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Flexibility and the Value of On-Orbit Servicing: New Customer-Centric Perspective

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A new customer-centric perspective on on-orbit servicing, where the value of on-orbit servicing is studied independently from its cost, is proposed. A framework is developed that captures the value of flexibility provided by on-orbit servicing to space systems. Several options are made available to space missions through on-orbit servicing, such as the option to service for life extension or to upgrade, that need not be set before launch; they can be exercised after the spacecraft has been deployed, depending on how events unfold (market changes, new military contingency, etc.). It is argued that only by accounting for this flexibility that the true value of on-orbit servicing can be evaluated. Applications of this framework to both nonprofit and commercial systems are provided that demonstrate the usefulness of this new perspective on on-orbit servicing.

Nomenclature

$C_{ops}(\Delta T)$	=	cost to operate a satellite during ΔT, $
$C(T_{life})$	=	spacecraft cost profile as a function of its design lifetime, $
E	=	cost to service the satellite (similar to the exercise price of an option), $
k	=	risk-adjusted discount rate (discrete case)
$P_{max\text{-}serv}$	=	maximum price a customer would be willing to pay for servicing, $
$P_{min\text{-}serv}$	=	minimum price a provider can afford to charge for servicing, $
r	=	risk-adjusted discount rate [$r = L_n(1+k)$, continuous case]
S	=	expected revenues to be generated during life extension, $
T_{life}	=	design lifetime, years
$U(t_1; t_2)$	=	aggregate utility provided between the $(t_1; t_2)$ time interval, $
V_{DTA}	=	project evaluated using decision-tree analysis, $
V_{flx}	=	value of flexibility, $
$V_{refueling}$	=	value of refueling, $
V_{serv}	=	value of servicing, $
α	=	expected rate of return
$\Gamma(x)$	=	step function (1 for $x > 0$, 0 elsewhere)
$\Delta C_{penalty}$	=	cost penalty incurred due to reduction of spacecraft design lifetime, $
ΔT	=	life extension, years
$\Delta T_{life\ lost}$	=	reduction of spacecraft design lifetime due to unplanned maneuvers, years
ΔV_{ph}	=	velocity increments required to perform a phasing maneuver, m/s
ΔV_{tot}	=	total velocity increment for stationkeeping over spacecraft design lifetime, m/s
$\Delta V(\Delta T)$	=	incremental value of a satellite per life extension ΔT, $
$\Delta\Phi$	=	change in the satellite phase, rad
ρ	=	quality actor for the staging of the spacecraft design lifetime
σ	=	volatility of the revenues S, %/year$^{1/2}$
Ψ	=	insurance premium contacted to mitigate risk of servicing operations, %

Introduction

ALTHOUGH the majority of weapon systems take advantage of logistics and maintenance support (e.g., aircraft operational lifetime and capabilities are extended through routine maintenance and payload upgrades), satellites remain the only complex engineering systems without maintenance, repair, and upgrade infrastructures.

The absence of space logistics and infrastructure, coupled with decision makers' desire to lower satellites cost per operational day, leads to the design of spacecraft for the longest operational lifetime. Over the past two decades, telecommunication satellites have seen their design lifetime, on average, increase from 7 to 15 years. Life extension occurred simply because it became technically feasible to design for a longer lifetime. The case of the AT&T's Telstar 3 communications satellites based on the Hughes HS-376 bus is a good example of this drive for longer design lifetime. The satellites have 10-year design lives, as opposed to 7-year lives for earlier satellite models. Life extension was made possible by the use of improved nickel–cadmium batteries and the introduction of solid-state power amplifiers in place of traveling wave tubes.

Designing for the longest technically achievable lifetime, however, hampers the rapid deployment of new technologies and capabilities because new technologies and capabilities can only be provided as the satellites retire. Life extension also increases the risk that the spacecraft becomes technically and commercially obsolete before the end of its mission. This tradeoff is illustrated in Fig. 1.

On-orbit servicing would provide a substantial advantage to commercial or military organizations over their competitors (or adversaries) by decoupling the drive to lower satellites cost per operational day through extended design lifetime from the ability to respond quickly to changing requirements and deploying new capabilities (Fig. 2). In other words, on-orbit servicing provides flexibility to space systems. Flexibility is defined here as the property of a system that allows it to respond to changes in its initial requirements and objectives, occurring after the system has been fielded, in a timely and cost-effective way.

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Numerous studies were written on the subject of on-orbit servicing in the 1970s and 1980s, assuming routine and economical access to space via the space shuttle, for example, the Space Assembly, Maintenance, and Servicing (SAMS) study. Other design studies were performed more recently, establishing requirements, constraints, and technology needs of robotic on-orbit servicing, and proposing point design solutions for on-orbit servicers [Spacecraft Modular Architecture Design (SMARD) global positioning system (GPS) servicing, etc.]. Despite these efforts, fundamental questions of applicability and cost effectiveness of on-orbit servicing remain unanswered.

This paper proposes a new perspective on on-orbit servicing where the value of on-orbit servicing is studied independently from its cost. A framework is developed that captures the value of flexibility provided by on-orbit servicing to space systems. Several options are made available to space missions through on-orbit servicing (e.g., option to service for life extension, or option to upgrade) that need not be set before launch; they can be exercised after the spacecraft has been deployed, depending on how events unfold (market changes, new military contingency, etc.). It is argued that only by accounting for this flexibility that the true value of on-orbit servicing can be evaluated. This paper is organized as follows: First, a background on on-orbit servicing is provided that includes definitions and taxonomy, a brief historical perspective, and a selected literature review. Second, the limitations of the traditional approach to on-orbit servicing are then discussed and contrasted with the new perspective that focuses on the value of servicing independently from its cost and where the problem is analyzed from the servicing customer's perspective, instead of the usual (servicing) provider's perspective. Finally, the advantages and limitations of this new approach to on-orbit servicing are also explored.

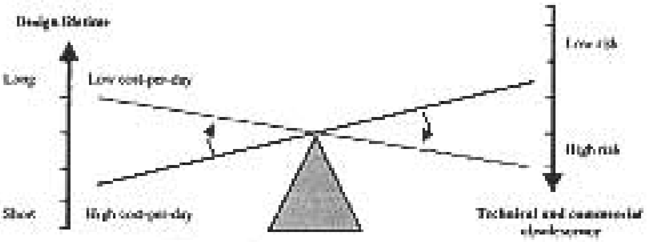

Fig. 1 Design lifetime tradeoffs.

Fig. 2 On-orbit servicing as a solution for decoupling the drive to lower satellites' cost per operational day through extended design lifetime from the ability to respond quickly to changing requirements and deploying new capabilities.

On-Orbit Servicing: Background

Definition and Taxonomy

On-orbit servicing comprises space assembly, maintenance, and servicing tasks to enhance the operational life and capabilities of space assets. Waltz[1] describes these three functions of on-orbit servicing in the following terms: 1) Assembly is the fitting together of manufactured parts into a structure, a subsystem, or elements of a subsystem. It is the on-orbit joining or construction of space systems and includes the deployment of solar arrays, antennas, and other appendages into their operational configurations. Assembly occurs before a space system becomes (fully) operational. 2) Maintenance is the upkeep of facilities or equipment (in space) either as necessary or as directed by a scheduled program. Preventive maintenance includes observation, inspection, surface restoration, realignment, recalibration, repair, replacement of modules, contamination removal, test, and checkout. Corrective maintenance includes all actions performed as a result of a system failure. 3) Servicing includes the on-orbit replenishments of consumables and expendables. However, the word servicing is often used to depict any or all of the functions discussed earlier.

Lamassoure[2] provides a different taxonomy of on-orbit servicing, as seen from the customer's perspective, instead of the traditional classification based on the on-orbit servicing provider's perspective. This classification consists of the following: 1) Life extension includes any on-orbit activity aimed at extending the operational life of the system in its initial design. This involves refueling, refurbishing, and repairing. 2) Upgrade includes any on-orbit activity aimed at improving the operational system in meeting its original mission goals. 3) Modification includes any on-orbit activity performed to make a space system meet new mission goals. Examples include design changes through payload addition.

In addition to either of the preceding classifications, another important partition of on-orbit servicing concerns the timing nature of the servicing activity. It can occur on demand or on a scheduled basis (Fig. 3).

Reynerson[3] introduced a cost consideration in defining on-orbit servicing and serviceable spacecraft. Because any spacecraft can be serviced on orbit given infinite resources, a spacecraft should not be considered serviceable unless the cost of servicing is justified by the benefits of doing so. His definition of a serviceable spacecraft follows from this reasoning: "Serviceable spacecraft: Any spacecraft for which the benefits of on-orbit servicing outweigh the associated cost. The purpose of servicing can be to replace failed or degraded components, to upgrade existing capabilities, or to add new functionality or capability."

Historical Perspective

Although on-orbit servicing became largely known through the Hubble Space Telescope experience, it has, nevertheless, been

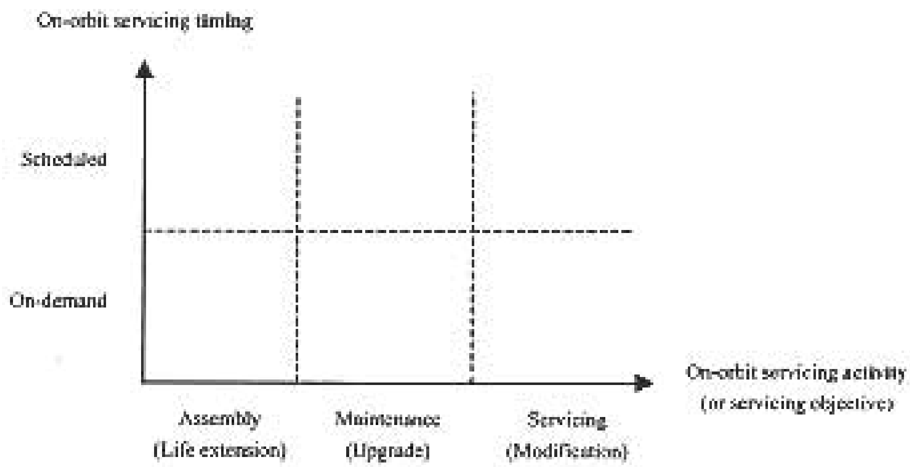

Fig. 3 On-orbit servicing taxonomy: timing vs on-orbit servicing activity (or servicing objective).

practiced since the early years of human space flight. Waltz[1] discusses significant servicing events. These include the Skylab servicing missions, the capture and repair in space of the Solar Maximum Mission (SMM) spacecraft; the on-orbit retrieval, repair, and redeployment of the SYNCOM-IV satellite; the on-orbit retrieval, attachment of a booster stage, and relaunching of the Intelsat 6 communication satellite; the Hubble Space Telescope repair and upgrade servicing missions; and many others. In this subsection, we briefly discuss the on-orbit servicing of Skylab and the SMM. The reader interested in a thorough discussion of the history of on-orbit servicing is referred to Waltz[1] or the SMAD study.

Skylab

Skylab was the United States's first experimental space station and solar observatory. It was launched into orbit by a Saturn V booster on 14 May 1973, and plunged back into Earth on 11 July 1979, scattering debris over the Indian Ocean and Western Australia. Skylab was discontinuously inhabited from 25 May 1973 until 8 February 1974.

The Skylab missions (SL-2, SL-3, and SL-4) included scheduled maintenance activities. The first flight, however (SL-1, uncrewed), experienced severe technical problems immediately after liftoff that required major unplanned maintenance efforts. Immediately after liftoff, the meteoroid shield, designed also to shade Skylab's workshop, deployed inadvertently and was torn away from the space station by atmospheric drag. One of the two solar panels of the craft was ripped off, and a strap of debris from the meteoroid shield wrapped around the other solar panel prevented it from deploying. This event and its effects prompted NASA, in an intensive 10-day period, to improvise new procedures and to train the crew to perform unplanned extravehicular activity to make the station operational and habitable. The various maintenance and repair activities performed by the successive crew included[1] the following: 1) the installation and deployment of a solar shield "parasol" that cooled the inside of the overheating station from 52 to 24°C, 2) the release and deployment of the jammed solar array, 3) the installation of a rate gyro package, and 4) major microwave antenna repairs and coolant system maintenance.

Skylab was NASA's first experience with on-orbit servicing. It demonstrated the effectiveness of crew members performing complex and unplanned repair tasks, without which Skylab would have been doomed to failure immediately after launch, and the 3400 h of onboard scientific experiments (solar observation, Earth observation, biomedical investigations, etc.) would not have occurred. This instance of on-orbit servicing raises the question of the value of on-orbit servicing vs its cost and the risk associated with performing it. In the case of Skylab, the value of salvaging the station and maintaining its habitablity for its 8-month mission was regarded as sufficiently high to outweigh the cost and risk of servicing the station.

SMM

The SMM was designed to provide coordinated observations of solar activity, in particular, solar flares, particle acceleration, formation of hot plasma, and mass ejection, during a period of maximum solar activity. The spacecraft was launched on 14 February 1980 into a quasi-circular orbit (512–508 km and inclination of 28.5 deg). Initially designed for a 2-year mission,[4] the 2315-kg spacecraft experienced, after 10 months of operation, a failure in its attitude control subsystem (ACS) that prevented the spacecraft from accurately pointing its instruments at specific regions in the sun. In addition, one instrument, the coronagraph/polarimeter, showed pronounced deterioration in its performance. The problem was traced back to its main electronics box (MEB). After the failure of the three momentum wheels, the spacecraft was put in backup slow-spin mode, thus allowing the spacecraft to collect sufficient energy on its solar panels, but precluding the use of three instruments. In other words, the failure of the ACS and the corrective action taken to salvage the mission (spin mode) dramatically crippled the spacecraft's ability to meet its scientific objectives.

A repair mission was decided on to prove the space shuttle's capabilities to rendezvous, repair, check out, and redeploy a free-flying spacecraft. (SMM was the first uncrewed spacecraft to be serviced.) In April 1984, after 1 year of training at various NASA facilities, astronauts onboard STS-41C (*Challenger*) captured the spinning spacecraft, replaced its attitude control module (primary objective), and repaired the faulty MEB of the coronagraph (secondary objective). SMM was then checked out, released into space, and resumed full operation. The SMM repair mission extended the lifetime of the spacecraft from 2 years to an additional 5 years after the repair, thus allowing for better coverage of the solar activity cycle. SMM collected data until 24 November 1989 and reentered Earth's atmosphere on 2 December 1989.

NASA estimated that a successful repair mission of the SMM would restore the $230 million spacecraft at one-fourth of its replacement cost.[4] Indeed, the cost of the repair mission was estimated by NASA Goddard Space Flight Center at $60 million (Ref. 1). Consequently, it was considered cost effective to opt for on-orbit repair of the SMM over total spacecraft replacement.

On-Orbit Servicing: A Brief Literature Review

While NASA engineers and astronauts were occasionally designing, training for, and performing on-orbit servicing, other members of the space community were investigating the design and consequences of a space-based servicing infrastructure. Indeed, numerous studies have been published since the early 1980s addressing various issues related to on-orbit servicing, such as 1) the analysis and design of on-orbit servicing architectures,[5,6] 2) the identification of serviceability requirements and spacecraft design implications,[5,7,8] 3) the design of robotic on-orbit servicers and the identification of technical challenges associated with performing on-orbit servicing,[5,9–12] and 4) the cost/benefit analysis of on-orbit servicing.[5,6,13]

SAMS Study

The SAMS study is the most extensive study of on-orbit servicing in the literature. A summary is available in Appendix B in Ref. 1. The program was a joint effort between the Department of the Air Force, the Strategic Defense Initiative Office, and NASA. The study sponsors provided the contractors with five design reference missions (DRM) as a means of exercising the SAMS study process for realistic conditions. From these DRMs, program requirements were generated and scenarios written for the spacecraft to be serviced, for the hardware/tools necessary to do the servicing tasks, and for the space/ground infrastructure necessary to support a SAMS program. The SAMS architecture that was developed included[1]: 1) a servicing facility at the space station (Freedom at that time); 2) a reusable orbital transfer vehicle using cryogenic propellants; 3) a remotely piloted orbital maneuvering vehicle, which can carry a servicing front end and appropriate spare modules for the serviced satellite; 4) a facility for the on-orbit storage and handling of cryogenic propellants; 5) a propellant transfer system, which can service satellites with storable propellant; 6) a tele-operated satellite servicer system, with dual servicing arms and stowage for fuel; and 7) a crewed orbital transfer module, which can be carried to a remote servicing location.

The study assumed routine and cheap access to space and was dependent to a large extent on the presence and support of humans in space. The 7-year program was terminated, however, after 16 months (phase 1). Its scope, (grand) scale, and assumptions proved to be its downfall. The study failed to inspire confidence in its conclusions regarding the cost effectiveness of on-orbit servicing.

After the SAMS study, the focus of on-orbit servicing studies shifted from high-cost crewed servicing infrastructure to uncrewed low-cost robotic servicing missions with the potential to reduce life-cycle costs of high-value space systems. The SMARD study and the on-orbit servicing of the GPS constellation study illustrate this trend. These two studies are summarized hereafter.

SMARD Study

The focus of the SMARD study was on uncrewed low-cost robotic servicing missions that have the potential to enhance the performance or reduce the life-cycle cost of high-value on-orbit assets. The study was performed in 1996 by the U.S. Naval Research Laboratory.[3,13] The study first identified and categorized different levels of servicing for a remote sensing constellation. [The architecture consisted of 10 satellites in low Earth orbit (LEO) with

2 satellites per plane. Details of the constellation and mission are considered classified.] Components of the satellite architecture were examined to determine the potential for replacement by a servicing mission: It was shown that one-third of the satellite components can be practically replaced, and many more could be replaced by adopting a more modular bus and payload design. Design modifications were suggested to make satellites better apt to being serviced. The study determined the following set of servicing needs of the satellite system: 1) replenishment of consumables and degradables (propellant, batteries, solar array), 2) replacement of failed functionality (payload and bus electronics and mechanical components), 3) enhancement of the mission through insertion of new technology.

On-orbit replacement of components in the SMARD study is performed functionally, not physically: All of the replacement components are packed in a single payload module, which a servicer satellite attaches to a docking interface on a satellite. This functional replacement strategy is considered to minimize the cost and complexity of the servicing mission and stands in contrast to physical replacement strategies advocated by other on-orbit servicing studies that consider human or robotic manipulation and (physical) replacement of failed or degraded hardware. Electrical and mechanical considerations were addressed to allow for functional replacement of components (modular data architecture design, docking interface, etc.).

A point design solution for a satellite servicer was developed as part of the study. The servicer consists of two payload modules and one bus module. Each payload module contains replacement components for one satellite. A servicer can, thus, repair or upgrade two satellites. "The point design was developed in such detail that a credible bottoms-up costing analysis could be conducted."[3] A costing evaluation was performed to determine the impact of servicing on the life-cycle cost of the constellation. The evaluation had three distinct components:

1) A cost evaluation of the proposed servicer vehicle was conducted. The costing included all design, development, integration, and ground test efforts.

2) An estimate was made of the cost impacts associated with redesigning the current satellites in the constellation to make them serviceable.

3) A set of life-cycle costs was developed for several on-orbit scenarios.

The study reports life-cycle cost savings from 10.3 to 38.2%, depending on the targeted life extension (from two to six years) and the number of servicers used, over a period of 20 years.

Despite its credible technical details and its encouraging cost/benefit analysis, the SMARD study did not have a follow up. The advantages shown in the study in terms of cost savings and availability did not outweigh the perceived technological risk and cost uncertainty associated with performing on-orbit servicing.

On-Orbit Servicing of the GPS Constellation Study

Two companion studies performed at the Air Force Institute of Technology[6] and The Aerospace Corporation[7] addressed the problem of servicing the GPS constellation. Leisman et al.[6] evaluated multiple architectures for on-orbit servicing of the GPS constellation and explored the costs and benefits of upgrading/repairing GPS satellites through robotic servicing systems. Their study, however, did not address "the complex technical and contractual modifications that would be necessary to make GPS satellites serviceable."[6] The structural modifications necessary to enable the servicing of the GPS IIF spacecraft were addressed by Hall and Papadopoulos.[7]

The objectives of the first study[6] were to identify the logistical support needs of the GPS constellation, to find multiple servicing support solutions, and to identify which of these solutions best meet those needs. The study proceeded as follows:

First, it identified logistical support needs of the GPS constellation through interviews with GPS managers and mapped the criteria decision makers consider important in evaluating a robotic servicer satellite. Responsive upgrade of the GPS constellation turned out to be of primary concern to GPS managers, whereas repair was considered desirable but not necessary:

> New technology or capabilities are provided only as the current satellites retire. The next generation of block IIF will have a design life of 12.7 years. Thus in the future, providing the full constellation with new capabilities will require ... approximately 13 years. The problem to be solved in this study is how to decrease cycle time for implementing new capabilities while still minimizing costs.[6]

Second, the study defined multiple architectures that could best meet customer needs. Architectures were differentiated according to the number of robotic servicers (RS) used per orbital plane, the type of propulsion system adopted, and the mass delivery capacity [orbital replacement units (ORU) of 50, 150, and 300 kg].

Third, each architecture was evaluated for costs and benefits over a 15-year operational period and for four servicing missions to each satellite. Costs were estimated using the NASA/U.S. Air Force NAFCOM 1996 parametric cost analysis program.

Finally, the study concluded that on-orbit servicing of the GPS constellation offers greater benefits and would be less costly than the current GPS satellite management paradigm (current policy of two satellite replacements/year): "Using current methods, the average cost of replacing a GPS satellite is approximately \$100 million. The most expensive of the top six [on-orbit servicing architectures] could upgrade the entire constellation for \$60 million per satellite."

Hall and Papadopoulos[7] complemented the previous study by conducting a preliminary assessment of structural modifications necessary to make the GPS spacecraft serviceable. The study focused on satellite upgrade through the addition of new components. Design modifications included upgrade slots that would be added to the GPS satellite baseline design and launched empty. The authors used (and modified) mass estimate relationships to evaluate the additional required to make the spacecraft serviceable. For instance, "Additional thermal control mass was added to account for increased complexity in thermal interfaces and heat loads that are added on-orbit. Instead of the baseline 3.7% of dry mass [mass of thermal control subsystem], 4–7.5% was used."

The study concluded that an additional mass of 3–15% would be needed to render the GPS spacecraft serviceable [baseline wet on-orbit mass of 2813 lb (1280 kg)]. The study, however, did not address design modifications at the subsystem level. This omission, on one hand, degrades the accuracy of the result and, on the other hand, fails to show whether the on-orbit servicing of the GPS constellation is actually feasible (even though the companion study showed that it was economical).

Limitations of the Traditional Approach to On-Orbit Servicing

The studies just discussed represent typical examples of the traditional approach to on-orbit servicing. With some minor variations, they all proceed as follows: First, the levels of logistical support for a given space mission are identified. Then, on-orbit servicing architectures are proposed that could meet these serviceability requirements. Parallel to this phase, designs for host vehicles that could perform on-orbit servicing are proposed, and the design modifications necessary to make spacecraft serviceable are addressed. Finally, the cost effectiveness of on-orbit servicing is assessed. This process is depicted schematically in Fig. 4.

Although this traditional approach to on-orbit servicing often represents sound systems engineering practice and offers numerous advantages (e.g., addressing the technical feasibility of on-orbit servicing), it nevertheless has intrinsic limitations that hamper the ability to make meaningful conclusions regarding the cost effectiveness of on-orbit servicing. These limitations are discussed next.

Cost Estimate Relationships Are Inappropriate to Estimate the Cost of a Robotic Servicer

Spacecraft costs depend on their size, complexity, technology readiness, and design lifetime, as well as other characteristics. Several governmental organizations have developed cost estimate relationships (CERs) over the years that relate spacecraft cost, or subsystem cost, to physical, technical, and/or performance parameters. The CERs are based on an appropriate historical database of past satellites programs. The basic assumption of parametric cost modeling

On-orbit servicing architecture	Modifications required to make spacecraft serviceable	Design of host vehicle to perform on-orbit servicing
# servicers per plane per satellite	Component accessibility	Autonomous Rendezvous and Docking capability (AR&D)
Characteristics of ORU canisters	Docking adapter/interface	Dexterous manipulator(s)
Space depots	Modularity, standardization (e.g., HST modular design allows 90 components to be replaced)	Electrical/mechanical interface

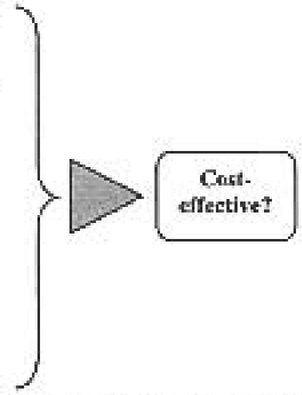

Fig. 4 Sequence of issues addressed in the traditional approach to on-orbit servicing; cost effectiveness of on-orbit servicing is left as an output of such studies.

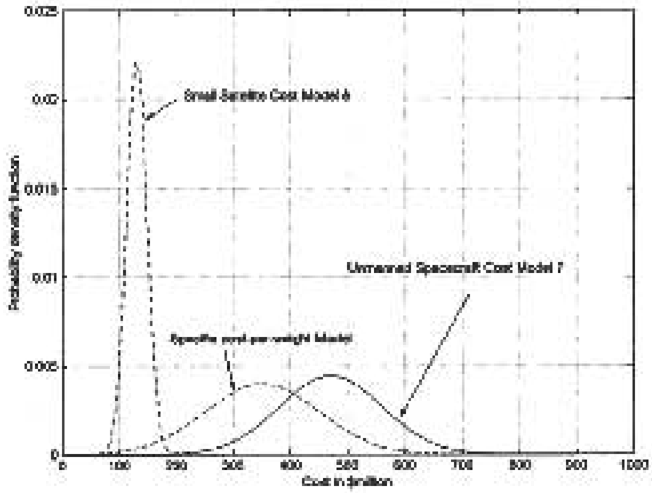

Fig. 5 Comparison of cost models results for four servicers with 200-kg cargo/payload; adapted from Ref. 2.

is that satellites will cost next time what they cost the previous time. Thus, the use of CERs to estimate the cost of a robotic servicer is doubtful because a servicer satellite would be substantially different from the historical data that were used to establish the CERs.

On-Orbit Servicing Cost Advantages Remain Smaller Than Cost Uncertainty

If it is assumed that the error in using CERs to estimate the cost of an RS can be quantified, Lamassoure[2] showed that, whereas there are situations in which on-orbit servicing proves cost effective, the cost advantage of on-orbit servicing remains smaller than the cost uncertainty, thus making "any definitive conclusion about the cost-effectiveness of servicing impossible." Figure 5 illustrates this point by comparing the probability distribution function of three different cost models for a typical servicer with 200 kg of cargo/payload.

Price a Spacecraft Owner/Operator Would Pay for Being Serviced Is Not Necessarily Equal to the Servicing Cost

In the traditional approach, the cost of the servicing architecture was compared with the overall constellation life-cycle cost savings to assess the cost effectiveness of on-orbit servicing. (All of the previous studies that have addressed the cost effectiveness of on-orbit servicing have developed servicing architectures for a constellation of satellites, for example, GPS and the classified LEO constellation in the case of the SMARD study.) However, the price a spacecraft owner/operator would pay to be serviced also depends on the development policy for the servicing infrastructure, and it is not reasonable to assume that the cost of a servicing architecture would be amortized by a single spacecraft and over a single servicing event. The cost of the whole servicing infrastructure can be amortized over several missions, or can be borne by a government agency such that only the marginal cost of servicing would be charged to individual spacecraft.[14] This undermines the traditional strategy of investigating the cost effectiveness of on-orbit servicing.

Traditional Approach to On-Orbit Servicing Overlooks the Intrinsic Value of Servicing for a Space Mission

Traditionally, on-orbit servicing has been analyzed from the (servicing) provider's point of view. It is surprising that no previous study has incorporated the (potential) customer's perspective on the subject. The value of servicing for a space mission should exist independently of any servicing architecture. In addition, by using traditional valuation tools such as net present value (NPV) calculations, previous studies have underestimated an important component of servicing value: Servicing provides space mission customers with options to react to the resolution of uncertain parameters, for example, evolving market needs and changing military contingencies. This flexibility is a significant advantage of servicing, however, its value is not captured by NPV calculations.[‡] Decision tree analysis (DTA) and real options calculations are more appropriate tools to capture the flexibility component in the value of servicing.

It is difficult to make a convincing case of the cost effectiveness of on-orbit servicing given the intrinsic limitations of the traditional approach discussed earlier. This motivates the development of a new perspective on on-orbit servicing that includes the (potential) customer's perspective, and where the value of servicing, including the value of flexibility it provides, is studied independently of the cost of servicing. This is elaborated on in the following section.

New Perspective on On-Orbit Servicing

The traditional approach to on-orbit servicing fails to recognize the intrinsic value of servicing for a space mission. This value, which we will define for the time being as the maximum price a space mission customer would be willing to pay for the on-orbit asset to be serviced, should exist independently of any servicing infrastructure. Highlighting the value of servicing adds a new dimension to on-orbit servicing studies, and shifts the focus from the traditional (servicing) provider's perspective to the (potential) customer's perspective. Figure 6 illustrates the two stakeholders' perspectives on on-orbit servicing.

The traditional approach to on-orbit servicing has explored (parts of) the left segment of Fig. 6. (See Fig. 4 for more details on this segment.) Suggestions have been made to investigate the effect of a servicing development policy where the cost of a servicing infrastructure would be borne by a government agency, and only the marginal cost of servicing charged to individual spacecraft efforts. Despite these efforts, not much confidence was shown in the traditional approach conclusions regarding the cost effectiveness of on-orbit servicing (for reasons already discussed). Ultimately, the decision to service an on-orbit asset lies with the potential customer (customer-centric perspective): A potential customer would opt for servicing if the value of servicing (V_{serv}) the spacecraft exceeds the cost to service it or the minimum price a provider can afford to charge for servicing ($P_{min\text{-}serv}$), given a servicing architecture, an

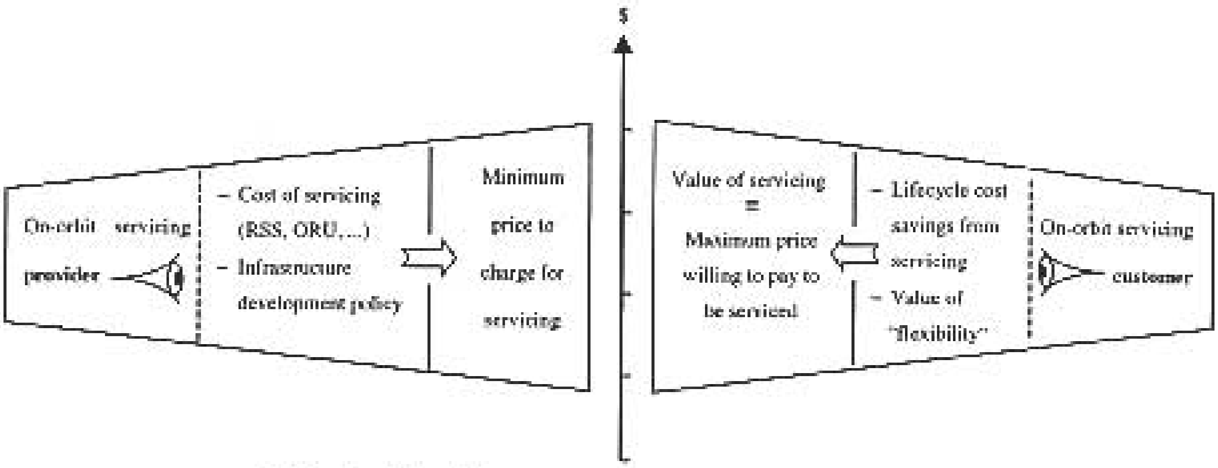

Fig. 6 On-orbit servicing provider's perspective vs customer's perspective.

infrastructure development policy, etc. This observation is captured in Eq. (1):

$$\underbrace{V_{serv} = P_{max\text{-}serv}}_{\text{as seen from the customer's perspective}} > \underbrace{P_{min\text{-}serv}}_{\text{determined by the provider}} \tag{1}$$

Separating the value of servicing from its cost presents several major advantages. First, the conclusions drawn are not dependent on a particular servicing architecture; instead they reflect the potential customer's valuation of on-orbit servicing independently of any servicing solution. Second, separating the value of servicing from its cost significantly reduces the uncertainty in the results that plagues the traditional approach to on-orbit servicing. Third, in identifying the maximum cost cap below which servicing makes economical sense, this approach helps guide the selection of space missions to target for servicing and provides a justification for a development policy of a servicing infrastructure. In addition, a major component of the value of servicing, the value of flexibility on-orbit servicing provides to space missions, is not taken into account by the traditional approach. Indeed, on-orbit servicing provides decision makers with options (to refuel, repair, upgrade, modify) that do not need to be set before launch. Instead, the decision to exercise such options depends on the resolution of parameters that were uncertain at the time of launch for example, market demand/uncertainty, military contingency, etc. The value of this flexibility is not captured by standard discounted cash flow techniques such as the NPV or the internal rate of return used by previous studies of on-orbit servicing.[3,5,6,13] In the following, we argue that only by accounting for this flexibility can the true value of on-orbit servicing be captured.

Accounting for Flexibility Provided by On-Orbit Servicing

The new perspective on on-orbit servicing presented herein is based on three main ideas. The principal idea of this new approach consists of estimating the value of servicing separately from its cost, thus, shifting the focus from the traditional (servicing) provider's perspective to the (potential) customer's perspective. The second idea lies in the observation that on-orbit servicing provides flexibility to space missions, as discussed earlier. Finally, contrary to what has been implicitly assumed by traditional approaches, the value of servicing is not limited to potential cost savings. Instead the value of flexibility provided by on-orbit servicing represents an important component of the value of servicing. In other words, the third idea consists of recognizing that the value of servicing should account for the value of flexibility provided by on-orbit servicing. Traditional discounted cash flow techniques such as the standard NPV calculation used in previous studies of on-orbit servicing cannot capture the value of flexibility. DTA, on the other hand is a more elaborate capital budgeting tool that is capable of accounting for the value of flexibility and is particularly useful for analyzing complex sequential decisions and in situations where uncertainty is resolved at distinct, discrete points in time. This is discussed further in the following section.

Failure of Traditional Valuation Tools to Capture the Value of Flexibility: Example of a Standard NPV Calculation vs DTA

The following example, adapted from Ref. 2, illustrates the shortcoming of the traditional NPV calculation to capture the value of flexibility and contrasts it with the use of DTA, a more elaborate capital budgeting tool than the NPV that is capable of accounting for the value of flexibility. A substantial body of literature exists that describes the shortcoming of NPV calculations; the reader is referred to Faulkner,[15] Trigeorgis,[16] or Amram and Kulatilaka[17] for more details.

Assume a project has a current value $S = \$200$ million and that its value after one year is discrete but uncertain: It can either increase to $S^+ = \$400$ million with a subjective probability p, or decrease to $S^- = \$100$ million. The owner of the project gives a potential buyer the option, but not the obligation, to acquire the project after one year for a price $E = \$280$ million. What is the value of this option? In other words, what price for the option will the owner and potential buyer agree on?

For discrete cash inflow C_n and outflow I_n over N periods of time, with a risk-adjusted discount rate k, the standard NPV calculation can be written as[18]

$$\text{NPV} = \sum_{n=1}^{N} \left\{ \frac{C_n}{(1+k)^n} - \frac{I_n}{(1+k)^n} \right\} \tag{2}$$

In our example, the NPV of buying the project is

$$\text{NPV} = p[(S^+ - E)/(1+k)] + (1-p)[(S^- - E)/(1+k)] \tag{3}$$

Assuming equal probability for the project value to go up or down, that is, $p = 0.5$, and taking a risk-adjusted discount rate $k = 20\%$, we get

$$\text{NPV} = -\$25 \text{ million}$$

Thus, from an NPV perspective, the project is not interesting, and the option to acquire it at the conditions stated will be discarded. This calculation, however, fails to take into account the managerial flexibility resulting from the asymmetry in having the right, but not the obligation, to acquire the project after one year. To avoid this deficiency of the traditional valuation, we revert to DTA.

DTA is a particularly useful tool for analyzing complex sequential investment decisions and in which uncertainty is resolved at distinct, discrete points in time such as in our example. DTA describes a sequence of decisions that are not set from the start, but depend on the resolution of some uncertain parameter(s). Unlike an NPV calculation, which is often misused by managers inclined to focus only on the initial decision to accept or reject a project at the detriment of subsequent decisions, DTA forces management to lay

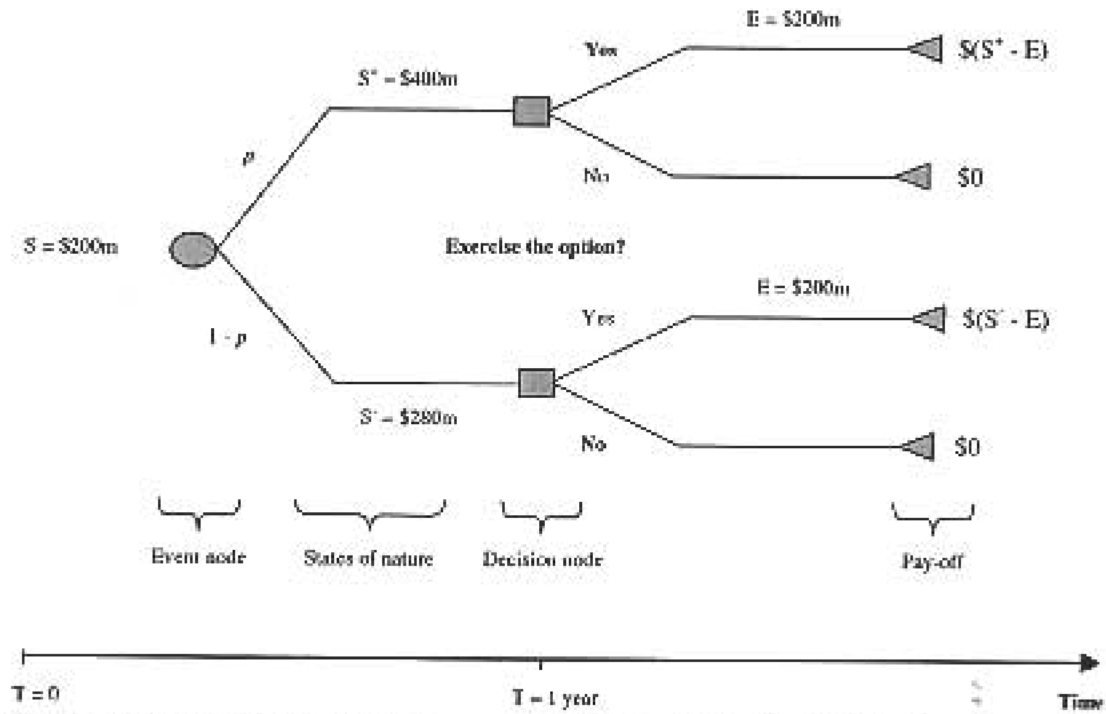

Fig. 7 Decision tree representing the investment problem in our example (standard notation); optimal decisions given each state of nature are written in bold.

out an operating strategy, and to recognize explicitly the interdependencies between the initial decision and subsequent decisions.[16] The optimal initial decision in a DTA is determined by starting from the end of the tree and working backward to the beginning. This dynamic programming, rollback procedure involves determining at each stage the expected risk-adjusted discount NPV (or expected utility) by multiplying all NPV (or utility) values calculated at the preceding, although chronologically following, stage with their respective probabilities of occurrences and summing up. Furthermore, the flexibility available to the decision maker is taken into account by considering only optimal decisions made at each evolution of the value of the project. Let us see how this applies to our example.

Figure 7 is a simple decision tree representing our investment example. If the value of the project increases, the optimal decision for the potential buyer (holder of the option) is to exercise the option and, thus, acquire the project. The payoff in this case is $\$(S^+ - E)$. If the value of the project decreases, the optimal decision is not to exercise the option, that is, not to acquire the project and, thus, to avoid the losses. There is no payoff if the project is not acquired.

The value of the option under these conditions becomes

$$V_{\mathrm{DTA}} = p\frac{\max(S^+ - E; 0)}{(1+k)} + (1-p)\frac{\max(S^- - E; 0)}{(1+k)} \tag{4}$$

Assuming equal probability for the project value to go up or down, that is, $p = 0.5$, and taking a risk-adjusted discount rate $k = 20\%$ as in the preceding calculations, we get

$$V_{\mathrm{DTA}} = \$50 \text{ million}$$

This calculation shows that, under the assumption of a rational decision maker (one that can make optimal decisions, that is, that maximize payoffs, after each decision node), the option of acquiring the project after one year is actually very attractive and is worth \$50 million. The difference between the NPV and the V_{DTA} results from the value of flexibility (V_{flx}) in having the right, but not the obligation, to acquire the project after one year:

$$V_{\mathrm{flx}} = V_{\mathrm{DTA}} - \mathrm{NPV} \tag{5}$$

This simple example is used to illustrate two points: First, the standard NPV calculation used by previous studies of on-orbit servicing cannot capture the value of flexibility. Second, the value of flexibility can constitute a substantial part of the value of a (flexible) project. In other words, project valuation using standard discounted cash flow techniques (i.e., not accounting for flexibility when it exists) is erroneous and often dramatically underestimated.

Limitations of the DTA

DTA is one tool for capturing the value of flexibility. However, like most tools, DTA has its limitations. First, DTA can often become an unmanageable "decision bush analysis" when actually applied in realistic settings because the number of different paths through the tree (or bush) expands geometrically with the number of decisions, or states, considered for each variable.[18] Second, it can only account for a finite number of decision nodes, occurring at discrete decision times, following discrete variations of the unknown parameter(s). In other words, DTA cannot account for uncertain variables that are continuous. Third is the problem of determining the appropriate discount rate. Using a constant discount rate presumes the risk borne per period is constant; this assumption is obviously not valid when options are available. Flexibility (availability of options) decreases a project's exposure to uncertainty and, thus, alters the project's risk. It is, therefore, more appropriate to use different discount rates in different periods. However, the problem of finding the appropriate discount rate (per period or not) still remains. Option-pricing theory, and its spinoff, real option theory are two other frameworks that capture the value of flexibility in financial and real assets and that solve the problem of the discount rate. The application of real option theory requires the identification of an appropriate underlying financial asset, or a "twin security" that has the same risk characteristics as the real asset (or the nontraded asset) to carry out the valuation. Such a twin security does not necessarily exist for some projects (or can not be constructed), thus, rendering a real option valuation impractical. Although this is the subject of on-going research, it is, nevertheless, beyond the scope of this work. The reader is referred to Ref. 16 for an elaborate discussion of real option theory, and to Ref. 19 for a discussion of the limitations and real options valuations and the development of a hybrid real options framework. In this work, we will use DTA. Although it represents an important improvement over traditional discounted cash flow techniques, and, most importantly, can capture the value of flexibility, it nevertheless has its limitations and would often undervalue a project when a constant discount rate is used throughout the tree.

What are the options made available to space systems through on-orbit servicing? These are discussed in the second section and illustrated in Fig. 3. They include the option to service a spacecraft for life extension, the option to upgrade a spacecraft, the option to modify its payload, and, of course, the option to repair after a random failure. The Hubble Space Telescope servicing missions are perfect examples of cases where all of these options have been exercised (repair of its primary mirror, replacement of degraded fine guidance sensor and failing tape recorders, upgrade of the main computer, and addition of two new scientific instruments).

In the following section, we will explore how potential customers of on-orbit servicing would assess the value of the flexibility (availability of options) provided by servicing, and discuss the implications of this valuation process.

Estimating the Value of Spacecraft Life Extension: Application of the New Perspective on On-Orbit Servicing to a Specific Instance of Flexibility

In the following, we apply this new perspective to capture the value of spacecraft lifetime extension provided by on-orbit servicing.

Simple Case: Value of Servicing Through Minimizing Cost

In this case, we assume that the customer, a nonprofit organization, for instance, seeks to evaluate three design alternatives, with the explicit purpose of achieving an effective lifetime of 15 years. We are not concerned, in this example, with a dynamic environment where issues of market uncertainty and technology obsolescence are relevant. The alternatives are the following: 1) launch a spacecraft designed for 15 years; 2) launch a spacecraft designed for T_0 years and, after T_0, replace the spacecraft with another spacecraft designed for $(15 - T_0)$ years; and 3) launch a spacecraft designed for T_0, and, after T_0, extend the lifetime of the spacecraft through on-orbit servicing (would include, for instance, refueling and/or replacing batteries, solar panels, thermal coating, etc.) to $(15 - T_0)$ years. Which alternative is the least costly for our customer?

Let us first explore alternatives 1 and 2. We have recently investigated the effects of varying the spacecraft design lifetime requirement on various subsystems, and deduced spacecraft cost profile (and mass) as a function of this requirement, $C(T_{\text{life}})$, all else being equal. A typical example of a spacecraft cost [to initial operating capability (IOC)] profile is given in Fig. 8 (Ref. 20).

We define a quality factor for the staging of the spacecraft design lifetime as follows:

$$\rho(T_0, \Delta T) = \frac{C(T_0 + \Delta T)}{C(T_0) + C(\Delta T)} \tag{6}$$

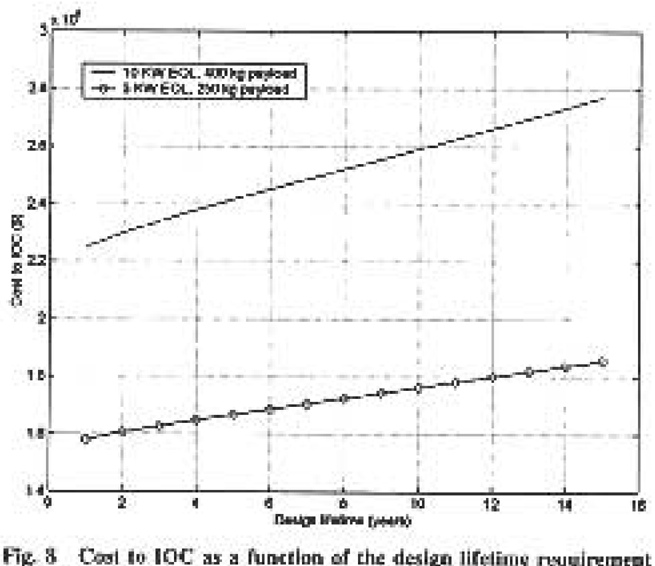

Fig. 8 Cost to IOC as a function of the design lifetime requirement [spacecraft in geosynchronous Earth orbit (GEO), mission reliability = 95%, three-axis stabilized, GaAs cells, and Ni-H2 batteries].

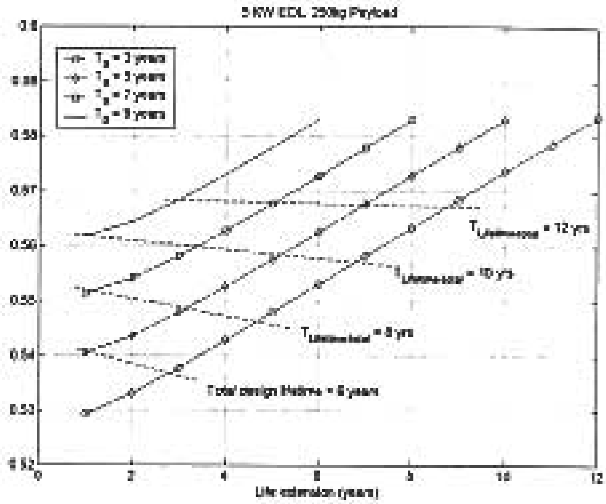

Fig. 9 Quality factor for the staging of the spacecraft design lifetime as a function of life extension.

where ρ is the ratio of the cost of designing a spacecraft for $(T_0 + \Delta T)$, divided by the cost for designing two spacecraft for T_0 and ΔT, respectively. For $\rho > 1$, it is less costly to stage the design lifetime in T_0 and ΔT than to design for $(T_0 + \Delta T)$ years. This illustrates the importance of establishing a cost profile, such as $C(T_{\text{life}})$, for all complex engineering systems, to guide the selection of the product's design lifetime requirement. Figure 9 shows a family of ρ for various T_0 and life extension ΔT.

Two observations are worth making based on Fig. 9. First, we note that $\rho < 1$ for all T_0 and ΔT. In other words, it is always cheaper to design a spacecraft for the maximum required lifetime $T_{\text{life-total}}$ than to stage the lifetime in two spacecraft designed for T_0 and $(T_{\text{life-total}} - T_0)$. Second, for a given design lifetime $T_{\text{life-total}}$, short life extensions are more expensive than longer life extensions. (For example, for $T_{\text{life-total}} = 8$ years, it is more expensive to design two spacecraft for 7 years and 1 year, than two spacecraft for 5 years and 3 years.) These conclusions are indeed expected given the high cost incurred to design and launch a spacecraft, and the smaller cost increments associated with increasing the design lifetime.

Alternative 1 is, therefore, always less costly than alternative 2. What about alternatives 1 and 3? What is the maximum price the customer would be willing to pay to extend the design lifetime of the spacecraft through on-orbit servicing ($P_{\text{serv-max}}$), such that alternatives 1 and 3 are cost equivalent? This condition can be written as follows:

$$\underbrace{C(T_0 + \Delta T)}_{\text{alternative 1}} = \underbrace{C(T_0) + P_{\text{serv-max}} \times e^{-rT_0} + (\text{risk premium})}_{\text{alternative 3}} \tag{7}$$

The left-hand side of the equation is the cost to design a spacecraft for $(T_0 + \Delta T)$ years; it represents alternative 1. The right-hand side represents the cost of designing a spacecraft for T_0 years and then extending its life for through on-orbit servicing. Because $P_{\text{serv-max}}$ is incurred at a later period than $C(T_0)$, that is, T_0 years later, it is discounted accordingly (r, discount rate). In addition, because servicing involves tampering with a spacecraft, it is inherently riskier than alternative 1; a risk premium is, thus, added to the left-hand side of the equation. Equation (7) can be written as follows:

$$P_{\text{serv-max}} = (1 - \Psi) \times [C(T_0 + \Delta T) - C(T_0)] \times e^{rT_0} \tag{8}$$

$P_{\text{serv-max}}$ is the maximum price a customer would be willing to pay, after T_0 years, to extend the spacecraft design lifetime by ΔT, instead of designing it for $(T_0 + \Delta T)$ years from the start, such that alternatives 1 and 3 are cost equivalent. Ψ is an insurance premium contracted to mitigate the financial risk incurred due to the servicing operation; it is a decreasing function of the reliability of the servicing operation. (As the probability of failure or crash into the host vehicle increases, Ψ obviously increases.) Figure 10 shows a family of $P_{\text{serv-max}}$ for different design lifetimes and life extensions.

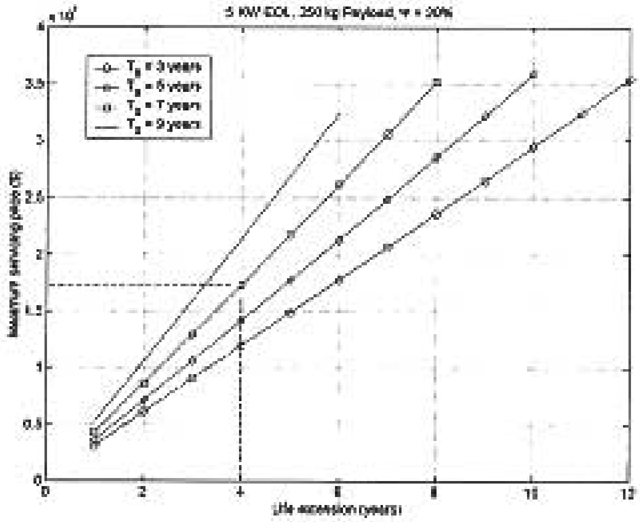

Fig. 10 Maximum servicing price as a function of life extension; a standard 10% discount rate is considered.

One particular point on the plot reads as follows: The maximum price of servicing a customer would be willing to pay to extend the design lifetime of a spacecraft for 4 additional years from 7 to 11 years is approximately \$17 million (with an insurance premium equaling 20% of the cost savings from designing for 7 years instead of 11 years). If on-orbit servicing cannot be achieved within this cost cap, it is not cost effective for the customer to have his/her spacecraft serviced for life extension.

Figure 10 represents the maximum price a customer would be willing to pay to extent the design lifetime of his/her spacecraft through on-orbit servicing ($P_{serv\text{-}max}$) and for which alternative 1 and 3 are cost equivalent. These curves are solutions of Eq. (7); they represent the value of servicing for life extension as seen from the customer's perspective (see Fig. 6). As expected, the value of servicing increases as the lifetime extension increases (from \$5 million to \$30 million, approximately). A potential customer would, therefore, opt for servicing only if the price charged for servicing is less or equal to the value of servicing ($P_{serv\text{-}max}$). Conversely, a servicing provider should constraint the design of a servicing architecture, RS, orbital replacement units, etc., to be able to deliver the on-orbit service for less than $P_{serv\text{-}max}$; otherwise, he/she will find no customer.

Let us further explore the idea of value of servicing through its impact on the spacecraft design lifetime. However, instead of life extension, we consider on-orbit servicing as a mean to counter spacecraft life contraction resulting from unanticipated but necessary orbit maneuvers. To do so, let us consider the following scenario.

A military communication satellite is designed for $T_{life} = 10$ years, with a 20% fuel margin for stationkeeping. The satellite was initially designed as part of a four-satellite constellation providing full Earth coverage. However, due to a launch mishap, only three satellites are operational. Thus, full Earth coverage is not achieved, and one satellite has to perform phasing maneuvers to track changing contingency locations. Equation (9) gives the incremental velocity ΔV required to change the satellite's phase by $\Delta\Phi$ in τ days (Fig. 11):

$$\Delta V_{ph}/V_0 = 2\left|\sqrt{2 - [\lambda/(\lambda - \Delta\Phi/2\pi)]^{\frac{2}{3}}} - 1\right|$$

$$\lambda = \text{integer}\,[\tau/T_0 + \Delta\Phi/2\pi] \tag{9}$$

Let ΔV_{tot} be the total velocity increment necessary to perform stationkeeping over the intended spacecraft design lifetime T_{life}. If the velocity increment required to perform the phasing maneuver exceeds the fuel margin, it will reduce the actual lifetime by $\Delta T_{life\text{-}lost}$:

$$\Delta T_{life\text{-}lost} = \Gamma(\Delta V_{ph} - \text{fuel margin}) \times \frac{\Delta V_{ph} - \text{fuel margin}}{\Delta V_{tot}} \times T_{life} \tag{10}$$

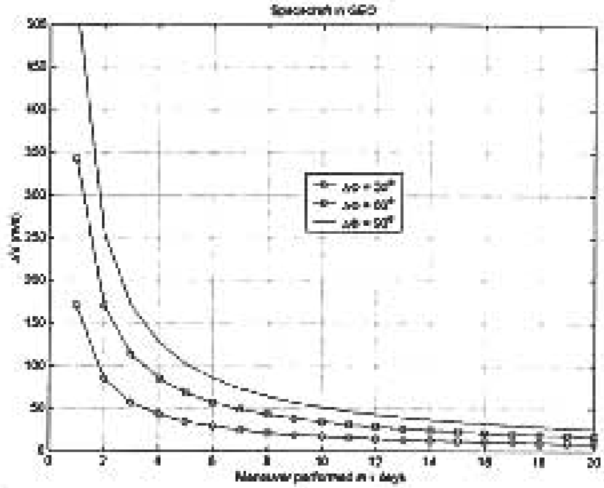

Fig. 11 ΔV required to perform a longitude change of $\Delta\Phi$ in τ days for a spacecraft in GEO.

$\Gamma(x)$ is a step function such that

$$\Gamma(x)\begin{cases} = 1 & \text{for} \quad x > 0 \\ = 0 & \text{elsewhere} \end{cases}$$

There are several ways we can translate this life reduction into a cost penalty. A simple way of doing so is to consider the spacecraft cost per operational day:

$$\text{Cost/day} = C(T_{life})/T_{life} \tag{11}$$

The cost penalty thus incurred due to the unanticipated, but necessary, orbit maneuver becomes

$$\Delta C_{penalty} = \Delta T_{life\text{-}lost} \times [C(T_{life})/T_{life}] \tag{12}$$

The customer could estimate that the spacecraft utility rate, for example, revenues per unit time for a commercial mission, exceeds its cost per operational day; therefore, the aggregate utility of the mission over $\Delta T_{life\text{-}lost}$ is greater than the cost penalty incurred due to the unanticipated but necessary orbital maneuver:

$$U[(T_{life} - \Delta T_{life\text{-}lost}; T_{life})] \geq \Delta C_{penalty} \tag{13}$$

On-orbit refueling of the maneuvering spacecraft becomes cost effective only if it can be achieved for less than $U[(t_0; t_1)]$. In other words, from a customer's perspective, on-orbit refueling is worthwhile only if it costs less than the aggregate utility provided during the life extension resulting from refueling. In the preceding example, we provided one simple way of estimating a lower bound on the aggregate utility for a noncommercial mission. The point of this example is more to emphasize the notion of the value of servicing rather than to estimate the utility aggregate provided during the life extension resulting from on-orbit refueling.

Numerical Example 1

We consider the MILSTAR 2 satellite that needs to maneuver to cover a new theater location 90 deg west of its current location in four days. The satellite cost to IOC (includes launch cost) is \$1.23 billion. It is designed for a 10-year lifetime. Its cost per operational day is

$$\text{Cost/day} = \frac{\$1.23\ \text{billion}}{10 \times 365.25} \approx \$337{,}000/\text{day}$$

The satellite is considered to provide a service per day whose value exceeds \$337,000 (per day). The satellite is in GEO. It has a 20% fuel margin and requires approximately 52 m/s for stationkeeping per year. The maneuver performed decreases the effective satellite lifetime by [Eq. (10)]

$$\Delta T_{life\text{-}lost} = \frac{130 - 0.2 \times (52 \times 10)}{52 \times 10} \times 10 \times 365.25 \approx 182\ \text{days}$$

The value of refueling the satellite at the end of its 10 years minus 182 days is worth as much as

$$V_{\text{refueling}} \geq \Delta T_{\text{life-lost}} \times \text{cost/day} \approx \$61 \text{ million}$$

Similar calculations can be carried out for remote sensing satellites in LEO: First, the maximum achievable lifetime is computed assuming no orbital maneuvers are performed and given the spacecraft propellant load. Second, the impact of an orbital maneuver (e.g., phasing maneuvers or lowering the spacecraft altitude) on the spacecraft lifetime is estimated ($\Delta T_{\text{life-lost}}$), and translated into a cost penalty. Third, assuming that the spacecraft utility rate (e.g., revenues per unit time for a commercial mission) exceeds its cost per operational day, the value of on-orbit refueling can be estimated using Eqs. (12) and (13):

$$V_{\text{refueling}} \geq \sum_{\substack{\text{all} \\ \text{maneuvers}}} (\Delta T_{\text{life-lost}})_i \times \frac{C(T_{\text{life}})}{T_{\text{life}}} \tag{14}$$

Numerical Example 2

Let us consider, in this example, a heavy satellite in LEO (290 × 1000 km). The satellite cost to IOC (includes launch cost) is approximately \$1.3 billion. It is designed for a 10-year lifetime. Its cost per operational day is

$$\text{Cost/day} = \frac{\$1.3 \text{ billion}}{10 \times 365.25} \approx \$355{,}900/\text{day}$$

The satellite is considered to provide a service per day whose value exceeds \$355,900 (per day). Orbit maintenance (atmospheric drag and J_2 effects) and stationkeeping require 400 m/s per year. Assume the satellite has to perform a maneuver to lower its perigee to 200 km, then raise it back again to 290 km. The maneuver consumes approximately 50 m/s, or 45 days of the satellite lifetime, assuming the satellite has no fuel margin [Eq. (10)]. The value of refueling the satellite at the end of its 10 years minus 45 days is

$$V_{\text{refueling}} \geq \Delta T_{\text{life-lost}} \times \text{cost/day} \approx \$16 \text{ million}$$

The value of refueling increases as the number of such orbital maneuvers increases [Eq. (14)].

In the two examples just discussed, the value of refueling is found to be considerable (for the particular maneuvers considered). This result is due to our choice of two particularly expensive satellites. It is likely, however, that the value of refueling for more standard satellites (\$100 million–\$200 million) would be an order of magnitude smaller. Although the purpose of these examples as stated earlier is to emphasize the notion of value of servicing and to illustrate one way of computing this value in the particular case of spacecraft life extension, the examples nevertheless show that refueling is likely to be cost effective for very high-value assets. These preliminary results are very promising for the future of on-orbit refueling.

On-Orbit Refueling, Time, and Risk

Decision makers have often perceived on-orbit servicing as a significant source of technological risk. As a result, they have been reluctant to explore the option of servicing their satellites, particularly when they were operating high-value assets. This, however, need not be the case: Technological risk, which we shall define in this case as the negative impacts resulting from the probability of crash/failure when attempting to dock with a host vehicle or while performing servicing, is a function of the timing of the servicing activity, that is, at what point during the lifetime of the spacecraft servicing occurs. According to this definition, it is riskier to service a newly launched spacecraft, for example, after one year of operations, than to service an aging spacecraft, after 10 years of operations, for example. Risk is minimized if servicing is performed at the end of a spacecraft lifetime when the customer can choose between end-of-life disposal or life extension through on-orbit servicing (refueling in our case). In other words, on-orbit refueling presents little risk if it is performed at the end of a spacecraft lifetime. The reader interested in a discussion on the relationship between time and risk is referred to Ref. 21, from which the following quote is taken: "Risk and time are the opposite sides of the same coin, for if there was no tomorrow, there would be no risk. Time transforms risk, and the nature of risk is shaped by the time horizon: the future is the playing field."

Flexibility and the Value of Servicing for a Commercial Mission with Uncertain Revenues

In the preceding section, we explored the concept of the value of servicing in a simple case where the customer, a nonprofit organization, sought only to minimize the cost associated with designing and operating a spacecraft and not to maximize its profits. Two ways for computing the value of servicing in the case of spacecraft life extension were suggested. The purpose of the preceding section was to illustrate the foundational idea of this new perspective on on-orbit servicing where the value of servicing, as seen from the (servicing) customer's perspective, is computed independently of any servicing architecture. For pedagogical reasons, no considerations were given to issues of flexibility. Indeed, because we did not consider any uncertainty characterizing the environment in which the spacecraft was to operate, flexibility was irrelevant: In a world of certainty, flexibility has no value.

In this section, we explore the value of servicing for life extension in the case of a commercial satellite with uncertain revenues. The value of flexibility provided by on-orbit servicing in this case, unlike our previous calculations, can and should be accounted for in estimating the value of servicing.

Story Line

Consider a commercial satellite designed for T_0 years, with an option to be serviced at T_0 to extend its lifetime by ΔT. E is the cost to service the satellite (E as the exercise price of a stock option) and S the present value of the revenues generated by the satellite after T_0 (S as the stock price). The revenues S are uncertain at the time of launch; their best estimate at the time of launch ($t = 0$) is S_0. A potential customer would select on-orbit servicing for life extension only if servicing costs less than the aggregate utility provided during the life extension resulting from servicing. In other words, a customer would select to extend his/her spacecraft design lifetime if the expenses incurred for life extension and operation during ΔT are smaller than revenues generated during this same period:

$$S \geq E + C_{\text{ops}}(\Delta T) \tag{15}$$

$C_{\text{ops}}(\Delta T)$ is the cost to operate the satellite during ΔT. The customer's choice to exercise the option on life extension or not is captured in the decision tree in Fig. 12.

The situation represented in the Fig. 12 is similar to the investment problem discussed earlier and represented in Fig. 7. The difference is that, whereas the value of the project in our investment problem could take only two discrete values $S^+ = \$400$ million and $S^- = \$280$ million, the uncertain parameter in this example (i.e., the revenues generated after T_0), can vary within a continuous range. Therefore, an infinite number of branches shoot out of the event node. However, only two are shown in Fig. 12 that correspond to a relevant boundary for the decision of exercising the option on life extension or not.

Let us now assume that the revenues S have a log-normal probability density function. This assumption is a standard result in real option theory; it results from the assumption that the future value of a real asset behaves as a financial stock; therefore, its rate of change can be described as a diffusion process (random walk) with volatility σ. The reader is referred to Ref. 16 for a comprehensive discussion of the diffusion process in modeling the dynamics of financial assets.

$$p(S) = \frac{1}{\sigma\sqrt{2\pi T_0}} \times \frac{S_0}{S} \times \exp\left\{-\frac{\left[L_n(S/S_0) - (\alpha - \sigma^2/2) \times T_0\right]^2}{2\sigma^2 T_0}\right\} \tag{16}$$

where σ is the volatility of the revenues after T_0 and α the expected rate of return of the revenues. We assume in the following that α is equal to the discount rate r. Equation (4), extended to the continuous

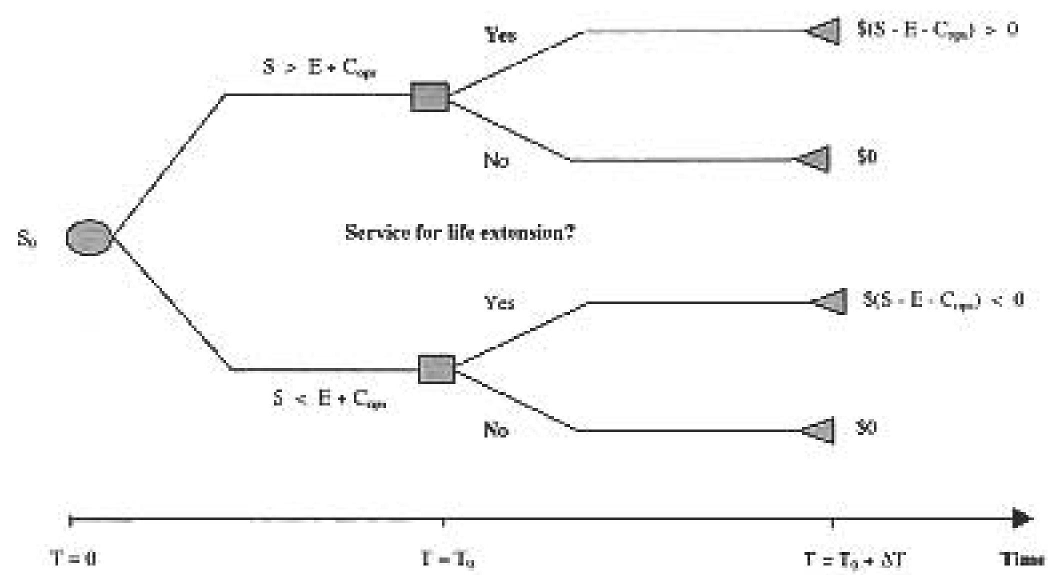

Fig. 12 Decision tree representing the option on life extension for a commercial satellite with uncertain revenues.

case, provides the value of the option to service the satellite for life extension:

$$V_{DTA} = \int_0^{E+C_{ops}} 0 \times p(S) \times dS + \int_{E+C_{ops}}^{+\infty} e^{-rT_0} \times (S - E - C_{ops}) \times p(S) \times dS \qquad (17)$$

Given Eqs. (16) and (17), the value of the option can be written as follows:

$$V_{DTA} = S_0 \times N(d_1) - e^{-rT_0} \times (E + C_{ops}) \times N(d_2) \qquad (18)$$

where

$$N(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-t^2} \times dt$$

$$d_1 = \frac{\left[\ln(S_0/E) + (r + \sigma^2/2) \times T_0\right]}{\sigma\sqrt{T_0}}$$

$$d_2 = d_1 - \sigma\sqrt{T_0}$$

for which N is the cumulative normal distribution function. Equation (18) is identical to the Black–Scholes equation (see Ref. 16), which was a key result in the foundation of option pricing in 1973 and earned its authors the 1997 Nobel Prize in Economics.

Value of Flexibility

In his 1997 Nobel Lecture, Merton[22] described the relationship between uncertainty and flexibility in the following terms: "The future is uncertain . . . and in an uncertain environment, having the flexibility to decide what to do after some of that uncertainty is resolved definitely has value. Option-pricing theory provides the means for assessing that value."

Merton[22] describes a positive correlation between uncertainty and the value of flexibility? But how much is flexibility worth? It is worth a lot if uncertainty is high. Let us first explore and quantify the value of flexibility provided by on-orbit servicing in the case of life extension as a function of the volatility of the revenues σ. The value of flexibility is calculated as shown in Eq. (5). Figure 13 shows a typical result of the value of the option to service the satellite for life extension (V_{DTA}), and the value of flexibility as a function of σ.

Figure 13 illustrates Merton's[22] preceding quote. In an uncertain environment, flexibility has value. Furthermore, the value of flexibility increases as the uncertainty, the volatility of the revenues in our case, increases. Figure 13 also shows that when there is little uncertainty on the expected revenues, option valuation [Eq. (18)] and NPV calculation [Eq. (2), or the continuous version of it] yield the

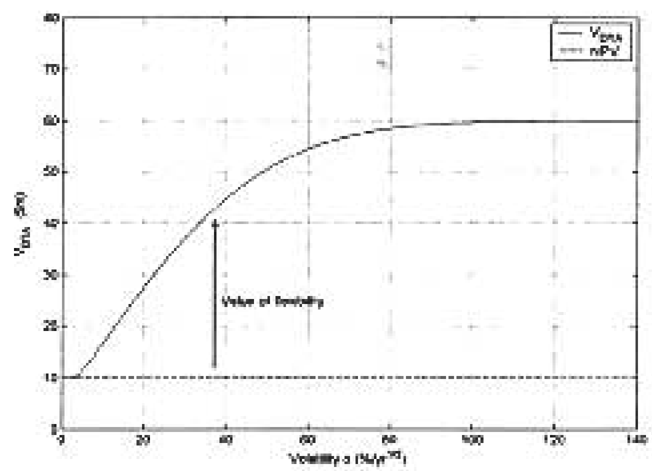

Fig. 13 Value of the option to service the satellite for life extension and the value of flexibility as a function of the volatility of the revenues σ (S_0 = \$60 million, $E + C_{ops}$ = \$100 million, r = 10%, and T_0 = 7 years).

same result. In other words, NPV is an appropriate tool to capture the value of a project or an investment when there is little uncertainty. However, because NPV cannot capture the value of flexibility, it is an inadequate tool for project valuation with high uncertainty.

The preceding discussion has addressed the effect of volatility of the revenues on the value of the option on life extension through on-orbit servicing. There are, in addition to the volatility, three other variables that affect the value of an option (four, if we consider the risk-free interest rate r). These variables can be easily read from Eq. (18). They include the following: 1) The present value S of the revenues generated by the satellite after T_0 can be read. As S increases, so does the value of the option on life extension. 2) The cost to service the satellite E can be read. As E increases, the value of the option to extend the life of the satellite decreases. 3) The time T_0 when the customer decides to exercise the option to service the satellite for life extension or not can be read. In financial parlance, this is called the time to maturity of an option. As the time to maturity increases, the value of the option increases.

In the preceding analysis (Fig. 13), cost to service the satellite at T_0 and to operate it for an additional ΔT years was fixed ($E + C_{ops}$ = \$100 million) and the volatility was allowed to vary. This allowed a clear reading of the value of flexibility as a function of the volatility, all else being kept constant. Figure 14 is a little more involved than Fig. 13: Figure 14 represents the value of the option to service the satellite for life extension as a function of the cost to service the satellite (E) and to operate the satellite. In the following

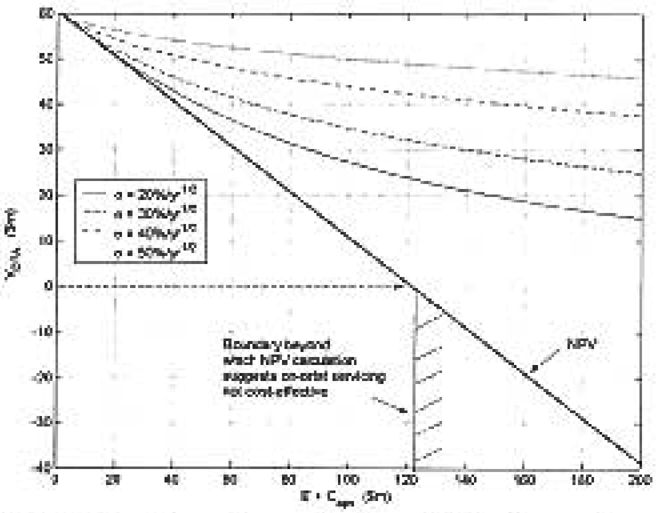

Fig. 14 Value of the option to service the satellite for life extension as a function of the price to service and operate it (S_0 = \$60 million, r = 10%, and T_0 = 7 years).

discussion, we will call this cost $(E + C_{ops})$ the strike price. Several observations can be made based on Fig. 14. First we see that the value of the option to extend the life of the satellite decreases as the strike price increases. This result is indeed intuitive and illustrates point 2. Second, we observe, as in Fig. 13, that for a given strike price, the value of the option to extend the satellite lifetime increases with the uncertainty of the revenues during the life extension. Third, we observe that the NPV always underestimates the value of the option to service the satellite for on-orbit servicing. This results from the inability of an NPV calculation to capture the value of flexibility, as discussed earlier. The value of flexibility accounts for the difference between the two valuation schemes (NPV and V_{DTA}). Fourth, we see that the maximum value of the option on life extension occurs when the strike price is zero and is equal to the expected revenues S_0. This asymptotic behavior of V_{DTA} is readily derived from Eq. (18) in the following way: As $(E + C_{ops}) \to 0$, $d_1 \to \infty$, and $N(d_1) \to 1$. Therefore, the value of the option as given in Eq. (18) simply becomes $V_{DTA} = V_{DTA\text{-}max} = S_0$. Finally, traditional NPV calculation establishes the existence of a boundary on the strike price (corresponding to NPV = 0), beyond which on-orbit servicing is no longer considered cost effective. This boundary, however, is not valid because the value of flexibility provided by on-orbit servicing is not taken into account.

Value of Servicing

In the discussion so far, we have quantified the value of flexibility provided by on-orbit servicing and illustrated several aspects and implications of option pricing as applied to our spacecraft life extension. However, we have not yet addressed the issue of value of servicing or the maximum price a customer would be willing to pay to extend the design lifetime of the spacecraft through on-orbit servicing. To do so, let us first define the incremental value of the satellite per life extension ΔT. This is simply equal to the expected revenues during ΔT minus the cost to design a satellite for an extra ΔT years and to operate it during this same period. Mathematically, it is written as follows:

$$\Delta V(\Delta T) = \int_0^{\infty} S \times p(S) \times dS - [C(T_0 + \Delta T) - C(T_0) + C_{ops}(\Delta T)] \tag{19}$$

Recall that S is the present value of the revenues generated by the satellite during ΔT and $C_{ops}(\Delta T)$, the cost to operate it during this same period. Equation (19) captures the intuition that designing a satellite for an extra ΔT years is cost effective only if the expected revenues during this same period exceed the incremental cost for designing the satellite for an additional ΔT, that is, when $\Delta V(\Delta T) > 0$.

We can now write the fundamental equation driving the value of servicing for spacecraft life extension in the case of a commercial system with uncertain revenues. The value of servicing in this case has been defined as the maximum price a customer would be willing to have the spacecraft serviced for life extension E_{max}. It is given by the solution to Eq. (20):

$$\underbrace{S_0 \times N(d_1) - e^{-rT_0} \times (E_{max} + C_{ops}) \times N(d_2)}_{V_{DTA}} = \underbrace{\int_0^{\infty} S \times p(S) \times dS - [C(T_0 + \Delta T) - C(T_0) + C_{ops}(\Delta T)]}_{\Delta V(\Delta T)} \tag{20}$$

The underlying principle of Eq. (20) is that having the option to extend the spacecraft life should be more valuable than designing up front for a longer design lifetime. E_{max} is the servicing price for which it is equally valuable to service the satellite as it is to design it up front for an extended period. E_{max} is, therefore, the maximum servicing price a customer would be willing to pay. For a servicing price greater than E_{max}, the value of the option to extend the satellite lifetime is smaller than the value of designing the satellite up front for a longer lifetime. This illustrates point 2, discussed earlier, where the value of an option decreases as the strike price increases (Fig. 14). For

$$E > E_{max} \Rightarrow V_{DTA} < \Delta V(\Delta T) \tag{21}$$

We now have a way for computing the value of servicing for a commercial mission with uncertain revenues [Eq. (20)]. The parameters required to perform this calculation are recapitulated in Table 1.

Figure 15 is a solution of Eq. (20). The two marked points read as follows: For a $\Delta V(\Delta T)$ = \$48 million, the value of serving for life extension ΔT increases as the volatility of the expected revenues increases. It is worth \$21 million (minus the cost to operate the satellite during ΔT) when the volatility of the revenues σ is equal to 20%/year$^{1/2}$ and \$58 million when σ = 40%/year$^{1/2}$.

The main trends in the value of servicing for life extension that are captured by Eq. (20) and illustrated in Fig. 15 are the following: 1) The value of servicing increases as the volatility of the

Table 1 Parameters required to compute the value of servicing for life extension [Eq. (20)]

Parameter	Symbol
Expected revenues during ΔT	S
Volatility of the revenues	σ
Satellite cost profile	$C(T_{life})$
Design lifetime and life extension	T_0 and ΔT

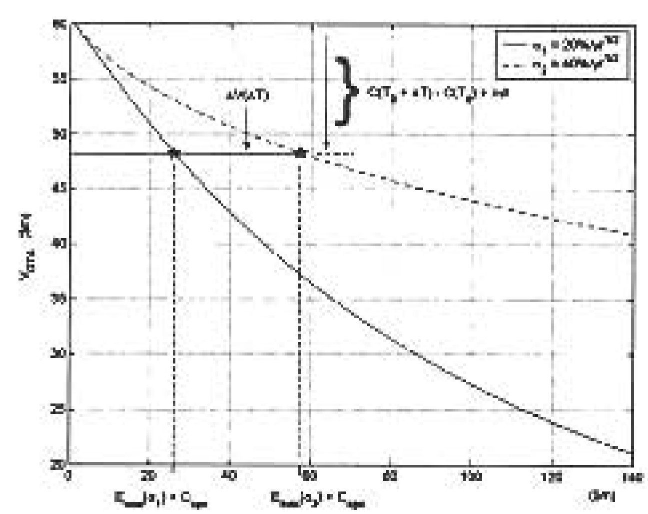

Fig. 15 Solution of Eq. (20), value of servicing as a function of the volatility of the expected revenues.

expected revenues increases. 2) The value of servicing decreases as the incremental cost to design a satellite for an extra ΔT years $C(T_0 + \Delta T) - C(T_0)$ decreases. In other words, if it does not cost much to design a satellite up front for an extra ΔT years, the customer would be willing to pay very little to have serviced on-orbit for life extension.

Conclusions

This paper introduced a new perspective on on-orbit servicing, where the value of servicing is studied independently of its cost or any servicing architecture. Highlighting the value of servicing adds a new dimension to on-orbit servicing studies and shifts the focus from the traditional (servicing) provider's perspective to the (potential) customer's perspective.

The new perspective on on-orbit servicing presented here is based on three main ideas. The principal idea consists of estimating the value of servicing separately from its cost. The second idea lies in the observation that on-orbit servicing provides flexibility to space missions. Third, contrary to what has been implicitly assumed by traditional approaches, the value of servicing is not limited to potential cost savings; instead the value of flexibility provided by on-orbit servicing represents an important component of the value of servicing. In other words, the third idea lies in recognizing that the value of servicing should account for the value of flexibility provided by on-orbit servicing. However, traditional discounted cash flow techniques such as the standard NPV calculation used by previous studies of on-orbit servicing can not capture the value of flexibility. To circumvent this deficiency, we used DTA as a valuation tool for capturing the value of flexibility provided by on-orbit servicing.

To illustrate this new perspective, we applied it in a specific context, that of capturing the value of spacecraft lifetime extension provided by on-orbit servicing. Two ways of assessing the value of servicing were discussed. In the first case, the customer was a non-profit organization, desiring minimum cost. The value of servicing a satellite for life extension ΔT was derived using a cost-equivalence principle. In the second case, the customer was a for-profit organization, desiring maximum profit. The value of servicing a commercial satellite with uncertain revenues was derived using a variant of the Black–Scholes equation and the incremental value of the satellite per life extension ΔT.

Regardless of the technical details or the mathematical analysis, this new perspective does not provide an argument for or against on-orbit servicing. Instead, it suggests a careful evaluation process of on-orbit servicing that focuses on the customer. Ultimately, a customer would opt for servicing if the value of servicing the spacecraft exceeds the cost of doing so, or the minimum price a provider can afford to charge for servicing. This framework identifies the value of on-orbit servicing. Future work will focus on capturing the value of flexibility and on-orbit servicing in the case of satellite upgrade or modification. This should prove particularly valuable for systems operating in a highly dynamic environment, such as an uncertain market or a fast-changing technology base.

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