (STS-61). This was one of the most complex and challenging human spaceflight missions ever attempted. In five consecutive days spanning 35 hours and 28 minutes of EVA, the crew successfully performed all of the planned activities. This "mother of all servicing missions" was fully successful, restoring the originally planned capabilities and in some cases improving beyond them. Once again, satellite servicing demonstrated its utility.

During this mission, activities focused on replacing Orbital Replacement Instruments (ORIs) and Orbital Replacement Units (ORUs). This was the design intent for HST as well as the servicing infrastructure that was planned to support it. In addition to repairing the optics (by installing COSTAR and WFPC2) and the solar arrays (by replacing the old solar arrays and one set of drive electronics), this mission also installed coprocessors for the flight computer, restored magnetometer function, replaced two Rate Sensor Units (gyroscope assemblies) and gyroscope electronic control units, and installed the Goddard High-Resolution Spectrograph redundancy kit. The replacement of the magnetometers was the first HST repair that used an interface that was not originally intended for on-orbit servicing.

In total, this extraordinary achievement was successfully repeated four more times over the next 16 years. This epic has been told in many forms.[18,19] Here we focus on the satellite servicing aspects.

In February 1997, Servicing Mission 2 advanced the scientific power of HST by installing two "second generation" instruments. These were ORUs by nature since they were designed to be removed and replaced by EVA. The Space Telescope Imaging Spectrograph (STIS) advanced spectroscopy and enabled studying supermassive black holes at the centers of galaxies. The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) opened up the near-infrared wavelength region on HST and enabled study of the distant supernovae that are key to solving the Dark Energy problem.

There was work to do on the spacecraft side as well. One of the Fine Guidance Sensors (FGS) was replaced and an electronics control box was added. This was the first FGS to incorporate hardware for spherical aberration correction. A solid state recorder was installed to improve the reliability of the engineering data stream, and a reaction wheel assembly was replaced. In addition, a Data Interface Unit (DIU) was replaced and the set of Solar Array Drive Electronics (SADE) that was not replaced on the FSM was replaced with a refurbished version of the returned unit from the FSM. Some of the unexpected damage to the light shield multi-layer insulation was repaired *in situ* using improvised tools and materials on board Discovery.

While the FSM still focused on ORU-level activities, three servicing developments are worthy of note. The DIU interfaces were very challenging and required extensive training and testing. This would pave the way for even more ambitious electrical

Figure 1.8 – HST Servicing Sophistication Progression – Servicing the Hubble Space Telescope demanded more than replacing hardware that was designed to be serviced. As unexpected issues arose during the past 20 years of the mission, many tasks required developing innovative techniques to solve specific problems. From left to right: First, the repair of the light shield during SM2. Second, the installation of the New Outer Blanket Layer during SM3A. Third, the attachment of the NICMOS Cooling System external radiator during SM3B. Last, the card removal for the Advanced Camera for Surveys Repair during SM4. Each repair required accessing interfaces that were not designed for servicing, and each was fully successful.

connector manipulations in the future. Secondly, the theme of returning hardware for refurbishment and later reinstallation was starting to emerge with the refurbished SADE installation. Finally, the contingency light shield repairs heralded an era of unplanned repairs of significant complexity.

Servicing Mission 3 (SM3) was split into two flights (Servicing Missions 3A and 3B) to respond to the schedule pressure from failing gyroscopes. Indeed, in December 1999, Discovery visited HST on SM3A while Hubble was in safe mode because the observatory lacked sufficient functional gyroscopes. This mission provided a fresh set of gyroscopes in addition to a new advanced computer, another refurbished FGS, handrail covers, a new transmitter, and another solid state recorder. A partial set of New Outer Blanket Layers (NOBLs) was installed to help manage temperature, as the original insulation had degraded with age. Again, the theme of reusing refurbished parts was reinforced with the FGS reflight. The installation of the NOBLs was the start of on-orbit assembly on HST.

In March 2002, Servicing Mission 3B saw Columbia carry the "scientific advancement" portion of the SM3 manifest. A new camera, the Advanced Camera for Surveys (ACS), took over the main imaging function from the aging WFPC2 instrument. An experimental NICMOS Cooling System (NCS) provided the NICMOS instrument with auxiliary cooling to permit operation after its cryogen was depleted. In addition, this mission installed rigid Solar Arrays that provided more power with less area, replaced a Reaction Wheel Assembly, replaced another set of gyroscopes, and replaced the Power Control Unit (PCU). Of note here is that the NCS was a custom-made design to respond to an unforeseen situation. Its installation required careful planning for both the interior of the HST and its exterior, where a large radiator was installed to remove the heat from a new mechanical cryocooler. This degree of on-orbit assembly is now "routine." The PCU replacement also represented a *tour de force* in training and manipulation of a unit with electrical connectors that were never intended to be removed and reconnected by EVA.

After SM3B came a long hiatus in HST servicing. The Columbia tragedy brought a deep examination into the roles of human spaceflight. During this time, significant advances were made in planning and preparing for robotic servicing of HST. Program plans and some hardware development were started in anticipation of the Hubble Robotic Servicing and Deorbit Mission (HRSDM). In April 2005, NASA decided that another space shuttle servicing mission would be allowed with some additional safety rigor incorporated into the mission training and operations. Work stopped on HRSDM to focus on the final human visit to HST.

In May 2009, Servicing Mission 4 was launched on the space shuttle Atlantis. It brought even more scientific capabilities to HST through the Cosmic Origins Spectrograph and the Wide Field Camera 3. Astronauts performed the first on-orbit circuit board replacements through the STIS and ACS repair activities. To leave the observatory in the best state possible, HST also received new gyroscopes, another new Fine Guidance Sensor, new batteries, and a new set of NOBLs. In anticipation of a future deorbiting requirement, a Soft Capture Mechanism and Low Impact Docking System was installed at the aft end of HST to provide a standard interface for autonomous rendezvous and capture (AR&C).

Each of the five HST Servicing Missions brought its own challenges (see Figure 1.8). They were all overcome to achieve 100% mission success over the course of a two-decade history—an extraordinary demonstration of the benefits and versatility of satellite servicing.

International Space Station, The "Killer App"
To date, the International Space Station (ISS) is arguably the "killer app" for satellite servicing. As humankind's largest artificial satellite, it orbits the Earth with a mass of over 385,000 kg (at assembly complete), spans 108.5 m in its longest dimension, and has 937 m^3 of pressurized volume. Its solar arrays cover an area of 3,567 m^2. Eighty-four kW of electrical power are distributed to operate ISS systems and experiments. The first module, the Functional Cargo Block or Zarya, was launched in 1998. The Expedition 1 crew of Bill Shepherd, Yury Gidzenko and Sergei Krikalev first occupied ISS on November 2, 2000. There has been a continuous human presence in space ever since. About 200 people representing 15 countries have been on ISS to date. It serves as an orbital human outpost where a wide variety of research is conducted and where many of the technologies needed for human exploration beyond Low Earth Orbit (LEO) are being demonstrated.

Figure 1.9 – ISS SSRMS Installing Cupola – In the grasp of the Canadarm2, the Cupola is relocated from the forward port to the Earth-facing port of the International Space Station's newly-installed Tranquility node. NASA astronauts Terry Virts, STS-130 pilot; and Kathryn Hire, mission specialist, moved the Cupola, operating the station's robotic arm from controls inside the Destiny laboratory. Also visible are a Soyuz spacecraft, the (space shuttle) Remote Manipulator System and portions of space shuttle Endeavour. This operation is a dramatic demonstration of the results of humans and robots working cooperatively.

ISS demonstrates the value and utility of on-orbit construction. The sheer size of the space station precludes ground assembly, test, and launch as an entire unit. As a result, standard interfaces between elements were well defined to facilitate on-orbit connection. Ground testing, including space qualification tests in thermal-vacuum chambers, was conducted at the module or subsystem level. Final integration and checkout of each new element occurred on-orbit as they were added. Assembly has taken 34 shuttle and 4 Russian (two Proton and two Soyuz launch vehicles) flights to date (through STS-132 in 2010) to deliver and outfit some 33 major ISS on-orbit elements. Construction of the ISS has thus far required 143 spacewalks—28 from the shuttle and 115 from the U.S. Quest airlock—for a total of about 900 hours, in addition to 34 spacewalks from the Russian Pirs airlock. The total EVA time on ISS is more than an order of magnitude greater than the total Apollo EVA time. Astronauts have performed a variety of on-orbit maintenance tasks including clearing solar array panels snagged during deployment, repairing a torn array, lubricating the ISS Solar-Array Alpha Rotary Joint, and removing and replacing failed components such as a Control Moment Gyroscope, as well as installation and retrieval of external research payloads. Most recently, ISS astronauts successfully repaired a failed cooling system in an ambitious application of servicing capabilities.

ISS internal and external research facilities support a broad array of experiments. Internal facilities include human and biological test facilities, physical science and materials, combustion, and fluid science research equipment racks. A nadir-facing, high-optical-quality window is available for performing Earth science observations. Three basketball-sized Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) are also now available as an ISS facility. These were originally developed by the Defense Advanced Research Projects Agency (DARPA) to conduct formation flying and constellation experiments in the ISS "shirt sleeves" microgravity environment.

There are a number of external research facilities on the ISS as well. These include several sites along the U.S. Truss where four ExPRESS Logistics Carriers (ELCs), two zenith and two nadir facing, will be attached. Each ELC has two locations where research payloads can be installed and operated. External experiments can also be installed and operated on the Japanese Kibo External Facility and the European Space Agency's Columbus External Payload Facility.

Robots have played an important part in ISS construction and maintenance (see Figure 1.9). The space shuttle robotic arm has removed a number of new ISS elements from the shuttle's payload bay and transferred them to the larger Space Station Remote Manipulator System (SSRMS) for berthing or pre-installation positioning. The SSRMS also provides a platform for spacewalking astronauts conducting assembly or maintenance operations. SSRMS is used to grasp and berth visiting vehicles such as the Japanese H-II Transfer Vehicle (HTV) and the future SpaceX Dragon and Orbital Cygnus.

The Canadian Special Purpose Dexterous Manipulator (SPDM), or Dextre, provides the capability to allow some operations previously requiring a spacewalk to now be performed robotically. Dextre is 3.5 m tall and has two independent robotic arms that can conduct much finer operations than the space shuttle arm or SSRMS. This enables activities such as the removal of failed components and installation of spare units. Dextre can be attached either to the SSRMS, onto the ISS Mobile Base System, or to a number of fixed locations around the ISS.

Figure 1.10 – ISS Solar Array Repair – While anchored to a foot restraint on the end of the Orbiter Boom Sensor System (OBSS), astronaut Scott Parazynski, STS-120 mission specialist, participates in the mission's fourth session of extravehicular activity (EVA) while space shuttle Discovery is docked with the International Space Station. During the 7-hour, 19-minute spacewalk on November 3, 2007, Parazynski cut a snagged wire and installed homemade stabilizers designed to strengthen the damaged solar array's structure and stability in the vicinity of the damage. Astronaut Doug Wheelock (out of frame), mission specialist, assisted from the truss by keeping an eye on the distance between Parazynski and the array. Once the repair was complete, flight controllers on the ground successfully completed the deployment of the array.

The ISS may be used as a platform for developing tools and techniques for human and robotic assembly of other large structures in space, such as large optical telescopes (see Figure 1.10). A number of demonstration concepts have been proposed to take advantage of the availability of astronaut spacewalks and dexterous robotics such as Dextre, as well as the utilities and support structures on the ISS.

Dextre is also a tool to develop new dexterous robotic applications. Operating telerobotically from the ground, it will be used to demonstrate the capability to service and refuel a satellite not originally designed to be serviced on orbit. The Robotic

Refueling Mission (RRM), discussed in Chapter 4, will include a number of task boards and refueling ports configured to represent typical legacy spacecraft. Special tools will be used by Dextre to remove thermal insulation, access test ports, cut safety wires, remove tertiary and safety caps, and transfer a fluid with properties similar to hydrazine (a typical satellite fuel) into a receiving tank.

The Dextre Pointing Package (DPP), also discussed in Chapter 4, will use Dextre to demonstrate a fine pointing capability for future Earth and space instruments. DPP, operating in Dextre's grasp, will also observe visiting vehicles approaching ISS to evaluate a number of sensors and to assist in the development of algorithms and techniques for autonomous rendezvous and capture.

Robonaut 2 (R2) is another robotic enhancement to ISS. R2 is a "human-equivalent" robot with fine hand and joint control (Figure 1.11). It will initially operate in the internal pressurized ISS environment. Eventually, a variant of R2 may be used as an astronaut aid on the outside of ISS.

Over the course of its assembly and utilization to date, ISS has put into practice and perfected the best lessons learned thus far in satellite servicing.

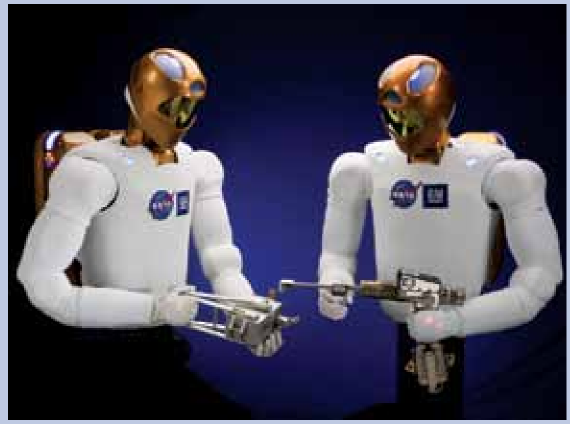

Figure 1.11 – Robonaut 2 – A "human equivalent" robot, Robonaut 2 (R2), handles tools similar to the ones it will use after its deployment to the International Space station in early 2011.

Technology Demonstrators

The potential of satellite servicing has not escaped the attention of most major organizations associated with space research. Here we list a few historical and recent examples of technology demonstration activities. The intent of these activities is to mature key servicing technologies to the point where we can confidently assemble the systems we are envisioning today.

NASDA: Engineering Test Satellite VII

On November 28, 1997, the National Space Development Agency of Japan (NASDA) launched the Engineering Test Satellite Number 7 (ETS-VII). It was the first demonstration of autonomous rendezvous and docking involving a "chaser" spacecraft and a "target" spacecraft. These parts were launched together in the H-II rocket fairing. The Chase Vehicle included a 2 m robotic arm used to grapple the Target. Relative GPS successfully provided navigation information to the Chase Vehicle to control the maneuvers. This successful mission demonstrated basic technologies of rendezvous and docking, not as a complete sequence, but in its component parts. It also supported several related experiments on teleoperation and latency, ORU exchange and assembly of a space structure, and dynamic coordination between the arm and the spacecraft.[20] It is remarkable that given the success of this mission, it would be another decade before the next and more complex demonstrations would take place.

U.S. Air Force: Experimental Spacecraft System

Starting in the late 1990s, the United States Air Force Research Laboratory built a series of low-cost "microsatellites." Among them were XSS-10, launched in January 2003, and XSS-11, launched in April 2005, both of which demonstrated key technologies for satellite servicing. XSS-10 acquired and tracked its own second stage, navigated around this object, and performed a series of inspections ranging from 100 m to 35 m from the second stage. XSS-11 demonstrated autonomous operations and in particular, autonomous proximity operations. It navigated to several U.S.-owned objects in space and moved around these objects while taking images.

Demonstration of Autonomous Rendezvous Technology

The Demonstration of Autonomous Rendezvous Technology (DART) mission was launched on April 15, 2005, with the intent of demonstrating a suite of on-orbit technologies that would support autonomous rendezvous and proximity operations. This was again a two-component experiment consisting of the DART spacecraft and the previously launched (1999) Multiple Paths, Beyond-Line-of-Sight Communications (MUBLCOM) satellite.

The launch, early orbit, and rendezvous operations were fully successful. The DART subsequently used significantly more fuel than planned during the proximity operations phase due to a sensor anomaly and a non-optimal software response. This resulted in a collision with the MUBLCOM and subsequent successful triggering of autonomous retirement operations for the DART spacecraft. The mishap report[21] identified a likely series of events and root causes that led to this anomaly. Among the recommendations in the report was a need for stronger systems engineering for such a technically challenging project. It also highlighted that the goals of this mission are central to our future endeavors in space, and that its classification and acceptance as a "high risk" mission (according to NASA procedures, currently specified as NASA Procedural Requirements NPR 8705.4, "Risk Classification for NASA Payloads") caused unintended consequences as the project team dealt with the usual cost and schedule challenges.

DARPA: Orbital Express

The Orbital Express mission sponsored by the Defense Advanced Research Projects Agency (DARPA) provided the first demonstration of successful end-to-end robotic satellite servicing activities. The system launched on March 8, 2007, and consisted of two spacecraft: the Autonomous Space Transport Robotic Operations (ASTRO) vehicle and a prototype modular NEXT-generation serviceable Satellite (NEXTSat). NEXTSat was designed with servicing in mind, and in particular, for servicing by ASTRO. During the mission, ASTRO successfully performed autonomous docking with NEXTSat and demonstrated fuel transfer as well as some ORU activities such as the insertion of a battery into NEXTSat and changeout of a flight computer on ASTRO. During its roughly 4-month mission, Orbital Express provided confirmation that key technologies needed for satellite servicing are now in place.

New International Initiatives

Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), the German Space Agency, announced in February 2010 that it had awarded contracts for five components of its on-orbit servicing demonstration, the German Orbital Servicing Mission. The contracts are for overall system management, tracking, and rendezvous with the customer satellite, disposal of the customer satellite, design of the customer satellite, and the design of the servicer's payload, which includes a robotic arm and docking mechanism. During the on-orbit demonstration, the servicer and customer satellite would be launched together and would separate once in orbit, similar to the Orbital Express mission. The servicer would rendezvous with and capture the customer satellite and then guide the system into an Earth reentry. Germany looks at this as a way to propel their country to the forefront of this technology.[22]

Canada's MacDonald, Dettwiler and Associates Ltd. (MDA) announced in March 2010 that it is designing a mission to demonstrate satellite refueling as well as moving inoperable satellites into "graveyard" orbits. The servicer would dock with the satellite's apogee kick motor, peel away insulation, connect to a fuel line, and deliver propellant. MDA is prepared to finance part of the mission itself, and it is talking with potential customers to establish enough of a demand to finance the rest of the mission. The eventual business model could have customers paying per kilogram of fuel that has been successfully added to their satellite; the affordable price per kilogram would be determined by the additional revenue generated by the operator from the extended operational life of the satellite. The mission would have an on-orbit life of about 5 years and would carry enough fuel to perform 10 or 11 refueling or retirement missions.[17]

In May 2010, MDA announced its plan to initiate a major investment in the on-orbit servicing business, calling it its most promising new business venture.[23] By July 2010, MDA seemed to have cleared most of the technical hurdles to achieving their goal. However, due to lingering and substantial financial and liability-related questions, it also appeared that their plans might be at risk.[24]

Historical Activities

More than two decades ago, NASA sponsored a multiyear series of studies and workshops on various topics in satellite servicing. Although the technology and candidate "customer satellites" have changed considerably, most notably in the capabilities of robot and sensor systems, many of the same issues assessed in the late-80s were considered in this study. In appreciating that 20-year-old work, it is worth remembering that neither the ISS nor HST had been launched when most of that material was written and recommendations were submitted to NASA Headquarters for action.

The breadth of satellite servicing studies were presented and discussed in four annual conferences on satellite servicing, culminating in June 1989 with the *Satellite Services Workshop IV* at NASA's Johnson Space Center (JSC-23655). This conference summarized much of the preceding half-decade's work and presented priority recommendations to enable future servicing in space. Significantly, the NASA Headquarters Office of Space Flight draft strategic plan for satellite servicing was presented and discussed (see also Levin, G. and Erwin, H. Jr., "An Overview of the Office of Space Flight Satellite Servicing Program Plan," *Acta Astronautica 8* (1988: 55-61). Specifically, the strategic plan highlighted use of the ISS with the Orbital Maneuvering Vehicle (OMV) and space shuttle to achieve four priority goals: (1) refueling or resupply, (2) repairing, (3) retrieving, and (4) system upgrade.

Presentations and discussion at this final workshop drew upon the recently released *Technology Assessment for a Robotic Satellite Servicer System* (1988, JSC 22970, Volumes III and IV; Volumes I and II are interesting background material and existing literature for that time on aerospace robotics). In addition to making recommendations for priority technology investments, an interesting conclusion in this report is that commercially available robotics systems *at the time* could often be adapted for space applications. This conclusion may have been largely due to the very limited investments that NASA had made in robotics technologies, a situation that has improved but still largely exists today.

NASA's servicing strategy at that time went on to outline a series of increasingly challenging objectives: building upon demonstrations at ISS and in Low Earth Orbit (LEO), then moving outward to Geostationary Earth Orbit (GEO) and other locations as the capabilities improved. Likewise, the strategy planned for increasingly capable robot systems, supported by agency technology investments. Throughout, the NASA strategy emphasized developing the "business model" basis for servicing: Were there sufficient numbers of candidate satellites that could be serviced?

Finally, a key element to the NASA servicing strategy was the necessity of establishing common standards among satellite designs to facilitate servicing and upgrading, including modularity of systems and commonality of connectors, ports, and grappling fixtures.

Ironically, almost exactly a year after the public presentation of NASA's servicing plan, the OMV "space tug" that was central to NASA's servicing strategy was cancelled due to budget pressure.

NASA completed no comparable, high-level planning for servicing after the 1989 workshop was published, although "lessons learned" on satellite servicing were compiled in 1990 (NASA 408-M&R-0302-0009) by the On-Orbit Servicing Steering Committee, which apparently only met a limited number of times. In the 1980s and 1990s, the NASA Telerobotics Program funded projects addressing on-orbit assembly and servicing, science payload tending, and planetary surface robotics.

Our study confirms these findings from the past, with updates based on the advances and experiences in the intervening years. The development of the satellite servicing discipline has taken a somewhat less direct path than predicted by previous studies. Nevertheless, it has advanced through a combination of need, technological readiness, and perhaps most importantly, a growing acceptance of its many benefits.

The Evolution of Tools and Techniques

As satellite servicing has evolved, so have the tools and techniques used to perform its functions. We have come to understand that the tools and techniques are a central part of any servicing activity. The "actor" (be it an astronaut or a robot) always has constraints on how it can perform operations. The specific servicing task places requirements that may or may not be easily satisfied within those constraints. The tools and techniques are how the capabilities of the actor are transformed into the actions required for the task. This evolution can be seen in a brief review of the servicing missions performed to date and the tools developed for these missions.

During Skylab 2, the first manned mission to that facility, repairs to the observatory's thermal shield and solar arrays were performed using human EVA. The tool design followed a utilitarian approach with telescoping rods, cable cutters and pry bars. Simple but effective, these efforts laid the groundwork for future servicing tool development.

Later in the space shuttle era, servicing tools and techniques evolved to make use of EVA and robotic tools developed to support the space shuttle's systems and its mission. The most notable robotic tool has been the Remote Manipulator System (RMS), first flown aboard the space shuttle Columbia during STS-2 in November 1981. A teleoperated robotic system, the RMS extended the shuttle's capabilities outside the payload bay through grasping, positioning, and control. EVA and robotic tools would come together for the first time for servicing during the Solar Maximum Mission (SMM) repair. A specifically engineered servicing tool, the Trunnion Pin Acquisition Device (TPAD), was developed to support EVA capture of SMM. The RMS ultimately grappled the SMM spacecraft and enabled the EVA crew to replace and repair SMM components using shuttle EVA tools. The successful SMM recovery and repair mission showed that servicing using a combination of standardized and specific EVA tools is possible, and that space shuttle and EVA crew capabilities can be enhanced by using those tools.

The HST Flight Systems and Servicing Project incorporated the lessons learned from SMM when developing the methodologies for the HST First Servicing Mission (FSM). Once again, the RMS would grapple the customer spacecraft. More significant evolution of servicing tools took place in the nature of the EVA tools (see Figure 1.12).

Figure 1.12 – EVA Power Tool Progression – Astronaut servicing tools have progressed as the complexity of servicing tasks has increased. Shown here is a series of EVA power tools—torque-producing, battery-powered, bolt-turning drivers—developed over the course of the space shuttle and ISS Programs. From left to right: the original shuttle Mini Power Tool is a low torque, household screwdriver with limited capacity and reliability. The Power Ratchet Tool was developed for the HST Deployment Mission to provide high-torque and long battery life, and continued in service for all HST Servicing Missions. The Pistol Grip Tool was developed jointly between the HST and ISS Programs, as both were in need of a medium-torque, highly accurate, and self-contained tool for precision and construction tasks. The Mini Power Tool was developed for HST Servicing Mission 4 as a high-speed, high-precision, illuminated dexterous screwdriver capable of removing hundreds of tiny fasteners.

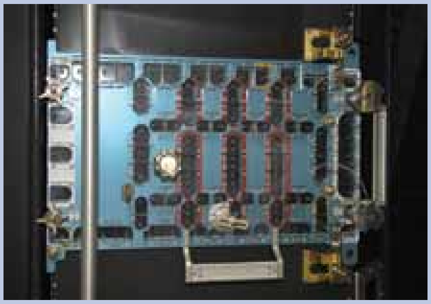

Figure 1.13 – Unique, Purpose-Built, On-Orbit Repair Tools – By the last HST Servicing Mission, servicing tools had progressed to the point where tasks that were complex on Earth were successfully completed on-orbit. During the HST Servicing Mission 4, two scientific instruments, the Space Telescope Imaging Spectrograph (STIS) and the Advanced Camera for Surveys (ACS), were both partially disassembled and repaired on-orbit by astronauts using purpose-built servicing tools. Neither instrument was designed to be serviced on-orbit. The disassembly operations required dozens of tiny screws to be removed and then contained to prevent them from floating into sensitive areas. The technology of the Fastener Capture Plate (left) facilitated these operations. Additionally, the instruments contained electronics boards that had to be replaced. This operation required ensuring that the astronaut be absolutely protected from dangers such as sharp edges, while simultaneously protecting the electronics boards from unintended contact and electrostatic discharge (ESD) damage. Unique tools such as the Card Extraction Tool and Wire Cutter Tool (middle and right) were created to accomplish these tasks. Today, both observatory instruments are operating again, in part because of the dexterity and efficiency made possible by these tools.

The servicing tasks required improved power tool performance in areas such as battery life, torque, and reliability that drove the tool development activities. Figure 1.12 shows the increasing use and necessity of power tools that enabled the vastly increased efficiency for the sequence of HST servicing missions.

HST servicing missions also required advancements in servicing tool dexterity and specialization as the complexity of EVA operations increased. This began with replacements of ORUs that were designed for EVA changeout (FSM and SM2) and progressed to non-EVA friendly ORU replacement and electronics board level repairs (SM3A/B and SM4). Again, servicing tool design evolved to meet the challenge (see Figures 1.13 and 1.14). By the end of SM4, HST repair astronauts had taken on-orbit servicing to a new level by not only proving that it is possible to remove and contain hundreds of tiny non-captive screws, but also by demonstrating how to go well beyond the interchange of Orbital Replacement Units to executing circuit board-level repair of embedded systems. A milestone achievement for servicing tool design, HST servicing missions proved that "brain surgery" is possible in space through the successful repair of the ACS Charge-Coupled Device detector readout electronics.[25]

Servicing tool evolution continues to this day, with special concentration given to the development of robotic tools for ISS demonstration activities. The success of on-orbit servicing continues to be directly tied to the heritage development of unique servicing tools, highlighting the importance of having the "right tool for the job."

Figure 1.14 – Astronaut Training Refines the Tools and Improves On-Orbit Performance of the Human-Machine Interface – Astronauts John Grunsfeld and Mike Massimino concentrate on their training with the Fastener Capture Plate.

Myths About Servicing

From the previous sections, it is clear that the extraordinary potential of satellite servicing has motivated a significant effort in both studies and practice throughout the world. Flight experience demonstrates that the technologies and tools to successfully execute servicing missions are well in hand. In spite of these successes, some common misconceptions persist. Such figments need to be addressed critically in order to enable advances in our paradigms for space exploration. In this section we explore three such myths.

> "There is nothing to service" is not true because strong business cases have been made for servicing commodity satellites that provide the communications infrastructure for modern life.
>
> "Servicing is too costly" is generally quoted with respect to the HST servicing experience, which is not representative of the majority of potential future servicing activities.
>
> "Satellites cannot be serviced unless they were designed to be serviced" is demonstrably false since many HST servicing successes were "impossible" tasks performed on hardware that was not designed to be serviced.

"There Is Nothing To Service"

Sullivan[8] studied all Earth-orbiting commercial, civilian, scientific, and military spacecraft launched from January 1984 to December 2003 and found that on-orbit spacecraft failures occur on a regular basis. Considering potentially telerobotically serviceable failures only, on an average annual basis there are about 4.4 component level spacecraft failures, 3.8 more complex systemic failures, and 0.3 deployment anomalies. Beyond component and system failures, a number of propulsive or refueling servicing opportunities also occur—about 1 spacecraft per year requires assistance to correct delivery into the wrong orbit (need transfer from launch shortfall to GEO), about 20 GEO spacecraft reach the end of useful fuel (could be refueled or relocated to disposal orbit), and about 13 spacecraft perform relocations in the GEO belt, using up station-keeping fuel.

Other opportunities that carry a less direct economic impact also occur. About 20 new spacecraft are deployed in GEO each year. Deployment monitoring of these 20 satellites is likely of value to many operators. Also, of the active population of GEO spacecraft (~200), an annual inspection for micrometeoroid and orbital debris damage along with general spacecraft health monitoring might become a paying service as well. Removal of non-operational spacecraft (~150 objects) from the GEO belt would reduce the chance of catastrophic collision significantly and benefit all GEO operators. Altogether, there is a substantial set of annual servicing opportunities: 10 dexterous, 20 GEO refuel, 14 relocation, and more. The potentially serviceable failures alone amounted to roughly $750 million (in FY 2003 dollars) in insured and uninsured losses annually between 1994 and 2003. These same failures have caused the industry to take a risk-adverse approach and to use redundancy, proven technology, and long operational lifetimes to attempt to mitigate this risk.

One example of an on-orbit failure is Orion 3, a Geostationary Earth Orbit (GEO) communications satellite that was launched in May 1999. The satellite cost $150 million, the launch cost $80 million, and there was a $265 million insurance claim after the second stage failed to place the satellite in the proper orbit.

This trend continues today. According to a vice president at one of the world's three principal insurance brokers,[17] in the last four years insurance underwriters have paid out some $700 million in claims for satellite failures caused by propulsion leak issues or due to the satellites being placed in the wrong orbit. With its ability to fix some of these problems, on-orbit servicing could have a sizable appeal to operators and/or underwriters.

The $400 million U.S. Air Force Defense Support Program missile warning satellite DSP-23, provides a further example. It is drifting eastward through the GEO belt at a rate of about 1° longitude per week.[26] Recently, control of Galaxy 15, a GEO communications satellite, was lost after five years of successful operations. It has also begun to drift away from its orbital slot with its communications payload broadcasting uncontrolled at near full power, potentially causing disruption to other satellites.

Orbital Satellite Services (OSS) claims[27] that there will be more than 140 commercial communications satellites in the next 10 years that will be due for decommissioning that would benefit from life extension, or about one per month. This life extension could be accomplished either by attaching a propulsive servicer satellite to the back of the customer satellite, as OSS proposes, or by adding fuel to the customer satellite. Unfortunately, satellites are operated today as airplanes were before aerial refueling—with limited scope and flexibility. However, on-orbit refueling does more than extend the satellite's life. Lift capacity of current launch vehicles limits the amount of fuel available to a satellite on-orbit. This prevents military planners from developing operations concepts that would consume large amounts of fuel. By refueling these satellites on-orbit, the ability to use them tactically would be enhanced. As one example, faster orbital position changes (which would consume more fuel) would significantly reduce the drift time to a new location in the GEO belt, reducing the repositioning overhead time for valuable assets.

The detailed business cases for these potential satellite servicing customers certainly need further consideration. Closing the business case depends on the details of the business, risk posture, insurance availability, and other considerations that are specific to a particular customer. However, as a part of this study, we have found that the claim "there is nothing in space to service" is based on outdated information or a set of very arbitrary constraints. This study finds that with appropriate planning, current technology supports refueling, orbit modification, repair, refurbishment, and other modifications of large classes of legacy spacecraft in addition to future spacecraft that could be designed with servicing in mind.

"Servicing Is Costly"

In spite of NASA's decades of successful satellite servicing activities, any discussion about the feasibility of satellite servicing eventually engenders the assertion that servicing satellites just costs too much. It might be, "Designing a satellite specifically to be serviced will increase the cost by at least XX%," or, "Why service anything when it's actually cheaper to build and launch a new one?" For current spaceflight developers, this myth is a strong barrier to candid assessments of options for mitigating risks and meeting mission objectives in the most cost-effective way. Much work has been done in academia and industry to describe the cost-benefit equation for servicing, yet this myth persists. It must be examined and the false portions put to rest as NASA moves forward to define future spaceflight architectures.

Many factors contribute to perceptions about the cost of servicing, often springing from erroneous generalizations of specific facts. Here we summarize three perceptions that contribute to the myth: 1) the cost of the current servicing paradigm, 2) the existence or viability of other servicing paradigms, and 3) the cost of designing a satellite to be serviced.

The most pervasive perceptions about the cost of the current servicing paradigm stem from the hugely successful Hubble Space Telescope (HST) servicing missions that are widely reported to have cost between $1–2 billion each, and to have used astronauts in potentially dangerous extravehicular activities to perform intricate tasks to refurbish a multi-billion-dollar observatory. Even these high numbers may underestimate the true cost of servicing HST since they do not include the full lifecycle cost of the space shuttle. A straightforward business case for servicing HST could be made by comparing the several-billion dollar initial cost of the telescope against the $1–2 billion cost for each servicing mission. If the servicing mission leaves HST in a "like-new" configuration and with expanded capabilities that are congruent with scientific demands, then building and launching a replacement would appear more expensive. However, any cost expressed in billions is a great deal of money, and given the high visibility of HST and its servicing missions, this enormous price tag has a profound influence on the perceptions and beliefs about the cost of satellite servicing.

Even with the reality of billion-dollar HST servicing missions, it is not realistic to assume that any successful servicing mission must follow the HST model and thus cost an appreciable fraction of the original investment. The cost and the sophistication of the tasks clearly place the HST servicing missions in the extreme category of servicing, where the business case resides more in the incredibly high scientific or strategic benefit than in the straightforward cost assessment. That case for HST has been made in many different ways.[28,29,30] Periodic refurbishment has kept this flagship observatory productive for over twenty years. The installation of new instruments created a state-of-the-art observatory with each servicing mission, a cadence that could never be supported by launching new observatories. The new instruments will also help ensure that the observatory's last years will be its most scientifically productive. However, HST is not the only model for servicing. More importantly, it is not the right model to use in assessing costs for a purely commercial business case for servicing.

Several academic theses identify the cost benefit of servicing, viable business cases, and cost break points for different models of satellite servicing.[8,31,32] Whether modeling a servicer with a single customer, a servicer that visits multiple customers in nearby orbits (e.g., a single inclination in GEO), or a constellation of servicers covering a larger orbit regime, a viable customer base and approach can be identified within the parameters studied. Some of these cases describe the exotic-car model of multi-billion-dollar missions, but most describe fleet or family car servicing models (see Henshaw analogy in Chapter 1, "Introduction—Why Is Satellite Servicing Important?").

Erdner presents one example in a study where he describes a constellation of 15 identical CubeSat satellites deployed just below the geostationary belt to inspect every satellite in GEO in less than a year.[33] The goal is to detect any co-orbiting objects close to known assets. His cost model estimates this fleet could be built and operated for a year for a total mission cost of $18 million (in FY 2000 dollars). While his well-documented cost model explicitly excludes many elements (e.g., launch), even at ten times that cost, this paradigm of a group of small inspection satellites is remarkably different from that of the sophisticated HST servicing missions and far less costly.

In our notional mission suite (see Appendix F), we present a servicer concept to autonomously rendezvous, capture and move to a super-synchronous disposal orbit multiple non-cooperative customers in GEO. Although the mission was not optimized for cost, the servicer was estimated to cost $545 million and could "super-sync" (place in super-synchronous disposal orbit) roughly ten non-cooperative customer spacecraft in GEO. Such a servicer would enable a customer satellite to remain in position until all its maneuvering fuel is expended and still comply with orbital debris requirements at end-of-life by purchasing a super-sync mission from the servicer. The same servicer could also be used to dispose of inoperable spacecraft.

The next evolution of the space program could incorporate such lower-cost models of satellite servicing. Rather than costing more, a new spaceflight architecture that incorporates refueling and servicing could actually *reduce* cost at the mission, program, and agency levels. A refueling infrastructure (e.g., a refueler that visits multiple customers) in GEO could reduce cost and reduce risk for new missions and extend the life of existing, legacy spacecraft simply by separating the launch of the majority of the propellant from the launch of the high-value satellite. A spaceflight architecture that includes a refuelable servicer in GEO would shift the risk of mission failure, reduce mission cost, increase mission performance and flexibility, and potentially enable new missions.[31]

Such ventures do not exist today due to obstacles such as liability issues[24] and myths about customers or technology readiness. However, their potential profitability is well documented, as described in the references above. These new ventures would open the possibility of a new paradigm for commercial and strategic satellites in a serviceable orbit. In the absence of servicing, satellite developers are driven towards proven, reliable designs and long operational lives. These drivers may unnecessarily stifle innovation and increase cost.[31] With satellite servicing, new space architecture trades are opened up with potentially significant cost-benefit improvement.

The third aspect of the "Servicing Is Costly" myth is the belief that designing and building for serviceability increases the concept-to-launch cost of the customer satellite. In response, we consider what it means to design for servicing and then assess the end-to-end life cycle costs and potential savings of such an approach. This report summarizes the question of designing a satellite to be completely cooperative to servicing (see Chapter 5, "Satellite Servicing: The Challenges," section "Making Future Missions More Serviceable"). However, the successful servicing of subsystems on HST that were never designed to be serviced proves that on-orbit servicing is feasible even with legacy hardware. Designing for servicing actually describes a spectrum of accommodation options. With each servicing accommodation that is incorporated into the design, a satellite moves gradually from being a non-cooperative (no accommodation) customer to a fully cooperative (all possible accommodations) customer.

For this cost discussion we group accommodations for servicing into two general categories: 1) adding external hardware elements (e.g., grapple fixture, rendezvous targets, handrails, holes, or handling points) and 2) designing modular subsystems with simplified and standardized interfaces. During a servicing mission, both types of accommodations transfer task complexity from the servicer to the customer, with concomitant reduction in the cost and risk of the servicing mission. However, for the moment, we only consider the cost that the customer satellite incurs during its design, build, integration, test, and launch periods.

The external hardware elements that accommodate the Autonomous Rendezvous and Capture (AR&C) phase and enable crew or robots to move around the satellite are quite simple. Few have moving parts or electronics. As standardized interfaces, the hardware requires no additional design; the project only determines where they will be placed. Standards provide guidance regarding placement, but servicing systems can tolerate wide deviation from the standards. The amount of additional hardware is a function of the size of the satellite and the type of servicing task. For example, the Orbital Express mission used a fully cooperative docking mechanism (32 kg) and refueling mechanism (50 kg). Combined, these added a little more than 3% to the mass of an ordinary GEO communications satellite (2,500 kg).[31] Such accommodations greatly simplify a servicing mission while minimally increasing the concept-to-launch costs of a satellite. However, there are circumstances where *any* additional mass requires the compromise of other mission objectives (e.g., less propellant can be carried, thus shortening the mission duration).

The second category, designing modular subsystems with simplified interfaces, is more interesting and challenging because it encompasses an array of options with associated costs and savings at different mission phases. To assess the costs and savings of such design principles, it is important to understand how satellites are traditionally built.

To some extent, satellites are already designed to be modular with well-defined interfaces, because proven subsystems are often built and delivered by different organizations or vendors. Ideally, this modular approach enables the smooth integration of elements and subsystems delivered by separate organizations into a functioning system. Thus, satellite developers currently design modular systems and simplify interfaces because doing so reduces overall mission risk and cost. Methods for implementing modularity and simple interfaces for ground processing and on-orbit performance have evolved as we have continued to build on past successes.

It is worth noting that designing a system that meets only the on-orbit mission requirements is insufficient. Every satellite system must successfully tolerate many different configurations and environments as hardware moves from manufacturing through launch. Typical development phases include, for example, subsystem-level testing, handling in the gravitational environment on Earth, and the launch environment. Each of these phases and environments imposes distinct requirements, and each additional requirement comes with costs and benefits that project managers must trade. Within this context, it is perhaps helpful to view servicing as one more phase that imposes requirements to be traded with all other mission phases.

With this perspective, we can speak in broad terms about the cost of modularity and simplified interfaces. Satellite developers currently build modular systems as a cost-effective approach for the concept-to-launch flow. Servicing can be considered another phase of mission development with requirements that drive further modularity and simpler interfaces. Many factors affect the cost of accommodating servicing in a specific satellite (e.g., the degree of challenge in meeting all other requirements, how tightly constrained the mission or subsystem is, the maturity of the implementation considered, and the sophistication of the servicing tasks anticipated). However, if one accepts that designing for servicing encompasses a spectrum of options, then project managers and systems engineers can tailor the level of accommodation and sophistication to the demands of the mission.

In finding the right balance between the additional requirements for servicing accommodations and the cost of those added requirements, project managers must recognize the extent to which these accommodations reduce the risk and cost of the Integration and Test (I&T) flow, and what other benefits they might bring. A system designed to support the replacement of a hardware element on-orbit can support similar task times on the ground. A system designed to provide easy access to hardware elements on-orbit would also provide easy access during ground processing. A sufficiently modular system that supports fully testing subsystems prior to delivery is likely able to proceed with system-level integration even as individual components require rework. For scientific missions, such a modular system allows the infusion of current state-of-the-art capability and technology as close as the year before launch, improving the discovery potential of the mission even if the satellite is never serviced.

It is impossible to exactly quantify the costs and savings of incorporating additional modularity to accommodate servicing in the abstract. Every set of mission requirements affects the complexity and the cost of any specific servicing accommodation. However, assessing the options for meeting mission objectives and mitigating risks in the most cost-effective way is the primary activity of the early design phases of every mission. Currently, designing for servicing is rarely even considered, in part because of the myth that servicing just costs too much.

As NASA integrates servicing into the next architecture, government, academia and industry developers will begin to accept that servicing is another option in the overarching systems engineering approach to meeting their objectives. They can then perform a cost-benefit analysis tailored to their missions, their requirements, and their own business cases.

"Satellites Cannot Be Serviced Unless They Were Designed To Be Serviced"

Another common myth in the satellite business is that on-orbit satellites cannot be serviced unless they were designed and manufactured to support it. The basis for this myth stems from the belief that 1) without *a priori* rendezvous targets/aids and docking fixtures, a servicing vehicle cannot adequately locate and reliably rendezvous and dock with an on-orbit satellite, and 2) without ground-tested cooperative interfaces, a servicing vehicle cannot perform any level of servicing on a legacy on-orbit satellite that would be of value. Both history and analysis demonstrate that these two statements are false.

In 2005 to 2006, the Experimental Spacecraft System Number 11 (XSS-11) mission demonstrated the capability to autonomously perform safe and reliable, fully autonomous rendezvous and proximity operations with a derelict or "non-cooperative" space object. By the time the mission was completed, XSS-11 had completed 50+ successful resident space object (RSO) rendezvous maneuvers with a Minotaur fourth stage; 300+ successful natural motion circumnavigations of a non-cooperative RSO; successfully demonstrated an on-orbit checkout of a collision avoidance system; performed 15+ successful station keeping maneuvers; 1,200+ hours of safe, autonomous proximity operations; and captured 2,000+ witness camera images. The XSS-11 mission was extremely successful, achieving all of its goals with 100% mission success and ultimately proving that the technology and systems integration knowledge and experience are available *today* to successfully perform intricate rendezvous and proximity operations on non-cooperative space vehicles and objects.

With regards to a capture and docking interface, most in-space non-cooperative vehicles share a number of similar "features" that can be used as docking interfaces. The DARPA Front-end Robotics Enabling Near-term Demonstration (FREND) project has performed ground demonstrations of autonomously grappling two such features with a robot arm—a vehicle's Marman clamp ring and bolt holes.[34] Both of these features are used to attach the spacecraft to the launch vehicle, so they are structurally sound capture points.

And what about servicing a vehicle that was not designed to be serviced? The answer obtained through years of experience successfully servicing portions of the HST that were not originally designed to be serviced is simply stated: "The right tool for the right task at the right location." Engineering evaluation of existing interfaces (through hardware engineering units, design and manufacturing drawings, and pre-launch photos) enables future teams to develop and ground test specialized manipulation tools that are capable of performing targeted tasks and potential contingency operations on-orbit. Coupled with *in situ* evaluations of the hardware to be serviced, these tools can provide servicing capabilities that include vehicle refueling, vehicle hardware upgrades and repair, and cryogenic replenishment.

What Are Appropriate Human and Robotic Servicing Paradigms?

When discussing the roles of humans and robots in any space exploration mission, two questions often arise: "When should humans be used and when should robots be used?" and, "If robots are used, how autonomous do they need to be?" Our conclusion is that robots should be used alone where their capabilities are sufficient, to minimize unnecessary risk to humans. Astronauts provide the ultimate in autonomy and adaptability to changing circumstances. These are fundamentally complementary modes of servicing that will need to be balanced and will likely work together to advance the art of satellite servicing.

Figure 1.15 – AERCam Sprint – Autonomous Extravehicular Activity Robotic Camera Sprint (AERCam Sprint) in the cargo bay of the Earth-orbiting space shuttle Columbia during STS-87. The AERCam Sprint is an experiment that demonstrates using a free-flying video camera for remote inspections. It is a 14-inch diameter, 35-pound sphere that contains two video cameras, an avionics system, and 12 small Nitrogen gas thrusters.

The current preference when planning space missions is to use Extravehicular Activity (EVA) when humans are present (space shuttle and ISS missions) and to use robots when humans are not present (e.g., planetary exploration), or when “super-human powers” are needed (e.g., grappling the Hubble Space Telescope with the space shuttle’s robotic arm or moving a 15-ton module around the ISS using its robotic arm), or to provide a platform for moving humans around. This has been an evolving process based on the extensive experience and lessons learned from the HST servicing missions as well as the assembly and maintenance of the ISS. The military often uses the 3 “D”s when talking about the role of robots—the robots perform the dumb, dirty, and dangerous work. As applied to spaceflight, the role of robots can be expanded to include the 6 “S”s, which follows the evolution of human-robot interaction proposed by Akin:[35]

- Robots as supplemental eyes: The robot provides an auxiliary view. NASA evaluated such a system during space shuttle mission STS-87 in November of 1997 by flying AERCam Sprint (Figure 1.15).
- Robots as subordinates: The human is the “primary” worker and robots carry tools and fetch hardware for the astronaut, as well as prepare and close out worksites. This saves limited EVA time for the more demanding and critical tasks that need to be performed by a human in a spacesuit.
- Robots as sidekicks: The robot works alongside and interacts with the human (Figure 1.16).
- Robots as surrogates: When the worksite is inaccessible to humans (Geostationary Earth Orbit [GEO], planetary precursor mission), there is limited or no human involvement.
- Robots as specialists: When a system is needed that exceeds the dexterity, strength, positioning accuracy, or speed of a human in a spacesuit. This is the role robots play in the construction industry and in robot-assisted surgery.
- Human-robot symbiosis: Use robot technology to augment or enhance human capabilities by creating exoskeleton-type

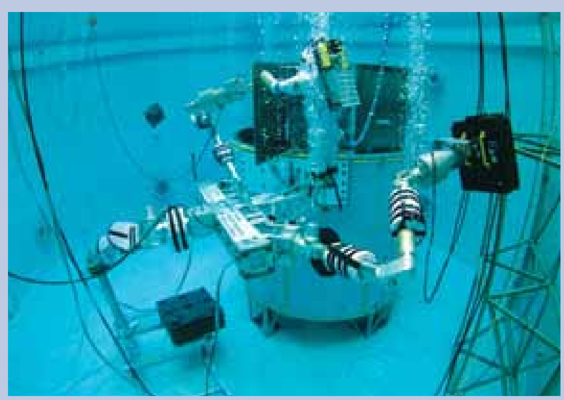

Figure 1.16 – Robotic Assistants – An astronaut in a simulated spacesuit is assisted during notional satellite servicing tasks by two robotic manipulators: one helping to open/hold the door while the other one stows an old battery and grabs a replacement. A free-flying camera platform observes the operation and captures this photograph.

spacesuits, or a "human-in-a-can" for EVA in higher-risk environments such as the Van Allen radiation belts.

The notional missions explored as part of our study as well as our mission sequence parallel this progressive interaction with a set of missions that include evolving human-robot interactions. Other than human-robot symbiosis (which is the most interesting, has the largest potential benefit, and therefore deserves further study), the other five roles for robots interacting with humans were all explored.

A few principles can guide decisions about the appropriate level of robot autonomy. When long one-way communication travel times are imposed, or the tasks to be performed by the robot are simple and well-defined tasks, autonomy has a clear advantage. However, when the planned tasks exceed the existing or projected capability of automation, another solution needs to be found. As with the human-robot interaction paradigms discussed above, humans can be part of the solution. All too often the argument is made that robots cannot perform a task because of their inability to deal with the unexpected. In such cases, a robot can be baselined to perform the tasks with the human providing assistance when needed, either by remotely reprogramming the robot to deal with the unexpected circumstance, by supervising the operation, or by remotely commanding the robot to perform the task. As we will always need to deal with the unexpected, humans will always be involved in any meaningful exploration. Due to Moore's Law,[36] autonomous systems will become more and more capable, so the amount of robot autonomy used will shift. This is similar to approaches taken with the Deep Space One (DS1) mission and the Mars rovers. DS1 demonstrated new capabilities in spacecraft autonomy and autonomous mission operations, during which mission developers checked out and invoked progressively more elements of the Autonomous Optical Navigation system until the spacecraft was completely under autonomous control.[37]

In their book "Robots in Space,"[38] Lanius and McCurdy take an interesting look at the competing visions for human versus robotic space exploration. Their conclusion is that neither will get far beyond the solar system without the other. They call for a new vision of human and robotic spaceflight that they call "transhumanism." It takes into account current trends in robotics, artificial intelligence, genetic engineering, and other fields that are rapidly changing the nature of both humans and robots. This thought is an extrapolation of decades of research and simulations by the Space Systems Laboratory at the University of Maryland demonstrating that the most capable and productive method for space operations is to use teams of humans and robots working cooperatively at an integrated worksite. This fact was stated in a different way by Don McMonagle, a former NASA EVA Program Manager, when he summarizes, "In the future, EVA and robotics will be synergistic, if not synonymous."

Ultimately, it comes down to the fact that humans are explorers: we want to go to new places, see new things, and experience new worlds for ourselves. A lesson that emerges from our previous experience exploring Earth and space is that although robots will assist, humans will take the lead in exploration. Oceanic and Antarctic exploration provide an appropriate parallel to the role of humans and robots in the exploration of the solar system. The evolution of those exploration programs involves a mix of forward-deployed robots and humans, surface ships and submersibles, autonomous *in situ* sensors and vehicles, and researchers working in their laboratories—all linked together by global satellite networks. The program has evolved a philosophy of *using the right tool for the right task in the right location*. Robot systems are becoming more intelligent and more capable all the time, extending our reach into places we never before imagined. The key to making satellite servicing and space exploration successful and safe will be to apply the proper balance of human and robotic systems without a bias toward one approach over the other, as they are fundamentally complementary. Failing to exploit this synergy would be to ignore the vast experience we have gained expanding our frontiers and gaining knowledge on and off this planet.

Chapter 2
Satellite Servicing: **The Vision**

The vision for satellite servicing is straightforward: to refuel, repair, or upgrade satellites after they are launched. Most satellites are expensive pieces of hardware that still have much utility after some critical resource has been expended or some critical technology has become obsolete. Sending a servicing craft to repair or replace a broken critical component or move the satellite into another orbit will derive additional utility from what would have been a loss. These capabilities develop into on-orbit assembly of large spacecraft that cannot be assembled and tested on Earth. Such spacecraft hold the promise of opening up new scientific vistas to reach beyond today's observatories. They could also provide depots for fueling spacecraft to venture to distant destinations. These servicing capabilities can also be applied to managing orbital debris, an area of growing concern in Low Earth Orbit (LEO) as well as Geostationary Earth Orbit (GEO).

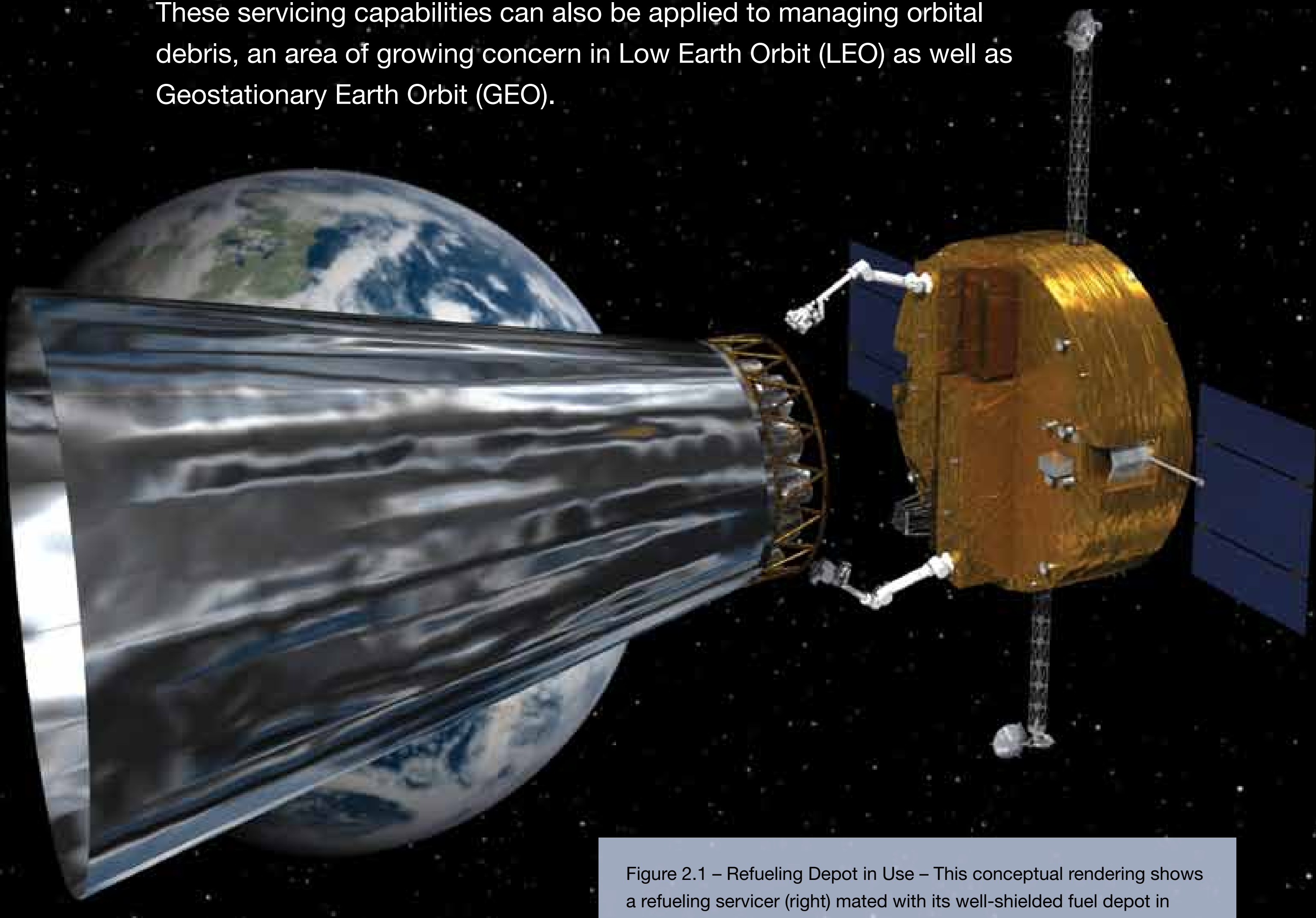

Figure 2.1 – Refueling Depot in Use – This conceptual rendering shows a refueling servicer (right) mated with its well-shielded fuel depot in geostationary Earth orbit (see Notional Mission 2 in Appendix F).

Refurbishment/Refueling of Satellites in Near-Earth Environments

One of the most basic servicing activities is to replenish an expendable resource or replace worn-out components. With these capabilities comes the extraordinary possibility that space-based assets can become better with time, and are no longer limited by the programmatic and technical constraints of their original design.

As with the HST, an upgrade of critical components to the latest technology can bring a satellite years of additional life at a higher capability level that was not possible at the time of the design or launch. Adding fuel to a satellite can extend its useful life by providing additional station-keeping, maneuvering, or deorbit propulsion capability. Every sector of satellite utilization—commercial, scientific, and national security—could use satellite servicing for increased efficiency, bringing the benefits of space operations at a lower overall cost.

Servicing satellites in near-Earth environments can be accomplished in two modes: pre-positioned and as-needed. The nature of orbital dynamics is such that it is expensive (from a propellant and time point of view) to change inclinations. Therefore, pre-positioned servicing assets should be placed in the most-used orbits. These include the Geostationary Earth Orbit (GEO) belt that surrounds the Earth at high altitude and low inclination (generally over the equator) and the Low Earth Orbit (LEO, 200-1,000 km altitude) near-polar inclinations. Pre-positioned servicers would move in these two orbital regimes to satisfy the requirements of many customers. These multi-mission, multi-customer servicing vehicles must have sufficient propulsion to move amongst nearby orbits and would be serviceable and refuelable themselves to maintain the most utility (see Figure 2.1). Highly maneuverable servicers in GEO would find a special utility in dropping from GEO to pick up satellites stranded in transfer orbits (a surprisingly common occurrence) and bringing them to their intended GEO altitude.

Other high-value servicing missions could also be conducted in other orbits, but likely on an as-needed basis. Satellites requiring long "hang-time" over northern latitudes use highly elliptical orbits. Large, expensive, astronomical observatories work best in the cold environments of deep space, such as at the second Sun-Earth Lagrange point (SEL2). Critical space weather missions stand watch between the Sun and the Earth at the first Lagrange point (SEL1). Staging depots for trips to and from the Moon, lunar orbit, and deeper space destinations are attractive at the semi-stable locations in the Earth-Moon system, namely Earth-Moon L1 (EML1). All of these orbits interact with the Earth's gravity and are considered near-Earth. The Earth-Moon locations, a few days' travel from Earth, would be easily reached with a small, crewed spacecraft as well as robotic servicers. The Sun-Earth locations, a few months' travel from Earth, would have long-stay human accommodations for a crewed mission. A customer spacecraft could also travel from an operational SEL2 location to EML1 for a servicing episode closer to Earth and then return to the operational location. Only a small amount of propellant is required to transfer between any two Lagrange points, though the flight times can be long.

Construction of Large Structures

Three types of large space structures can be enabled by in-space servicing or assembly: observatories, depots, and interplanetary spaceships. All three of these are physically large, expensive, and not launched from the surface of the Earth in one piece or in their operational configuration. Human and/or robotic servicing enables these elements to be assembled and configured for operation, tested, and even maintained, upgraded, and supplied over a long service life.

With such a servicing infrastructure in place, the future could have extremely large space observatories probing the scientific frontiers in astronomy (looking up) and enhancing collection for Earth science and national security (looking down). Very large observatories would be launched in multiple pieces and require the capabilities of an in-space servicer to assemble them. Expensive observatories would benefit from servicing to upgrade instruments to the latest technology, supporting dramatically more demanding science at a fraction of the cost of building and launching an entirely new observatory. Large observatories would likely be precision structures and lightweight for their size (gossamer structures), requiring a lighter, more precise touch compared to the "brawny" manipulation needed for depots and interplanetary spaceships.

Satellite servicing could provide the large space depots to fuel operational craft in Earth and near-Earth orbits as well as give planetary missions an outbound fill-up. Depots could be created with the tanks and fuel from multiple launches with small, low-cost rockets (see Figure 2.2). Long-lived depots could be used many times and would be tended by a co-located or visiting servicer that can fix, upgrade, and test the functions of the depot. Concepts proposed for post-ISS long-duration habitation facilities offer opportunities to achieve multiple goals for scientific and human spaceflight, including assembly and upgrade of complex structures.[39]

Large interplanetary spaceships, both crewed and robotic, could be put together, configured, fueled and thoroughly tested. These expensive craft would be verified in near-Earth space before their outbound voyage to Mars or beyond. The servicer capability would be of such value in this role that it might be brought along for the trip.

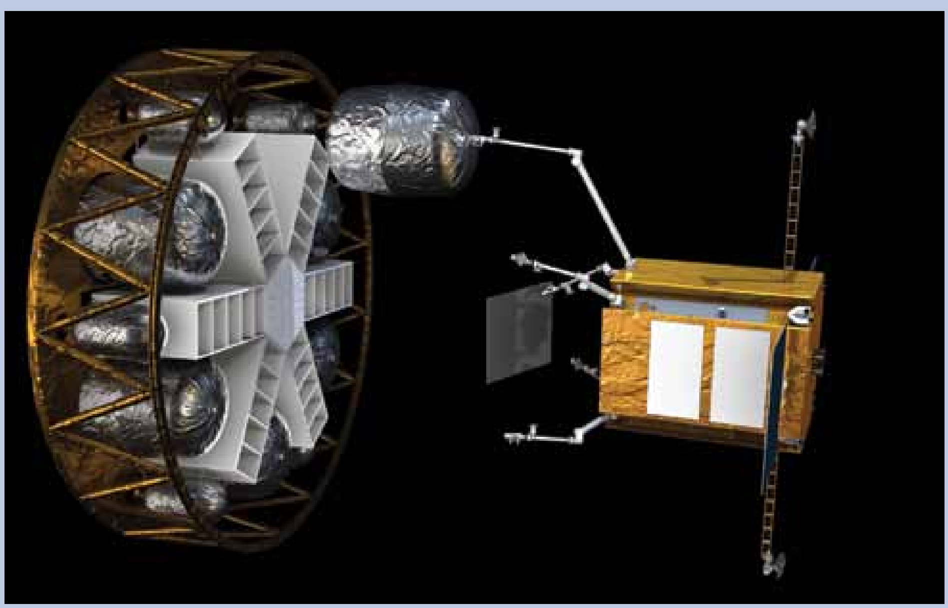

Figure 2.2 – Refueling Depot Assembly – This conceptual rendering shows construction of a orbiting fuel depot (see Notional Mission 2 in Appendix F).

Orbital Detritus Management

The problem of orbital debris is growing and will reach a tipping point in the near future if there is no mitigation. Studies show that even with no future launches, the debris from collisions between objects already in orbit will cascade in the crowded orbits.[40] This cascade effect, known as the "Kessler Syndrome," has been understood since the 1970s[6] and is already manifesting itself in low Earth orbits through recent collisions and near-misses. Removal of several tons of debris per year from this critical orbital regime will bring our planet slowly back from the brink of runaway orbital debris that would render useless any Earth orbit below 1,000 km.

The same vehicle technologies required for servicing could be used for debris removal. These include orbital maneuvering, autonomous rendezvous and docking, and robotic manipulation. It might even be that a general-purpose servicing craft could spend much of its time in between servicing customers working on debris removal. The challenge of orbital debris removal is not in the technology, but in the "business case." Although every nation and corporation using these orbits has a vested interest in their continued usefulness, it is no one entity's responsibility. In economics, this is "the tragedy of the commons." Demonstrated national leadership and international cooperation will be required to mandate a program of debris removal. A market based on removed debris tonnage will be established when the value of an investment in future access to space is realized. Many types of debris in the polar Low Earth Orbit (LEO) would be removed through these efforts: first, large intact pieces such as rocket bodies and defunct satellites, and eventually smaller pieces, down to the limits of what can be detected and tracked.

Figure 2.3 – Orbital Modification – This conceptual rendering shows a servicing spacecraft (left) mated with a customer spacecraft (right) to effect orbital modification – changing its orbital parameters to suit mission needs (see Notional Mission 1 in Appendix F).

Current international law presents a complication to such activities because it stipulates that the owners of a satellite also own all the orbiting hardware resulting from the launch of the satellite.[41] According to case studies and as upheld by international courts, if a spent stage causes damage, the owners (and insurers) of the satellite that the spent stage put into orbit would be liable. Unless the owners authorize removal of the "garbage," the chain of responsibility becomes entangled.

Of course, the owners would not voluntarily incur the added expense of removal unless it were required.

A separate, but related, problem in orbital debris removal exists in the GEO belt. There, satellites near the end of life are placed into "graveyard" orbits above the critical GEO altitude; this is called "super-syncing" a satellite. Currently there is no practical way to gauge remaining propellant in zero-gravity, so satellite operators retire the spacecraft based on estimates with margins. The ability to fully deplete station-keeping propellant and rely on a servicer to complete the required super-sync maneuver would extend the life of every satellite. Other satellites die or become uncontrollable before they are super-synced, so a service that moves these satellites into the desired end-of-life orbit is necessary in order to keep GEO clear for operational satellites (see Figure 2.3). Again, progress will require national leadership or new international standards that set requirements on assured end-of-life disposal. Meeting these requirements through the guarantee of an on-call super-sync service would allow the satellite to operate until its station-keeping fuel or some critical subsystem was exhausted or failed. This kind of service is well-defined and has economic benefit to the owners; if provided, the owners of the assets could avoid the legal complications discussed above.

Chapter 3
Satellite Servicing: **The Benefits**

Ever since the first artificial satellite was launched, we have faced a consistent and familiar set of constraints on mission success. Almost any improvement in mission capability involves more mass. Mission capability and robustness are thus limited by launch technology. The launch process itself is one of the most risky phases for a space mission, potentially affecting hardware integrity and function. Unintended mechanical interferences or deployment failures may result. Access is limited or impossible after launch, causing even small failures or oversights to lead to serious consequences. The space environment is very harsh and often unsupportive of equipment reliability. Expendables limit operational life, and their quantities need to be carefully managed. These are the unavoidable ramifications and challenges of spaceflight. What is *not* unavoidable are the consequences of these constraints. As we venture beyond our immediate environment, we have the tools to create robust mission profiles that dramatically improve the chances of mission success. Satellite servicing holds the promise of altering current paradigms of satellite construction, operation, and maintenance to enable reaching this goal. In particular, it is a tool that provides the reliability improvements that will be required to meet the upcoming challenges in space exploration.

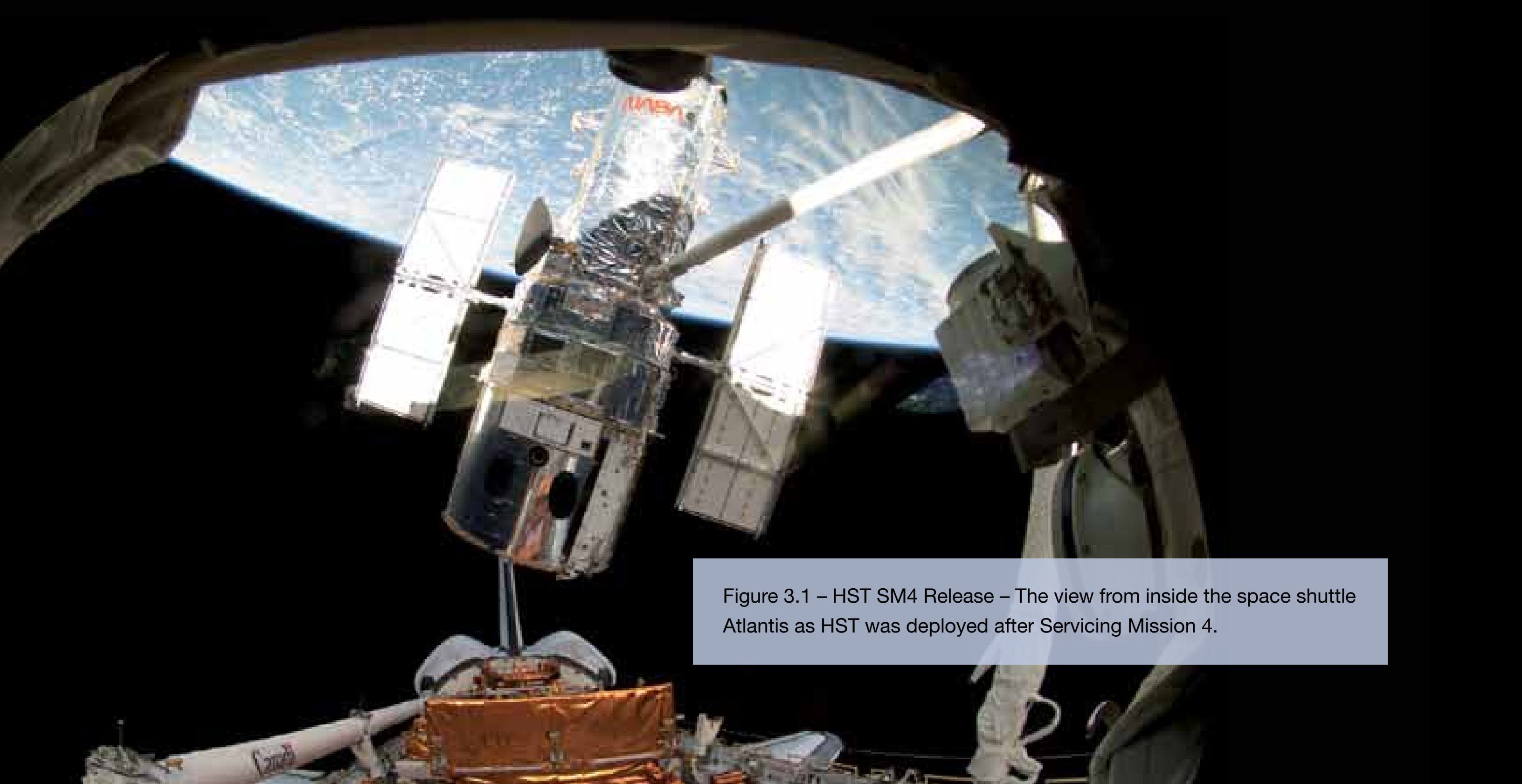

Figure 3.1 – HST SM4 Release – The view from inside the space shuttle Atlantis as HST was deployed after Servicing Mission 4.

Commercial Benefits

Commercial space applications pervade many aspects of modern life. We have live news coverage from almost every corner of the globe. Television networks also distribute entertainment programs internationally and instantaneously. Telephone networks connect distant locations, and where there are no networks, one can connect "direct to satellite." We can also include the transforming nature of satellite positioning systems and satellite imagery. The impacts of these satellite-enabled technologies cannot be overstated and affect our quality of life as well as our safety. The cost of these services, however, is based on existing models of satellite operation. Satellite servicing offers a mechanism for deriving more utility from existing assets, thus strengthening the commercial bottom line. In this arena, the applications of satellite servicing would most likely be in the areas of refueling and orbital modification.

All of the commercial services cited above rely on extensive fleets of satellites, orbiting at specific locations around the Earth. They provide a commodity—information—either in the form of a transponder for information relay, imagery, or signals to determine position. These commodities are provided, bartered, sold, rented, and replenished. All decisions about these satellites are business driven. Is it economically viable to operate a satellite? If not, throw it away. Do we have enough capacity to support projected growth? If not, build another satellite.

Many communications and weather-monitoring satellites are in Geostationary Earth Orbits (GEO), allowing them to occupy an almost-fixed position relative to the surface of the Earth. These orbits are a limited resource. Ideally, they are circular, equatorial orbits (at roughly 35,786 km altitude) with a period exactly equal to the Earth's sidereal rotation period. Both the inclination and altitude of the spacecraft may vary depending on the mission requirements and spacecraft functionality (within 200 km of the ideal altitude and 15° from the equator). Consequently, the positions of these spacecraft are carefully regulated in order to avoid physical as well as communication interference. The International Telecommunication Union establishes and maintains these allocations, which currently are spaced at roughly 2° intervals around the orbital path (some slots may contain multiple satellites controlled by the same operator). The GEO orbits are not stable. There are disturbances from astronomical sources (e.g., the Moon and solar wind), as well as effects from orbital mechanics (e.g., Earth oblateness). In general, an uncontrolled GEO spacecraft would tend to migrate along the GEO orbit until it arrives at one of the two stable longitudes (gravity well). These satellites need to carry expendables to remain operational, to remain in their allocated orbital slot, and to support disposal at end-of-life. Proper disposal would position the satellite in a "graveyard" orbit at a slightly higher altitude and then decommission the satellite.

Of primary benefit to these satellites would be refueling (Figure 3.2) or, at a minimum, orbit modification (Figure 2.3). Every year, approximately 20 satellites are retired because their propellants are exhausted. The satellite is usually otherwise fully functional, so replenishment of the propellant is a natural means to extract more economic value

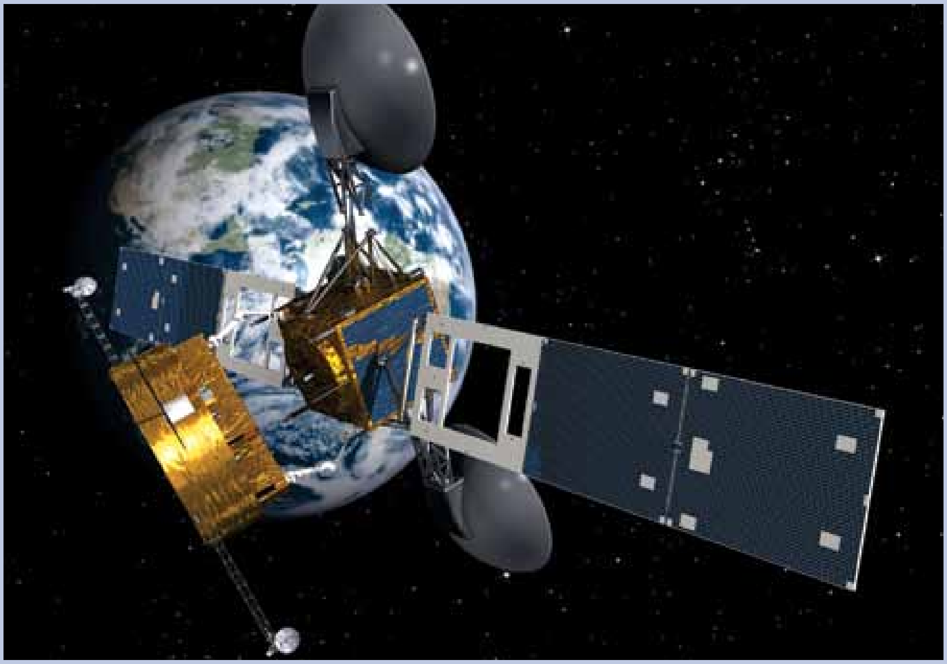

Figure 3.2 – Refueling an Orbiting Communications Spacecraft – This conceptual rendering shows a refueling servicer (left) capturing and refueling a typical communications satellite (right, see Notional Mission 2 in Appendix F).

from the asset and provides a straightforward model for establishing the business case.[31] Even without refueling, if independent means were available to relocate these satellites at end-of-life, roughly six months of additional operational fuel could be used for revenue generation.[42] These benefits have motivated the investigation into Notional Missions 1 and 2, discussed in Chapter 4.

Because GEO orbital slots are a limited resource, there is also the problem of rogue satellites that have experienced some sort of failure that prevents them from maintaining their assigned orbits. There are currently more than 150 dead satellites and rocket stages that will drift for centuries in the GEO belt. In 2008 and 2009 alone, four GEO satellites were left to expire without performing end-of-mission orbit-raising maneuvers.[43] Most recently, in April 2010, Intelsat lost contact with one of its approximately 50 GEO satellites, Galaxy 15. This satellite, with transmitters fully powered, wandered through neighboring slots and almost immediately caused concern due to interference with AMC 11, which relays digital programming for cable television channels.[44] Working cooperatively with Intelsat, the owner of AMC 11, Société Européenne des Satellites, successfully avoided service interruption through a series of evasive maneuvers and by temporarily augmenting the AMC 11 slot with another spacecraft, SES-1. In such cases, the ability to rendezvous with the errant spacecraft and effect orbit modification to put it into a benign location would be of significant economic value.

Of course, it is also possible to perform repairs on these satellites. Within the automobile analogy, there are times when even fleet cars are economically viable to repair. One example is to have a robotic arm assist in correcting a failed deployment. There are valid economic arguments for on-orbit servicing of these satellites with the goal of improving technology or increasing reliability without increasing the initial cost.[31] Such benefits would require a change in the current paradigms of satellite architectures.

Most interestingly, Long [31] points out that satellite servicing could offer new pathways to reduce life-cycle costs. For instance, to reduce cost, satellites could be built with less redundancy or with provisioning for a shorter life, with the expectation that servicing could be used later. Also, high-value components might be separated from low-value components like fuel so that more reliable launch vehicles (i.e., also more expensive) could be used on the former, and cheaper ones for the latter. Servicing would combine these parts post-launch. These new paradigms for satellite development and operations are just beginning to be explored.

Scientific and Technological Benefits

Scientific and technology development missions are the most likely missions to "push the envelope" for some aspect of mission performance. For these types of missions, satellite servicing provides the means to update components to take advantage of newly developed capabilities. Compared to the 5- or 10-year technology "lag" commonly experienced by major scientific missions, a 2- to 3-year lag to launch a new technology could significantly improve the scientific return from a mission. This is particularly true for technologies that are rapidly developing, such as imaging sensors, especially if the refreshment occurs on a regular basis. This ability to refresh technology could also drive a different mission model—phased capabilities that are based on previous discoveries or otherwise expand mission capability in some new way. We can avoid the "all eggs in one basket" problem that accompanies a large mission by flying a series of smaller ones instead. The repair, refurbishment, and assembly aspects of satellite servicing would be most applicable in this arena.

Repair and refurbishment are the obvious first applications with scientific and technological benefits. A clear example is the HST model, which we need not overstate here. The main benefits of such a model are:

1. Rapid deployment of new technologies to improve mission performance by replacing subsystems. These would cover scientific performance areas such as sensors or instrument design, as well as spacecraft components such as transmitters, power systems, or computers and avionics.
2. Repair and maintenance to keep a unique and valuable asset operational, essentially improving it beyond its design lifetime or the reliability of its subsystems. This includes the replenishment of expendables such as cryogens as well as spacecraft components.
3. Phased approach to deploying capabilities, allowing modification of goals as scientific and technological needs demand. In the case of scientific missions, subsequent scientific instrumentation could be designed for specialized follow-up observations.
4. Correction of design features with unintended consequences in order to improve mission robustness. In spite of our best practices, we will continue to be challenged as systems become more complex. Satellite servicing offers a unique capability to improve risk posture through post-launch operations.
5. Return and reuse of existing assets. In many cases, the original design was adequate and reuse is a possible strategy to reduce cost. Returning space assets to Earth also allows for unique studies on the effects of the space environment.

Satellite servicing is the "master enabler" for new space architectures. In-space construction (Figure 3.3) would allow for very large structures that could not otherwise be imagined. The ISS is the first example of such a structure. The lessons learned can be applied to future architectures for large observatories, refueling depots, power farms, or other large structures. These kinds of benefits and applications motivated the mission profile for Notional Mission 6, discussed further under Chapter 4.

NASA is currently planning the Flexible Path implementation, which involves some potentially complex architectures. As these plans become more concrete, the benefits of satellite servicing could provide the edge for mission success that enables the most challenging visions.

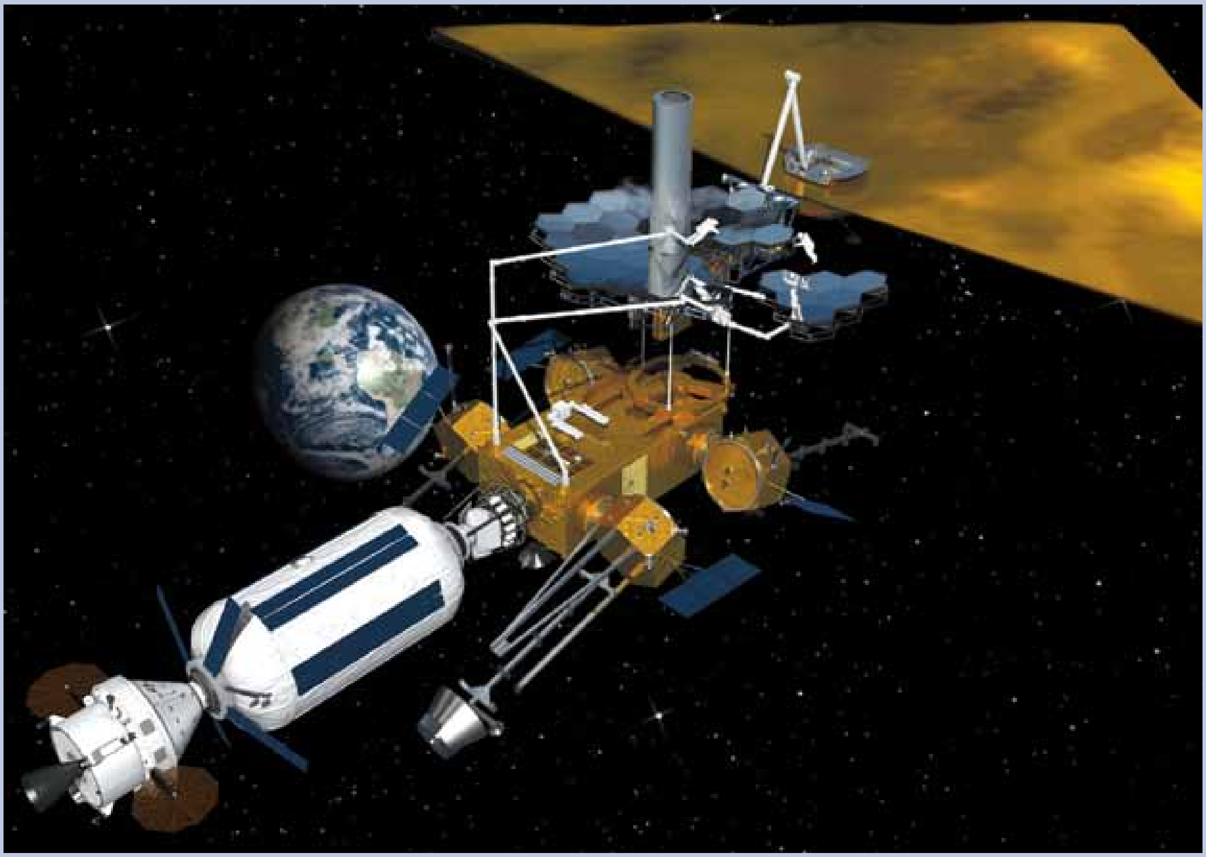

Figure 3.3 – On-Orbit Assembly – This conceptual rendering shows a human and robotic servicer (left) assembling a large space telescope (right) in space (see Notional Mission 6 in Appendix F).

Strategic Benefits

While strategic interests have not been the focus of this study, a discussion of using satellite servicing capabilities for these applications cannot be avoided. Indeed, defense organizations have provided some of the most exciting demonstrations of satellite servicing technologies to date (e.g., Orbital Express). There is a large defense infrastructure for communication and surveillance that is based on many similar spacecraft. An ability to maintain this infrastructure is key to maintaining national security. Conversely, the ability of other agents to "maintain" these spacecraft could be deemed a threat (Figure 3.4). Since strategic assets span a wide range of complexity, the full spectrum of satellite servicing capabilities (refueling, repair, refurbishment, orbit modification, and perhaps assembly) would apply.

As in the commercial arena, refueling and expendables replenishment is the first step to improving operations for a wide range of strategic satellites. There are many similarities, even though the cost structure could be somewhat different. Military communications satellites have very similar constraints to their commercial counterparts. However, unlike commercial satellites that typically remain in a predefined orbit, surveillance satellites are able to reposition themselves to commanded locations, so they require more fuel. The more fuel they have available, the faster they can respond and the longer they can operate.

Some strategic satellites may approach or exceed the complexity of the most sophisticated scientific observatories. For example, it is publicly discussed that HST is likely based on the KH-11 series of surveillance satellites,[45] of which there were nine or ten. For satellites of this complexity, repair and refurbishment could be appropriate servicing activities.

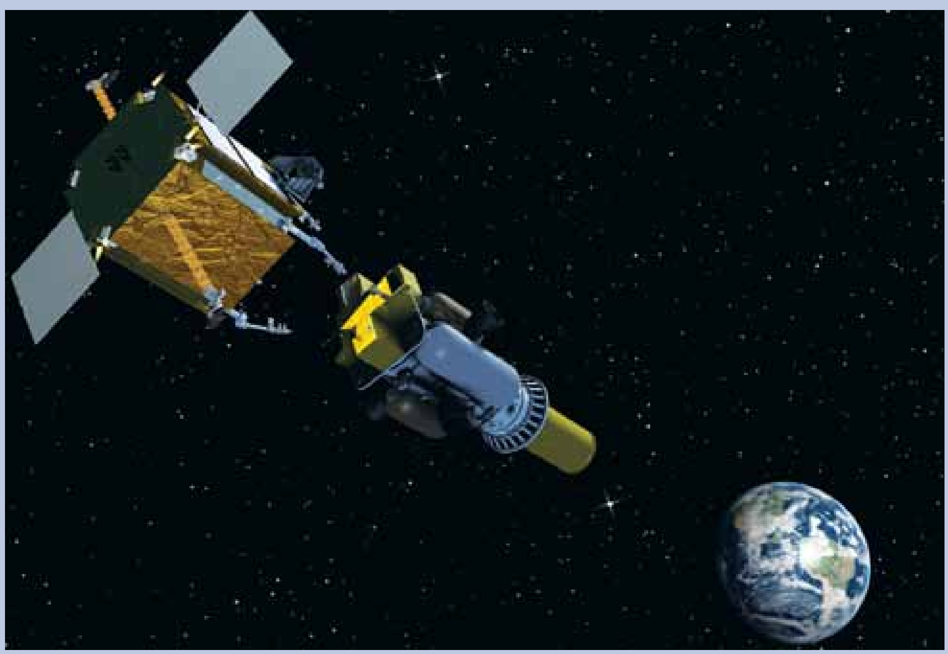

Figure 3.4 – Removal of Undesirable Spacecraft – This conceptual rendering shows an orbital modification servicer (left) approaching a military asset (right) for relocation.

More importantly, the ability to approach and affect an orbiting satellite has obvious implications to the health and safety of the satellite. It is a technology that could affect our national security, and is an area of obvious military interest. By developing advanced commercial, scientific, and technological applications for satellite servicing, we have the means to encourage the expanded use of space for peaceful purposes.

Outreach Benefits

Human presence, breathtaking images, and groundbreaking science are a powerful combination that captures the imagination of the public and gives relevance to NASA's missions. So far, such a mix has only been possible in the context of servicing missions. The marriage between human spaceflight and orbital maintenance of a major scientific research instrument is a unique highlight in NASA's history. It brings with it a wide range of challenges. The solutions to these challenges cross multiple disciplines and connect with an equally diverse range of public interest. In the future, we expect that this interest will carry over to robotic and human/robotic servicing activities in space.

The servicing missions to the Hubble Space Telescope (HST) engaged public interest like no other NASA mission since Apollo. Combining the real-time drama of humans performing challenging tasks in space with the world's most well-recognized and beloved space observatory puts humans visibly in the midst of great scientific achievements. These missions reached a remarkably diverse, even jaded, public by touching a broad spectrum of interests. They provided the ultimate in "Reality TV" to audiences, with the stream of live video from the spacewalks presenting an unedited look at the drama, energy, synergy, and ingenuity of performing complex tasks in space. The servicing missions inspire belief and pride in the human "can-do" attitude by setting and successfully carrying out lofty goals: travel and work in space, complete on-the-spot repairs, create and harness ingenious technology, engineer innovative tools and procedures, become real heroes, do great science, and capture the beauty of the Universe.

The payoff from the astronauts' "high-wire" acts was almost immediately tangible: spectacular new images from the refurbished HST were released to the world within weeks of the mission. These have been showcased in over 6,000 Internet articles. Without the participation of astronauts in HST's scientific mission, the observatory would likely have remained much more abstract to the public. It also may not have been so revered as a valuable national asset, where the public feels ownership and pride. There would still be the steady stream of evocative and colorful space pictures, but seeing astronauts perform surgery on a bus-sized vehicle communicated a sense of scale, technological complexity, tangibility, and a connection to humanity.

The hours of footage from the HST servicing missions, including cameras on the EVA astronauts' helmets, present a "you-are-there" look at the danger and challenge of space exploration. Amid melodramatic twists and turns and uncertainties, HST and its human attendants persevered. Major media channels have produced numerous hour-long science documentaries that capture and condense this story. The recent *Hubble 3D* IMAX® film documentary has opened in theaters around the world to record attendance.

The servicing missions provide numerous lessons for teachers and students: teamwork, problem solving, overcoming adversity, and a "can-do" attitude. The missions portray diverse teams of scientists, engineers, technicians, and managers as role models for students. The Space Telescope Science Institute's "Amazing Space" web site provided educators and students across the country with an opportunity to participate in Servicing Mission 4 as it unfolded in real time, with daily updates and supporting educational activities. Internet traffic to HubbleSite.org tripled through this period (see Figure 3.5).

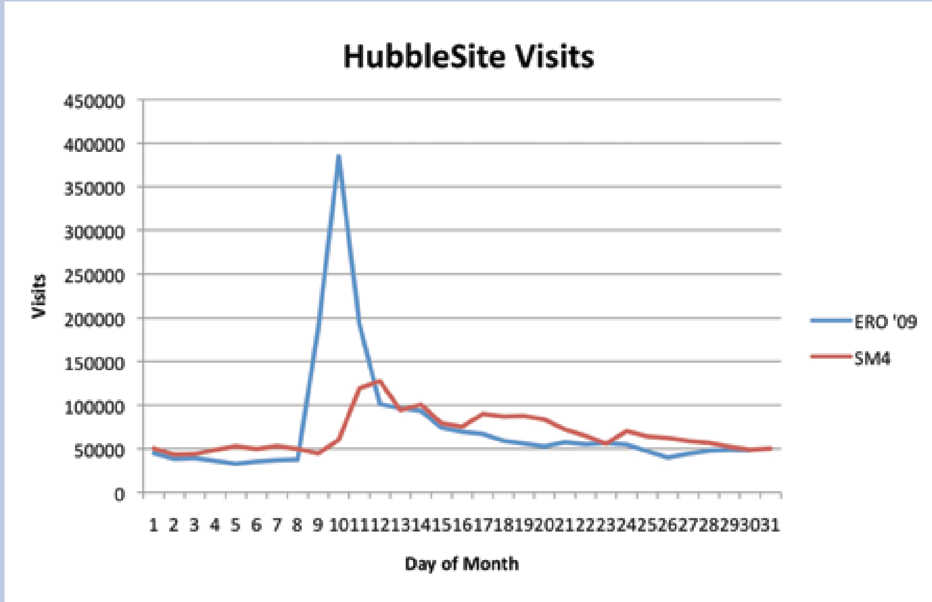

Figure 3.5 – HubbleSite Visits During HST SM4 – This plot summarizes the level of public interest during the Hubble Space Telescope (HST) Servicing Mission 4 (SM4) and also during the Early Release Observations (EROs)—the first images released from HST after Servicing Mission 4. The plot is for the days of the month in May 2009 for SM4 and September 2009 for the EROs.

- Early Release Observations (Released September 9, 2009)
    - Peak visits: > 380,000 (seven times normal daily traffic)
    - Visits during the event: 1.1 million (typical of a month's worth of traffic)
    - 40% increase in baseline traffic after event
- HST Servicing Mission 4 (May 11–24, 2009)
    - Peak visits: >127,000 (three times normal daily traffic)
    - Visits during event: 747,000 (approximately 20 days worth of traffic)
    - 20% increase in baseline traffic after event

Overall, the engagement of the public—fueled by the excitement of the servicing missions and the scientific productivity of HST—has been significantly higher and longer sustained than other NASA space science missions. Such interest has a lasting effect in its ability to enhance Science, Technology, Engineering and Mathematics (STEM) educational initiatives. This reflects the power of satellite servicing in the scientific context and its impact on the public.

In the future, we would expect that large classes of human or robotic servicing missions could engender similar interest. We already have the example of the Mars rovers performing robotic exploration. This mission was also extremely successful from an outreach perspective. We conjecture that with current and future video capabilities, the "you-are-there" look and excitement can be conveyed for servicing activities involving humans, robots, or any combination of the two. Public interest will remain high as long as the mission conveys a sense of urgency and importance, demonstrates complicated tasks, and provides quick feedback on the results of those tasks. These intangibles are evident in public forums such as web sites and blogs after a successful servicing mission.[46]

Chapter 4
Satellite Servicing: **The Implementation**

The transition from concept to reality is never straightforward, especially for complex systems with potentially "game changing" rewards and a non-negligible cost of development. One result of this study is an executable plan that provides satellite servicing capability development in conservative steps. This plan is based on a systems engineering analysis of the key challenges for satellite servicing missions, a set of notional missions to quantitatively explore these challenges, a mission sequence that provides immediate benefits while validating the designs, and a technology gap assessment that identifies how to develop future capabilities. Using the ISS as a versatile test bed, near-term demonstrations are underway for some of these key technologies.

Figure 4.1 – The Flight Hardware for the Notional Missions – This graphic shows the flight hardware studied for the six Notional Missions (NMs) described in the text and in Appendix F, grouped by orbital location of the potential servicing activity. In the lower left corner is low Earth orbit, showing NM3—upgrade in low Earth orbit. In the middle band is Geostationary Earth Orbit (GEO), showing NM1—orbit modification in GEO (left) and NM2—refueling in GEO (right). The upper band represents farther away locations, and shows NM4—assembly at Earth-Moon Lagrange point 1 (left), NM5—upgrade in highly elliptical orbit (lower right), and NM6—assembly at Sun-Earth Lagrange point 2 (upper right).

The Map of Servicing Capabilities

There are a large number of ways to carry out an assessment of satellite servicing. To enable discussion of disparate applications, one needs a categorization system in which to frame the discussion. This study developed and adopted a particular scheme that was used initially to characterize and discuss the topic, and subsequently to determine the content of detailed case studies.

Satellite servicing is a broad term that was not precisely defined at the start of this study. The team worked to identify factors that could vary and thus become significant factors in mission design. After much discussion, research, and thought, several categories were identified: Task, Execution, Rendezvous and Capture, Location, Latency, Customer Design, and Customer Attitude. The figures that follow display these characteristics in columns, with complexity increasing from bottom to top.

Tasks include broad categories of servicing. From most simple to most complex, tasks include simple orbit modification (which most satellites accomplish on their own, but it could be accomplished using a tug), three tasks related to refueling, the replacement of hardware elements designed to be replaced on-orbit (Orbital Replacement Units or ORUs), assembly of large structures designed for on-orbit assembly (e.g., the International Space Station [ISS]), and the repair or replacement of a hardware element that was not designed to accommodate servicing.

Execution can be accomplished with robots, humans, or a combination of both, with increasing levels of machine autonomy defined as increasing complexity. The "human + robot" element appears at the simple end of the list because it is a shuttle-style grapple arm. The "robotic autonomous" and "robotic teleoperated" elements describe more dexterous robotic systems.

Rendezvous and Capture describes how a servicer will approach and dock with a customer spacecraft. The least complex method is with humans in-the-loop *in situ* capturing a customer that is designed to be serviced (i.e., cooperative). The most complex method is a completely autonomous servicer docking with a customer that is not designed to be serviced (i.e., non-cooperative).

Location is simply the orbit at which the servicing is performed, and increasing complexity is defined as increasing distance from Earth. *Latency* is the time required for communication between the Earth and the servicing location. Although latency is obviously a function of the location, the issue of latency was deemed important enough to warrant its own column.

Customer Design defines what on-orbit servicing accommodations are designed into the customer spacecraft. A fully cooperative customer has navigational aids (passive or active), a berthing mechanism, grapple points, handling fixtures, is fully controlled at capture, and then has an operational mode that yields control authority to the servicer while they are joined together as a "stack." Increasing complexity in this column is defined as fewer accommodations, and at the top is a legacy customer—a customer spacecraft that is currently on orbit with no intentional servicing accommodations.

Customer Attitude defines whether the customer spacecraft is under control and can present a favorable surface towards the servicer at the time of capture. The most complex is a spacecraft that is not controlled at all, cannot be commanded, and the dynamics of the orbit leave the customer tumbling (spinning about one or more axes).

The first use of the trade space figure was to map the regions that have been demonstrated in flight either as an experiment or as part of a mission. Figure 4.2 displays the previously demonstrated elements and a seminal mission where the work was performed. Note that many options have been completed on-orbit multiple times; but unless a mission sampled a unique additional area of the trade space, only the first occurrence is recorded in the figure.

Having mapped these sampled elements, Figure 4.3 divides the trade space into two regions: elements already completed on-orbit (historical) and elements that have not been completed on-orbit (unsampled).

At an early stage of the study, it was interesting to discover that all the satellite servicing tasks have already been largely sampled in flight. It is a common myth that servicing happens rarely because the tasks are so complex they require the development of new technologies. This populated trade space demonstrates that, in fact, tasks of great complexity have already been accomplished on-orbit. The unsampled region of the trade space is described by increasing distance, increasing autonomy, and identifying customers with decreasing levels of accommodation.

With this understanding of the unexplored region of the satellite servicing trade space, the team developed a suite of six notional missions designed to sample the unexplored region (see Figure 4.4).

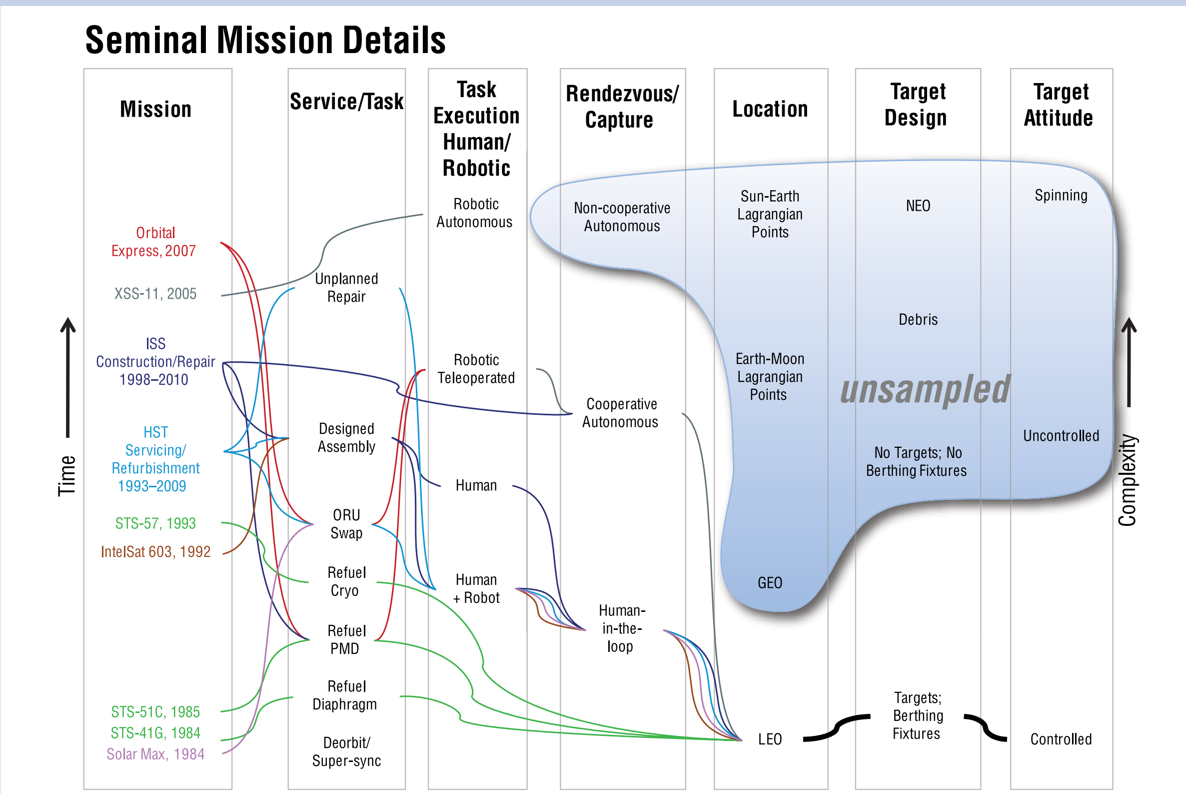

Figure 4.2 – Seminal Mission Coverage of the Servicing Study Trade Space – This graphic maps several missions for satellite servicing onto the servicing mission trade space. The colored lines trace the path of these missions through the trade space diagram. The Refueling tasks have been split into those using a static feature in the storage tanks called a Propellant Management Device (PMD) or those using a diaphragm for propellant management.

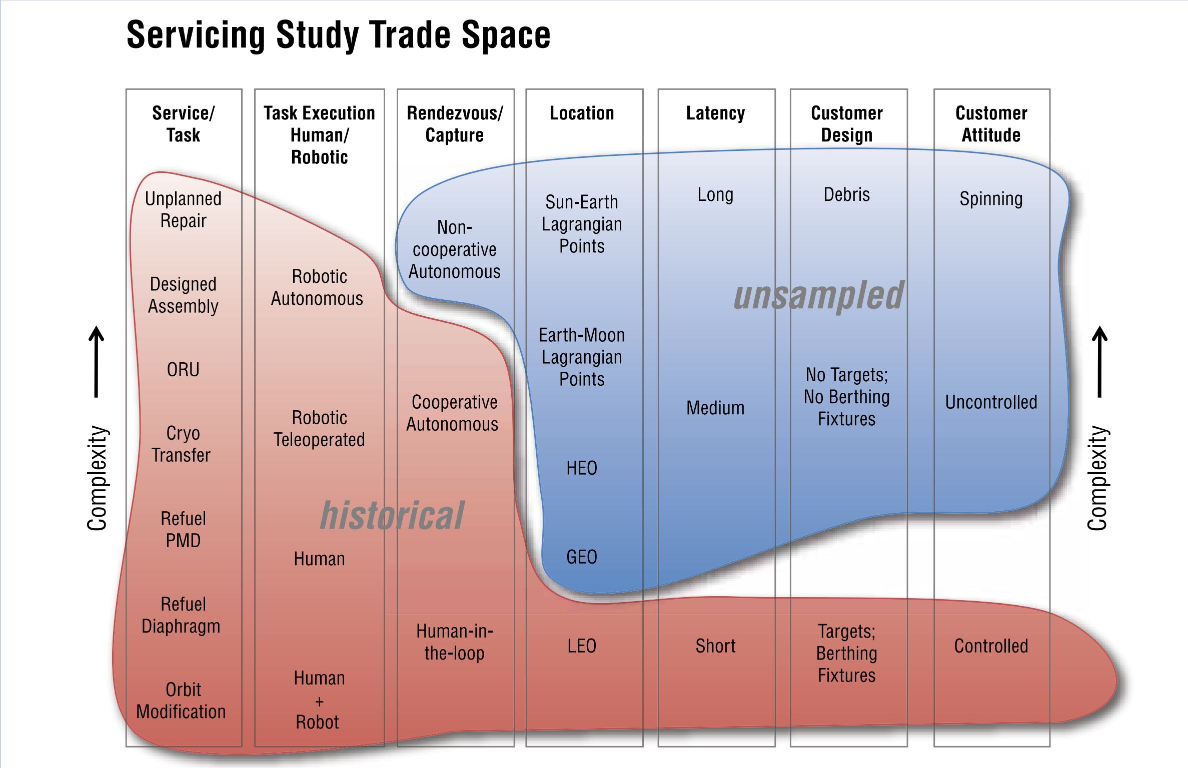

Figure 4.3 – Servicing Study Trade Space Regions Covered by Historical Missions – This graphic summarizes the regions of the trade space diagram that have been sampled already (historical) or are yet to be sampled (unsampled).

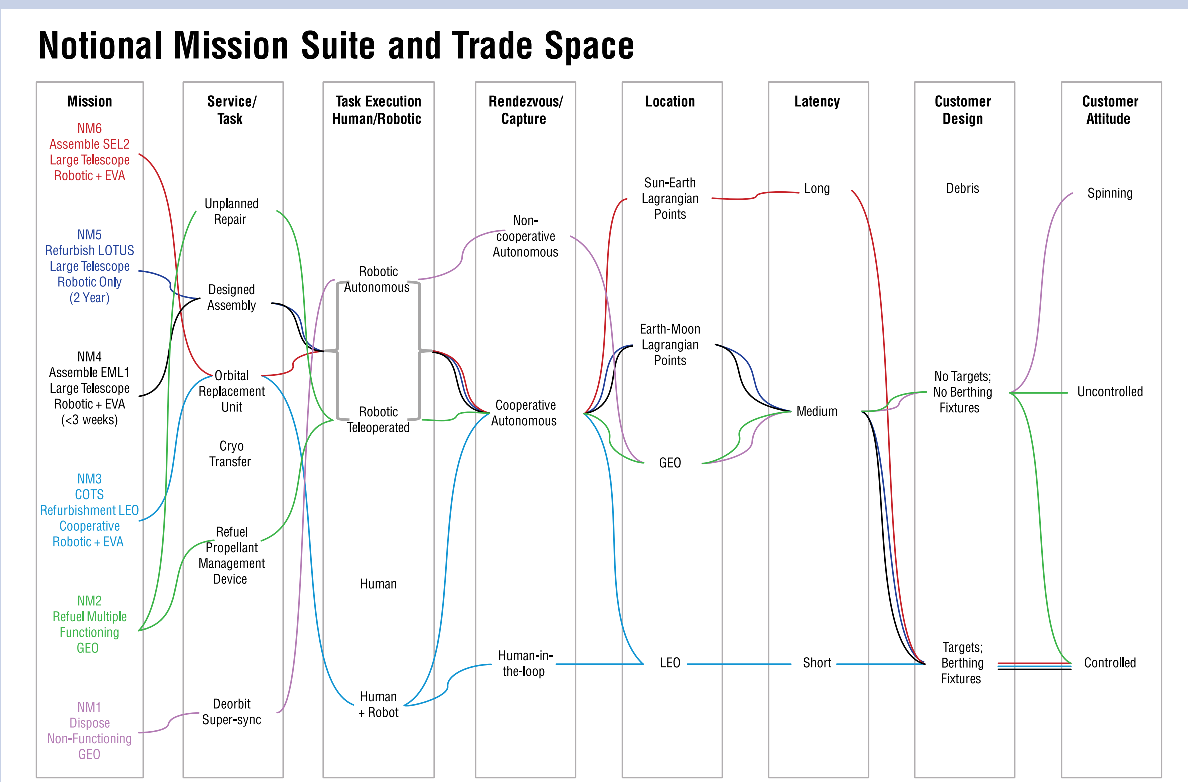

Figure 4.4 – Notional Mission Suite Coverage of the Servicing Study Trade Space – The notional missions were designed to cover every area of the diagram so that we can sample a range of trade space possibilities.

The Notional Missions

This study examined a total of six "notional" missions that are intended to span the parameter space for the range of possible servicing activities. They follow the map of servicing capabilities discussed previously, and provide the basis for engineering analyses and trade studies. Appendix F contains more detailed results for all the notional mission studies. We summarize these missions here while underscoring a few key findings in the areas of Autonomous Rendezvous and Capture (AR&C) and robotic technologies, as well as some of the interesting results discovered in astrodynamics. In particular, we present a new orbit design that has some unique features for human servicing of missions operating at the Earth-Moon Lagrange point 1 (EML1).

Notional Mission Characteristics

The team deliberately chose not to research all the aspects of the satellite servicing trade space equally. Instead we used the servicing capabilities figure to identify six discrete servicing scenarios that would be examined in detail in a series of design charrettes. We called these servicing scenarios "notional" missions because they were deliberately designed to investigate the unsampled corners of the satellite servicing trade space. This allowed us to identify unique obstacles as well as the common elements of seemingly disparate missions.

Thus, the notional missions do not describe an architecture or a map of recommended missions (see the "Mission Sequence" section in this chapter). In fact, they were not even driven by identifying practical or cost-effective solutions for flight projects. The notional missions enabled the team to identify successful engineering solutions that could be used as data in subsequent analyses, rather than to produce optimized designs for a real mission.

Where possible, existing satellites and launch vehicles were employed in the design process. It is not possible to design a servicer spacecraft and a servicing mission in one week while simultaneously designing the customer spacecraft. Customer satellites were chosen solely to facilitate the design charrettes and not to favor one particular mission. For example, HST was the customer satellite in the third notional mission because it is an existing, cooperative (designed to be serviced), LEO satellite. Its interfaces exist and are well known, which allowed the team to develop well-defined requirements for those interfaces on the notional servicer (dimensions, power, and data). Other mission aspects, such as Commercial Orbital Transportation Services (COTS) and crew habitats were assumed to exist if the mission needed them, and these are also not discussed beyond their basic interfaces.

Table 4.1 enumerates the high-level characteristics of each of the studied missions. Appendix F provides additional information for all the notional missions.

Mission Design Methodology and Cost Estimation

Once the notional mission suite was identified, each mission was developed into a mission concept at NASA's Goddard Space Flight Center (GSFC) Integrated Design Center (IDC). The IDC consists of two "labs": the Instrument Design Lab (IDL) where conceptual designs of spaceflight instruments are formulated, and the Mission Design Lab (MDL) where conceptual designs of spacecraft and other

Table 4.1 – Notional Mission Summary Table

Case	Orbit	Task/Service	Task Execution	Customer Design	Attitude	Latency
NM 1	GEO	orbit modification	robots	legacy	spinning	short
NM 2	GEO	refueling	robots	legacy	3-axis stabilized	short
NM 3	LEO	upgrade	humans (COTS) + robots	designed for upgrade	3-axis stabilized	short
NM 4	EML1	assembly	robots	designed for assembly	3-axis stabilized	medium
NM 5	HEO	upgrade	humans (Orion) + robots	designed for upgrade	3-axis stabilized	medium
NM 6	SEL2	assembly	humans (Orion + habitat) + robots	designed for assembly	3-axis stabilized	long

mission elements to support the instruments and science objectives are conducted. The IDC brought the study team together with an independent team of experienced discipline engineers in an integrated design environment that allowed for concurrent, focused, and rapid systems design. Since 1997, the IDC has conducted over 500 such studies, contributing to many successful GSFC flight instruments and missions.

One major advantage of treating the notional missions as repeated design charrettes with a consistent staff, assumptions, approach, and costing tools, is that the resulting engineering products are a consistent body of data from which we can make comparisons and draw conclusions. In addition, the six notional missions provided the study team an opportunity to refine and improve the requirements at the start of the run and for the combined study and IDC teams to build on the insights from the previous runs. So, although an identical process was used for each notional mission, the products grew more refined with each successive notional mission run. This was both beneficial and challenging. It was challenging because, in the end, the study team must understand the feasibility of servicing as well as the business case for servicing based on a set of mission studies with disparate and progressive refinement. It was beneficial because the final, very complex mission studies were of such high caliber, and the study team had learned so much from the IDC team that they were well prepared—in insight and in design products—to do the necessary work.

Both IDC labs were used for this effort, with the IDL focusing on rendezvous and docking packages and robotics, and the MDL providing servicing platform and mission designs. IDC customers come with mission requirements and work with the IDC engineers to create point design concepts to a level of detail sufficient to support a hypothetical proposal. The IDC customer determines the objectives of the assessments and shapes the "run" to meet their requirements through real-time decisions with the engineers during the study. In our case, the IDC customers were Satellite Servicing Study Team members with servicing experience from the HST Development Project. The level of these studies is such that 1) key aspects of the mission concept and architecture are defined, 2) top-level mission requirements are assessed (e.g., power, mass, uplink/downlink, mission specific subsystems, navigation, avionics, operations), and 3) rough cost estimates are generated.

Cost estimates can be difficult to validate, especially for systems that have never before been built. However, for the purposes of this study, we believe that reliable *relative* cost estimates can be obtained for the notional missions considered. The *absolute* costs were reserved for future study.

This study used a commercially available, parametric cost-estimating tool called Parametric Review of Information for Costing and Evaluation-Hardware (PRICE-H). PRICE-H was developed by the RCA Company in the 1960s for the U.S. Navy, Air Force and NASA, and commercialized by PRICE Systems, LLC. PRICE-H estimates cost by parametrically defining the hardware to be built (starting from a master equipment list), the development and manufacturing environments, the operational environment, and the overall schedule.

GSFC's IDC has more than ten years of experience using the PRICE-H tool to develop costs for the mission pre-proposal phase. In addition, GSFC has used the PRICE-H tool to support over 100 spacecraft studies and proposal efforts outside the IDC, including the recent Step 2 Mars Atmosphere and Volatile EvolutioN (MAVEN) and Gravity and Extreme Magnetism Small Explorer Mission (GEMS) Concept Study Reports, and prior cost studies for Aeronomy of Ice in the Mesosphere (AIM) and Time History of Events and Macroscale Interactions during Substorms (THEMIS) Confirmation Reviews. Full mission life-cycle costs are estimated from the PRICE-H data by adding non-hardware elements as a percentage of the hardware costs. The accuracy of this approach and the percentages used are assessed periodically using data from independent costing agencies and reported costs for flight missions. For the notional missions in this study, costs were confirmed in parallel through a grassroots costing exercise. The result is a point estimate based on the current best estimates of parameter values. The next step in cost estimation would be to perform a cost risk analysis to generate a probabilistic assessment, but this has not yet been completed for the notional mission elements.

We reiterate that costing tools and absolute costs were not a focus of this study. Instead, we selected a specific method for generating costs (PRICE-H), and then used the results as one data element in the comparisons and general observations about the notional missions. It is also worth noting here again that cost was not a constraint during the notional mission studies. The notional missions were designed to probe what is possible, with a resulting cost estimate.

Table 4.2 reports the current-best-estimate cost (with no margin) of the servicer designed for each notional mission. The servicer is defined as everything that launches with the servicing platform that is required to perform on-orbit servicing. It does not include the launch vehicle, propellant, or any hardware that will be installed in the customer. For Notional Missions 3 (NM3) and 5 (NM5), the cost of an airlock (with associated consumables) and human tools is included because they are baselined to launch with the servicer. However, in Notional Mission 6 (NM6), all human-related elements travel with the humans rather than with the servicer, so they are not included in the servicer cost. Note that even without the cost of the human servicing elements or the observatory that will be assembled, NM6 requires the most costly servicer due to the complexity and sheer size of the mission.

Total mission costs were also modeled and are reported in the notional mission appendix (see Appendix F); however, the disparate mission concepts and varying fidelity of customer information make true cost comparisons at the mission-level far more complex.

In looking at the relative costs of the servicers, it is not surprising to find that the servicers designed for missions with more ambitious goals cost more. At the most basic level, it is commonly understood that costs are driven by the mass of the hardware flown, and the more ambitious missions require more hardware. However, we also learned of the strong dependence of cost on design choices that affect reliability, such as using "class S" electronic parts (screened for space applications), block-redundant designs (flying two or three duplicate avionics boxes), and cross-strapping. These servicers were designed to be self-serviced (that is, no fleet of servicers was assumed to exist, only the one under current study), so some systems required the same high reliability and long lifetime that affects legacy spacecraft. Thus, recreating these notional missions with different assumptions about the human flight architecture or the existence of a servicing infrastructure would profoundly affect the costs.

It is also worth noting that cost savings were realized on robotic elements by assuming a modular, self-reconfigurable robotic architecture. The

Table 4.2 – Servicer Costs for Each Notional Mission

Notional Mission		Spacecraft Bus Cost (FY10)	AR&C Cost (FY10)	Robotic Elements Cost (FY10)	Human Elements Cost (FY10)	Servicer Total Cost (FY10)
Num	Description					
NM1	GEO Supersync	$140M	$75M	$330M Centralized 4 @ 2 m Grapple	None Tools in Robotic Elements	$550M
NM2	GEO Refueler + Depot	$220M	$60M	$240M Centralized 2 @ 2 m Grapple	None Tools in Robotic Elements	$520M
NM3	LEO COTS Refurbish	$670M	$60M	$350M Distributed Human Rated 2 @ 15 m Grapple	$300M Airlock, Tools	$1,380M
NM4	EML1 Robotic Assemble	$600M	$60M	$1,330M Reconfigurable 2 @ 15 m Grapple 2 @ 2 m Dexterous Pairs	None Tools in Robotic Elements	$1,990M
NM5	HEO Human Refurbish	$760M	$60M	$1,230M Reconfigurable 2 @15 m Grapple 2 @ 2 m Dexterous Pairs	$300M Airlock, Tools	$2,350M
NM6	SEL2 Human Assemble	$2,100M	$60M	$1,340M Reconfigurable 2 @ 15 m Grapple 2 @ 2 m Dexterous Pairs	None All Human Elements Launch with Humans	$3,500M

architecture was assumed in order to create servicers with sufficient flexibility to address the needs of multiple missions, and one might conclude that such flexibility costs more. However, such development moves away from the common paradigm of "one-off" builds, where every mission receives a custom system. Building multiples of smaller subsystems allows even a single mission to take advantage of lower-cost production runs for robotic components that can be assembled into the desired custom configuration. In the broader spaceflight architecture, reconfigurable robots allow every robotic mission to benefit from a single technology development program and larger scale production-run costs. The savings of such an approach is apparent even in the conceptual phase cost modeling.

Autonomous Rendezvous and Capture Technology

One of the technical areas we investigated was the technology required for Autonomous Rendezvous and Capture (AR&C). This study in the Instrument Design Lab (IDL) produced several key findings and identified areas for future work. The results are provided in Appendix E and summarized here.

The first finding is that a capable AR&C sensor package can be assembled using current technology, and that this package can support the extreme case of capturing an uncontrolled, tumbling customer spacecraft (see Notional Mission 1 in Appendix F). Furthermore, this AR&C sensor package has modest mass, volume, and power requirements.

Another key IDL study finding is that during AR&C with a legacy (non-cooperative) customer spacecraft, the AR&C sensor package must be designed to operate with only bearing-angle measurements during the early phases of the process (without complementary range measurements). This requires that the AR&C package include optical sensors capable of acquiring the customer spacecraft at long range (several hundred kilometers or more). This has significant implications for the rendezvous trajectory design in terms of the evolution of the relative motion geometry and the timing, direction, and magnitude of rendezvous maneuvers. In short, the rendezvous sequence should be designed to provide adequate knowledge of the relative spacecraft position and velocity using only bearing-angle measurements. Note that this constraint would be relaxed if the operating distance of range sensors, such as laser rangefinders, could be extended. Note also that this constraint is largely removed during cooperative AR&C scenarios in which a Radio Frequency (RF) ranging signal can be transmitted between the servicer and customer spacecraft (though this was beyond the scope of the IDL study).

The IDL study also revealed that the usefulness of a pan/tilt unit for the AR&C sensor package is unclear, since the study did not have sufficient scope to complete the trade. A pan/tilt unit, which allows for pointing the sensors independent of the spacecraft orientation, may provide more flexibility in the servicer spacecraft's attitude profile while maintaining AR&C sensor pointing at the customer, but at the cost of tripling the AR&C sensor package's mass, increasing its required power by 50%, and complicating the pointing-error budget. However, this pan/tilt capability would be required if the various servicer spacecraft attitude constraints including, but not limited to, Sun tracking for solar power, communication antenna pointing, and customer spacecraft tracking cannot all be simultaneously satisfied.

Mission analysis to support the Mission Design Laboratory (MDL) studies of the notional missions included the design of relative motion trajectories to facilitate AR&C between spacecraft on Lagrange point orbits for Notional Missions 5 and 6. While the necessary trajectory targeting equations to accomplish this between spacecraft in LEO or GEO are well known, this not the case for spacecraft on Lagrange point orbits. Thus, in order to determine the total ΔV required for AR&C on Lagrange point orbits (e.g., a Lyapunov orbit about EML1 in Notional Mission 5 and a halo orbit about SEL2 in Notional Mission 6), new algorithms had to be developed for the relative motion trajectory targeting.

These new AR&C trajectory algorithms revealed unusual characteristics of the natural relative motion between spacecraft occupying the same Lagrange point orbit. They also indicated that there are preferred locations on a Lagrange point orbit for performing AR&C due to a strong dependence of the total required ΔV on the location along the Lagrange point orbit at which AR&C is performed.

Computing the ΔV requirements for AR&C between spacecraft on highly elliptical orbits was driven by the use of the L1 Orbit Trajectory Used for Servicing (LOTUS) in Notional Mission 5. While the necessary guidance equations are known, we do not currently have practical experience with performing AR&C in this type of orbit. Our traditional concepts of operations for AR&C will therefore have to be expanded to properly account for features of the relative motion dynamics between spacecraft on elliptical orbits in order to ensure safety during AR&C.

From these considerations, the areas for future work became apparent. One is the need for high-fidelity attitude profile analysis to determine whether the degrees of freedom for pointing offered by a pan/tilt unit are necessary, or at least beneficial to the point of making a pan/tilt unit a compelling option. Other future work topics include analysis of the effective operating range of an infrared camera (which would provide bearing-angle measurements during adverse lighting conditions); analysis of the minimum distance at which pose measurements can be acquired (since the customer spacecraft will generally be larger than the pose sensor field-of-view at distances of several meters or less); development of guidance, navigation, and control algorithms to support safe AR&C between spacecraft on highly elliptical orbits or Lagrange point orbits; and development of AR&C concepts of operations appropriate for spacecraft on elliptical orbits.

Robotic Technology

Robotic technology is a second area that benefitted from an initial study in the Instrument Design Lab (IDL). These results are presented in Appendix E and summarized here.

For the six notional missions (see Appendix F), the study team developed two distinct robotic architectures springing from the current state of the art in robotics. Two robotic systems that could accomplish the first two notional missions (Geostationary Earth Orbit [GEO] super-sync and GEO refuel) exist today. The first is the Front-end Robotics Enabling Near-term Demonstration (FREND) system,[34] developed by Alliance Spacesystems and the Naval Research Laboratory for the Defense Advanced Research Projects Agency (DARPA), and designed for a GEO super-sync mission (Figure 4.5).

The second is the Ranger system, developed by the Space Systems Laboratory at the University of Maryland as a Low Earth Orbit (LEO) technology demonstration mission. The Ranger system (Figure 4.6) consists of two dexterous arms that are positioned at the worksite by either a grapple arm or a positioning leg. It was designed to perform inspection, maintenance, refueling, and orbit adjustment. The tasks it can perform range from simple task-board operations to very complex EVA worksite setup using hardware that was never intended for robotic handling. The program also served as a training ground for young engineers in a hands-on environment.

For the remaining, more ambitious notional missions, a robotic architecture was developed that is similar to robotic systems used on the International Space Station (ISS)—a big grapple arm coupled with a pair of dexterous arms.

This study revealed two technology areas within robotic systems where development will enable key future capabilities. The first is the development of modular, mobile robotic systems that can be reconfigured on-orbit to optimize their kinematic configuration for the wide variety of tasks needed for broad-reaching servicing missions. The second is improved camera views at the worksite for situational awareness.

The last three notional missions highlighted the need for robotic systems that can reconfigure

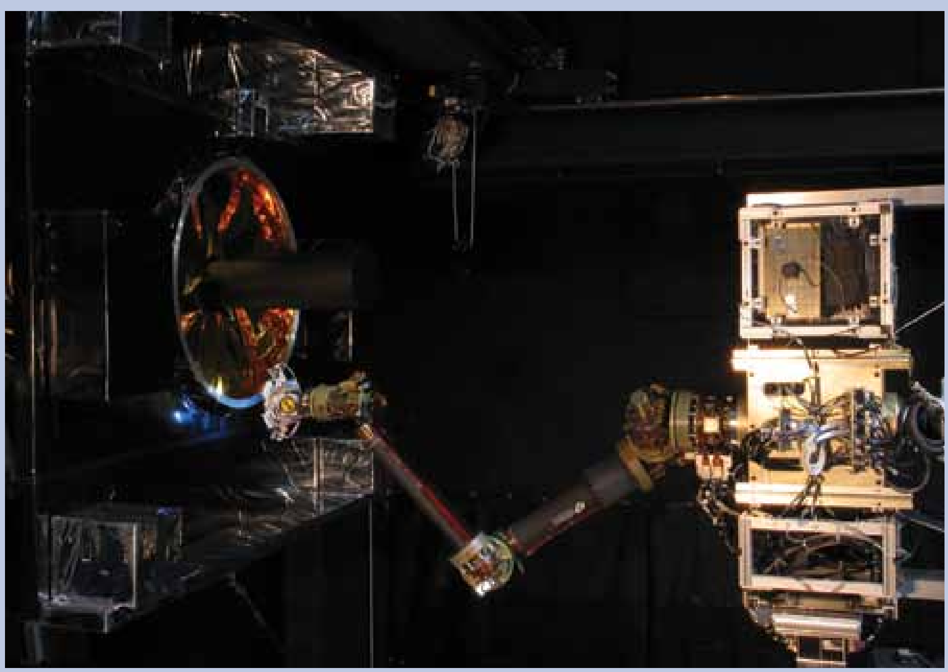

Figure 4.5 – Front-end Robotics Enabling Near-term Demonstration (FREND) System – The FREND system performs full-scale rendezvous and autonomous robotic grapple testing using the Naval Research Laboratory's Spacecraft Proximity Operations Test Bed.

Figure 4.6 – Ranger Telerobotic Shuttle Experiment – The Ranger dexterous manipulator pair mounted to a head that is attached to a positioning leg. This hardware was designed to be positioned at a worksite using a grapple arm or a positioning leg.

themselves to save launch volume and mass. These missions involved tasks as varied as grappling supply barges, moving astronauts or other robots around, replacing failed components, and performing unforeseen tasks. They demonstrated that systems that can adapt by reconfiguring themselves eliminate the need to carry multiple systems with innumerable custom tools for every conceived task. Stand-alone mobility also simplifies the assembly process for extremely large observatory structures. For example, the International Space Station (ISS) robotic systems move around the station exterior using robot data and power accommodation "ports" built into the ISS exterior. This solution may not be practical for large observatories, as the features may only be used during the assembly sequence, and power is not routinely required throughout the exterior of an observatory. However, a robotic system that can move around on its own, carrying its own data and power accommodations adds flexibility in achieving mission objectives.

Some work has been done to develop such systems for space applications, but more development is required to enable the ambitious objectives of the notional mission suite. The Space Systems Laboratory at the University of Maryland developed a concept for a modular system capable of self-reconfiguration for DARPA.[47] The Palo Alto Research Center has also done some work.[48] This is an active, but unfunded, area of research that will empower robots to perform the tasks we envision for satellite servicing.

Another need illustrated during the notional missions is a way to get visual feedback to the operator for better task and situational awareness. The approach taken in the notional missions was to use cameras on the end of an arm to provide visual feedback to the operator. The view could be provided by a camera (or stereo pair) attached at the end of a separate robot arm that autonomously follows the dexterous arm doing the work. Alternatively, individual cameras at the end of the dexterous arm, end-effector, or tool that is performing the task could be used. One limitation to this approach is that sensors on the end of arms require power and data lines capable of handling large amounts of data. This data rate then drives the downlink data rate requirements, and even low-resolution images at relatively low frame rates create a challenging amount of data for the current flight-to-ground data infrastructure. In addition, cameras require lighting. For task awareness, where the camera is relatively close to the work site, lighting can readily be provided with some additional power and mounting space. For situational awareness, where the camera may be far removed from the task or area of concern, lighting presents a greater challenge. Alternative sensors exist (e.g., infrared cameras), but they are not yet in wide use for space robotics systems.

The notional missions used an approach similar to what was developed for the Hubble Robotic Servicing and Deorbit Mission: put cameras everywhere, as they are "cheap." The implementation of running power and data to the camera systems placed around the servicer and potentially to the telescope or structure being built highlighted the need for a better solution. Several possible approaches have been proposed. Data from various sensors (visible and infrared cameras, laser radars, stereo vision, proximity sensors, etc.) could be integrated and interpreted locally (by processors on-board the servicer), and then the resulting model of the worksite and the broader situation could be transmitted to the ground. Camera platforms that can reposition themselves at the worksite, possibly by using free-flying camera platforms, could be developed to provide flexibility with far less infrastructure. Other sensors (e.g., infrared cameras) could be developed to provide feedback to the operator with low- or no-lighting requirements. This study did not perform any trades on the possible solutions, but this was an area identified as a key technology ripe for investment and system-level maturation.

Astrodynamics

All servicing mission concepts require that the servicer spacecraft (whether robotic or carrying humans) rendezvous with the customer spacecraft, perform proximity operations with the customer spacecraft, and then capture, be berthed to, or dock with the customer spacecraft. These activities are part of the discipline of astrodynamics, in which spacecraft perform an intricate "dance" under the influences of gravity and thrusters.

The relative motion dynamics between two spacecraft in an Earth-centered orbit are well understood, particularly in the case where the customer spacecraft is on a circular or nearly circular orbit. The orientation of the orbit is not generally an important factor for relative spacecraft motion, whereas the orbit shape (circular or appreciably eccentric) does have a strong effect. The characteristics of and techniques for performing relative spacecraft motion design with the customer spacecraft on an eccentric orbit are understood theoretically, but performing rendezvous and proximity operations with respect to a spacecraft on an eccentric orbit is uncommon in practice.

Rendezvous, proximity operations, and capture, berthing, or docking can generally be performed for modest ΔV (i.e., expenditure of propellant) by utilizing one of a variety of sensible strategies. For the notional mission studies presented here, the passively safe co-elliptic rendezvous strategy was used for rendezvous with customer spacecraft on essentially circular orbits in the Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) regimes. In this strategy, the servicer spacecraft is placed onto an orbit of the same orientation and shape as that of the customer, but with a slightly different altitude. The rendezvous sequence generally begins with the servicer several tens of kilometers below and several hundred kilometers behind the customer spacecraft. The servicer will naturally drift towards the customer spacecraft parallel to its orbit track, where the drift rate is proportional to the difference in altitude between the orbits. The servicer will periodically perform small maneuvers (e.g., Hohmann transfers) to gradually raise its orbital altitude as it approaches the customer from behind. Once within several km of the customer, the servicer begins the proximity operations phase and will generally insert itself into a small safety ellipse, up to approximately 100 m in diameter, centered on the customer spacecraft.

Safety ellipses are natural periodic relative motion trajectories in which the servicer spacecraft will fly around the customer spacecraft on an elliptical path centered on the customer (see Figure 4.7). The time required for the servicer to fly around the customer once is equal to the customer's orbit period. The safety ellipse motion can be maintained by the servicer with a modest expenditure of orbit maintenance fuel. Safety ellipses are so named because they are tilted with respect to the plane of the customer's orbit such that the servicer never crosses the customer's velocity direction, making the relative motion passively safe. Thus safety ellipses provide an efficient configuration from which the servicer spacecraft can repeatedly fly around the customer to gather situational awareness data: collect range, bearing, and pose measurements, and allow the relative navigation filter sufficient time to converge.

During the final approach phase in a capture scenario, the servicer may have to expend considerable fuel if the customer spacecraft is in an uncontrolled attitude state with appreciable tumble rates. If the

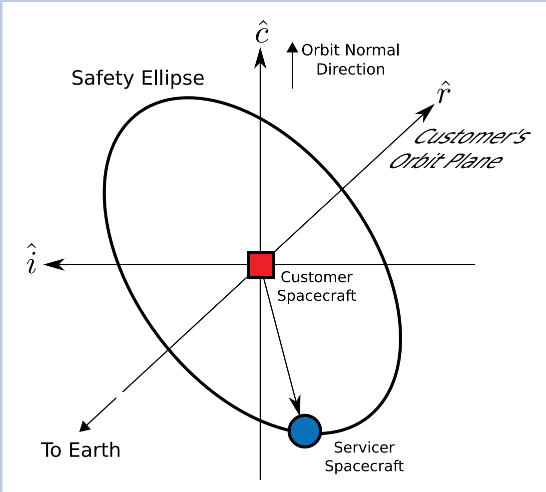

Figure 4.7 – Safety Ellipse – By orbiting with a slightly different orbital eccentricity and inclination, the servicer spacecraft naturally flies around the customer once per orbit without crossing the customer's velocity direction, making the relative motion passively safe.

tumble rates are large enough—generally greater than 1°/s per axis—the ΔV required for final approach can become the largest contributor to overall rendezvous ΔV. Otherwise, the ΔV required to match the customer's orbit plane prior to the initiation of the co-elliptic rendezvous sequence is generally the dominant factor in the total rendezvous ΔV (all else being equal).

Moving beyond LEO and GEO, Lagrange points (also known as libration points) are the five equilibrium points found in any Restricted Three-Body Problem (RTBP). An object placed precisely at one of these points with zero velocity will theoretically remain at the point indefinitely. An RTBP is a configuration of two celestial bodies referred to as the primaries, such as the Earth and the Moon, or the Sun and the Earth, and a third small body of comparatively negligible mass, such as a spacecraft.

Lagrange points are only points when viewed in a rotating coordinate system whose origin is located at the center of mass of the primaries. The motion of the smaller primary is often modeled as a circular orbit about the larger primary, yielding a Circular RTBP (CRTBP). The Earth-Moon and Sun-Earth systems are well approximated by the CRTBP for preliminary mission design purposes. The rotation rate of the coordinate system is defined such that the centripetal acceleration balances the gravitational acceleration between the primaries, thus causing the primaries to remain stationary in the rotating frame. Thus, the Lagrange points are paths in space rather than points when viewed in an inertial (non-rotating) coordinate system.

The Lagrange points are conventionally labeled EML1 through EML5, as shown in Figure 4.8. While they are all equilibrium points, only the EML4 and EML5 points are theoretically stable. The EML1 through EML3 points are theoretically unstable, but all five points are in fact unstable when the gravity of other solar system bodies is accounted for. This is why the Lagrange points of the Earth-Moon system are empty of natural debris such as asteroids. However, the near-equilibrium offered by these points in practice means that spacecraft can station-keep with relatively little fuel expenditure at or near these points for an extended period of time. This, along with the geometrical advantages offered by these points for communication, the sky coverage access for astronomical observations, and a stable thermal environment makes the Lagrange points ideal locations for deploying a variety of spacecraft missions.

Spacecraft can be placed into relatively small, slightly irregularly shaped orbits about Lagrange points. There are three types of Lagrange point orbits: Lyapunov, halo, and Lissajous. Lyapunov orbits and halo orbits are both periodic orbits, meaning that they are nominally closed, repeating paths. Lissajous orbits are quasi-periodic and hence do not form closed paths, though they will remain in the vicinity of the Lagrange point. Lyapunov orbits lie in the XY plane of the rotating coordinate system (e.g., the plane containing the Earth and the moon), while halo and Lissajous orbits do not have to lie in a particular plane.

Lagrange point orbits are readily reached from Earth with modest launch energy, insertion ΔV, and flight time. Additionally, the rich dynamics of RTBPs permit interesting trajectories that travel between Lagrange points for very little ΔV, though the flight times can be relatively long. Specialized orbits, such as those described in the next section, can also be designed to meet mission-specific requirements. The relatively large size of halo orbits about the Sun-Earth Lagrange points, such as Sun-Earth L2 (SEL2), allow a spacecraft stationed on those halo orbits to receive continuous sunlight and thus avoid eclipses. Designing eclipse-free orbits about Earth-Moon Lagrange points is more challenging and has been identified as a topic for future work. Rendezvous and proximity operations between spacecraft on Lagrange point orbits is an area in which we have little theoretical development and no practical experience, though it is a key element of all servicing missions that will take place in the vicinity of Lagrange points. Preliminary studies have shown that the ΔV and flight times are reasonable for spacecraft rendezvous and proximity operations on Lagrange point orbits, but more study is required to develop rigorous theory and algorithms for the relative motion trajectory guidance, navigation, and control.

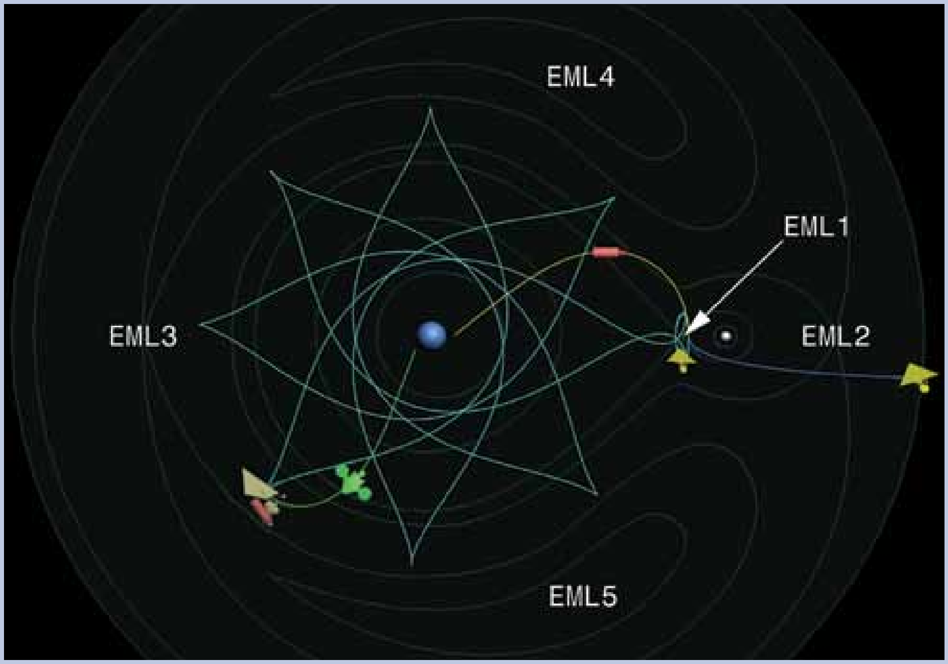

Figure 4.8 – The LOTUS – This figure depicts the LOTUS in the context of the mission sequence for Notional Mission 5. The robotic servicing vehicle travels to a Lyapunov orbit about Earth-Moon L1 (top center red cylinder), where the large telescope later arrives from Sun-Earth L2 to be captured. After the servicer and telescope are joined (lower left yellow/red spacecraft), they insert into the LOTUS with a very small ΔV and are later met by the crew vehicle (lower left green spacecraft).The crew vehicle, robotic servicer, and telescope remain together on the LOTUS until servicing of the telescope is complete, at which time the crew vehicle deorbits. The LOTUS proceeds to naturally carry the servicer and telescope back to L1, where the servicer will reinsert into the Lyapunov orbit for long-term station-keeping. The telescope performs a small maneuver to exit the Earth-Moon system and return to its operational orbit about Sun-Earth L2 (right).

The L1 Orbit Trajectory Used for Servicing (LOTUS)

Notional Mission 5, which involves human/robotic servicing of a large telescope in the Earth-Moon system, presented unique challenges out of which the L1 Orbit Trajectory Used for Servicing (LOTUS) was born.

In Notional Mission 5, a large telescope stationed at Sun-Earth L2 (SEL2) is to return to the Earth-Moon system and rendezvous with a robotic servicing vehicle. Afterwards, a crew vehicle carrying astronauts will rendezvous with the stacked robotic servicer and telescope, and servicing will begin. After servicing is completed, the crew vehicle returns to Earth, the telescope returns to SEL2, and the robotic servicing vehicle continues to station-keep in its orbit within the Earth-Moon system for 25 years, remaining available for future servicing activities. Several competing objectives resulted from this concept of operations.

Telescope maneuver magnitudes should be minimized so as to conserve telescope propellant and avoid large structural loads on the telescope.

Additionally, the orbit occupied by the servicer must be easily accessible by both the telescope and the crew vehicle, and must be able to be maintained for a modicum of fuel since the servicer will be expected to station-keep for 25 years (which allows for two additional servicing missions with some margin). Finally, the crew vehicle must be able to fly trajectories to and from the servicer's orbit that yield adequate available time for servicing work while respecting the crew vehicle's fuel budget and the maximum preferred crew mission duration of approximately 21 days. Other constraints on the crew vehicle trajectory include minimization of exposure to the Van Allen radiation belts, avoidance of the Geostationary Earth Orbit (GEO) belt, and the option of a free return from launch in the event of a crew vehicle systems failure.

The first thought was to place the servicer on the same Lyapunov orbit that was utilized for Notional Mission 4. The advantages offered by this Lyapunov orbit include a modest station-keeping ΔV of 60 m/s (annual) and easy access for the telescope. (The telescope can travel between the Earth-Moon L1 (EML1) Lyapunov orbit and the SEL2 halo orbit for a total ΔV of approximately 45–50 m/s and a one-way flight time of 50–130 days, depending on conditions.) It also offers a free return for the crew from launch, modest launch energy (-2.6 km^2/s^2) and insertion/departure ΔV (600 m/s) requirements for the crew, and a very tractable ΔV requirement of approximately 30 m/s (depending on conditions) for Autonomous Rendezvous and Berthing (AR&B) between vehicles on the Lyapunov orbit.

We determined that the crew will need to have 15 days of servicing work time available on orbit, but the fastest one-way flight time for the crew to go between Earth and the EML1 Lyapunov orbit is approximately 4.5 days (it can be as long as 6 days), and allocating 1 day for AR&B leaves the crew only 11 days for servicing activities because of the 21-day mission limit.

This prompted the search for a different orbit for the servicer that could be reached by the crew vehicle more quickly without adversely impacting any other aspects of the mission. The ensuing analysis uncovered a class of orbit that is dynamically connected to the EML1 Lyapunov orbit. This new type of orbit was named the L1 Orbit Trajectory Used for Servicing (LOTUS) since it facilitates servicing missions such as the one described here, and also resembles a lotus flower when viewed in the canonical rotating reference frame of the Earth-Moon system.

The LOTUS is a Highly Elliptical Orbit (HEO) with a period of approximately 10 days, an eccentricity of 0.54, and a perigee of approximately 84,000 km (which keeps it well above both GEO and the Van Allen radiation belts). A spacecraft can enter the LOTUS from the EML1 Lyapunov orbit for a ΔV of only 10 cm/s, and after 98 days the LOTUS will naturally carry the spacecraft back to the EML1 Lyapunov orbit, at which time the spacecraft can reinsert itself into the Lyapunov orbit for a modest ΔV of 45 m/s.

The servicer can therefore inhabit the EML1 Lyapunov orbit for its long-term station-keeping as originally planned, and the telescope can rendezvous with the servicer on the Lyapunov orbit. Then the servicer/telescope stack can easily enter the LOTUS, after which the crew vehicle will rendezvous with the stack to perform servicing. After servicing, the crew vehicle returns to Earth and the servicer/telescope stack will naturally return to EML1 a couple of months later. At that time, the telescope can separate from the servicer and travel back to SEL2, and the servicer can reinsert itself into the EML1 Lyapunov orbit for station-keeping.

The advantages of the LOTUS for the crew are as follows. First, the flight time for the crew to reach the LOTUS varies between 0.6 and 3.4 days, depending on whether the crew chooses to insert into the LOTUS at perigee or apogee. The launch energy for the crew to reach LOTUS perigee is only -8 km^2/s^2, while the launch energy for the crew to reach LOTUS apogee is -3 km^2/s^2. For reference, the launch energy to travel to the Moon is -2 km^2/s^2, so launching to the LOTUS always requires less launch energy than a typical lunar mission. Additionally, the crew always has a free return to Earth available when launching into the LOTUS. The ΔV required for the crew to insert into the LOTUS after launch is 1,800 m/s if inserting at LOTUS perigee and 560 m/s if inserting at LOTUS apogee. The ΔV requirements are similar for the crew to deorbit from the LOTUS and return to Earth, yielding a total post-launch ΔV requirement for the crew vehicle between 1,120 and 3,600 m/s. These combinations of launch energy and total ΔV for the LOTUS are all less than for a lunar mission, meaning that any lunar architecture for launch and crew vehicles is more than capable of utilizing the LOTUS.

The key advantage of the LOTUS for servicing is that the amount of time the crew spends on the LOTUS is fully selectable, since the crew can insert at and deorbit from any points on the LOTUS. For example, the crew can launch into LOTUS apogee with a 3.4 day flight time, spend 1 day performing AR&B with the servicer/telescope stack, spend 15 days servicing, and then have a 1.16 day flight back to Earth, for a total mission time of 20.56 days, just within the 21-day limit. The launch energy for the mission is -3 km^2/s^2 and the total crew vehicle ΔV, including AR&B, is 2,120 m/s. For comparison, typical values for a lunar mission are a launch energy of -2 km^2/s^2 and a total crew vehicle ΔV capability of 2,800–3,000 m/s.

Mission Sequence

There are a rich variety of meaningful servicing missions that could be undertaken within the next five years. There are also a number of more challenging, visionary missions that are foreseeable further in the future. What we refer to as the "mission sequence" is the choice of stepping-stones to get from one to the other. This choice will be driven by fiscal constraints, engineering prudence, and—perhaps most importantly—the higher-level goals of the Agency.

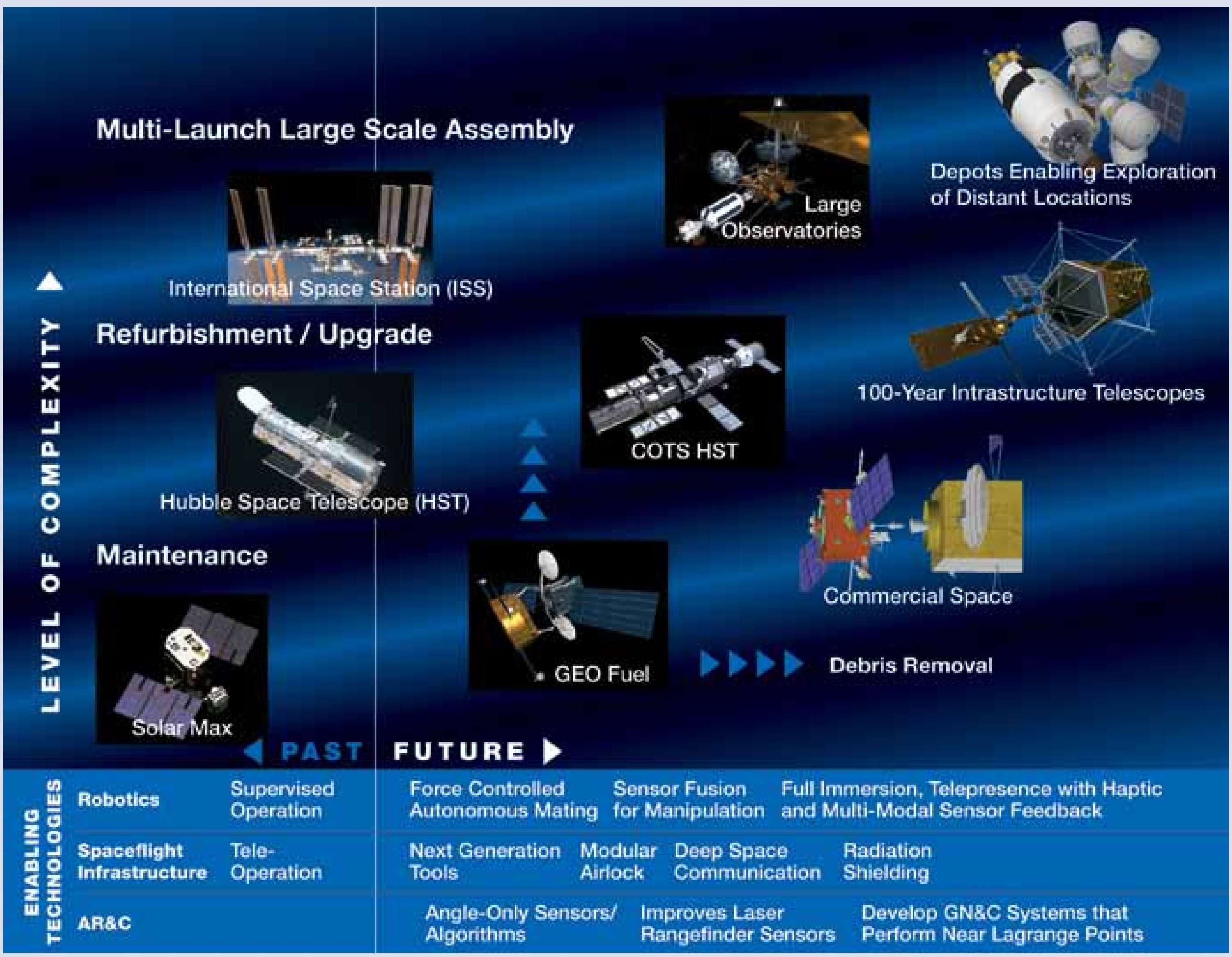

Figure 4.9 – The Recommended Mission Sequence – This diagram summarizes our recommended mission sequence. The horizontal axis represents chronology and time. The top section shows the missions. The bottom section shows the enabling technologies for those missions, separated into three technical categories. The vertical axis for the missions conveys a general sense of increased complexity. Note that we recommend three parallel paths for development of satellite servicing: maintenance, refurbishment/upgrade, and multi-launch, large-scale assembly. These are shown as bands, along with the representative missions. The GEO Fuel mission has two blue arrows indicating how it could evolve into a refurbishment/upgrade capability, and also a government or commercial debris removal capability.

Our study has assessed the range of satellite servicing capabilities against some reasonable assumptions to recommend a logical mission sequence. Figure 4.9 shows our concept for a three-tier progression of missions. They progress from the short-term achievable (lower left corner) to the long-term ambitious missions (upper right corner).

The first tier of missions falls under the category of maintenance. As discussed in previous sections, there is a strong case for refueling large classes of Geostationary Earth Orbit (GEO) satellites. There is also a strong case for performing orbital modifications. Such services would be of great interest for commercial and military satellites, so there would be a diverse customer base. The elements needed to provide these services were studied in Notional Missions 1 and 2. We conclude that the first logical mission in this sequence would be an all-robotic servicer to GEO that provides both orbit modifications and refueling to customers.

This servicer would have the ability to autonomously rendezvous with and capture an existing satellite, modify its orbit, and/or transfer additional propellant. In some cases, it may be beneficial to remove propellant from a non-operational satellite to reuse it for other satellites. These basic technologies are well-established and mature. Some were demonstrated in space in the Orbital Express mission, others in laboratory programs, and some are the subject of ISS verification experiments described in later sections.

We propose that the initial sortie for the servicer, known as GEOServ, would be to 1) capture a derelict satellite, 2) raise its orbit altitude ~350 km to the GEO super-synchronous disposal orbit, and 3) release. This mission profile has the benefit of removing a derelict satellite that is a hazard to others in the GEO belt, and would provide a highly visible demonstration of satellite servicing utility without the risk of damaging an operational satellite.

The second sortie for GEOServ would be to grapple a functioning U.S. government satellite and robotically transfer propellant to it. There would be immediate gains for the customer, and the successful application of refueling technologies would lower the perceived risk for future commercial customers.

The now fully validated and operational GEOServ would then proceed from customer to customer performing orbit modifications and/or refueling until it had just enough propellant remaining to super-sync itself. A burgeoning commercial GEO satellite refueling industry would be expected to rapidly emerge once GEOServ blazes the path.

The success of GEOServ would naturally open the door to two types of follow-on missions: relocation/orbit modification and refueling. The former would execute debris removal services in a targeted area, such as the GEO belt, or polar LEO where there are 140 large objects.[49] The latter would be optimized for refueling and would begin a commercial refueling industry.

In parallel with the maintenance tier, it is recommended that a second, more robotically challenging set of missions be undertaken. This tier is associated with the refurbishment, upgrade, or retrieval of on-orbit satellites. A first mission could be a Hubble Space Telescope (HST) servicing or disposal mission, since more is known about the interfaces on HST than on any other legacy vehicle. The refurbishment of HST with additional instruments and Orbital Replacement Units (ORUs) would spur development of additional robotic technology. More autonomy could be employed in the execution of the robotic tasks. There are obviously other Low Earth Orbit (LEO) vehicles that could use upgrades, but these would pose much higher risk for this first mission since less is known about their interfaces. The successful completion of this mission would provide confidence that all-robotic servicing of other legacy spacecraft is feasible. Other customers could then be refurbished/upgraded, such as an infrared imagery spacecraft whose cryogen has been depleted.

Another logical follow-on mission in the refurbishment and upgrade tier (for legacy spacecraft) is the replacement of 19% efficient double-junction solar arrays that have radiation-darkened cover glass with new 27% triple-junction arrays. This would provide beginning-of-life power to a legacy spacecraft. For example, between 1987 and 1998 there were insurance claims totaling $347 million on GEO spacecraft with solar array anomalies.[8]

Eventually, as more refurbishment and upgrade missions were undertaken, our technical capabilities would advance to support modular assembly of very large astronomy missions. Rather than designing and flying just 3- or 5-year observatories, long-duration observatories could be entertained whose instruments and bus components would be modular so that robotic changeout is easily accomplished, thus supporting extremely long operational lifetimes. This brings us to the third and final tier of the mission sequence.

The third tier is the assembly of large-scale, multi-launch structures that would accomplish the Agency's long-term goals. One such goal is an Earth-departure vehicle that could transport humans to Mars on a time scale consistent with the requirement of the human spaceflight program. There are many techniques and technologies from the ISS that would lend themselves directly to enabling the on-orbit assembly of a multi-launch structure such as a cryo-depot, an Earth departure vehicle, a trans-planet habitat complex, etc. As the architecture for those missions becomes defined, the assembly technologies would be mapped so that existing capabilities could be cataloged and technology gaps could be identified and targeted for development.

This three-tier mission sequence presents a logical path forward with the end goal of providing a rich set of meaningful capabilities that benefit the commercial telecommunications industry, government agencies, and the human exploration community. It is the result of combining the benefits of satellite servicing with the notional mission analyses into an executable sequence that brings immediate results while setting the path for more ambitious future goals.

Technology Gap Assessment

Evaluating the notional missions and subsequently constructing the mission sequence also resulted in an assessment of the technologies required to implement the missions. While many of these technologies are largely in-hand (see Figure 4.10), the complex system-level algorithms required for fully autonomous operations, or the intricate end-effectors and tools used for legacy satellite repairs, for example, would benefit from additional verification. We have begun to achieve this goal via ISS demonstrations. Future missions would exploit the results of these demonstrations. These future missions would also provide the platforms to verify even more complex algorithms required for highly autonomous operations in very remote locations that have high Earth communication latencies.

All of the technologies required for satellite servicing exist at a fairly high level of maturity, with the exception of those associated with autonomous operations. While there can be a fine line between classifying a development need as new technology or hard engineering, none of the servicing scenarios envisioned have a box labeled "invention needed here." Deficiencies in technology readiness exist mainly in regard to demonstrating the performance of integrated servicing hardware and control systems in a space environment. For the more ambitious notional missions, considerable work is required to integrate

Figure 4.10 – Tools for Closing the Technology Gap – Both the Space Station Remote Manipulator System, shown in action (left), and the Relative Navigation System (right, in the space shuttle bay before launch for the Hubble Space Telescope Servicing Mission 4) are tools that will demonstrate Autonomous Rendezvous and Capture capabilities and help close the technology gap.

and fully exploit the advantages offered by satellite assembly and servicing, but this is an issue of effective application of technology, i.e., good engineering and rigorous existing systems engineering, rather than technology development.

To explore further the adequacy of servicing technology, the following discussion decomposes a satellite servicing system into the spacecraft bus element and four key technology areas for the servicer element: rendezvous and docking, manipulation, refueling, and autonomy.

Servicer Spacecraft Bus

Other than for human spaceflight, the six notional missions studied identified no new technology requirements for the servicer spacecraft bus. The servicer element imposed requirements on spacecraft subsystems such as attitude control, electrical power, command and control, data handling, communications, propulsion, thermal control, and structures and mechanisms that are fully mature and well within the current state of the art. Advances in lighter-weight or more power-efficient components and subsystems would, of course, improve capability in a given mission class, but no new technologies are required for the spacecraft bus.

Rendezvous and Berthing/Capture/Docking

The current experience base provides mature technology for rendezvous and docking with cooperative, non-spinning customers via teleoperation or semi-autonomous control. Rendezvous and docking are separated into three sequential phases. The first is rendezvous, wherein the servicer vehicle maneuvers from hundreds of kilometers to less than 100 meters from the customer. Proximity operations close the separation to a few meters along the desired approach corridor. Finally, the servicer and customer spacecraft are coupled via berthing, capture or docking. In docking, the servicer maneuvers until contact is made with the customer and mechanical couplings engage, as performed in the Gemini and Apollo programs in the 1960s and currently done by the space shuttle, Soyuz, Progress, and ESA Automated Transfer Vehicles (ATV) with the ISS. Berthing involves the servicer maneuvering to position the customer within range of a manipulator arm which grapples the customer. The manipulator can then dock the two vehicles if both are so equipped. Berthing was used on the Orbital Express mission in addition to direct docking. Berthing is also the approach used on the ISS with the JAXA HTV (H-II Transfer Vehicle). It will be the method used by the SpaceX Dragon and OSC Cygnus automated resupply vehicles expected to fly within the next couple of years under NASA's Commercial Orbital Transportation Services (COTS) and Commercial Resupply Services contracts.

Docking or berthing becomes more complex if the customer spacecraft is spinning or tumbling out of control. Control algorithms must determine the spin rate, spin axis orientation, and any nutation. Proximity operations must then be planned and executed to maneuver the servicer along the customer's spinning approach axis and match spin rates prior to grappling or docking (as depicted so well in the film *2001: A Space Odyssey* over 40 years ago). These operations have been simulated on the ground, but not yet attempted in space.

Berthing, capture and docking all require knowing the "pose," a term for the combination of position and orientation, of the customer relative to the servicer. In autonomous docking or grappling, cameras or Light Detection and Ranging (LIDAR) vision systems identify and track features on the customer to allow for a computational determination of the customer's pose. This task has been solved for reference fiducials purposely placed on the customer spacecraft. If there are no such fiducials, other features must be identified and tracked. One method would be to use cameras or a LIDAR to map the customer's surface and then compare that map to a model of the customer's exterior to determine its pose. These technologies have been demonstrated in laboratories (3D LIDAR tracking) and on the Orbital Express mission (2D optical tracking). There are multiple U.S.- and Canadian-produced LIDAR sensors and supporting camera systems that have been demonstrated in recent years on NASA and Department of Defense (DoD) space missions.

The required spacecraft actuators (thrusters and capture arms) are technology that has existed since the 1970s. It is the sensors and algorithms required for autonomous rendezvous and berthing/capture/docking that have seen development only in the last decade. The state of the art for on-orbit demonstrations includes non-spinning/non-tumbling customers. The next steps for technology development should include a demonstration with spinning and/or tumbling customer scenarios.

Manipulation

Manipulators, also known as "robot arms," end-effectors, and tools are necessary for all physical interaction between spacecraft, be it berthing, Orbital Replacement Unit (ORU) exchange, fluid coupling engagement, access panel removal, or camera positioning for inspection.

There are a few paradigms when considering what to place on the end of the robot arms. One is to use an end-effector that provides basic functions, such as a parallel jaw grippers, socket driver, etc. This is the type of end-effector used on the ISS SPDM system. The end-effector can be used for multiple tasks as long as those tasks are compatible with the end-effector's limited functions and standardized electromechanical mating interface. ORU replacement, for example, is a task that can typically be accomplished with such an end-effector. The end-effector could be designed such that it could be swapped out with another end-effector at the end of the arm. More specialized tasks, such as cutting a safety wire, require the end-effector to grasp the appropriate specialized tool. The range of possible tool designs and applications is nearly limitless, and very specialized devices have been built and used. Another paradigm is to develop a more dexterous end-effector that incorporates tools as part of its design. This end-effector/tool combination can be exchanged on the end of the arm to perform a specific task. This is the general philosophy behind the Ranger and FREND robotic systems. An extreme end of this spectrum is to develop an anthropomorphic hand that requires an extensive tool set for specific tasks like in the Robonaut system. These various paradigms were studied in the GSFC design lab and the results are summarized in Appendix E.

Some evolutionary advances in manipulation that would allow for more efficient operations include reduced mass and increased speed of manipulators, increased spatial resolution touch sensors (haptics), non-contact sensors that can detect the presence of nearby objects, narrow wavelength band cameras and illumination sources to eliminate sensitivity to solar glare and harsh direct solar illumination, and more autonomous systems. Fusion of manipulator sensory data and virtual environment simulation will provide teleoperators with "superhuman" senses.

Space robotic manipulation is in various stages of maturity. Basic teleoperation of manipulators is well established. However, autonomous control requires some validation and demonstration. There has been extensive teleoperation experience with large arms (15–17 m long) such as the space shuttle Remote Manipulator System (RMS) and the Space Station Remote Manipulator System (SSRMS). These are the equivalent of zero-gravity space cranes, and they played pivotal roles in assembling ISS. For finer, more precise motions and operation in more constrained work zones, smaller manipulators are required. The use of smaller manipulators for space servicing is less mature, with space experience limited to a few experiments in space (ROTEX, ETS-VII, and Orbital Express) and a few systems coming online now (SPDM/Dextre, JEM-Fine Arm, and Robonaut). The Viking 1 and 2, Phoenix, Spirit and Opportunity manipulators also add to the experience base, and some of the technology has been applied to free-space servicing tasks.

On the other hand, ground-based industrial robot technology is very mature, with nearly one million industrial robots now in use worldwide. However, space robotics differs from terrestrial applications in the structural characteristics of manipulators and payloads in zero-gravity. Consequently, control algorithms for space manipulators must take into account flexible-body dynamics and free-body contact dynamics. Real-time closed-loop control and disturbance reduction will be demonstrated with the Dextre Pointing Package (DPP) experiment on ISS.

Manipulator technology (arms, joints, end-effectors, motors) has existed since the 1970s. Improvements are being developed now in the areas of more diverse sensors suites and autonomous control. The state of the art for on-orbit demonstrations includes autonomous and teleoperated tasks. The next steps in technology development would include a demonstration with an access panel and refueling manipulation with multiple end-effectors and/or tools. These will be a part of the Robotic Refueling Mission demonstration that is planned on the ISS.

Refueling

The Orbital Refueling System (ORS) experiment on the Shuttle STS-41G mission in 1984 demonstrated the ability to refuel satellites in space. Following an Extravehicular Activity (EVA) to attach a flexible propellant line to a typical satellite valve in the payload hardware, six transfers of hydrazine between two diaphragm tanks were successfully conducted. Additional zero-gravity fluid transfer experiments were successfully conducted on Shuttle STS-57 in 1993 with the Super Fluid Helium On-Orbit Transfer (SHOOT) and Fluid Acquisition and Resupply Experiment (FARE) test articles.

The ISS is refueled using automated fluid couplings incorporated into the docking mechanisms on the Russian service module of ISS. Refueling is routinely performed by Russian Progress resupply vehicles and was also conducted by the ESA *Jules Verne* Automated Transfer Vehicle (ATV) spacecraft. In a similar manner, an automated fluid coupling and propellant transfer between two docked spacecraft was demonstrated by the Orbital Express program.

When joined spacecraft are not equipped with automated fluid coupling mechanisms, a manipulator can be used to interconnect a fluid transfer line and actuate valves. This will soon be demonstrated on the ISS with the Robotic Refueling Mission (RRM), which will perform tasks representative of those required to refuel a spacecraft using its legacy—i.e., not designed for robotic operation—propellant fill-and-drain valve. Similar fluid coupling and transfer demonstrations are needed for cryogenic systems applicable to high-specific-impulse propulsion systems and instrument cooling.

In addition to refueling via propellant transfer between propellant tanks, there is also the option of entire tank replacement using robotic manipulation in a manner similar to ORU replacement. Fluid line couplings can either be incorporated into the tank's mechanical interface or mated via robotic manipulation of flexible propellant lines. At an even higher level of integration, an entire propulsion module—propellant tanks plus thrusters and associated plumbing—can be designed as an ORU. The Multimission Modular Spacecraft (MMS) spacecraft incorporated a replaceable propulsion module. Refueling via whole tank replacement has not been demonstrated in space (although it is common for backyard barbeque grills).

The required spacecraft refueling technology is very similar to on-ground filling for simple fuel systems. It is autonomous refueling that has seen development in the last decade. The state of the art for on-orbit demonstrations includes refueling through pre-designed connections for docked spacecraft. The next steps in technology development include a demonstration of the autonomous refueling of a satellite that was not designed for on-orbit refueling.

Autonomy

Robot control sophistication ranges from simple and direct master-slave teleoperation, to automatic operation, and to increasing levels of autonomy. Automatic control methods such as those based on state-machine approaches, e.g., Experimental Spacecraft System Number 11 (XSS-11), are mature technologies from established principles in cybernetics. For a structured and pre-planned mission, an automatic capability is adequate. Autonomous capability is required only when the task is unfamiliar or complex, or when communication issues exist.

The benefits of autonomy include improvements in efficiency, robustness, and capability. Efficiency is improved by the robot performing more tasks prior to pausing to await human operator status assessment and approval to proceed. This becomes more important when latency—robot-to-operator communication time—is high or when communication time periods are limited. Robustness is improved by the robot controller analyzing sensor data and tailoring its actions accordingly. The robot control system can rapidly and tirelessly process a variety of sensor data and perform complex calculations to recognize and adjust to changes in the work environment while also constantly performing safety and health checks. Robustness is also improved due to faster controller response time due to local autonomous control eliminating communication-link latency. This same data processing capability and quick response time also enable some tasks to be performed faster and with greater sensitivity and accuracy than possible via teleoperation or Extravehicular Activity (EVA). At higher levels of autonomy, artificial-intelligence-like algorithms enable the robot to learn as it operates and improve task planning for future activities. In the last few years, much has been learned through higher-level applications of industrial robots about how robots can efficiently do their tasks. Similarly, the last few years have brought much experience with robots being operated by and around humans by the military (e.g., drones, building reconnaissance, and bomb disposal).

The expected level of autonomy demonstrated in spacecraft has steadily increased. Note that any servicing task could be done with any level of autonomy. The state of the art for on-orbit demonstrations includes autonomous docking and Orbital Replacement Unit (ORU) changeout for Orbital Express. The next steps in technology development would include evaluating several levels of autonomy with any and all future servicing demonstrations.

Satellite Servicing Integration into Mission Design

None of the technology gaps identified above are roadblocks to implementing significant use of satellite servicing technologies. Looking at the big picture, the key work may lie in determining how best to take advantage of in-space assembly and servicing to expand mission capability while also reducing mission cost and risk. What is the optimum balance between designing more capable robots versus designing space systems to maximize use of a core set of standard servicing capabilities and reduce additional costs associated with mission-specific servicing requirements? How can servicing be exploited to relax reliability and redundancy requirements? How can the deployment of large space systems be best staged to spread out hardware development and smooth out resource requirements? These system-level questions are not a technology gap, *per se*, but the answers will help inform the decisions that need to be made to determine the nature of these gaps.

ISS Demonstration Activities

The International Space Station (ISS) is our long-term human and robotic resource in space, making it a natural platform on which to demonstrate human and robotic systems that support satellite servicing. Several key technologies identified in our gap analysis are planned to be validated on ISS near-term via the Robotic Refueling Mission (RRM) and the Dextre Pointing Package (DPP) experiments.

The technology to direct the dexterous movements of a robotic system on-orbit has been demonstrated by the Special Purpose Dexterous Manipulator (SPDM, aka Dextre) on the ISS, and on-orbit robotic servicing was adeptly demonstrated on cooperative interfaces by the Orbital Express mission conducted by the Defense Advanced Research Projects Agency (DARPA). However, neither of those systems manipulated legacy hardware. They both interfaced with hardware that was designed for robotic manipulation. Accordingly, a risk reduction approach was undertaken that performs on-orbit demonstrations of legacy hardware manipulation. NASA is maturing selected technologies through feasibility demonstrations of servicing capabilities on Earth and on-orbit.

The near-term goals of the Space Servicing Capabilities Project (SSCP) are to expand selected servicing tasks and technologies and advance them to flight or mission status. These goals will be achieved through the development and flight of two independent payloads to the ISS.

By taking advantage of the ISS infrastructure as a platform to test servicing capabilities, these two independent payloads will demonstrate the ability of a robot like SPDM to meet the current needs of selected U.S. space assets at a cost and schedule much less than would be the case if these technologies were demonstrated on a stand-alone dedicated satellite mission.

There are four major stakeholders who stand to benefit by these payload experiments:

- The spacecraft users throughout the U.S. government, who will be able to have their spacecraft serviced on-orbit rather than replaced.
- The aerospace community, which will benefit from the advancements in technology research and development.
- The American taxpayers, who will see a more cost-effective use of their tax dollars.
- Future ISS experimenters. By learning to effectively use the ISS as a test platform, we could make significant progress in paving the way for subsequent ISS payloads, especially those utilizing the unique capabilities of SPDM.

The ISS payload experiments will increase NASA's technical abilities to use robots in space. The SSCP will design the flight hardware and Ground Support Equipment (GSE) for these payloads. It will also execute a demonstration of robotic refueling of a spacecraft, as well as the manipulation of a ground avionics test port and non-propellant fluid valves. The project will provide all the engineering required to accomplish these tasks and will coordinate the interfaces and required documentation with NASA's Johnson Space Center and Kennedy Space Center.

Robotic Refueling Mission (RRM)

In preparation for a potential future refueling of an orbiting spacecraft, the RRM (see Figure 4.11) will validate the capability by performing all the robotic

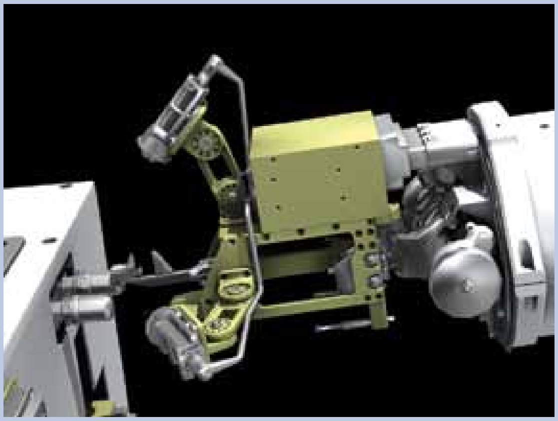

Figure 4.11 – Robotic Refueling Mission (RRM) – This rendering shows the RRM hardware on the International Space Station. This hardware will demonstrate the technologies needed for on-orbit spacecraft refueling.

Figure 4.12 – Dextre Pointing Package (DPP) – This rendering shows the DPP hardware being used on the International Space Station for Earth observations. This hardware will demonstrate fine pointing of the robotic arm using algorithms developed to support robotic servicing operations.

tasks required for such a mission. The demonstration will use the SPDM robot to locate and access the multi-layer insulation covering the fuel valve, cut multiple safety wires, remove the tertiary cap, remove the safety cap, then connect a nozzle tool that will turn the actuation nut and transfer a working fluid from one tank to the other, and finally disconnect from the tank receiving the fuel. On a separate panel, SPDM will remove SubMiniature Version A (SMA) termination caps from a ground test port, revealing exposed coaxial RF connectors. In a subsequent mission, coaxial cables will be flown and mated to the connectors. This will demonstrate that the capability exists to potentially bypass a failed or outdated avionics unit on a free-flying asset. Thirdly, there will be a fluid access panel on the demonstration hardware that will be accessed by SPDM. Using advanced robotic tools, SPDM will manipulate these non-propellant fluid valves to demonstrate the capability to replenish fluids on-orbit. This demonstration will also include general robotic operations using a "busy board." These boards provide various spacecraft interfaces to verify with machine vision algorithms (i.e., partial Marman clamp, mock thruster and various types of multi-layer insulation patches). The mission is designed for an operational life of two years and will execute the refueling demonstration and general robotic operations over a six-month period during the two-year window.

Dextre Pointing Package (DPP)

In preparation for servicing missions requiring greater dexterity and tracking capability, the DPP (see Figure 4.12) will demonstrate the algorithms and control mechanisms to locate and point at a specific location on Earth or a celestial object, as well as track and perform relative state estimation of vehicles visiting the ISS. DPP performs attitude determination using a star tracker and an Inertial Measurement Unit (IMU). It will receive target parameters via commands from a ground terminal and will send rate requests to the ISS Robotic Workstation Software (RWS) to achieve the desired instrument pointing. This closed-loop control of Dextre enables real-time pointing and disturbance reduction that are beneficial for future servicing architectures.

Not only can the ISS serve as a robotic test bed, it can also be used to evaluate the complementary nature of human and robotic servicing. Astronauts are available for Extravehicular Activity (EVA) servicing that may or may not include the use of robotic assets for items attached to the exterior of the ISS. Also, the crew could be used to perform tasks inside the space station to demonstrate and evaluate tasks in a zero-gravity environment.

Even for demonstration activities, thorough validation and verification are still required. Building upon the knowledge gained during preparations for the Hubble Robotic Servicing and Deorbit Mission (HRSDM), NASA's Goddard Space Flight Center (GSFC) and West Virginia University (WVU) have developed two unique facilities that deliver tool- and task-level, hardware-in-the-loop, contact dynamics simulations of any space robot interacting with its environment. Similar in concept and scope to astronaut training facilities, the Space Servicing Demonstration Facilities at NASA GSFC and the WVU-NASA Robotics Center for On-Orbit Servicing of Space-Based Assets provide essential tools for evaluating, practicing, and demonstrating procedures for current and future missions. Using the facilities in conjunction with proximity operations, hardware-in-the-loop test beds, and neutral buoyancy facilities as part of a larger demonstration, test, and validation program, full-scale, flight-accurate simulations can be performed that meet the requirements for different satellites, regardless of their size or specifications. All of these facilities help to achieve the goal of being able to rendezvous with and service any satellite, in any orbit, at any time.

The Recommended Actions

Figure 4.13 – Astronaut in Action – Astronaut Ron Garan, STS-124 mission specialist, participates in the mission's third scheduled session of Extravehicular Activity (EVA) as construction and maintenance continue on the International Space Station (ISS). During the six-hour, 33-minute spacewalk, Garan and astronaut Mike Fossum (out of frame), mission specialist, exchanged a depleted Nitrogen Tank Assembly for a new one, removed thermal covers and launch locks from the Kibo laboratory, reinstalled a repaired television camera onto the space station's left P1 truss, and retrieved samples of a dust-like substance from the left Solar Alpha Rotary Joint for analysis by experts on the ground. The ability to perform such feats on-orbit provides the inspiration for developing the art of satellite servicing.

This study has taken a comprehensive look at the history of satellite servicing, the current state of servicing-enabling technology and know-how today, and specific servicing missions for reaping significant near-term benefits. In the end, no study can achieve benefits without appropriate follow-through action and hardware commitment. Here we attempt to identify some specific actions that we believe would put us on the path toward realizing the benefits of satellite servicing. They represent relatively small investments for maturing a discipline that almost certainly will change the paradigm of space exploration in the coming decades. These actions are identified in Table 4.3 and subsequently discussed in more detail.

Table 4.3 – Table of Recommended Actions

Recommended Action	Result
Optimize engineering design and trade studies for the identified mission sequence.	Refined technical and cost assessments.
Invest in key enabling technologies such as 1) increased autonomy for robotic systems, 2) improved systems for rendezvous/docking/refueling, 3) advanced tools and end-effectors for astronauts and robots, 4) modular, self-reconfigurable, and mobile robotic architectures and systems that can move around large structures in space, and 5) advanced imaging/pose-estimating capabilities.	Proven technologies that will serve as the basic building blocks for complex servicing activities to allow future missions to focus on mission-specific challenges and solutions.
Assess a range of customers for satellite servicing.	Defined benefits for a suite of executable missions.
Create design recommendations for future spacecraft.	Accepted standards for spacecraft design that improve serviceability.
Establish customer/provider working groups.	A routine venue for discussion and feedback to implement lessons learned and best practices.
Integrate a satellite-servicing infrastructure with NASA program architectures and priorities.	The benefits of satellite servicing will be exploited where available and appropriate.
Initiate plans for executing the missions described in the Mission Sequence section (Chapter 4).	Immediate benefits provided by satellite servicing while refining the technologies needed for further advances.

Optimize Engineering Design and Trade Studies

The work reported here is clearly preliminary and primarily serves as "existence proofs" of designs for astronaut/robotic servicing systems that could carry out basic satellite upgrades and servicing. The obvious next activity will be to develop the engineering designs further, continuing to bear in mind that a major goal of our work has been to identify technology capabilities that are common among the different servicing concepts. This will result in refined technical and cost assessments for the proposed mission sequence.

Invest in Key Enabling Technologies

There are a small number of key technologies that would benefit from early—and sustained—investments, even at a modest level. These include 1) increased autonomy for robotic systems, 2) improved systems for rendezvous/docking/refueling, 3) advanced tools and end-effectors for astronauts and robots, 4) modular, reconfigurable, and mobile robotic architectures and systems, and 5) advanced imaging/pose-estimating capabilities. Most of these technologies are ready for application. By creating and exercising satellite servicing *systems* based on these technologies, they will serve as basic building blocks to support complex servicing activities. This should allow future missions to concentrate on mission-specific challenges and solutions rather than the basic tools.

Assess a Range of Customers for Satellite Servicing

In most studies to date, the candidates for satellite servicing—observatories and other major scientific spacecraft or communications satellites—have been treated somewhat as generic customers without a great deal of detail. The next step will be to include specific designs and operations, and in particular, specific customers with identified needs and similarities. This will result in a suite of executable missions with defined benefits. An additional result of such an assessment is that specific technology needs will be identified, should they exist.

Create Design Recommendations for Future Spacecraft

A major challenge to having a more efficient national aerospace industry is the lack of widely agreed-upon standards for spacecraft design that would permit more straightforward on-orbit upgrade, refueling, and recovery. We recommend that a joint government/industry working group be established to develop basic design standards for such subsystems that would be serviceable, such as fueling ports, connectors, power systems (batteries, solar arrays), antennas, and instruments whose components are likely to take advantage of technological improvements. Such voluntary design standards would improve the on-orbit serviceability of new spacecraft and could potentially improve ground processing efficiency as a side benefit.

Establish Customer/Provider Working Groups

Work on designs for satellite servicing, including development of precursor and demonstration experiments, has often proceeded with relatively little coordination from the beginning between the provider of a new capability and the customer (e.g., the satellite owner). We suggest establishing regular working groups (or workshops) made up of decision-makers who have the authority to direct and provide input to develop new capabilities and design new generations of spacecraft. These working groups would provide routine venues for discussion of requirements and feedback to implement lessons learned and best practices.

Integrate the Satellite Servicing Infrastructure with NASA Program Architectures and Priorities

Until very recently, satellite servicing has proceeded as an activity relatively isolated from NASA's scientific and human spaceflight architecture. This isolation has led to scientific satellites with little or no capability to be upgraded, thus reducing the potential scientific return on some very expensive missions. It would be advantageous for NASA to have a process for assessing on-orbit satellite servicing capabilities for future missions in order to exploit the benefits of satellite servicing where appropriate.

Execute the Mission Sequence

Our recommended mission sequence provides a balance of reaping immediate benefits from satellite servicing while refining the technologies required for more ambitious ventures. These missions are ready for execution now and should be incorporated into near-term plans for NASA. We recommend that plans begin immediately to develop the robotic front-end system to support the servicing capability needs identified by this study. A commitment by NASA to develop an operational servicer, demonstrate its capability on-orbit, and make it available for use will help ensure that the design recommendations mentioned above will be incorporated into future spacecraft designs and that the outputs of the customer/provider working groups will have a positive effect.

Chapter 5
Satellite Servicing: **The Challenges**

This study has summarized the case for, and charted a path towards, a future that provides the benefits of an advanced satellite-servicing infrastructure. While there are challenges to face, a key finding of this study is that very few of these are technical. We have the technologies in-hand to perform very sophisticated tasks on worthwhile satellite servicing missions. Further technological development is always desirable, *but is not required* to take the first steps in the plan. The challenges lie in several different realms, but with perhaps a common theme: insufficient credibility. Our recommended path attempts to further strengthen this credibility through sequential demonstrated steps so that the achieved benefits will become more commonly accepted (e.g., by satellite builders, insurance companies, fleet operators). Reducing the perceived and actual risk will increase demand and help to further validate the specific business cases.

Figure 5.1 – Earthrise from the Moon – This photograph of Earth rising above the lunar horizon was captured by Apollo 8 on December 24, 1968. Apollo 8 was the first human spaceflight mission to leave Earth orbit. It subsequently orbited the Moon and safely returned to Earth. Among many firsts for the Apollo program, NASA realized that setting and achieving an ambitious goal was key to capturing the hearts and imagination of the American people. It is an appropriate reminder that the challenges faced by our predecessors were successfully met with a planned sequence of missions designed to validate their technologies while performing meaningful work. This extraordinary image is one result of their labors. It has come to represent the beauty and fragility of our celestial home for generations past, and likely for generations yet to come.

Technological Challenges

On-orbit servicing of satellites that are designed to be serviced, as well as those not designed to be serviced, requires relatively little new technology development. However, it does require a disciplined systems approach in order to use existing technologies successfully and effectively.

The first challenge is to ensure that a servicing vehicle can locate and then rendezvous and dock with or berth to the customer spacecraft to be serviced. With existing technologies, this can be (and has been) performed through teleoperation, as long as the communication link time delays and latencies are manageable. A host of sensor systems and software packages presently exist (e.g., laser radar, visual-based natural feature recognition systems, and collision avoidance algorithms) that enable safe rendezvous and docking operations. Once outside the limits of teleoperation, autonomous operations must be considered. This is no different than how we presently safely operate our spacecraft around or on distant planets in our solar system. Autonomous docking was demonstrated on the Orbital Express program, and will be developed further very soon with the Orion spacecraft and its Sensor Test for Orion Relative-navigation Risk Mitigation (STORRM) demonstration. Servicing a spacecraft that was not designed to be berthed, captured, or docked with can be accomplished with some additional planning and specialized tool development

When refueling, the challenge is to mate the fluid connectors. In some missions, the fluid coupling will mate automatically during the docking process, such as with Orbital Express. Otherwise, a robotic manipulator can be used to mate the fluid connectors as in NASA's planned Robotic Refueling Mission (RRM) flight demonstration on ISS. There are no new technological challenges to refueling propellant. However, there could be a challenge if cryogenic replenishment is desired. Deep cryogenic transfers have been demonstrated during the Superfluid Helium On-Orbit Transfer (SHOOT) mission on STS-57 in June 1993, and this work needs to be extended to make such operations routine.

On-orbit assembly, Orbital Replacement Unit (ORU) changeout, and component changeout are also tasks to consider when servicing. The types of tasks required for these activities, such as removing and containing fasteners, cutting back thermal blankets, opening J-hooks, aligning boxes, etc., are all typical robotic manipulation tasks. The technology for teleoperating a space manipulator is known, and has been demonstrated through the utilization and test of the space shuttle Remote Manipulator System (RMS), the Rotex arm, and the manipulator on the Engineering Test Satellite Number 7 (ETS-VII). The key to manipulation is having an appropriate end-effector plus the right tooling to do the job. As robots are operated throughout the Earth-Moon system via teleoperation from Earth, there are system-level trades to be performed to determine the appropriate mix of autonomous systems and teleoperation using time delay mitigation strategies.

More ambitious programs with autonomous operations are a challenge, as defined by the technologies identified in the technology gap assessment. Autonomous operations would enable autonomous rendezvous and capture, the autonomous exchange of ORUs, sensors, batteries, and instruments. A fully autonomous servicing mission requires integration of the autonomy technologies of planning, state, and health information, and decision making as they are proven.

Since satellite servicing requires few new technologies, the key challenge lies in integrating the technologies that already exist into an end-to-end mission. As each demonstration leads into full missions, each additional mission adds maturity and confidence in the component technologies. The recommended approach is to follow our mission sequence and insert autonomy technologies as they mature. The need for autonomy is to supplement the system when problems with the teleoperation communication system arise, or when in-space operations increase the distance from ground control. The ultimate goal is a servicing system that is robust and capable. The path to this goal requires a strong systems engineering approach to combine the available technologies, tools, and procedures necessary to successfully create such a system.

Economic Challenges

Satellite systems may be the only complex systems without a routine maintenance, repair, or upgrade program. Typically, maintenance or upgrade means launching a new satellite to replace something that may have a fully functional set of subsystems. To recoup this high cost, the design lifetimes of satellites are made longer, which drives up their cost.

The real economic challenge lies in determining the value of servicing and then finding a business case that closes. For the simplest case, the economic aspects of on-orbit servicing include comparing the cost of a servicing mission to the cost of replacing the failed satellite as well as the potential returns from the serviced satellite. The returns can be revenue, scientific data, or continued and improved operations. The simplest case is for commercial communications satellites. For example, the 1999 Orion 3 satellite, which cost $150 million (plus $80 million for the launch) and was inadvertently placed in an incorrect orbit, resulted in a $265 million insurance payout. The potential operating revenue per year was around $43 million.[8] Because the design life of the satellite was 15 years, $645 million in potential revenue was lost.

Hubbard[50] looked at the possibility of extending a satellite's life through the use of on-orbit servicing and found that fuel depletion has a significant impact on satellite operations in geostationary orbit. By using a cost-per-year approach and comparing the replacement cost of a satellite and its design life to the cost of a servicer and its refueling capacity, his analysis showed that the servicer must refuel three to five customer satellites to be cost-effective.

Unfortunately, these simplified analyses do not tell the entire story, as they do not take into account the intrinsic value of servicing, such as providing options that allow the mission to adapt to changing requirements. They also overlook the effect that a servicing paradigm would have on driving down costs by encouraging satellites with shorter lifetimes and reduced redundancy, thus making them cheaper to build. Reynerson[51] considered some of this by looking at the additional value provided to a satellite operator by servicing as a function of the benefit that a customer satellite delivers to its operator, the risk associated with servicing, the operator's perception of those risks, and all costs associated with operating and servicing the customer satellite. He realized that non-monetary benefits include potential military and scientific observations, the discovery efficiency provided by servicing something like HST, or the increased accuracy of weather prediction by installing new detectors or sensors on-orbit.

Lamassoure and Hastings[52] developed a general way to estimate the value of servicing to space systems that took into account the options that servicing provides to the decision makers. Their results showed that the traditional approach of modeling servicing tended to *underestimate* the value of servicing and showed a cost advantage that was smaller than the cost uncertainty. Using Globalstar and Iridium as examples, their analyses showed that on-orbit servicing has significant value for commercial space missions in the flexibility it provides.

Rather than directly finding the cost of servicing missions, one can examine the break-even cost between a program with servicing as part of the regular program and a program without servicing.[32] Servicing was found to act as insurance against uncertainty, which included technology growth (future instruments provide enhanced capability), component failure (critical components fail over time, which is mitigated by introducing redundancy into current systems), and changing mission requirements (more data in different wavelengths or different types of measurements).

As seen from these discussions, assessing the economic challenges of satellite servicing is a very active field. Nevertheless, the general conclusions are that there are large classes of commercial satellites that could be economically viable to service. Exactly how many—and under what conditions—can be debated, and depends on some non-economic factors, such as perceived risk and whether or not satellite servicing capabilities are exploited as a part of the total mission design.

Making Future Missions More Serviceable

When it comes to assessing the on-orbit serviceability of a spacecraft, the "servicing mission" can be broken down into the different operational phases of the mission. At the highest level, these phases can be split out into the following: rendezvous, capture, service, release, and on-orbit verification. A more detailed discussion of servicing mission elements can be found in Appendix D. There are design philosophies, approaches, and implementations that are critical at each phase of the mission in order to ensure success. Some of the implementations of the "serviceability features" are quite different based on the different phases being assessed, but many of the philosophies are similar. The post-servicing phases will not be discussed here, as they are not relevant to the design philosophy for servicing.

Getting Close Enough

The first step in any servicing activity is to get close enough to a spacecraft to do some work. Thus, our goal is to make all potential customer spacecraft serviceable from the perspective of Autonomous Rendezvous and Capture (AR&C) by ensuring that spacecraft are capable of being cooperative customers for rendezvous, proximity operations, and berthing, capture, or docking.

Adding the following features and mechanisms to a spacecraft make it a cooperative customer for AR&C:

- Optical retro-reflectors
- Radio Frequency (RF) transponders for ranging and telemetry exchange
- Distinct, visible, possibly reflective, surface features
- Grapple fixtures
- Proper Attitude Control System (ACS) modes in flight software for quiescence when required

Optical retro-reflectors allow laser-based relative navigation sensors on the servicer spacecraft to acquire the customer spacecraft at greater distances and also provide better tracking quality for bearing-angle sensors. The pattern in which retro-reflectors are positioned on the customer can also allow optical or laser-based sensors on the servicer to measure relative attitude at closer ranges during proximity operations and final approach.

Radio Frequency (RF) transponders for ranging and telemetry exchange serve two important purposes. First, the exchange of a two-way ranging signal between the servicer and customer vehicle provides the servicer with a very accurate estimate of the range between the vehicles and aids in far-field acquisition of the customer. Onboard processing of these range measurements over time helps the servicer spacecraft's onboard relative navigation filter converge more rapidly on an accurate solution for the relative state of the customer vehicle. This is crucial for onboard AR&C guidance calculations. Moreover, the utility of the range measurements is enhanced when combined with bearing-angle measurements. Second, the exchange of telemetry between the vehicles allows them to share state information, which can further improve the servicer's relative navigation solution and provide important situational awareness data. For instance, a developing and unsafe condition onboard the customer vehicle might be detected by the servicer through analysis of the customer vehicle's telemetry.

Prominent surface features may help visible spectrum camera-based relative navigation sensors (e.g., a bearing sensor) acquire the customer at greater distances by virtue of reflecting sunlight more brightly, thus causing the customer vehicle to be more visible against the background. Even if not particularly reflective, surface features at known locations in the customer spacecraft's body frame help natural feature recognition pose sensor algorithms measure the relative position and attitude of the customer spacecraft when at closer ranges (i.e., during proximity operations and final approach).

Grapple fixtures offer a safe, robust means for the servicer vehicle to attach itself to the customer vehicle in a berthing or capture scenario. They are relatively small mechanical features with shapes and protrusions that are attached to the surface of the customer vehicle at points on the spacecraft structure that are capable of bearing anticipated loads during grapple, subsequent berthing or capture, and mated operations. The shape and protrusions of the grapple fixtures generally offer purchase to the end-effector of a robotic arm with grasping capability. While they may be specifically designed to be intrinsically compatible with a particular type or model of end-effector, they should also be designed and documented to be generally useful in any grapple scenario.

Finally, the availability of proper ACS modes ensures that two important conditions will be met. First, the customer vehicle will be in an acceptable attitude state throughout the AR&C sequence. This is especially important during the final approach phase, during which the servicer vehicle must engage in forced motion along an approach vector fixed in the customer vehicle's body frame. If the customer vehicle has any significant attitude rates during this phase, the servicer vehicle will have to consume significant amounts of fuel to stay on the rotating approach axis and complete the final approach. Second, the customer vehicle will be capable of becoming completely quiescent, ensuring that its ACS algorithms and actuators will not be attempting to counteract the forces and torques imparted by the servicer during capture, berthing, or docking operations and subsequent mated operations.

Note that the majority of these additional features have relatively little impact on the customer spacecraft systems. The mass and volume are quite small for retro-reflectors, visible surface features, and grapple fixtures, and none of them requires power or any other accommodations. Some spacecraft systems can accommodate this additional mass with less of an impact than others. For communications spacecraft, even a few kilograms of hardware added to accommodate servicing is a few kilograms less of station-keeping propellant, which can be translated into a number of days lost on-station and a cash value of transponder-day leases not available. In these cases, the servicer will have to be able to rendezvous with a less servicing-friendly target. The RF ranging and telemetry system will require an RF transponder, an omni-directional antenna, and appropriate signal-processing algorithms on both spacecraft. The RF equipment, including antennas, will have some mass and volume, and the equipment will require some power. However, the mass, volume, and power requirements are typically modest, particularly in comparison to other systems. Note also that the data bandwidth required for ranging and telemetry exchange is typically quite manageable and minimal compared to other RF links. Finally, the additional ACS modes for quiescence should be no more difficult to program than the other standard modes in the spacecraft flight software. In short, the single greatest challenge associated with making spacecraft more serviceable from an AR&C perspective is for spacecraft designers and program managers to make the choice to do so.

Mode of Servicing

Regardless of the purpose of servicing, *a priori* knowledge of the mode of servicing—astronaut-based and/or robot-based—is extremely helpful.

If a spacecraft can be designed for a specific type of servicing, it can greatly enhance the servicing efficiency.

There is overhead involved with each mode of servicing: humans require handholds, tether points, grasp points, visual markings, and specific tooling to interface to the worksite. Robots require their own form of these items: grasp points, stabilization aids, visual aids, targets, and specific tooling.

This is not to say that a spacecraft that is not designed for a specific servicing mode cannot be serviced. History has shown that it most certainly can. However, it must be understood that there are additional inefficiencies involved in such a servicing mission. Additional tooling and time may be required, and unique, innovative approaches for each task may be necessary. There are numerous examples where on-orbit repairs to hardware that was not designed for servicing have been made: all five HST Servicing Missions are excellent examples. On each mission, repairs were made to HST hardware that was never designed or intended to be serviced.

As already noted, there are unique differences between the needs of humans and robots in their interfaces on the hardware for on-orbit servicing. The NASA-funded Space Applications of Automation, Robotics and Machine Intelligence Systems (ARAMIS) study [53] in the 1980s found that one way to deal with this difference is to design the robot end-effectors and tools to interface with EVA interfaces. This is not to say that all robot end-effectors should mimic the human hand. As the team discovered in the second IDL design run, the robot system should be designed to take advantage of the "super human" capabilities provided by a robot; not the limitations of a human hand in a spacesuit.

Serviceability

One of the clear lessons learned from the multiple HST servicing missions is the old expression: "Never say never." The HST was designed with different modules having different levels of serviceability, some being very straightforward and others being very difficult (because they were never intended to be serviced). However, due to a combination of technology advancements and a creative enough engineering team, all challenges were overcome. The lesson learned from those missions was to make as many interfaces as possible common, accessible, and serviceable.

The expression "design for serviceability" can be interpreted in a number of ways. Our interpretation is that all of the features most people think of when they think about servicing should be incorporated into the spacecraft design. The more "serviceability" features are incorporated into the design from the start and documented, the easier the planning will be for servicing and its eventual implementation.

"Designing for serviceability" includes the following: common connectors throughout the spacecraft; standardized fasteners; workspaces with good access and visibility (including good pre-flight closeout photos); clear markings and labeling; alignment guides and cues; Orbital Replacement Unit (ORU) mounting with compliance; photographs of all harnessing, multi-layer insulation, lockwire and any other hardware that drawings cannot adequately represent; ORUs with good preflight metrology; good preflight photos of ORUs and interfaces; connectors that can be remotely driven and blind-mated; standardized module mounting; and motions that are all simple, and ideally, linear.

From an overall systems perspective, "design for serviceability" means modular design, ideally with critical functions split among different connectors and potentially among different modules. In such a design, single connector anomalies do not affect critical functions, but only impact redundant functions. The redundancy among modules can accommodate module replacement so that no critical functions of the spacecraft are lost while replacement is occurring. A good example of this is replacement of solar arrays, batteries, or spacecraft computers. In many current spacecraft designs, replacement of any of these would cause significant impact to the vehicle. In addition to designing-in modularity and redundancy for critical functions, there should be hardline input of external power, data, and commands, so that command and telemetry between the two vehicles is not dependent upon antenna positioning. This would also provide the ability to power the serviced vehicle from the servicer in the event that solar arrays were shadowed or taken off-line for servicing.

It is important to note that servicing has advanced well beyond the simple replacement of intended ORUs, and a complete replacement of an ORU is not always the best approach. The important criterion is having an available, well documented, and well understood interface. Examples include fuel fittings, cryogenic fittings, power bus connections, and computer interfaces/ground test ports. Once these existing interfaces are identified, appropriate planning and tools can usually enable a successful servicing approach. For example, on the first HST servicing mission, a 386 coprocessor was installed on the DF-224 flight computer to provide greater computing capability as well as memory redundancy. An existing test connector provided access to the internal data bus, which served as the communication path for the new hardware.

Design Commonality

To elevate the idea of design commonality, there would ideally be a set of standards against which spacecraft would be designed and evaluated. This may start small, perhaps at the government level, then expand to include commercial entities, then continue to expand from there (see Table 4.3).

Such a rating would determine a spacecraft's commonality against some ideal standard for serviceability, as defined in the established standards. From this an assessment could be made as to the ability to service spacecraft using common servicing tools (operational assessment tools, robots, end-effectors, robot tools, EVA tools, etc.). By providing common interfaces—not just within the spacecraft, but also across families of spacecraft, and then across agencies (NASA, NOAA, DoD, etc.), and ultimately across the aerospace industry with the goal of supporting on-orbit servicing—the serviceability of spacecraft would be greatly enhanced, even if some of those vehicles are never serviced.

An attempt was made to do something similar by the American Institute of Aeronautics and Astronautics in the early 1990s. Their *Guide for On-Orbit Spacecraft Servicing*[54] was a starting point for designers to use when developing serviceable spacecraft. To our knowledge, these guidelines were never widely applied.

Consequently, one encounters the issues that exist today. With regard to certain interfaces, there are limited vendors or design options, but in other areas of spacecraft design, there are numerous options that make design commonality uncertain and unlikely (e.g., the proliferation of connector types and sizes, and the options for mechanical layout and assembly).

Understanding that there is resistance in the spacecraft manufacturing community to adopt such guidelines, as a first step designers can simply select spacecraft hardware and use them in such a way that makes them more accessible. This should not make the spacecraft any heavier or more expensive to integrate, but it does increase the likelihood that it can be serviced, and makes any potential servicing task easier.

Chapter 6
Conclusion

This study has surveyed the international community, studied the literature, and examined the historical precedent on the vision, benefits, and challenges of on-orbit satellite servicing. During the months in which this work was carried out, the most common question—and one repeatedly echoed by the Satellite Servicing Workshop participants—has been, "Why are we not already doing this?"

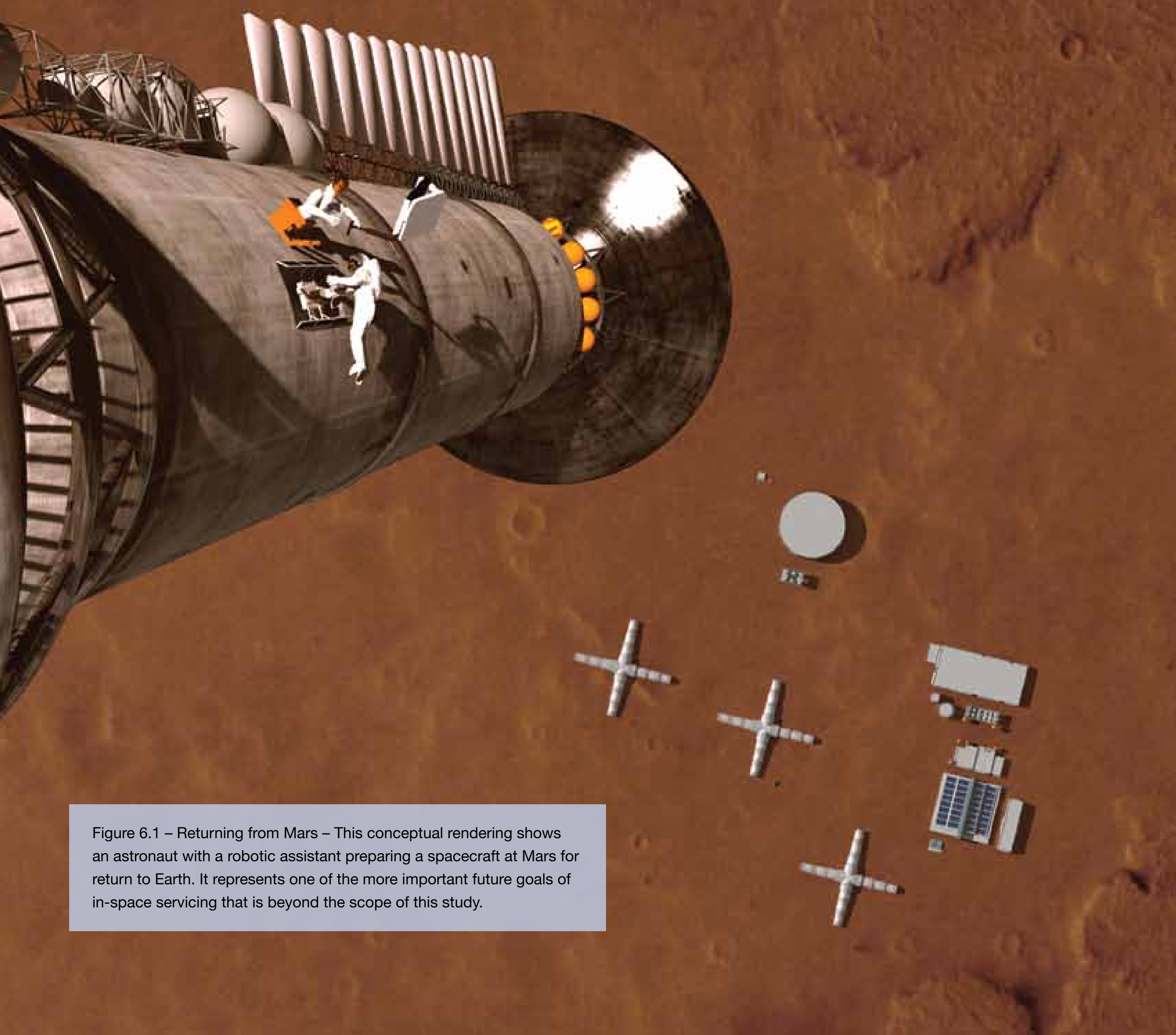

Figure 6.1 – Returning from Mars – This conceptual rendering shows an astronaut with a robotic assistant preparing a spacecraft at Mars for return to Earth. It represents one of the more important future goals of in-space servicing that is beyond the scope of this study.

As we have emphasized in the body of this report, the reasons that a highly capable in-space servicing system does not now exist are numerous and extend over many years; but none are related to technological readiness, or available customers, or a viable business case. This is evident from the extraordinary successes of the few cases where satellite servicing has been used to rescue a high-visibility mission. This On-Orbit Satellite Servicing Study was undertaken at the urging of the NASA Advisory Committee, the National Academy of Sciences, the House Authorization Committee, and the FY 2009 and FY 2010 NASA Appropriations Bills, and has resulted in an in-depth system-level assessment of space servicing.

What is needed now to change the paradigm of space operations is to expand the deployment of enabling capabilities. We have produced recommended actions and missions as one implementation to achieve this goal. They will enable us to more fully use the assets we already have in space through refueling, repair, and refurbishment to derive more economic value through extended use. We would also be able to manage our spent assets in space so that they do not impinge on the valuable orbital locations that are essential to everyday life. In the end, our recommendations would create the systems and new space architectures necessary to unlock the greatest secrets of the Universe and enable human exploration of new and distant frontiers.

During this study, several high-level recurring themes emerged.

1. *In examining the range of tasks required for servicing, the tasks themselves (and the hardware to support them) do not appear to be the limiting factors.* Extremely complex servicing tasks have already been successfully performed in orbit, including operations on legacy satellite customers as well as repairs on hardware not originally intended for on-orbit servicing. Advanced robotic analogues of these tasks are routinely demonstrated on the ground. The advancements needed are mostly in the areas of increased autonomy to support such tasks farther from Earth, and the systems engineering to create sufficiently robust servicing architectures. While all the technologies and techniques are available, their application in a mission requires maturation. For this, we recommend a robust on-orbit verification program using accessible platforms such as the International Space Station in combination with vetted ground simulators and test beds.
2. *Legacy satellites can be successfully serviced.* In fact, much of the servicing performed to date has been on legacy hardware never intended for on-orbit servicing. The range of applicable servicing activities includes repair, refurbishment, refueling, and orbit modification. Successful implementation requires identifying the correct interfaces, developing the appropriate tools and procedures, and training for and executing a well-planned mission, all of which have been demonstrated. Servicing these legacy satellites provides an immediate customer base on which to build a future satellite-servicing infrastructure. The business case for commercial satellites is favorable if the capability is available and well understood. The first step of the proposed mission sequence is to realize this capability for satellites in GEO.
3. *Modular, reconfigurable robotic architectures that are mobile around large structures are important to provide a cost-effective and upgradeable servicing infrastructure.* A part of the initial technology assessment would be to further develop these systems and demonstrate their adaptability.
4. *Launch mass and orbit modification capacity drive servicing mission design.* Here, the available launch vehicles could impact the architecture and even the feasibility and cost-effectiveness of satellite servicing. For example, for reaching distant destinations, there is a trade between heavy-lift rockets with refueling depots and multiple small launches with on-orbit assembly of small modules. These trades could also be affected by advanced propulsion

systems. Our technology gap assessment identifies other investment goals.

5. *Astrodynamics is a major factor in mission design, especially when there is human presence.* We paid close attention to this aspect for the satellite servicing locations that we considered. Interesting results include useful orbits that support satellite servicing.
6. *Satellite servicing is critical to our national interests*. As a nation, we need to develop this capability in order to maintain our leadership in space for scientific, commercial, and strategic reasons.

We return to the question, "What will this study contribute?" We investigated a carefully derived set of notional missions that provide a data-driven basis for assessing the feasibility and practicality of satellite servicing. In so doing, we examined key aspects of how common design choices and interfaces make a satellite more serviceable and the challenges in implementing this commonality. We also reviewed the technologies needed to implement satellite servicing at greater distances from Earth with increasing autonomy, and assessed their readiness for these next steps. Some of these technologies are being demonstrated in near-term ISS activities. Finally, we constructed a mission sequence that advances satellite servicing as an integral part of a robust and meaningful spaceflight architecture.

As this study drew to a conclusion, the future plans for NASA were becoming better defined, as expressed in the 2010 NASA Authorization Bill. The NASA-wide Human Exploration Framework Team (HEFT) is charged with developing the new space exploration plans based on this Congressional direction. The comprehensive HEFT study will include studying the development of an in-space servicing capability and identifying those areas where human participation in servicing is required or beneficial. We anticipate that the results of this study will inform the HEFT deliberations and provide the basis for developing a strong in-space servicing infrastructure to support these new plans.

Of even greater significance is the larger question of whether or not we as a nation are going to play a leadership role in satellite servicing. If, as announced, other countries develop this capability and we do not, the strategic and defense implications would be extremely dire.

We are at a turning point in America's space program. Our nation can continue to claim remarkable achievements in science, engineering, technology, and robotic and human exploration in space. As we deliberate the sometimes-conflicting goals to form the vision for the next decades, some things are very clear. For any meaningful future endeavor in space, success is more assured with architectures that include satellite servicing. For our national security, a domestic satellite servicing capability is paramount.

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Acronyms

ACS	Advanced Camera for Surveys (HST)
	Attitude Control System
AERCam	Autonomous Extravehicular Activity Robotic Camera
AIM	Aeronomy of Ice in the Mesosphere
AR&B	Autonomous Rendezvous and Berthing
AR&C	Autonomous Rendezvous and Capture (including Grapple, Berthing, and Docking)
ASTRO	Autonomous Space Transport Robotic Operations
ATP	Authority To Proceed
ATV	Automated Transfer Vehicle
C&DH	Command and Data Handling
COSTAR	Corrective Optics Space Telescope Axial Replacement (HST)
COTS	Commercial Orbital Transportation Services
CRTBP	Circular Restricted Three-Body Problem
CW	Clohessy-Wiltshire
DARPA	Defense Advanced Research Projects Agency
DART	Demonstration of Autonomous Rendezvous Technology
DIU	Data Interface Unit (HST)
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Space Agency)
DoD	Department of Defense
DPP	Dextre Pointing Package (GSFC)
DS1	Deep Space One
ELC	ExPRESS Logistics Carrier (ISS)
DTO	Detailed Test Objective
EML1	Earth-Moon Lagrange point 1 (between the Earth and the Moon)
ESA	European Space Agency
ETS-VII	Engineering Test Satellite Number 7
EVA	Extravehicular Activity ("spacewalk")
FARE	Fluid Acquisition and Resupply Experiment
FGS	Fine Guidance Sensor (HST)
FREND	Front-end Robotics Enabling Near-term Demonstration (Naval Research Laboratory, DARPA)
FSM	First Servicing Mission (HST)
FT	Functional Test
FY	Fiscal Year
GEMS	Gravity and Extreme Magnetism Small Explorer Mission
GEO	Geostationary Earth Orbit
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System
GSE	Ground Support Equipment

GSFC	NASA's Goddard Space Flight Center (in Greenbelt, MD)
HEFT	Human Exploration Framework Team (NASA)
HEO	Highly Elliptical Orbit
HGA	High-Gain Antenna
HRSDM	Hubble Robotic Servicing and Deorbit Mission
HST	Hubble Space Telescope
I&T	Integration and Test
IDC	Integrated Design Center (GSFC)
IDL	Instrument Design Laboratory (GSFC)
IMU	Inertial Measurement Unit
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experoment Module (ISS)
JWST	James Webb Space Telescope
LEO	Low Earth Orbit
LIDAR	LIght Detection And Ranging
LOTUS	L1 Orbit Trajectory Used for Servicing
MAVEN	Mars Atmosphere and Volatile EvolutioN
MBS	Mobile Base System (on ISS)
MDA	MacDonald, Dettwiler and Associates Ltd. (Canada)
MDL	Mission Design Laboratory (GSFC)
MMS	Multimission Modular Spacecraft
MMU	Manned Maneuvering Unit
MSS	Mobile Servicing Systems (on ISS)
MUBLCOM	MUltiple paths, Beyond-Line-of-sight Communications (satellite)
NAC	NASA Advisory Council
NASDA	National Space Development Agency of Japan
NCS	NICMOS Cooling System (HST)
NEXTSat	NEXT-generation serviceable Satellite
NICMOS	Near-Infrared Camera and Multi-Object Spectrometer (HST)
NOBL	New Outer Blanket Layer (HST)
NPR	NASA Procedural Requirement
NSSK	North South Station Keeping
OD	Orbit Determination
OMV	Orbital Maneuvering Vehicle
ORI	Orbital Replacement Instrument
ORS	Orbital Refueling System
ORU	Orbital Replacement Unit

OSS	Orbital Satellite Services
PCU	Power Control Unit (HST)
PMD	Propellant Management Device
PRICE-H	Parametric Review of Information for Costing and Evaluation – Hardware
R2	Robonaut 2
RF	Radio Frequency
RFI	Request For Information
RRM	Robotic Refueling Mission
RMS	Remote Manipulator System (on the space shuttle)
ROTEX	RObot Technology EXperiment
RSO	Resident Space Object
RTBP	Restricted Three-Body Problem
RWS	Robotic Workstation Software
SA	Solar Array
SADE	Solar Array Drive Electronics (HST)
SEL1	Sun-Earth Lagrange point 1 (between the Sun and the Earth)
SEL2	Sun-Earth Lagrange point 2 (on Sun-Earth line beyond the Earth)
SHOOT	Superfluid Helium On-Orbit Transfer (space shuttle mission)
SM3	Servicing Mission 3 (HST)
SM3A	Servicing Mission 3A (HST)
SM3B	Servicing Mission 3B (HST)
SM4	Servicing Mission 4 (HST)
SMEX	Small Mission EXplorer
SMM	Solar Maximum Mission
SPDM	Special Purpose Dexterous Manipulator (on ISS, aka Dextre)
SPHERES	Synchronized Position Hold Engage Reorient Experimental Satellites
SSCP	Space Servicing Capabilities Project (GSFC)
SSRMS	Space Station Remote Manipulator System (on ISS)
STEM	Science, Technology, Engineering and Mathematics
STIS	Space Telescope Imaging Spectrograph (HST)
STORMM	Sensor Test for Orion Relative-navigation Risk Mitigation
STS	Space Transportation System (space shuttle)
TDRS	Tracking and Data Relay Satellite
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TPAD	Trunnion Pin Acquisition Device
WFPC2	Wide Field and Planetary Camera 2 (HST)
WVU	West Virginia University
XSS-10/11	Experimental Spacecraft System Numbers 10 and 11

Appendixes

These appendixes provide backup information that supports the conclusions in this report. There are descriptions of the Congressional language that this report responds to, summaries of the RFI responses and the Workshop, a description of the systems engineering decomposition of what it means to conduct a servicing mission, technical summaries of the supporting technologies from the Integrated Design Laboratory exercises, and the notional mission summaries. Many of these working documents are sufficiently general that we hope they will help guide future ventures in satellite servicing.

Figure A.1 – The Hubble Space Telescope after Servicing Mission 4 – This photograph captures the Hubble Space Telescope redeployment after all the Servicing Mission 4 activities were completed in May 2009. This event marked the completion of an extraordinarily successful series of servicing missions to this international icon and is a tribute to the dedication and effort of the Hubble Space Telescope Team over the past two decades. This project report captures some of the rationale for and lessons learned from the satellite servicing aspects of these efforts.

Appendix A – Congressional Legislation and Reports Bearing on Science with the New Space Transportation Architecture

(as of 1/15/10)

Public Law 110–422 October 15, 2008
“National Aeronautics and Space Administration Authorization Act of 2008”

TITLE IV—EXPLORATION INITIATIVE
SEC. 409. SCIENCE AND EXPLORATION.

It is the sense of Congress that NASA’s scientific and human exploration activities are synergistic; science enables exploration and human exploration enables science. The Congress encourages the Administrator to coordinate, where practical, NASA’s science and exploration activities with the goal of maximizing the success of human exploration initiatives and furthering our understanding of the Universe that we explore.

TITLE V—SPACE SCIENCE
SEC. 502. PROVISION FOR FUTURE SERVICING OF OBSERVATORY CLASS SCIENTIFIC SPACECRAFT.

The Administrator shall take all necessary steps to ensure that provision is made in the design and construction of all future observatory-class scientific spacecraft intended to be deployed in Earth orbit or at a Lagrangian point in space for robotic or human servicing and repair to the extent practicable and appropriate.

Public Law 111–8 March 11, 2009
“Omnibus Appropriations Act, 2009” (H.R. 1105)

DIVISION B—COMMERCE, JUSTICE, SCIENCE, AND RELATED AGENCIES
Conference Report

TITLE III – Science
NASA Science

Servicing Opportunities for Science Missions.—Recognizing the historic successes NASA has achieved through the servicing of the Hubble Space Telescope, the National Research Council’s recent report Launching Science: Science Opportunities Provided by NASA’s Constellation System recommends that “NASA should study the benefits of designing spacecraft intended to operate around Earth or the Moon, or at the libration points for human and robotic servicing.” This recommendation parallels the guidance provided by section 502 of the NASA Authorization Act of 2008 (P.L. 110–422), which recommends that provision be made for servicing of future scientific spacecraft to the extent practicable. Therefore, it will be critical that the Constellation program demonstrate unique capabilities to maintain synergies between free-flying scientific spacecraft and human spaceflight endeavors. Accordingly, the bill provides $20,000,000 for NASA to undertake an assessment of the feasibility of using the Constellation architecture to service existing and future observatory-class scientific spacecraft, fully utilizing the unique, core expertise and competencies for in-space servicing developed by the Goddard Space Flight Center and its private sector partners for the Hubble Space Telescope. NASA shall provide to the House and Senate Committees on Appropriations a plan for expenditure of this funding no later than 30 days after enactment of this Act.

House Report 111-149 June 12, 2009
COMMERCE, JUSTICE, SCIENCE, AND RELATED AGENCIES APPROPRIATIONS BILL, 2010

TITLE III—SCIENCE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Astrophysics other missions and data analysis - Within the amounts provided, not less than $50,000,000 is available to continue efforts in the use of the next generation of human space flight architecture to service existing and future observatory-class scientific spacecraft as identified in the conference report accompanying division B of Public Law 111-8.

Senate Report 111-34 June 25, 2009
COMMERCE, JUSTICE, SCIENCE, AND RELATED AGENCIES APPROPRIATIONS BILL, 2010

TITLE III—SCIENCE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Servicing Opportunities for Science Missions.—The Committee provides $50,000,000 to continue efforts to use the next generation of human space flight architecture to service existing and future on-orbit observatory-class scientific spacecraft as provided for in the statement of managers accompanying division B of Public Law 111–8. The Committee directs that this shall be a joint project of the science and exploration mission directorates, with supervision provided by the Associate Administrator and the Chief Engineer, and shall include technology demonstrations for both robotic and human servicing capabilities.

Ares V.—The Committee believes that the Ares V cargo launch vehicle will be a critical national asset for carrying exploration and scientific payloads beyond low Earth orbit to the Moon and beyond. To facilitate the earliest possible start of the development of the Ares V, the Committee recommends a funding level of $100,000,000.

December 13, 2009
Conference Report to Accompany H.R. 3288 - Consolidated Appropriations Act, 2010
DIVISION B - COMMERCE, JUSTICE, SCIENCE AND RELATED AGENCIES

Astrophysics, servicing opportunities for science missions.- Funding for this activity has been provided within funds appropriated under the heading “Space Operations.”

International Space Station (ISS) operations.- Within the amounts provided for ISS operations, $50,000,000 is provided to continue efforts in the use of next generation of human space flight architecture to service existing and future observatory-class scientific spacecraft as identified in the conference report accompanying division B of Public Law 111-8. The activities to be undertaken shall be a joint project of the space operations, science and exploration mission directorates, and shall include technology demonstrations for both robotic and human servicing capabilities.

Appendix B – RFI Responses Summary

At the start of this study, NASA issued a Request For Information (RFI) to provide the satellite servicing community with an opportunity to participate in the study process by sharing their perspectives on satellite servicing. Subsequently, most speakers for the International Workshop on On-Orbit Satellite Servicing were selected from these responses. If the author of an RFI response presented at the workshop, a detailed summary appears in Appendix C. RFI responses that could not be accommodated by a presentation at the workshop are summarized in this appendix.

Advanced Optical Systems, Inc.

RFI Response Number One

Advanced Optical Systems (AOS) is developing enabling technology flexible enough to support Rendezvous, Proximity Operations, and Docking (RPOD) operations for both cooperative and non-cooperative satellites with a single sensor system. AOS's technology extension to the ULTOR Passive Prose and Position Engine family of 6 Degrees of Freedom (DOF) state estimation algorithms is called ULTOR ACT, and combines a 2-D camera and 3-D Light Detection and Ranging (LIDAR). ULTOR ACT is a classic two-plus-two-equals-eight solution in which the application of real-time processing of two sensor data streams provides a more robust, accurate and precise solution than either sensor provides alone. ULTOR ACT technology is estimated at TRL 3, but given the maturity of each subsystem, AOS expects it can reach TRL 5 by 2011 through hardware-in-the-loop testing of prototype systems.

RFI Response Number Two

AOS developed the ULTOR Passive Pose and Position (ULTOR P3E) system to provide real-time 6 DOF estimates of objects using 2-D data that is almost always present on space vehicles for rendezvous missions. An earlier version of the technology flew on the Hubble Space Telescope Servicing Mission 4, STS-125, and AOS is currently working with NASA/JSC to demonstrate a more advanced version of the P3E sensor processing as a candidate Automated Rendezvous and Docking sensor for the ORION crew capsule using the centerline docking camera. ULTOR P3E is extremely portable and has been ported into six different platforms, including two different space hardware platforms. ULTOR P3E is currently at NASA TRL 8 after the SM4 mission to Hubble, and has been demonstrated to TRL 5 for the Orion implementation.

RFI Response Number Three

The current AOS product for Automated Rendezvous and Docking (AR&D) based on the Advanced Video Guidance Sensor (AVGS) design is called ULTOR Active. This system includes state-of-the-art detector technology and improvements to the processing hardware that allow a much smaller footprint while providing an order of magnitude increase in accuracy over the previous AVGS design. ULTOR Active is designed to provide immunity to extreme lighting variations, a potential and significant problem with most AR&D sensors. The previous AVGS technology is evaluated at TRL 8 based on the Orbital Express (OE) and Demonstration of Autonomous Rendezvous Technology (DART) missions, and the ULTOR Active is at TRL 6.

ARES Corporation

ARES Corporation attributes much of its vast range of experience in the aerospace industry to the previous experiences of its personnel. Several employees were involved in making the tools, fixtures, and procedures used in the capture and return of Palapa B-2 and Westar VI spacecraft, which were stranded in useless orbits when both spacecraft suffered identical failures when the carbon-carbon nozzle on each of the perigee kick motors shattered approximately eight seconds into the perigee burn. ARES personnel helped in a mission to capture and return the two spacecraft for repair and relaunch. ARES personnel were also involved in the on-orbit repair of the LEASAT F3 in 1985 to bypass a flawed electronics unit that prevented the spacecraft from turning on. ARES' experience with on-orbit servicing could help with a variety of future servicing needs.

CSA Engineering

Vibration and Jitter Control

Vibration control can be divided into several categories: vibration suppression, vibration damping, vibration cancellation, and vibration isolation. Vibration control can use several different power sources, and can serve multiple purposes: failure prevention, performance improvement, or testing. CSA has developed mechanical vibration dampers that have been used on the Hubble Space Telescope's (HST) solar array masts and LDCM, in addition to other vibration control systems for a variety of applications. Vibration control can help do things like reduce optical jitter, aid in-space assembly, and protect delicate components during launch. CSA continues to pursue enhancements to their systems to achieve greater vibration control and new mission applications.

On-Orbit Assembly

On-orbit assembly enables a new class of ultra-large spacecraft that offer greater opportunity and potential benefit for scientific, military, and commercial applications. Many challenges exist, but for certain types of missions, space-based assembly can offer a high-performance, efficient solution. Whenever physical size matters, on-orbit assembly is beneficial, and assembly also opens the door for new spaceflight architectures. Due to the inhospitable space environment and lengthy amount of time required for assembling a large structure, robotics become a necessary part of any mission. When considering any on-orbit assembly mission, on-orbit structural verification and on-orbit management of vibration and other motions become key considerations in the planning process. CSA and Moog's strengths in space-rated actuators and electronics and expertise in the areas of structural dynamics, experimental modal analysis and related instrumentation, control system design and control-structure interaction, could be leveraged for use in on-orbit assembly missions.

Emergent Space Technologies

Emergent was founded to provide engineering services and technology research and development for the autonomous space operations industry. Initial emphasis was on formation flying and constellations, but with NASA's Constellation Program coming online in the early 2000s, Emergent's focus shifted to autonomous rendezvous, proximity operations, and docking (ARPOD). Emergent has several relevant technologies, including specialized algorithms for designing efficient tours of Near-Earth Asteroids for Discovery-class missions, which could also be applied to efficient transfers of Project Constellation vehicles, Retro-GEO orbits, CubeSats for ARPOD mission support, and algorithms for safe proximity operations, rendezvous, and capture. Emergent has supported GSFC in its satellite servicing studies through its work with an Instrument Design Laboratory run and a Mission Design Laboratory run, and in the post-analysis of Rendezvous Navigation Systems data collected during the STS-125 mission to the Hubble Space Telescope. Emergent's experience in ARPOD and formation flying, combined with its subject matter expertise in orbit determination, attitude determination and control, maneuver and trajectory design, collision prediction and avoidance, orbital debris modeling, and systems automation and autonomy makes them a great resource for on-orbit servicing missions.

Honeywell Defense and Space

As the avionics supplier for over half of the shuttle avionics, the International Space Station (ISS) avionics, and the Orion avionics, Honeywell is well positioned to support NASA's Goddard Space Flight Center in a trade study defining the feasibility of using existing Constellation assets and other space equipment in creating a flight support system used in servicing future spacecraft. Honeywell is also the incumbent avionics supplier for the existing Shuttle Flight Support System. Honeywell's system engineering credentials and process for supplying cost-effective support, experience with the existing Flight Support System for the Multi-Mission Spacecraft, capability to support integration into the existing Orion avionics and Control and Data Handling (C&DH) system, and capability in supporting robotic assistance for both Orion and other spacecraft makes them a cost-effective teammate to support Flight Support Equipment Trades.

ITT Corporation

The Hubble Space Telescope and Solar Max missions have shown that human spaceflight is an excellent resource that can be used for maintenance or repair. These missions demonstrated that human spaceflight could extend the life of high value on-orbit systems, though they were very expensive. The Special Purpose Dexterous Manipulator (SPDM, aka Dextre), which was delivered to the ISS in 2005, has the manipulative resources for some very complicated assembly and repair operations. This type of program could reduce the cost of future astrophysics missions by providing a more robust maturing Technology Readiness Level and by demonstrating technologies that are difficult to show on the ground or through analysis. ITT is working on developing ideas and technologies for such a program.

Jefferson Institute

To truly enable the unique core expertise and competencies for in-space servicing (human and robotic) by the Goddard Space Flight Center and other NASA centers, the research aperture needs to be widened to use all national and international assets. The Jefferson Institute has had the privilege the last two years to assist NASA's Marshall Space Flight Center (MSFC) in the development of the Ares V heavy-lift vehicle as a national asset. The Jefferson Institute helped develop several workshops that were hosted by Ames Research Center, with the goal of having MSFC listen to potential users directly in an effort to explore what potential users would like to see in a new heavy-lift vehicle. To assist GSFC in transforming space servicing from a single user, the Jefferson Institute would use variations of the same approaches to kindle national interests.

John Frassanito & Associates

A near-term, high confidence Heavy-lift Launch Vehicle (HLV) could be developed using well understood, legacy elements of the Space Shuttle system, which offers significant performance, reliability, schedule, risk, cost, and work force transition benefits. The HLV could be ready for first flight as soon as 54 months after an Authority to Proceed. This refined HLV could be developed for less than $8 billion, and operated at costs as low as $450 million per launch, depending on mission configurations, flight rates, and operating concepts. As an example of the on-orbit servicing capabilities enabled by this shuttle-derived HLV, John Frassanito and Associates describes a 172 metric ton prototype Space Based Solar Power satellite that could be delivered to GEO starting as early as 2016.

MDA

MDA has developed unique, reliable robotic solutions for more than 30 years. Such robotic systems can and have been used as mission enablers, and in the future they can enable even more missions in space observatory assembly and servicing, satellite servicing, orbiting stations and service depots, and space exploration. Servicing has already been shown to reduce mission risks and costs while providing life-extension or performance enhancement, and robotics have been key to both human and robotic servicing solutions. Robotic systems and servicing have already been demonstrated with Hubble and the ISS, and have enabled great scientific returns at relatively low costs. With existing state-of-the-art robotics onboard, the ISS is an ideal development platform for testing new on-orbit servicing capabilities. MDA is prepared to support both NASA and the CSA in expanded utilization and experimentation with the ISS robotic systems.

Michigan State University

Recently, researchers at Michigan State have developed and experimentally tested a computationally efficient, general-purpose vision architecture, suited for general image understanding in uncontrolled environments. This architecture bridges a wide technology gap between concrete image features and abstract task concepts, by enabling goal-directed deliberative reasoning with pixels. Existing artificial vision systems cannot match the performance of a trained human observer. Existing systems that control platform motion, sensor-pointing angle or perform foveated sensing are brittle in performance. By contrast, biological systems like those being developed accomplish these tasks seemingly effortlessly. Moving the neural processing taking place in the operator's brain to computer processing on a NASA robot platform will reduce both operator workload and bandwidth.

Moog Space and Defense Group

Moog has developed several technologies for use in space missions which could be applied to on-orbit satellite servicing. They have developed advanced technology solutions for precision motion and fluid controls, launch vehicle control technologies, propulsion systems and components technology, technology for vibration control, and technology for tactical missiles solutions. Moog has significant experience with technologies necessary to support the development of on-orbit fluid transfer and servicing missions, and proposes the development of an on-orbit autonomous cryogenic fuel transfer system. Moog has also produced six degrees of freedom systems for space applications. Finally, Moog proposed a notional mission for space debris cleanup.

NASA's Goddard Space Flight Center

Using NASA's Constellation Architecture to Achieve Major Science Goals in Free Space

Future space science missions developed to achieve the most ambitious goals are likely to be complex, large, publically and professionally very important, and at the limit of affordability. Consequently, it may be valuable if such missions can be upgraded, repaired, and/or deployed in space, either with robots or with astronauts. A team at Goddard developed a concept for astronaut-based in-space servicing at the Earth-Moon L1 and L2 locations that may be implemented using elements of NASA's Constellation architecture. This libration point jobsite could be of great value for major heliospheric and astronomy missions operating at Earth-Sun Lagrange points. The team explored five alternative servicing options that could be available within about a decade, and highlights one that appears to be the least costly. It most efficiently uses Constellation hardware that appears to be available by the middle of next decade: the Ares I crew launch vehicle, Orion crew exploration vehicle, Centaur transfer vehicle, and an airlock/servicing node developed for lunar surface operations.

LASOPOST

LASOPOST (LEO-Assembled, SEL2-Operated, Phasing Orbit-Serviced Telescopes) is a concept for assembling, operating, and servicing a broad range of sizes and types of space telescopes. The main objective of LASOPOST is to enable maximum science capability while requiring minimum development of supporting space infrastructure. In the LASOPOST concept, space telescopes would be deployed or assembled in a LEO that either matched the International Space Station orbit or was easily reachable from the ISS orbit in case of deployment or assembly issues. After deployment or assembly, the space telescope would be checked out and gradually boosted to a Sun-Earth Lagrange point 2 orbit for science operations. Periodically, the space telescope could be dropped back into a Lunar Phasing Orbit for servicing (supported by a crewed Orion capsule), after which the telescope could return to SEL2 Orbit.

In-Space Robotic Integration System (IRIS)

It is impossible to plan a construction of large structures in space without developing a versatile, reliable, and cost-effective joining technology. Also, human experience shows that in-space repairs of existing assets will be required in order to support our prolonged presence in space. Vacuum brazing is a mature process used for new construction and repair in many aerospace, aircraft, automotive, nuclear, and medical systems. Its potential application in space has been demonstrated by Russian cosmonauts, as well as by the experiments performed on American and European payloads. A team at Goddard proposes to develop a reliable, safe and cost-effective joining technology based on electron beam vacuum brazing for in-space construction and repair. Cost of future endeavors such as permanent orbital platforms can be reduced and risk can be better mitigated by launching compact, collapsible pallets containing stowed modular elements (struts) of the future structures and assembling them in space.

Applications of DMDs for Astrophysical Research

Digital Micromirror Devices (DMDs), used as optical switches, provide a most powerful solution that allows for the design of a new generation of instruments with unprecedented capabilities. A DMD spectrograph can take the next step in addressing the next big astronomical questions. Utilizing servicing, a DMD spectrograph could be installed on the Hubble Space Telescope (HST). Equipped with a DMD multi-object spectrograph, HST would represent an ideal complement to the James Webb Space Telescope.

SPectroscopic All-sky Cosmic Explorer (SPACE)

Exploiting the enormous advances in nanotechnology, SPACE is a mission capable of producing a three-dimensional evolutionary map of the Universe over the past 10 billion years. SPACE improves the figure of merit for knowledge of dark energy by more than an order of magnitude and fully discriminates between theories of dark energy and theories of modified gravity. SPACE achieves its remarkable sensitivity, sky coverage, and sampling frequency by performing multi-slit near-IR spectroscopy in outer space, fully exploiting the sky background about 500 times lower than from the Earth. SPACE, originally conceived as a joint ESA-NASA project, has won the ESA selection (medium-class) for the Cosmic Vision 2015–2025 planning cycle. SPACE, as originally proposed, has by far the most exciting capabilities, with a scientific potential so broad and compelling that it exceeds even the investigation of dark energy.

NASA's Marshall Space Flight Center

The Advanced Technology Large-Aperture Space Telescope (ATLAST) is a mission concept for the next flagship UV/optical/Near-IR (UVOIR) space observatory, to answer some of the most compelling astronomical questions, including "Is there life elsewhere in the Galaxy?" Two different observatory architectures for ATLAST have been explored in detail, but both can tackle the same set of scientific goals. Although ATLAST requires some technology development, both observatory concepts take full advantage of heritage from previous NASA missions, as well as technology developments currently underway for missions in development. The non-cryogenic nature of ATLAST makes the construction and testing of the observatory much simpler than for JWST, and a key attribute of the design of ATLAST is its ability to be serviced and upgraded on orbit.

Northrop Grumman

NASA's great observatories—the Hubble Space Telescope, Compton Gamma-Ray Observatory, Chandra X-Ray Observatory, and Spitzer Space Telescope—have clearly demonstrated the need for multi-spectral observations to unveil the mysteries of the universe. These observatories could be accommodated with existing launch vehicles, requiring only their antenna booms and solar arrays to be folded up. NASA's next generation of large space observatories—James Webb Space Telescope (JWST), Space Interferometry Mission (SIM), Constellation-X (Con-X), Terrestrial Planet Finder Interferometer, and Single Aperture Far Infrared telescope (SAFIR)—will use segmented optics with complex deployment schemes and/or multiple launches and formation flying to satisfy their requirement for apertures much larger than the about 5-meter diameter of current launch vehicle fairings. If telescope aperture sizes continue to follow historical trends, the space observatories launched in the 2030 to 2040 period to follow up on discoveries by JWST, SIM, Con-X, and SAFIR will be too large to be launched and deployed from a single launch vehicle. Thus, NASA's "Vision Missions" such as Stellar Imager, Life Finder, SPECS, and Planet Imager will require on-orbit assembly. To maximize the scientific return from these facilities, they should also be designed for on-orbit servicing and instrument replacement.

Odyssey Space Research

Odyssey Space Research is a company focused on commercial and government applications of on-orbit GN&C and Rendezvous and Proximity operations.

Odyssey is currently working on five spacecraft that perform the rendezvous, proximity operations and capture (RPOC) operations critical to any on-orbit servicing operation. Odyssey believes that some of these spacecraft, or major components of the spacecraft, could be re-tasked to support on-orbit servicing missions. At the very least, the RPOC capabilities can be used in the development of an on-orbit servicing system. Odyssey has also studied the potential applications and implementations of an on-orbit servicing system through its own internal research as well as through a Small Business Innovation Research (SBIR) entitled "Automated Rendezvous and Docking Infrastructure to Support Commercial Space Development." In addition to the spacecraft and mission design work that Odyssey supports, Odyssey is working on a number of relevant technologies such as new guidance, navigation and control algorithms; navigation sensor techniques; and a very unique testing capability to introduce flash LIDAR sensors into closed loop hardware-in-the-loop simulation.

Physical Sciences, Inc.

Physical Sciences, Inc. (PSI) possesses an enabling technology that addresses two principal missions: on-orbit assembly of modular space systems too large or too fragile to launch, and repair or replacement of failed or under-performing components. PSI's technology is called AUTOCONNECT (Auto-Configuring Electromechanical Interface), which is an intelligent, universal, electromechanical interface for autonomous space systems assembly. AUTOCONNECT will enable rapid on-orbit assembly of space systems—both astronaut-assisted and robotic. AUTOCONNECT was developed by PSI under sponsorship of NASA's Marshall Space Flight Center and DARPA under Small Business Innovation Research programs.

Teledyne Brown Engineering

A Robust, Orbit Mechanics Enabled, Minimal Cost Approach to Orbit Debris Remediation

To meet the increasing threat to the safe access to space posed by space debris, methods are being sought to reduce the amount of large debris in space through active debris removal. Capturing large, uncooperative debris in either high-, medium-, or low-earth orbit is arguably the most significant challenge to orbit debris remediation. Most, if not all, space-based approaches require active pointing/targeting or grappling to effect capture, approaches which levy considerable requirements on knowledge of the target's physical geometry, condition, and motion in addition to the requisite capabilities for targeting and grappling. Teledyne Brown proposes a solution that utilizes a filament mesh to passively encompass and capture the target body, rather than capture by grappling or otherwise directly contacting the target body. This capture system is amenable to any disposal system, either for boosting to a higher parking orbit, or reentry from low-earth orbit.

Robust, Adaptive Control of Evolving Systems for On-Orbit Robotic Servicing

On-orbit robotic servicing of spacecraft has great potential as a safe and cost-effective means for maximizing the return on the investment in high-value space assets, and as a means to enabling complex missions that cannot be accomplished otherwise. To enable on-orbit robotic servicing will require advanced technology and avionics guicxxdance, navigation, and control. In particular, the robust attitude control problem for evolving systems is a technical challenge that heretofore has not been met in a satisfactory manner. Teledyne Brown is researching autonomous control of a structure during and after the connection or mating of two or more components of its subsystem. The autonomous assembly of actively controlled subsystems is the central element of Evolving Systems.

Texas A&M University

Optimal Servicing of Geosynchronous Satellites

To be cost-effective, satellite servicing will require the servicing vehicle to service numerous satellites, which will require raising and lowering of altitude and plane changes. Plane changes require a lot of fuel, so any servicing architecture will have to minimize the total plane change. Consequently, geosynchronous orbit is probably the region in which servicing will be the most cost effective, because all the satellites are in almost the same plane. Researchers at Texas A&M University developed a method for optimally visiting numerous satellites in geosynchronous orbit.

Enabling Propellant/Fluid Transfer in Microgravity

Phase separation is a critical technology for pressure-driven fluid transfer under reduced gravity. Texas A&M and Boeing designed a propellant transfer system for the International Space Station.

Appendix C – International Workshop on On-Orbit Satellite Servicing

March 24-26, 2010
Hosted by NASA's Goddard Space Flight Center

Executive Summary

An enthusiastic assembly of more than 250 aerospace industry leaders, technology companies, universities, NASA officials, and other Federal Government representatives joined together to discuss and debate the current and future state of satellite servicing. There was unanimous consent that the time is right for meaningful on-orbit servicing to be executed. Technology exists today that can enable both robotic-only and human-robotic cooperative on-orbit servicing.

Robert Strain, Director, Goddard Space Flight Center.
Mr. Strain opened the Workshop with welcoming remarks.

Ron Ticker, Manager for Space Station Development, NASA Headquarters; Chairman of International Workshop on On-Orbit Satellite Servicing.
Mr. Ticker reported on the goals of the Workshop, the quantity of the RFI responses, and set the stage for the presentations to begin.

Christopher Scolese, Associate Administrator, NASA Headquarters.
Mr. Scolese described the background, history, and importance of Multimission Modular Spacecraft, Solar Maximum, and the Hubble Space Telescope (HST) to satellite servicing. He then explained the International Space Station's (ISS) assembly and robotic integration, and the need for more maintenance to extend its life to 2020. He finished with a poignant comment about the opportunities lost with past space assets such as Skylab, and concluded with what can be done in the future.

Dave Radzanowski, Deputy Associate Administrator for Program Integration, NASA Headquarters. "NASA Perspectives on Developing Spacecraft Servicing Capabilities."
Mr. Radzanowski began with a status report on ISS assembly and the directive that it will serve as a technology test bed going forward. ISS operations have been extended to 2020, which provides time to have technology demonstrations launched and installed. In the next two years, $2.5 billion are allotted for ISS extension. Current U.S. operations are at 50% utilization, and we want to get to 100%. Utilization increase will be spread across the servicing study, technology demonstrations, and other programs. There are two main technology demonstration programs: Flagship missions and a technology demonstration flight that includes fuel transfer and Advanced Rendezvous and Capture (AR&C). Other new technologies that are slated for development are: a safety spin decouple, materials and structures, environmental studies, formation flying, lightweight materials, and power and energy solutions. Mr. Radzanowski also mentioned that he is focusing on servicing technologies that are "enabling" across more than one NASA program (namely, the Exploration, Mission, and Technology directorates at NASA). He also stressed that the community needs to make the business case for servicing by incorporating servicing into broad concepts and architectures, instead of "one-off" events.

Dr. Stephen Huybrechts, Vice President, Applied Minds, Inc. "Thoughts on On-Orbit Servicing for the National Security Community."
Dr. Huybrechts relayed his personal opinions from a background of national security experience. His perspective is that while no Department of Defense assets are currently designed for servicing, having such services available in-orbit would be useful for unexpected events or challenges. Such in-orbit services would make most sense in orbits with multiple satellites (i.e., GEO). He noted that storable propellant might not be the area where he would devote technology development money, as electric propulsion systems limit the need for refueling, and it may be easier to fly extra fuel for end/late mission life operations. Rather, servicing is useful to fix flaws, rescue stranded assets, and remove acquisition delays; overall, to extend the life of legacy systems while their replacements work through their own delays. He also stressed that flexibility is a key attribute of servicing capability, especially when a team does not know the mission in advance.

Ed Horowitz, Founder and Board Member, U.S. Space LLC. "The Role of the Private Sector."
U.S. Space LLC is a privately financed company that provides rapid satellite communication solutions to the U.S. and its allies. Mr. Horowitz has significant experience with commercial satellites, including Home Box Office (HBO). He noted that in the commercial satellite field, one must consider the value (revenue stream) of the service provided versus the satellite's cost (hardware/operations), as well as the lost value (revenue) of business (communication) interruptions. He also explained that the business model for a replacement satellite is "just-in-time delivery." Since a satellite does not depreciate until it is launched, an asset in production or in storage is "better" for accounting purposes. However, refueling (especially after full depreciation) appears to be a marginal incremental cost when compared to the large revenue stream that would be enabled by continued satellite operations. It was his opinion that opportunities for satellite servicing are

reaching alignment; however, they are still in a formative stage and will ultimately be shaped by insurers, satellite companies, and technology developers. The strategy should be to align NASA (with its technology development) with commercial needs while building servicing, or at least refueling, into future satellites. When an audience member asked if his company would be willing to be the anchor customer for satellite servicing, he replied, “Yes.” They have designed refueling into their satellites at no design cost. Another audience member posed the question, “Nobody wants to pay up front for satellite servicing, but they want it in a crisis—how can we bridge the gap?” His answer was that there will need to be at least 12 in-space assets, from both the Department of Defense and the commercial sector (UHF system) that are either in crisis or on their last fumes. They have not been approached with a solution. If they were given one, they would compare the amount of time that it would take for a satellite servicer vehicle to launch versus the amount of time it would take to replace existing assets.

Frank Cepollina, Deputy Associate Director, Space Servicing Capabilities Project. “Servicing Study Objectives.”

Mr. Cepollina indicated that he has been trying to have servicing capabilities built into satellites for decades, but nobody thinks in terms of future (servicing) needs. Engineers never predict failures or problems because they are generally too optimistic. He asserted that the da Vinci robot is capable of impressive teleoperation, and since that capability exists on the ground, it should also be feasible in space. He observed that the aerospace community’s desire to implement satellite servicing “is not there yet,” and that it needs to be coached and encouraged over the next 12 months. To that end, his group at NASA’s Goddard Space Flight Center is engaged in fabricating hardware that will demonstrate refueling on the International Space Station (ISS). The goal of these demonstrations is to mitigate risk to real satellites. Their development efforts also include ground demonstrations that are six months ahead of flight experiments. He adamantly believes that the time is right to move ahead on flight servicing. It is time to stop talking and start building. The workshop attendees responded with a cheer of support.

Missions and Customers of Satellite Servicing

Session Chair: Harley Thronson

Associate Director for Advanced Concepts in Astrophysics, NASA’s Goddard Space Flight Center

Although the capabilities exist—or will, in the near future—to service complex systems in LEO, the “business case” or a positive return on investment has yet to be fully established.

Dr. Matt Mountain (Director, Space Telescope Science Institute) opened the session with a compelling discussion of the breadth of the scientific return that was made possible by a series of successful servicing missions to the Hubble Space Telescope (HST). However, these observatory upgrade missions took place in LEO with the space shuttle, which will soon no longer be available.

However, the future of servicing of scientific satellites lies well beyond LEO. Presentations by **Dr. Dan Lester** (Research Fellow, University of Texas, Astronomy Department, “Servicing and Lagrange Point Operations for Astronomy”), **Dr. William Oegerle** (Director, Astrophysics Science Division, NASA’s Goddard Space Flight Center, “Servicing ATLAST!”), and **Dr. Matthew Greenhouse** (Astrophysicist, NASA’s Goddard Space Flight Center, “Extra-Zodiacal Exploration: An Architecture for Servicing-Sustained Cosmic Discovery”) summarized the value both of different orbits for astronomical observatories, and again, the importance of designing observatories that can take advantage of being upgraded on orbit.

It was important for the attendees to recognize that “servicing” was a term that included more than changeout of instruments on a flagship scientific satellite or construction of the ISS. **Dr. Charley Noecker** (Staff Consultant, Ball Aerospace & Technologies Corp., “External Occulter Planet Finder Mission at L2—A Potential ‘Customer’ for Robotic Servicing”) outlined how an occulting system to search for extra-solar planets might be enabled by advanced space robotics, **Tom Kessler** (Program Manager, Boeing Advanced Systems, “NIMITZ”) described the concept for robotic on-orbit space debris removal, and **Bruce Campbell** (Manager, Integrated Design Center, NASA’s Goddard Space Flight Center, “Solar Sail Assembly/Deployment in Earth Orbit: An Enabling Capability for an Enabling Capability”) discussed the potential of solar sails to achieve multiple goals in free space.

On-orbit refueling and fuel depots have been identified for years as a future capability that would enable missions that otherwise would be very difficult. **Dallas Bienhoff** (Manager, In-Space & Surface Systems, The Boeing Company, “LEO Depot Servicing Impact on Space Missions”) discussed recent work to develop depot concepts in greater depth.

Lunchtime Presentations

Chair: Benjamin Reed

Advanced Materials and Avionics Manager, Space Servicing Capabilities Project, NASA’s Goddard Space Flight Center

Steven Johnston, Director of Advanced Space Exploration, The Boeing Company. “The Future of Commercial Human Space Flight.”

In commercial programs such as 737 airplane program, Boeing assumes all the risk. There are about 200 customers, and the FAA approves the design through a well-established process. In contrast, other programs are funded by one customer, such as the Navy Poseidon program where the Navy retained authority. For a commercial crew vehicle program in aerospace, there will be a mix where the commercial company and NASA would define the requirements. For example, NASA would have authority for human rating, while Boeing would fund the design and retain the design rights. The challenge is to find a business model to balance the risk. For instance, if you lose one customer for the 737 program it is not the end of the world; however, such a situation would be catastrophic for satellite servicing. A strong binding contract is therefore needed to get servicing started. The overarching design drivers for a crew vehicle are: 1) that it be safe and reliable, 2) that it be cost effective to operate, and 3) that the risk be burned down.

Boeing needs to share costs and design an architecture that is built in a smart, simple way. The concept needs to be flexible, to accommodate a crew from three to seven people, and be modular, lightweight, and compatible with many launch vehicles. In addition, a combined design, manufacturing, test and training center should be created for efficiency.

Bernard Kutter, Manager, Advanced Programs, United Launch Alliance. "United Launch Alliance Launch Services."

United Launch Alliance (ULA) has an extensive launch history and plans to have about one launch per month in the near foreseeable future. Mr. Kutter reported 1,300 successful launches; the program should therefore be considered extremely safe. The A402 may be able to launch a crew vehicle, and a second rocket with this capability is in development. ULA has been working on the CRYogenic Orbital TEstbed (CRYOTE) for a number of years. The tank would sit in a Payload Adapter Fitting (PAF) much like LCROSS did. It would also take advantage of the extra gas (N2, O2) from the rocket's upper stage. Present capability allows us to carry a 9-ton payload to Lagrangian point 2 (L2); a fuel depot in orbit would enable a 20-ton payload to L2.

Bob Richards, Vice President, Human Spaceflight Systems. "Orbital's ISS Resupply Service."

Mr. Richards reported on Cygnus and the Taurus launch complex. Cygnus is a cargo vehicle designed to resupply the ISS, but it could morph into satellite servicing. Orbital sees itself and Cygnus as a turnkey system. The Taurus II launch site is under construction at Wallops Island. For Cygnus, Mission Operations at Dulles are tied to Mission Operations at NASA's Johnson Space Center. The pressurized model is being built by Millenia and is close to delivery. Cygnus just completed Critical Design Review (CDR) and Phase 2 of the Safety Review Panel. Taurus II is beyond CDR and is in production and testing.

Barry Miller, Systems Engineer, Lockheed Martin Space Services Company. "On-orbit Satellite Servicing–Overview of Lockheed Martin Satellite Servicing Capabilities and Products."

Over the last two years, Lockheed Martin has looked at on-orbit satellite servicing from a robotic and autonomous standpoint, with the idea of looking at a multi-mission servicing concept that is service-oriented based, has a fairly long life, and is capable of doing several missions. The basic servicing concept overview is that Lockheed Martin can deploy the asset and have the GEO-focused asset on numerous orbit applications in LEO or geosynchronous orbit. Deploying a near-term asset, a highly flexible robotic servicer with a chemical based propulsion system, would allow you from a technology development standpoint to focus on the high-risk items that Frank Cepollina mentioned earlier. Once the asset is in position it can do several missions, including repositioning active or dead satellites. Lockheed Martin has also looked at refueling missions that carry on-board refueling propellant. One could have either a monoprop or biprop system that allows you to service satellites that need fuel; or you could do repair operations; or perhaps go in and touch something that is in failsafe and move it into an un-fail state. That kind of asset can then go on and do several missions. Periodically, you could refuel your servicer and upgrade your own assets through mission customization.

Lockheed is trying to map where they can use low risk capabilities and technologies and marry them with some of the more immature technologies to bring them together into a servicing architecture that is both reliable and responsive to do multiple missions in a short amount of time.

Baard Eilertsen, Senior Vice President, Business Development, Swedish Space Corporation. "The Orbital Life Extension Vehicle—an AOCS Backpack."

There were two competing programs for the commercial satellite business back in the 1980s. The commercial satellites had trouble with their launch vehicles, and the Swedes developed a system to service them. This system has developed with the following attributes: cold gas propulsion for maneuvering, electric propulsion (20 weeks to get to GEO), and cameras to navigate to customer. The Servicer would park at one meter and send a probe into the thrust nozzle of the customer for attachment. The Servicer would then stay attached and act as the ACS until the customer's end of life (EOL). At EOL, the Servicer would super-sync the customer, release, and find a new customer. An obsolete satellite with one or two months of fuel left on board would be ideal for experimentation.

Lt. Col. Fred Kennedy, Space Lead, Space & C4ISR Branch, Joint Staff/J-8, Dept of Defense. "Orbital Express."

Orbital Express (OE) was designed to demonstrate in-orbit servicing. Astro was the servicer; NextSat, the customer, was equipped with retro reflectors. Mission Operations were located in Kirkland, Huntington Beach, and Houston. The two satellites were launched mated together. One of the first tasks was to transfer 15 kg of Hydrazine from Astro to NextSat without pumps. The pumped transfer came later. NextSat also moved propellant to Astro. The mission replaced both batteries and computers in orbit. Throughout the mission, numerous anomalies occurred and were overcome with real-time problem solving by the ground ops team and the systems onboard the two satellites. For example, the biggest problem with rendezvous was not collision avoidance, but finding NextSat. Lt. Col. Kennedy suggests incorporating sensors that can view in all directions (four pi Steridian), and believes that it is possible to attach to common satellite fixtures such as Marman rings, bolt holes, etc., in the future.

In summary, the OE mission demonstrated the technical feasibility of on-orbit docking and servicing. This may allow a reduction of redundancy and testing (which are expensive) in future missions. He believes in-orbit servicing could extend satellite lifetime and maneuverability.

Business and Commercial Case for Satellite Servicing

Session Chair: Mansoor Ahmed

Associate Director of Flight Projects for the Astrophysics Projects Division, NASA's Goddard Space Flight Center

Keynote Speaker: **Joe Rothenberg**, International Development and Integration, Swedish Space Corporation. "Commercial Satellite Servicing Needs and Challenges."

Servicing commercial satellites hinges on investment returns. In the current environment, it takes eight to ten years to get a return on an investment from a commercial satellite. The upfront funding acquisition takes about three years. It takes another three to five years to develop and launch a satellite. So, the return on investment will be minimum of eight years after the project begins. The types of commercial satellites will dictate if servicing is warranted and financially profitable. If a satellite is small and non-unique, the cost of servicing could be the same as launching a new satellite. If a satellite is large and unique, it will have higher potential for servicing need and return on investment. Potential servicing customers may include remote-sensing operators and satellite brokers. Commercial satellite servicing is considered a high investment risk. Risks include the return on investment, cash flow if paid after servicing, and investor confidence. Commercial satellite servicing is an unproven market with high entry costs, and not enough customers have been identified to make it profitable. The concept of servicing commercial satellites and extending satellite life threatens the existing business model of building new replacement satellites.

Charles Miller, Senior Advisor for Commercial Space, Office of the Chief Technologist, NASA Headquarters. "Should NASA Foster a Commercial Satellite Servicing Industry?"

NASA Headquarters is providing funding to the commercial space industry for future technology development and the creation of new market. Satellite servicing is a potential new commercial market. It was suggested that NASA and other government agencies could foster a commercial satellite program. The National Advisory Committee for Aeronautics (NACA) approach was provided as a proven and open innovation model. The NACA approach focused on industry, with industry being both partner and customer. It developed key partnership with all key agencies (United States Air Force, the Department of Transportation, and the Department of Commerce). The guiding strategy was to develop consensus and practical solutions. The strategy also included smaller, more numerous, and more frequent projects and programs. Miller advocated the NACA approach and provided numerous examples of NACA successes. He also emphasized that the early NACA successes did not require a significant amount of cash. NACA focused on building a healthy competitive industry. It solved a practical aviation problem with a small amount of cash. NACA, whose focus was external customers, was a critical driver in American aviation. The NACA-like options to foster a commercial satellite servicing industry are: 1) purchase commercial satellite, 2) fund COTS program, 3) joint-sponsor research, 4) loan guarantees, 5) partner with DoD and national security team, 6) identify and help solve other non-technical items (ITAR), and 7) develop new technology.

Baard Eilertsen, Senior Vice President, Business Development, Swedish Space Corporation. "Market Interest in Fleet Management On Orbit Services—A Commercial Approach."

The on-orbit services are life extension, relocation, rescue and deorbiting. For one scenario, a satellite's life can be extended by 12 years. Based on a market research of commercial telecom satellite operators, satellite servicing has a market if the cost of servicing is 30 to 50% of buying a replacement satellite. So this tells us that if the cost of servicing is less than 50% of a replacement satellite, the servicing is cost-effective. A satellite servicing development program with ESA financing and oversight took the ConeXpress-OLEV through a full and successful Preliminary Design Review. An initiated contract with a launcher, Optus, had to be cancelled due to cost increase. A new and more cost-efficient servicing satellite platform project was initiated. Commercial satellite operators do not want to pay for new technology; however, they may be willing to try if it were offered at a reduced cost and risk. Investors are not willing to pay the cost above the nominal price. The industrial shareholders cannot finance the development costs. Investments, strategic partner and financing entities are required. Technical solutions to on-orbit servicing are ready, and potential customers have been identified. But to date, it has been difficult to find investors who are willing to take the risk.

Bretton Alexander, President, Commercial Spaceflight Federation. "Commercial Human Spaceflight: Context and Capabilities."

The Commercial Spaceflight Federation includes developers and operators. This activity is funded 100% privately and does not involve government funding. To date, over $1.5 billion has been invested into the commercial spaceflight industry. The Federation has executive and associate members, with executive members providing orbital and suborbital spacecrafts as well as spaceports, and associate members providing training services, medical services, and life support services. The membership represents 2,600 employees in 30 states. NASA's commercial crew program, robotic precursor missions, and technology demonstration programs promote commercial space industry. Specifically, there is much interest in NASA's technology demonstration program. NASA's COTS program has fueled progress and success in the commercial industry, as seen by the Falcon 1 success. Currently, the commercial industry capability is limited to Low Earth Orbit. Its destination missions are LEO servicing and the ISS. The potential customers are the U.S. government, industry, research, private individuals, and foreign clients. Its capabilities include launch and reentry, in-space assembly and servicing, and satellite rendezvous and inspection. The goal is to develop a commercial spaceflight entity that does not depend on NASA.

Zach Bailey, Graduate Student, MIT Space Systems Laboratory. "Determining the Value of On-Orbit Telescope Servicing."

Space astronomy constantly strives to discover the new and unknown, and enhanced detecting capabilities are key to achieving this goal. As the Hubble Space Telescope successfully demonstrated, on-orbit servicing can increase science capability as well as extend instrument life. Serviceability costs can be estimated by assessing the ease of system serviceability. If the system design allows for easy servicing through modularity, docking interfaces, etc., the servicing cost can be predicted with more certainty. Serviceability is also an insurance against future uncertainty. If a telescope can be serviced to upgrade its detecting capability, then the cost of building and launching a new telescope can be deferred. Serviceability's value can be quantified by estimating the break-even cost between a program with servicing and a program without servicing. A baseline example may be a servicing program where a telescope would be replaced after two or more failures. A servicing model is created in order to compare servicing and replacement. Costs are developed for servicing and replacement. The difference in cost between replacement and servicing defines the upper boundary for what a servicing program should cost. It is recommended that mission concept design periods include a study of satellite servicing. This approach should be applied to all expensive long-life satellites.

Barry Miller, Systems Engineer, Stf, Lockheed Martin, "On-Orbit satellite Servicing—Is There a Case?"

There is a market for satellite rescue. A satellite that, due to non-catastrophic launch failure, fails to achieve its desired orbit may be inserted into the wrong orbit. Such an asset could be saved if a satellite were launched to capture and relocate the original satellite to a correct orbit.

While a market survey on servicing capability showed very little interest in on-orbit repair, it indicated that there is a high level of interest in orbit maintenance and launch rescue. However, a successful on-orbit demonstration of such a capability is required. The historical record indicates that 1 out of 120 satellites have been lost. The value of servicing depends on whether there would be total or partial loss of the satellite, the replacement costs, and what is considered market value. As the cost of Department of Defense (DoD) satellites is unknown, it would be impossible to use this technique to assess the value of even a critical DoD mission that received servicing.

The diverse and large on-orbit servicing market is difficult to estimate and capture. And if the right value proposition is poorly defined, the opportunity for a servicing market will be closed. Customer interest highly depends on the servicing business model, and this model requires that the developer assume risk up front.

Human Servicing

Session Chair: Jim Corbo

Systems Engineering Manager, Space Servicing Capabilities Project, NASA's Goddard Space Flight Center

Keynote Speaker: **Dr. John Grunsfeld**, Deputy Director, Space Telescope Science Institute. "Hubble SM4: Space Servicing in Action."

Dr. Marc Postman, Astronomer, Space Telescope Science Institute. "The Science Rationale for Servicing and Considerations for Existing and Future Space-based Astronomical Observatories."

On-orbit servicing provides three key functions that directly extend or magnify the scientific impact of space observatories: 1) restoration of operation by the repair of failed components, 2) extension of lifetime by the replacement of expendables or life-limited items, and 3) expansion of capability by upgrading to newer technology.

The benefits of upgraded instrumentation include the ability to undertake investigations that were not even conceived of when the observatory was launched. For example, the study of environments around other planets as was done by STIS but had not yet been conceived at the launch of HST. Fifth-generation HST science instruments have been conceived that could give huge increases in scientific output using gigapixel CCDs. In theory, launching a series of telescopes with updated instruments would have the same effect; however, this does not happen. Astronomy is fortunate to have one observatory launched per decade, so keeping a flagship observatory operational for 20–25 years is important.

The benefits of lifetime extension by the replacement of expendables could be shown on the James Webb Space Telescope (JWST). Since JWST requires fuel for station-keeping, having the ability to refuel JWST could allow it to operate well beyond its nominal 10-year lifetime.

In addition, the benefits of on-orbit repair to restore operation could be shown on JWST with a repair of micro-meteor damage to the sunshield.

Telescopes this large would likely need to be assembled in space and would utilize active optical systems of segmented apertures, as well as a modular serviceable architecture for replacing expendables. Existing human spaceflight infrastructure can be used as a test bed to develop and advance the technological readiness level of human-guided robotic servicing in space, including autonomous rendezvous and capture, the installation of new avionics and science instruments, and life-extension upgrades. Such a pathfinder could employ existing, actuated, ultra-lightweight primary mirror technology that could be fabricated four times faster than conventional glass mirrors.

Dr. Donald Hall, Astronomer, Institute for Astronomy, University of Hawaii. "Hubble Legacy Telescopes for the International Space Station."

Science on ISS is a multiphase program. One proposal is to attach a .5 m to 1 m telescope to confirm ISS as a suitable location for telescope observations, attach a similar-sized cryogenic telescope to extend to near-infrared wavelengths, and augment spectral coverage by adding "clone" telescopes. The goal is to scale the telescopes to the largest possible ISS aperture, potentially to the HST 2.4 m range.

The ISS program objectives are to show scientific and engineering results by 2015, which would result in a full-scale "great observatory" in 2016–2020. This would provide a thousand-fold improvement in discovery efficiency over HST and demonstrate key technologies for assembling, verifying, and operating facilities from ISS.

The science drivers for these new telescopes include the thousand-fold increase in gain over HST's Wide Field Camera 3 with Gpxl Infrared sensors. A 4-Mpxl Hawaii-2RG, SIDECAR ASIC, and 16-Mpxl 2 x 2 MOSAIC on the NIRCAM will fly on JWST. These developments can lead to a direct path for space qualification of the 1-Gpxl detectors. This telescope would be an excellent survey telescope for JWST and 8- to 30-meter class ground-based telescopes.

Concerns for the ISS-based telescopes include vibration isolation, EMI, contamination, and field-of-view zone constraints.

The advantages of ISS telescopes include: 1) final assembly, alignment, and verification on-orbit in zero-gravity, 2) allows launches in robust modules, 3) location allows for rapid response for maintenance and repair, 4) allows for regular opportunities for refurbishment and augmentation, and 5) attractive baselines for interferometry. The benefits to ISS from these telescopes include providing a high-profile science program, helping to develop robotic assembly and servicing, and providing ISS with excellent educational and public outreach opportunities as well as recognition.

Max Vozoff, Director, Civil Business Development, SpaceX. "Dragon as an In-Orbit Servicing Platform."

SpaceX has offices, manufacturing, and production facilities in Hawthorne, CA (near Los Angeles) as well as a Propulsion and Structural Test Facility in central Texas. SpaceX vehicles include the Falcon 1, Falcon 9, and Dragon spacecraft.

Falcon 9's inaugural flight is currently scheduled for April 2010 from Cape Canaveral. Falcon 9 is a two-stage Evolved Expendable Launch Vehicle (EELV)-class vehicle designed to meet NASA man-rated safety margins and failure tolerances. The Falcon 9 has a 5.2 m fairing and is capable of carrying 10,500 kg to LEO. Ground tests of the Falcon 9 have been completed all the way up to release.

The Dragon spacecraft has 3 main sections: 1) the nose cone, which is jettisoned after stage separation, 2) the capsule, which contains the pressurized cargo, crew compartment, hatches, thrusters, propellant, parachutes and heat shield, and 3) the trunk, which contains unpressurized cargo and small deployable satellites. The trunk is jettisoned before reentry. Dragon has a total payload capacity of 6,000 kg to LEO with a capsule down-mass capability of 2,500 kg.

SpaceX has contracts to supply 12 cargo missions to ISS between 2010–2015, with a minimum of 20,000 kg delivered. SpaceX also has plans for a free-flying recoverable platform for microgravity research and technology demonstration, which will provide regular, frequent, commercial access to space. The first DragonLab flight is planned for 2011.

The ISS cargo accommodations support power, data, and thermal services inside and outside the pressurized section.

Dragon can also be used as a generic spacecraft bus with the following features:

- 15 m^3 pressurized volume for crew or pressurized cargo
- >2,000 W (>4,000 W peak) power for payloads
- Active thermal control for payloads
- Payload mass capacity up to >6,000 kg at 200 km, >2,400 kg at 600 km, or >1,000 kg at 2,000 km

Dragon performs most functions required as an on-orbit robotic servicing platform, including proximity sensing, relative & absolute navigation; guidance, navigation and control; 2-fault tolerance to catastrophic hazards; free drift mode; autonomous & remote control modes; and a recoverable capsule that can return instruments or tools and servicing hardware as well as crew members.

Dragon can accommodate 5–7 crewmember configurations for ISS crew transportation. Three-seat configurations with pressure suits and EVA equipment can also be accommodated. Dragon has no airlock, so EVAs would require consumables to replenish the cabin air. Servicing tools and instruments can be housed in the trunk, with a limited ability to return old equipment in the cabin since the trunk is not recoverable.

Dragon has the ability to interface with the Low Impact Docking System (LIDS) interface for an HST deorbit or servicing mission, and SpaceX has developed a straw-man plan for providing robotic servicing to HST.

Dallas Bienhoff, Manager, In-Space and Surface Systems, The Boeing Company. "Human Servicing Mission: Sun-Earth L2 Telescope."

Boeing is developing a Sun-Earth L2 (SEL2) Human Servicing Mission (HSM). The Boeing plan uses a crew of six (four EVA, one pilot, and one commander) with a mission duration of 42–94 days. The crew would launch in either the Boeing Crew Vehicle or the SpaceX Dragon and would use a Bigelow Sundancer habitation module. EVAs would be executed via an ISS or shuttle airlock using HST-type EVA tools.

SEL2 HSM manifests require 11–160 ton launch capability, depending on the whether a depot is used and whether an aerobrake return or direct entry return is utilized. Having a LEO propellant depot reduces the SEL2 HSM Heavy Launch Vehicle requirement from 70–160 tons to 25–60 tons.

Mike Gold, Director, D.C. Operations and Business Growth, Bigelow Aerospace, "Expanding the Final Frontier: Commercial Missions to the ISS and Beyond."

The purpose is to create and deploy expandable space habitats that expand after launch to their full volume. Bigelow says that the habitats offer better protection against micrometeor impact than standard aluminum structures.

The expandable space habitat has been validated on the Genesis 1 and 2 missions. Genesis 2 launched in June 2007 on a Russian nuclear missile. Due to the success of the Genesis 1 and 2 demonstration flights, subsequent test launches were cancelled.

Bigelow is now ready to launch Sundancer, which is their first human-rated habitat. A node bus and/or a second Sundancer could also be launched to provide a Full Standard Module. Bigelow is considering launching on either Atlas V or the SpaceX Dragon.

Additional future missions include concepts for launches beyond LEO, including L1, L2, or a Moon base.

Dr. Harley Thronson, Associate Director for Advanced Concepts in Astrophysics, NASA's Goddard Space Flight Center. "Human Servicing Operations Beyond LEO: 'Gateways' and Precursor Concepts."

Two concepts for human servicing beyond LEO have been assessed: 1) using elements of Constellation (or equivalent) with the goal of achieving the earliest, least-expensive human servicing missions beyond LEO, and 2) a Gateway human operations facility that would build on ISS experience to demonstrate the capabilities for long-duration human spaceflight and to manage/assemble/upgrade major on-orbit facilities.

Proposed capabilities offer opportunities for satellite servicing throughout the Earth-Moon system by creating a servicing "jobsite" at the Earth-Moon libration points. The concept of operation is to use a pair of Ares I/EELV vehicles to carry astronauts to Earth-Moon L1/L2 jobsites within 10 years. The Orion crew exploration vehicle would be launched by Ares 1/EELV to LEO. The servicing node, including the airlock, robot arm, and storage, and a Centaur Earth-to-L1/2 transfer vehicle would launch on a second Ares 1/EELV to rendezvous in LEO with Orion. The telescopes would then be serviced at the Earth-Moon L1/2 location.

The "Gateway" architecture goals including understanding how to live in space long-term, continue international cooperation, have human exploration on the lunar surface, prepare for long-term human voyages beyond the Earth-Moon system, and continue the on-orbit upgrade and maintenance of complex science facilities. The Gateway design uses an inflatable habitat launched by a heavy-lift vehicle to Earth-Moon L1/2.

Sam Scimemi, Deputy, International Space Station, NASA Headquarters within the Space Operations Mission Directorate. "International Space Station Assembly Lessons Learned."

ISS assembly has evolved over the years, requiring more complex external assembly and orders of magnitude more EVAs than originally planned. In addition, dependence on a single launch vehicle significantly set the program back.

From the top level, if another similar complex mission were undertaken, we should limit the number of assembly missions to less than 10 and require EVAs only when absolutely necessary by using more robotic and Intra-Vehicular Activy (IVA) assembly. For ISS, the investments in EVA over the years made EVA assembly tasks the preferred mode of operation, but the ISS required nearly 1,000 EVA hours. While most external maintenance tasks were designed to be robotically compatible, this has not been utilized. SPDM (aka Dextre) has been installed on-orbit for two years but still has not been used, although a demonstration is planned soon using ground controls.

Lessons learned from ISS assembly include:

- Human operations are very compatible with robotic operations, as demonstrated by many simultaneous EVA and robotic assembly operations.
- Robotic operations can be accomplished remotely without on-board crew intervention.
- Systems and component designs should be accessible and maintained on-orbit, even for systems that "do not require" servicing when originally conceived.
- System design should be paralleled by maintenance and servicing design activities.

Scott Christiansen, Engineering Director, Sierra Nevada Corporation—Space Systems. "SNC Advanced Manipulator Technology for Spacecraft Servicing."

SNC Space Systems Group is a merge of several small spacecraft technology companies, such as SpaceDev, Inc. and MicroSat Systems, Inc., which design, build and test the structures and systems that make things move, including motors, hinges, and latches. SNC provided several subsystems and design support for critical functions on Orbital Express, including the launch adapter fitting and capture system. Orbital Express showed successful robotic manipulator assisted and unassisted autonomous capture.

Manned and unmanned servicing applications include routine maintenance to replenish consumables and replace/upgrade components, remote servicing for unplanned problems, orbit adjustment, and spacecraft reconfiguration. Some tasks are considered beyond the capability of existing space manipulators; however, SNC's configurations have been developed to specifically address some of the current limitations.

Trajectory planning and control requires inverse kinematics to calculate the joint angles and motion to create the desired tool state. Typical manipulators are characterized by multiple copies of offset joints requiring extensive calculations and resulting in multiple answers. Multiple offsets make it difficult to vary operations quickly to handle contingencies. The SNC manipulator minimizes the offsets, resulting in inverse kinematics that are simpler with single solutions.

For general use, a 6 Degrees of Freedom (DOF) minimum is required for full tool control, while one or more additional DOF improves workspace coverage and ease of use. Typical manipulators use a 7th DOF to control the shoulder-elbow-wrist plane to help avoid collisions. SNC's manipulator includes an 8th DOF by utilizing 4 DOF in the shoulder-to-wrist and 4 DOF in the wrist-to-tool. The additional DOF in each group allows for robust avoidance of collisions, and it also allows the inverse calculations to be separated into two 4th order problems that are easier than a single 6th or 7th order problem.

SNC's wrist configuration is characterized by a short wrist-to-tool distance for better dynamic response and less arm movement to accommodate tool movement. The short wrist-to-tool distance, combined with the skew Roll-Pitch-Yaw-Roll (sRPYR) configuration, improves the angular range over conventional wrists. In addition, only one sRPYR singularity is possible, so that singularity is easily avoidable due to the redundant wrist DOF.

Traditional controls utilize two stick control inputs and rate control, which make it difficult to stop at a desired location and require speeds that must be limited for safety. In this case, motion is generally limited to one axis at a time. The SNC control configuration has 6 DOF in one hand controller for a more natural motion. In this case, one operator can operate two arms simultaneously, and speed does not need to be artificially limited.

For future capability, SNC is developing the Dream Chaser human spacecraft under NASA Commercial Crew Development (CCDev) funding. The deployment of the SNC dexterous manipulator on Dream Chaser could provide a capable commercial servicing capability using a highly maneuverable space vehicle, human presence for real time operation, and an operational system with a rapid response time. In this case, servicing could be accomplished by the crew during an EVA, during a robotically assisted EVA, or as a fully robotic task.

Question and Answer Session with all of the "Servicing with Humans" Session Speakers:

Question 1:
For Max Vozoff (SpaceX) and/or Dallas Bienhoff (Boeing): Can EVAs be conducted from vehicles by a non-returnable airlock in the trunk?

- SpaceX has looked at including an airlock or inflatable (for tourism, etc.) on the nose of Dragon
- Boeing says this is a viable option that could be used on the Genesis 1 or 2 architecture.

Question 2:
For John Grunsfeld (STScI): Have detailed analyses been conducted on the returned HST Servicing Mission 4 (SM4) hardware to determine the cause of the anomalies; i.e., was micro-welding an issue?

- Yes, all the returned parts have been studied carefully, including a study of the micrometeor hits on the WFPC2.
- It is believed that no micro-welding occurred because our parts are coated with Braycote. More likely, the issues were caused by installation differences in tools, thermal cycling while on orbit, and tolerance buildups.

Question 3:
For Max Vozoff (SpaceX): What is the capacity of Dragon for payload return to Earth?

- Dragon can return approximately 2,500 kg.

Question 4:
For Donald Hall (Institute for Astronomy, University of Hawaii): How can stability be obtained for an ISS-based telescope?

- Imaging for both visible and IR science can be controlled by active wavefront control.
- These active wavefront controls would be used on ISS as a test bed platform for future free-flying telescopes.
- Currently have some Japanese science active on ISS, so stability is being controlled.
- Bigelow says their science focus in microgravity is looking at a soft dock between the crew cabin and the cargo so it would be close to a free flyer.

Question 5:
For Sam Scimemi (NASA Headquarters): Why was there such a long delay between the launch of Dextre and its first use? What task will Dextre do?

- The initiation of Dextre operations was delayed because the hardware was ready to fly before the procedures were completed.

Question 6:
For Donald Hall (Institute for Astronomy, University of Hawaii): Can the Zero Signal/Noise detectors be ready to fly in 24 months? (Question posed by Frank Cepollina.)

- Twenty-four months is too soon for Zero S/N flight detectors because they need to complete more lab tests first. The lab results are continuing to improve.
- Once the detectors are shown to be reproducible in the lab, it will be easy to bring them up to a TRL 6 and beyond.

Question 7:
For Mike Gold (Bigelow): How can you connect habitats, and what vehicle would you use?

- The habitats could launch on Atlas V or a Dragon and would be connected on-orbit.
- The Sundancer could be connected to a Node Bus (BA 330) on-orbit, and these two components would give a habitable environment volume greater than the ISS.

Question 8:
For Mike Gold (Bigelow): How would Sundancer and the Node Bus be grappled and docked on-orbit?

- Sundancer docking has been designed to be independent; however, it will be tested on orbit and then manned prior to docking a Node Bus so that humans will be there to assist in the grapple and docking as needed.
- Bigelow does not use the LIDS system because it was deemed too heavy and too complicated for their system.

Question 9:
For John Grunsfeld (STScI): What percentage of the SM4 hardware installation could have been done solely by a robot?

- The SM4 mission was not designed for robotics; however, we did show great capability for that during the HST Robotic Servicing and Deorbit Mission (HRSDM).
- For SM4, WFPC2/WFC3 and COSTAR/COS could have been done robotically. The batteries would need to be installed externally and the gyros would need to be installed on WFC3 for robotic installation, as was the plan for HRSDM.

Question 10:
For John Grunsfeld (STScI): What difference would it have made to have two robotic arms instead of one?

- It would be more convenient and efficient to have two arms working together, especially to have the cooperation of a human and a high-precision robot working together.

Question 11:
For John Grunsfeld (STScI): What criteria should be used to decide between human and robotic servicing?
- Robots should be sent to places that a human cannot go, such as Jupiter (due to the radiation environment).
- For other places where humans could go, such as Saturn's moons, humans and robots should work in concert. He recommends growing from HST and undersea experience to build on robotic technology.

Question 12:
For John Grunsfeld (STScI): Should EVAs be minimized?
- He loves "magical" EVA time; however, it is very risky and not to be undertaken lightly. To that end, critical subsystems needing frequent servicing should be designed for access from inside the vehicle, so that they do not require repeated EVAs.
- EVAs should focus on tasks that cannot be done from inside a vehicle, such as exploring Mars, or for situations requiring quick "thinking on your feet."

Question 13:
For Sam Scimemi (NASA Headquarters): Does the ISS have any long-term lifetime worries?
- Structural analyses support a lifespan to 2028. The ISS was designed to be fully serviceable and replaceable—even the Solar Arrays or the Control Moment Gyroscopes.

Question 14:
For Max Vozoff (SpaceX): Can Dragon support a four-person crew? How many two-person EVAs could be accommodated?
- Dragon can support five- and seven-person crews, although seven crewmembers make the space extremely close and is only intended for limited-duration flights to the ISS.
- In addition, since Dragon has no air lock, EVAs would require venting the entire capsule and would require a way to store EVA suits and consumables.
- John Grunsfeld added that spacesuits are not currently available for many future EVAs, since only 11 suits exist, and most of them are on the ISS.
- The development of new spacesuits was stopped, and it would take a significant amount of time to restart design and production. Launch vehicles will likely be available to launch humans by mid-decade, however, spacesuits will not be available to support EVA activities.

Robotic Servicing Technology

Session Chair: Jill McGuire
Robotic Technology Manager, Space Servicing Capabilities Project, NASA's Goddard Space Flight Center

Keynote Speaker: **Dr. Glen Henshaw**, Roboticist, U.S. Naval Research Laboratory. "Orbital Robotic Servicing."

Dr. Henshaw highlighted the differences in servicing needs and priorities among commercial, government, and NASA spacecrafts. He noted that the basic technologies necessary for servicing already exist, and the task remains to develop systems that address viable business models. It is also necessary to gain "mind share" with decision makers and improve technologies in order to strengthen the case for robotic servicing.

Don McMonagle, Vice President of NASA Programs, Raytheon Missile Systems. "Raytheon SARCOS Robotic Systems: Technology for Application to Satellite On-Orbit Servicing."

Robotic dexterity and virtual presence are improving through the use of sensors, servos, actuators, cameras, and communications. Raytheon has several teleoperated robots: Dextrous Arm, GRLA, and TOPS (teleoperated hand), all of which utilize the master and slave relationship and have 10 to 22 degrees of freedom. Artificial intelligence research has produced robots capable of balancing, juggling, playing air hockey, and walking. In all of Raytheon SARCOS's robotic systems, a few technologies are key: servo valves, actuators, control and sensor networks, and MEMS sensor networks. Several dextrous hand models have been developed, including the UTAH/MIT Dextrous Hand (UMDH), which has 16 DOF. SARCOS employs a behavior-based design approach that defines desired objectives and employs quantitative performance criteria. Their control approach uses seven levels of control that are subdivided into three categories: variable control (command production, variable autonomic), intrinsic control (fixed autonomic, servo control, passive intrinsic properties), and power systems (actuation systems, energy storage systems). Raytheon SARCOS has developed force-reflecting teleoperated robots capable of performing a myriad of tasks in addition to producing humanoid systems with 43 DOF and a robotic exoskeleton. McMonagle concluded his presentation by saying that robotics technology enables operations in environments that are inhospitable to humans and where the tasks are either unknown or ill defined.

John Lymer, Chief Engineer, Robotics, MDA Corporation. "Robotic Solutions for On-Orbit Servicing."

MDA's previous work with robotics provides a foundation for the design and execution of future servicing missions. Eighty-six shuttle missions have employed robotic operations, and there have been 9 years of ISS robotic assembly and support operations. These operations have provided experience in operations planning and workarounds, man and machine coordination, robotic control from the ground (including signal delay and safety), robotic performance in zero-gravity, and supportable on-orbit robotic equipment. The capabilities for autonomous servicing of prepared clients were demonstrated in 2007 with the DARPA Orbital Express mission. MDA is also able to service clients designed to non-robotic standards, as demonstrated by GSFC and MDA's dexterous robotics work with the HST high-fidelity mockup in 2004–2005. During this work, tools were developed for non-traditional robotic tasks, and supervised autonomy accommodated up to 7 seconds of command path latency. This showed that robotic servicing can be applied to a client that is designed to any standard, and therefore planned robotic compatibility can be non-invasive to a client. The Dextre robot on the ISS would provide a perfect test bed for ground-controlled, dexterous servicing demonstrations. CSA funded development to advance Next Generation Missions, which will aid exploration missions beyond GEO and help optimize mass, cost, and operations. Lymer concluded his presentation by saying, "Robotic technologies are sufficiently mature for GEO satellite servicing." A cost-effective servicing mission could validate the operating principles and value of a serviceable space infrastructure. To that end, MDA is designing a servicer that can add 50 years of life to 9 to 11 existing GEO satellites through the resupply of propellants, by towing clients to graveyard orbit, or by adjusting orbit.

Brian Wilcox, Principal Investigator, NASA Jet Propulsion Laboratory. "Lessons Learned at JPL about Servicing."

The Telerobot Project was initiated and funded by Ron Larson, Mel Montemerlo, and Dave Lavery of NASA Headquarters from 1984 to 1992. It sought to develop and demonstrate needed technology for satellite servicing and attempted the integration of force-reflecting teleoperation with autonomous robotics, shared and traded control, predictive displays, and more. Wilcox notes that every task can arguably be decomposed into a sequence of operations that each reduce the number of DOF by one—mechanical primitives. Such operations generally require maintaining modest contact forces and torques in some number of dimensions while "sliding" in the remaining free dimensions until some termination condition is met. Wilcox concluded his presentation with several key elements of a workable satellite servicing system: the ability to associate objects in the worksite with their associated computer representation, and verification back to the operator that correct identification and localization has been achieved; the ability of a human operator to indicate key physical elements; the ability of a remote-site robot to manage forces and torques at a reasonable bandwidth and to execute "slide-until" commands to change the number of DOF of a worksite to accomplish assembly, disassembly, repair, or maintenance tasks. All of these abilities assume that the time-delay to a human operator is a few seconds.

Dr. Robert Ambrose, Chief, Software, Robotics and Simulation Division, NASA Johnson Space Center. "Dexterous Robotics and the Robonaut Series."

Robonaut 1 was developed from 1998 through 2006. Robonaut 2 has been in development from 2007 to the present. It was publicly released in February 2010 and is undergoing various forms of testing.

Daniel Rey, Head, Exploration Systems, Canadian Space Agency. "CSA Activities in On-Orbit Robotic Servicing."

CSA has delivered three state-of-the-art robotic systems for operational use in LEO: the Shuttle Canadarm, the ISS Canadarm 2, and the ISS Dextre. The Mobile Servicing System (MSS), completed in 2008, now has the following capabilities: assembly, inspection, payload handling, capture and berthing, cooperative servicing (EVA support), and robotic servicing through the changeout of Orbital Replacement Units (ORUs). The MSS is also self-serviceable on-orbit, with six types of robotically friendly ORUs. The accuracy and abilities of CSA's manipulators continue to improve, with Canadarm 2 and Dextre both having a sense of touch and being capable of automatic accommodation of forces and moments during contact tasks. Dextre and MSS are capable of performing several additional tasks that were envisioned for them in the 1980s, with some other tasks only needing an additional tool to complete. CSA has several studies regarding on-orbit robotic servicing, and finds that "On-Orbit Robotic Servicing is an enabling technology that can benefit from further TRL advancements and cost reductions." In the future, TriDAR can be used to guide rendezvous and docking operations, which are essential to on-orbit servicing missions. Dextre's operations will advance the knowledge of on-orbit robotic servicing, and several tools will help increase Dextre's capabilities. The Next Generation Canadarm is in development, and will further increase the functions of on-orbit robotic servicing. CSA sees a future of servicing other scientific satellites, such as JWST, SAFIR, MUST, ATLAST, and TPF. Some of the same technologies developed for on-orbit robotic servicing have been and will continue to be used for on-orbit servicing and exploration.

Dr. Dave Akin, Director, Space Systems Laboratory, University of Maryland. “Robotic and EVA/Robotic Servicing: Past Experience, Future Promise.”

The Space Systems Lab has a background in space robotics that includes structural assembly, formation flying, orbital maneuvering vehicle operations, walking robots, a crane-type positioning robot, and multiple cooperating robots. Current robotics projects include Autonomous Deep Submergence Manipulators, Free-Flying Inspection and Light Transport Robots, Lightweight Modular Self-Reconfiguring Robots, advanced dexterous robotics, and complex satellite servicing. Human systems projects regarding in-suit metabolic workload, the Maryland Advanced Research/ Simulation (MARS) Suit MX-2, ballasted partial gravity simulation, advanced life support systems, biomechanics instrumentation, and advanced spacesuit gloves are currently underway. Human/Robot Interaction Projects include morphing spacesuit components, EVA/ Robot cooperative space operations, an exoskeleton shoulder rehabilitation robot, power-assisted spacesuit components, and suit-integrated manipulators. The Space Systems Lab is working on several design activities, including advanced human/robot systems, transportation and landing systems, orbital habitats, robotic HST servicing, full-scale mockups for human testing, lunar and Mars rovers, and planetary surface habitats.

Bill Vincent, Aerospace Engineer, U.S. Naval Research Laboratory. “Front-End Robotic Enabling Near-term Demonstration (FREND) Technologies and Associated Servicing Architecture.”

FREND stands for Front-end Robotics Enabling Near-term Demonstration. The DARPA program helped to develop and demonstrate a flight robotic arm with associated end-effectors and algorithms that can perform autonomous, unaided grappling. FREND focuses on “space tow truck” operations at GEO (life extension, disposal, slot changes, etc.). Three key FREND technologies apply to on-orbit robotic servicing: *in situ* characterization, holding relative pose at close range, and autonomous robotic capture. No prior knowledge of the customer is required, and no standard targets or interfaces are required on the customer. Techniques to perform *in situ* characterization of customer satellites are necessary to generate a detailed approach and grapple plan. Techniques from FREND allow for actively holding a relative pose at ranges of less than 2 meters with objects tumbling up to 1 deg/sec about any axis. Robotic hardware and control algorithms were developed to autonomously grapple a variety of hard points. A fully autonomous grapple was a program requirement in the event that tumbling debris may prevent ground communications. Several algorithms were developed for autonomous capture, including a mission sequencer, grapple feature tracking, a trajectory planner, and compliance control.

Todd Colangelo, East Coast Operations Manager, Oceaneering Space Systems. “Oceaneering Robotics: Parallels to Satellite Servicing.”

Oceaneering International, Inc. is an industry leader in enabling humans to perform work safely and effectively in harsh environments ranging from the depths of the sea to the outer reaches of space. Oceaneering is very experienced in subsea teleoperation, as they have 248 Remotely Operated

Vehicles (ROV) in use, with an average of over 5,700 days of ROV operations every month. Oceaneering also has virtual simulation capabilities that they use to support training, uncover design issues and risks before operation, and overlay the work environment in real time to eliminate lag issues. They have also developed and flown tools for capturing and servicing satellites, and have been developing EVA tools since 1978, delivering and providing sustaining engineering for 3,659 EVA flight tools since 2005. With Oceaneering’s subsea operations, they have developed work packages for use with similar tasks or in similar work areas, as well as standardized tools and interfaces for robotic servicing. Oceaneering’s evolution of subsea robotic servicing was driven by cost and safety needs, and they are now able to work on a variety of packages and tasks at depths of up to 20,000 feet. They have created several work packages, which are predefined sets of tools packaged together for ease of operation on a set of like tasks. Their package tasks include fluid storage and injection; assembly; testing; power and communication; tool storage; and salvaging. Oceaneering’s subsea robotic tasks include inspections; removing and replacing electronics; assembling electrical, mechanical and fluid connections; valve operations, troubleshooting and monitoring; leak detection, sealing and fluid insertion; *in situ* testing and commissioning; jacket removal, jumper/ flow line cuts and installation; decommissioning and debris removal; and salvaging. Oceaneering’s subsea operations are similar to robotic on-orbit servicing in mission scenario planning, simulation software, training and human factors, situational awareness, and controls with time lag and human factors. With current satellites having been built before servicing standardization, a humanoid robot is the answer to servicing existing satellites now. Satellites on-orbit were originally built by humans, and human-like scale and dexterity allows the use of heritage EVA tools, which saves tool development costs. Oceaneering has several lessons learned from past servicing missions in sea and space: design tasks for single arm operations, minimize fasteners and complexity of mechanism actuations, provide clear visual and physical access, minimize motion requirements, provide alignment guides and targets, provide adequate visual cues, maintain loose tolerances between parts, limit or minimize forces required to operate mechanisms, provide status indicators for all activated functions, provide clear identification of objects and directional cues, and provide operational margins with redundant capabilities. Mr. Colangelo concluded his presentation with the statement that deep-water robotic servicing is a mature industry that has evolved continuously over the past 30 years, and that robotic servicing in space, an industry in the earliest stages, would benefit from leveraging the lessons of the deep water industry.

Kiel Davis, Vice President, Engineering, Honeybee Robotics Spacecraft Mechanisms Corporation. "Honeybee Robotics: An Overview of OOS Capabilities."

Honeybee Robotics are the developers of technology and products for robotic systems with sensors, manipulators, end-effectors, and tools, as well as spacecraft mechanisms capable of deployment, positioning, and attitude control. Both their robotic systems and spacecraft mechanisms employ automation components like motors, transmissions, slip rings, EVA/EVR compatible couplings, connectors, and fasteners. Honeybee Robotics is a privately owned small business equipped with a clean room, machine shop, and test facilities, employing over 30 engineers, scientists, and inventors. Honeybee's on-orbit servicing background lies in the robotic assembly of large truss structures and in helping with the development of the Flight Telerobotic Servicer. With NASA Goddard, Honeybee has developed the "Capaciflector" Sensor Array, HST Tool Box Gripper, and Conformal Gripper. Honeybee has also worked on technologies for the Orion Crew Exploration Vehicle, surface systems, and robots for *in situ* resource utilization, fabrication, and repair. Their 3-D Mini-LIDAR Vision Sensor allows close proximity hi-resolution and fast 3-D mapping. Honeybee has also developed robust connection mechanisms for electrical and fluid connections. These enable spacecraft berthing, docking, mooring, electrical and fluid power transfer, ORU transfer, and robotic tool quick-change. Honeybee is helping to develop Electron Beam Free-Form Fabrication, which can be used for *in situ* fabrication and repair. Mr. Davis also shared some additional technologies Honeybee is developing, including rapid structural assembly, attitude control and positioning mechanisms for small satellites, and a web-capture spacecraft docking system. Mr. Kiel concluded his presentation by reiterating Honeybee's development of technology and products for advanced robotic and spacecraft systems, its long history in on-orbit servicing, and its new technologies in development for servicing.

Doyle Towles, Systems and Advanced Technologies Manager, ATK Space Systems. "Improved Robotic Enablers for Satellite Servicing."

Doyle Towles of ATK Space Systems discussed the various technologies they are helping to develop to enable robotic satellite servicing. He noted that improved robotic tools provide the capability to perform unique and complex tasks. ATK has experience developing tools in conjunction with Goddard for manned missions such as the HST servicing missions and ISS crew operations. These tools allowed astronauts to perform complex tasks not originally designed for servicing. They have also worked on several robotic tools for the Hubble robotic servicing and deorbit mission and the ISS Detailed Text Objective (DTO) for refueling. ATK is developing tools for use in future robotic missions, including a spacecraft capture and docking mechanism; lubrication and harness management; thermal blanket repair or replacement; improved electronics box level replacement and card changeout; and small or stuck fastener removal, retention and replacement. They are working on smart end-effectors (designed for vision, proximity assessment, and tool interfaces), to more efficiently perform capture and servicing activities. Mr. Towles noted that autonomous rendezvous and capture requires advanced sensors and on-board processing, and stated that technologies exist to perform simple, non-manipulative servicing missions today. Near-term developments will facilitate the most challenging missions. ATK's kinematic and dynamic simulations provide testing and training capabilities to prepare for on-orbit conditions. Their thermal control of robotic servicing satellites provides improved environmental conditions for robotic systems, while their composite material technologies provide lightweight, smart structures. Mr. Towles concluded his presentation by saying that the foundations exist to develop applicable technologies for on-orbit robotic servicing, and previous technologies can be leveraged to help accomplish new tasks. In the near-term, ATK is working on a DTO for a refueling capability demonstration on ISS, and efforts are underway to develop specific enhancing technologies.

Professor Louis Whitcomb, Professor, Johns Hopkins University, "Enabling Technologies for Remote Robotic Manipulation with Time Delay."

The Laboratory for Computational Sensing and Robotics (LCSR) was founded by the School of Engineering in 2007 as the center for robotics research at the Johns Hopkins University. They use the basic principles of engineering science to further their research in design and control, sensing and interpretation, human-machine interaction, robotics in extreme environments, robotics in medicine, and bioengineering. Professor Whitcomb argues that telesurgery framework, such as that used with the da Vinci surgical system, could be leveraged for use in robotic servicing. He notes that virtual fixtures can be used as force and motion constraints, while allowing high-level human decision-making and low-level robotic accuracy and precision. He suggests creating a relationship between images and a 3-D model for satellite servicing, surveying a spacecraft with a camera and extracting features from the images, relating the features to the geometry of the spacecraft manually, and finally storing each relationship in a database. During actual operations, one would obtain an image from the spacecraft, extract features, match the features to the database, and use robust regression to estimate the pose of the spacecraft.

Physics-based simulations can accurately model robot dynamics and interactions with the environment, while high-level planning and motion planning can compute collision-free and dynamically feasible motions that enable the robot to accomplish a high-level task. Whitcomb concluded his presentation by using the Nereus Underwater Vehicle as an example of successful remote teleoperation in extreme environments and by summarizing the key enabling technologies discussed in the presentation.

Servicing Technology Session

Session Chair: Tupper Hyde

Associate Chief of the Mission Engineering and Systems Analysis Division, NASA's Goddard Space Flight Center

The Servicing Technology session included presentations on various technologies with applications in satellite servicing. Innovative propulsion, sensing, and autonomous rendezvous and capture systems were discussed, and many have already flown or are ready to be demonstrated in orbit. Presentations also discussed test beds for developing technologies, and several companies' experiences with aspects of satellite servicing that can be applied in future servicing missions.

Dr. David Chato, Aerospace Engineer, NASA Glenn Research Center. "In-Orbit Fluid Transfer for Satellite Servicing."

Dr. Chato discussed in-orbit propellant transfer as "game-changing" technology for satellite servicing. He noted that in-orbit transfer of hypergolic propellants has been demonstrated and is done routinely, and that with appropriate development, the in-orbit transfer of cryogenic propellants can be taken to the same level of technical maturity. He noted that an integrated large-scale prototype demonstration, such as Orbital Express with cryogens, is needed to bring risk within acceptable levels for a large-scale mission.

Therese Griebel, Space Flight Systems Manager, NASA Glenn Research Center. "Solar Electric Propulsion Application for Orbital Servicing."

Ms. Griebel discussed the benefits of solar electric propulsion for applications to NASA and on-orbit satellite servicing, and noted that it is a technology that could be a quick return and would benefit NASA, commercial, and DoD customers. With respect to propulsion and power systems, Ms. Griebel stated that there are several technologies that are at good TRL levels and could be applied to a demonstration that would be applicable to multiple mission needs. She discussed DARPA's Fast Access Spacecraft Testbed (FAST) and the NASA Evolutionary Xenon Thruster (NEXT) programs as examples of a power system and a propulsion system that could be used together as an electric propulsion stage that would quickly integrate emerging technologies into an operational spacecraft.

Joe Cassady, Director, Business Development—Emerging Space Systems, Aerojet. "Innovative In-Space Propulsion for Spacecraft Servicing."

Mr. Cassady discussed Aerojet's work with what they refer to as "high-efficiency in-space transportation": using solar electric propulsion on the Flexible Path. He adamantly declared that electric propulsion is ready, and discussed Aerojet's use of the technology on a large number of spacecraft and missions. He noted that such propulsion systems will cut the cost of logistics in half, and that the technologies need to do so are ready for demonstration. Mr. Cassady also discussed several areas that deserve investment to further advance innovative in-space propulsion.

Joseph Maly, Associate Principal Engineer, CSA Engineering, Inc./Moog. "ESPA as Base Vehicle for Servicing Missions."

Mr. Maly discussed CSA's EELV Secondary Payload Adapter (ESPA) ring and its applications as a structural building block for on-orbit servicing missions. ESPA is a secondary payload adapter that can facilitate numerous mission configurations, and is a natural base vehicle for servicing missions. He explained several of ESPA's past and potential applications, and concluded by noting that the ESPA is a robust adapter structure with a flight-proven heritage.

Warren Frick, Program Manager, Orbital Science Corporation. "Satellite Servicing Using the Cygnus Advanced Maneuvering Vehicle."

Mr. Frick discussed the Cygnus vehicle and how it can be used for satellite servicing. Cygnus is Orbital Science's modular vehicle that they are designing to service the space station. Cygnus is being built right now and has the fault tolerance needed to mate with the Space Station and be the reentry vehicle. It has been through its Phase II safety board, and while it has not yet reached maturity, it will have flight experience in 2011. Mr. Frick concluded his presentation by saying that the Cygnus is versatile and can utilize technologies such as the FREND and Robonaut systems for satellite servicing.

Dr. Javier De Luis, Vice President of R&D, Aurora Flight Sciences
Ms. Swati Mohan, Graduate Research Assistant, Massachusetts Institute of Technology. "SPHERES as a Servicing Testbed."

Dr. Javier De Luis and Dr. Swati Mohan discussed SPHERES as a science test bed for measuring and controlling physical phenomena whose behavior fundamentally changes when in microgravity. SPHERES creates a testing facility that is reconfigurable, risk tolerant, and allows the testing of low TRL technologies—in particular, guidance, navigation, and control algorithms—under microgravity conditions. SPHERES can advance satellite servicing technology in two ways: through algorithm development and through its expansion port, which allows the testing of satellite payloads. SPHERES helps test capabilities such as autonomous rendezvous and docking with a tumbling target and other technologies applicable to satellite servicing, with relatively low cost and a fast turnaround time.

Ian T. Mitchell, Division Staff, Charles Stark Draper Laboratory. "Autonomous Rendezvous and Proximity Operations."

Mr. Mitchell described Draper Laboratory's experience with autonomous rendezvous and capture operations, stating that many satellite servicing and exploration missions rely on autonomous rendezvous as a critical capability. Draper Laboratory is building on past technologies and making advances in areas such as propulsion, advanced sensors, and increased on-board automation and auto nomy. Mr. Mitchell noted that systems engineering is key in the development of such rendezvous and capture systems, and Draper Lab's expertise in that area could be helpful to many programs.

Kevin Miller, Ball Aerospace and Technologies Corporation. "Advanced Imaging and Relative Navigation Technology for Satellite Servicing."

Mr. Miller discussed Ball's work with advanced imaging and relative navigation technologies as they apply to human and robotic servicing. He asserted that the critical technologies for satellite servicing are mature at the component level, and suggested that future systems in need of technology maturation would be well served by several demonstration missions. Such missions included an ISS capability verification flight, a robotic servicing demonstration, teleoperated support demonstrations, and flight testing with non-cooperative targets.

Tom Gardner, Senior Principal Systems Engineer, NASA/Space Applications Group, Raytheon. "GN&C and Sensors for Rendezvous and Capture; Missile Systems Technology Applied to the On-Orbit Servicing Challenge."

Mr. Gardner described Raytheon's work with Guidance, Navigation and Control (GN&C) and sensors for rendezvous and capture, and how such technologies developed by a missile company through funding by the military and the DoD could be used for satellite servicing. Raytheon has developed several technologies for use with autonomous rendezvous and destruction of missiles, and such technologies could be easily adjusted to allow for docking instead. Mr. Gardner concluded his presentation by noting that there are a lot of technologies, especially in the areas of sensing and data fusion, that the DoD has spent a lot of money developing, and that many of those technologies are available and can be used for other applications.

Dr. Roger Stettner, President, Advanced Scientific Concepts, Inc. "3D Flash LIDAR Cameras for OOS Applications."

Dr. Stettner discussed the work that his company, ASC, is doing with 3-D flash LIDAR, and how it can be used for servicing. ASC's DragonEye, which flew on STS-127, showed that their systems work for rendezvous and docking. 3-D flash LIDAR can also be used for navigation, detection, and inspection, as it is essentially a 3-dimensional video camera that generates precise distances and dimensions. ASC is continuously developing more advanced and smaller versions of their systems, and can often design systems much more cost-effectively and quickly than aerospace companies, as they are a small company themselves. ASC has several new developments that only need a customer and funding to progress.

Stéphane Ruel, Project Manager, Neptec. "TriDAR Model Based Tracking Vision System for On-Orbit Servicing."

Mr. Ruel described TriDAR, a model-based tracking 3-D vision system, and its numerous applications in space for determining the position and orientation of an object. TriDAR can be used for rendezvous and docking, robotic manipulation, navigation, or landing. It is very helpful in that it can identify unknown targets based on their geometry. TriDAR's flexibility allows adaptability, and can help deal with unexpected situations that might arise on a servicing mission. TriDAR was demonstrated on STS-128 and met great success.

Appendix D – Functional Decomposition of the Activities Required for Satellite Servicing

The term "on-orbit servicing" invokes a multitude of definitions depending on the customer, the provider and the application. To give structure and definition to what it means to perform on-orbit servicing, this appendix presents a systems-level decomposition of the functions and activities performed during satellite servicing operations. The result is a high-level framework of generalized functional elements. It provides a common starting point for customers to begin formulating mission-specific servicing operations and requirements, and to identify technology development needs.

SERVICING MISSION LIFE CYCLE

A servicing mission operational life cycle is established to identify the activities executed during the course of a servicing mission. Figure D.1 outlines the mission-level functions performed in a notional servicing mission. The numbers in the titles identify the sections in this appendix that provide additional details.

These mission-level activities are broken down into greater detail to identify the working elements that are required to complete the function. The end result is a listing of guidelines, pre-mission considerations, and the basic activities that make up the servicing mission.

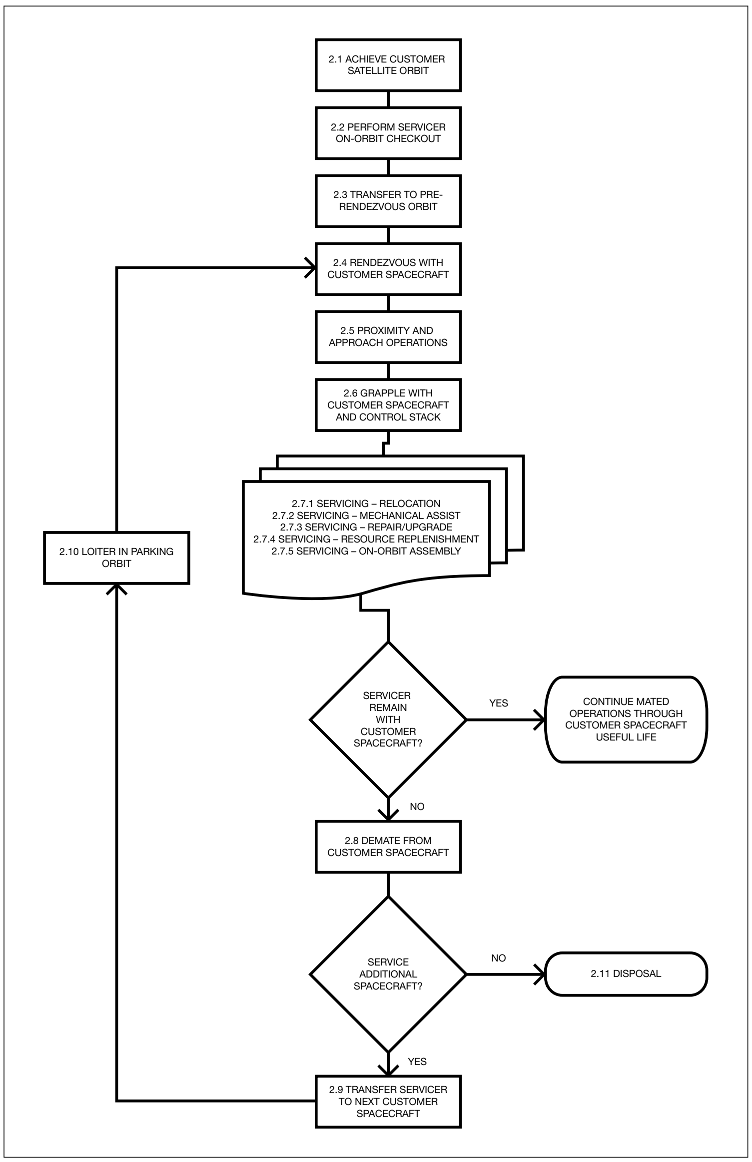


Figure D.1: Mission-level functions for a notional servicing mission

HOW TO USE THIS INFORMATION

The decomposition presented here provides the starting point for defining mission-specific requirements. Identifying the elements of a servicing mission is intended to lead to follow-on studies of enabling technology needs and mission-specific requirements development. The flowchart in Figure D.2 illustrates this example.

The activities are system-architecture independent to allow general use in any customer system. Because the definitions are architecture independent, the functions described do not distinguish between human or robotic servicing, as the functions

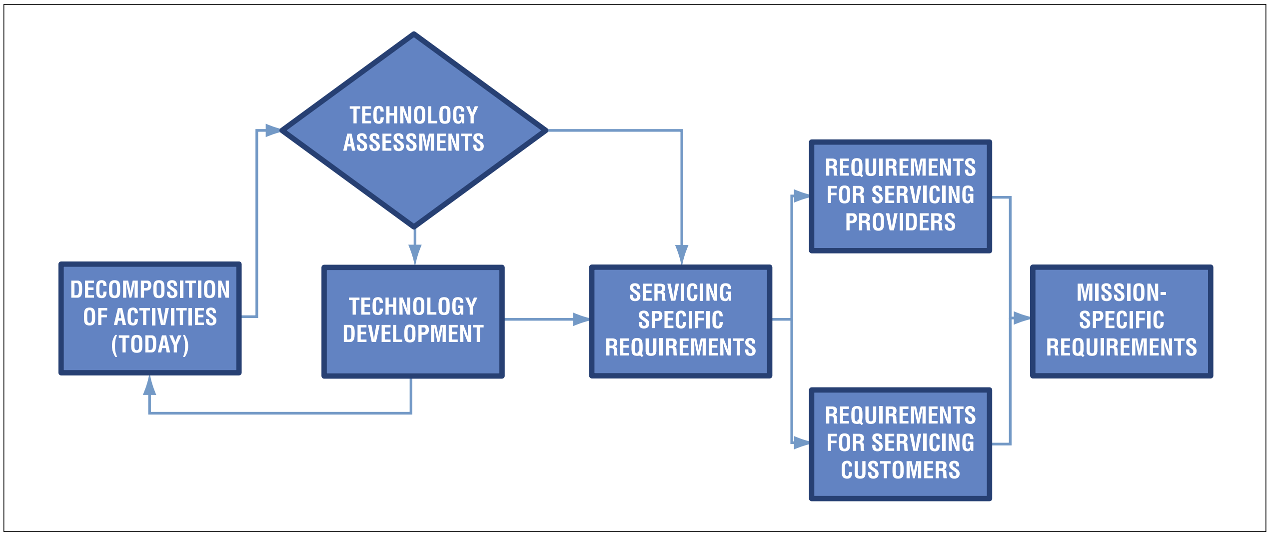


Figure D.2: Flowchart of a notional servicing mission development cycle

defined need to be accomplished regardless of the presence of humans in space. Decomposing the functional elements of on-orbit servicing in this way provides a suitable means of evaluating possible system architectures, including human space flight elements, against the functions those systems will need to provide.

Technology assessments are a means of evaluating the functions of satellite servicing and determining the readiness level of technology to accomplish those functions. Given the wide range of functions defined under satellite servicing, it is expected that the level of technology readiness will vary. This functional decomposition provides guidance on where resources should be expended in order to perform the more complex functions of satellite servicing. The need for experimentation, study and technology development will tie to these assessments and aid the justification and business case for making those investments. Alternatively, technology assessments can be used to revise servicing requirements for specific missions to match technology readiness.

Requirements definition follows technology assessment and development. Servicing-specific performance requirements can be derived from the functional decomposition using the identified technologies to perform the servicing operations. The resulting requirements will naturally be different for providers of servicing functions and their customers.

FUNCTIONAL DECOMPOSITION OF SATELLITE SERVICING OPERATIONS

1. PRE-MISSION CONSIDERATIONS

This section is for generic pre-mission considerations that affect the functions performed during the interactions between servicer and customer spacecraft.

1.1 SERVICER SPACECRAFT BUS (REQUIRED)

All servicing spacecraft will require a vehicle–the bus–to provide a support system to the servicing payloads that will be used to perform servicing on the customer spacecraft. The main function of the servicer spacecraft vehicle is to provide electrical power, commanding, data downlink, thermal control, and structural support for these servicing payloads.

1.1.1 Orbit

On-orbit servicing will be performed in the customer spacecraft orbit and all systems will need to be designed to function in this environment. Orbit classifications include:

- Low-Earth Orbit (LEO)
- Highly Elliptical Orbit (HEO)
- Geosynchronous Earth Orbit (GEO)
- Libration Point Orbits (Earth-Moon and Sun-Earth)

1.1.2 Mission ΔV Requirements

The bus propulsion system (type and size) will depend on the specific mission ΔV requirements.

1.1.3 Customer Spacecraft ORU and Replenishables Mass

Depending on the servicing mission, the bus may need to accommodate Orbit Replacement Units or replenishables (also known as consumables).

1.2 MISSION OPERATIONS

A mission operations plan is developed based on the servicing functions to be performed and may include the following:

- Communications
- Command Plan
- Timeline
- Sun-angle or shadowing constraints due to thermal and/or electrical power limits
- Safeing
- Servicer disposal at End-of-Life

1.3 MAINTAINING CUSTOMER AND SERVICER SPACECRAFT CONSTRAINTS

On-orbit servicing activities will need to take into account the operational constraints of both the servicer and customer spacecraft. Impacts and risks to violating the constraints of either spacecraft will need to be known prior to performing servicing operations. A preferred way of assessing and documenting these impacts and risks is through a mission impact analysis that is approved as part of a mission operations plan agreed upon by both the provider and customer of the servicing activity. The subsections below are some of the identified impact areas where system constraints shall be observed.

1.3.1 Cause no degradation to both servicer and customer vehicle—e.g., hardware damage to solar arrays, radiator panels, other external spacecraft appendages.

1.3.2 Maintain power positive mode—customer vehicle attitude, servicer shadowing, customer vehicle op power configuration.

1.3.3 Maintain spacecraft components within operate and/or survival temperature limits—allowable spacecraft attitudes or maneuver/task duration times defined based on transient analyses.

1.3.4 Maintain mechanical integrity of customer vehicle/servicer vehicle interface—limit servicer applied forces/torques on the customer vehicle to ensure the integrity of the interface.

1.3.5 Maintain contamination level requirement—define required servicer plume direction to maintain the contamination requirements of the customer vehicle.

1.3.6 Provide means to mitigate the effects of voltage differentials between customer vehicle and servicer.

1.3.7 Operations performed by the servicing spacecraft shall respect the customer spacecraft keep out zones and envelopes (planned and negotiated with customer).

1.4 PLANNING FOR AUTONOMY

Some functions of on-orbit servicing can or will be performed autonomously using systems on board the servicer spacecraft. Autonomous operations will require additional planning and resources in order to execute servicing activities in a safe, precise, and intended manner. The functions performed autonomously will need special verification applied prior to execution, and the verification levels may change depending on the hazards presented by the system architecture, the operation, and the environment. The subsections below are some of the identified activities and actions that will be impacted by performing autonomous operations.

1.4.1 Autonomous operations require a GN&C command interface to autonomy control systems in order to provide authority and control over the spacecraft.

1.4.2 If autonomous operations are to be performed, systems will need to be capable of switching between operating modes from ground commands.

1.4.3 Autonomous tasks can be accomplished by ground-provided task lists of appropriate commands to the current operating mode. Ground authority-to-proceed (ATP) commanding can be built into these lists as checkpoints.

1.4.4 If ground-provided task lists are executed as part of autonomous operations, then systems will need the functionality to switch between task lists in order to modify the operational steps and/or sequence.

1.4.5 Autonomous operations will require the monitoring of performance and status to detect unsafe conditions and initiate pre-defined abort sequences. Some examples of items that would be monitored and responded to are: 1) sensor/end-effector health, 2) relative position and collision avoidance sensors/systems, 3) activation of spacecraft safe mode triggers, and 4) battery depth of discharge.

1.4.6 If autonomous operations are to be performed, systems will need to be capable of suspending operations if commanded to by the ground or other external source.

1.4.7 If autonomous operations are to be performed, systems will need to be capable of aborting operations if commanded by the ground or other external source, i.e., an override needs to be provided.

1.4.8 If autonomous operations are to be performed, the servicer spacecraft systems need to be capable of executing GN&C abort sequences based on current spacecraft state in response to automated or ground commanded abort commands.

2. PERFORM ON-ORBIT SERVICING

This section identifies the activities that together encompass the execution of an on-orbit servicing mission. The activities are described at a system-level and in some cases broken down to additional details and options that are encountered when planning for servicing.

2.1 ACHIEVE CUSTOMER SATELLITE ORBIT

The first step a servicing spacecraft must complete is to achieve the necessary orbit plane to position itself to interact with the customer spacecraft. The first orbital configuration will need to support setup, checkout, and commissioning of the servicing spacecraft before any servicing operations begin.

2.1.1 The initial orbital location of the servicer spacecraft shall be part of a mission-specific plan with planned inclination, ascension, eccentricity and semi-major axis.

2.2 PERFORM SERVICER ON-ORBIT CHECKOUT

A pre-determined checkout procedure for all systems involved in the servicing operations shall be performed prior to performing rendezvous with the customer spacecraft. Given the criticality of operations involved in on-orbit servicing (i.e. close proximity operations, fuel transfer, etc), confirmation of the functionality of these systems is required prior to interaction with customer spacecraft.

2.2.1 Servicing payloads such as robotic systems that rely on telemetry and control need to be verified to have positive telemetry and control using all planned operational interfaces prior to commencing servicing operations.

2.2.2 Autonomous rendezvous and capture (AR&C) payloads included on a servicer spacecraft should be confirmed operational via checkout with a resident space object (RSO) prior to commencing servicing operations.

2.2.3 Payloads included on a servicer spacecraft should be verified to be within calibration prior to first operational use during servicing operations.

2.2.4 A servicer spacecraft should be equipped with systems capable of providing a visual inspection of the servicer spacecraft payloads associated with on-orbit servicing. This is to verify status and condition of the payloads prior to interaction with the customer spacecraft. This visual inspection can include robotic systems, autonomous rendezvous and capture sensors, telecommunication systems, and power systems.

2.3 TRANSFER TO PRE-RENDEZVOUS ORBIT WITH FIRST CUSTOMER VEHICLE

After checkout, the servicer spacecraft performs orbital transitions to position itself to rendezvous with the customer spacecraft. This maneuver is designed to position servicer spacecraft within close proximity to customer spacecraft to begin the rendezvous phase. Pre-mission analysis shall be performed to confirm the design servicer spacecraft trajectory is free of orbital debris and satellites.

2.4 RENDEZVOUS WITH CUSTOMER SPACECRAFT

Rendezvous is the series of activities that are performed in order to 1) acquire and track (via sensors) the customer spacecraft to be serviced, and 2) close the relative distance between the servicer and customer spacecraft. Rendezvous occurs at relative positions approximately between 1 km and 300 km apart. The goal of rendezvous operations is to approach the customer spacecraft as quickly, as efficiently, and as safely as possible in order to prepare for proximity operations. The following provide additional details on the activities that occur during rendezvous operations.

2.4.1 The customer spacecraft will be located (acquired) via long-range sensors (far-field acquisition). This applies to Earth orbiting servicing missions (Libration Point Orbit servicing missions are excluded).

2.4.2 Following acquisition, the servicer spacecraft closes its relative position with customer spacecraft through a series of orbital translational maneuvers. These maneuvers can be performed autonomously provided the autonomous operational constraints are maintained. The servicer spacecraft shall maintain sensor pointing at the customer spacecraft to provide current knowledge of relative position and closer rates. AR&C payloads should be capable of confirming no other resident space objects are in the vicinity of the two spacecraft and that conditions are ready for proximity operations.

2.5 PROXIMITY AND APPROACH OPERATIONS

Proximity and Approach Operations are the series of activities that are performed in order to 1) perform inspection of customer spacecraft to confirm systems are ready for grappling, and 2) transition from coarse to fine relative translational maneuvers up to and including maintaining relative position and attitude. Proximity and approach and operations occur at relative positions approximately between 1 km and 30 m apart. The goal of proximity and approach operations is to close the relative position between the two spacecraft as safely as possible given the increased risk of collision while performing final checks to prepare for grappling and mating. The following provide additional details on the activities that occur during proximity and approach operations.

2.5.1 A primary function of the proximity and approach operation activity is to inspect the customer spacecraft, determine its readiness for servicing, and confirm the servicer spacecraft approach is proceeding as planned.

2.5.2 The systems of the servicer spacecraft shall be capable of controlling relative position with respect to customer spacecraft. This means controlling relative attitude, position and rates. The servicer spacecraft will require fine maneuvering capability to accomplish these functions.

2.5.3 The systems of the servicer spacecraft shall be capable of maintaining communication links with all appropriate communication partners including servicer to ground, customer spacecraft to ground, and (if commanding of the customer spacecraft is performed by the servicer spacecraft) servicer spacecraft to customer spacecraft.

2.5.4 It is during the proximity and approach operations phase that the servicing spacecraft should be configured for servicing. This includes solar array positioning, robotic reconfiguration, etc.

2.6 GRAPPLE WITH CUSTOMER SATELLITE AND CONTROL STACK

Grappling and the subsequent activities that are performed while grappled (other than servicing) are the key activities performed in this mission phase. The term "grappling" refers to the mating or joining of the two spacecraft and can result from using planned or unplanned connection points. A passive grapple fixture on a customer spacecraft being grasped by an active grapple mechanism on a servicing spacecraft is an example of a planned connection point.

Two spacecraft can be considered grappled when the connection between the two is sufficient to meet the requirements of the operations performed while connected. This often means grappling will need to be performed in two phases—the first phase, where a non-permanent connection is made to stabilize or hold the two spacecraft relative to one another, and a second phase where the connection between the two spacecraft is rigidized or otherwise reinforced in order to complete the grappling maneuver.

Activities that are performed while the two spacecraft are grappled, other than servicing operations, include attitude control, communications relay, and inspection. These functions, combined with the servicing functions, are referred to as mated operations.

2.6.1 Before grappling can be attempted, the configuration and interactions of the servicer and customer spacecraft must be in known conditions that are favorable for grappling. These conditions include the health of both spacecraft, attitude and relative positions, and the configuration of mating interfaces.

2.6.2 The status of the grappling connection should be known during grappling. Mated operations including verification of mechanical locks and electrical connections as well as interface forces at the connection interfaces. Maintaining an allowable interface force at the connection interface below a pre-defined maximum is a servicing mission constraint.

2.6.3 During mated operations while grappled, one spacecraft (typically the servicer spacecraft) shall perform attitude determination and control for the combined stacked spacecraft. Constraints for each spacecraft and their combined interfaces shall be maintained during mated operations.

2.7 PERFORM SERVICING (MATED OPERATIONS)

Servicing Operations are the activities that occur between the grappling/mating operations and the eventual separation and/or disposal of the spacecraft. It represents the purpose of the servicing mission and is tied to the functional objectives of the mission. These functional objectives are outlined in the following sections.

2.7.1 Relocation of Customer Satellite

The function of performing customer satellite relocation involves the spatial repositioning of the customer satellite to a predetermined position. Relocation servicing functions include (but are not limited to) the following.

- Correcting orbital insertion errors.
- Raising satellite orbit to correct for orbit decay.
- Super-synchronizing spacecraft as to not interfere with other current or future spacecraft on the same orbital plane or trajectory.

2.7.2 Mechanical Assist

The function of performing mechanical assistance of a customer satellite involves providing an external (to the customer spacecraft) source of supporting or promoting the completion of a mechanical reconfiguration of the spacecraft as it was originally designed. Mechanical assist servicing functions include (but are not limited to) the following.

- Physical manipulation of jammed spacecraft mechanisms (solar arrays, booms, antennae) such that they complete their original deployment.
- Physical manipulation of failed mechanisms such that their original function is achieved. Example: opening a aperture door with a failed mechanism.

2.7.3 Repair/Upgrade

The function of performing repair or the upgrade of a customer satellite involves returning original systems or components to service that are malfunctioning, as a pre-emptive operation for anticipated future malfunctions, or to upgrade systems, instruments, or components to take advantage of new technology. Repair/upgrade servicing functions include (but are not limited to) the following.

- Replacement of modular components or systems in order to restore the original functionality of or to upgrade the spacecraft.
- Disassembly and reassembly of a spacecraft component or system in order to correct a defect or malfunction in the system.

2.7.4 Resource Replenishment

The function of resource replenishment involves returning capacity to or providing capacity to a customer spacecraft system. Resource replenishment servicing functions include (but are not limited to) the following.

- Refueling the spacecraft propulsion system.
- Augmenting a depleted propulsion system by performing orbital adjustments while mated.
- Returning thermal control systems to original state by cleaning thermal control surfaces, adding insulation, or replenishing cryogenic fluids.
- Increasing functionality of current systems through added capacity.

Resource replenishment does not involve returning inoperable original systems or components to service (repair), but rather increasing the useful life at the subsystem or system level. Resource replenishment does not involve replacement of components or systems.

2.7.5 ON-ORBIT ASSEMBLY

The function of on-orbit assembly involves performing construction services to create a new on-orbit entity. On-orbit assembly servicing functions include (but are not limited to) the following.

- Construction of an on-orbit telescope, which can vary in complexity from relatively simple assembly of a few modules launched in an essentially complete state to complex assembly and outfitting of hardware launched at the component and subassembly level.
- Delivery of components or systems to a on-orbit assembly operation (e.g., ISS construction).
- Adding an instrument to an existing spacecraft.

2.8 DEMATE FROM CUSTOMER SPACECRAFT

The demating function of a servicing mission is essentially the inverse of the grappling function in that the connecting interfaces between the servicer and customer spacecraft are terminated. This may occur in two phases—the relaxation of the rigidized connection followed by the release of the temporary connection. All servicer and customer spacecraft constraints shall be maintained and the final state of the customer spacecraft—attitude, rate determination, physical configuration—shall be confirmed to be within mission guidelines.

2.9 TRANSFER SERVICER TO NEXT CUSTOMER SPACECRAFT

One possible option following the demating from a customer spacecraft is for the servicer spacecraft to make preparations to perform servicing on a second customer spacecraft. This would be common for a servicer vehicle performing servicing on a constellation of customer satellites that require the same or similar servicing functions. This function results in returning to the starting state of the mission sequence with the servicer spacecraft having translated to a pre-rendezvous orbital position for the new customer. From there the mission functions are repeated. This cycle can continue for as many cycles as the servicer spacecraft is designed to complete.

In addition, this mission function could also include a translational maneuver to a servicing depot that would allow for the replenishment of the servicer spacecraft systems or consumables that would be used to perform servicing on the next customer spacecraft. For example, a servicer spacecraft could visit a refueling depot between servicing customer spacecraft in order to replenish its own propulsion system as well as to recharge its refueling system.

2.10 LOITER IN PARKING ORBIT

Another possible option following the demating from a customer spacecraft is for the servicer spacecraft to make preparations to loiter in a temporary parking orbit while waiting for additional servicing opportunities. This would be common for a servicer vehicle performing servicing on multiple customer satellites, but the availability of the subsequent customer spacecraft requires a delay. This is similar to the transfer servicer function above, but loitering operations imply additional considerations. The servicer spacecraft is stored on-orbit until its next usage, and servicer systems need to be designed for this inactivity, the length of which may or may not be known. Loitering may also require an increase in the life of the spacecraft systems.

2.11 DISPOSE OF SERVICER AT THE END OF LIFE

At the end of its useful life, the servicer spacecraft will need to be dispositioned in accordance with NASA NPR 8715.6. The servicer spacecraft can be said to have completed its usable life if any of the following occur.

- Servicing activities/mission is complete.
- Failure of servicer spacecraft system, preventing future servicing activities.
- Failure of customer spacecraft, preventing future servicing activities.
- Failure of mating mechanism to disconnect the servicer and customer spacecraft, resulting in non-operational assets.

2.11.1 The servicer spacecraft will need to maintain minimum spacecraft resources in order to perform spacecraft end-of-life dispositioning.

2.11.2 The servicer spacecraft will need to be capable of performing spacecraft end-of-life dispositioning while mated to the customer spacecraft.

2.11.3 The servicer spacecraft will need to be configured safe for disposal per NASA NPR 8715.6.

3. PREPARING THE CUSTOMER SPACECRAFT FOR ON-ORBIT SERVICING

This section is for design and configuration considerations that customer spacecraft should consider implementing in order to prepare for the activities performed in the servicing mission phases.

3.1 DESIGN CUSTOMER SPACECRAFT TO BE SERVICING FRIENDLY

The sections below outline suggested design elements that customer spacecraft can implement in order to facilitate on-orbit servicing.

3.1.1 Provide capture aids.

Capture aids are features that by function or presence assist in the grappling operations. An example of a capture aid is a grapple fixture mounted on the customer spacecraft.

3.1.2 Provide navigation aids.

Navigation aids are features that by function or presence assist in the relative navigation between the servicer and customer spacecraft during rendezvous, proximity and approach, and grappling operations. An example of a navigation aid is a retroreflector mounted on the customer spacecraft.

3.1.3 Provide inter-vehicle communications for separated ops.

Inter-vehicle communications refers to protocols that can transmit status and commanding between the servicer and customer spacecraft for the purpose of assisting servicing operations. For transmissions that occur during mission phases other than mated operations, this protocol would be wireless communication. An example of this type of communication would be the transmission of ranging information from the customer spacecraft to an approaching servicing spacecraft during proximity operations.

3.1.4 Provide inter-vehicle communications for mated ops.

Inter-vehicle communications refers to protocols that can transmit status and commanding between the servicer and customer spacecraft for the purpose of assisting servicing operations. For transmissions that occur during mated operations, this protocol can be hardwired or wireless communication. An example of this type of communication would be commanding information that passes through an electrical grappling interface from the servicer spacecraft to the customer spacecraft.

3.1.5 Provide inter-vehicle power for mated ops.

Inter-vehicle power refers to the transmission of or receipt of electrical power between the spacecraft during mated operations.

3.1.6 Provide servicing-friendly mechanical interfaces.

Servicing friendly mechanical interfaces refers to the mechanical connection points that the servicer spacecraft uses to manipulate on the customer spacecraft to assist in servicing operations. This includes robot-friendly refueling valves, standard size fasteners, and standardized robotic end-effector interfaces.

3.1.7 Provide servicing-friendly spacecraft configuration.

Servicing friendly spacecraft configuration refers to status of the customer spacecraft systems that can be reconfigured to assist in servicing operations. This includes deployable systems, attitude control system modes, and protective systems. An example of this would be slewing the customer spacecraft solar array in an orientation that allows greater access for the servicer spacecraft.

3.1.8 Design customer spacecraft for stacked operations.

Designing a customer spacecraft for stacked operations refers to the design of the spacecraft systems to support or accommodate the servicer spacecraft. Such systems include mechanical systems (structural), power systems, and thermal control systems.

3.2 CONFIGURE CUSTOMER SPACECRAFT OPERATIONALLY

This section outlines the functions that a customer spacecraft can perform during the mission sequence in order to assist in its being serviced.

3.2.1 Maneuver to capture attitude.

The customer spacecraft can work in conjunction with the servicer spacecraft for an efficient rendezvous and grapple by maneuvering to a pre-determined attitude.

3.2.2 Configure systems for rendezvous and servicing.
The customer spacecraft can assist with servicing mission operations by configuring its systems to accommodate the operation. Suggested systems for configuration to aid in servicing operations include:

- Power System
- Optics and Instruments
- Propulsion System
- Guidance Navigation and Control

3.3 MISSION CONSTRAINTS

The following constraints are recommended for the interactions between customer spacecraft and servicer spacecraft in order to promote successful servicing operations.

3.3.1 Customer spacecraft functionality should be maintained during rendezvous, proximity and approach, and grappling operations.

3.3.2 The customer spacecraft should maintain minimum propulsion for disengagement maneuvers to re-attempt grappling.

3.3.3 The servicer spacecraft shall not plume customer vehicle such that its solar cells/power system are degraded.

3.3.4 The servicer spacecraft shall maintain customer vehicle thermal control capabilities (minimize pluming of mirrors, etc).

3.3.5 Servicing loads imparted to customer spacecraft by the servicer spacecraft during mated operations shall not exceed structural limits of either vehicle.

3.3.6 The customer spacecraft should have primary and backup grappling points.

ACTIVITY LIST

This activity list complements foregoing functional decomposition of servicing activities by illustrating their hierarchical relationships. The table below is a list of activities created by the study team to describe the possible actions that may be performed during the servicing mission functions.

Activity List				
1	Pre-Mission Considerations			
	1.1	Servicer Spacecraft Bus		
		1.1.1	Orbit	
			1.1.1.1	Low Earth Orbit
			1.1.1.2	Highly Elliptical Orbit
			1.1.1.3	Geosynchronous Orbit
			1.1.1.4	Libration Point Orbits
		1.1.2	Mission ∆V Requirements	
		1.1.3	Customer Spacecraft ORU and Replenishables Mass	
	1.2	Mission Operations		
	1.3	Maintaining Customer and Servicer Spacecraft Constraints		
		1.3.1	Cause no degradation (e.g., pluming appendages)	
		1.3.2	Maintain power-positive mode	
		1.3.3	Maintain temperature limits	
		1.3.4	Maintain mechanical integrity of interfaces	
		1.3.5	Maintain contamination requirements	
		1.3.6	Provide means to mitigate customer-servicer voltage differentials	
		1.3.7	Conform to customer spacecraft kept-out zones and envelopes	
	1.4	Planning for Autonomous Activities		
		1.4.1	Provide GN&C command interface to autonomy control systems	
		1.4.2	Provide capability to switch operating modes via ground commands	
		1.4.3	Provide capability for scripted autonomy with ground authority-to-proceed gates	
		1.4.4	Provide capability to switch between task lists via ground commands	
		1.4.5	Provide capability to autonomously monitor performance and status and respond with appropriate, pre-defined abort sequences	
		1.4.6	Provide suspend mode capability that responds to external commands and flags	
		1.4.7	Provide abort mode capability that responds to external commands and flags	
		1.4.8	Provide on-board capability to monitor spacecraft state and respond to unsafe conditions with appropriate GN&C abort sequences	
2.	Perform On-Orbit Servicing			
	2.1	Achieve Customer Satellite Orbit		
		2.1.1	Launch and insertion into transfer orbit	
			2.1.1.1	To mission specific designated inclination
			2.1.1.2	To mission specific designated right ascension

			2.1.1.3	To mission specific designated eccentricity	
			2.1.1.4	To mission specific designated Semi-major axis	
	2.2	Perform Servicer on-orbit checkout			
		2.2.1	Checkout the robot(s)		
			2.2.1.1	Verify telemetry and control	
			2.2.1.2	Release sensor launch locks and checkout sensors	
			2.2.1.3	Release manipulator launch locks and exercise all actuators	
		2.2.2	Checkout AR&C system		
			2.2.2.1	Calibrate sensors (alignment, dark noise, etc)	
			2.2.2.2	Checkout system with resident space object (RSO) (i.e. upper stage)	
			2.2.2.3	Verify telemetry and control	
			2.2.2.4	Release launch locks and exercise all actuators (pan-tilt, scanning lidar, etc)	
		2.2.3	Checkout remaining servicer systems		
		2.2.4	Perform inspection of servicer using cameras on robotic arms		
	2.3	Transfer to pre-rendezvous orbit with first customer vehicle			
		2.3.1	Ground performs analysis to design servicer trajectory that is free of debris and satellites		
		2.3.2	Servicer performs translational maneuvers		
			2.3.2.1	Ground performs orbit determination for servicer	
			2.3.2.2	Ground plans maneuver(s) to reach desired orbital state	
				2.3.2.2.1	Maneuver design constraints include: power, comm constraints (no maneuvers in the blind), operational constraints (vehicle and staffing)
				2.3.2.2.2	Within relative navigation phase, additional maneuver constraints include: lighting constraints, orbital debris/conjunction avoidance, customer vehicle readiness, relative navigation sensor acquisition constraints
			2.3.2.3	Verify maneuver performance from onboard sensor data and ground based tracking	
	2.4	Rendezvous with customer spacecraft			
		2.4.1	Find customer (far-field acquisition)		
			2.4.1.1	Point long-range sensors at customer	
			2.4.1.2	Acquire customer	
			2.4.1.3	Confirm customer acquisition	
		2.4.2	Close relative position with customer		
			2.4.2.1	Perform autonomous tasks	
				2.4.2.1.1	Store a ground updatable sequence of tasks
				2.4.2.1.2	Autonomously execute a sequence of AR&C tasks
				2.4.2.1.3	Exercise context-dependent autonomous abort as needed
				2.4.2.1.4	Accept ground authority-to-proceed (ATP) commands
			2.4.2.2	Maintain sensor pointing on customer. Assume customer has been acquired, good knowledge of relative position and rates.	
				2.4.2.2.1	Compute line-of-sight vector to customer

				2.4.2.2.2	Determine servicer inertial attitude		
				2.4.2.2.3	Compute attitude maneuvers and/or pan-tilt platform orientation to keep sensor bore sight aligned within LOS vector		
					2.4.2.2.3.1	Compute required attitude	
						2.4.2.2.3.1.1	Error budget (required attitude driven by sensor error budget)
					2.4.2.2.3.2	Estimate current attitude	
						2.4.2.2.3.2.1	Compare to Error budget
					2.4.2.2.3.3	Compute required torque	
					2.4.2.2.3.4	Activate attitude actuators (bus GN&C or pan-tilt mechanism) to generate torque	
						2.4.2.2.3.4.1	Compare to error budget (attitude control execution error)
			2.4.2.3	Determine relative position and rates to customer			
				2.4.2.3.1	Take sensor measurements		
					2.4.2.3.1.1	Initialize/calibrate sensors	
					2.4.2.3.1.2	Relative range and rate	
					2.4.2.3.1.3	Relative Bearing and Rate	
					2.4.2.3.1.4	Acceleration during maneuver	
					2.4.2.3.1.5	Absolute orbit determination (OD) of servicer	
				2.4.2.3.2	Process measurements - extended Kalman filter		
					2.4.2.3.2.1	Maintain accelerometer bias knowledge and other filter states and covariance	
					2.4.2.3.2.2	Initialize filter - customer to ground absolute OD solution	
					2.4.2.3.2.3	Estimate relative position and covariance	
					2.4.2.3.2.4	Estimate relative velocity	
					2.4.2.3.2.5	Estimate absolute position of servicer and customer	
					2.4.2.3.2.6	Estimate absolute velocity of servicer and customer	
					2.4.2.3.2.7	Perform FDIR (fault detection, isolation and recovery)	
			2.4.2.4	Translate servicer while respecting servicer pointing requirements			
				2.4.2.4.1	Maintain servicer Integrity		
					2.4.2.4.1.1	Servicer power system	
					2.4.2.4.1.2	Servicer thermal system	
					2.4.2.4.1.3	Servicer RF comm system	
					2.4.2.4.1.4	Servicer C&DH system	
					2.4.2.4.1.5	Servicer GN&C (momentum management, fuel, etc.)	
				2.4.2.4.2	Provide force in any direction		
					2.4.2.4.2.1	Minimize self contamination	
					2.4.2.4.2.2	Minimize self impingement	
					2.4.2.4.2.3	Minimize customer impingement	
				2.4.2.4.3	Determine desired relative position/velocity		

					2.4.2.4.3.1	Verify current relative position and velocity	
					2.4.2.4.3.2	Perform guidance (customizing) per autonomous task sequence	
				2.4.2.4.4	Compute required control impulse (plan maneuver)		
				2.4.2.4.5	Determine required attitude for burn		
					2.4.2.4.5.1	Maintain sensor lock and/or “Turn and Burn”	
				2.4.2.4.6	Deliver required impulse (execute maneuver)		
					2.4.2.4.6.1	Monitor fuel	
					2.4.2.4.6.2	Monitor attitude during burn	
					2.4.2.4.6.3	Determine which thrusters to fire	
					2.4.2.4.6.4	Maintain attitude during maneuver	
					2.4.2.4.6.5	Fire thrusters	
						2.4.2.4.6.5.1	Thruster direction error
						2.4.2.4.6.5.2	Thruster magnitude error
						2.4.2.4.6.5.3	Latency between command and thruster firing
						2.4.2.4.6.5.4	Total force required
					2.4.2.4.6.6	Monitor/calibrate measured delivered acceleration/torque	
					2.4.2.4.6.7	Accommodate thruster failure	
				2.4.2.4.7	Evaluate maneuver performance as determined by sec. 2.2.2		
			2.4.2.5	Confirm customer neighborhood is free of other Resident Space Objects (RSOs)			
				2.4.2.5.1	Configure camera		
				2.4.2.5.2	Configure lighting		
				2.4.2.5.3	Optically image customer		
				2.4.2.5.4	Send image to ground		
			2.4.2.6	Confirm readiness for proximity operations			
		2.4.3	Maintain vehicle momentum				
		2.4.4	Manage servicer autonomy per section 1.4				
	2.5	Proximity and Approach Operations					
		2.5.1	Survey/inspect customer				
			2.5.1.1	Image the customer			
				2.5.1.1.1	Receive info on specific area of the spacecraft		
				2.5.1.1.2	Configure camera		
				2.5.1.1.3	Configure lighting - servicer or natural		
				2.5.1.1.4	Take images		
				2.5.1.1.5	Process and store images		
			2.5.1.2	Transfer image to ground			
			2.5.1.3	Ground process image			
		2.5.2	Control relative position with respect to customer				
			2.5.2.1	Maintain sensor pointing on customer			
			2.5.2.2	Measure relative attitude of customer			

			2.5.2.3	Measure relative attitude rates of customer	
			2.5.2.4	Measure relative position to customer	
			2.5.2.5	Measure relative position rates to customer	
			2.5.2.6	Translate servicer (fine maneuvering) See Section 2.4.2.3	
		2.5.3	Maintain communications		
			2.5.3.1	Servicer to ground	
			2.5.3.2	Servicer to customer (if customer has the capability)	
			2.5.3.3	Customer to ground (if customer has the capability)	
		2.5.4	Configure servicer for capture (unstow, re-verify and position arms, etc.)		
		2.5.5	Maintain customer spacecraft constraints per section 1.3		
		2.5.6	Manage servicer autonomy per section 1.4		
	2.6	Grapple with customer satellite and control stack (both human or/and robot)			
		2.6.1	Prepare to grapple		
		2.6.2	Verify States (Health) of customer satellite and servicer		
			2.6.2.1	Obtain state of customer satellite	
				2.6.2.1.1	Evaluate customer for suitability for grapple
				2.6.2.1.2	Select appropriate end-effector
			2.6.2.2	Obtain state of servicer	
			2.6.2.3	Receive ATP to begin grappling process	
			2.6.2.4	Image worksite	
				2.6.2.4.1	Minimum frame rate and resolution
				2.6.2.4.2	Maintain downlink of required data about worksite
			2.6.2.5	Maintain relative navigation	
			2.6.2.6	Control relative position and attitude to remain in capture box	
		2.6.3	Grapple the customer		
			2.6.3.1	Move arms to ready to capture position	
			2.6.3.2	Engage soft capture as applicable	
			2.6.3.3	Engage hard capture	
			2.6.3.4	Autonomous Compliance Control	
			2.6.3.5	Move arms to stacked configuration	
			2.6.3.6	Maximum force and torque applied to customer (sensor to detect excessive torque)	
			2.6.3.7	Rigidize arms in stacked configuration	
			2.6.3.8	Verify grapple Success	
		2.6.4	Control stack (servicer vehicle controls attitude of combined servicer and customer)		
			2.6.4.1	Perform attitude determination and control for stack	
				2.6.4.1.1	Perform maneuvers to estimate mass properties of combined stack
				2.6.4.1.2	Control stack attitude as required for servicing task
			2.6.4.2	Maintain imparted loads within specifications	
	2.7	Perform servicing (mated operations)			

		2.7.1	Relocation of customer satellite			
			2.7.1.1	Evaluate customer for serviceability		
			2.7.1.2	Re-orient (combined) vehicle to firing position, include burn		
				2.7.1.2.1	Pre-burn check gate	
				2.7.1.2.2	Verify conditions required for burn (rates, attitude, safeing system, etc)	
			2.7.1.3	Perform orbital maneuver		
			2.7.1.4	Verify final orbit		
			2.7.1.5	Deploy Customer		
				2.7.1.5.1	ATP, separation/release customer	
					2.7.1.5.1.1	Verify subsequent separation
				2.7.1.5.2	Perform main separation maneuver	
					2.7.1.5.2.1	CCAM (collision contamination avoidance maneuver)
				2.7.1.5.3	Set servicer to nominal configuration and mode	
					2.7.1.5.3.1	Verify servicer status
				2.7.1.5.4	Set customer to nominal configuration and mode	
					2.7.1.5.4.1	Verify customer status
		2.7.2	Mechanical Assist (hardware stuck)			
			2.7.2.1	Verify customer satellite and servicing vehicle is ready/configured for mechanism deployment		
			2.7.2.2	Identify anomalous/stuck mechanism		
			2.7.2.3	Survey mechanism for anomaly/obstruction		
			2.7.2.4	Identify and provide corrective action		
				2.7.2.4.1	Monitor and maintain applied forces/torques and motion kinematics within limits	
		2.7.3	Repair/Upgrade			
			2.7.3.1	Verify customer satellite and servicing vehicle is ready/configured for hardware replacement		
				2.7.3.1.1	Identify hardware and Interfaces	
				2.7.3.1.2	Survey worksite	
			2.7.3.2	Perform repair or upgrade		
				2.7.3.2.1	Maintain integrity of replacement hardware (thermally etc.)	
				2.7.3.2.2	Verify tool compatibility with interfaces	
				2.7.3.2.3	Gain access to hardware	
				2.7.3.2.4	Perform checkout of new hardware	
		2.7.4	Resource Replenishment			
			2.7.4.1	Receive ATP to deploy servicing arm		
				2.7.4.1.1	Begin continuous downlink of arm camera	
				2 .7.4.1.2	Match resolution and refresh rate to task	
			2.7.4.2	Retrieve necessary tool		
			2.7.4.3	Move arm into position to evaluate worksite (e.g.- refueling valve)		

			2.7.4.4	Identify port location	
				2.7.4.4.1	Image, ground verification
			2.7.4.5	Remove MLI (tool for removal, secure, contamination control)	
			2.7.4.6	Cut safety wire (tool for cutting)	
			2.7.4.7	Remove cap	
				2.7.4.7.1	Place in the temporary storage
				2.7.4.7.2	Retrieve appropriate tool
				2.7.4.7.3	Turn to release
			2.7.4.8	Connect consumable supply line	
			2.7.4.9	Open valves	
			2.7.4.10	Monitor pressures/temperature of both tanks	
			2.7.4.11	Close valve (reach time or pressure limit)	
			2.7.4.12	Disconnect consumable supply line	
		2.7.5	On-Orbit Assembly		
			2.7.5.1	Receive ATP to deploy servicing arm	
				2.7.5.1.1	Begin continuous downlink of arm camera & sensor data
				2.7.5.1.2	Match data resolution and refresh rate to current task
			2.7.5.2	Prepare worksite	
				2.7.5.2.1	Survey worksite
				2.7.5.2.2	Verify tool compatibility
				2.7.5.2.3	Configure interfaces
				2.7.5.2.4	Select or verify tools are ready for use
				2.7.5.2.5	Verify ready to proceed
			2.7.5.3	Access Stowage	
				2.7.5.3.1	Verify integrity of hardware
				2.7.5.3.2	Install tether or secondary restraint
				2.7.5.3.3	Retrieve hardware for assembly
				2.7.5.3.4	If necessary safe and secure stowage container
			2.7.5.4	Execute assembly function for hardware component	
				2.7.5.4.1	Position servicing arm
				2.7.5.4.2	Make hardware connection with interface
				2.7.5.4.3	Verify hardware position and orientation within limits for latching
				2.7.5.4.4	Drive latch mechanism as appropriate or send notification of readiness for externally commanded latching of interface
				2.7.5.4.5	Remove tether or secondary restraint after assembly step complete
			2.7.5.5	Continue until assembly completed, swapping tools as appropriate	
			2.7.5.6	Receive ATP to re-stow servicing arm	
			2.7.5.7	Re-stow servicing arm	
	2.8	Demate from customer spacecraft			
		2.8.1	Verify servicer state (rates, position)		

		2.8.2	Perform post-servicing inspection or monitoring of customer as required	
	2.9	Transfer servicer to next customer		
		2.9.1	Ground performs analysis to design servicer trajectory that is free of debris and satellites	
		2.9.2	Servicer performs translational maneuvers	
	2.10	Loiter in parking orbit		
		2.10.1	Servicer configured for loiter/on-orbit storage	
		2.10.2	Servicer station-keeping maneuvers	
			2.10.2.1	Servicer performs translational maneuvers
		2.10.3	Servicer momentum unload maneuvers	
	2.11	Dispose of servicer at end of life		
		2.11.1	Transfer to disposal location	
			2.11.1.1	Perform plane change
			2.11.1.2	Perform altitude change
		2.11.2	Safe servicer for disposal	
			2.11.2.1	Safe servicer per NASA NPR 8715.6
	2.12	Manage servicer Autonomy		
		2.12.1	Provide GN&C command interface	
			2.12.1.1	Commands originating from AR&C
			2.12.1.2	Command originating from the ground
		2.12.2	Receive ground command to switch between operational mission modes	
		2.12.3	Execute ground-provided task lists appropriate to current operational mode	
			2.12.3.1	Validate uplinked task lists
			2.12.3.2	Provide ATP checkpoints
			2.12.3.3	Sequence commands & monitor grapple arm interface to accomplish tasks
			2.12.3.4	Activate sensor/effector HW to accomplish tasks
		2.12.4	Switch between task lists	
		2.12.5	Monitor performance and status to detect unsafe conditions and initiate pre-defined abort sequences	
			2.12.5.1	Sensor/end-effector health
			2.12.5.2	Relative servicer/customer orientation and location – predict servicer/customer collisions
			2.12.5.3	Indication of spacecraft safemode trigger
			2.12.5.4	Vehicle battery life remaining
		2.12.6	Receive ground commands to suspend execution of task	
		2.12.7	Receive ground commands to execute abort	
		2.12.8	Execute GN&C abort sequences based on knowledge of current state in response to automated or ground commanded abort commands	
3.	Preparing the Customer Spacecraft For On-orbit Servicing			
	3.1	Design customer spacecraft to be servicing friendly		
		3.1.1	Provide capture aids	
			3.1.1.1	Provide grapple aids

			3.1.1.2	Provide docking aids	
			3.1.1.3	Allow transmission of forces/torques	
		3.1.2	Provide navigation aids		
		3.1.3	Provide inter-vehicle communication subsystem for separated ops		
		3.1.4	Provide inter-vehicle communication subsystem for mated ops		
		3.1.5	Provide inter-vehicle power for mated ops		
		3.1.6	Provide servicing-friendly mechanical interfaces		
			3.1.6.1	Provide compatible consumable ports	
			3.1.6.2	Provide handling fixtures	
		3.1.7	Provide servicing-friendly vehicle configuration		
			3.1.7.1	Configure deployables (stowable)	
			3.1.7.2	Provide attitude control system modes	
			3.1.7.3	Design load limits to accommodate servicer induced impulses	
				3.1.7.3.1	Design load limits to accommodate docking
				3.1.7.3.2	Maneuver
				3.1.7.3.3	Servicing
			3.1.7.4	Provide contamination protection	
			3.1.7.5	Provide ground path to servicer vehicle interface to minimize ESD	
		3.1.8	Design customer spacecraft for stacked operations		
			3.1.8.1	Power	
			3.1.8.2	Thermal	
			3.1.8.3	RF Communication	
	3.2	Configure customer spacecraft operationally			
		3.2.1	Maneuver to capture attitude		
		3.2.2	Configure RF communication subsystem		
			3.2.2.1	Enable inter-vehicle comm (if available and required)	
			3.2.2.2	Configure comm deployables (HGA,etc.)	
			3.2.2.3	Verify all downlink paths enabled (ground, TDRS, other comms)	
		3.2.3	Configure optics and instruments (if applicable)		
		3.2.4	Configure for contamination control		
			3.2.4.1	Shutters, deployable covers	
		3.2.5	Configure prop system for servicing		
			3.2.5.1	Bleed-off, inter-tank transfer, ullage dump	
		3.2.6	Configure for thermal protection		
			3.2.6.1	Pre-heat considerations, deployable radiators	
		3.2.7	Configure power system		
			3.2.7.1	Fully charge battery	
			3.2.7.2	Configure SA	
			3.2.7.3	Set minimum SOC for batteries and include in docking wave-off criteria	
		3.2.8	Minimize ESD; Provide ground path to customer vehicle interface		

		3.2.9	Safe customer vehicle systems	
			3.2.9.1	Identify safe mode processes that might counter servicing vehicle operations (despin, pointing, etc.)
		3.2.10	Command customer to capture mode	
	3.3	Mission constraints		
		3.3.1	Servicing approach, rendezvous, capture attempts shall maintain customer functionality.	
		3.3.2	Maintain minimum prop for customer maneuvers and back-off.	
		3.3.3	Do not plume customer such that its solar cells/power system is degraded.	
		3.3.4	Maintain customer thermal control capabilities (minimize pluming of mirrors, etc).	
		3.3.5	Servicing loads imparted to customer shall not exceed structural limits.	
		3.3.6	Identify primary and backup capture points on customer.	

Appendix E – Results of the Integrated Design Center (IDC) Instrument Design Laboratory (IDL) Study on Autonomous Rendezvous and (Berthing, Capture, Docking) Sensor Package, and Robots 1 through 3

Autonomous Rendezvous and (Berthing, Capture, Docking) Sensor Package

The Instrument Design Laboratory (IDL)—part of NASA Goddard Space Flight Center's Integrated Design Center (IDC)—was enlisted to design an integrated Autonomous Rendezvous & Capture (AR&C) sensor package. The design was largely driven by the requirements imposed by the scenario presented in Notional Mission 1—GEO Supersync: capture a non-cooperative (possibly rapidly tumbling customer spacecraft) at GEO altitude; repeat for 10 non-cooperative customers, each with an 80-hour duration, all within five years.

Note that while the sensor package is referred to as the AR&C sensor package, this nomenclature is due to the fact that all of the rendezvous, proximity operations, and final approach sequences for Notional Mission 1 concluded with capture rather than berthing or docking, since all of the customer spacecraft were non-cooperative vehicles that merely needed to be grasped (captured via robotic arms) so that their orbits could be modified by the servicer. However, the "AR&C" sensor package described herein is also perfectly suited to Autonomous Rendezvous & Berthing (AR&B) or Autonomous Rendezvous & Docking (AR&D) missions. As noted in the sections describing AR&(B,C,D) for each of the notional missions, modifications were made to the overall AR&(B,C,D) sensor suite when appropriate. For instance, in cases where cooperative spacecraft customers could be assumed, a Radio Frequency (RF) ranging and telemetry transponder were added. However, none of the sensors present in the original "AR&C" sensor suite were ever removed. For simplicity and congruency with the IDL design nomenclature, the sensor suite is referred to as the AR&C sensor package, suite, or system throughout the remainder of this section.

The AR&C sensor suite was designed to provide bearing, range, and pose measurements of the customer spacecraft throughout the AR&C sequence, which nominally begins when the servicer spacecraft is approximately 200–300 km away from the customer. Furthermore, the AR&C package was designed to meet the measurement accuracy requirements given in Figure IDL1-1. When AR&C begins is largely determined by the far-field distance at which the bearing sensors can first acquire the customer spacecraft; this was conservatively estimated to be 200–300 km during the IDL study. However, AR&C sensor technology is rapidly evolving, and it is now believed that the maximum bearing sensor acquisition range could be as far away as 1,000 km; during cooperative AR&C scenarios the inter-spacecraft RF ranging crosslink will certainly be capable of providing range measurements at such distances. Nevertheless, there is no particular disadvantage associated with defining the beginning distance for AR&C to be 200–300 km, so that convention is maintained except where noted in the individual notional mission descriptions.

The AR&C sequence, shown in Figure IDL1-2, was divided up according to spacecraft distance intervals so as to specify which sensors and measurements would be available at various distances to the customer. Four logical divisions of spacecraft distance during AR&C were identified:

- Far-Field Rendezvous: 200 km–25 km (more generally, > 25 km)
- Near-Field Rendezvous: 25 km–300 m
- Proximity Operations: 300 m–50 m
- Final Approach: 50 m–1 m

To provide measurements during these distance intervals, the AR&C sensor suite consists of the following instruments:

- A Modified Star Tracker Electronics Box and Modified Star Tracker Camera Heads from Micro ASC (plus baffles) (4)
- Narrow Field of View (NFOV) Camera (2)

		Required Accuracies for Measurements					
Mission Phase	**Distance Interval**	**Range**	**Bearing**	**Acceleration[1]**	**Transverse**	**Relative Pitch/Yaw**	**Relative Roll**
Far-Field Rendezvous	>25 km	±0.1%	±1 milli-radian	±1% of T/m	N/A	N/A	N/A
Near-Field Rendezvous	25 km –300 km	±0.1%	±1 milli-radian	±1% of T/m	N/A	N/A	N/A
Proximity Operations	300 km – 50 m	±0.1%	±1 milli-radian	±1% of T/m	N/A	±5°	±5°
Final Approach	50 m – Dock	±10 cm	N/A	N/A	±5 cm	±0.5°	±1°

Explanatory Notes:
1. T = Thrust and m = mass

Figure IDL1-1: Required Accuracies for Measurement

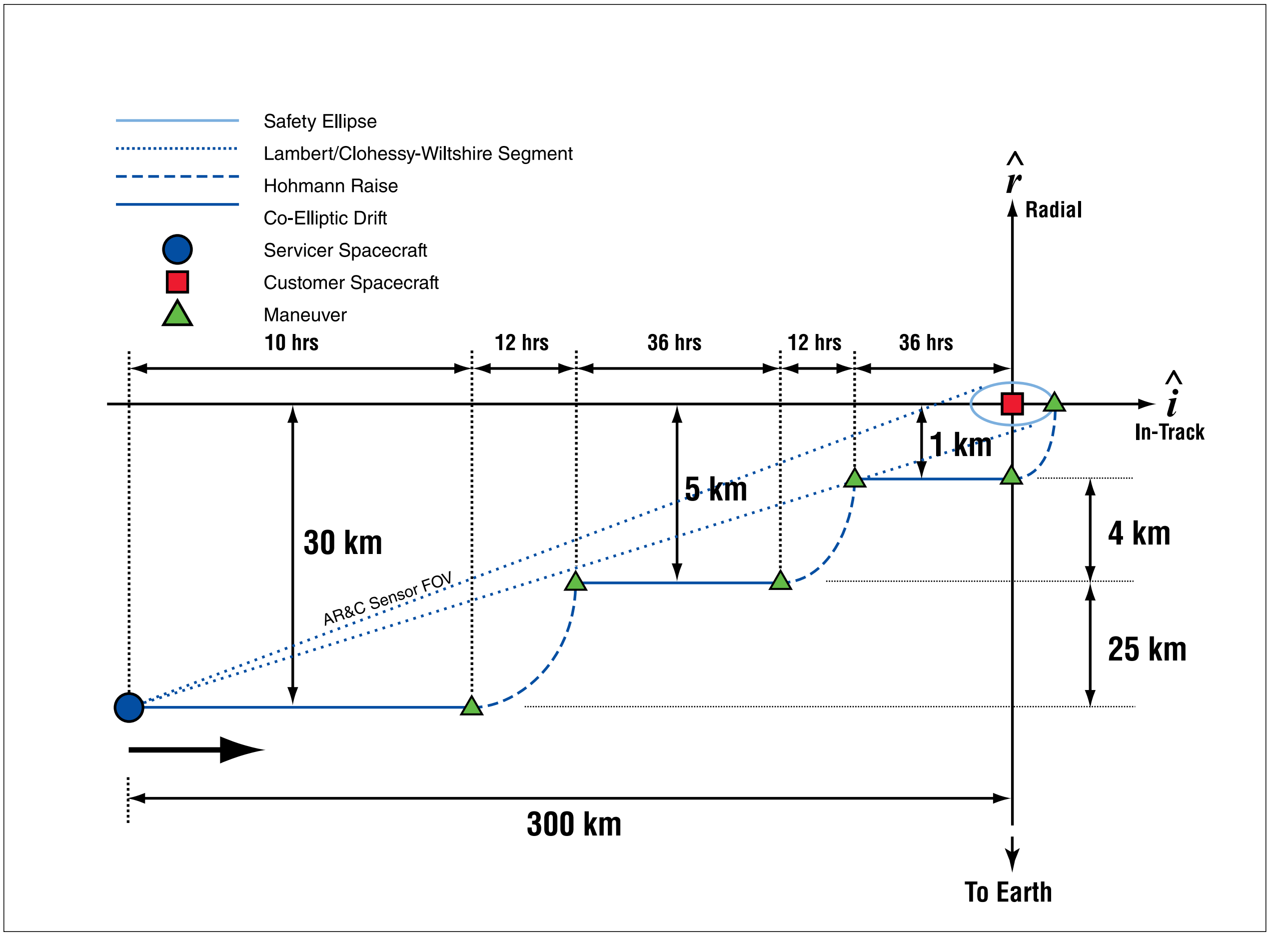


Figure IDL1-2: Rendezvous Sequence

- Bearing angle measurements from 200 km–100 m (possibly > 200 km)
- Images from 100 m–25 m for pose determination
- Wide Field of View (WFOV) Camera (2)
  - Bearing angle measurements from 200 km–50 m (possibly > 200 km)
  - Images from 50 m–1 m for pose determination
    - Pose determination down to a distance of 1 m assumes that the camera can focus adequately at such short distances and that recognizable physical features of the customer will be present within the field of view, since the customer will generally be larger than the field of view at extremely close distances such as 1 m, and may be rotating
- Long Range Laser Rangefinder (1)
  - Range measurements from 75 km–50 m
- Infrared Camera (1)
  - Bearing measurements from 20 km–TBD
    - Minimum distance at which bearing measurements can be acquired is currently unknown
  - Intended for use during adverse lighting conditions
- Flash/Ranging LIDAR (1)
  - Range measurements from approximately 100 km–1 m
  - Pose measurements from 50 m–1 m
- Short Range Laser Rangefinder (1)
  - Range measurements from approximately 1 km–1 m

The overall AR&C package includes the sensor suite described above as well as two Main Electronics Boxes (MEB) modeled after the SpaceCube 2.0. One MEB is active, while the other is fully redundant. The MEB is responsible for processing images from the visible and infrared cameras, along with measurements from the other sensors. Additionally, the MEB provides processing for Guidance, Navigation, and Control (GNC) during the AR&C phase of the mission. This includes state estimation/propagation, maneuver calculations for autonomous operations, and general autonomy. The GNC processing within the MEB also receives inputs from the standard sensors on the servicer spacecraft bus which are not considered to be part of the AR&C sensor suite, including the vehicle's star tracker and coarse sun sensors for inertial attitude determination, the inertial measurement unit for measuring accelerations due to thrust, and the GPS used for orbit determination (absolute inertial state estimation). During AR&C operations, the spacecraft bus enters a mode which allows the GNC function of the AR&C MEB to command the spacecraft's actuators (which are also considered to be part of the standard spacecraft bus and not part of the AR&C system proper), including thrusters, reaction wheels, and momentum wheels. In addition to these critical GNC functions, the AR&C MEB also performs housekeeping functions, including video compression and storage, power distribution, and thermal control. All of the AR&C components are mounted on a pan/tilt mechanism. The total mass of the AR&C package is 141.1 kg, its peak power draw is 128.9 W, and its peak data rate is 996 Mbps without compression (786 Mbps with compression).

Pan/Tilt Mechanism

The first design of the AR&C package included a pan/tilt mechanism upon which all of the AR&C sensors and both of the MEB were mounted, as shown in Figure IDL1-3. The pan/tilt mechanism has two degrees of rotational freedom, and is capable of rotating +/- 60 deg about each of its two axes (pitch and yaw). The goal was to allow the servicer to point its AR&C sensors at the customer vehicle continuously with only minimal attitude maneuvers, particularly during the complex translational and attitudinal motion that might be required during proximity operations and final approach to capture an arbitrarily tumbling non-cooperative customer spacecraft. However, by the end of the study it was not clear that the pan/tilt mechanism offered sufficient advantages to outweigh its disadvantages; nor was it clear that additional degrees of freedom afforded by the pan/tilt mechanism could not be achieved via attitude maneuvers by the servicer, combined with gimbaled solar arrays, gimbaled communications antennae, and strategic distribution of AR&C sensor heads around the servicer's structure. The perceived advantages and disadvantages of the pan/tilt mechanism are as follows:

Pan/Tilt Mechanism Advantages

- Can simplify servicer spacecraft pointing requirements
  - May result in reduced propellant consumption and/or momentum storage
- Can increase customer spacecraft visibility to the AR&C sensors by increasing the extent of the overall AR&C sensor field of regard and the duration for which the customer is within the field of regard

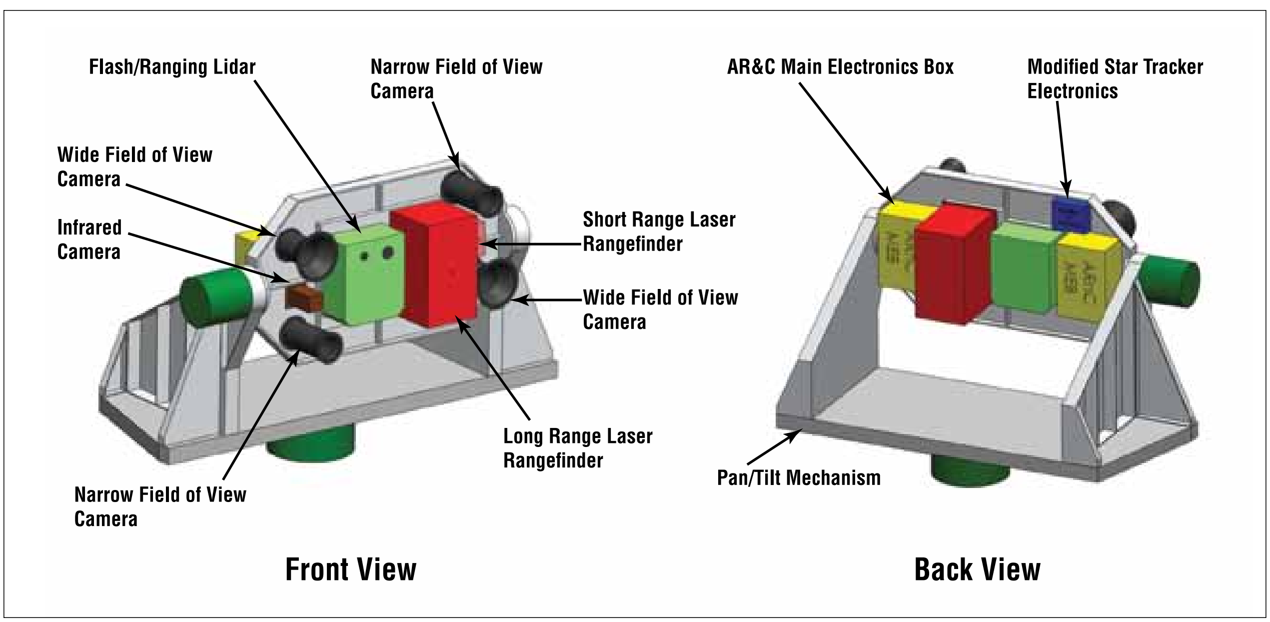


Figure IDL1-3: AR&C on the Pan/Tilt Mechanism

- Can provide for biasing of sensor orientation, allowing solar image avoidance
- May enable searching for the customer spacecraft (during far-field, and possibly near-field rendezvous) without requiring attitude maneuvers

Pan/Tilt Mechanism Disadvantages
- Additional software is required to control the mechanism
- Mechanism control software reliability is low
- Baseline for stereo ranging is lower (compared to distributing sensors on spacecraft bus)
- Higher cost (distributed additional sensors may cost less than the pan/tilt mechanism)
- The inclusion of the pan/tilt platform complicates the pointing error budget
  - Adds a source of pointing error
  - The spacecraft bus is capable of sufficient pointing accuracy without the pan/tilt system
- Decreases modularity
- Thermal control is complicated
  - Variable thermal loads based on platform position
  - Difficult to remove heat across the pan/tilt gimbals
- Massive: with a mass of 99.8 kg, it comprises 70.8% of the AR&C system mass
- The power requirement for the pan/tilt mechanism alone is 40 W (2 motors at 20 W each), which comprises 1/3 of the 128.9 W of total power consumed by the AR&C system.

The pan/tilt mechanism was incorporated into the servicer spacecraft design for Notional Mission 1 (the study which immediately followed the AR&C IDL study described herein), but not long afterward it was decided that the disadvantages of the pan/tilt system (particularly its large mass and relatively substantial power draw) were not outweighed by the potential advantages it offered. Therefore, beginning with Notional Mission 2, the decision was made to eliminate the pan/tilt mechanism from the spacecraft design, a decision which was held throughout the remainder of the notional mission suite studies. Figure IDL1-4 shows the AR&C sensor suite without the Pan/Tilt Mechanism.

Making Spacecraft Serviceable from the Perspective of AR&(B,C,D)

Making spacecraft serviceable from the perspective of AR&(B,C,D) means ensuring that spacecraft are capable of being cooperative customers for rendezvous, proximity operations, and berthing, capture, or docking. All spacecraft servicing activities begin with an AR&(B,C,D) sequence that brings the servicer and customer spacecraft together.

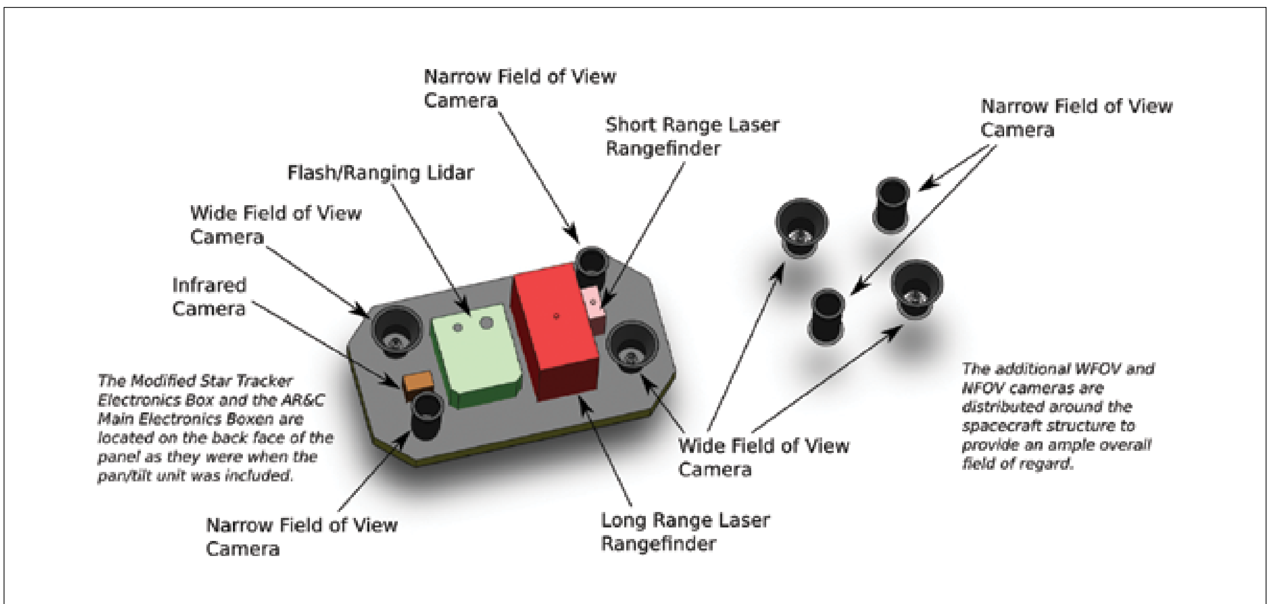


Figure IDL1-4: AR&C Sensor Package—No Pan/Tilt Unit

The servicer spacecraft is typically the active vehicle during the AR&(B,C,D) sequence and the customer vehicle is passive (i.e., not maneuvering to translate towards the servicer).

Fundamentally, a cooperative rendezvous customer is one which does nothing to hinder the AR&(B,C,D) process and offers features that make the AR&(B,C,D) sequence easier. By contrast, a non-cooperative vehicle does not offer features that facilitate AR&(B,C,D) and may have characteristics that inadvertently hinder AR&(B,C,D). An uncooperative vehicle (vs. a non-cooperative vehicle) is one which actively and deliberately attempts to foil AR&(B,C,D). Note that uncooperative vehicles are not considered herein.

Adding the following features and mechanisms to a spacecraft design make it a cooperative customer for AR&(B,C,D):

- Optical retro-reflectors
- RF transponders for ranging and telemetry exchange
- Visible, possibly reflective, surface features
- Grapple fixtures
- Proper ACS modes in flight software for quiescence when required

Optical retro-reflectors allow laser-based relative navigation sensors on the servicer spacecraft to acquire the customer spacecraft at further distances and also provide better tracking quality for bearing-angle sensors.

Radio Frequency (RF) transponders for ranging and telemetry exchange serve two important purposes. First, the exchange of a two-way ranging signal between the servicer and customer vehicle provides the servicer with a very accurate estimate of the range between the vehicles and aids in far-field acquisition of the customer. Second, the exchange of telemetry between the vehicles allows them to share state information, which can further improve the servicer's relative navigation solution and provide important situational awareness data.

Visible, possibly reflective, surface features at known locations in the customer spacecraft's body frame help natural feature recognition pose sensor algorithms measure the relative position and attitude of the customer spacecraft when at closer ranges (i.e., during proximity operations and final approach).

Grapple fixtures offer a safe, robust means for the servicer vehicle to attach itself to the customer vehicle in a berthing or capture scenario.

Finally, the availability of proper ACS modes ensures that two important conditions will be met. First, the customer vehicle will be in a friendly attitude state throughout the AR&(B,C,D) sequence; this is especially important in the final approach phase during which the servicer vehicle must engage in forced motion along an approach vector fixed in the customer vehicle's body frame. If the customer vehicle has any significant attitude rates during this phase, the servicer vehicle will have to consume significant amounts of fuel to stay on the rotating approach axis and complete the final approach. Second, the customer vehicle will be capable of becoming completely quiescent, ensuring that its ACS algorithms and actuators will not be attempting to counteract the forces and torques imparted by the servicer during capture, berthing, or docking operations and subsequent mated operations.

Note that the majority of these additional features have relatively little impact on the customer spacecraft systems.

IDL Robot 1

The robot system developed in the first Instrument Design Laboratory run was a "notional" dexterous robot based off of two very similar existing space robot systems—Ranger, developed by the University of Maryland's Space System Laboratory, and FREND, developed by Alliance Spacesystems (since acquired by MacDonald, Dettwiler and Associates Ltd. [MDA] of Canada) and the Naval Research Laboratory for the Defense Advanced Research Projects Agency. The FREND arm was designed to do a very similar task as proposed in Notional Mission 1 (grapple the back end of a satellite), and Ranger was designed to do dexterous tasks very similar to those proposed in the other five notional missions (refueling, assembling structures, replacing aging and failed spacecraft components, etc.).

The 7 degree-of-freedom (DOF) notional arm developed during the week-long design run has a 3-DOF shoulder, 2-DOF elbow, and a 2-DOF wrist as shown in Figure Robot 1-1. Total arm length is approximately 2 meters, divided equally between the upper arm and lower arm, and the arm fits within a 0.35 m^3 volume. The total weight of the arm and associated electronics is 157 kg (with the electronics weighing 34 kg), requires 380 W during operations, and can pass 1 Mbps of data.

Each robot joint contains a DC brushless motor, a transmission, a brake, and encoders. The joints also have temperature sensors. The end of the arm has a force-torque sensor.

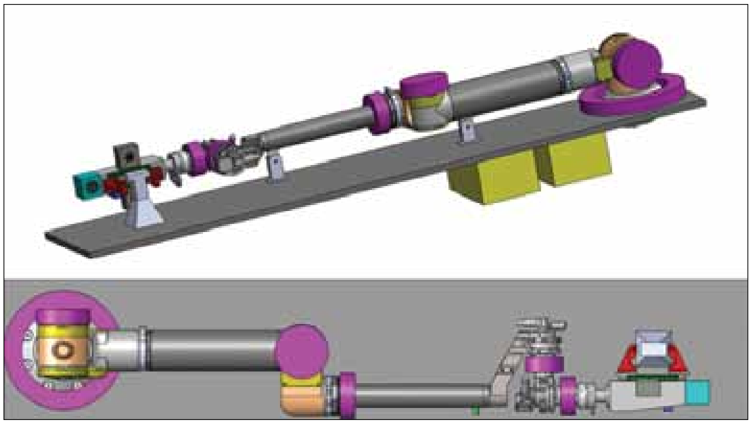


Figure Robot 1-1: Notional Robot Arm with a Grapple End-Effector

The notional end-effector (shown in Figure Robot 1-2) is a basic gripper that can be used to grapple a satellite. Cameras and lights (LED illuminators) on the end-effector are used to take images of the satellite, which are fed to a processor in the electronics box, which performs a pose estimate and autonomously commands the arm to complete the grapple. A proximity sensor is included to assist the autonomous vision algorithm. A force-torque sensor mounted between the wrist of the robot and the end-effector is used for compliance control algorithms, allowing the arm to "gently" grapple the customer satellite.

The control electronics (Figure Robot 1-3) are in one centralized location in two boxes—the Arm Control Electronics (ACE) and the Data Management Unit (DMU). The ACE is used for servo control and includes the servo boards, boards for data digitization, input/output boards, and any miscellaneous preprocessing needs. The DMU supports the autonomous grapple system, and also supports the arm with control algorithms (compliance control, health & status information, end-point trajectory calculations, and potentially a sequencer of robot motions including collision avoidance). SpaceCube 2.0 is baselined as the DMU.

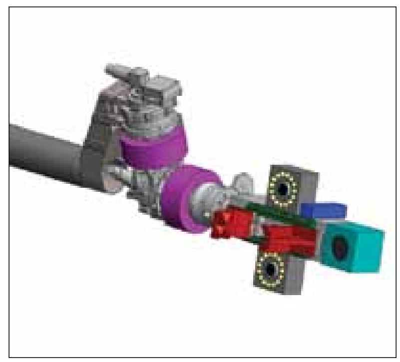


Figure Robot 1-2: Notional End-Effector

Power distribution for the arm comes from the spacecraft bus at 28 VDC. The arm will also require ±5 VDC for signal and other miscellaneous needs. The wire hardness is routed down the outside of the arm using ribbon cables.

The arm design incorporates 200-mils thick aluminum shielding to cover sensitive components that effectively reduces radiation to 40 krad. This is one advantage of having the control electronics located in a centralized location instead of distributed along the arm. It also helps with thermal design.

For robot interface, the shoulder joint is hard-mounted to the structure. As a payload, the robot is afixed to the spacecraft interface plate (honeycomb aluminum), which in turn is attached to the spacecraft structure

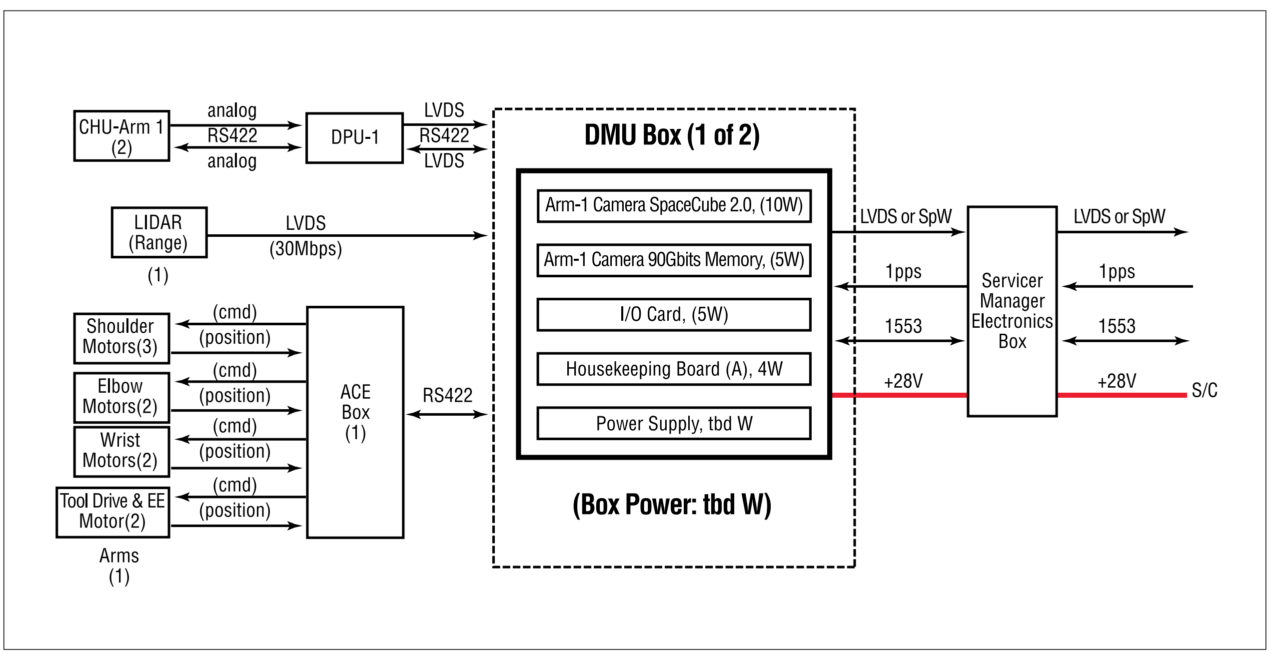


Figure Robot 1-3: Control Electronics

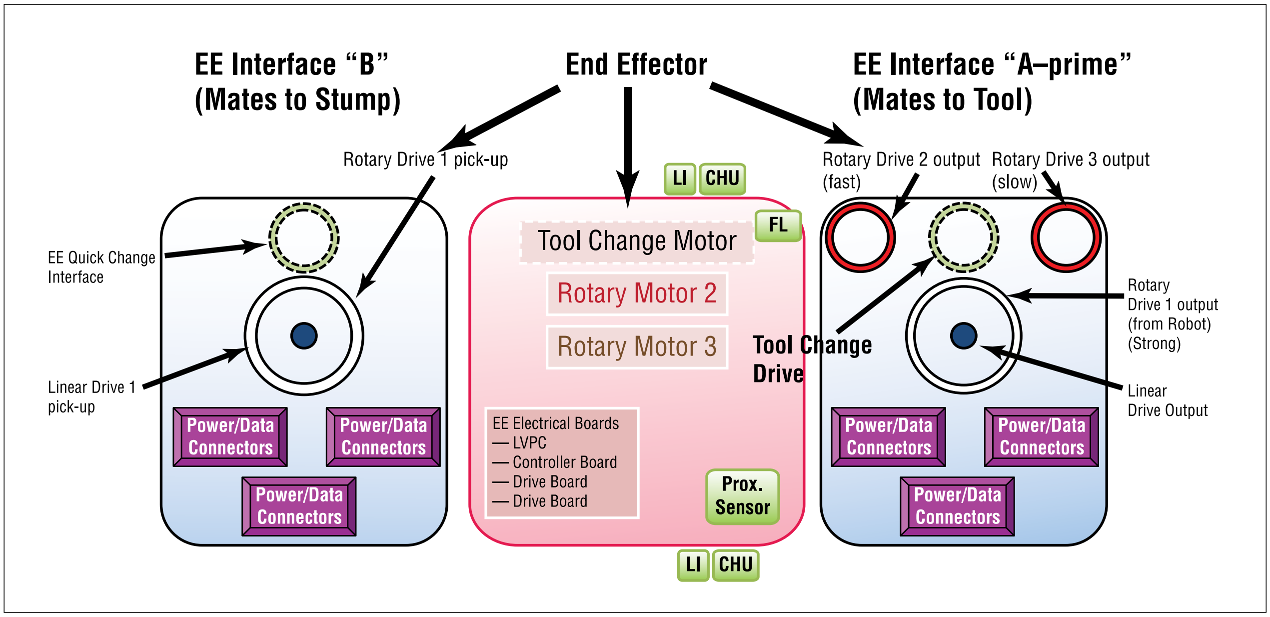


Figure Robot 2-1: End-Effector Interfaces

with mechanical fasteners. Power, command, and telemetry is passed between the robot and the spacecraft. Its interface is though the 1553 spacecraft bus, Spacewire for instrument data, RS-422 to control the sensors, and a PCI interface to the joints and end-effector. The robotics executive software on the DMU interfaces with the Vehicle Autonomy Manager software on the spacecraft. When launched, the arm is saddled onto its three launch locks in a stowed configuration. The fail safe brakes in each joint are on and provide additional means of rigidity for the arm to better withstand launch loads.

IDL Robot 2 (End Effector Study)

The goal of the second IDL robot run was to define the interfaces required between the robot arm and the end-effector as well as an initial set of requirements for an end-effector that could accomplish a variety of servicing tasks.

The initial trade study that was completed looked at the pros and cons of various robot end-effector and tooling paradigms. The first was an anthropometric end-effector (such as on Robonaut). While this would be a good tool to have in the robotic tool box, it is not the ultimate end-effector design as it has too many drawbacks—no redundancy in the many moving parts in the fingers; no easy way to pass power, data, and video across to the tool without a hard-to-manage-harness; limited clamping force capability (and therefore would not be able to grab and hold on to the back of a satellite). The second was a multipurpose end-effector (similar to a Swiss army knife). This was dismissed because of the mass and volume required to carry all the tools at the end of the robot. The third was an interchangeable end-effector mechanism that would allow different tools to be swapped on and off the end of the robot, and this is the option that was explored.

Time was spent determining the services that needed to be passed across the interface between the robot arm and the end-effector or on to the tools. The architecture that resulted was one in which a mission could fly a few specialized end-effectors for specialized tasks. An end-effector could grasp tools or be used alone if specific features are incorporated into the design. For example, adding specialized jaws to the output of an end-effector would allow it to grapple a satellite without the need for a specialized tool). Tools could be used by attaching them directly to the end of the arm (referred to as the "stump") or an end-effector. Making the end-effectors very capable reduces the complexity (and cost) of the specialized robot tools that interface with the worksite. This hopefully leads to a mass and cost savings, as a few "smart" end-effectors can be flown along with many "dumb" tools. This concept also offers the greatest flexibility, an expected lower cost, and is a better option for incorporating redundancy.

It was determined that three rotary drives were desirable at the output of the end-effector. This would allow for high torque, high speed, and low speed drives, thus reducing the need to add transmissions to the tools. One of

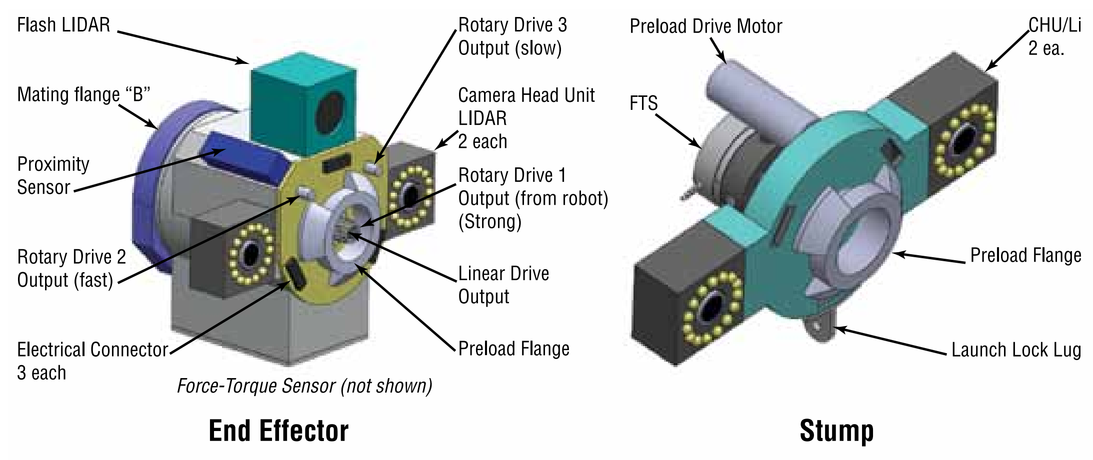


Figure Robot 2-2: End-Effector and End of the Arm (Stump)

these drives would be on the end of the arm and would be passed through the end-effector. A linear drive (also on the end of the robot arm and passed through the end-effector) is also needed to actuate certain features in some of the tools or to switch settings in a transmission if one needed to be added to any of the tools. In addition to the mechanical tool drives that are needed to actuate the tools, it was determined that up to eight analog pairs would be needed for sensors such as a force-torque sensor, cameras and LED illuminators, strain gauges, proximity sensors, touch sensors, a leak detector, temperature sensor, and a pressure sensor; four pairs of SpaceWire; and four pairs for 10A power. A summary of the interfaces are depicted in Figure Robot 2-1.

The end of the arm incorporates a force-torque, electrical connectors, two cameras with LEDs, and a preload drive motor as shown in Figure Robot 2-2. As mentioned earlier, the end of the arm (shown in the right-side of Figure Robot 2-2) can interface with the end-effector (shown in the left-side of Figure Robot 2-2) or a tool (if a tool has the same "B" interface as the end-effector, it can be mounted directly on the end of the arm). Two camera and LED pairs on the end of the arm provide visual data to the autonomous of manual process of mating the arm with an end-effector or tool, and the preload drive motor is used to complete the connection. In one version, the end-effector also supports the mounting of cameras, lights, a proximity sensor, and a flash LIDAR as shown in the left side of Figure Robot 2-2.

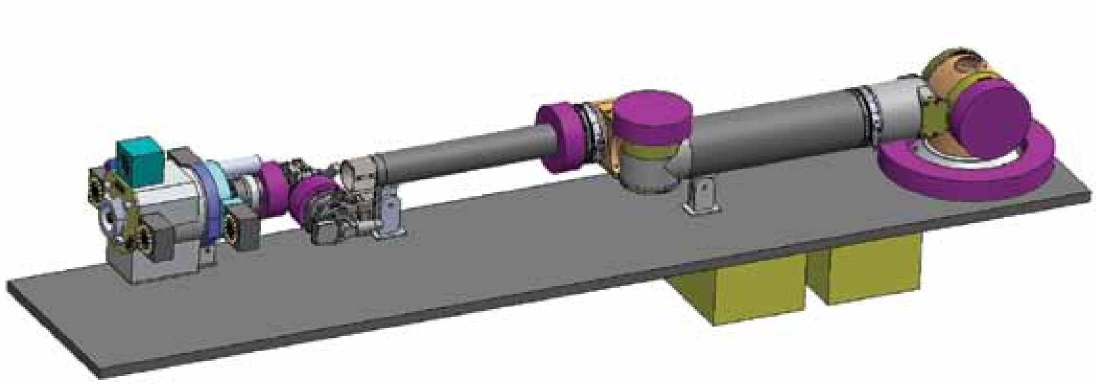


Figure Robot 2-3: Arm (on right) and the End-Effector (on left)

The changeout system is very reliable and robust. It is tolerant to temperature variations, and its motors include dual windings for redundancy. The mechanical features on its mating flanges provide coarse alignment for connector mating. When the end-effector and arm are combined as a system (shown in Figure Robot 2-3) and used on a five-year mission, the system has a predicted reliability of 98.9%.

IDL Robot 3 (Reconfigurable Human-Rated Robot)

While Study 1 focused on a robot manipulator system and Study 2 focused on the end-effector design, Study 3 focused on some key aspects of the robot design. This study took the manipulator to the next level, making some fundamental changes to the control architecture and addressing the notion of modularity. The result is not one manipulator, but a family of manipulators with varying characteristics. They can be assembled to make the same basic arm structure, but they can also be reconfigured or modified with extra parts, leading to new conceptual designs. In addition to the manipulator, this effort investigated the node and other support equipment.

This study does not go into the depth of the previous studies in terms of a defined mission task, joint configuration, actuator details, types of sensors, arm reach, work volume, etc. It utilizes information from the two previous studies, such as actuator designs, having a force/torque sensor, including capabilities for swappable tools, and having toolbox operations. The key change to computer processing is that it is now distributed (made local) and the notion of having two centralized electronic boxes is eliminated. Power for the arm comes from the spacecraft bus at either 120 VDC or 28 VDC through the nodes or other connections with the platform. These arms will still have an external robot arm harness and shielding to mediate thermal and radiation issues. However, cabling, thermal protection, and radiation shielding will be a problem due to reconfigurability, and these needs must be addressed. The control system for the arm will incorproate a combination of position, force, and rate control. The flight software will run on a real-time operating system such as VxWorks and utilize the SpaceCube 2.0 as the flight processor. Power, command, and telemetry are still passed between the robot and the spacecraft through a 1553 spacecraft bus, Spacewire for instrument data, RS-422 to control the sensors, and a PCI interface to the joints and end-effector. The robotics executive software will either interface with the Vehicle Autonomy Manager software on the spacecraft or the Vehicle Autonomy Manager will have to be moved onto the robot.

In this system-level study for the robot, key changes included: 1) implementing distributed control electronics, 2) designing an arm that is reconfigurable and serviceable, and 3) designing a human-rated arm for human-robot missions.

For each of the arm groupings (shoulder, elbow, and wrist), the associated electronics and computer processing units are mounted externally in a housing on the actuator structure. These Local Processing Units (LPUs) will control the motors, sensors, cameras, safety functions, switches, thermostats, FPGAs, all servo commanding, housekeeping, and some communication functions such as Spacewire. A subset of these electronics will be located in link modules to support segments.

All the various modules and spares are reconfigurable. To enable reconfiguration, every piece (joints, segments, and nodes) has grasp points, as shown in Figure Robot 3-1. The reconfigurable arm increases the serviceability of robots by allowing swapping out of failed segments, provides an economy of scale with common interfaces, and

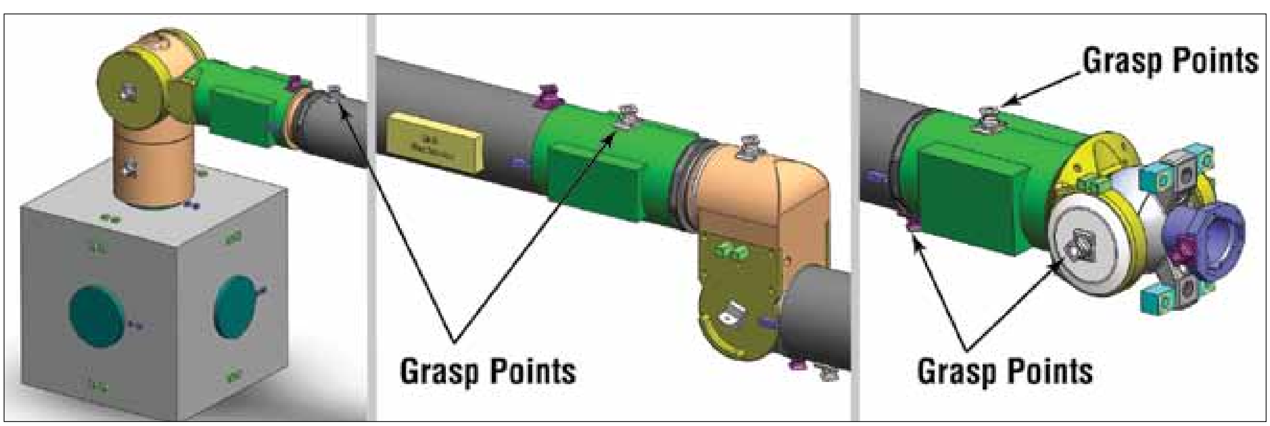


Figure Robot 3-1: Robot Node, Segments, Grasp Points

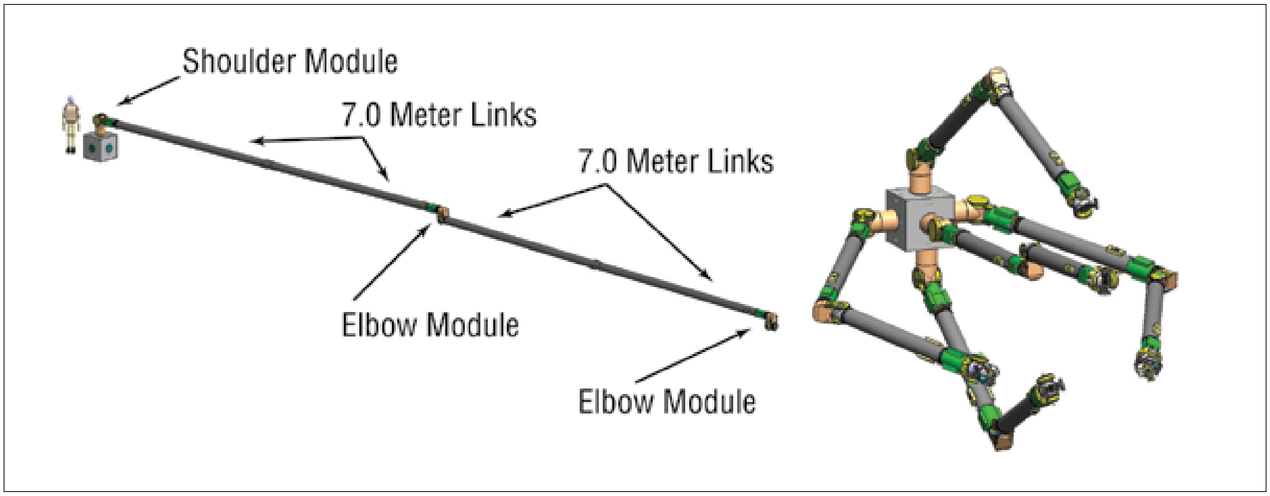


Figure Robot 3-2: “Big Hauler” Configuration (on left) and Max DOF Work-Bot (on right)

affords the ability to upgrade the arm as necessary. The arm can be reconfigured to accomplish the tasks of a “big hauler” or a “dexterous arm.” The study investigated a crane-like arm (Figure Robot 3-2) with a 30 m reach, able to manipulate a 30,000 kg payload.

The dexterous arm is a smaller, 2 m long manipulator. Taking the concept of dexterity to the extreme, the study investigated what they named the “Max DOF Work-Bot.” The Work-Bot consists of five arms of equal length attached to a node: one arm for grappling, two dexterous manipulators, and two arms used for video and cameras. This configuration provides a total of 43 DOFs, requires an average of 852 W for operational power, and has a total data transfer rate of 230 Mbps. The “Big Hauler” and Max DOF Work-Bot” are shown in figure Robot 3-2.

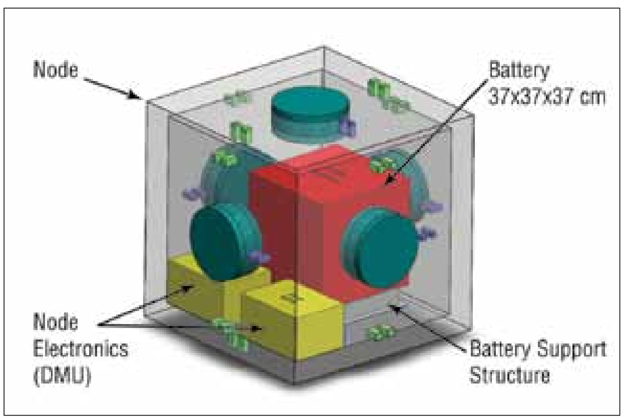


Figure Robot 3-3: Node

Figure Robot 3-3 shows the Node and its components. Nodes are used to connect manipulators together in pairs and replace the DMUs from the previous studies. The nodes are detachable and will house a battery, battery support structure, and node electronics. When a node is detached, it will employ RF communications with the platform. The node can go on a “walkabout” on the target with or without the spacecraft, moving arm over arm across the target and recharging when attached to the spacecraft. There are two types of nodes: “smart” nodes and “dumb” nodes. The dumb nodes do not have any processing capabilities and serve only as structural supports between arm segments and to pass power and data. The dumb nodes were not thoroughly investigated in this study. Smart nodes act as the brains for larger robotic tasks, and have a camera on each face, C-type interface parts, and an omni-patch antenna.

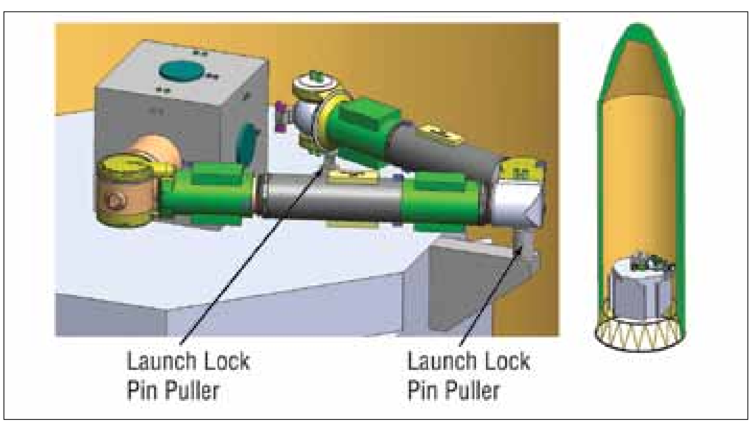


Figure Robot 3-4: Robot Modular Segments

The node electronics include arm control, safety, mission sequencing, commanding, housekeeping, image processing, power management, the Spacecube processor, sensors (switches and thermostats), and communications (i.e. Spacewire, 1553 bus, and RF to talk to the spacecraft).

This modular, multi-segment concept allows for greater flexibility in on-orbit configurations and can reduce the per-segment launch loads. Figure Robot 3-4 shows how the modular segments could be connected. The configuration takes advantage of the typical grasp point and the grasp/override point locations. This study also investigated the sequence for an on-board asembly of a robot arm with the shoulder, link, elbow, link, and wrist assembly sequence by another robot manipulator. Additional arm pieces are stored in "quivers" attached to the outside of the spacecraft (Figure Robot 3-5).

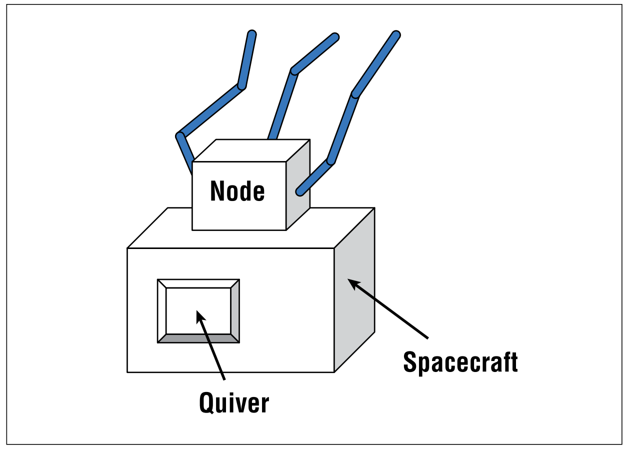


Figure Robot 3-5: Node with Quiver

Due to the reconfigurable nature of the robot segments of this study, developing a cost estimate for the robot was difficult. A "Cost-Bot" was designed that contains each of the segments that was studied, and is used only for costing purposes. The Cost-Bot and a single node would have a combined mass of 549 kg. This configuration is shown in Figure Robot 3-6.

The Cost-Bot manipulator has 7 DOF with a shoulder, elbow, wrist, lower arm segment, and upper arm segment. The figure is only notional for costing purposes, because in reality, the distance between the shoulder and the elbow, and the distance between the elbow and the wrist will be approximately the same. Another Cost-Bot configuration (with 0.75 m links) that was not considered a launch configuration is depicted in Figure 3-6.

Cost of the Robot Systems

As discussed in Chapter 4, cost estimates can be extremely difficult to validate, especially for systems that have never been built. A similar problem exists when comparing modeled costs to those reported for systems that have been built, since these comparisons require a detailed understanding of what was included in the reported costs. Reported development costs for a robotic system could be offset by many factors, such as 1) a vendor using previous design or software development experience, 2) parallel development of robotic systems for two different customers so that the non-recurring costs were divided between two customers, 3) a build-to-print duplicate of an existing, proven design, 4) any cost-sharing arrangements, 5) including or not including flight spares, system-level integration and test, etc. in the modeled costs. However, some useful observations can be made by comparing the modeled costs of individual components for the notional missions, with reported costs of similar robotic systems proposed and flown in the past.

Consider the case of a complex robotic system with two grapple arms and two dexterous pairs, as was modeled for the last two notional missions (NM5 and NM6). Of the $1.2B cost reported earlier for the robotic

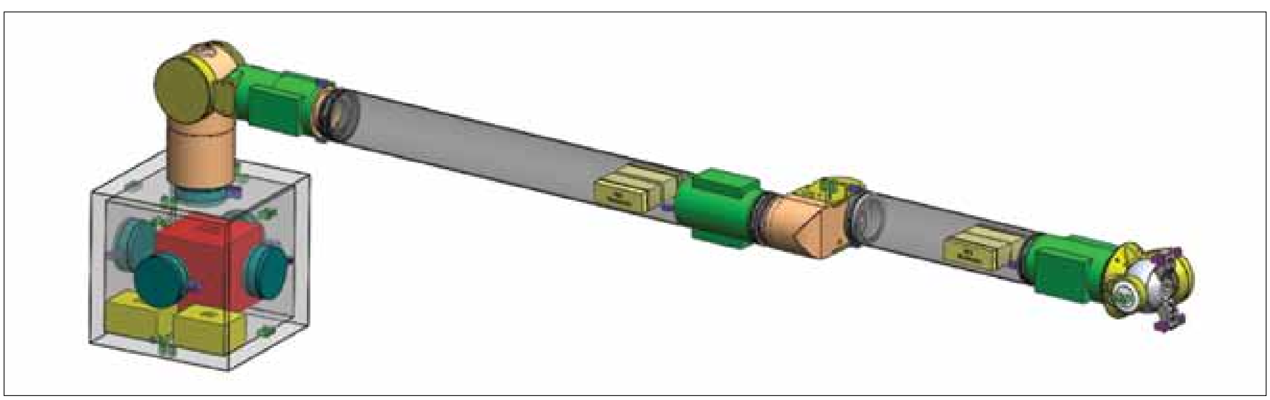


Figure Robot 3-6: Cost-Bot Configuration

system, $230M ($ FY 10) was for the development of the first 15 m, human-rated grapple arm and $290M ($ FY 10) for the development of the first modular, on-orbit reconfigurable pair of dexterous robot arms.

The additional costs modeled for the robotic system are as follows:

Flight system (including sub-elements listed below)	$ 750M
Design, systems engineering, management, and mission assurance for complete system	
Hardware and electronics for two human-rated grapple arms and two on-orbit reconfigurable dexterous pairs	
Engineering test unit for full flight system	$ 250M
Flight software (including sustaining engineering)	$ 38M
Miscellaneous	$ 190M
ground support equipment, system-level environmental test, flight spares, spacecraft-level integration and test	

This compares reasonably well to reported costs for the development of the Space Shuttle's Remote Manipulator System (RMS). The original development cost has been reported as $108M ($ FY 81) ($260M in $ FY 10). Based on that experience, Cooper (of the Canadian company MacDonald, Dettwiler and Associates) reported in his testimony before Congress that the cost for developing a similar grapple arm robotic system for the Hubble Robotic Servicing and Deorbit Mission (which was a non-human-rated system) was only $25M (FY 05; $28M in FY 10). In the same testimony, a cost of $129M (FY 05; $144M FY 10) was reported for the development of an exact duplicate of the International Space Station's Special Purpose Dexterous Manipulator. So the total cost of developing the grapple arm and dexterous pair robotic system would be estimated as $172M (FY 10).

Using these reported cost data for RMS and HRSDM to predict the cost of developing the complex robotic system required for our Notional Missions yields the following. Developing two human-rated grapple arm robotic systems ($260M + $28M) and two on-orbit reconfigurable dexterous pairs (2 x $144M) would be expected to be roughly $570M. This compares favorably with the cost model for notional mission 6, which showed a $750M development cost for two grapple arms and two dexterous pairs.

It is worth noting that The Aerospace Corporation also modeled the HRSDM robotic system in 2005, with quite different results. They estimated $700M ($ FY 05) for the development of the HRSDM robotic system, more than four times the $150M ($ FY 05) estimated by Cooper. As indicated earlier in this section, the wide disparity between HRSDM estimates could stem from cost elements that were included in the Aerospace model that were not included in Cooper's estimate, (e.g., flight software development, test units, environmental testing) or from cost offsets included in Cooper's estimate that were not included in the Aerospace model (e.g., spare parts borrowed from the shuttle RMS program).

Thus, as with any spaceflight hardware, in assessing or comparing cost estimates for robotic systems it is crucial to obtain all possible details about the costing tool used and all inputs and assumptions.

Appendix F – Notional Mission Studies

Introduction

The Satellite Servicing Study Team developed six Notional Mission design concepts for on-orbit servicing. The suite of Notional Missions was designed to probe the corners of the unsampled areas of the Satellite Servicing Trade Space (see Chapter 4). The six Notional Missions (NMs) are GEO Supersync (NM1), GEO Refueling (NM2), LEO Refurbish (NM3), EML1 Robotic Assembly (NM4), HEO Human/Robotic Refurbish (NM5, and SEL2 Human/Robotic Assembly (NM6).

Each notional mission in this appendix includes a model of total mission costs for the purpose of comparison; however, disparate mission concepts and varying fidelity of customer information make true cost comparisons at a mission-level far more complex. A comprehensive overview of how these cost estimates were generated is provided in Chapter 4, "Mission Design Methodology and Cost Estimation." As stated, cost estimates can be difficult to validate, especially for systems that have never before been built. However, for the purposes of this study, we believe that reliable relative cost estimates can be obtained for the notional missions considered. The absolute costs are reserved for future study.

It is worth reiterating that costing tools and absolute costs are not a focus of this study. Instead, we selected a specific method for generating costs (PRICE-H), and then used the results as *one data element* in the comparisons and general observations about the notional missions. It is also worth noting here again that cost was not a constraint during the notional mission studies. The notional missions were designed to probe what is possible, with a resulting cost estimate.

Notional Mission 1: GEO Supersync

Mission Study Objectives

The objective of the Notional Mission 1 (NM1) study is to design a Servicer spacecraft that can sequentially capture and control several legacy, non-cooperative satellites in nearly co-planar geosynchronous orbits and relocate them to a disposal orbit 350 km above the GEO belt. Potential customer satellites in this orbit include Solar Dynamics Observatory (SDO) and Geostationary Operational Environmental Satellite (GOES). The Customer satellites are assumed to be tumbling at a modest rate of 0.25 degrees per second per axis. The mission design includes an estimate of the number of times that the Servicer can rendezvous with, capture, and boost a Customer satellite during a series of sorties while remaining within the fuel budget.

Mission Overview

The Servicer spacecraft launches into geosynchronous orbit and then executes sorties to roughly 10 Customer satellites, assuming approximately one degree of orbit plane change between Customers. Orbital dynamics dictates that greater plane changes between Customers increases fuel consumption and yields a mission with fewer Customers serviced, all else being equal. At the start of the mission, the Customer satellites (at the end of their mission life) are on-orbit waiting for a boost to a disposal orbit. The Servicer satellite is equipped with all hardware, algorithms, and fuel necessary for supervised autonomous rendezvous and capture (AR&C) and supersync of the Customers. The NM1 concept of operations is illustrated in Figure NM1-1.

This study estimated the number of sorties possible based on some simplifying assumptions about the distribution of Customer satellite orbits and attitude states. During the second notional mission study, an algorithm was formulated to furnish near-optimal solutions to the "traveling salesman" optimization problem for orbit rendezvous. This algorithm was utilized with actual orbital data for representative GEO satellites to maximize the number of sorties achieved during Notional Mission 2.

The Servicer satellite is launched and inserted directly into GEO in the plane of the first Customer satellite. The AR&C sequence begins with the Servicer spacecraft in its delivery orbit 300 km behind and 30 km below the Customer spacecraft, as shown in Figure NM1-2. The Servicer uses a combination of co-elliptic drifts and Hohmann transfers to gradually close distance with the Customer spacecraft over the course of approximately 4.5 days, at which point the Servicer inserts itself onto a safety ellipse about the Customer spacecraft. The Servicer remains on the safety ellipse for at least one period of the Customer's orbit (~24 hours). During this time the Servicer collects situational awareness data, confirms the status of the Customer, and performs pose estimation to accurately determine its position and attitude relative to the Customer. Once the ground deems the situation safe and the relative navigation solutions have converged, the Servicer spacecraft executes a series of maneuvers to acquire and translate down a capture axis that constitutes a straight-line approach in the Customer's body-fixed frame. The Servicer maneuvers the robotic arms to within approximately 1 meter of the Customer (placing the arms in a

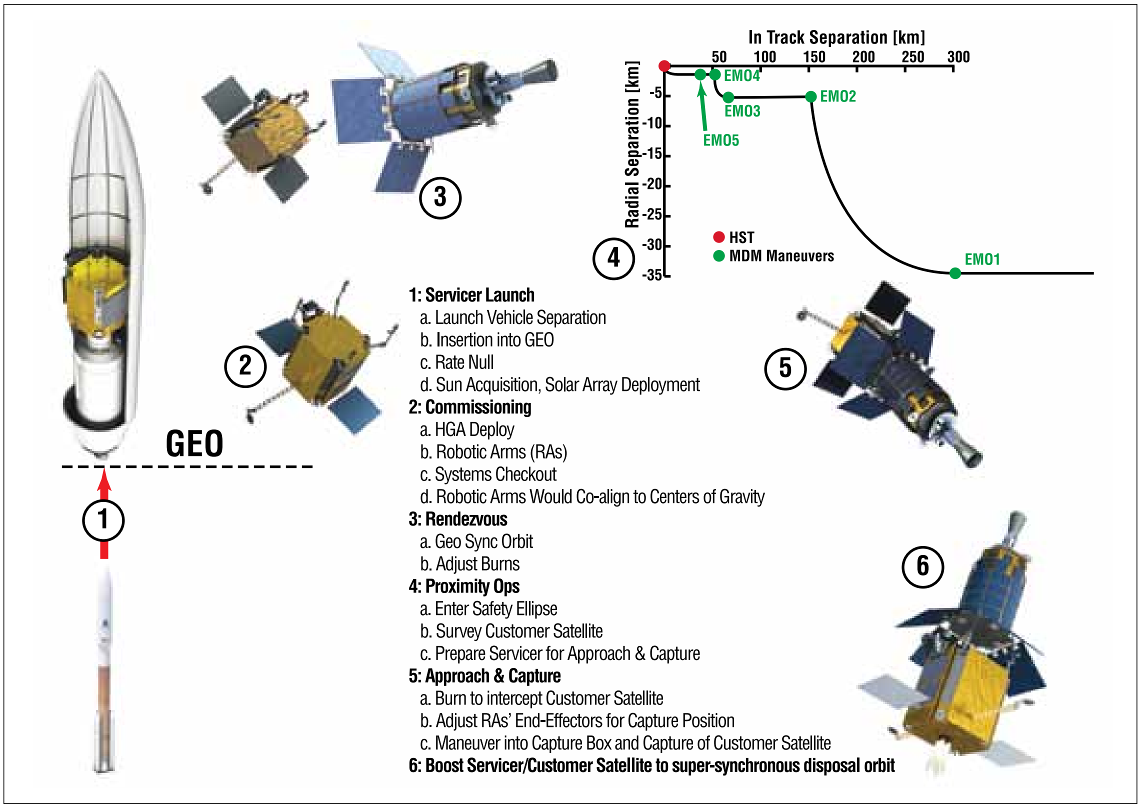


Figure NM1-1: Geosynchronous Supersync Concept of Operations

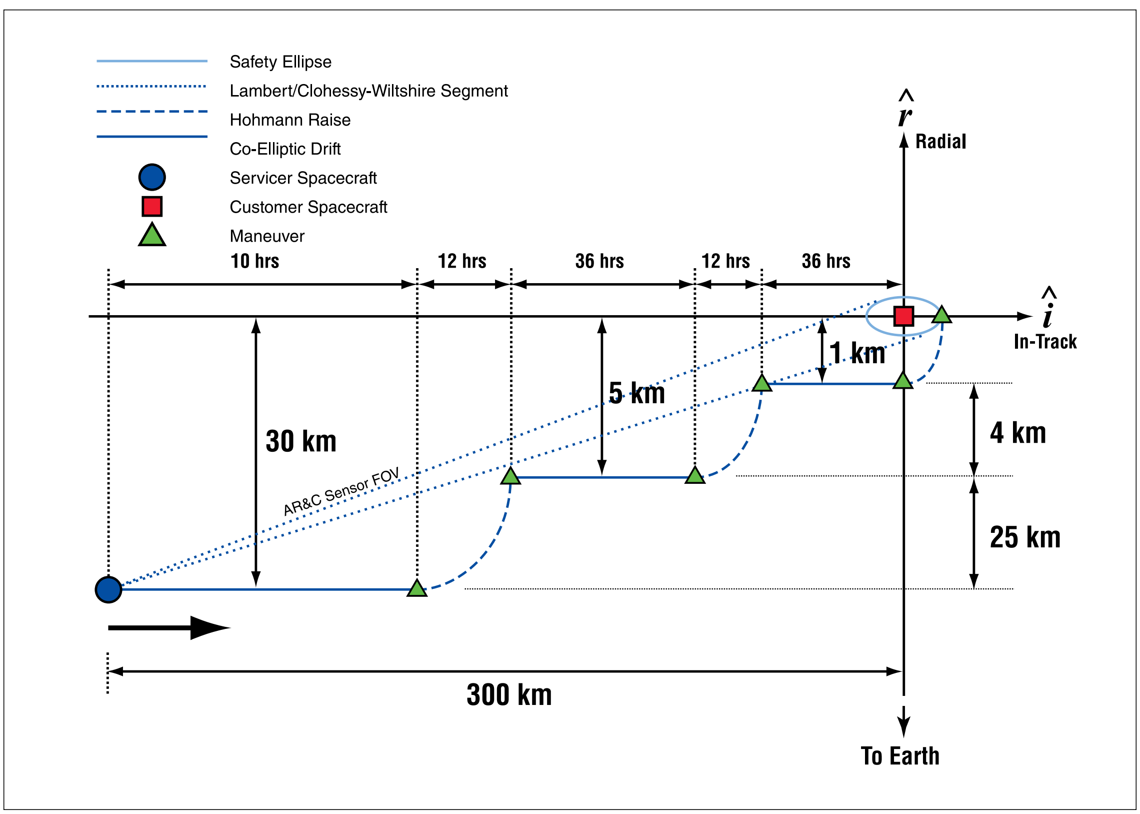


Figure NM1-2: AR&C Sequence

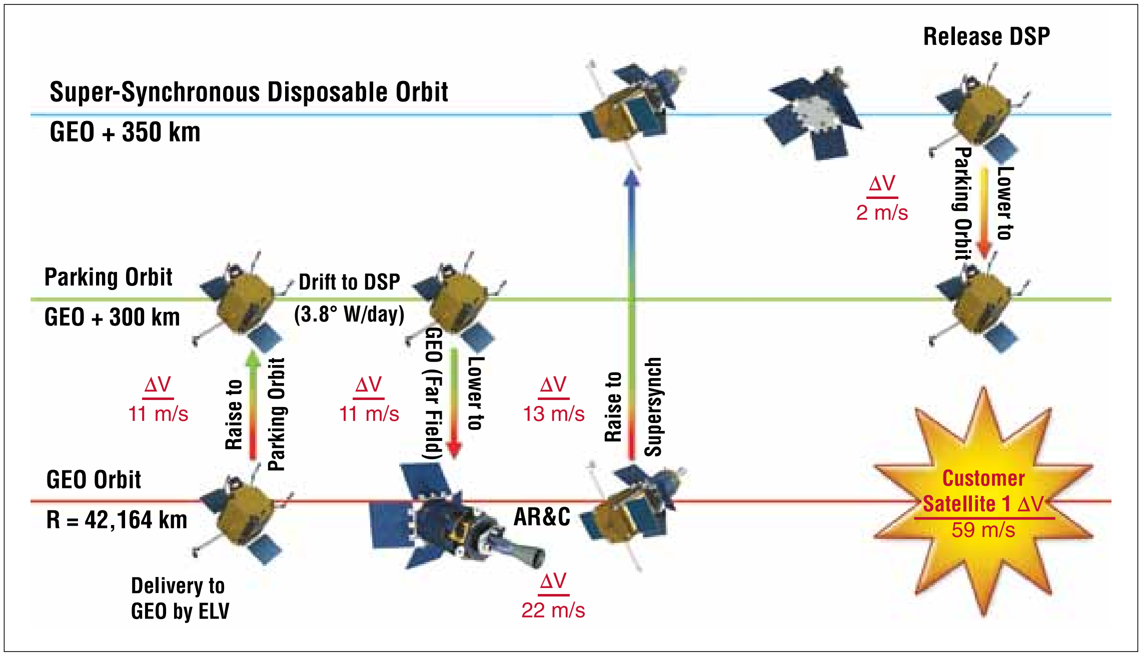


Figure NM1-3: Orbital Maneuvers Performed during Customer Capture and Boost

predefined capture box). The robotic arms then autonomously grasp the Customer at predefined grapple points and complete the capture.

At this point, the Customer satellite goes into free drift and the Servicer controls the stacked spacecraft. It is assumed that non-functional spacecraft will already be in free drift by definition, and furthermore, that functional spacecraft can be commanded to go into free drift. The Servicer boosts the stack into a super-synchronous disposal orbit (GEO + 350 km) as per NASA-STD-8719.14 (Process for Limiting Orbital Debris). The Servicer releases the Customer satellite and then lowers itself to a parking orbit approximately 300 km above GEO. The Servicer stays in this parking orbit until the next Customer is ready for removal. Figure NM1-3 illustrates the orbital maneuvers performed during Customer capture and boost. After the last Customer is supersynched, the servicer and the Customer both remain in the super-synchronous disposal orbit. The NM1 mission life is 5 years, during which 10 Customer satellites will be serviced.

Servicing mission operations are conducted from the NASA's Goddard Space Flight Center's (GSFC) Servicing Mission Operations Center (SMOC). The AR&C phase is supervised from the ground and includes scheduled hold points, during which the ground team assesses the situation and provides permission for the Servicer to proceed autonomously between hold points. After the AR&C phase, the robotic activities will be teleoperated from the ground.

System Description

The Servicer spacecraft design includes sensors, algorithms and four robot arms for autonomous capture of non-cooperative Customer satellites in geosynchronous orbit and subsequent boost to disposal orbit. This mission uses an AR&C package (sensors and avionics) with a pan/tilt unit designed during the associated IDL study (see Appendix E). The total AR&C package mass is 141.1 kg; the peak power draw is 128.9 W; the peak data rate is 996 Mbps (786 Mbps with compression), and the enveloping dimensions of the AR&C sensor and avionics package on the pan/tilt unit are 1400 × 750 × 723 mm.

The Servicer has four identical 2 m robot arms affixed to the sides at the front corners. The arms autonomously grasp the customer spacecraft and hold it as the Servicer boosts the stack. As a result, the arms are an integral component of the Servicer's AR&C capability. The robot arms are designed to be robust enough to withstand the loads generated while de-spinning a Customer. Each arm is attached to the Servicer via a mounting surface that houses the arm on the external surface and its centralized control avionics on the internal surface. The mounting pallet is then hard mounted to the spacecraft structure, which allows the arms to be fully verified at the assembly level prior to integration with the spacecraft.

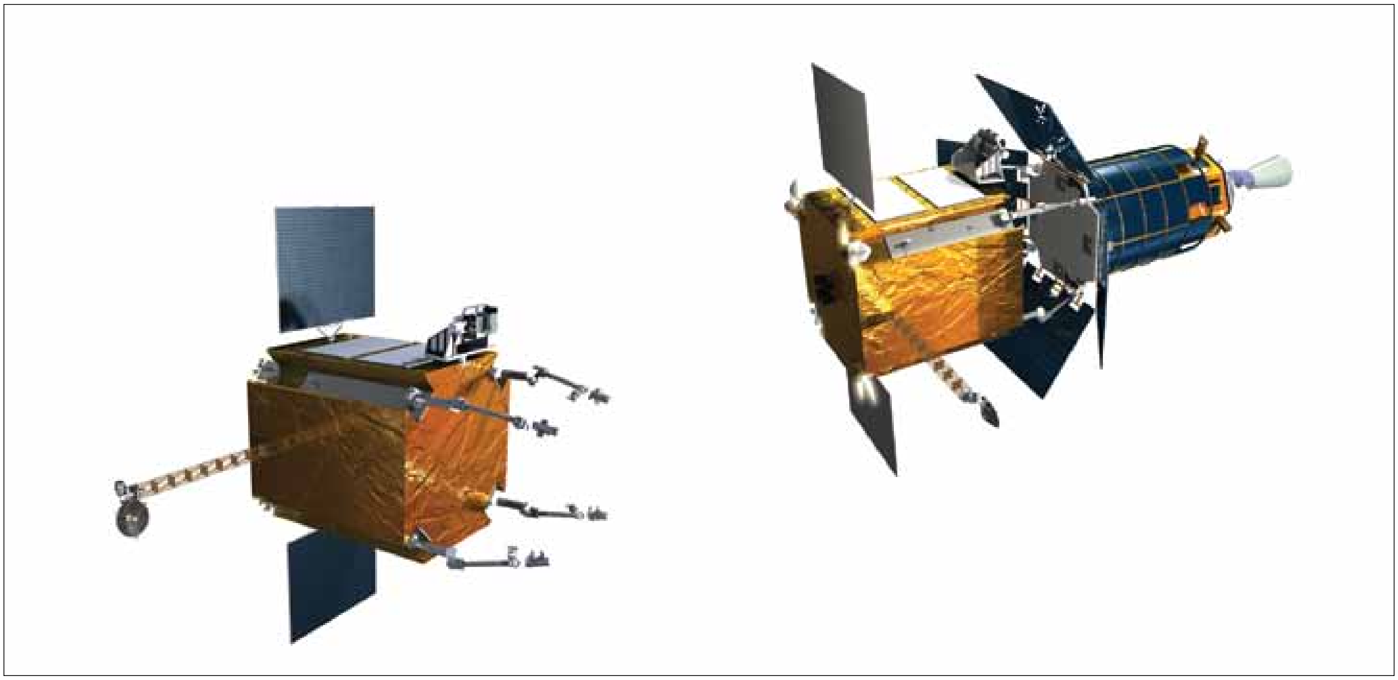


Figure NM1-4: Servicer in Launch, Deployed and Docked Configuration

A gripper is envisioned to attach to the grapple points and is equipped with a LIDAR to sense the Customer. Except during the AR&C phase, the arms are teleoperated from the ground. The total signal latency from ground command to robot motion, including all security measures, is predicted to be less than 3 seconds; the requirement is that the latency be less than 7 seconds during a sortie.

The Servicer is a 3-axis stabilized, sun-pointing, fully redundant bus system. The AR&C avionics handle collision avoidance while approaching the customer satellite. The two deployable, gimbaled solar arrays are mounted 180 degrees apart. The power system provides approximately 1,500 W of total average power and has two 100 Ahr Li-Ion batteries. The data rate is 10 Mbps, and the system has 250 Gbits of data storage capability. The data communication protocols are CCSDS, S-band for housekeeping and X-band for operations. Figure NM1-4 shows the Servicer configuration during three phases: launch, deployed and stacked (holding the Customer).

The baseline Servicer spacecraft design utilizes chemical propulsion. The Servicer dry mass (including 30% contingency) is 2,352 kg, with a wet mass of 3,694 kg. This notional Servicer could be launched to GEO on an Atlas V with only 7% margin, or on a Delta IV Heavy with 70% margin.

I&T and Schedule

The Servicer mission integration and test (I&T) is executed at the NASA Goddard Space Flight Center. The AR&C sensor/avionics package and robot systems are delivered to GSFC ready for integration and test with the Servicer vehicle. Both are fully qualified prior to delivery for Servicer I&T. The development schedule is shown in Figure NM1-5.

The Servicer test and verification includes alignment and calibration of bus sensors (e.g., star trackers). Deployables (solar array, high gain antenna booms) undergo integrated functional verification at the bus level.

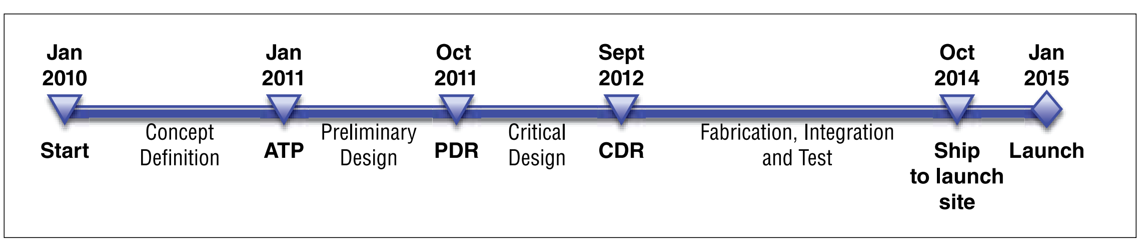


Figure NM1-5: NM1 Mission Schedule

Enabling Technologies

No specific technology needs have been identified for this mission. However, a less massive spacecraft bus would decrease launch mass and allow the Servicer to carry more fuel, which would increase the number of Customer spacecraft that could be serviced. Additionally, a detailed analysis of the use of solar electric propulsion for this mission should be performed. While using solar electric propulsion for the orbit plane change maneuvers between Customers would increase the mission duration, it could also allow a significantly larger number of Customer satellites to be boosted to super-synchronous disposal orbit by virtue of propellant mass savings.

Key Assumptions

The ability of the Servicer to capture and "supersync" (place in a super-synchronous disposal orbit) multiple Customers depends strongly on the actual masses and attitude rates of the Customers. The masses of Customer satellites may vary, though our team made the simplifying assumption that all of the Customer satellites will have similar mass properties to the first. Also, the ΔV required for capture depends on the Customers having attitude rates of, at most, 0.25 degree per second per axis. However, if some Customers have higher attitude rates, this can drive up the ΔV required for capture significantly. For example, if a Customer has an attitude rate of 1 degree per second per axis, the capture ΔV is approximately 20 m/s, compared to 2 m/s for the 0.25 degree per second per axis case. Generally, all else being equal, the required ΔV for capture increases in proportion to the square of the Customer's attitude rate. Thus, as Customer attitude rate increases, it can begin to compete with the plane change ΔV between Customers, and even surpass it to become the main driver of total mission ΔV.

NM1 GEO Supersync Mission	Current Best Estimate Phase A-F ($M, FY 10)
Robot (4 dexterous arms)	$330
AR&C (w/PTU)	$75
Bus	$140
Launch Vehicle	$190
Operations	$14
Everything Else	$160
Total Servicing Cost	**$910**

Notional Mission 2: GEO Refueling

Mission Study Objectives

The objective of this study is to develop a mission concept, Refueler spacecraft design, and on-orbit fuel depot design to facilitate the refueling of multiple Customer spacecraft at GEO. This mission design is intended to address the in-orbit refueling portion of the on-orbit servicing trade space.

Mission Overview

Notional Mission 2 (NM2) is designed to refuel satellites in the GEO belt. The NM2 is composed of two satellites: the Refueler and the Fuel Depot. The Refueler spacecraft is small and agile, and is designed to carry enough fuel to refuel five Customer satellites during a sortie. In between sorties the Refueler spacecraft will rendezvous with the Fuel Depot to take on more fuel. The fuel Depot carries sufficient fuel to allow the Servicer to refuel up to 25 Customer satellites, based on some key simplifying assumptions regarding the distribution of Customer satellite orbits. A minimalist approach was taken for the design of the Fuel Depot itself, and consequently, it is only equipped with adequate subsystems to exist passively at GEO. Figure NM2-1 presents the on-orbit refueling concept of operations.

The Refueler and Depot are launched together on a Delta IV Heavy to 100 km above GEO, where the Depot remains. The Refueler nominally delivers fuel to five Customer satellites before returning to the Depot to refuel itself. While attached to the Depot during its own refueling, the Refueler executes maneuvers to maintain the Depot

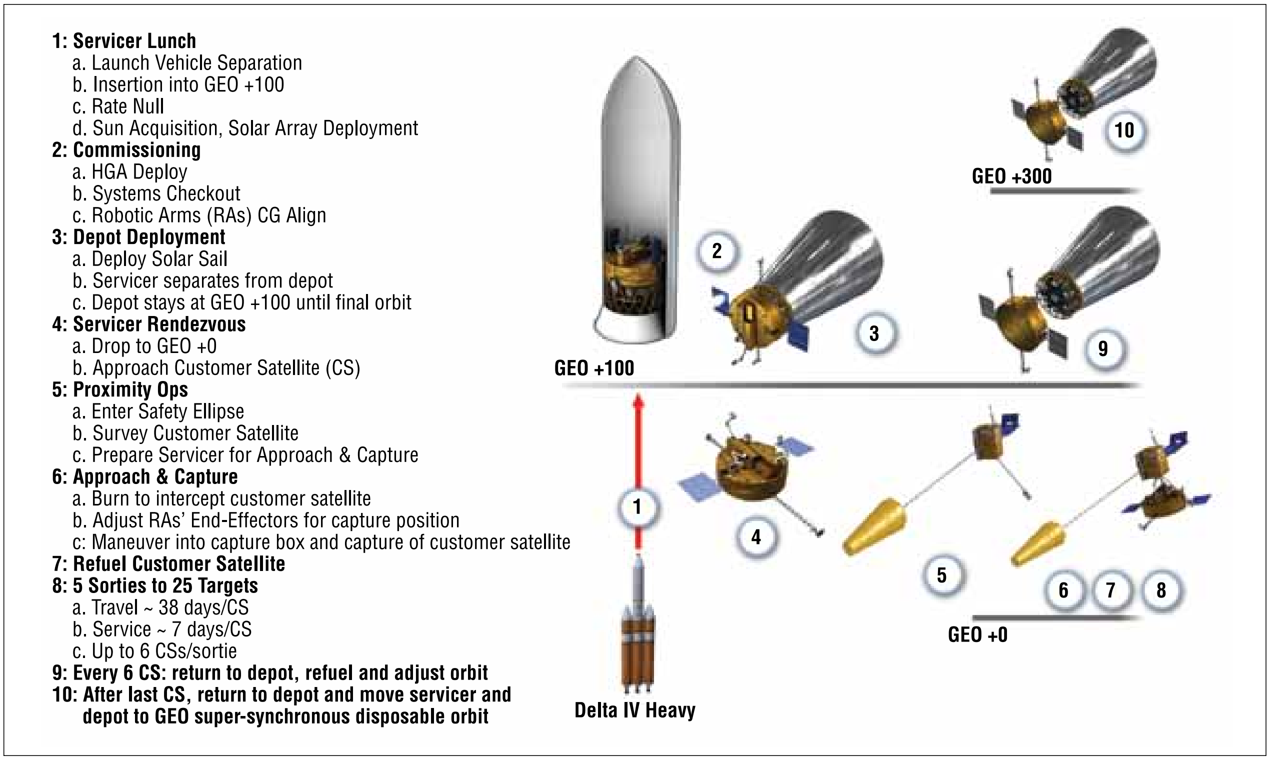


Figure NM2-1: On-Orbit Geosynchronous Refueling Concept of Operations

orbit plane (which drifts under the influence of natural perturbations). Figure NM2-2 is the nominal scenario for the refueling mission.

The NM2 study assumes mission launch in 2015 and mission life of 10 years. The Figure NM2-3 depicts the refueling operations concept, including autonomous rendezvous and capture (AR&C) with the Depot. During each AR&C phase, the Refueler AR&C system (sensors and avionics) commands the bus GN&C system. The Customer satellites are assumed not to be in uncontrolled attitude states (3-axis stabilized) and are able to enter free drift prior to capture. It is further assumed that the Customer satellites each need to receive only 20 kg of Hydrazine per refueling.

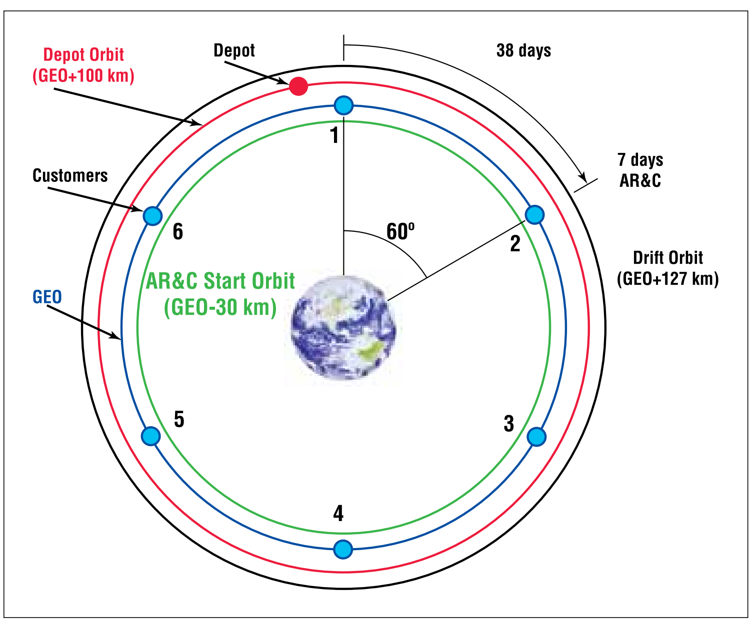


Figure NM2-2: Nominal Refueling Mission Scenario

During nominal operations, the Customer satellite is commanded by its ground controllers to enter free drift towards the end of the AR&C sequence. However, this presumes that the Customer satellite still has adequate remaining propellant to be controlling its attitude prior to AR&C. If the Customer satellite is completely out of fuel before receiving the refueling service, then an assumption made in NM1 is applied, which is that the maximum uncontrolled Customer attitude rates are no more than 0.25 degrees per second per axis. However, in contrast to NM1, the NM2 study assumes that none of the Customer satellites are non-functional. Thus, it is assumed that even if the Customer satellite is completely out of fuel and not controlling its attitude, the Customer ground controllers can still command the Customer satellite's control system to become completely quiescent. This will prevent the Customer spacecraft's control system from inadvertently attempting to counteract the forces and torques imparted by the Refueler spacecraft during mated operations (after refueling and prior to release).

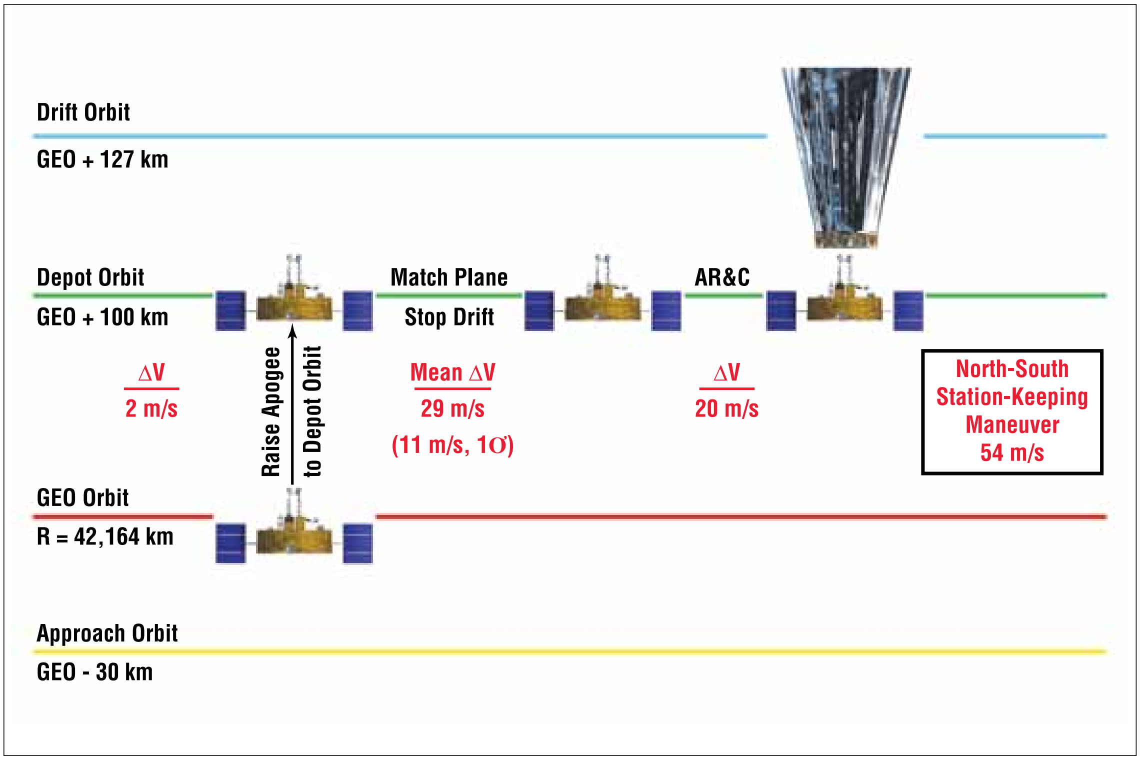


Figure NM2-3: Refueling Concept of Operations and AR&C with Depot

Furthermore, provisions are included in the design of all AR&C sequences in the notional mission suite studies such that the Refueler spacecraft can gracefully retreat along the approach axis in response to any anomalies that may occur during the final approach phase of the AR&C sequence, and then re-approach when anomalies are resolved. This allows multiple capture attempts to be made if necessary, while ensuring the safety of both the Refueler and Customer spacecraft.

Refueling mission operations are conducted from the NASA Goddard Space Flight Center Refueling Mission Operations Center (MOC). AR&C sequences between the Refueler and the Customer satellites are autonomous but supervised by the ground, with scheduled hold points during which the mission operations team assesses the situation and provides permission for the Refueler to proceed autonomously between hold points. After the AR&C phase, refueling activities will be teleoperated from the ground. To accommodate teleoperation from ground, communications will be continuous, thus providing constant telemetry and commanding during refueling. One contact per day with the Refuler is planned for monitoring between Customer satellite refuelings.

Refueler and Depot System Description

The Refueler spacecraft carries the modified AR&C system (without a pan/tilt unit but with four extra cameras), two robot arms, two toolboxes, and the refueling system/package. The dry mass for the Refueler spacecraft, including payload elements, is 1,894 kg (includes 30% contingency).

After initial separation from the Depot post-launch, the Refueler raises its orbit from GEO + 100 km to GEO + 127 km in order to drift between the Customer spacecraft below at GEO. As shown in Figure NM2-2, this study makes the simplifying assumption that all of the Customer spacecraft are evenly spaced around the GEO belt. A further assumption is that Customer spacecraft orbit planes are within ±1° of the equatorial plane. Once the Refueler is within 300 km of a Customer, the Refueler will lower its orbit to GEO – 30 km in order to begin the same AR&C sequence described in NM1. Accordingly, 20 m/s of ΔV on the part of the Refueler is budgeted for each of these AR&C sequences. After capture and refueling, the Refueler releases the Customer and then transfers back to a GEO + 127 km orbit to drift to the next Customer. This cycle repeats until six Customers have each had 20 kg of propellant delivered to them, at which time the Refueler raises its orbit to GEO + 70 km, drifts to within 300 km of the Depot, and executes the standard AR&C sequence with the Depot. After attaching to the Depot and taking on propellant, the Refueler performs a maneuver to correct the Depot's orbit plane (which has drifted by approximately 1° under the influence of natural perturbations while the Refueler was performing sorties). The Refueler then tops off its fuel tanks and proceeds to conduct further sorties. Once the Refueler and Depot only have enough fuel remaining for their disposal, the Refueler will perform AR&C with the Depot once more and then boost the Refueler/Depot stack to GEO + 300 km for proper disposal.

A parallel study was completed shortly after the MDL study which utilized a special algorithm to perform near-optimal ordering of the Customer spacecraft, drawing upon a database of orbital elements for actual operational U.S. GEO satellites that use Hydrazine propellant. The results of this parallel study demonstrated that—with near-optimal ordering and proper selection of the first Customer satellite in the sequence—the Refueler design is indeed capable of visiting and refueling up to 26 customer satellites. Thus, the Refueler will perform a total of five sorties. Four sorties consist of six satellites each, and the fifth sortie consists of two customer satellites.

The Refueler has two 2-m long robots affixed to the front/top of the bus structure on a mounting surface. This mounting surface houses the arm on one side with its electronics (DMU & ACE) mounted on its back (or internal) surface. The mounting pallet is hard mounted side by side to the Refueler spacecraft structure. The arms perform an autonomous capture and will be teleoperated for the refueling tasks. There are two toolboxes on the Refueler. These toolboxes can and will be exchanged with toolboxes in the Depot for servicing different Customer satellites. Power comes from the bus through the Power System Electronics (PSE) in the Refueler spacecraft. Command and control of the robot arm (or signals for data, control, monitoring, and timing) is through the CSI hard lines to the avionics/C&DH subsystem on the Refueler bus.

The Refueler bus structure is of composite truss design with composite/aluminum honeycomb decks. The thermal system includes Multilayer Insulation (MLI), heaters, thermistors, thermostats, variable conductance heat pipes, and radiators sized for potential full sun load. The RF communication system includes S-band Omni, and X-band HGA, capable of 10 Mbps downlink. The solar array has a total area of 7.2 m2 and uses Tj GaAS cells with dual-axis SA drives. There are two 100 Ah Li-Ion JSB batteries. The power system is sized for two 72-minute maximum eclipse seasons twice per year. The baseline power system electronics system consists of a heritage 28 VDC battery-dominated bus. The ACS is thruster-based and its components include star trackers, IRU, CSS, and GPS. Figure NM2-4 presents the Refueler, robot arms, and bus components.

The Depot is designed to be a passive spacecraft that can exist passively at GEO with minimal support. The dry mass for the Depot is 1,326 kg (includes 30% contingency). Its mechanical structure is of a composite truss design with composite/aluminum honeycomb decks. The thermal system includes MLI, heaters, thermistors and thermostats. The Depot has no RF communication system and no avionics. It has ~1m^2 of solar array but it has

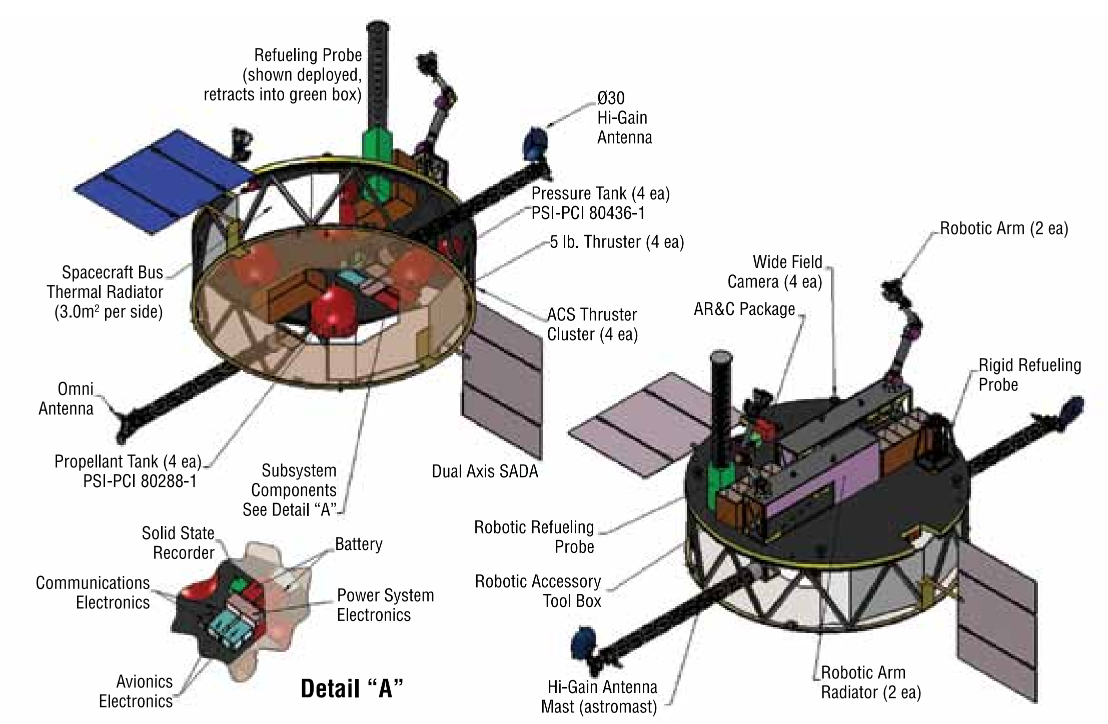


Figure NM2-4: Refueler Spacecraft Components and Robot Arms

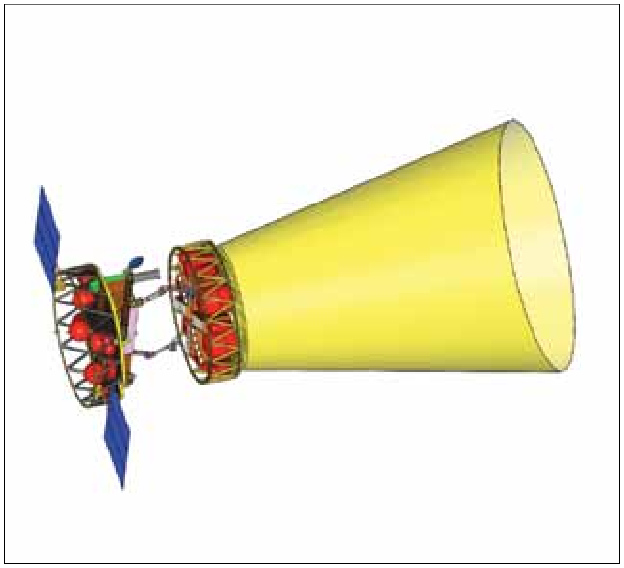


Figure NM2-5: Depot with Refueler Attached

Figure NM2-6: Customer Satellite with Refueler Spacecraft Attached

no battery. The ACS system passively maintains the Depot in a sun-pointing attitude through use of a deployable solar sail and a libration damper. The Depot itself does not have thrusters, but carries both Hz propellant and N^2 pressurant. Depot telemetry is read by the Refueler when it is attached to the Depot. The Depot is designed to be a passive and cooperative rendezvous customer for the Refueler and therefore has retroflectors mounted on its surface. It also contains six toolboxes that can be used by the Refueler to service different Customer satellites. Figure NM2-5 shows the Depot and the Refueler together, while Figure NM2-6 shows the Refueler with a Customer satellite during refueling.

I&T and Schedule

Figure NM2-7 shows development schedules for the Refueler and Depot. They are scheduled to begin at approximately at the same time so that they would complete their individual environmental test programs in time for “stack” integration and test and launch no earlier than Fall of 2015.

Enabling Technologies

Enabling technologies for this mission are TRL 6 and above.

Key Assumptions

Two key assumptions are that the Customer satellites will have rates less than 0.25 deg/sec/axis and that the Refueler solar array will have no less than 30% illumination. It is also assumed that two toolboxes on the Refueler will be adequate to refuel five Customer satellites at a time, and the additional six toolboxes on the Depot are sufficient to refuel the follow-on Customer satellites.

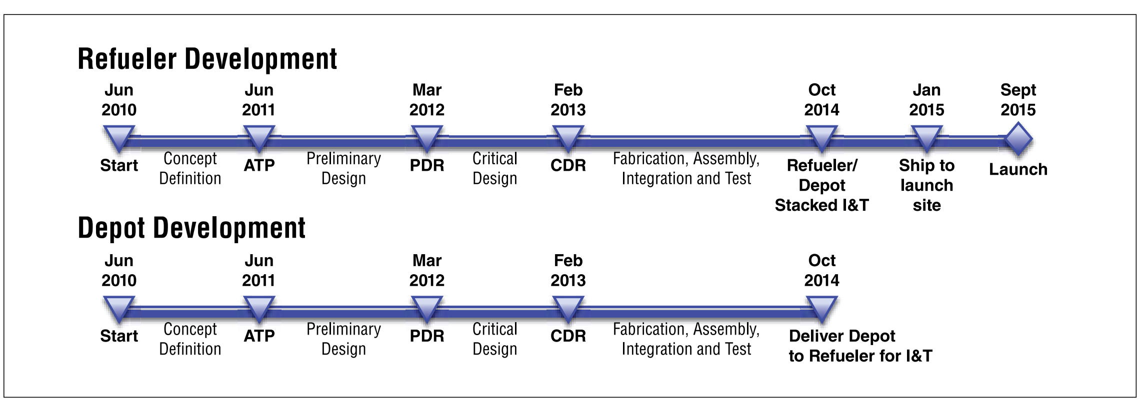


Figure NM2-7: Refueler ahd Depot Schedules

NM2 GEO Refueling Mission (Servicer + Depot)	Current Best Estimate Phase A-F ($M, FY 10)
AR&C	$60
Robot (2 dexterous arms)	$240
Payload	$80
Bus (Servicer & Depot)	$220
Launch Vehicle	$300
Operations	$80
Everything Else	$200
Total Servicing Cost	**$1,180**

Notional Mission 3: Robotic and Human Servicing of Satellite in LEO

Mission Study Objectives

The Notional Mission 3 (NM3) study objective is to develop a Servicer spacecraft design to support a non-shuttle-based human/robotic mission to refurbish a cooperative customer satellite in LEO that was designed to be serviced. The Servicer carries and accommodates all the robotic elements and tools, the airlock and all associated consumables, and all the replacement/upgrade hardware that is to be installed in the customer satellite. The Servicer is also equipped with all the necessary sensors and algorithms to perform AR&C with the cooperative customer satellite, and to support subsequent cooperative rendezvous and berthing of a Commercial Orbital Transportation Services (COTS) crew vehicle with the Servicer and Customer in their mated configuration. The Hubble Space Telescope (HST) serves as the cooperative customer satellite in LEO, and the SpaceX Dragon serves as the crew vehicle.

Mission Overview

The NM3 flight segments include the Servicer spacecraft, known as the Dexterous Service Module (DSM), HST, and Dragon. The DSM is the only vehicle to be designed during the NM3 study; the HST and Dragon are assumed to exist and be ready for use.

At the start of the month-long servicing mission (see Figure NM3-1), the HST is operating in LEO with a known set of required hardware refurbishment/replacement tasks. The DSM launches equipped with two robotic arms, the airlock and consumables for five cycles of EVA repress and depress, two active LIDS, tools, and new HST hardware to be installed during the mission. After launch and separation, DSM completes orbit insertion into a circular LEO at 537.5 km and performs systems checkout. Prior to crew launch, DSM completes in-orbit checkout (IOC), performs AR&C with HST, and performs predefined robotic get-ahead tasks in a manner that satisfies “operationally safe to release” criteria established for previous STS servicing missions.

Following successful AR&C and servicing get-aheads of HST, the stacked DSM/HST participates in a AR&C sequence with Dragon. Following the current plan for International Space Station (ISS) procedures, Dragon maneuvers into a defined capture box near the DSM/HST stack, after which the robotic arm on DSM autonomously grapples Dragon. A scripted berthing procedure is then executed to mate Dragon to the DSM airlock. A wireless communication system allows the Dragon crew to perform the grapple and berth procedures manually if necessary. Figure NM3-2 presents the concept of operations.

The four-person crew performs two days of Extravehicular Activity (EVA) during which two EVA crew members are assisted by the DSM robotic systems that are operated by the Intra-vehicular (IV) crew. During sleep periods between the EVA days, the ground team teleoperates the DSM robots, completing clean-up or get-ahead tasks in preparation for the next day’s work. This synergistic combination of dexterous robotic work and human EVA enables the servicing mission to accomplish significantly more work during the month-long mission than a human crew could during the two planned EVA days.

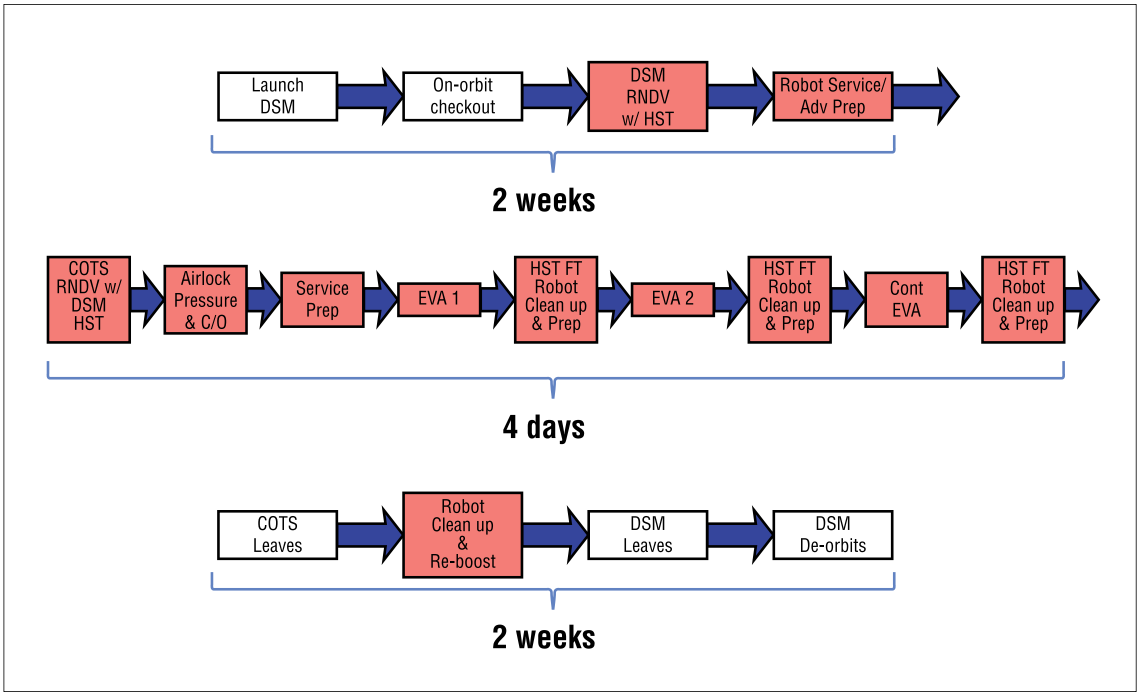


Figure NM3-1: Mission Timeline

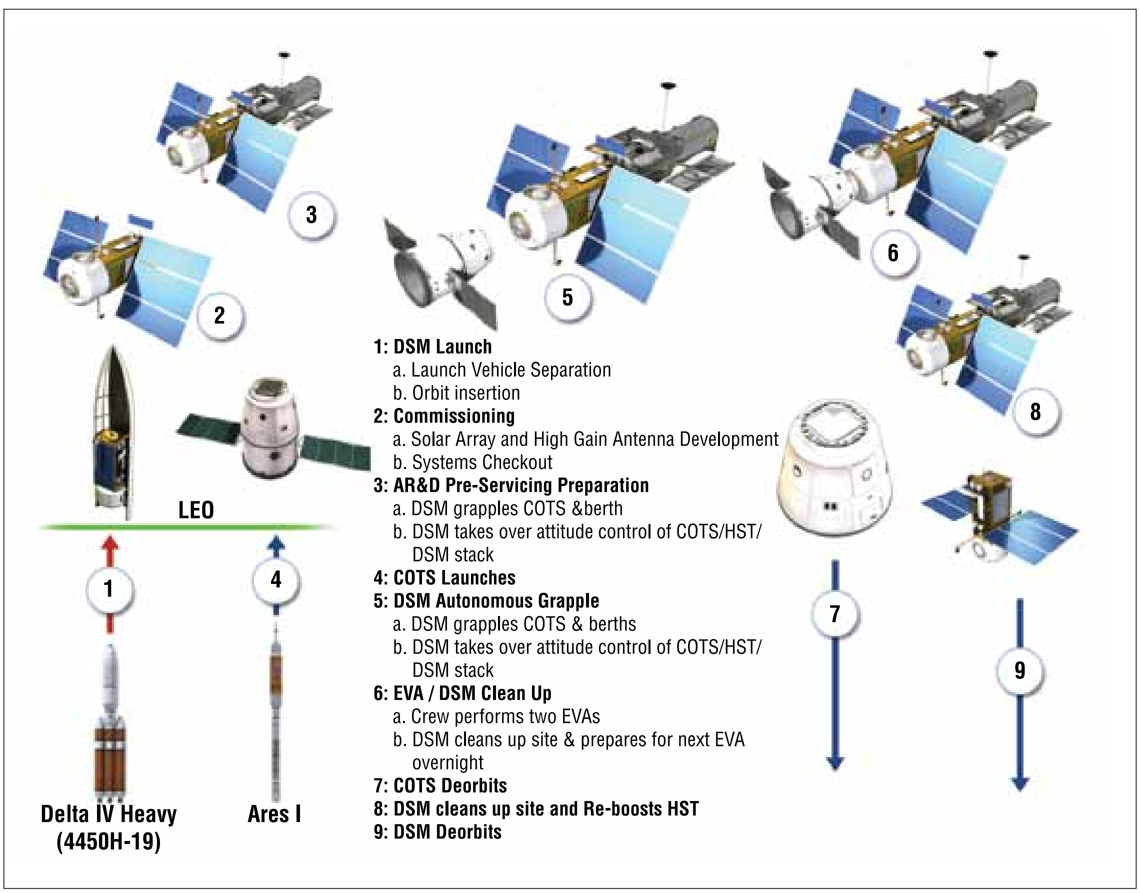


Figure NM3-2: Robotic and Human Servicing of Satellite in LEO Concept of Operations

After completion of the EVA tasks, Dragon is deployed by DSM and the crew proceeds to return to Earth. The ground team then teleoperates the DSM robotic arms to complete closeout and HST hardware safing tasks, returning HST to nominal operation. The DSM then boosts HST's orbit by as much as 60 km and deploys HST. Finally, DSM performs a deorbit maneuver and reenters the atmosphere. Figure NM3-2 shows the mission timeline, and Figure NM3-3 shows the DSM orbital maneuvers during rendezvous with and capture of HST.

Dexterous Servicer Module (DSM) Description

The DSM consists of a spacecraft bus, robots, tools (in toolboxes), HST hardware, and the necessary sensors and algorithms for AR&C with HST and AR&C with Dragon. The AR&C hardware includes the standard sensor package without the pan/tilt unit and retroreflectors. The DSM bus contains an active LIDS to which HST is berthed, and a CBM/LIDS to which Dragon is berthed. The bus also contains 12 Multi-Function Ports (MFP), which provide structural/power/data interfaces to robot arms and other payloads such as the sunshield. Figure NM3-4 shows the DSM components.

Two robots are affixed to the front side of the DSM, with a robot arm on either side of the LIDS mechanism. Both arms are human-rated, two-fault tolerant systems with manual override options for critical operations and capabilities. A 14 m, two-link robot arm is used to berth and deploy Dragon and to position an astronaut at the various worksites during EVAs. The second 7 m robot arm can also position an astronaut, but it is designed to use a specialized end-effector to perform more dexterous manipulation. Both arms are hard-mounted to the servicer structure, and the arm electronics for each arm are identical, centralized avionics. The arms are teleoperated from the ground except while the crew members are conducting an EVA, in which case the arms are operated by an IVA crew member in Dragon. Power and data for the robot arm are passed through Robot Mounting Points (RMPs) to the DSM bus systems.

The DSM bus structure is comprised of composite/aluminum honeycomb panel construction with deployable payload bay doors. The thermal system includes a 15.5 m^2 radiator with embedded heat pipes, loop heat pipes for payload and bus components, thermostatically controlled heaters, multi-layer insulation (MLI), and coatings. The RF communication system consists of Ka band High Gain Antennas (HGA) to TDRS, S-band omnidirectional antenna to ground, UHF to the Dragon (for video), S-band to the HST, and GPS for orbit determination. The bus contains eight 100 Ahr Li-Ion batteries and a 110 m^2 Tj GaAs solar array. The power system buses are block redundant, and

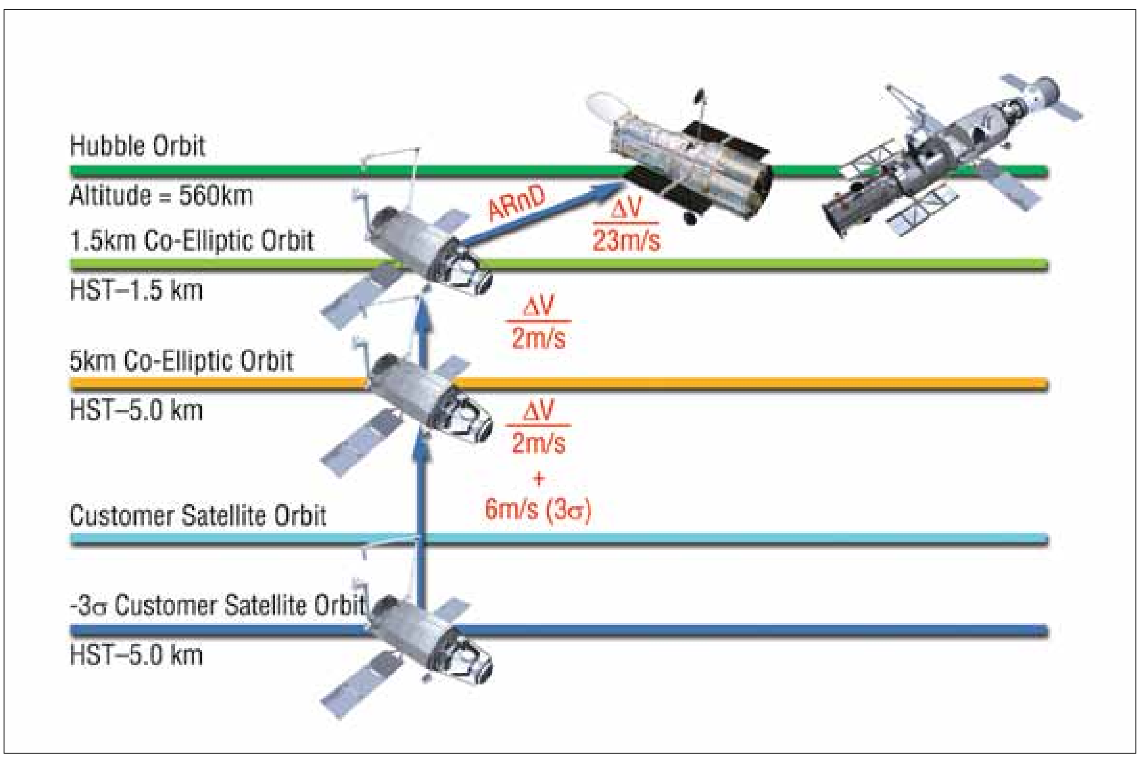


Figure NM3-3: DSM Orbital Maneuvers to Rendezvous with and Capture HST

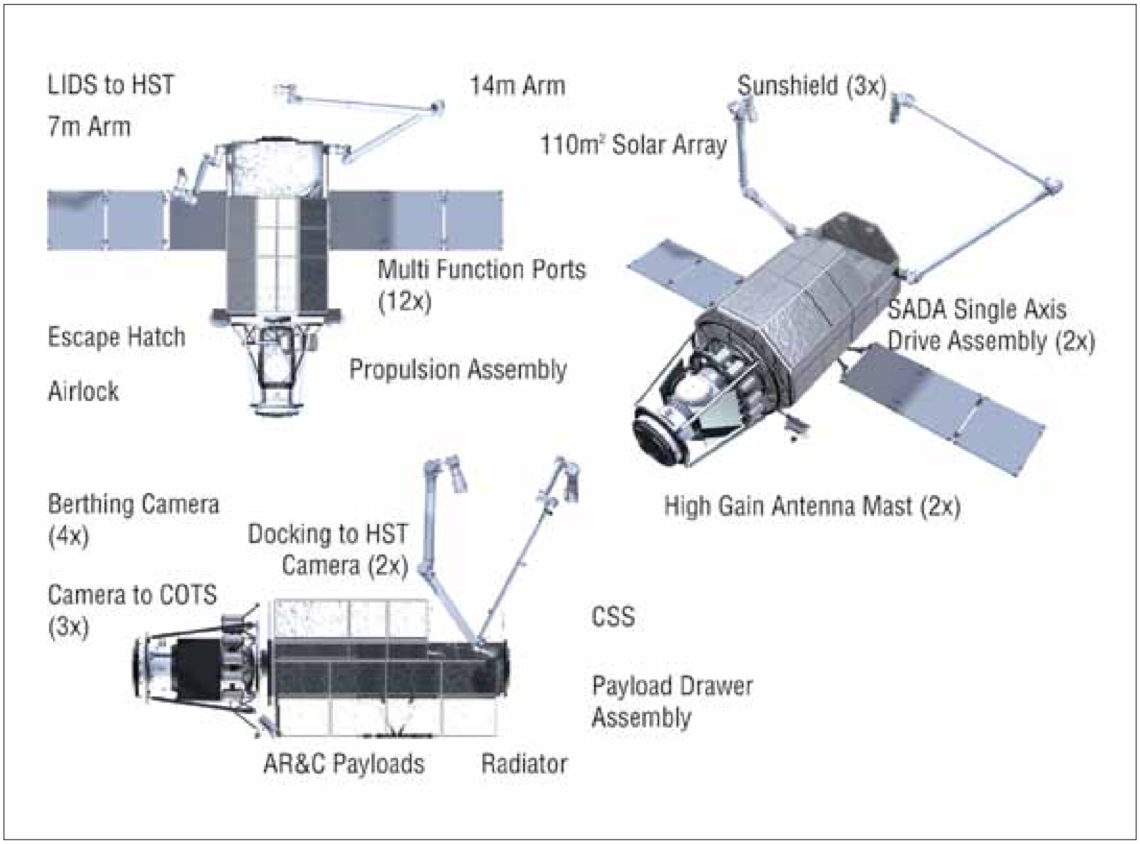


Figure NM3-4: Dexterous Servicer Module (DSM) Components

the attitude control system (ACS) is thruster-based with 6-DOF control. Large engines are used for orbit maneuvers, while the small engines are for proximity operations and attitude control. During stacked operations, solar-inertial attitude supports solar array pointing and worksite shading. The ACS components also include star trackers, IMUs, and CSS. The propulsion system has two modes with regulated pressure, allowing either bipropellant or monopropellant operation. The total propellant mass is 4,350 kg. Thrusters are canted 60o from sensitive areas to minimize plume-induced structural loads, heating and contamination. There are three main flight computers with auto FDIR and voting. Figure NM3-5 shows DSM and HST mated together. Figure NM3-6 depicts the COTS/DSM/HST Stack.

I&T and Schedule

For the purpose of mission study planning, phase A is 12 months in duration and phase B starts in July 2011. The DSM launch date is March 2017, and 39 months are allowed for DSM fabrication and integration of bus and payloads. The schedule allows staggered payload deliveries; the airlock is delivered first during DSM fabrication, and EVA tools are delivered last at NASA's Kennedy Space Center (KSC) during prelaunch. The conceptual mission schedule is presented in Figure NM3-7.

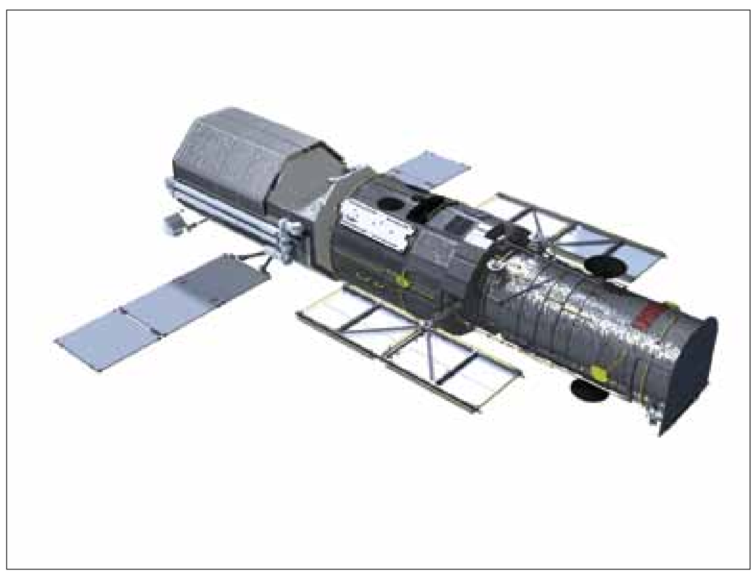


Figure NM3-5: DSM/HST Stack

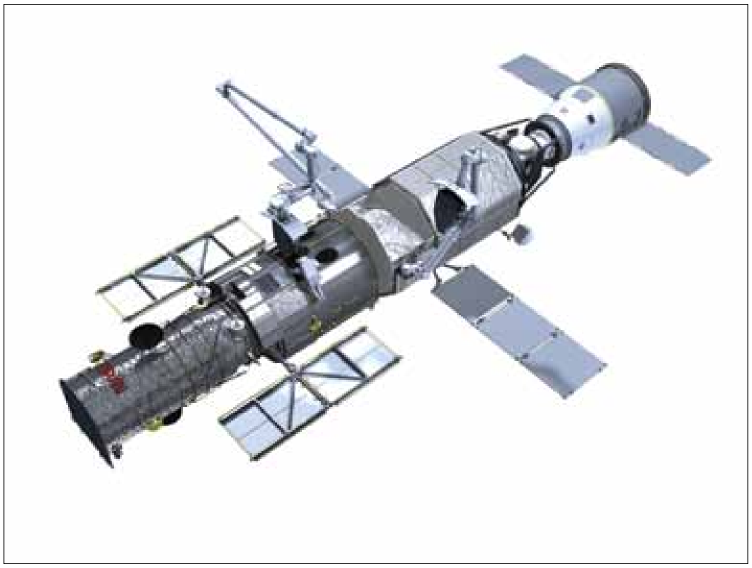


Figure NM3-6: COTS/DSM/HST Stack

Enabling Technologies

No new technology development needs have been identified for this mission.

Key Assumptions

The Hubble Space Telescope (HST) is used as the Customer for this run because it is an excellent historical source of defined interfaces that drove Servicer requirements during actual previous missions. As a notional Customer, HST provides known tool, crew, and vehicle interfaces, keep-out and "no-touch/no-damage" zones, and limits on plume impingement and hardware temperatures. Having set standards for tool development over five servicing missions, it is a proven test bed for LEO on-orbit repair and refurbishment. These well-understood interfaces allowed the study team to focus on developing the Servicer.

NM3 LEO Refurb COTS Mission	Current Best Estimate Phase A-F ($M, FY 10)
AR&C	$60
Robot (2 human rated GAs)	$350
Payload	$460
Servicer Bus	$670
Airlock	$200
Operations	$30
Launch Vehicle	$300
Everything Else	$500
Total Servicing Cost	**$2,570**

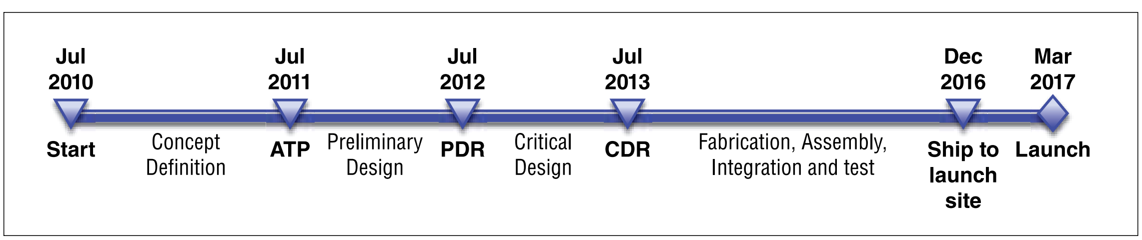


Figure NM3-7: Mission Schedule

Notional Mission 4: Assembly of the Thirty-Meter Space Telescope (TMST) at EML1

Mission Study Objectives

The Notional Mission 4 (NM4) study objective is to develop a Servicer design concept that provides a platform for robots to assemble a Thirty-Meter Space Telescope (TMST) at EML1. The Servicer carries the robotic elements and mounting points for the observatory and is also designed to be a passive, cooperative customer vehicle for AR&C with the Construction Barges that will be sent to it prior to TMST construction. Additionally, the Servicer will possess the sensors and algorithms required to perform AR&C with the TMST for periodic post-construction servicing. All subsystems are serviceable and are sized to accommodate the TMST requirements during the two-year assembly process. Following the deployment of the assembled TMST, the Servicer remains at EML1 for 20 years and serves as a platform for robotic servicing of the TMST or other customers.

Mission Overview

The NM4 flight segments include the Robotic Telescope Construction Servicer (RTCS) and eleven Barges carrying the parts that will be assembled to create the TMST, additional tools, and robot modules. Three of the eleven Barges carry hardware needed for the periodic servicing of the TMST. All flight segments are launched on a Delta IV Heavy launch vehicle, which limits the mass that can be carried up with the RTCS and dictates the number of launches required to complete the entire mission. Thus, at launch, the RTCS consists of a spacecraft bus with all the accommodations necessary to complete the assembly mission and AR&C mission phases with a single, operational robot arm. The first Barge carries all remaining robotic hardware (in a Quiver) and tools (in a Toolbox), a deployable solar array to augment the power system, and the first pieces of the observatory.

The RTCS is launched directly into a high-energy Earth departure trajectory towards the EML1 Lyapunov orbit insertion point. The launch energy (C_3) is approximately -2.4 km2/s2, meaning that the launch vehicle (and its upper stage) has to impart slightly less energy to the RTCS than it would for a lunar mission. The flight time required for the RTCS to arrive at the Lyapunov insertion point is approximately 6 days. Upon arrival at the insertion point, the RTCS performs a ΔV of approximately 600 m/s to insert itself into the EML1 Lyapunov orbit. This trajectory sequence is depicted in Figure NM4-1. The RTCS will station-keep on this orbit while awaiting the arrival of the Construction Barges. The characteristics of the EML1 Lyapunov orbit are also shown in Figure NM4-1. The Lyapunov orbit has a period of approximately 12.135 days, is approximately 60,000 km in size along its longest axis, and is approximately 16,850 km wide along its shortest axis. One of the key advantages of this orbit is that the RTCS need only execute at most 60 m/s of ΔV annually to maintain the Lyapunov orbit.

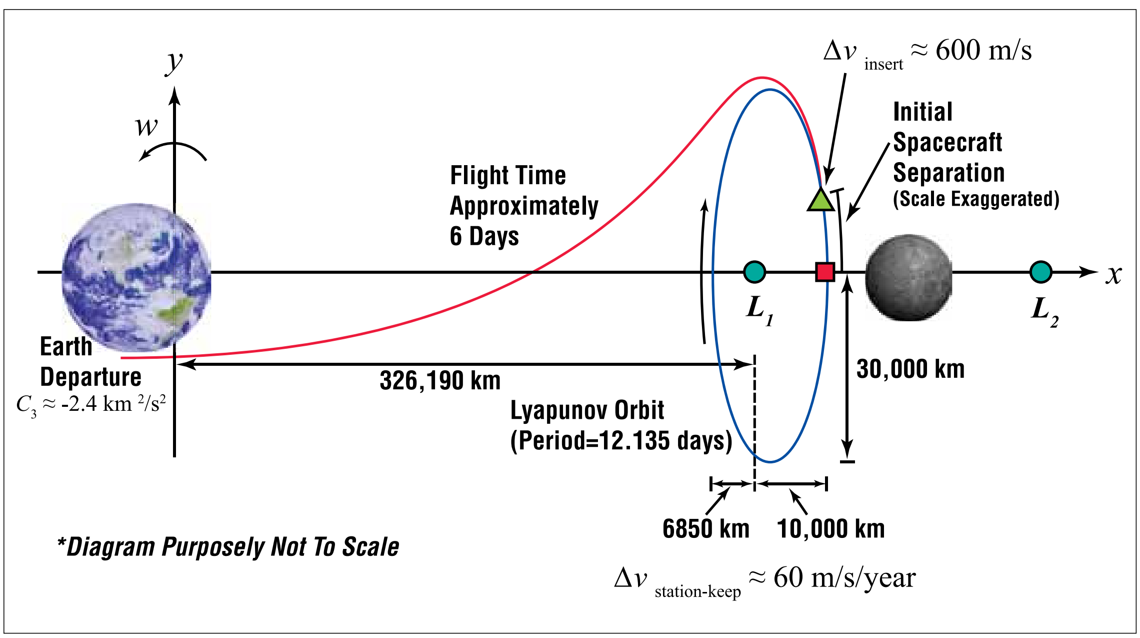


Figure NM4-1: Trajectory from Earth to EML1 Lyapunov Orbit

The Construction Barges launch after the RTCS is on-station in the EML1 Lyapunov orbit. The trajectories they fly from Earth are nearly identical to the RTCS trajectory, with one exception. The Barges insert into the Lyapunov orbit approximately 1,000 km behind the RTCS, at a time when the RTCS is located at its original insertion point. This allows the Barges to exploit features of the natural relative spacecraft dynamics on Lyapunov orbits to help them gradually close distance for AR&C with the RTCS over the course of approximately 1 week. Under these conditions, the AR&C sequence between a Barge and the RTCS requires only 12 m/s of ΔV from the Barge.

The Barges are not addressed in this study except to the extent that interfaces drive the RTCS and mission design. For example, the AR&C sequences between each Barge and the RTCS drive the specification of hardware and algorithms to create a completely cooperative rendezvous system. Similarly, the lengthy operation of two mated spacecraft requires an autonomy manager to determine the proper course of action for the stack, should any flight element request safing. A workable interface was defined to allow the RTCS design to move forward in cases that would otherwise have required detailed Barge design, and it is assumed that the Barge elements can accommodate those interfaces.

The NM4 launch date is not before the middle of the 2020s, and the TMST construction period is two years. Upon completion, the TMST is deployed to SEL2 for science investigation, and the RTCS remains at EML1 for future on-orbit servicing. The RTCS station-keeps on the EML1 Lyapunov orbit for 20 years, available to service the TMST or another spacecraft every five years. The RTCS is refurbished to upgrade or repair aging hardware prior to each Customer servicing, as well as to receive replacement hardware for the Customer and refuel. After a total of 22 years on-orbit, the RTCS departs EML1 on a disposal trajectory.

Figure NM4-2 shows the NM4 concept of operations. The figure illustrates mission sequences from launch to RTCS disposal.

RTCS System Description

The RTCS system includes the spacecraft bus, sensors and algorithms to support the AR&C phases, robots, and mounting points for telescope and robots. The AR&C sensor package includes retro-reflectors and RF

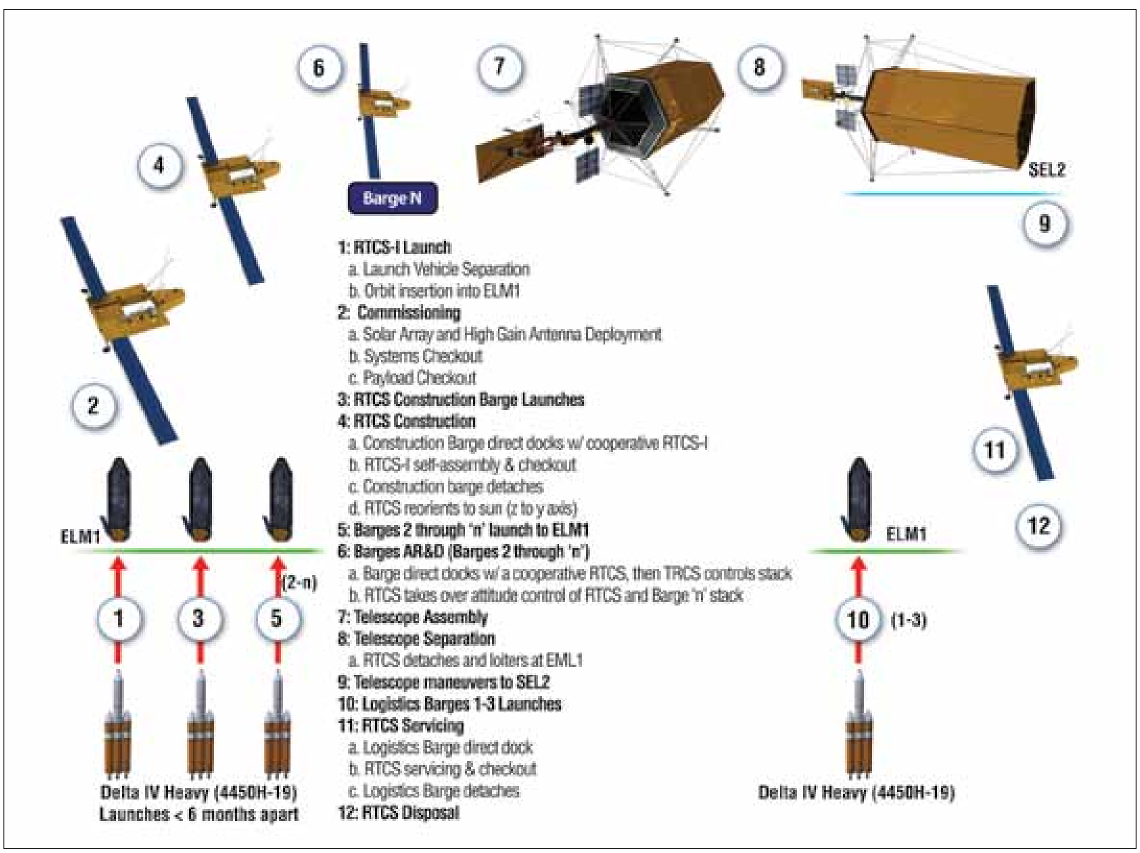


Figure NM4-2: Concept of Operations

transponders for two-way ranging with the Barges and the observatory. The robot system consists of two 6 m arms, a 20 m arm, a robot "quiver," and robot toolboxes.

The RTCS will be launched in two segments (RTCS-I and Construction Barge) and will be assembled at EML1 in a final configuration. The two-launch option was selected due to launch volume limitations of the Delta IV super-heavy launch vehicle. The RTCS-I includes all of the spacecraft subsystems except deployable solar array with PSE, AR&C package and one 6 m robot arm. The Construction Barge will contain a deployable solar array with the associated PSE and the rest of the robot arms, the Quiver and Toolboxes. The completed RTCS dry mass is 6,592 kg (with 30% contingency).

The NM4 robot system consists of two dexterous 6 m arms, a 20 m arm, a robot "quiver", and robot toolboxes. The 20 m grapple arm is used to move the dexterous pair to various worksites. The two 6 m dexterous robot arms are mounted as pairs on either side of a box, called a node, and are used for dexterous work including assembling and disassembling other robots. The barge contains Robot Mounting Points (RMP) to which robots can interface and allows the 20 m arm to move end-over-end from RMP to RMP. There is a robot "motel" which provides safe haven for 6 m robot arms, and provides a means for electrical recharging and data transfer. The arms will be teleoperated from the ground. The 6 m dexterous arms use an end-effector to interface with various tools needed to accomplish the tasks. There will be toolbox(es) located on the servicer for additional tools.

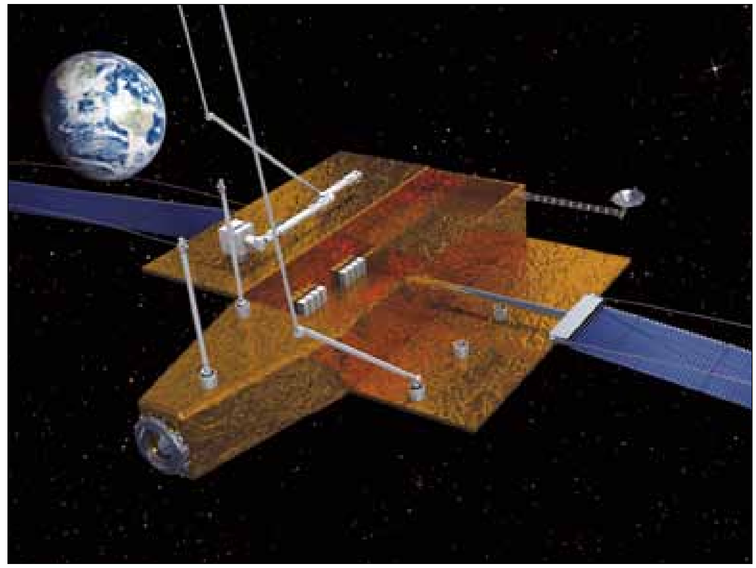


Figure NM4-3: RTCS with Robot Arms and Solar Array Deployed

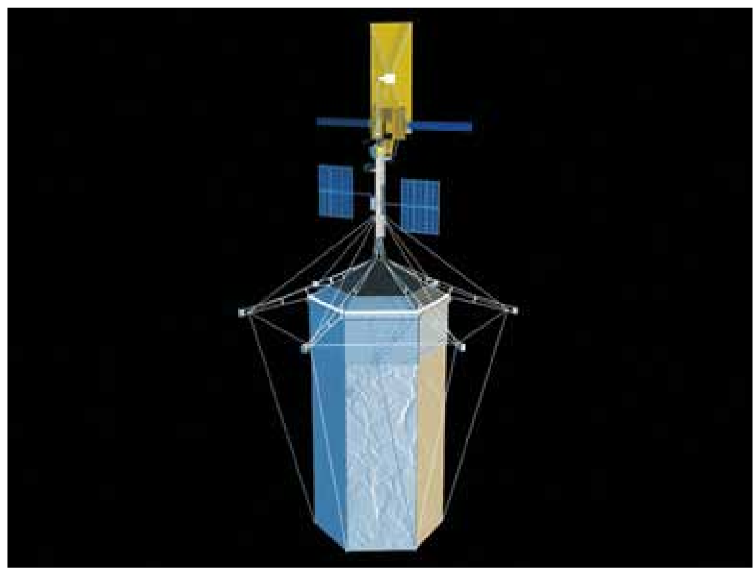


Figure NM4-4: RTCS with TMST

The RTCS bus is made of honeycomb panel construction and provides interfaces to the telescope, barges, and robot nodes. It is designed for the on-orbit assembly and servicing of subsystems and payload components. The thermal system is both passive and active: it includes heat pipes from component plates to radiators, MLI blankets on components, and survival heaters for components. The RF communication system includes four Ka band 1 m HGAs, two S-band omni antennas, and six Ka band omni antennas. Two HGAs are located on the telescope to facilitate a space-to-ground communication link. The Electrical Power System (EPS) is designed to accommodate solar electric propulsion. It includes both body-mounted and deployable solar arrays, along with twenty-six 100 Ah Li-Ion batteries. The ACS includes two star trackers and two gyros, and the propulsion system includes two large and eight small bipropellant Hz/NTO thrusters. The propulsion system also includes four gimbaled solar-electric Xenon thrusters. The RTCS contains six flight computers and two solid state recorders. The solid state recorders offer a 4 Tb user capability.

The RTCS bus is designed to be serviceable. The mechanical components in bays are mounted to thermal conductive plates to allow serviceable access. The RF communication system has A-side and B-side boxes for Ka to/from ground. The solar array has extra interface ports so that additional solar array sections may be added during servicing. There are three PSE boxes and thirteen battery boxes. The ACS and propulsion system have A-side and B-side serviceable components. The Avionics system has A-side and B-side boxes for active support during servicing after a single fault. Figure NM4-3 shows the RTCS with the robotic arms and solar arrays deployed. Figure NM4-4 shows the RTCS (robot arms stowed) attached to the observatory during the final stage of construction.

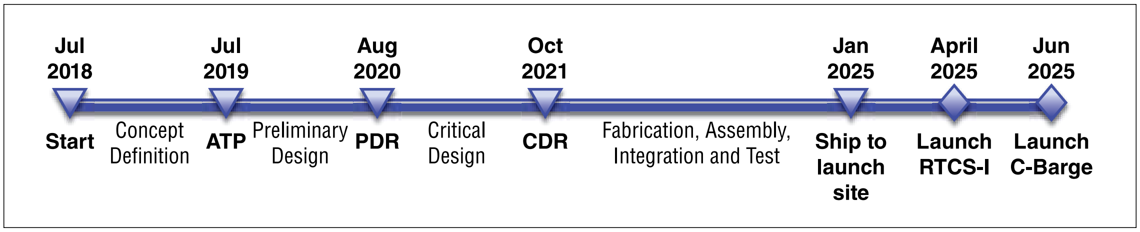


Figure NM4-5: Mission Schedule

I&T and Schedule

The conceptual mission schedule is shown in Figure NM4-5. The notional project start date is July 2018, allowing 12 months for Phase A and 14 months each for Phases B and C. A total of 36 months are allocated for spacecraft fabrication and integration and test for the bus and payloads. This conceptual schedule allows for technology development activities and will be support launch in the middle of the next decade.

Enabling Technologies

Xenon refueling components, Ka band omni antennas, and transponders are currently TRL 5. These will need to be brought up to TRL 6 before launch. Robot system power loads and radiator sizing may have been too conservative, and should be revisited in the future. The telescope assembly sequence should be reevaluated to make the assembly more efficient and to off-load requirements onto the RTCS.

Key Assumptions

The RTCS is in two pre-integrated, similar halves with dissimilar components: the RTCS-I and the Construction Barge. RTCS-I is designed to be self-sufficient on-orbit without the Construction Barge. When the RTCS-I and the Construction Barge are mated and completes into the final RTCS configuration, the on-orbit telescope construction can begin.

NM4 Assemble EML1 Robotic	Current Best Estimate Phase A-F ($M, FY 10)
AR&C	$60
Robot (2 GA+2 dexterous pairs+tools)	$1,330
Servicer Bus	$600
Launch Vehicle	$300
Operations	$150
Everything Else	$590
Total Servicing Cost	**$3,030**

Notional Mission 5: Servicing of the Advanced Technology Large Aperture Space Telescope (ATLAST)-9.2m Observatory with Robots and Humans in HEO

Mission Study Objective

The Notional Mission 5 (NM5) study objective is to develop a Servicer design concept that enables humans and robots to refurbish the ATLAST-9.2m observatory after 10 years of operation at Sun-Earth L2 (SEL2). The servicing mission takes place in a Highly Elliptical Orbit (HEO) that can be accessed relatively easily from an orbit around Earth-Moon L1 (EML1) and by crew launching from Earth. The particular HEO designed for Notional Mission 5 is referred to as the L1 Orbit Trajectory Used for Servicing (LOTUS), since it has unique properties that facilitate the servicing mission profile treated in Notional Mission 5, in which an EML1 Lyapunov orbit is used as the staging location for the Servicer. The Servicer carries the robotic elements, tools, replacement hardware for the observatory, docking points for the observatory, and an airlock with consumables for seventeen cycles (replenishable). No crew habitat is used in this mission within the Earth-Moon system, so the crew mission duration was limited to 21 days.

Mission Overview

The NM5 flight segments include the Human/Robotic Telescope Servicer (HRTS), ATLAST-9.2m, the Orion crew module, and a servicing barge. The HRTS is the only element developed into a design concept for the NM5 study; all other flight segments are assumed to exist and be ready to support the mission.

The NM5 Concept of Operations is found in Figure NM5-1. At the start of the mission, the ATLAST-9.2m observatory is stationed at Sun-Earth L2 (SEL2) after nine years of on-orbit operation. The HRTS is launched on an Ares V heavy-lift launch vehicle for insertion into a Lyapunov orbit about EML1. After a successful checkout of the HRTS, ATLAST-9.2m transits back to the Earth-Moon system and inserts into the EML1 Lyapunov orbit occupied by the servicer. The servicer then performs AR&C with the observatory, which requires 10–30 m/s of ΔV and takes 1–3 days. Next, the HRTS/ATLAST-9.2m stack performs a small maneuver (~10 cm/s) to insert itself into the LOTUS, bringing it to a rendezvous point with the crew vehicle ~23.5 days later. The crew vehicle launches approximately 20 days after the servicer/observatory and inserts itself into the LOTUS. The crew vehicle then performs AR&C with the

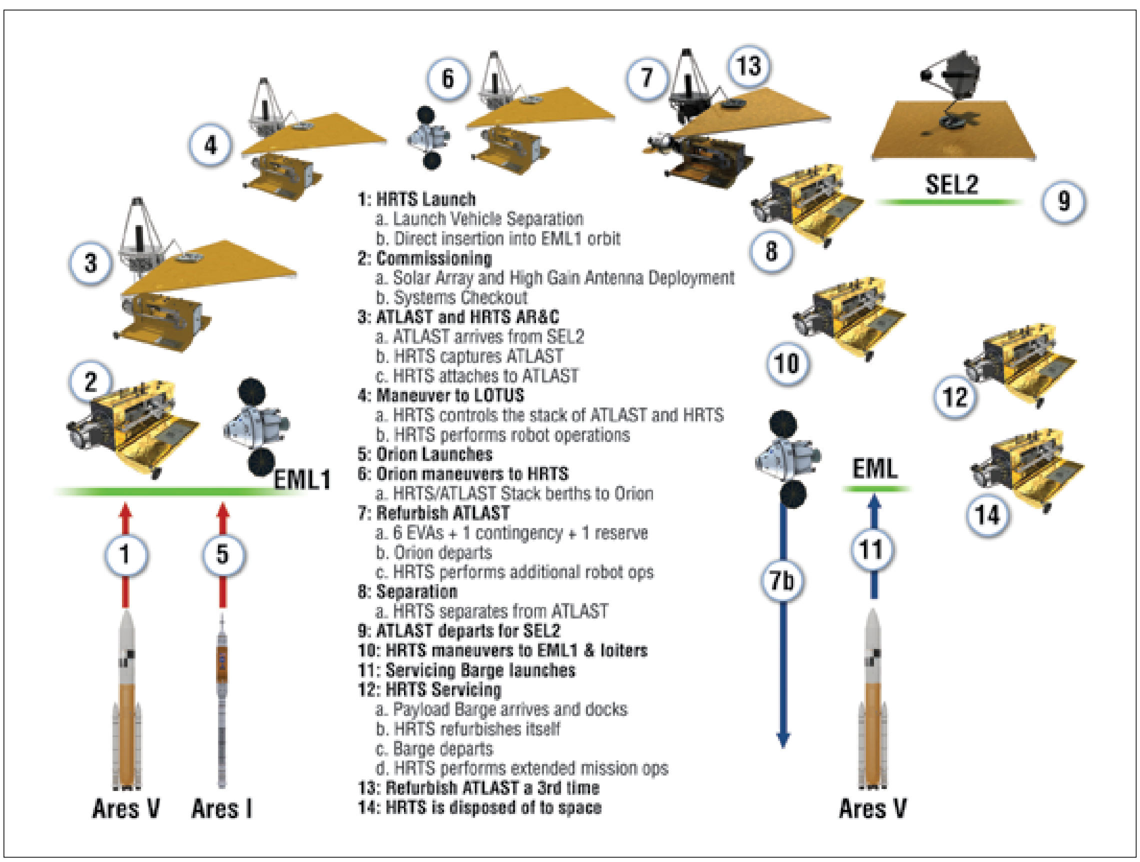


Figure NM5-1: Concept of Operations

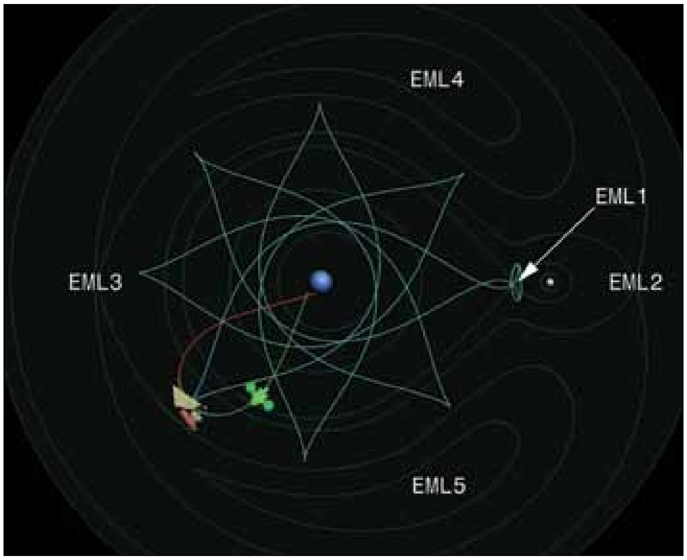


Figure NM5-2: LOTUS Free Return

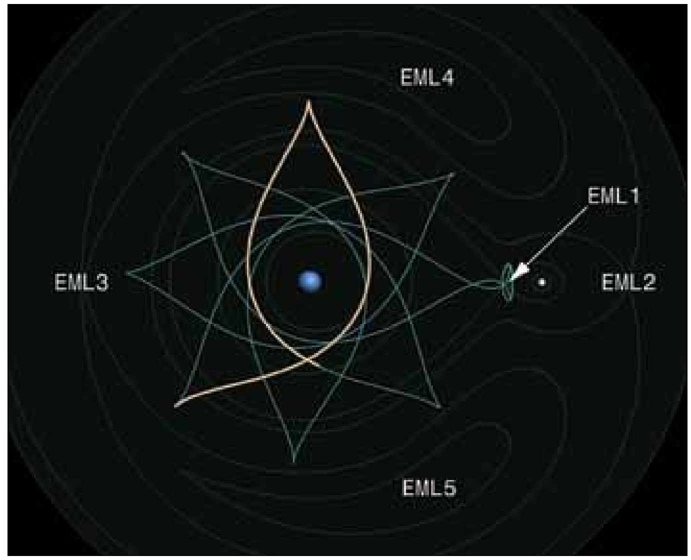


Figure NM5-3: LOTUS Servicing

HRTS/ATLAST stack, which requires ~1 day and ~30 m/s of ΔV on the part of the crew vehicle. Note that during this AR&C sequence, the HRTS/ATLAST stack is a passive, cooperative rendezvous target for the crew vehicle. After fifteen days of servicing, the crew vehicle separates from the stack and performs a deorbit maneuver to return home. The HRTS/ATLAST stack remains on the LOTUS and, under the influence of the Earth-Moon system dynamics, naturally returns to the vicinity of EML1 approximately 2 months after the crew vehicle departs. A few days prior to EML1 return, the observatory separates from the HRTS and performs a small maneuver to place it onto a trajectory that will exit the Earth-Moon system and return to SEL2. The HRTS simply reinserts itself onto the Lyapunov orbit about EML1 with a small maneuver and resumes station-keeping. The LOTUS free return is shown in Figure NM5-2. Figure NM5-3 shows LOTUS Servicing.

After approximately 10 years in orbit, a refurbishing barge will be launched with replacement units for the HRTS and ATLAST-9.2m, as well as consumables for the airlock. While an essential flight element of the HRTS is to perform more than one servicing mission, the barge was not developed into a design concept for this study. After HRTS refurbishment, ATLAST-9.2m returns to EML1 for a second servicing mission. This cycle will repeat at the 20-year mark, and after the third servicing mission of ATLAST-9.2m, the HRTS will be disposed of in space.

HRTS System Description

Figure NM5-4 provides an overview of the HRTS components while Figure NM5-5 shows an artist's rendition of HRTS. The HRTS is a modular, serviceable, refuelable spacecraft with a dry mass of 31,870 kg (includes 30% contingency). The HRTS design accommodates two Autonomous Rendezvous and Capture (AR&C) phases: as the active vehicle in the AR&C of ATLAST-9.2m, and then as the passive, fully cooperative vehicle in the AR&C with the Orion crew module.

The HRTS houses the robotic systems required for the servicing mission, human-rated grapple arms and dexterous robotic pairs, and robot toolboxes. Two 20 m grapple arms are used for the berthing activities and for translating the crew and large hardware elements across longer distances. Two 2 m dexterous robot arms are mounted as pairs on either side of a box called a node. They are used for complex, dexterous tasks and to assist the crew. The grapple arms can be operated autonomously (to enable the servicer to berth ATLAST), locally by the crew when Orion is docked, or via scripted autonomy or teleoperation from the ground. The dexterous robot pairs can be operated locally by the crew or from the ground. Both the grapple and dexterous arms have their avionics distributed along the arm that communicates with a Data Management Unit (DMU). The HRTS has eight Robot Mounting Points (RMP) that provide power and data interfaces to which either end of the grapple arm or one face of the node of the dexterous robot pairs can be attached. This architecture allows the grapple arms to move end-over-end from RMP to RMP (the grapple arms have identical end-effectors at both ends to allow for this). The grapple arms can also maneuver the dexterous robot pairs around and provide power and data across the mounting interface.

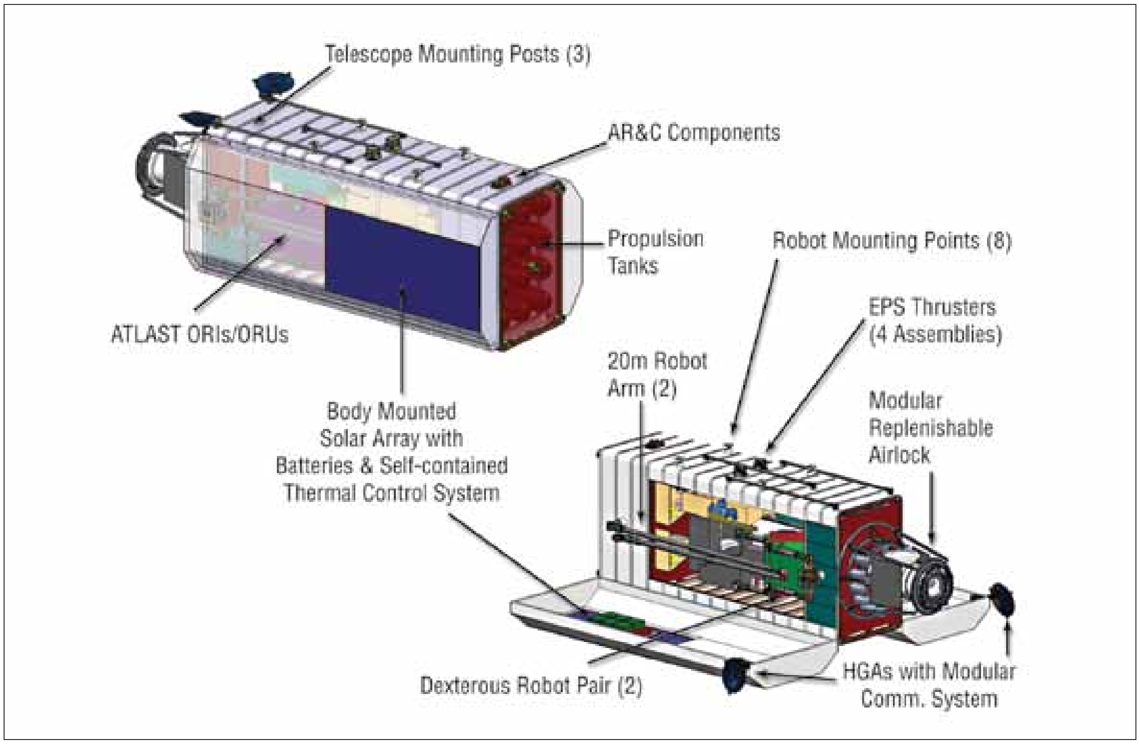


Figure NM5-4: HRTS Components

The HRTS has three Telescope Mounting Points that provide 4 kW of power to and a 40 Mbps data link from the observatory during servicing. The HRTS uses a voltage-regulated bus at 120 VDC with bidirectional converters for battery charge and discharge to provide the peak power of 11,087 W (includes 30% contingency). This power is provided by body-mounted (yet replaceable) arrays with a total area of 49.67 m^2 using Tj GaAS, 28% efficient cells. Each of the ten, 100 Ah Li-Ion batteries is by-pass switched to provide fault protection. The battery capacity is driven by the need to provide power to ATLAST-9.2m during eclipses, while the solar array is sized to accommodate the electrical propulsion system.

The HRTS propulsion system is comprised of both a chemical system and an electric propulsion system. The pressure regulated bi-prop chemical system is used for high thrust, short time-scale maneuvers and consists of one Main ΔV engine for orbit insertions (900 lbf/4000 N, $_{Isp}$ 310 sec), 4 auxiliary ΔV engines for attitude control during main engine firing (200 lbf/890 N, $_{Isp}$ 310 sec), 20 Reaction Control Engines (5 lbf/22 N, $_{Isp}$ 310-320 sec) and 21 tanks of fuel, oxidizer, and pressurant. The electric propulsion system is used for station-keeping during the loiter phase only. It consists of 4 Gridded Xenon-Ion thrusters (NEXT engine, 0.055 lbf/.24 N, $_{Isp}$ 4,100 sec—two located on the sun-facing side and two located on the anti-sun-facing side—and three tanks of Xenon. The total fuel load for both systems is 17,213 kg. Figure NM5-6 shows HRTS with ATLAST 9.2m.

The up-link data rate to the HRTS is 132 Kbps with a down-link rate of 160 Mbps. The communication system is comprised of two switchable 1.2 m Ka HGAs (2-axis gimbaled), two Ka omnis, four S-band omnis, four Ka transponders and four S-band transponders.

The HRTS bus Attitude Control System (ACS) is three-axis stabilized in all modes. ACS components include star trackers for primary attitude determination, IRUs for angular and linear rate determination, and coarse sun sensors for sun pointing mode. Rotation and translation actuation is performed using thrusters.

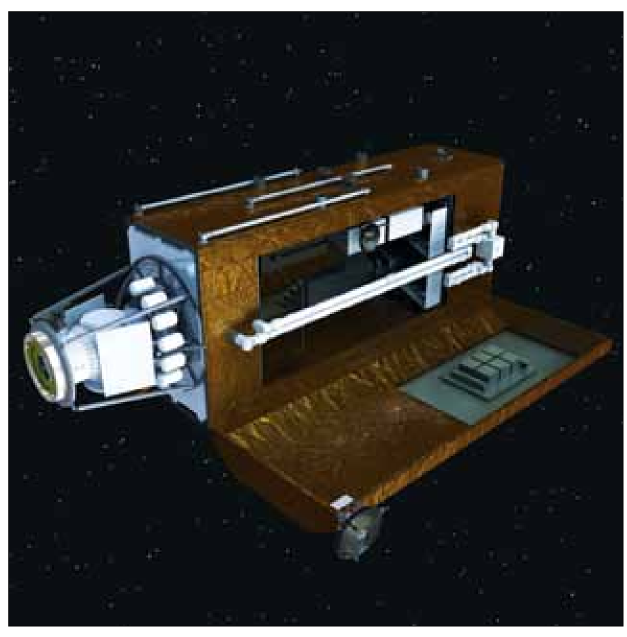


Figure NM5-5: HRTS

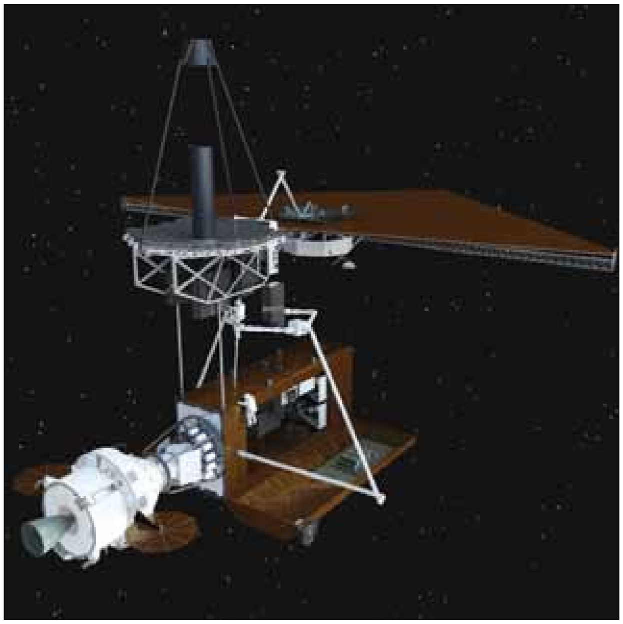


Figure NM5-6: HRTS with ATLAST 9.2m

I&T and Schedule

With a Phase A start assumed in January 2028, the HRTS would be scheduled to launch in 2036. The total integration and test duration is 4.3 years (including funded reserve). The AR&C system, robots, airlock, and orbital replacement instruments and units would be fully qualified prior to integration into the Servicer, and it is assumed that no additional testing of these is required. The mission schedule is shown in Figure NM5-7.

Enabling Technology

At this time, the Ka Band transponders and omni antennas are at TRL 5, but are expected to be at least TRL 6 prior to 2020. Due to the extremely large sunshade and the possible impact to AR&C, a detailed plume study should be completed. The observatory contamination issue is of lesser concern. Thruster firing for attitude control could be optimized for station-keeping purposes if performed at the proper time.

Key Assumptions

The HEO orbit is strongly favored by astronauts due to a natural return to Earth's proximity, and the LOTUS was specifically designed to return to EML1 naturally. In addition, this orbit maximizes the "on-station" time that the astronauts have to perform servicing.

This mission involves human activity; therefore critical systems are required to be dual-fault tolerant. Much time was spent discussing which systems are critical and what architecture to adopt to provide for two-fault tolerant systems (i.e., multiple active buses and internal redundancy). These decisions will need to be made by the project office on a system-by-system basis.

NM5 LOTUS Refurbish with Humans+Robots	Current Best Estimate Phase A-F ($M, FY 10)
AR&C	$60
Robot Arms (2 GA+2 dexterous pairs)	$1,230
Payload (ORUs)	$1,000
Airlock+tools	$300
Servicer	$760
Launch Vehicle	$300
Operations	$80
Everything Else	$990
Total Servicing Cost	**$4,720**

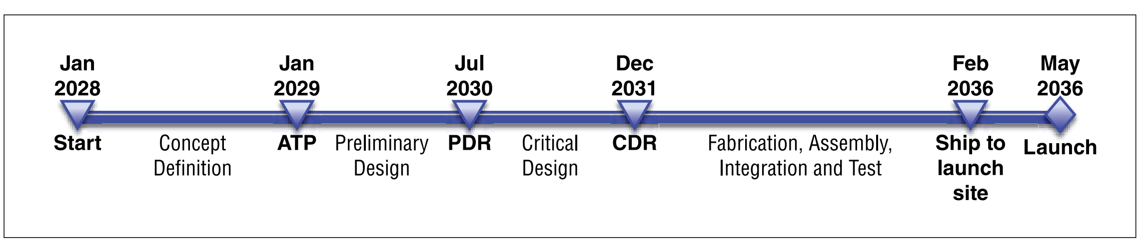


Figure NM 5-7: Mission Schedule

Notional Mission 6: Assembly of the 15.5 m ATLAST Observatory at SEL2 with Humans and Robots

Mission Study Objective

The objective of the Notional Mission 6 (NM6) study is to develop a Servicer design concept that provides a platform for robots and humans to work in concert to assemble a large observatory at SEL2. The Servicer carries the robotic elements and tools and accommodates the berthing of several observatory hardware transport barges and the crew vehicle/habitat/airlock stack during assembly. As it is assembled, the observatory is also mounted to the Servicer. The Servicer remains at SEL2 for 20 years following the deployment of the assembled observatory to provide a platform for human or robotic servicing of the flagship observatory or other missions.

Mission Overview

The NM6 flight segments include the Human and Robotic Telescope Construction Servicer (HRTCS), four Modular Propulsion System and Telescope (MPST) elements, a human habitation facility, an airlock, and the Orion crew module. Figure NM6-1 illustrates these flight segments, as well as the ATLAST observatory stowed in the MPSTs. The NM6 study focused on the design of the HRTCS segment. All other flight segments are used to drive the interface requirements on the Servicer and are assumed to exist and be ready to support the mission.

The NM6 Concept of Operations can be found in Figure NM6-2. The HRTCS is the servicing platform that supports the robotic and human construction of the observatory, and it houses the robotic tools and a quiver holding parts for the reconfigurable robot arms. The MPST is a spacecraft bus that transports observatory parts to SEL2, while the Orion spacecraft is used to transport the crew to and from the SEL2 halo orbit. An expandable-type habitat provides additional living space and perhaps radiation protection for the crew during orbital transfer. An airlock is required so that the crew can perform EVAs, and an Earth Departure Stage (EDS) is required to inject the Orion/Habitat/Airlock stack into the outbound trajectory towards the SEL2 halo orbit, after which the spent EDS is discarded.

The HRTCS is launched into the SEL2 halo orbit on a heavy-lift launch vehicle, assumed to have performance characteristics commensurate with the current notional design for Ares V. Six months later, the first MPST launches

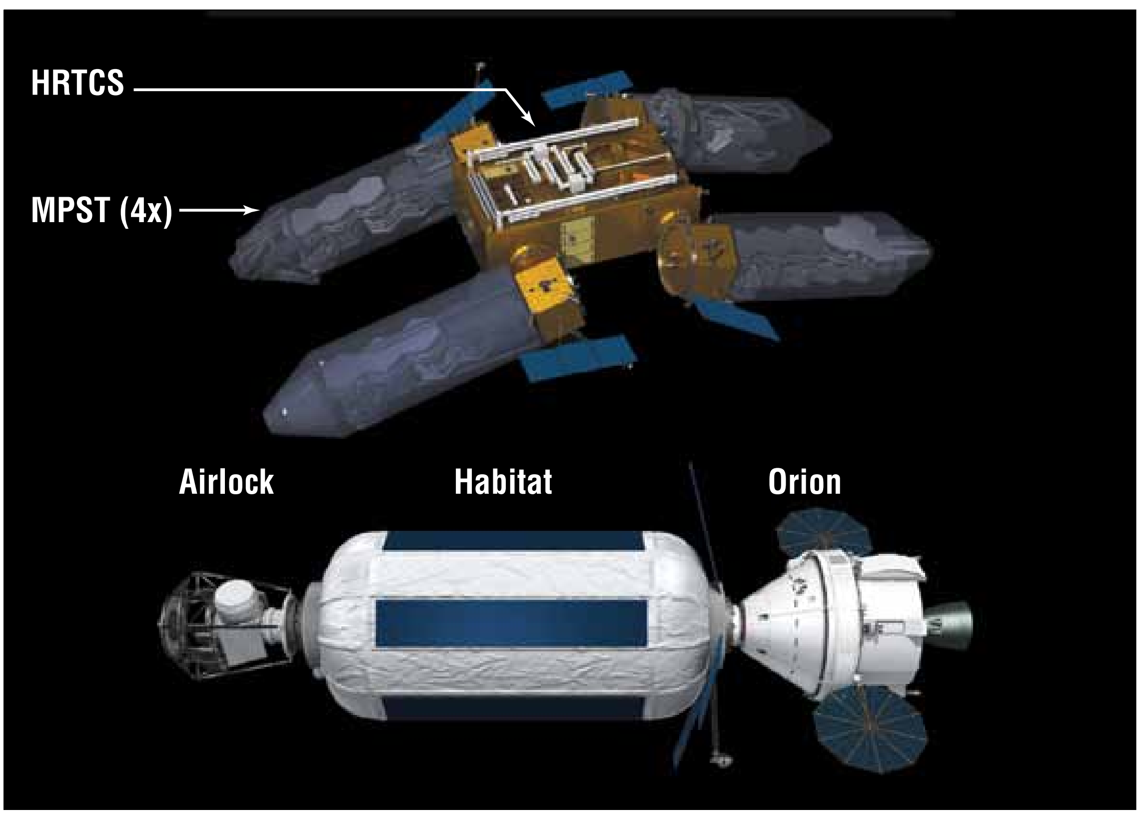


Figure NM6-1: Flight Segments

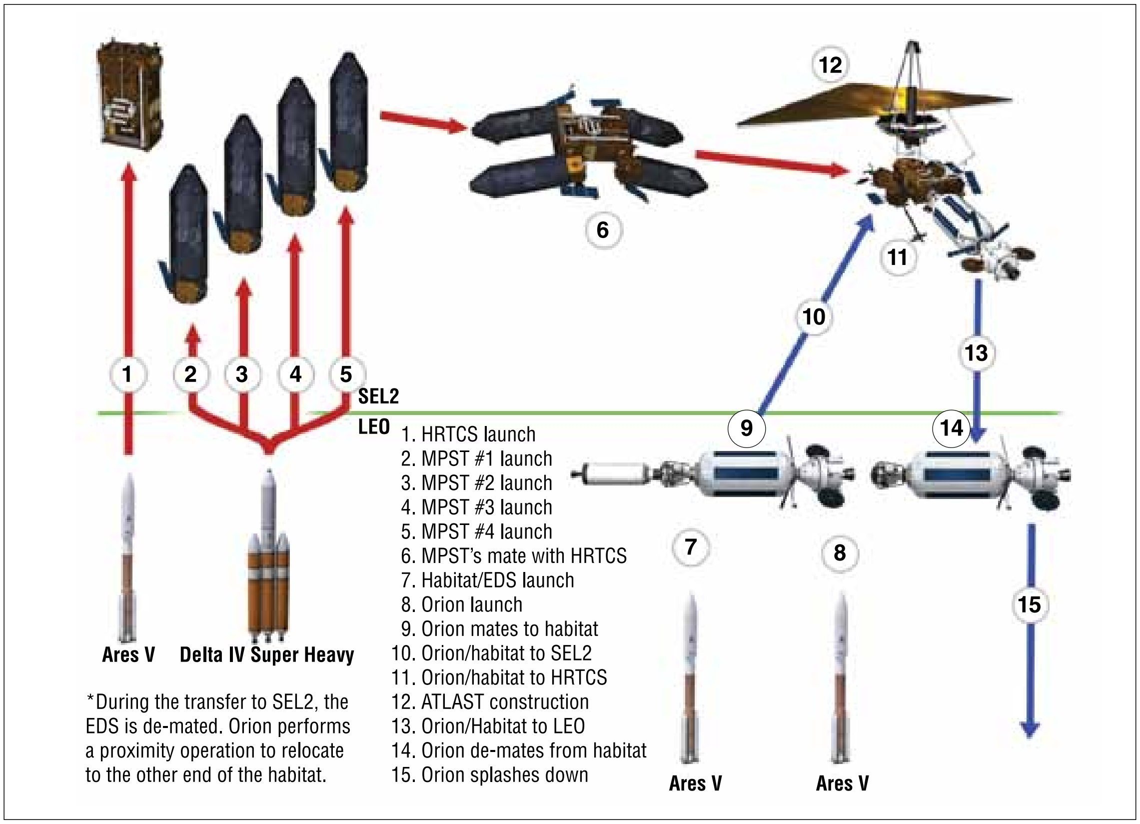


Figure NM6-2: NM6 Concept of Operations (Observatory Assembly Phase)

into the SEL2 halo orbit on an upgraded Delta IV Heavy launch vehicle. MPST-2, -3, and -4 are launched at 3-month intervals. Intervals between launches allow time to refurbish the launch pad and also serialize launch vehicle integration and payload preparation activities at the launch site. The 3-month allocation is driven by the dynamics of the SEL2 halo orbit, which has a minimum insertion ΔV every 6 months and a less desirable, but achievable, insertion ΔV halfway between the two minima. However, MPST-3 is the heaviest MPST and needs to travel to SEL2 on the lower insertion ΔV trajectory.

The four MPSTs perform AR&C with the HRTCS, and the stacked configuration of HRTCS and MPSTs then waits for the human elements to arrive. As feasible, teleoperation of the robotic arms from the ground can be done to prepare for the telescope assembly during this period. The habitat, airlock, and Earth departure stage (EDS) are launched into LEO on an Ares V launch vehicle (or equivalent), followed by Orion, which is launched into LEO on an Ares I (or equivalent). In LEO, Orion performs AR&C with the habitat/airlock/EDS stack, at which point the habitat is inflated and checked-out. The habitat/airlock/EDS/Orion stack is then inserted into the outbound trajectory towards the SEL2 halo orbit by the EDS. The EDS is discarded after its fuel is depleted, which occurs while still well within the Earth-Moon system. After the spent EDS is discarded, Orion performs a short proximity operations maneuver to reposition itself on the opposite end of the habitat (previously occupied by the EDS).

The habitat/airlock/Orion stack performs AR&C with the HRTCS on the SEL2 halo orbit. Humans and robots then work in concert for 39 days to assemble the ATLAST-15.5 m observatory. Large-element mechanical assembly tasks are completed using two 20 m grapple arms teleoperated by the crew on-site and occasionally from the ground. Complex or dexterous tasks are completed in a series of 17 crew Extra-Vehicular Activities (EVAs) along with robot assistants equipped with a pair of 2 m arms. Once final testing is complete, the observatory is de-mated from HRTCS and deployed. The habitat/airlock/Orion stack then de-mates from HRTCS and transfers back to Earth. Shortly before Earth arrival, the habitat and airlock de-mate from Orion and the crew capsule performs a ballistic reentry. Using methods beyond our scope for study here, such as aerocapture, the habitat with airlock is kept in orbit for use during a future mission. The total duration of the manned mission is 79 days. The total duration of the assembly mission is 607 days. The HRTCS loiters in SEL2 for 20 years, discarding and properly disposing of the MPSTs as their fuel is depleted.

Every 10 years, the HRTCS is serviced in preparation for the next planned upgrade of the ATLAST observatory. During servicing, HRTCS critical systems (e.g., solar arrays, propellant) are replaced as needed, and it receives additional MPSTs with Orbital Replacement Units (ORUs) for the upcoming observatory servicing mission. In addition, during the loiter phase (periods between ATLAST servicing), the HRTCS is available for use as a platform for any other assembly or servicing tasks in the SEL2 halo orbit.

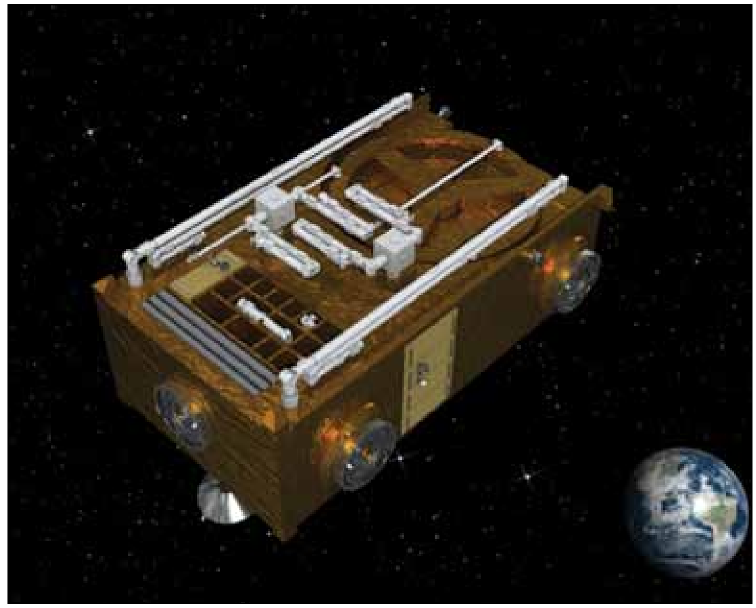


Figure NM6-3: HRTCS with Robot Arms Stowed

HRTCS System Description

Figure NM6-3 shows the HRTCS with robot arms stowed and Figure NM6-4 provides an overview of the HRTCS components. The HRTCS is a spacecraft with a dry mass of approximately 27,000 kg (includes 30% contingency), designed to accommodate AR&C activities with the Orion/habitat/airlock stack and four MPSTs. In particular, the HTRCS is designed to be a passive, cooperative rendezvous target for the MPSTs, and the HRTCS/MPSTs stack is designed to be a passive, cooperative rendezvous target for the crew vehicle stack.

Two 20 m robotic arms are used for the berthing activities and large-scale assembly tasks. The HRTCS has six Robot Mounting Points (RMPs), and the robotic arms are able to move end-over-end using the RMPs. Two 2 m robotic arms assist the astronauts during EVAs. While the crew is sleeping, dexterous robots (a node and two 2 m arms) perform worksite preparation tasks using a combination of ground teleoperation and scripted autonomous tasks. The HRTCS robotic system has a total of 10 cameras to support teleoperation.

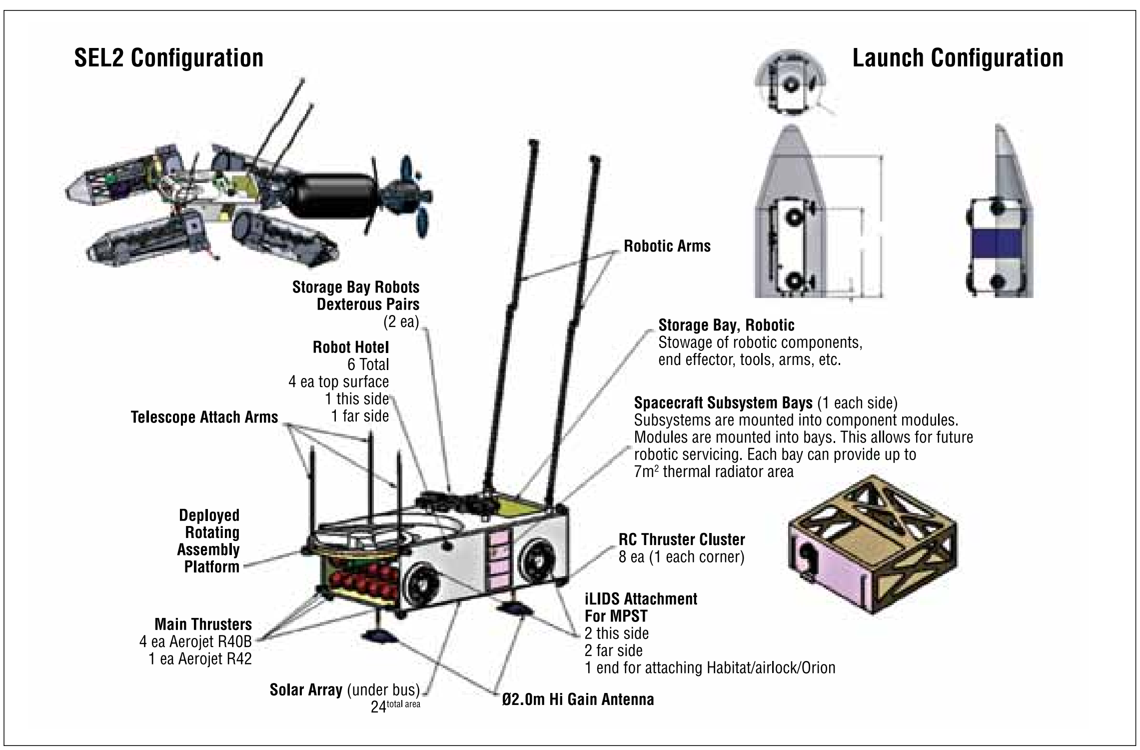


Figure NM6-4: HRTCS Components/Launch and SEL2 Configurations

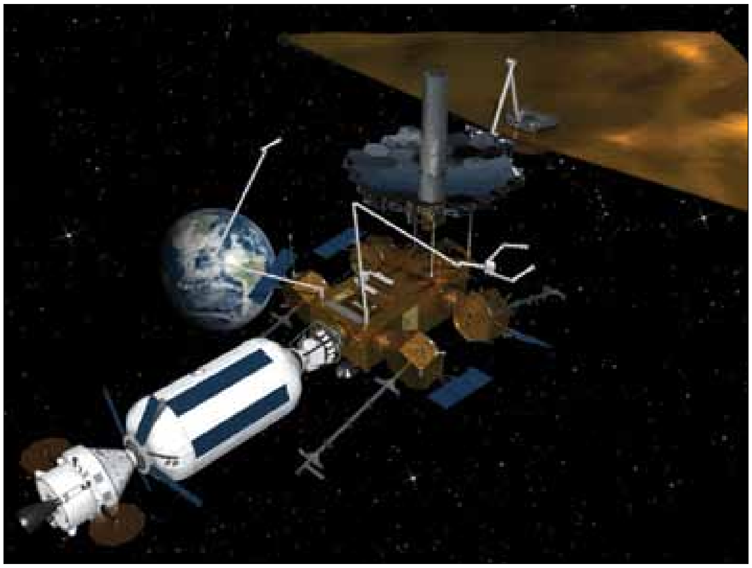
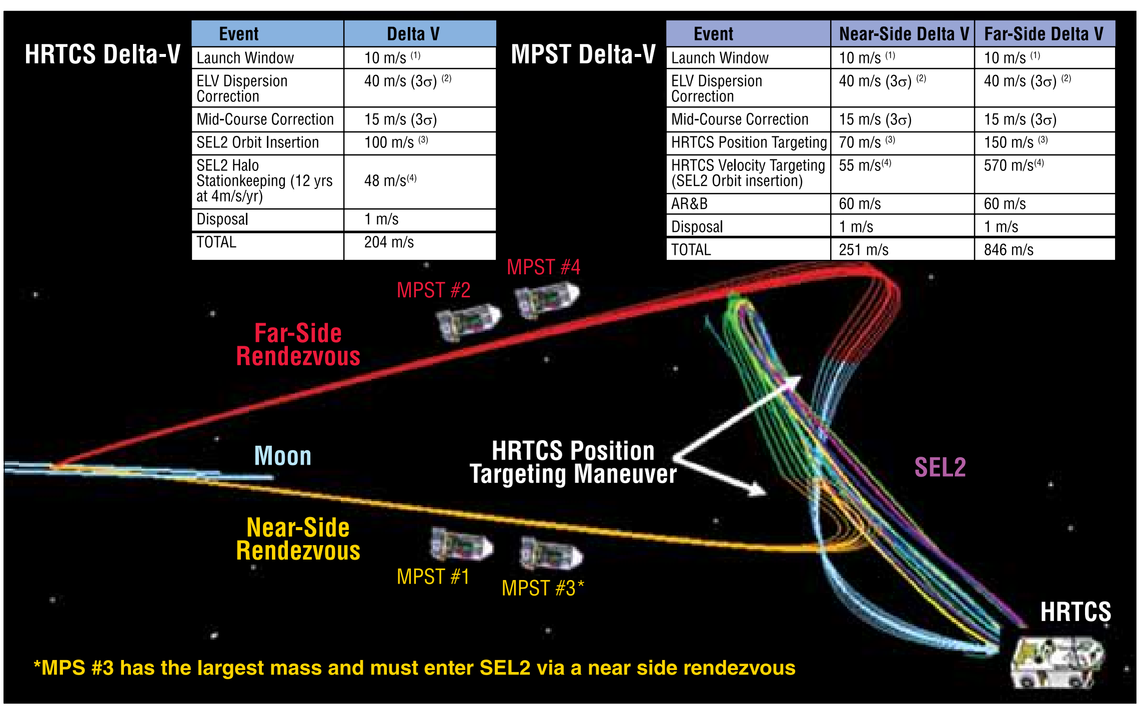


Figure NM6-5: HRTCS/Orion/Airlock with ATLAST

The observatory is assembled on the HRTCS turntable (6-meter diameter), which provides 500 W of power and a 40 Mbps data link to the observatory. The ATLAST spacecraft bus remains in an MPST with its solar array deployed and facing the sun, and is electrically connected to the HRTCS turntable. This allows the ATLAST solar array to provide 3,500 W of power to the observatory during construction and to control and checkout ATLAST components as they are assembled. This approach also reduces the power load on the HRTCS system to that of providing power just for itself (including robots and sensors) and an additional 500 W of power to the observatory. Figure NM6-5 shows the stacked configuration of the HRTCS/Orion/Airlock with ATLAST.

The HRTCS uses a 120 V DC power system to provide the peak power of 4,431 W. This power is provided by two body-mounted arrays with a total area of 21.65 m^2. Two 100 Ahr LiIon batteries provide electrical power storage and incorporate by-switches for fault protection against dead cells. The HRTCS propulsion system is comprised of five ΔV engines and 16 RCS thrusters on Canfield gimbals. To fully utilize all available propellant and to increase options for thruster selection, the HRTCS assumes control of the RCS systems on docked MPSTs. An overview of the HRTCS and MPST orbital mechanics and required ΔVs can be found in Figure NM6-6.

The up-link data rate to the HRTCS is 67 Mbps, and the down-link is 54 kbps. The communication system is comprised of two dual 2.0 m Ka high gain antennas (HGA) (2-axis gimbaled), two Ka omnidirectional antennas, two Ka transponders and four S-band transponders. The communication system has 1.1 Terabits of storage and can store nearly 6 hours of video, telemetry and housekeeping data. The avionics system uses three single-board voting computers and requires 67 units and 315 cards. All avionics, batteries and solar arrays are replaceable for servicing. With no Earth gravitational attraction and no orbital debris, the SEL2 halo orbit presents a significantly reduced risk of hypervelocity impacts.



HRTCS Delta-V

Event	Delta V
Launch Window	10 m/s (1)
ELV Dispersion Correction	40 m/s (3σ) (2)
Mid-Course Correction	15 m/s (3σ)
SEL2 Orbit Insertion	100 m/s (3)
SEL2 Halo Stationkeeping (12 yrs at 4m/s/yr)	48 m/s(4)
Disposal	1 m/s
TOTAL	204 m/s

MPST Delta-V

Event	Near-Side Delta V	Far-Side Delta V
Launch Window	10 m/s (1)	10 m/s (1)
ELV Dispersion Correction	40 m/s (3σ) (2)	40 m/s (3σ) (2)
Mid-Course Correction	15 m/s (3σ)	15 m/s (3σ)
HRTCS Position Targeting	70 m/s (3)	150 m/s (3)
HRTCS Velocity Targeting (SEL2 Orbit insertion)	55 m/s(4)	570 m/s(4)
AR&B	60 m/s	60 m/s
Disposal	1 m/s	1 m/s
TOTAL	251 m/s	846 m/s

Figure NM6-6: Flight Dynamics/ΔVs

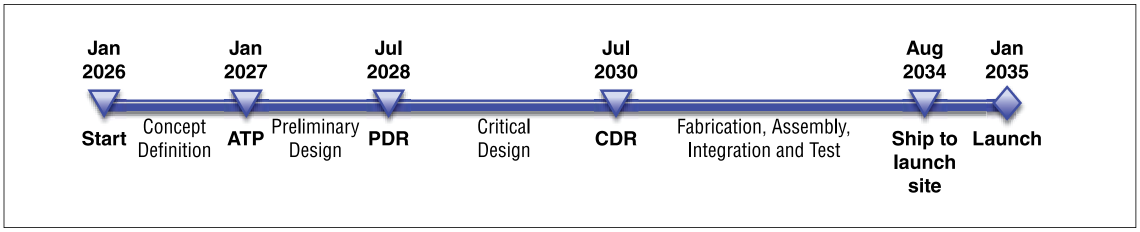


Figure NM6-7: Mission Schedule

I&T and Schedule

In order to meet an assumed 2035 launch date, Phase A starts in 2026. The total integration and test duration is 8.43 years (including funded reserve). The mission schedule is shown in Figure NM6-7 (TBS).

Enabling Technologies

The Canfield gimbals provide improved range of motion that results in a significant reduction in the number of required thrusters. These gimbals are at TRL 5 and are expected to reach TRL 6 prior to Phase A for this mission.

Key Assumptions

This mission requires a launch vehicle capable of launching 32,715 kg to a SEL2 halo orbit insertion point. This falls between the upgraded Delta IV capacity (15,000 kg) and a notional Ares V capacity (60,000 kg). Heavy-lift is a necessary enabling technology for this mission, though the notional Ares V is not specifically required. A new launch vehicle offering intermediate launch mass capabilities could be used for this mission.

NM6 SEL2 Refurbish with Humans+Robots	Current Best Estimate Phase A-F ($M, FY 10)
AR&C (no PTU)	$60
Robot Arms (2 GA+2 dexterous pairs+tools)	$1,340
Servicer Bus	$2,100
Launch Vehicle	$500
Operations	$240
Everything Else	$1,040
Total Servicing Cost	**$5,280**

“Where the willingness is great, the difficulties cannot be great.”

Niccolò Machiavelli

“Opportunities multiply as they are seized.”

Sun Tzu

National Aeronautics and Space Administration

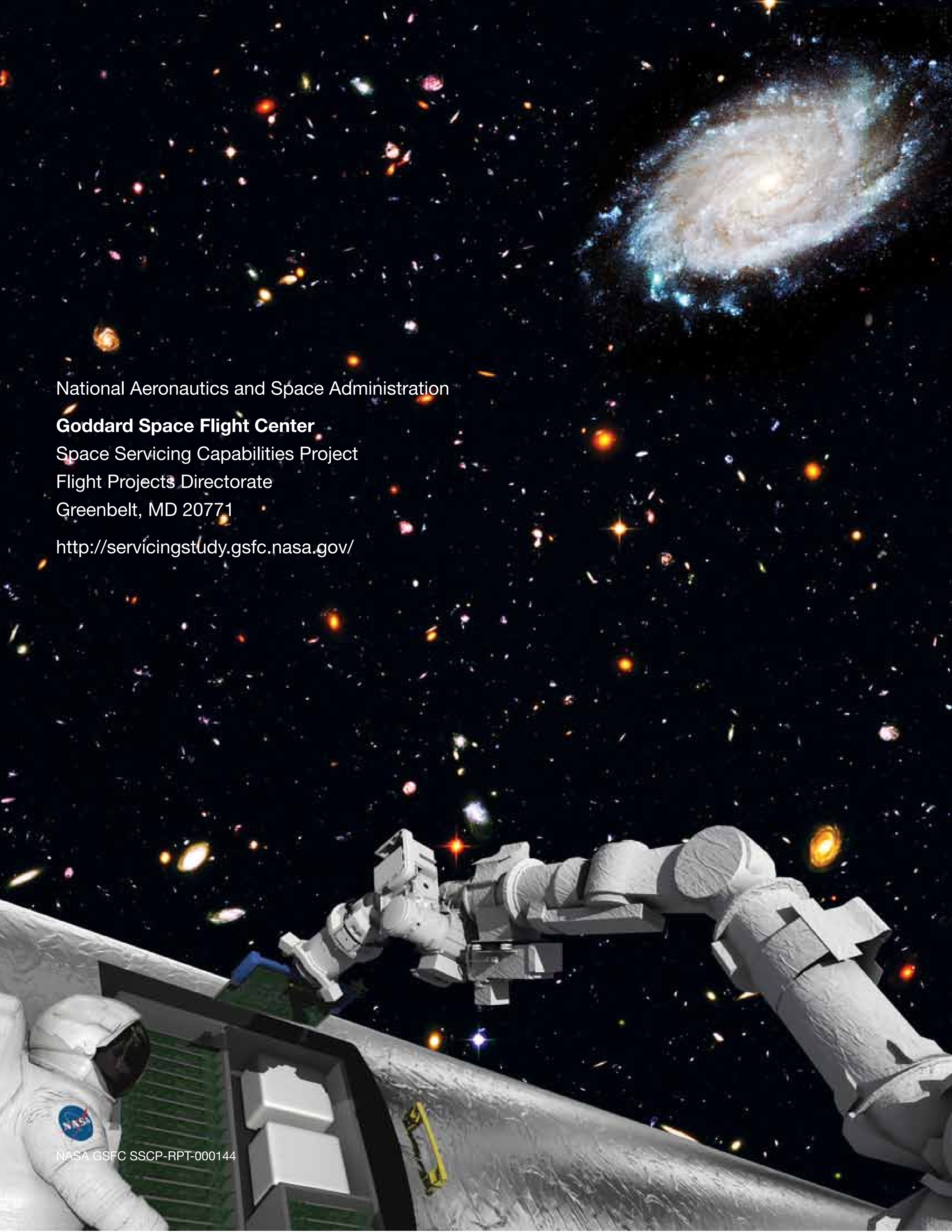
Goddard Space Flight Center

Space Servicing Capabilities Project

Flight Projects Directorate

Greenbelt, MD 20771

http://servicingstudy.gsfc.nasa.gov/



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