Versatile On-Orbit Servicing Mission Design in Geosynchronous Earth Orbit

Jennifer S. Hudson and Daniel Kolosa
Western Michigan University, Kalamazoo, Michigan 49008-5343

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Nomenclature

\[ F = \text{force, N} \]
\[ m = \text{mass, kg} \]
\[ r = \text{satellite position, km} \]
\[ s = \text{number of satellites in each mission sequence} \]
\[ T_i = \text{time from beginning of mission to completion of satellite operation } i, \text{ days} \]
\[ T_i, \text{allow} = \text{time allowed to complete operation } i \text{ before daily penalties begin, days} \]
\[ V = \text{revenue from a servicing operation, U.S. dollars} \]
\[ \beta = \text{time penalty representing lost revenue per day of client satellite nonoperation, days} \]
\[ \lambda = \text{longitude, deg} \]
\[ \mu = \text{standard gravitational parameter, km}^3/\text{s}^2 \]

I. Introduction

Robotic spacecraft servicing is approaching viability. To date, on-orbit servicing has only been attempted on a limited scale; demonstrations have involved client space objects that were selected individually by mission designers for specialized operations [1–4]. However, in the near future, robotic servicing satellites may be able to perform a wider range of operations on a larger number of client spacecraft. Several ongoing research and development programs aim to demonstrate on-orbit servicing in the next two to three years. The Defense Advanced Research Projects Agency’s (DARPA’s) Robotic Servicing of Geosynchronous Satellites (RSGS) program intends to demonstrate versatile on-orbit servicing capabilities (including rendezvous and proximity operations, three-dimensional client imaging, docking, and robotic operations) in geosynchronous Earth orbit (GEO) in the next three years [5]. The NASA Restore-L program aims to demonstrate similar capabilities in low Earth orbit [6]. In industry, several companies are also developing commercial satellite servicing capabilities [7]. The Consortium for Execution of Rendezvous and Servicing Operations has been established as an industry-led international forum to develop technical and operations standards for on-orbit servicing operations [8].

These programs would enable a range of new physical capabilities in space, including standoff inspection, refueling, repair (e.g., deployment of anomaly correction or modular subsystem replacement), repositioning, and end-of-life satellite disposal. Recent analyses of the on-orbit servicing market have predicted that there will be sufficient client demand to support a persistent servicing capability [9–12]. Several studies have investigated the costs and benefits of future on-orbit servicing paradigms [13–18]. To maximize profitability, the new robotic servicing vehicles (RSVs) would be versatile spacecraft that can rendezvous with multiple clients and perform various operations over a mission lifetime of several years. The existing literature on spacecraft servicing contains a wide range of proposed capabilities (see Refs. [19,20] for definitions of services). As robotic servicing becomes available to hundreds of potential client satellites, the question of how to design high-value multiclent missions becomes significant.

Fuel-optimal two-impulse trajectory design between multiple GEO clients has been addressed in Refs. [21,22]. In addition to trajectory considerations, a satellite service operator’s profitability would be closely linked to the frequency at which clients could be visited and the fees that clients would be willing to pay.

This Note addresses the problem of optimal mission design for a multiclent robotic servicing spacecraft in a client environment that is not fully known before launch. We expand upon previous work, in which economic and technical risks were investigated and a genetic algorithm was used to identify high-value mission sequences in a specific demand scenario [23]. Here, a more realistic client environment is considered. Although the previous work assumed all clients were known at the start of an RSV’s mission, this Note considers scenarios in which clients may appear, with variable servicing needs and urgency, at any time during the RSV’s operational lifetime.

This analysis focuses on robotic servicing in geosynchronous Earth orbit, which is the intended location of the DARPA RSGS program. Five servicing operations are considered: standoff inspection, robotic repair, repositioning to a new GEO location, refueling, and retirement to disposal orbit (located approximately 300 km above GEO). Assumptions for client satellite locations, demand, and costs are based on current GEO satellites and recent anomaly rates. Two types of RSV propulsion are considered: chemical (high-thrust) propulsion and electric (low-thrust) propulsion. High-thrust mission scenarios are simulated in MATLAB using simple models to rapidly evaluate a large number of mission sequence permutations. Low-thrust mission scenarios are modeled in the Systems Tool Kit (STK) environment using custom plug-ins to simulate continuous thrust for the RSV’s client-to-client rendezvous maneuvers.

Significant features and trends in high-value servicing missions are identified. The findings provide insight into the expected operational environment and the most likely GEO servicing scenarios, which can be used to inform the ongoing design of future robotic servicing vehicles.

II. Client Satellites

Recent studies of the on-orbit servicing market have estimated the average rates of commercial satellite anomalies and maneuver events. Each year, GEO satellites experience about 30–40 events that could be addressed by on-orbit servicing, if such capabilities were available [10,11,24]. Although some anomaly events could not be addressed by an RSV (e.g., failure of systems that are not accessible from the spacecraft exterior), many could be addressed by robotic operations.

The average annual rates of these events are shown in Table 1.

The average revenue generated by a commercial GEO satellite is approximately 50 million U.S. dollars (USD) per year, or 600–750 million USD over a 12–15 year lifetime [24]. Thus, the value of robotic servicing (particularly for operations that enable recovery of spacecraft functionality after an early-life anomaly or operations that extend a client’s operating lifetime by several years) is quite high.
Reference [10] estimated fees of 3–10 million USD for standoff inspection and 5–15% of the remaining value at risk for deployment assistance (corresponding to fees of 12.5–37.5 million USD for a five-year life extension), based on the perceived value of the service to the client satellite operator. We assume repair operations will have the highest fees because they include greater technical risk and greater potential to increase long-term client revenue [25], followed by refueling operations, and then repositioning, retirement, and standoff observation. In this study, we maintain the assumptions for servicing prices that were developed in Ref. [23]: repair operations are associated with a client fee of approximately 25 million USD; refueling operations are 15 million USD; and inspection, repositioning, and retirement are 10 million USD each.

To investigate the RSV mission design problem, a representative set of client satellites was defined. Ninety-three current GEO satellites were identified as active U.S.-owned spacecraft, and therefore representative of potential clients for an initial RSV mission. Satellites in the representative client set were assigned servicing needs based on approximate annual rates of serviceable incidents. Tables 1 and 2 show the probability assumed for each type of servicing operation. The probability of repair operations was estimated to be slightly above historical rates of occurrence because it was assumed that some anomaly events were not publicly documented but would be amenable to on-orbit servicing if it were available. Table 2 also shows the estimated client fees (RSV revenue) for each type of service, the estimated time to complete each operation, and the revenue penalty for operations completed after an allowed wait time. For this study, it was assumed that the client and RSV operator agreed to a contract in which operations must be completed within 120 days of the contract date or else a daily penalty was deducted from the client fee. Time-sensitive operations (repair, repositioning, and refueling) incur a penalty of 100,000 USD per day that the operation is overdue, based on the operator’s approximate daily losses for a nonfunctioning satellite that was intended to earn 50 million USD of annual revenue. Non-time-sensitive operations (inspection and retirement transport) incur a small penalty of 5000 USD per day that the operation is overdue, which represents the costs of ground support personnel and tracking while the operation is pending. This penalty provides an incentive to select mission sequences with minimal transfer times, if all other factors are equivalent. More details on the selection of the parameter values in Table 2 are available in Ref. [23].

### III. On-Orbit Servicing Cost Model

The value of a multiclient servicing mission is a function of the client satellites selected, their assigned operational needs, orbital locations, and the order in which the RSV visits them. Mathematically, it is a moving-target traveling salesman problem with variable values for each node [26]. We adopt a design model for the RSV that enables versatility in the types of operations performed; assume the RSV is equipped for proximity maneuvers, docking, robotic manipulation, propellant transfer, and transport of client satellites.

In Ref. [23], several objective functions to quantify the value of a mission sequence were proposed. Various formulations of the objective function considered client fees; penalties for operational delays; and technical risks to the RSV and clients, such as the risk of damaging a client or losing functionality of the RSV’s robotic arms. Trends in the highest-value mission sequences were shown to be relatively insensitive to risk considerations.

As the more complex risk models did not significantly influence the mission sequencing process, in this analysis, a simplified objective function was chosen to assess the value of servicing mission sequences. The value of a mission sequence, from the RSV operator’s perspective, is defined by Eq. (1). The two terms in Eq. (1) represent the revenue from client fees and revenue penalties due to late service:

\[
\text{Maximize } J = \sum_{i=1}^{n} [V_i - \beta_i \max(0, T_i - T_{i,\text{allow}})]
\]

where \( V \) is the client fee, \( \beta \) is the daily penalty for overdue operations, \( T \) is the date on which a servicing operation is completed, and \( T_{i,\text{allow}} \) is the 120-day allowance in the RSV contract. The completion date \( T \) represents the total, cumulative time since the client was identified (the contract date), including all preceding transfer times and operation times. If the time to complete operation \( i \) exceeds \( T_{i,\text{allow}} \), then a penalty \( \beta_i \) is deducted from the RSV revenue for each extra day. Optimizing the sequence of operations for a multiclient mission requires the RSV operator to trade client-to-client transfer times against the incentive to service the highest-value clients as quickly as possible.

### IV. Client Rendezvous: Impulsive Maneuvers

RSV missions were evaluated with both high- and low-thrust propulsion models for transfers between satellite clients. First, for the high-thrust case, RSV trajectories were modeled with two-impulse phasing maneuvers for all transfers between GEO locations [27]. Figure 1 shows the impulsive \( \Delta V \) required for various GEO longitude changes in a fixed number of days, assuming no changes in orbit inclination. For the mission simulations reported in this Note, it was assumed that the RSV would perform all impulsive client-to-client transfers with phasing orbits sized for a drift rate of \( \pm 2^\circ \) longitude per day, which corresponds to a total \( \Delta V \) for each transfer of approximately 11.4 m/s.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
<th>Probability of occurrence, %</th>
<th>Revenue from client fee ( V_i ), USD(^a)</th>
<th>Operation time, days</th>
<th>Time penalty ( \beta_i ), USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspect</td>
<td>Standoff close inspection for health and status verification</td>
<td>10</td>
<td>10M</td>
<td>10</td>
<td>5,000</td>
</tr>
<tr>
<td>Repair</td>
<td>Docking and robotic operations (e.g., mechanical assistance to correct deployment anomaly)</td>
<td>10</td>
<td>25M</td>
<td>30</td>
<td>100,000</td>
</tr>
<tr>
<td>Reposition</td>
<td>Transfer to new GEO location using RSV propulsion (space tug)</td>
<td>25</td>
<td>10M</td>
<td>20 + transfer time</td>
<td>100,000</td>
</tr>
<tr>
<td>Retire</td>
<td>Transfer to disposal orbit above GEO using RSV propulsion</td>
<td>25</td>
<td>10M</td>
<td>20 + transfer time</td>
<td>5,000</td>
</tr>
<tr>
<td>Refuel</td>
<td>Docking and propellant transfer</td>
<td>30</td>
<td>15M</td>
<td>30</td>
<td>100,000</td>
</tr>
</tbody>
</table>

\(^a\)M denotes millions.
V. Dynamic Client Environment

The unpredictability of the client environment is one of the greatest challenges in RSV mission design. On-orbit servicing vehicles may be launched with some initial clients identified, but they must also respond to new clients that present servicing needs at later dates. To address the analytical challenges of a dynamic client environment, a model of real-time client needs was designed.

A mission scenario was developed in which an RSV starts a mission with five known clients. As the mission progresses, new clients are introduced at random times, until a total of 10 clients are known. Each client, including those in the initial set and the clients introduced later, is assigned a servicing need according to the occurrence probabilities shown in Table 2. At the beginning of the mission, and after each new client appears, the optimal mission sequence is determined by testing all permutations of the remaining clients to maximize the value of the objective function [Eq. (1)].

A representative mission result is shown in Table 3. At the start time, five clients were known (indicated by a “client appear time” of zero). The initial optimal mission sequence was determined by evaluating all permutations of the available clients. As the RSV moved through its sequence of operations, new clients appeared on randomly chosen dates. After each new client appearance, the RSV completed its current task and then recalculated the optimal sequence for all remaining operations. For example, on day 30, as the RSV was completing its first operation, a new repair client appeared at 314.99° longitude. The mission sequence was recalculated, and it was found that the best time to perform the repair operation was in the fourth operation slot. New clients also appeared on days 160, 178, 284, and 340; and the optimal mission sequence was reevaluated after each appearance. One of the initial clients, which was a retirement operation, was postponed until the last mission in the sequence because this allowed the RSV to visit all the clients with minimal time penalties. Figure 2 shows the GEO positions of the client satellites and the order in which the RSV visited them.

This model of the GEO client environment was simulated using a Monte Carlo approach. The dynamic client scenario previously described was repeated 1000 times. Each time, new clients were selected and new servicing operations were assigned using the probabilities in Table 2. The optimal mission sequences that resulted from these simulations were different each time, depending on the servicing needs and locations of the clients, as a result of the time penalty term in Eq. (1). In some cases, it was cost effective for the RSV to simply proceed eastward or westward around the GEO belt and complete each operation before the 120-day time limit was reached. In other cases, if all clients could not be serviced within their time limits, it was more profitable for the RSV to prioritize repair, repositioning, and refueling operations. Occasionally, it was possible for the RSV to perform non-time-sensitive operations between high-value operations if the client locations were serendipitous, such as performing a quick inspection operation at a location that was “on the way” to another client.

The results of these trials are shown in Fig. 3. The results point to the most common attributes of high-value realistic mission sequences. For example, retirement transports occurred most often at the end of a mission sequence, and refueling and repositioning operations occurred most often at the beginning. Repair operations and inspections were less common, with repairs typically occurring near the beginning of a mission and inspections typically occurring near the middle and end.

These results provide some indications of the types of client-demand scenarios that RSV operators are likely to encounter. Nearly all of the simulated missions included refueling operations and either repositioning or retirement operations, and so the RSV would be required to provide both propellant delivery and “space tug” services in most missions. Approximately 35% of the simulated missions did

| Table 3 Example mission sequence in the dynamic environment simulation |
|---|---|---|---|---|
| Client | Longitude, ° | Operation | Client fee, in millions of USD | Client appear time, days | Operation complete, days |
| 1 | 72.08 | Refuel | 15 | 0 | 30 |
| 2 | 105.02 | Repair | 25 | 0 | 77 |
| 3 | 249.86 | Reposition | 10 | 0 | 198 |
| 4 | 314.99 | Repair | 25 | 30 | 234 |
| 5 | 307.00 | Retire | 10 | 0 | 258 |
| 6 | 277.02 | Reposition | 10 | 284 | 370 |
| 7 | 319.49 | Refuel | 15 | 340 | 456 |
| 8 | 338.01 | Retire | 10 | 178 | 486 |
| 9 | 254.91 | Retire | 10 | 160 | 548 |
| 10 | 224.99 | Retire | 10 | 0 | 583 |

Fig. 1 Total ΔV vs GEO longitude change for impulsive phasing maneuvers between client satellites.

Fig. 2 Example mission shown in Table 3.
not include any repair operations, and so they could be completed by an RSV without complex robotic manipulators (although most of these missions included refueling operations, which would likely require some robotic capabilities).

VI. Client Rendezvous: Low-Thrust Maneuvers

To evaluate the mission implications of the type of propulsion system used on the RSV, the high-value mission sequences found in the initial analysis were reevaluated with low-thrust propulsion assumptions. For the low-thrust case, it is assumed that the RSV is equipped with an electric propulsion system that can produce continuous thrust with variable magnitude and direction. To estimate the relationship between time, longitude change, and thrust magnitude, low-thrust phasing maneuvers were simulated using a two-body model:

$$\mathbf{\dot{r}} = -\frac{\mu}{r^2} \mathbf{r} + \frac{F}{m}$$  \hspace{1cm} (2)

Figure 4 shows simulation results for a maneuver that starts at GEO, applies a continuous thrust opposite the velocity direction to lower the orbit below GEO, and then reverses the thrust direction to return to GEO. By varying the duration of the thrust arcs, the relationship between total longitude change and transfer time is determined. Three electric propulsion systems were simulated in Fig. 4: NASA Solar Technology Application Readiness (NSTAR) [28], NASA Evolutionary Xenon Thruster (NEXT) [29], and the High Power Electric Propulsion (known as HiPEP) [30].

The NEXT system, with a maximum thrust of 236 mN and a specific impulse of 4190 s, was selected for further low-thrust simulations. A third-order polynomial was found to fit the low-thrust phasing maneuver time vs the longitude change curve. For the NEXT thruster, the maneuver time can be approximated as

$$\text{Time (days)} = 3.1 \cdot 10^{-6} (\Delta \lambda)^3 - 1.15 \cdot 10^{-3} (\Delta \lambda)^2 + 0.19 (\Delta \lambda) + 2$$  \hspace{1cm} (3)

where the longitude change $\Delta \lambda$ is measured in degrees.

As a higher-fidelity approach to compare low-thrust RSV mission sequences to impulsive-thrust sequences, mission simulations were performed in the STK software environment. Low-thrust propulsion was implemented in STK using a custom engine plug-in representing an ion thruster with variable thrust magnitude and direction. The thrust vector was defined with three orthogonal components that could vary independently. The RSV trajectory with the time-varying thrust vector was evaluated using STK’s Astrogator module and high-precision orbit propagator, which included a full gravitational field model, third-body perturbations from the sun and moon, atmospheric drag, and solar radiation pressure.

Unlike the preceding models, the higher-fidelity simulations included variations in orbit inclination and right ascension among the client satellites. Client-to-client rendezvous maneuvers were implemented as low-thrust phasing maneuvers, which were performed in two parts. First, thrust was applied along the in-track direction only to change the orbit radius. Second, thrust was applied along the radial, in-track, and cross-track directions to return to GEO and intercept the client. STK’s differential corrector, which is an iterative numerical optimization process, was used to select the magnitude of each thrust component to meet the targeting objectives. The first phase targeted only the semimajor axis; the second phase targeted the relative distance to the client. It is assumed that, upon intercept, the relative velocity between the RSV and the client is sufficiently small that final rendezvous $\Delta V$ could be achieved using a separate proximity-operations propulsion system.

The results of the STK numerical optimization process, including total $\Delta V$ and propellant expenditure, were used to evaluate the value of different mission sequences relative to one another using Eq. (1). An example of a 10-client mission sequence simulation in STK is shown in Fig. 5. Figure 5a shows the initial locations of the client satellites in the GEO belt; Fig. 5b shows the GEO longitude path traversed by the RSV; Fig. 5c shows the RSV’s thrust vector components in the radial $x$, in-track $y$, and cross-track $z$ directions; and Fig. 5d shows the RSV’s total mass, (left axis) including client mass during retirement transports and fuel mass (right axis) throughout the mission. The RSV is assumed to have an initial mass of 3500 kg and a propulsion system capable of continuous thrust up to 236 mN.

For the mission sequence shown in Fig. 5, given the initial RSV total mass of 3500 kg, about 335 kg of chemical propellant and 398 kg of electric propellant, there would be 3 days of mission time would be required to visit all 10 clients using impulsive phasing maneuvers. The same mission sequence with an electric propulsion system would require 253 kg of propellant and 858 kg of electric propulsion, which would be enough for 435 days. These values are typical for comparisons of chemical and electric propulsion missions; electric propulsion cases typically require less propellant but longer mission duration.

VII. Propulsion Comparison for Dynamic Environment Simulations

To evaluate the mission implications of the type of propulsion system on board the RSV, several high-value mission sequences were generated by the dynamic environment model and then simulated under both impulsive maneuver and low-thrust conditions. The client selection and sequencing process described in Sec. V was used to generate 10 representative missions. The client sequences in these missions were optimized for the unique set of client orbital states, operational needs, and appearance dates in each case, assuming the RSV would perform all transfers using impulsive maneuvers with a phasing orbit drift rate of 2° longitude per day. Then, the same mission sequences were simulated under low-thrust assumptions using STK.

Figure 6 compares the value of the objective function [Eq. (1)] for the 10 representative missions resulting from the dynamic environment. For sequences 8, 9, and 10, which had the highest overall value, there was minimal difference in the objective function between the low-thrust and impulsive maneuver cases. In the other
sequences, however, the propulsion type was a significant factor in mission value. Although the client parameters were the same across both types of simulations, the two propulsion strategies led to differences in the RSV’s mission trajectory. The thrust levels were significantly greater in the impulsive maneuver simulations, but the continuous thrust arcs in the low-thrust simulations allowed many GEO transfers to be performed with an average longitude change faster than 2° per day. Thus, the mission value was often higher for the low-thrust simulations because the RSV was able to complete more operations within the contracted timeframe. Figure 7 shows the total mission time for the 10 representative missions with both types of propulsion.

The highest-value mission sequences with impulsive maneuvers were not necessarily the same as the highest-value sequences with low-thrust propulsion. For example, sequence 8 had the third-highest objective function value in the impulsive maneuver simulations, but its value was among the lowest of the low-thrust simulations. It is also noteworthy that sequence 1 had a negative objective function value in the impulsive maneuver case, which indicates that it would not be profitable to operate on that sequence of clients if the RSV were to perform all transfers as impulsive phasing maneuvers with 2°-per-day longitude drift. To illustrate the differences between the high- and low-value missions, Fig. 8 compares sequence 1 and sequence 10, which are the lowest- and highest-value missions in the impulsive maneuver simulations. Clearly, the objective function value is related to the proximity of the clients in the GEO belt, as well as the types of operations they require.

Although it was expected that low-thrust propulsion on the RSV would usually require longer mission durations, this was not the case in most of the missions simulated. The results indicate that the comparisons are sensitive to the drift rate selected for the impulsive phasing case and the maximum thrust allowed in the low-thrust cases, as well as the assumptions regarding financial penalties for overdue servicing operations.
VIII. Conclusions

On-orbit robotic servicing has strong economic potential, particularly for extending the lives of high-value satellites in GEO. For operators of versatile, multiclient RSVs, mission sequencing and trajectory design will have a significant impact on profitability. Previous research has found that, when all clients are known before RSV launch, high-value mission sequences are typically ordered by operation type: first, repair and refuel operations; then, standoff inspections; and then, retirement and repositioning operations.

This Note investigated dynamic environments in which all client satellites are not known before RSV launch. The simulations indicate that actual GEO servicer missions are most likely to begin with refueling and repositioning operations and end with retirements. Repair and inspection operations occur less frequently, with repairs typically taking priority early in the mission. These trends are driven by the consideration of contractual time limits and overdue service fees in the cost model. The rates of occurrence of various types of client needs as well as the client orbital locations, fee revenues, and propulsion-related transfer times all have an impact on optimal mission design. Based on the historical rates of satellite events, the dynamic environment simulations indicate that a versatile RSV would be called upon to provide refueling and transport services in nearly all multiclient missions, as well as robotic repairs in approximately 65% of missions consisting of 10 clients. These results can be used to inform and prioritize capability development in RSV design.

Multiclient servicing missions are feasible with both impulsive and low-thrust propulsion. It is well known that electric propulsion offers greater propellant efficiency than chemical propulsion, but its effects on optimal mission sequencing are complex. Profitable RSV missions can be designed with both types of propulsion, but the selection and sequencing of clients within those missions may vary. Other system design considerations, such as the future availability of orbital propellant deports or the mass of propellant feed systems and other onboard hardware required to operate the propulsion system, may also influence designers’ choices of RSV propulsion systems.

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M. A. Ayoubi
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