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On-Orbit Servicing: A New Value Proposition for Satellite Design and Operation

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The use of humans to service satellites designed for servicing has been adequately demonstrated on the Hubble Space Telescope and International Space Station. Currently, robotic on-orbit servicing technology is maturing with risk reduction programs such as Orbital Express. Robotic servicing appears to be technically feasible and provides a set of capabilities which range from satellite inspection to physical upgrade of components. However, given the current design and operation paradigms of satellite architectures, it appears that on-orbit servicing will not be heavily used, and, as a result, is not likely to be economically viable. To achieve the vision of on-orbit servicing, the development of a new value proposition for satellite architectures is necessary. This new value proposition is oriented around rapid response to technological or market change and design of satellites with less redundancy.

Nomenclature

a_{phase}	=	semimajor axis of the phasing orbit for the servicer
a_{target}	=	semimajor axis of the target satellite orbit
CP_{Ser}	=	servicing cost penalty
C_{op}	=	cost of satellite operations
C_{sat}	=	cost of satellite development
k_{servicer}	=	no. of phasing revolutions of the servicer
k_{target}	=	no. of phasing revolutions of the target satellite
N_{Trans}	=	no. of transponders
P_{markup}	=	markup for serviceable satellite
$\Re\mathrm{IFR}$	=	interest free discount rate
$\Re\mathrm{INF}$	=	inflation rate
$\Re\mathrm{INS}$	=	insurance premium
$\Re\mathrm{IRR}$	=	internal rate of return
t_H	=	expected end-of-life year of the satellite
t_k	=	decision year
t_0	=	initial launch year
X_0	=	initial value of a GEO satellite communications market
$\Delta V_{\mathrm{phase}}$	=	velocity change necessary for servicer to adjust its phase to match target satellite
$\Delta V_{\mathrm{proximity}}$	=	velocity change necessary for servicer to adjust to proximity operations at target satellite
ϑ	=	initial angular separation between servicer and target satellite

I. Introduction

CURRENT satellite architectures are designed for the space vehicle to operate in an inaccessible, hostile environment. Following launch, traditional satellite operations are tightly constrained by an inability to access the orbiting vehicle. With the exception of software upgrades from ground controllers, operators are wedded to supporting payload technologies that become rapidly obsolete and to bus structures that degrade in the harsh environment of space. The inaccessibility of satellites following launch makes them vulnerable to failures before reaching end of life (EOL). Historical analysis indicates that the combination of the 9% failure rate of satellites during their operational lives with the 4–5% failure rate of launch vehicles will cause approximately one out of seven satellites to fail before EOL [1]. This is particularly unfortunate given that a typical geosynchronous Earth orbit (GEO) satellite costs approximately $125 million for the satellite and launch vehicle [2]. In addition to the high cost of space commercialization, critical mission areas fulfilled by government space programs and the drive for investor return by the commercial space industry has led to an extremely risk-averse industry. This environment has driven satellite designers toward three common elements of design: redundancy, proven technology, and long operational lives.

Space systems incorporate massive redundancy to mitigate the risk of component failure. Components may fail due to design flaws, emergent interaction effects with other spacecraft systems, exposure to the harsh environment of space, or other random events. Incorporating redundancy leads to very complex systems, increasing spacecraft mass and cost. Furthermore, the value of redundant systems is only realized in the event of component failure.

As a response to the risk-averse nature of the satellite industry, designers are pressured to incorporate proven (i.e., legacy) hardware on space systems. For example, NASA uses technology readiness levels (TRL) as a metric for technological maturity. Classified on a scale of 1–9, most spacecraft designs require a TRL of at least 8 to insure "flight qualified" hardware. Although the use of proven technology helps to mitigate mission risk, it also has the negative effect of limiting satellite performance and stalling industry innovation.

The high costs associated with increasingly complex payloads and improvements in supporting bus subsystems (e.g., ion propulsion) have led to the need to increase satellite design lifetimes to provide a sufficient return on investment (see Fig. 1).

One downside of long design lifetimes is the inability to update space-based capabilities with modern avionics in a timely manner during an era dictated by "Moore's law" (i.e., the doubling of the processing speed of new computer chips every 18–24 months). This slowdown of the space industry's "clock speed" limits the agility of satellite operators in capturing emergent terrestrial markets [4]. Given these limitations of the traditional satellite architecture paradigm and the lack of a maintenance industry for satellites (which is a cornerstone of terrestrial systems such as in the aviation and automotive industries), on-orbit servicing (OOS) has been proposed

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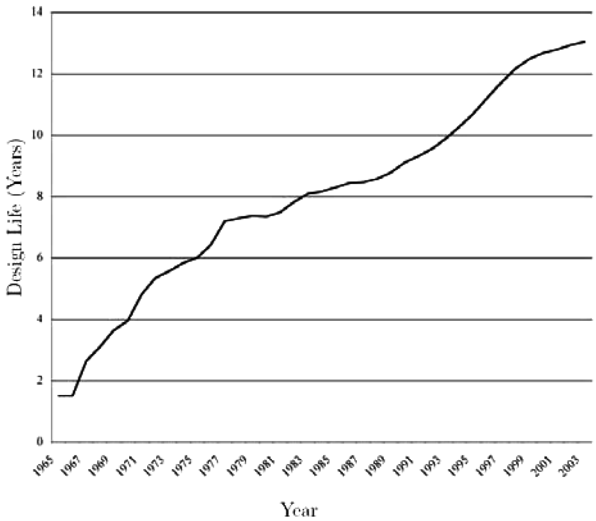


Fig. 1 Average design life of active GEO satellites [3].

as a means to provide flexibility to decision makers in satellite design and operations [5].

The goal of this paper is to evaluate OOS in the current satellite paradigm and propose a new paradigm. We begin with a qualitative discussion of the promise of OOS. Because most operational satellites are GEO communication satellites, we next examine whether OOS would bring value to the existing fleet of GEO satellites. We show that OOS does not offer much added value because the existing design paradigm provides enough redundancy such that GEO satellites are reliable and long lived. We next examine the case where GEO satellites are upgraded with new technology via OOS and show that frequent technological improvements can bring substantial added value. This is consistent with the significant value added to the Hubble Space Telescope (HST) by its servicing missions. However, the periodic upgrading of satellites with new technology would represent a new design and operations paradigm for satellites that has consequences that are far broader than just OOS. This new paradigm might have shorter-lived satellites with frequent upgrading, replacement, and rapid launch.

II. What Is On-Orbit Servicing?

The promise of on-orbit repair, upgrade, assembly, and relocation has been studied extensively for over two decades. In 1999, the spacecraft modular architecture design (SMAD) study identified six potential benefits of on-orbit servicing: 1) reduced life-cycle costs, 2) increased payload sensor availability, 3) extended spacecraft orbital lifetime, 4) enhanced spacecraft capabilities, 5) enhanced mission flexibility and operational readiness, and 6) prelaunch spacecraft integration flexibility [6]. Despite the potential benefits, commercial satellite developers and operators have not embraced OOS. In this paper, we show that, given the traditional paradigm for how satellites are built and operated, this reluctance is reasonable, and that OOS is economically viable in the presence of rapid technological change.

On-orbit servicing is the process of improving a space-based capability through a combination of in-orbit activities that may include inspection, rendezvous and docking, and value-added modifications to a satellite's position, orientation, and operational status. OOS activities include remote sensing, orbital modification, satellite rescue, refueling, upgrading, assembly, and repair operations. The activities can be categorized into five high-level functions: 1) inspect, 2) relocate, 3) restore, 4) augment, and 5) assemble. These functions are not mutually exclusive. For example, inspection may be required to support the docking activity of relocation missions. Although the uplink of software does constitute improving a space-based capability, it is excluded from this definition of *in-orbit* servicing activities. This function is considered outside the scope of this paper.

A. Inspect

Observation of a space object from an attached position or a remote surveillance vehicle provides space situational awareness and may be a necessary precursor for other OOS activities. The inspection function includes proximity operations to assess a space object's physical state (i.e., position, orientation, and operational status). In the case of a satellite, inspection may include characterization of the spacecraft payload and assessment of the bus exterior for damage. For example, on the Space Shuttle's return to flight mission (STS-114), Discovery's robotic arm incorporated an orbiter boom sensor system with a camera and laser to inspect for tile damage on the shuttle's protective skin [7].

B. Relocate

Modification of the orbit of a space object may be desired to support constellation reconfiguration, tactical maneuvering, boosting GEO satellites to higher orbits for EOL retirement, controlled reentry of low Earth orbit (LEO) spacecraft, and rescue of satellites stranded from a maneuver or due to launch vehicle failure. For example, a rescue capability might have saved \$1.2 billion of taxpayer dollars in April 1999 when the Milstar 3 satellite failed to reach its operational slot in GEO due to an upper stage failuren [3].

C. Restore

Returning a satellite to a previous state (or intended state) enables a wide range of capabilities. Restoration activities include refueling for lifetime extension and maneuvering spacecraft, docking and providing stationkeeping to extend mission life, repairing or replacing faulty hardware, and deploying appendages which fail to reach operational orientations at beginning of life (BOL). In October 1984, the crew of Challenger on STS-41G demonstrated the feasibility of on-orbit refueling by transferring 60 kg of hydrazine between two pallet-mounted tanks. Two astronauts completed the operation during a three-hour extravehicular activity (EVA) [8]. A renowned example of on-orbit satellite restoration occurred in December 1993 on STS-61 with the installation on the Hubble Space Telescope of the corrective optics space telescope axial replacement (COSTAR)—compensating for the aberration on the original mirror [9].

D. Augment

Increasing the capability of a satellite consists of replacing or adding hardware that improves spacecraft performance. For example, Hubble's modular design has allowed NASA to equip the orbiting observatory with state-of-the-art instruments every few years [9]. Joppin [10] developed a utility metric for Hubble instrumentation called "discovery efficiency," which is defined as the product of the field of view and the throughput of the instrument. Applying this metric, it was found that the third-generation wide field planetary camera (WFPC) envisioned for the fourth servicing mission has discovery efficiency 180 times greater than the first-generation WFPC. Thus, OOS missions have tremendously augmented the capability of the telescope.

E. Assemble

Mating modules to construct space systems enables the construction of large space platforms that could not be transported by existing launch vehicles. For example, the International Space Station (ISS), which is still being assembled on orbit, has an overall mass of nearly 200,000 kg while the shuttle's payload capability to the ISS (51.6 deg inclination) is 18,300 kg [11]. Additionally, the performance of heavy-lift variants of the evolved expendable launch vehicle (EELV) program peaks at less than 25,000 kg of payload to LEO (e.g., the theoretical LEO maximum for Delta IV Heavy is 23,260 kg [11]).

III. Why Service Satellites?

The only existing operational satellites that are serviced are the Hubble Space Telescope and ISS. Humans maintain these space systems in expensive servicing operations carried out by the space shuttle and Russian spacecraft. Given these costs, the human servicing model is clearly not applicable to the majority of commercial space systems. However, the existence of this capability demonstrates that there are no fundamental technological or physical hurdles to overcome with respect to OOS (e.g., solar maximum repair on STS-41C [12], Intelsat 603 rescue on STS-49 [13]). Developments in autonomous and teleoperated vehicle technology as well as the potential for sharing the cost of an on-orbit servicing infrastructure across multiple target satellites allow a business case to be made for robotic servicing in certain markets.

Servicing provides options for space missions traditionally constrained by inaccessible satellites, mitigates vulnerabilities to monolithic spacecraft, and generally enables a more robust space enterprise. Benefits of servicing can be divided into five broad categories: 1) reduce risk of mission failure, 2) reduce mission cost, 3) increase mission performance, 4) improve mission flexibility, and 5) enable new missions.

A. Reduce Risk of Mission Failure

A space-based servicing infrastructure reduces the risk of satellite failure across the entire life cycle. Consider the potential savings if the failure of Milstar 3's upper stage had been mitigated by launching a space tug—a vehicle designed to rendezvous and dock with a space object; make an assessment of its current position, orientation, and operational status; and then either stabilize the object in its current orbit or move the object to a new location with subsequent release [14]—for a rescue mission of Milstar 3. Faulty spacecraft systems discovered at BOL can be remedied (e.g., compensating for aberrations in Hubble's optical assembly with COSTAR installation during the first servicing mission [9]). Brown [15] also explored the possibility of replacing the paradigm of launching monolithic systems on a single heavy-lift vehicle (single-point failures) with the launch of redundant spacecraft components separately on small launch vehicles followed by on-orbit assembly.

B. Reduce Mission Cost

Given the Hubble and shuttle experience, on-orbit servicing is typically associated with higher mission costs. The servicing provider will charge a fee and the target satellite may pay a mass penalty for incorporating a modular bus structure with docking and refueling ports. However, the target satellite mass penalties for docking and refueling interfaces are relatively low. For example, the redundant docking mechanism and refueling mechanism associated with the Defense Advanced Research Projects Agency (DARPA) Orbital Express program have masses of 32 kg and 50 kg, respectively [16]. (A GEO communications spacecraft such as XM-2's Boeing 702 has a dry mass of 2500 kg [17].) In fact, OOS offers several pathways to reduce life-cycle costs. First, operators may choose to incorporate less redundancy into spacecraft. Second, operators may choose to design satellites for a shorter life, reducing upfront costs while delaying the decision either to allocate funds for servicing or to abandon at a later date. Third, the high-value components of a satellite (e.g., payload, bus structure) might be separated from low-value components (e.g., propellant) during the launch phase. Traditional, expensive launch vehicles might be used for high-level components while emerging, low-cost launch vehicles (e.g., Space Exploration Technologies' Falcon I and Falcon V are priced at \$5.9 and \$12 million, respectively [11]) might transfer propellant to servicers that refuel the satellite at BOL.

C. Increase Mission Performance

Servicing activities may improve spacecraft performance in terms of mission life and payload utility. Servicing tasks may be performed to extend spacecraft life (e.g., refuel, dock and provide stationkeeping, repair faulty components). More notably, servicing may be employed to increase payload capabilities. Operators may choose to upgrade to maximize revenue generation and science returns, or to prevent technological obsolescence, particularly in the later years of a satellite's operation or in cases where technology is rapidly improving.

D. Improve Mission Flexibility

An on-orbit servicing infrastructure also offers satellite operators an option to modify space system requirements following launch. New payloads may be incorporated for new missions. Emergent terrestrial markets might be captured more efficiently, and spiral deployment of fleets of satellites might be enabled with the benefits of constellation reconfiguration. Relocating satellites with space tugs might be particularly valuable to support wartime surge capability over theaters of operation.

E. Enable New Missions

Another case for on-orbit servicing can be made when identifying capabilities of such technology that cannot be offered by existing systems. The refueling servicing activity enables new missions in the areas of tactical maneuvering for unpredictable orbits and extremely low altitude, high-drag orbits for Earth observation satellites. Although low altitude orbits are important for imaging satellites, they would be particularly valuable for space-based synthetic aperture radar systems in which the power of the radar signal decreases as the inverse of the altitude to the fourth power.

IV. OOS for the Existing GEO Communications Satellite Architecture

In the previous section, we explored qualitatively the technological feasibility of OOS and the kinds of activities in space that can benefit from on-orbit servicing. However, a valuable question to ask is OOS of value to the existing operational satellites around the Earth? That is, if existing satellites had incorporated docking and refueling interfaces but otherwise maintained the same design paradigm (i.e., high redundancy, long design life), would OOS make sense? We examine this question by considering the 773 functioning satellites which are currently in orbit around the Earth (as of 11 March 2006) [17]. As a means to rapidly survey the operational population of satellites for OOS targets, the Union of Concerned Scientists (UCS) satellite database was used [17]. The database is derived from open-source information and is available in Excel as well as a tab-delimited text format. Updated quarterly, the database includes 21 fields of basic information on each active satellite. Technical information about each satellite's launch mass, dry mass, power, and launch vehicle type are included in the database as well as orbital parameters and information on the user, owner, operator, and builder.

Of the 773 satellites included in the UCS database, 534 are communications satellites (318 of which reside in GEO and 203 in LEO). Astronomy and Earth observation spacecraft reside primarily in LEO (with GEO early warning satellites being the primary exception for Earth observation). Navigation satellites (i.e., U.S. Navstar GPS and Russian Glonass) comprise the preponderance of medium Earth orbit (MEO) systems.

Table 1 shows the distribution of satellites.

Other than navigation satellites in MEO, operational satellite orbits largely consist of LEO for mapping Earth resources, meteorology, and communications and GEO for communications spacecraft. In LEO, resolution and aperture requirements drive orbits to lower altitudes while coverage, lifetime, and survivability drive orbits to higher altitudes [18]. Of the 352 operational LEO satellites, one is in equatorial orbit, 141 are in intermediate orbits (with inclination between 20 and 85 deg), 86 are in polar orbits (with inclination between 85 and 95 deg), 122 are in sun-synchronous orbit (with inclination between 95 and 104 deg), and two are in retrograde orbits (with inclination between 104 and 180 deg). Over 90% of active satellites are in LEO and GEO. Figure 2 illustrates satellites near GEO altitude with inclinations less than 15 deg. To test the value

Table 1 General distribution of active satellites

	LEO	MEO	GEO	Elliptical	Total
Astronomy	53	0	1	17	71
Communications	203	2	318	11	534
Earth observation	87	0	23	2	112
Navigation	9	44	3	0	56

of OOS, we examine an agent-based model of OOS for this highly concentrated set of satellites in the GEO belt.

A. Agent Model of Satellite Servicing Based on Orbital Transfers

With the context of a multiyear servicing campaign in the GEO belt, an agent model of OOS was constructed consisting of a series of phasing maneuvers between GEO parking slots [19,20]. An agent model is a computational method for simulating a population of independent agents (satellites) to observe aggregate emergent behavior. Each agent is implemented as an object with internal states and rules of behavior [21]. In the agent model developed here, OOS is treated as a multivariable optimization problem with the principal trade of minimizing both ΔV expenditures and transfer time. Assuming current launch vehicle, propulsion, and robotic technology for servicing vehicles, the focus in the model is on the serviceability of target satellites. Servicing vehicle operations are simulated over time, completing maneuvers as a function of path-dependent servicing operations. With servicing operations initiated by requests from target satellites that issue "tickets" in a binomial process, a Monte Carlo analysis is performed to derive general results. Primary outputs of the agent model are the cost of servicing (mean ΔV expenditure by servicing vehicle for satisfying tickets) and the performance of target satellites (availability for mission operations).

Upon explaining the scope of the model, the two agents (target satellites and servicing vehicles) are described with a discussion of potential states and the rules governing state transitions. Assumptions regarding servicing vehicle capabilities and initial conditions are also discussed before presenting results.

Activities involving physical manipulation of target satellites are "black box" operations in the agent model. Additionally, the serviceability framework presented here focuses on servicing multiple satellites at or near GEO. This initial focus on GEO is driven by the two main factors, the high propulsive cost of LEO plane changes using existing technology and the current concentration of high-value satellites in GEO.

For a typical satellite in LEO, a plane change of only 3 deg requires on the order of 10% of the mass of the satellite. With the cost of the propellant approximately $10,000/\mathrm{kg}$, the life-cycle cost of a LEO servicing system would be high. Relative to LEO, servicing operations in GEO require relatively small amounts of propulsive effort (e.g., 70–120 m/s for the servicing architectures is calculated in Sec. IV.D). Despite large physical distances separating GEO satellites, most satellites are in essentially the same orbit. Greater servicing demands are also possible with the concentration of high-value satellites.

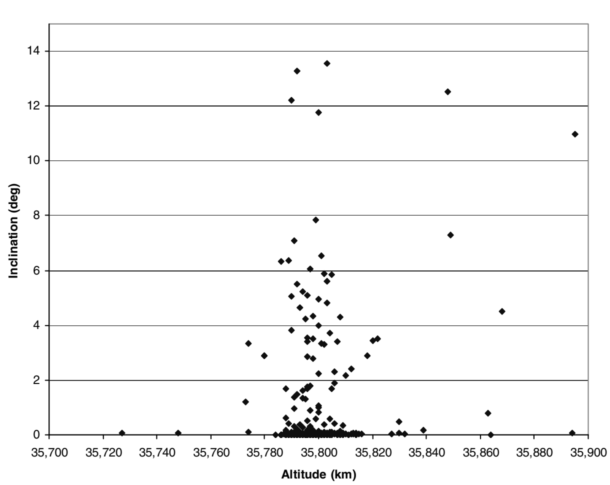


Fig. 2 Distribution of geostationary and near-geostationary satellites.

B. Agents, States, and Behaviors

Each of the two agents in the OOS model, target satellites and servicing vehicles, has a variety of potential states that are governed by underlying behavioral models.

1. *Target Satellites*

Target satellites may be in one of three states: full health with no need of servicing, full health with a request for scheduled servicing, and not operational with a request for urgent servicing. Requests are communicated to servicing vehicles through tickets by target satellites in need of attention. Table 2 illustrates the annual OOS market size in GEO. Based on empirical data compiled on satellite operations between 1957 and 2000 [3], five potential types of servicing missions are identified: refuel, orbital replacement unit (ORU) replacement, general repair, relocation in GEO, and deployment assistance. The probabilities in Table 2 inform the frequency of servicing ticket requests in the OOS model with tickets issued in a binomial (discrete Poisson) process. One hour is used as the time step in the model with annual servicing requests mapped to the hourly probability of an individual satellite requesting a given servicing mission. Over the course of a given 5-year servicing campaign, 130 servicing tickets can be expected to be generated (on average) by the set of 335 GEO satellites.

If in need of servicing, two types of tickets may be issued by the target satellite: scheduled and urgent. Whether a ticket is scheduled or urgent is assumed to be a function of the predictability of the servicing operation (i.e., unpredictable servicing missions cause urgent servicing tickets to be initiated). (In this discussion, a predictable mission does not imply that it is known years in advance. Rather, it implies that a servicing vehicle may respond in weeks rather than days without strongly affecting the value proposition to the target satellite.) Table 2 shows the assumed predictability of each OOS mission. With refueling needs readily projected and ORU replacement as a preplanned activity, the first two OOS missions trigger normal servicing tickets. Repair and deployment assistance missions are assumed to be opportunistic servicing events that are not generally predictable. These trigger urgent servicing tickets. Relocation missions are assumed to be equally divided between predictable (e.g., movement of commercial communications satellites to capture emergent terrestrial markets, retirement) and unpredictable (e.g., surge communication need in conflict, sudden loss of attitude control). It is important to note that the service functions specified in this table do not change the basic capability of the satellite. Rather, the service returns the target satellite to its original capability or allows the capability to be deployed in a new location.

2. *Servicing Vehicles*

Servicing vehicles may be in one of four states: parked in GEO, in transit to a target satellite, servicing a target satellite, or out of fuel. When a ticket is issued, each servicing vehicle calculates the ΔV

Table 2 Annual number of GEO servicing opportunities

Service	Average annual opportunities	Average GEO opportunities	Predictable?
Refuel	20.0	8.9	Yes
ORU replacement	4.4	2.0	Yes
General repair	3.8	1.7	No
Relocation in GEO	13.0	13.0	Yes and no
Deployment assistance	0.3	0.1	No

required to complete the mission ($\Delta V_{\text{phase}} + \Delta V_{\text{proximity}}$) and compares this value to its remaining propellant. Of the servicing vehicles possessing enough fuel, the servicing vehicle that will expend the least amount of ΔV is selected for the servicing mission. Upon "grabbing" a ticket, the servicing vehicle transits to the target satellite with circular coplanar phasing maneuvers.

One of the parameters subjected to sensitivity analysis in the simulation is the transit time for the servicing vehicles to the target satellite. The key trade in the model is between transfer time and ΔV efficiency. Should a servicing provider expend extra fuel to transit more quickly (i.e., reducing the number of phasing orbit revolutions) to a target satellite that has issued an urgent ticket? This issue is addressed by treating response time as a parameter and modeling two servicing architectures: 1) treating all servicing tickets as equals, using a constant number of phasing orbit revolutions, and 2) distinguishing between servicing tickets by varying the number of phasing orbit revolutions as a function of ticket urgency. Equation (1) informs the selection of the number of phasing orbit revolutions.

$$a_{\text{phase}} = a_{\text{target}} \left(\frac{k_{\text{target}}(2\pi) + \vartheta}{2\pi k_{\text{servicer}}} \right)^{2/3} \tag{1}$$

Given a common orbit and an initial phase angle, the only parameters to trade are the number of revolutions for the target satellite and for the servicing vehicle during phasing. Since ΔV is minimized the closer a_{phase} is to a_{target}, the quantity in parentheses in Eq. (1) should be as close to 1 as possible. Given that the phasing angle varies between $-\pi$ and π, it follows that k_{servicer} and k_{target} should be equal.

The next issue to resolve is to determine the appropriate number for k_{servicer} and k_{target}. The greater their value, the smaller the ΔV expenditure will be. However, large numbers of phasing revolutions will take more time (Fig. 3a). In general, this trade between speed and fuel efficiency should be settled by a competitive OOS market (i.e., servicing urgency may drive OOS market segmentation). For the purposes of the agent model of OOS here, it is only necessary to select a baseline value. A heuristic investigation indicates that an even tradeoff between fuel expenditure and time of travel occurs at approximately $k_{\text{servicer}} = k_{\text{servicer}} = 5$ (Fig. 3b).

One constraint on the number of phasing revolutions is the need to select a number of revolutions for the target satellite that does not cause the perigee of the transfer orbit to impose a ΔV penalty due to atmospheric drag or to pass through the Earth. The high velocities and high drag characterizing extremely low altitude orbits impose a ΔV penalty for orbit maintenance (which could apply if servicers traverse low altitudes when using highly eccentric phasing orbits). So to make this ΔV penalty trivial, a constraint is imposed on the servicing vehicle (in the case when it trails the target satellite) such that the perigee of the transfer orbit may not be less than 1000 km in altitude.

Upon reaching the target satellite, the servicing operations begin. The ΔV and time costs to the servicing vehicle for operations are assumed to be constants of 50 m/s and one day, respectively. The mission completes with the servicing vehicle assuming a parking orbit in GEO adjacent to the target satellite it just serviced. As such, the orientation of servicing vehicles in the simulation is dependent upon the location of the last set of target satellites.

C. Initial Conditions

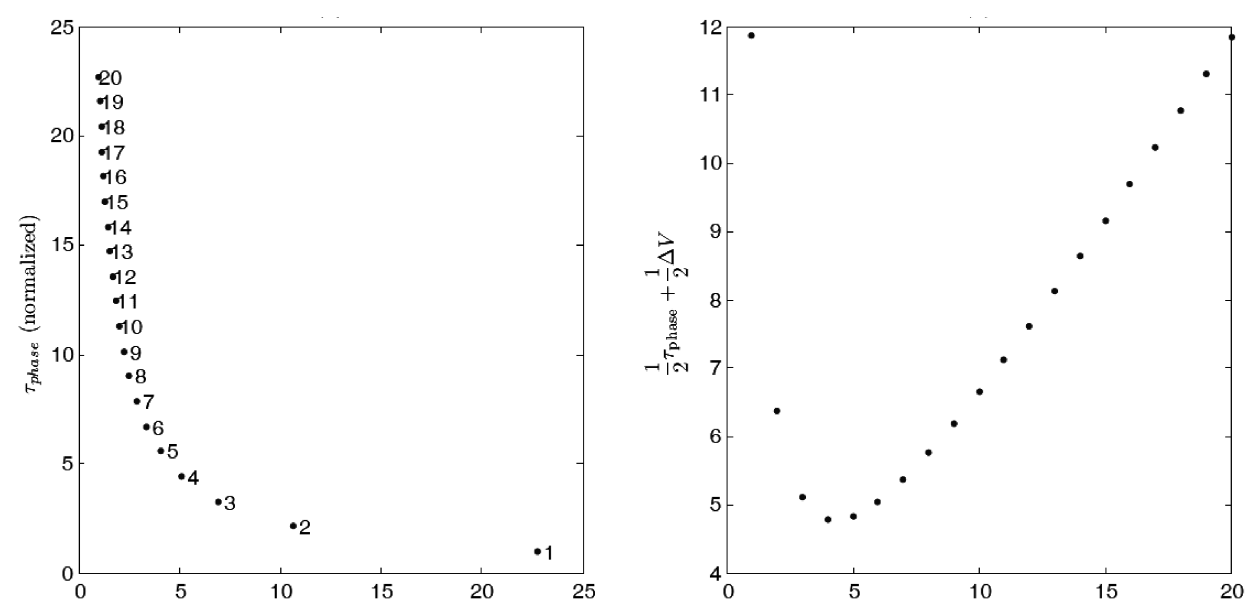
Initial conditions for the target satellites in the model are based on the orbital elements provided on GEO spacecraft in the UCS satellite database. Four servicing vehicles are assumed to be parked in the GEO belt.

1. *Target Satellites*

Target satellites are initialized based upon the UCS satellite database. Of the approximately 800 total spacecraft in the database, 335 are listed as being in GEO and contain true anomaly data. The GEO spacecraft comprise the target satellites used in the model and are assumed to be at GEO altitude with zero degree inclination (a close approximation of reality). Figure 4 illustrates the density of these 335 satellites (in 12 deg slices) over five continents. North American Aerospace Defense Command (NORAD) identification tags are also tracked in the simulation to establish traceability to satellite attributes beyond orbital elements (e.g., mission area, operator, payload) for later postprocessing. Local maxima may be observed over Europe and North America.

2. *Servicing Vehicles*

Although the purpose of the OOS model is not to design a servicing provider architecture [22], it is necessary to assume a baseline set of servicing vehicles from which the physical amenability of target satellites to rendezvous activities may be derived. For the provider architecture in the model, four servicing



a) b)

Fig. 3 Determining numbers of phasing revolutions—baseline servicing architecture.

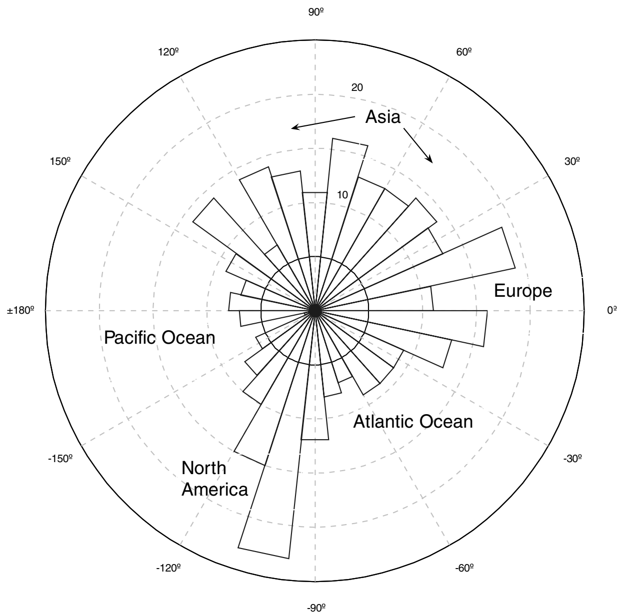


Fig. 4 GEO satellite density.

vehicles are assumed to be parked in the GEO belt with initial locations of 0, 90, 180, and 270 deg around the globe.

Current robotic, launch, and propulsion technologies are assumed in the simulation. Each servicing vehicle is based on ESA's geosynchronous servicing vehicle (GSV) [23]. With a dry mass of 1200 kg, the GSV consists of a conventionally designed bus, an augmented attitude maneuver and transfer capability, a sensor system for both rendezvous and docking and visual monitoring, and teleoperated robotic arms for mechanical manipulation (Fig. 5). Assuming launch with a Delta IV Heavy, the wet mass of the GSV delivered to GEO is 6276 kg [11]. This leaves 5076 kg of fuel for each GSV maneuvering in GEO. Assuming a bipropellant with a specific impulse of 300 s for the GSV [23], the rocket equation yields

$$\Delta V_{\text{total}} = g(I_{\text{sp}})\,\ell n\,\frac{M_p + M_f}{M_f} = 9.81(300)\,\ell n\left(\frac{5076 + 1200}{1200}\right) \approx 4869\ \text{m/s} \tag{2}$$

D. Results

Figure 6 depicts a sequence of three snapshots taken of the OOS agent model "dashboard" over the course of a typical servicing simulation. The four bars in each row depict remaining ΔV capabilities of the four servicing vehicles. The cumulative number of servicing tickets issued by target satellites is displayed above these "fuel bars." Polar views of the Earth are depicted in the right column. Small dots represent GEO satellites and the four large dots each represent a servicing vehicle. Time is displayed above the polar view. While time steps in the model are tracked in 1-h increments, the time step depicted in the tool dashboard is 30 days. At $t = 0$ (6a), each of the four servicing vehicles possesses a full ΔV capability (i.e., 4869 m/s). No tickets have been issued and the servicing vehicles are evenly spaced in GEO parking orbits. At $t = 30.4$ (6b), 2.5 years have passed and 65 tickets have been issued. Each servicing vehicle is parked in the slot of its last servicing operation and has between 3 and 4 km/s of ΔV capability remaining. After 5 years have passed (6c), 135 servicing requests have been made. Each simulation terminates at the end of the fifth year ($\sim$61 30-day increments). Five years was arbitrarily selected such that the availability calculation of servicing vehicles would not be influenced by servicing vehicles running out of fuel. Simulating servicing vehicle refueling or replacement is outside of the scope of the agent model and left to future work.

Performing a sensitivity analysis on servicing provider responsiveness is important for understanding the extent to which assumptions regarding the servicing architecture impact the serviceability results. Because the principal trade in the servicing architecture is between transfer time and ΔV efficiency, the number of allowed phasing orbit revolutions is treated as a parameter as a means to assess its impact on the relative performance of satellites in the serviceability metrics (i.e., availability and ΔV expenditure per servicing mission). Therefore, two 5-year OOS campaigns in GEO are investigated. In the first campaign, servicing vehicles use a constant number for phasing orbit revolutions ($k = 5$). In the second campaign, the numbers of phasing orbit revolutions for the servicing vehicle varies as a function of servicing ticket urgency ($k = 5$ for normal tickets, $k = 1$ for urgent tickets). Because servicing tickets are issued probabilistically, and, because ΔV expenditures and response times are functions of both the location of the target satellite of the current servicing mission and the target satellite of the last servicing mission, calculations in the agent model are path dependent. As such, a Monte Carlo analysis, consisting of 1000 runs of each servicing campaign, is performed to derive meaningful results.

The following two sections explain the results of the Monte Carlo analyses for the two servicing provider architectures: equal service (i.e., $k = 5$) and priority service (i.e., variable k). The discussion is focused on two key "orbit serviceability" parameters: the availability of target satellites in a particular orbital slot for mission operations (where availability between target satellites is distinguished only by the response time of servicing vehicles) and the average ΔV expenditure for OOS missions to a particular orbital slot (where ΔV expenditure is driven only by the rendezvous activities).

1. Servicing Campaign—GEO Satellite Availability

Availability is defined as the percentage of the time in the simulation in which a given satellite is able to perform its operational mission. Satellites issue urgent servicing tickets (for repair, relocation, or deployment assistance) when they are unable to perform their operational mission. Availability is extremely high for both servicing architectures (i.e., only $\sim$4 h each year of satellite downtime for "equal service" and 1–3 h of satellite downtime each year for "priority service"). As observed on the scatter plot in Fig. 7, availability is also relatively constant across GEO orbital slots. Although more variation was expected, this result is not altogether surprising given the small probability of urgent servicing tickets being issued and the fact that servicing operations always succeed.

2. Servicing Campaign—ΔV Expenditures

Although availability is not a good metric for distinguishing between orbital slots, Fig. 8 illustrates that ΔV expenditure for servicing missions does vary across the GEO belt as a function of the concentration of other target satellites. Figure 8 plots the median ΔV expenditure for servicing missions in each GEO orbital slot. GEO

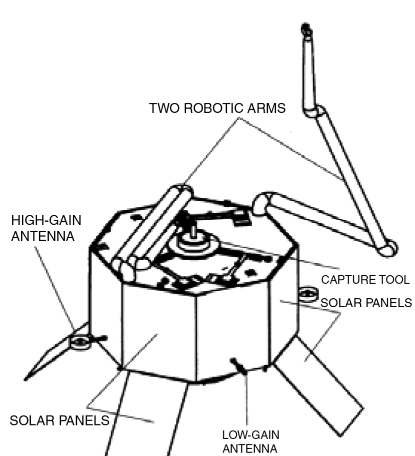
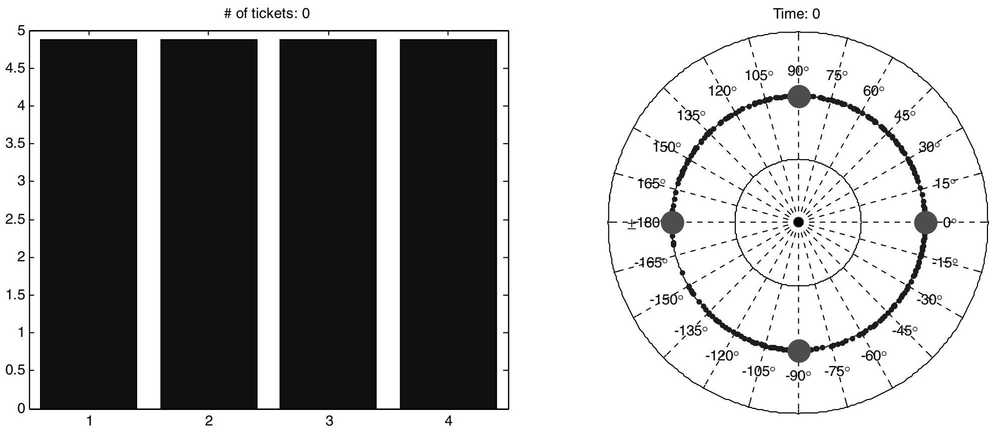
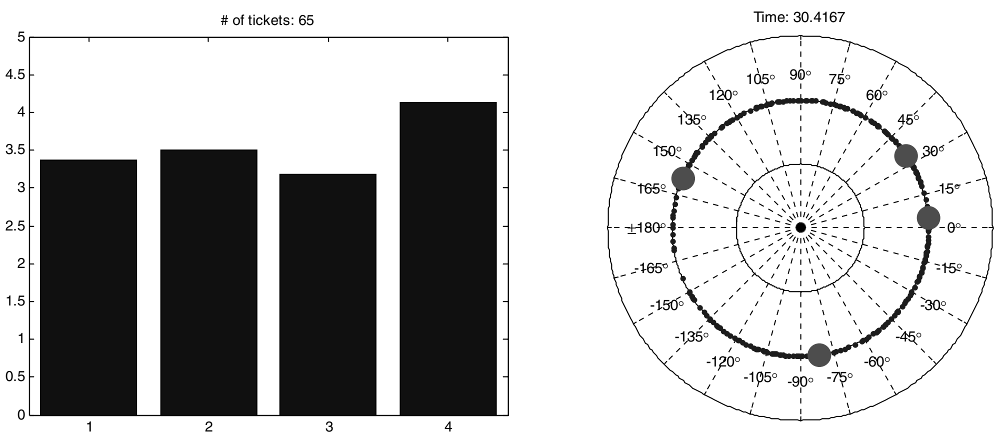


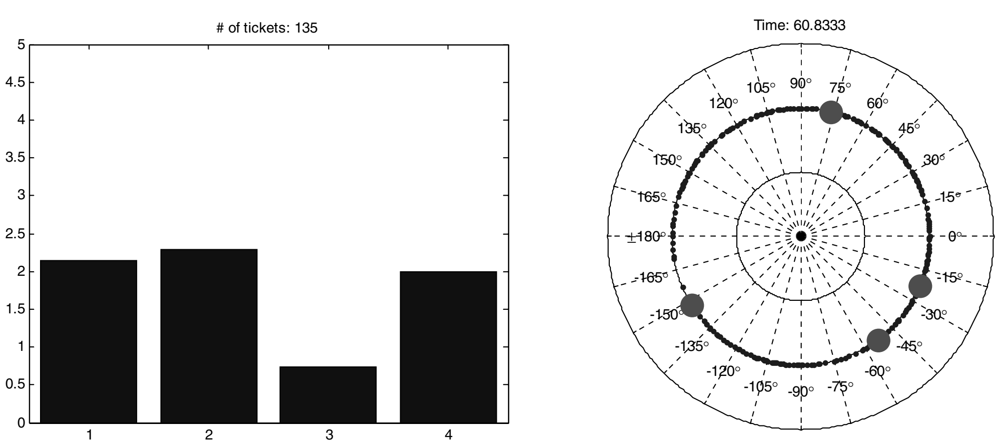
Fig. 5 Proposed GSV configuration [23].



a) Time=0 years (Δ V=4869 m/s for each servicing vehicle, 90º spacing)



b) Time=2.5 years (ΔV varies between 3 and 4 km/s for each servicing vehicle, variable spacing)



c) Time=5 years (ΔV varies between 0.5 and 2.5km/s for each servicing vehicle, variable spacing)

Fig. 6 Servicing vehicle evolution over 5 years—dashboard snapshots of OOS agent model.

satellite density is provided to illustrate the inverse correlation between satellite density and ΔV expenditures. In the case of constant response time (labeled equal service), GEO satellites are expected to cost servicing vehicles an average of $\sim$80 m/s for each servicing mission. Unlike availability, ΔV expenditure is not constant around the belt as satellites above North American (-80 to -120 deg) cost around 70 m/s with a sharp rise to 95 m/s above the Pacific Ocean (-120 to 150 deg). European (0–30 deg) ΔV expenditures are expected to be around 75 m/s, rising irregularly to around 85 m/s in the Far East (120–150 deg). In the case of a servicing provider architecture with variable response time (labeled priority service), GEO satellites are expected to cost servicing vehicles an average of $\sim$95 m/s for each servicing mission. Again, ΔV expenditure varies between target satellites as a function of orbital slot. North American values constitute the minimum median ΔV expenditure at approximately 85 m/s. GEO slots are most costly above the Pacific Ocean with ΔV expenditures of $\sim$110 m/s. European ΔV expenditures are $\sim$90 m/s, rising irregularly to around 95 m/s in the Far East. An important outcome of this figure is that the correlation of high satellite density and low ΔV expenditure for servicing missions is consistent across servicing provider responsiveness. This allows conclusions to be drawn about the serviceability of target satellites independent of the servicing architecture. Another interesting outcome of this figure is the roughly 20% increase in ΔV expenditure across orbital slots from the first servicing campaign. Given that approximately 30% of servicing

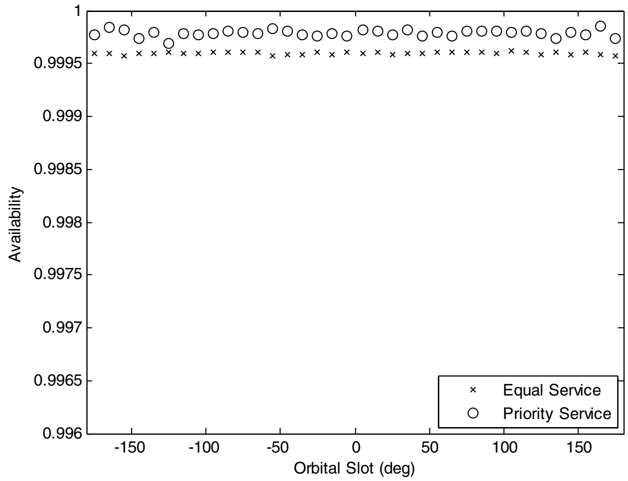


Fig. 7 Target satellite availability.

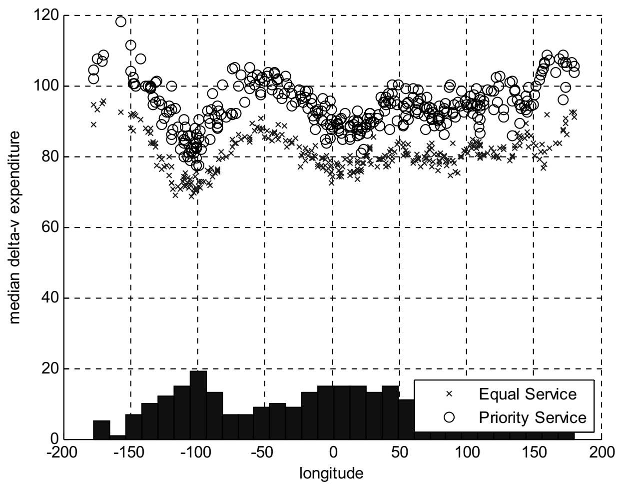


Fig. 8 ΔV expenditure for both servicing campaigns with GEO satellite density.

tickets are urgent, this suggests that reducing the number of allowed phasing revolutions from five to one on a priority servicing mission increases the required ΔV expenditure by 67%.

E. Discussion

Many interesting lessons emerged from the agent-based model of OOS with implications for both serviceability assessments of target satellites and servicing provider architecture. Most fundamentally, the high availability of GEO satellites in the model suggests that satellites work too well to stress a simple OOS system. Even in the first simulation with the intermediate response time, servicing vehicle availability exceeded 90%. The vast majority of the time the servicing vehicles are underutilized (e.g., the probability of two or more servicing vehicles conducting servicing missions simultaneously was less than 1%). Underscoring this high availability of servicing vehicles is the fact that all servicing opportunities in the model initiated servicing tickets. Although GEO servicing is potentially the most lucrative with a high concentration of valuable spacecraft and friendly orbital dynamics, satellites launched over the past two decades are designed with too much reliability for frequent utilization of four servicing vehicles. Of course, one servicer could meet the needs of all satellites in our model. However, this would come at the expense of response time and ΔV, and even then, the single servicer would be substantially underutilized.

This simulation indicates that the existing satellites in GEO would not use an OOS architecture with sufficient frequency in the current design paradigm. In the next section, we explore a new paradigm enabled by OOS that seeks to augment satellite value through technology upgrades.

V. Commercial Communications Satellite Upgrade Example

In the last section we showed that by not providing an increase in the value proposition for existing satellites, a servicing architecture would not be highly used. In this section, we consider the case of asset augmentation (an increase in value proposition) and examine OOS from an economic (fee-based) standpoint. We again focus on GEO communications satellites as a likely target market. Unlike the previous example, which examined the design of supporting OOS architectures, the objective of this example is to focus on the demand side of satellite servicing and determine the circumstances under which a satellite upgrade provides a significant enough increase in the satellite's value proposition, thereby providing the foundation for a satellite servicing business case.

A. Model Description

In this example, we examine the case where a commercial GEO satellite operator seeks to maximize the value (i.e., revenue) that will be provided by a newly developed satellite. First, the operator is faced with two decisions regarding the design of a communications satellite. The first option is to design a serviceable satellite and upgrade the satellite during its operational life with new technology, thereby generating additional value [24]. The second option would be to provide additional value by subsequent deployment of a more advanced satellite to replace a nonserviceable satellite.

Because the future in which the satellite operator would make the decision to upgrade or replace the initial satellite is unknown, we employ decision analysis to determine how operators should initially design their satellite. Value is determined from the decision tree represented in Fig. 9. This decision tree illustrates a satellite operator's two-part decision analysis consisting of 1) the decision to design for servicing or not and 2) potential future operational decisions based upon the initial decision. It is assumed that the operator is not provided with the option to decommission a satellite (based upon the fear of losing market share).

When the expected future value of the upper branch in the decision tree (nonserviceable option) provides more value than the lower branch (serviceable option), the operator would choose to develop a nonserviceable satellite. In the case when the lower branch provided greater expected future value over the upper branch, the operator would choose to develop a serviceable satellite.

In the event of a servicer failure, the value delivered by the satellite would equal the revenue generated by the satellite until the time of failure. It is also assumed that the operator incurs a loss equal to the amount of the expected future revenues and remaining costs associated with the procurement of the satellite. For the examples discussed in this section, satellite failure due to servicing was assumed to occur in 5% of all servicing cases.

Determining the value delivered by the satellite (whether serviceable or not) is fairly straightforward. The only real unknown is the price the operator will pay for upgrading. Because of the commercial demand-based context of this example, the servicing price is assumed to include all costs associated with providing the

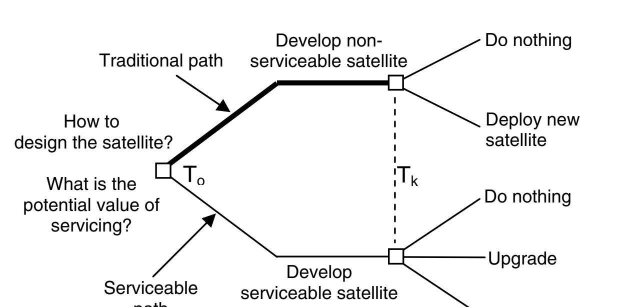


Fig. 9 Satellite design decision tree.

satellite upgrade. Therefore, the servicing provider's price must account for the cost of servicing vehicles, launch, component upgrades, and insurance, among other factors.

By varying the provider's servicing price, one can determine the price at which the option to service no longer provides greater value over the alternative options (i.e., do nothing or replace with new satellite). This servicing price is then the price at which the additional value provided by a satellite upgrade is zero—the maximum servicing price for the operator. A satellite operator would therefore not design a serviceable satellite for those cases in which the projected servicing price exceeds their maximum price. By varying the price associated with satellite upgrades with the increases in satellite value as the result of technology upgrades and the readiness of the technology upgrades, one can determine the circumstances under which a satellite operator would initially design a serviceable satellite.

B. Model Assumptions

1. Value Provided Through Technology Upgrades

In this example, two technologies are examined as possible ways in which to increase satellite operator value: upgrades to satellite transponder technology and upgrades to satellite bus technology. First, advancement in new satellite transponder technology is assumed to increase the overall communications throughput of each transponder, allowing for more communications traffic to traverse the satellite and thereby increase the value provided by each transponder. (Exactly how advancement in transponder technology can or would increase the overall throughput of each transponder is considered outside the scope of this study because it would require a detailed discussion regarding the design of the serviceable satellite and exactly which satellite components can be serviced.) Second, advancement in satellite bus technology is assumed to increase the overall capabilities of the bus and allow a satellite to support additional transponders, thereby increasing the value delivered relative to the capabilities of the initial satellite design. It is assumed that any new transponder technology can be applied to any satellite on orbit (given that it was designed for servicing or was a replacement satellite) but that new bus technology can only be incorporated into replacement satellites.

2. Value Provided by Communications Satellites

The total communications throughput of a given satellite depends upon the efficiency of its transponders, the number of transponders aboard the satellite, and the operational band of the transponders. A baseline communications satellite design is chosen for this study in both the serviceable and nonserviceable satellite design paths. The baseline satellite consists of 23 Ku-band and 76 C-band 36-MHz equivalent transponders; 36 MHz is the industry standard with regards to transponder sizing. This baseline satellite is modeled after INTELSAT 903 and 904 [25], both of which were launched in 2002. The incorporation of any new transponder technology by OOS is represented as a unit-value increase in the efficiency of each transponder by a given percent, ΔU. For advancement in satellite bus technology, it is assumed that the incorporation of new bus technology results in a new generation of satellites capable of supporting 70 C-Band and 36 Ku-band 36-Mhz equivalent transponders. This "advanced" satellite bus designed was modeled after INTELSAT 10-02 [25], which was launched in 2004.

The cost of the initial baseline satellite is \$200 million for the spacecraft [26] and \$171 million [27] for launch. These same values are assumed for the replacement satellite (with appropriate inflationary terms applied for a given launch and development time frame). It is assumed that designing the initial satellite to support on-orbit servicing requires a 20% price markup to account for the additional engineering, hardware, and interfaces. (This is the first estimate we have made regarding the cost of designing for serviceability.)

The revenue generated by the satellite is determined by the satellite's total capacity and the annual market price for GEO communications traffic, measured in bit per second (bps). The total value provided by the satellite is a combination of the number of each type of transponder on the satellite (N_{Trans}), the bandwidth associated with each transponder in hertz (B), the efficiency (bps/Hz) of the frequency of each transponder, and the annual market price (X). Equation (3) describes the method for calculating the satellite's value.

$$\begin{aligned}\text{Revenue} &= [(N_{\mathrm{Trans}})_{\mathrm{Ku}}(B)_{\mathrm{Ku}}(\mathrm{bps/Hz})_{\mathrm{Ku}}](X)_{\mathrm{Ku}} \\ &\quad + [(N_{\mathrm{Trans}})_{C}(B)_{C}(\mathrm{bps/Hz})_{C}](X)_{C}\end{aligned} \tag{3}$$

The overall efficiency of a particular transponder is determined by the increase (if any) in the transponder efficiency (ΔU), the percentage of small and large terminals support by the transponder (%TotalCapacity), and the efficiencies associated with communicating with these terminals (bps/Hz). Table 3 lists the percentage of large and small terminals and the associated bps/Hz ratios. Satellite capacity (C and Ku band) is distributed such that 25% goes to small terminals with the remaining 75% to large terminals [29]. The expected data rate capacity for a given frequency range (C or Ku) is determined by the product of the bps/Hz ratio for a particular terminal, the percentage of dedicated satellite capacity for that terminal, and any increase in efficiency due to new transponder technology. After this quantity is calculated for each type of ground terminal, the products are summed together to get an average data rate capacity for a given transponder [Eq. (4)].

$$\begin{aligned}(\mathrm{bps/Hz})_x &= (1+\Delta U)(\%\text{Total Capacity})_{\mathrm{large},x}(\mathrm{bps/Hz})_{\mathrm{large},x} \\ &\quad + (1+\Delta U)(\%\text{Total Capacity})_{\mathrm{small},x}(\mathrm{bps/Hz})_{\mathrm{small},x}\end{aligned} \tag{4}$$

3. Communications Market

The underlying market for communications over C and Ku bands is specified in the model as the selling price for an annual 1 Gbps contract. For simplicity, the annual market price associated with C and Ku markets is assumed to be equivalent. (In reality, the prices for C and Ku bands differ slightly from one another depending upon the underlying market and geographic location.) The initial value of the satellite's underlying market (X_0) at the time of launch is computed by taking the weighted average price for the various forms of satellite communications contracts. Typically, commercial communications contracts exist in four forms: 1-month, 3-month, 1-year, and 10-year contracts, each with its own distinct annual price. Commercial contract prices are based on market data found in Table 3.

To determine the annual market price for 1 Gbps of satellite capacity, it is assumed that the total capacity of the satellite is distributed among the various contracts in the following manner: 5% to 1 month, 5% to 3 month, 40% to 1 year, and 40% to 10 year. As a result of this capacity distribution, the total load per satellite is 90%. The remaining 10% of the satellite capacity is assumed to be either held in reserve or not used. After the initial expected price for 1 Gbps of capacity is computed, the change in the underlying market is modeled as a lognormal binomial tree distribution. A −4% annual drift rate [29] is used for the underlying communications market as is an assumed annual volatility of 20%.

4. Assumptions Regarding Technology Readiness

To capture the effect of a technology development period, a technology freeze of 3 years beyond the launch date is assumed on all technology. This implies that, at a minimum, it will take 3 years to develop any new technology regardless of the operator's action. Now, in reality, an operator could always increase the rate of technology development by increasing research and development funding, but this effect is not accounted for in the analysis. Although the technology freeze limits the earliest possible readiness date of any technology, the actual readiness of technology is uncertain. To account for this uncertainty, a Poisson process of technology development is assumed with an exponential probability distribution [30]. (It is further assumed that any technology that is ready following the first day of a given year may be deployed at the start of

Table 3 Commercial GEO communication satellite characteristics

Model parameters	Value
Model start time, t_0	2002
Model stop time, t	2002
Planned replacement	2012
Initial satellite cost	\$200 M (\$FY 2002), 10 yr operational life [26]
New satellite cost	\$200 M (\$FY 2002), 10 yr operational life [26]
Launch cost	\$171 M (\$FY 2002), Ariane 5 [27]
Satellite operating cost	\$1 M per year [28]
P (launch failure)	2%
Insurance, $\Re_{\mathrm{INS}}$	15% [26]
Inflation rate, $\Re_{\mathrm{INF}}$	2%
Internal rate of return, $\Re_{\mathrm{IRR}}$	8%
Interest free discount rate, $\Re_{\mathrm{IFR}}$	10% ($\Re_{\mathrm{INF}} + \Re_{\mathrm{IRR}}$) [22]
Markup for serviceable satellite—P_{markup}	20%
Percent small terminals (C & Ku bands)	25% [29]
Percent large terminals (C & Ku bands)	75% [29]
Ku-band large terminal bit rate	1.1 bps/Hz [29]
C-band large terminal bit rate	1.1 bps/Hz [29]
Ku-band small terminal bit rate	0.5 bps/Hz [29]
C-band small terminal bit rate	0.29 bps/Hz [29]
Transponder bandwidth (Ku and C)	36 MHz [29]
Satellite 1&2: 10-yr contracts (1998)	\$58 M annually, 40% of capacity [29]
Satellite 1&2: 1-yr contracts (1998)	\$77 M annually, 40% of capacity [29]
Satellite 1&2: 3-month contracts (1998)	\$154 M annually, 5% of capacity [29]
Satellite 1&2: 1-month contracts (1998)	\$274 M annually, 5% of capacity [29]
Market drift	−4% [29]
Market volatility	20%
Initial satellite transponder mix	76 C band & 23 Ku band (36 Mhz) [25]
Replacement satellite transponder mix	70 C band & 36 Ku band (36 Mhz) [25]

the succeeding year.) Because of the technology freeze, the upgrade or replacement of the target satellite cannot occur until the fourth year of operation. To account for a new satellite development period, it is assumed that a decision maker waits 2 years between a decision to launch a new satellite and the deployment of that satellite.

In addition to the value provided by upgrading or replacement, the operator has the unique option to incorporate new technology into the replacement satellite if both technologies are available at the same time. The incorporation of both technologies results in a replacement satellite with upgrades in transponder technology (increasing the value of the transponder) and upgrades in satellite bus technology (allowing for more transponders aboard future satellites). For an operator to launch a replacement satellite using both new transponder technology and new bus technology, the technologies need to be readied before the operator's decision for replacement.

The mean recurrence time for the readiness of new satellite bus technology is assumed to be 5 years. In the analysis, the mean occurrence time of the new transponder technology is varied to observe the effects of fast- and slow-evolving technologies.

C. Sample Results

Figure 10 is a sample output from the commercial GEO communication satellite upgrade example and provides a decision map for whether to pursue a serviceable design. Because of the uncertainty surrounding the availability of new technologies and the effect this availability will have on the operator's decision process (i.e., design for servicing vs do not design for servicing, and upgrade vs do nothing vs replace satellite), the decision analysis represented in Fig. 9 is subjected to Monte Carlo simulation. The simulation was run 1000 times and the resulting operator value was computed as the mean of the operator's value over all simulations.

For the results in Fig. 10, the value provided by new transponder technology is assumed to increase the data rate/Hz ratio of a single transponder by 50%. In reality this would be extremely high, but this value is used only to show the effect; the variation of this performance assumption will be examined later. The mean occurrence time for the readiness of the new transponder technology is assumed to be 1 year. The X axis represents the decision year beyond the launch of the initial satellite. At each decision year the operator can choose between available options, which depend on how the satellite was initially designed. Therefore, decision makers who design for servicing can choose to do nothing, replace, or service their satellite at the decision point. However, if a decision maker does not design for servicing, the option to service will not be available to the operator.

On the Y axis, Fig. 10 provides three distributions with respect to time: P(New Sat), P(New Tech), and the servicing cost penalty (CP_{Ser}). P(New Tech) represents the cumulative probability as a function of time for the readiness of the new transponder technology. Because of the assumption of an imposed technology freeze of 3 years and the uncertainty associated with the readiness of the transponder technology, one cannot expect with absolute certainty that the transponder technology will be ready in year three. As one waits until later decision points, the probability of technology

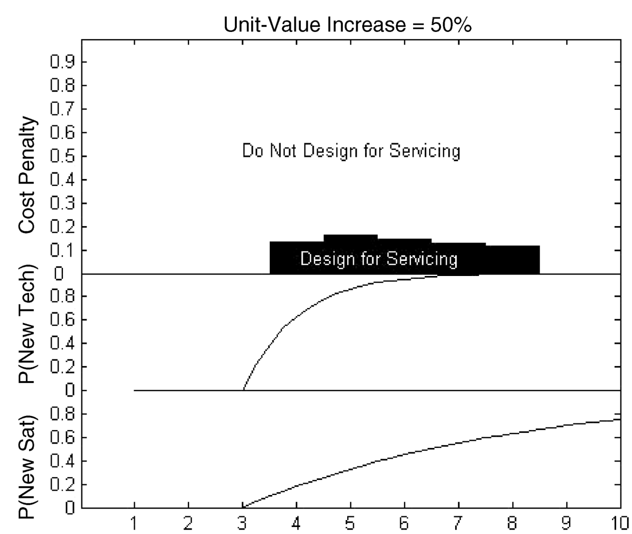


Fig. 10 Sample output for the commercial GEO communication satellite scenario.

readiness increases and approaches certainty. Note that the cumulative probability only describes the expected readiness of one generation of technology. Additional generations of the technology will certainly be developed as time goes on, but in this case only the development of one generation of technology was assumed.

P(New Sat), as *P*(New Tech), represents the cumulative probability as a function of time for the readiness of the new satellite bus technology. Recall, this technology allows the operator to incorporate additional transponders on future replacement satellites. In this case a decision maker can reasonably expect that new transponder technology will be ready before new bus technology. This is due to the assumption that the new transponder technology development occurs at a faster rate (occurrence time of 1 year) while the bus technology takes longer to develop (occurrence time of 5 years).

The distribution for the servicing cost penalty (CP_{Ser}) represents the mean change in relative program costs for which the decision to service provides the operator with the greatest expected value. The servicing cost penalty in each case is computed by determining the difference between the cost of pursuing the nonserviceable satellite design and deciding to do nothing when faced with future operational decisions ($C_{\mathrm{Nonserviceable\ Satellite}}$) and the cost of designing a serviceable satellite along with any incurred cost resulting from the decision to service. The servicing cost penalty is, thus, the fraction of the baseline costs that must be spent to pursue the highest-value servicing strategy.

It is assumed that the cost penalty associated with designing a serviceable satellite (P_{Markup}), the cost of initial development (C_{sat}), the satellite insurance premium ($\Re$INS), and the cost of operations (C_{op}) are all known. The cost associated with developing new transponder technology is assumed to be independent of the operator, while the cost of developing new bus technology is factored into the cost of the replacement satellite. The only remaining unknown cost in the servicing cost penalty is the servicing price. Each value of the servicing cost penalty above the minimum incurred cost (assuming costs where the servicing price is zero) is calculated by varying the servicing price. Therefore, the distribution for the servicing cost penalty describes the range of acceptable servicing prices under which an operator should initially design a satellite for servicing.

$$CP_{\mathrm{ser}} = \frac{C_{\mathrm{Serviceable\ Satellite}} + C_{\mathrm{Servicing}} - C_{\mathrm{Nonserviceable\ Satellite}}}{C_{\mathrm{Nonserviceable\ Satellite}}} \tag{5}$$

The purpose of examining the distribution is to determine whether an operator should design a satellite for servicing and whether the operator will service. If the cost of servicing is such that the servicing cost penalty lies within the distribution, designing a serviceable satellite is probabilistically the most valuable strategy for the operator. The distribution then becomes a "go/no go" gauge with respect to designing for servicing: "go," if the expected servicing cost penalty within the distribution and "no go" otherwise. For example, in Fig. 10, if the expected servicing cost penalty associated with servicing the target satellite in year five is 10%, the operator should design the satellite for servicing.

Because the distribution describes a range of acceptable servicing prices, the upper boundary of the distribution represents the maximum servicing price an operator is willing to spend on servicing as a function of the decision year. The operator's mean maximum servicing price is estimated using Eq. (6) where t is the expected end-of-life year of the satellite, t_0 is the initial launch year, t_k is the decision year, and $\Re$IFR is the operator unique interest free rate.

$$\text{Service Price}_{\mathrm{Max}} = \frac{C_{\mathrm{Sat}}(CP_{\mathrm{Ser,Max}} - P_{\mathrm{Markup}})[(1 + \Re_{\mathrm{INS}}) + C_{\mathrm{op}} \sum_{t=t_0}^{t_n} e^{-\Re_{\mathrm{IFR}}(t-t_0)}]}{e^{-\Re_{\mathrm{IFR}}(t_k - t_o)}} \tag{6}$$

Although the results in Fig. 10 show that a feasible market exists if an operator expects to service during years four through eight, these results are only one example of a potential market. In fact, there are several design elements that can affect the feasibility of OOS. For this example, the sensitivity of the operator's maximum servicing price was examined by varying the increase in transponder efficiency brought about by new technology and the speed of new technology development. The remaining figures in this paper display only the maximum servicing cost penalty. A feasible servicing range exists for all servicing prices below the maximum servicing cost penalty shown in the graphs.

1. *Sensitivity to New Transponder Technology Improvement*

Figure 11 shows the effect of varying the increase in the transponder efficiency on the operator's maximum servicing price. The change in efficiency is varied between 10, 30, 50, 70, and 90%. As the increase in efficiency from new transponder technology becomes greater, the range of servicing prices increases uniformly at all points in time. This linearly increasing pattern is likely the result of the value function's linear dependence on the benefit generated by the satellite. In this case, the operator is a commercial entity. For commercial companies, value is computed using profit = revenue − cost. From the figure it can be seen that an increase in efficiency of 10 and 30% is not sufficient to overcome the servicing cost penalty and thus does not lead to the creation of a feasible servicing market.

It is reasonable to assume that, if there is a high correlation between the increase in performance and the benefit delivered by that increase, there will be a high correlation between the increase in performance and the operator's maximum servicing price. Therefore, to significantly increase the operator's maximum servicing price, a service provider should focus on technology upgrades that result in significant increases in the operator's value.

2. *Sensitivity to Technology Readiness*

Figure 12 shows the effect of varying the mean recurrence time of new transponder technology on the operator's maximum servicing price. The mean technology recurrence time is varied between 1, 3, and 5 years. From the figure, the earlier that the new transponder technology is expected to be ready, the more value it delivers to the operator. However, the benefit of fast-evolving technologies is reduced as a decision maker waits to implement the technology. OOS can therefore provide operators with additional value by enabling the integration of fast-evolving technologies earlier than could have been accomplished with current satellite designs—demonstrating that OOS provides a new and improved value proposition by allowing the satellite operators an ability to integrate new technologies that could not have otherwise been integrated.

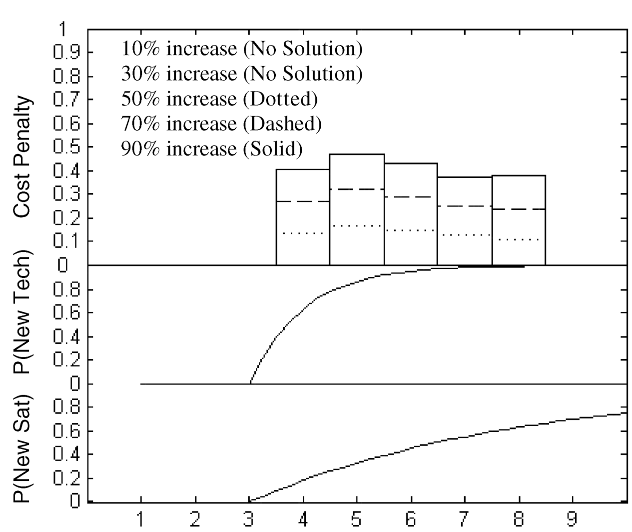


Fig. 11 Effect of varying increases in transponder efficiency.

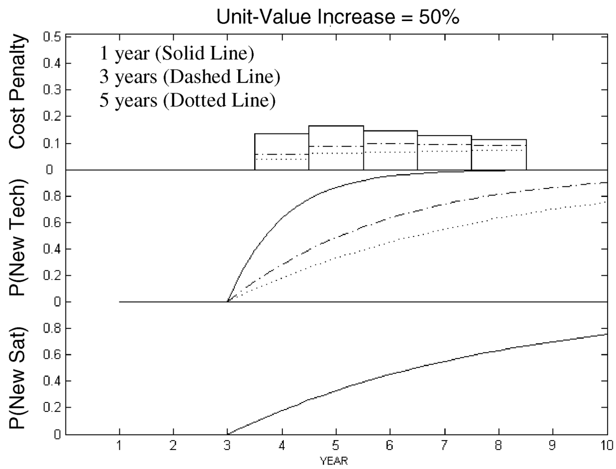


Fig. 12 Effect of varying technology readiness time.

D. Discussion

It has been shown that the operator's maximum servicing price depends upon a number of variables. The most significant variable is the increase in satellite capability due to the incorporation of new technology. Regardless of the effect of the other variables, if the increase in satellite capability from servicing is not significant enough, then OOS for the purpose of asset augmentation never makes sense. This conclusion is consistent with the findings of Joppin [10] regarding the value of upgrading the HST: that servicing HST was justified when the discovery efficiency changed by 3 orders of magnitude.

When comparing the effect that technology development rates have on the feasibility of satellite servicing, it was found that fast-evolving technologies provide the greatest value for the operator. Additionally, it was found that while fast-evolving technologies provided the greatest value, the value delivered decreased the longer it took to implement the new technology (i.e., as improved satellite bus technologies began to overshadow the value provided by the fast-paced technology). The main conclusion that can be drawn from the examination of technology development on the feasibility of on-orbit satellite servicing is that, not only is new technology vital to the feasibility of satellite servicing, the pace at which that technology development occurs is fundamental to the success of OOS.

VI. Conclusions

As a means to bring the benefits of on-orbit servicing to space systems beyond flagship programs such as the Hubble Space Telescope and International Space Station, the application of robotic technology for the purpose of on-orbit satellite servicing is promising. Two main conclusions are drawn based on the existing literature and the simulations described in this paper:

1) Confined to the existing value proposition of communication satellites, the economic feasibility of on-orbit servicing is questionable: The viability of robotic OOS is an open question. In analyzing the physical amenability of satellites to OOS, it was found that the current generation of spacecraft is simply too reliable to ensure a significant market size for potential OOS providers. Grounded in empirical data of annual servicing opportunities, the agent model of OOS applied to geosynchronous orbit found that servicing provider utilization could have increased by an order of magnitude without stressing the utilization factor of 4 servicing vehicles.

2) The development of a servicing infrastructure in space is dependent on the incorporation of new value propositions into the design and operation of satellites: This paper and other companion studies [10] have shown that the economic viability of OOS is heavily dependent upon the delivery of large performance gains over the long design lifetimes of current satellite architectures. Alternatively, a paradigm shift in geosynchronous communication satellites to shorter design lives [4] is another viable implementation strategy for a responsive space enterprise. Looking ahead, development of an OOS infrastructure will be driven by changes in the existing paradigm of the acquisition and operation of space systems. The responsiveness offered by OOS provides flexibility to capitalize on emergent technology and market opportunities and robustness to mitigate risks, better equipping the satellite industry to deliver value in changing contexts.

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References

[1] Sullivan, B., and Akin, D., "A Survey of Serviceable Spacecraft Failures," AIAA Paper 2001-4540, Aug. 2001.

[2] Pratt, T., Bostian, C., and Allnutt, J., *Satellite Communications*, 2nd ed., Wiley, Hoboken, NJ, 2002.

[3] Sullivan, B., "Technical and Economic Feasibility of Telerobotic On-Orbit Satellite Servicing," Ph.D. Dissertation, Department of Aerospace Engineering, University of Maryland, College Park, MD, 2005.

[4] Saleh, J., Hassan, R., Torres-Padilla, J-P., Hastings, D., and Newman, D., "To Reduce or Extend a Spacecraft Design Lifetime?," *Journal of Spacecraft and Rockets*, Vol. 43, No. 1, Jan.–Feb. 2006, pp. 207–217.

[5] Saleh, J., Lamassoure, E., and Hastings, D., "Space Systems Flexibility Provided by On-Orbit Servicing I," *Journal of Spacecraft and Rockets*, Vol. 39, No. 4, July–Aug. 2002, pp. 551–560.

[6] Reynerson, C., "Spacecraft Modular Architecture Design for On-Orbit Servicing," Albuquerque, NM, AIAA Paper 99-4473, Sept. 1999.

[7] Heiney, A., "Lending a Hand, an Arm, and a Boom," NASA STS-114, Kennedy Space Center, FL, Jan. 2005 (Press Release).

[8] Collins, M., Aldrich, A., and Lunney, G., "STS 41-G National Space Transportation Systems Program Mission Report," NASA TM-105473, Johnson Space Center, TX, Nov. 1984.

[9] National Research Council, "Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report," The National Academy Press, Washington, D.C., March 2005.

[10] Joppin, C., and Hastings, D., "On-Orbit Upgrade and Repair: The Hubble Space Telescope Example," *Journal of Spacecraft and Rockets*, Vol. 43, No. 3, May–June 2006, pp. 614–625.

[11] Isakowitz, S., Hopkins, J. B., and Hopkins, J. P., *International Reference Guide to Space Launch Systems*, 4th ed., AIAA, Reston, VA, 2004.

[12] "Major NASA Satellite Missions and Key Participants, Volume 4: 1984 and 1985," National Aeronautics and Space Administration, NASA TM-109257, Goddard Spaceflight Center, MD, Jan. 1985.

[13] Fricke, R., "STS-49 Space Shuttle Mission Report," National Aeronautics and Space Administration, NASA TM-108104, Washington, D.C., July 1992.

[14] Richards, M., Springmann, P., and McVey, M., "Assessing the Challenges to a Geosynchronous Space Tug System," *Proceedings of SPIE Defense and Security Symposium*, edited by P. Motaghedi, The International Society for Optical Engineering, Bellingham, WA, 2005, Vol. 5799.

[15] Brown, O., and Eremenko, P., "The Value Proposition for Fractionated Space Architectures," AIAA Paper 2006-7506, Sept. 2006.

[16] McVey, M., "Valuation Techniques for Complex Space Systems: An Analysis of a Potential Satellite Servicing Market," M.S. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2002.

[17] Union of Concerned Scientists, *UCS Satellite Database* [online database], http://www.ucsusa.org/global_security/space_weapons/satellite_database.html [retrieved 11 March 2006].

[18] Wertz, J., and Larson, W., *Space Mission Analysis and Design*, 3rd ed., Space Technology Library, Microcosm Press, El Segundo, CA, 1999.

[19] Richards, M., "On-Orbit Serviceability of Space System Architectures," Dual M.S. Thesis, Department of Aeronautics and Astronautics and Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, 2006.

[20] Richards, M., Shah, N., and Hastings, D., "Agent Model of On-Orbit Servicing Based on Orbital Transfers," AIAA Paper 2007-6115, Sept. 2007.

[21] Epstein, J., and Axtell, R., *Growing Artificial Societies: Social Science from the Bottom Up*, MIT Press, Cambridge, MA, 1996.

[22] Saleh, J., Lamassoure, E., Hastings, D., and Newman, D., "Flexibility and the Value of On Orbit Servicing—A Customer Perspective," *Journal of Spacecraft and Rockets*, Vol. 40, No. 2, March–April 2003, pp. 279–291.

[23] de Peuter, W., Visentin, G., Fehse, W., Elfving, A., Brown, D., and Ashford, E., "Satellite Servicing in GEO by Robotic Servicing Vehicle," *ESA Bulletin*, No. 78, May 1994, pp. 33–39.

[24] Long, A., "Framework for Evaluating Customer Value and the Feasibility of Servicing Architectures for On-Orbit Satellite Servicing," Dual M.S. Thesis, Department of Aeronautics and Astronautics and Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, 2005.

[25] "Spacecraft Performance and Transponder Frequency Layout," Intelsat, Ltd., Pembroke, Bermuda, Dec. 2006.

[26] DeSelding, P., "Cost of Insuring Satellite Launches Down by $10 Million," *Space News*, Vol. 17, No. 36, 18 Sept. 2006, p. 8.

[27] "Space Transportation Costs: Trends in Price Per Pound to Orbit 1990–2000," Futron Corp., Bethesda, MD, 6 Sept. 2002.

[28] "GEO Commercial Satellite Bus Operations: A Comparative Analysis," Futron Corp., Bethesda, MD, 13 Aug. 2003.

[29] Bonds, T., Mattock, M., Hamilton, T., Rhodes, C., Scheiern, M., Feldman, P., Frelinger, D., and Uy, R., "Employing Commercial Satellite Communications: Wideband Investment Options for DoD," RAND Corporation, MR-1192-AF, Santa Monica, CA, 2000, p. 29.

[30] Ang, A. H-S., and Tang, W., *Probability Concepts on Engineering Planning and Design. Volume I—Basic Principles*, Wiley, New York, 1975, p. 121.

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