IAC-25-B6,IP,12,x97470

Responsive RPO for Commercial Application

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Abstract

Rendezvous and Proximity Operations (RPO) are essential for on-orbit servicing (OOS) applications such as inspection, repair, upgrades, life extension, and orbit relocation. Recently, interest has grown in responsive RPO, which aims to accelerate system preparation and in-orbit operations. While defense needs—such as rapid threat assessment—have driven much of this demand, responsive RPO also holds strong commercial potential. This paper explores the value of responsive RPO for commercial use and the key challenges to enable it. Responsive RPO allows operators to quickly address anomalies through emergency inspections, repairs, and recovery support. Each year, multiple satellite failures occur where such emergency on-orbit services could be effective, indicating potential market demand. Long procurement cycles of OOS force operators to make uncertain forecasts, whereas a more agile approach—where RPO systems are deployed shortly after a request—enhances the readiness of OOS benefits. Currently, RPO demonstration missions require several years for development, verification, manufacturing, launch, and in-orbit operation. To make responsive RPO viable, these phases must be shortened without compromising safety. Unlike cooperative missions (e.g., with the ISS), emergency OOS often targets non-cooperative, non-predetermined objects, requiring robust safety measures to avoid collisions. Key technical challenges include developing versatile and robust relative navigation and automation of trajectory and operation planning. Cost efficiency is also critical. Reusing the Servicer Vehicles across multiple Client objects improves economics, but servicing multiple Client objects requires extensive time-of-flight and delta V to perform potentially large orbital transfers. Advancements in high-thrust electric propulsion and refueling technologies are needed to overcome delta V limitations and long times-of-flight. Addressing these challenges will unlock scalable, responsive RPO solutions for the growing commercial OOS market.
Keywords: Responsive, RPO, on-orbit service, in-orbit service

1. Introduction

On-orbit servicing (OOS, or in-orbit servicing: IOS) provides capabilities such as inspection, repair, upgrades, life extension, orbit relocation, and debris removal, contributing to more sustainable, economical, and flexible space operations. To move OOS beyond demonstrations and toward regular use, several challenges must be addressed—including technology maturation, benefit justification, and regulation establishment. Past and ongoing efforts have focused on demonstrating core technologies like Rendezvous and Proximity Operations (RPO) with non-cooperative clients and robotics. More recently, emphasis has shifted toward validating the practical value of OOS and aligning it with real user needs. One emerging practical demand is responsive RPO, which enables faster reaction to service requests. Traditional OOS demonstration missions often take years from requirement definition to completion. Responsive RPO aims to shorten system preparation and in-orbit operation execution. While defense applications have driven much of this interest[1], rapid and on-demand RPO also offers strong commercial potential. This paper explores the commercial potential of responsive RPO and the key challenges to enabling it.

2. Value of Responsive RPO for Commercial Application

2.1 Application of Responsive RPO

Responsive RPO serves two key purposes: enabling urgent on-orbit servicing when rapid execution is required, and improving user accessibility to OOS by reducing service procurement lead time. For defense usage, the aspect to perform RPO urgently is mainly highlighted for applications like rapid threat assessments and the protection of owned assets.

For commercial and civil usage, there are the following applications of urgent on-orbit servicing.

- Emergency detailed anomaly inspection
- Repair or release-support for failed deployment mechanism
- Recovery Support (Rescue): Attitude stabilization support to recover power-safe attitude mode and communication-safe attitude mode, to enable rebooting flight software, recovery action planning, etc.

In-orbit inspection enables detailed assessment of spacecraft anomalies that cannot be fully understood through telemetry, ground-based observation, or long-range space-based observations. Emergency inspections support effective recovery actions but must be completed rapidly—before the spacecraft becomes irrecoverable. Thus, fast and on-demand RPO is essential for timely and actionable inspection services. Failed deployable systems such as solar arrays or antennas or launch separation mechanisms result in significant losses of mission and revenue. Repairing or assisting them to be deployed or released can avoid such a loss, but it must occur within a limited timeframe to be effective. Some satellites lose communication or attitude control while still operational. If the OOS Servicer Vehicle can stabilize the satellite's attitude—restoring safe power and communication modes—it can give additional time for the spacecraft operator to attempt recovering their satellites. However, this must be done before an irreversible mission loss.

Responsive RPO reduces the lead time for on-orbit services such as debris removal, life extension, and refueling. Currently, these services require years from mission definition to execution, making it difficult for operators to align with dynamic business needs. Long procurement cycles force customers to rely on uncertain long-term forecasts, complicating strategic planning and investment decisions. Delivering RPO and on-orbit services on-demand and within short timeframes enhances accessibility, and improves the overall utility of space servicing.

2.2 Magnitude of Demand for Emergency Inspection, Recovery Support (Rescue) and Repair

In this section, the magnitude of potential market demand of commercial application of responsive RPO is assessed based on statistics of anomaly events. The database of Seradata[14] was used. Anomaly events which resulted in insured loss, total or partial loss of mission and function (Class I and II in Seradata's definition), or remarkable component anomalies (power, propulsion) are counted.

LEO:

From 1 January 2015 to 31 December 2024, 511 spacecraft with anomalies in LEO are reported in Seradata. 107 of 511 (21%) are for spacecraft with a mass less than 100 kg. 321 of 511 are reported as anomalies related to Starlink. 22 spacecraft with a mass more than 5000 kg for ISS missions are reported. Spacecraft of 100 kg to 3500 kg mass with anomalies for which emergency Inspection, Deployment Repair and Recovery Support (Rescue) might be useful are counted as shown in Figure 1. Those spacecraft are 2.7 per year in average from 2015 to 2024, and the emergency Inspection, Deployment Repair and Recovery Support (Rescue) might be potentially useful for those spacecraft.

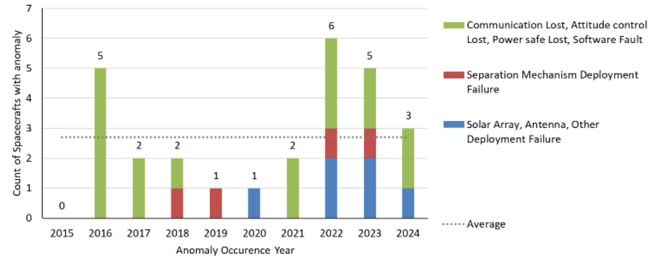


Figure 1: LEO Spacecraft with critical anomaly (2015 – 2024, excluding Starlink) for which emergency Inspection, Repair, or Rescue could be useful

GEO:

From 1 January 2015 to 31 December 2024, 33 spacecraft with anomaly at GEO are reported in Seradata. Spacecraft which experienced failed deployment, communication loss, attitude control loss, power loss or software fault are 0.9 per year in average from 2015 to 2024.

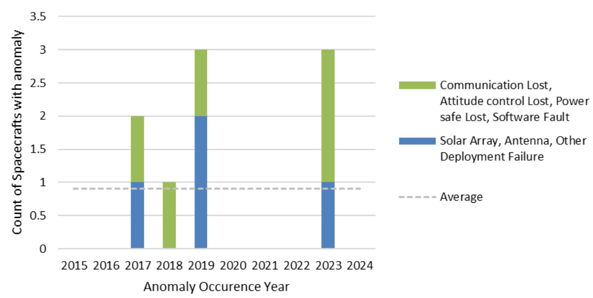


Figure 2: GEO Spacecraft with critical anomaly (2015 – 2024) for which emergency Inspection, Deployment, Repair, or Rescue might be useful

3. General Challenges to enable Responsive RPO

Responsive RPO faces several challenges across commercial, civil, and defense applications. Currently, total lead time spans several years from the timing of mission request defined to the timing of completion of RPO, broken down into tasks shown in Figure 3. Below are the main bottlenecks and potential enablers to reduce duration of the tasks.

A. RPO Mission and System Development

Designing and qualifying an RPO mission and system—including trajectory, operations, payloads, spacecraft bus, and ground systems—requires significant time. Even with heritage systems, differences in Client object geometry, materials, and mission conditions often demand redesign and requalification. Hardware and software obsolescence due to tech evolution also adds complexity.

Enablers to reduce time of this task are:

- Robust and versatile relative navigation and computer vision algorithm adaptable for arbitrary satellite

- Automated generation and validation of trajectory plans and operation plans
- Reconfigurable and scalable RPO payload (e.g., On-board computer scalable to sensor suites and algorithms)
- Universal spacecraft platform compatible with a wide range of orbit conditions and delta V capacity and payload

B. Flight System Build

Includes component procurement, integration, and testing. The time of this task can be reduced by pre-building stock spacecraft, but this requires versatile algorithms and universal platforms. Even if pre-manufactured satellites remain on standby at launch sites or in orbit, other delays remain as shown below.

C. Launch Campaign

Covers launch vehicle preparation and integration with spacecraft, as well as finalizing launch condition. Enablers to reduce time of this task are:

- Responsive launch

D. Far-Range Rendezvous

Approach from several thousand km to hundreds of km. Time varies by mission architecture. For example, direct launch near Client orbit minimizes the time of flight for this.

Enablers to reduce time of this task are:

- Propulsion system with high delta V capacity and high thrust
- Dedicated responsive launch

E. Mid- and Close-Range Approach

Approach within meters requires careful handling of collision risks and navigation uncertainty, especially for non-cooperative clients. Multiple waypoints and GO/NOGO checks are essential for safety and are mandated by standards. In fact, it is required in some technical standards and space act laws to accommodate the GO/NO-GO check operation[15][16][17][18][19]. Traditional RPO missions, such as those with the International Space Station, involve cooperative client objects with known parameters. In contrast, OOS often requires approaching unspecified, non-cooperative objects, necessitating rigorous safety measures to prevent unexpected collisions.

Enablers to reduce time of this task are:

- Versatile and robust relative navigation and computer vision algorithm
- Automated generation and validation of trajectory plans and operation plans
- High accuracy ground-based tracking solution to reduce the complexity of on-board navigation

To enable versatile and robust relative navigation and computer vision algorithms, experience with numerous in-orbit missions is important to collect a meaningful amount of data and lessons learned. It would be challenging to guarantee robust relative navigation without multiple realistic experiences. For example, in the ADRAS-J mission, it took approximately one month to approach from 100 km to 50 m relative distance for the first attempt of approach. However, for the second attempt, re-approach was reduced to one week by leveraging the lessons learned during the first approach [2].

F. Servicing

Covers actual on-orbit servicing and data downlink. Enablers to reduce time of this task are:

- High-rate continuous links such as intersatellite link using optical communication
- In-orbit edge computing for reduction of downlink bandwidth requirements

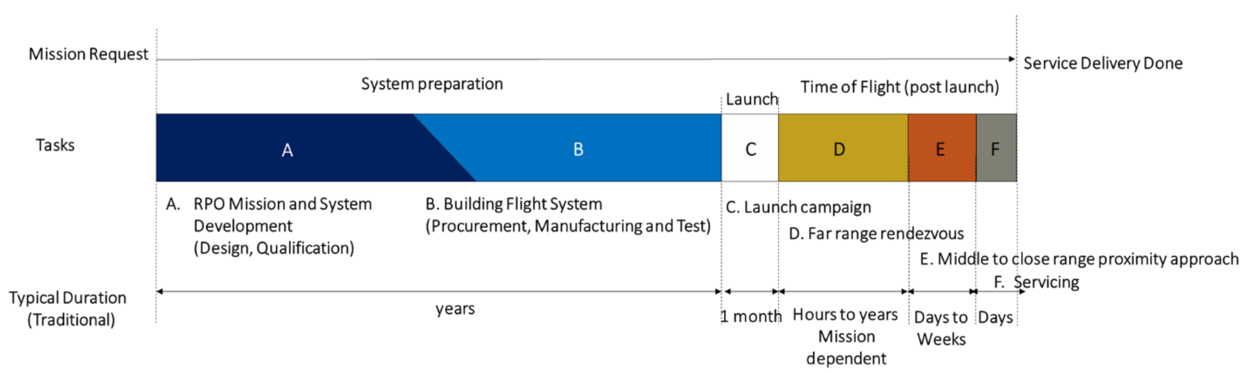


Figure 3: Breakdown of lead-time of RPO mission delivery

4. Unique Challenges for Commercial Application

4.1 Feature of Commercial Demand

4.1.1 Low Cost

A unique challenge in commercial responsive RPO is achieving low-cost implementation. Commercial satellite operators are unlikely to adopt OOS unless there are clear economic advantages. Recent technological innovations, increased satellite production volumes, and relaxed launch constraints have significantly reduced the cost of commercial satellites. For emergency OOS services—such as emergency inspection, recovery support (rescue), or repair—to be viable for commercial operators, the service cost must be low enough to offer clear economic value. For example, LEO microsatellites of commercial operators around 100 kg cost a few million dollars, with some ultra-low-cost models priced below $1 million[10][11]. Even larger satellites exceeding 1 ton are now being offered by modern manufacturers at economical prices around $15 million[12]. In contrast, LEO satellites used by government or civil agencies may cost much higher. GEO commercial satellites generally have longer lifespans and higher costs. However, recent developments in smaller and more affordable GEO satellites are gaining momentum[13]. In the short term, emergency OOS services such as emergency inspection, recovery support (rescue), and repair are more likely to be economically feasible for GEO satellites or high-cost civil LEO satellites, which have greater price tolerance. However, to extend economic value to a broader range of commercial users, service costs must be reduced to levels acceptable even for low-cost LEO commercial satellites. Currently, many demonstration missions for OOS and RPO are in the $10s million–$100 million range and typically focus on servicing one or two specific client satellites. Achieving a versatile RPO system that can adapt to various client satellites, while also reducing costs, remains a significant challenge for manufacturers of RPO systems.

4.1.2 Responsiveness

The required responsiveness of RPO is assessed by examining the duration between anomaly occurrence and the end date of recovery actions. If we define the end date of recovery actions as the deadline for emergency inspection, rescue, or repair, then the RPO operation must be completed within that timeframe to be effective.

Using data from Seradata and publicly available sources, anomaly cases where the recovery end date was known are analysed as shown in Figure 4. Among those cases, if RPO operations could have been completed within several months, more than 50% of anomaly events could have been addressed in time, making the service viable in terms of delivery lead time. Anomalies such as solar array deployment failure and loss of spacecraft control to maintain positive power balance and communication sometimes result in the loss of spacecraft within a few days due to loss of power charge. However, according to the investigated spacecraft anomaly events, even in power critical anomalies, some spacecraft survived or recovery actions were attempted months after the anomaly occurred, as shown in Table 1.

It is noteworthy that responsiveness requirements may be different between defense and commercial applications. Defense missions may demand more immediate action, while commercial operators may tolerate longer lead times depending on the satellite's value and mission criticality.

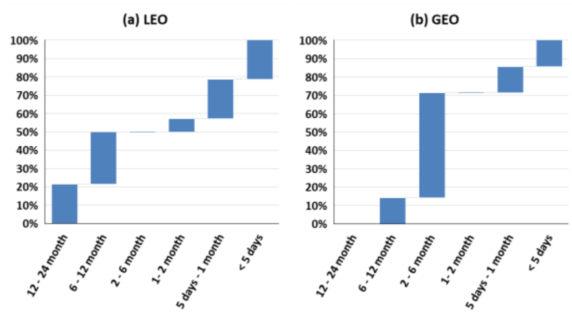


Figure 4: Period between the date of failure occurrence and the date of recovery action ended (estimate)

Table 1: Example of spacecraft with anomaly in solar array deployment or attitude control to maintain power and communication

Spacecraft Anomaly case	Orbit	Timeline (days)	Survived days , or duration attempting recovery
1	LEO	• L+0: Launch • L+1141: All communications lost with spacecraft. Unexpected rotational rate but only a very low rate. • L+1151: The automatic command loss recovery system failed to recover the spacecraft • L+1183: commands sent to rotate the solar array. No change observed in the ballistic coefficient • L+1382: announced the mission was formally ended	42 days
2	LEO	• L+0: Launch. Launched and released successfully, detumbled and deployed its solar arrays successfully	< 16 days

		and initially communicated with the ground • L+1: Communications with the spacecraft failed soon after launch. • L+17: Reported that it could no longer verify if the spacecraft were still functioning.	
3	LEO	• L+0: Launch. • L+194: Power issue, entered in safe mode • L+507: Communications with the satellite was finally lost. Retired/Failed.	< 313 days
4	LEO	• L+0: Launched. The satellite was successfully released from the rocket and powered up. It successfully communicated with the ground. • L+0: Due to a suspected orientation issue resulting from a GPS receiver antenna fault, the spacecraft soon ran out of power once its battery had run out. • L+1: Failure to stably point spacecraft caused power to run out and retirement.	<1 days
5	LEO	• L+0: Launch. • L+5: Reported that they lost communication with the satellite. After an investigation it was determined that the root cause was a failure in the power supply system from the solar cells • L+220: Reported abandoned recovery. Retirement	< 215 days
6	LEO	• L+0: Launch. • L+0: Experienced a solar array deployment anomaly. Was able to acquire power. This was due to one of solar arrays being operational. • L+35: All solar arrays eventually deployed and the satellite is operating as expected. Formally declared operational.	35 days
7	LEO	• L+0: Launch. • L+0: Failed to deploy solar arrays properly. Body mounted solar cells were still working but the spacecraft had a power shortfall. • L+4: Solar array deployment/power issue led to such a shortfall of power that contact was temporarily lost with the spacecraft. Issue led to educed power and limited communication. • L+51: Power and communication faults mainly fixed.	51 days
8	GEO	• L+0: Launch • L+15: Initially had a fault during deployment of one of two solar arrays after launch. • L+100: the failed array was causing a 55% payload capacity loss. The satellite is insured.	< 85 days

4.1.3. Approach distance

There is possibility that the required approach distance is different between commercial and defense applications. For defense applications, for observation of third-party objects for space domain awareness, the required minimum approach distance of RPO may be up to 10 km [8] [9]. For commercial applications, approach distances may be down to a few meters or less to dock with Client objects or to inspect details. The difference in approach distances affects the required times of flight. Closer approach distances increase the complexity in system development and in-orbit operation to validate the robustness of relative navigation and safety during RPO, which tends to make the lead-time of RPO longer, making responsive RPO for commercial applications more challenging. The difference of requirements between defense and commercial application is summarized in Table 2.

Table 2: Difference of requirements between Defense and Commercial application

	Commercial	Defense
Responsiveness (Required RPO duration)	Months at least	Hours or Days
Cost Tolerance	Very Low	Higher than commercial, depending on mission
Approach distance	A few meters or less	In case of observation, up to a few km to 10 km

4.2 Present Existing Solution

4.2.1 Ground Standby

The most straightforward option for responsive RPO is to keep the Servicer Vehicle and launch vehicle on standby on the ground. The Servicer Vehicle and launch vehicle remain on standby until an urgent RPO request arises, at which point they are launched quickly. Since the Servicer Vehicle can be directly inserted into an orbit near the Client object's orbit, the time required to adjust the orbital elements can be minimized, ensuring responsive RPO. The method of "direct orbital insertion near the Client object to minimize time for RPO" is the most reliable approach with proven success in RPO missions for ISS docking. Also, this method is proven even for non-cooperative objects, in demonstration missions such as the ADRAS-J mission (by Astroscale, JAXA, launched on 18 February 2024 by Rocket Lab's Electron). However, this method is disadvantageous in cost because the dedicated launch vehicle must always be ready for launch.


Figure 5: ADRAS-J mission

4.2.2 In-orbit Standby

For commercial applications, minimizing cost is essential. Therefore, the cost for maintaining a launch vehicle on standby is disadvantageous for commercial applications. An alternative strategy is to keep the Servicer Vehicle on standby in orbit and initiate its approach to the client satellite when needed. This method allows the Servicer Vehicle to be launched via low-cost rideshare opportunities. However, the in-orbit standby approach does not guarantee that the Servicer Vehicle will be positioned close to the client satellite's orbit. Consequently, significant differences in orbital parameters—such as plane, altitude, or phase angle—may exist between the Servicer Vehicle and the Client object, which can result in a long time-of-flight (ToF) and delay the completion of RPO.

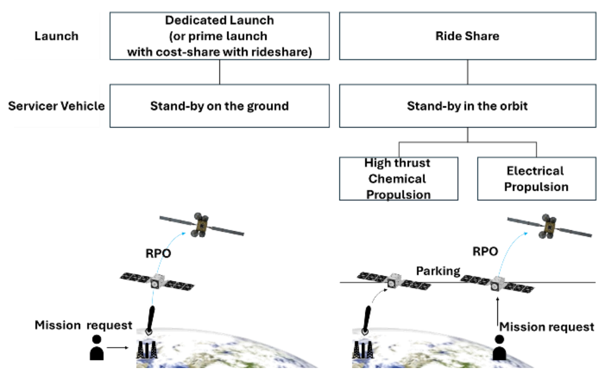


Figure 6: Options of architecture for Responsive RPO

Time of Flight (ToF) for LEO RPO mission is given by:

$$ToF_{LEO\ RPO} \approx ToF_{RAAN\ matching} + ToF_{proximity\ approach} \quad (1)$$

$ToF_{RAAN\ matching}$ is duration of RAAN matching between the Service Vehicle and the Client object. The RAAN drift rate is given by:

$$\dot{\Omega}_{perturb} = -\frac{3}{2}J_2\sqrt{\frac{\mu}{a^3}}\left(\frac{R_E}{a(1-e^2)}\right)^2 \cos I \quad (2)$$

where a is semi-major axis, I is inclination, e is eccentricity and Ω is right-ascension-of-the-ascending-node (RAAN). For a LEO RPO mission, duration to match orbital elements, particularly RAAN, drives total ToF of RPO in cases where the Servicer Vehicle cannot be launched directly into the orbit plane of the Client.

ToF for GEO RPO mission is given by:

$$ToF_{GEO\ RPO} \approx ToF_{longitude\ amatching} + ToF_{proximity\ approach} \quad (3)$$

$ToF_{longitude\ matching}$ is the duration of matching longitude. The longitude drift rate is given by:

$$Mean\ motion\ n = \frac{2\pi}{T} \quad (4)$$

$$Orbital\ period\ T = 2\pi\sqrt{\frac{a^3}{\mu}} \quad (5)$$

$$Relative\ longitude\ drift\ rate\ n_c - n_s = \frac{2\pi}{T_c} - \frac{2\pi}{T_s} \quad (6)$$

Where, n_c is mean motion of the Client object and n_s is of the Servicer Vehicle. In cases where the Client object is a satellite at GEO altitude, $T_c = 2\pi\sqrt{\frac{35786\ km^3}{\mu}}$. For a GEO RPO mission, the duration to match orbital elements, particularly longitude, drives total ToF of RPO, in cases where the Servicer Vehicle cannot be launched directly into the orbit plane of the Client.

Several mission architectures for the in-orbit standby method can be considered depending on system features of the Servicer Vehicle. The features of each architecture are discussed in the following sections.

4.2.2.1 Servicer Vehicle with High thrust CP

The first option of in-orbit stand-by is the architecture to use high-thrust chemical to quickly fill the orbital element gap between the Servicer Vehicle and the Client object. It is advantageous in the ability to perform rapid orbital changes. However, the low Isp of chemical propulsion (CP), typically 200 sec to 330 sec, requires a large amount of propellant, and the Servicer Vehicle most likely becomes less capable to offer RPO and OOS for multiple Client objects. Therefore, this architecture is potentially disadvantageous for cost-conscious commercial applications.

For LEO mission:

In LEO, ToF of RPO is driven by duration of far range rendezvous to match RAAN. There are two strategies to match the RAAN. One is to fill the RAAN gap directly by maneuver, if the Servicer Vehicle has sufficient delta V capacity. This can complete far-range rendezvous including RAAN matching in a very short time with high-thrust propulsion . The delta V to directly change RAAN, Inclination and semi-major axis in combined way is given by:

$$\Delta v_{\Omega,a,I} = \sqrt{v_1^2 - 2v_1v_2\cos\Delta\theta + v_2^2} \quad (7)$$

$$\cos\Delta\theta = \cos I_1 \cos I_2 + \sin I_1 \sin I_2 \cos(\Omega_2 - \Omega_1) \quad (8)$$

The other RAAN matching strategy is to change the Servicer orbit to have an off-set in altitude and inclination against the Client object to accelerate relative RAAN drift rate. This strategy may greatly increase the overall RAAN matching time, but it has the advantage of minimizing the required delta V. With these strategies, as shown in Figure 7, more than 1000s m/s is required to achieve RAAN matching duration within several months. Therefore, the Servicer Vehicle mostly likely becomes a one-shot disposal system for a single client, since a large amount of chemical propulsion fuel is required. This disadvantage of chemical propulsion in LEO could be resolved by in-orbit refueling.

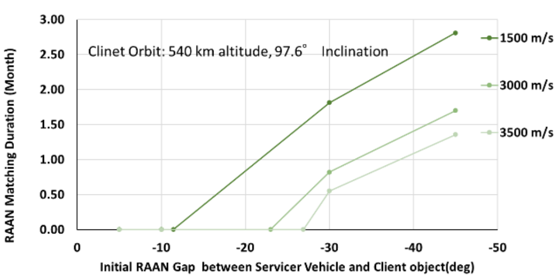


Figure 7: RAAN Matching Duration with High-thrust chemical propulsion, at LEO, by delta V capacity of Servicer Vehicle

For GEO mission:

In GEO, ToF of RPO is driven by the duration of far range rendezvous to match longitude. Relative longitude gaps between the Servicer Vehicle and the Client object can be closed by having a semi-major axis (SMA) off-set against the Client orbit to drift east or west. Example required SMA off-sets between Servicer and Client orbits and associated delta V values to go to the drift orbit and back to GEO is shown in Table 3. Longitude matching duration by required delta V is shown in Figure 8. At GEO, the delta V for RPO is much lower than in LEO. As long as the ToF for RPO can be several months, Servicer Vehicles with high thrust chemical propulsion can be sufficiently reusable to visit multiple client objects, better aligning the solution with market demand. For example, 17.1 m/s is sufficient to change 90 deg longitude within 1 month, and 59 changes of 90 deg longitude within 1 month can be done with 1000 m/s delta V capacity, as shown in Table 4. However, if the required ToF of RPO is much shorter, for example within hours, the Servicer Vehicle's service capacity will be greatly reduced. For example, the entire 1000 m/s delta V capacity could be consumed for only a single change of 90 deg longitude if it must be done in one day.

Table 3: Relative longitude drift rate, required delta V, altitude off-set

Drift Orbit's SMA offset from GEO (km)	Relative Longitude Drift Rate (deg/day)	Delta V : from GEO to Drift Orbit, then back to GEO (m/s)	Duration to change relative longitude (hour)			
			5 deg change (hour)	15 deg change (hour)	30 deg change (hour)	90 deg change (hour)
5000	55.9	335.1	2	6	13	39
1000	12.5	71.6	10	29	58	173
200	2.6	14.5	47	141	282	846
100	1.3	7.3	94	281	562	1687
50	0.6	3.6	187	561	1123	3369

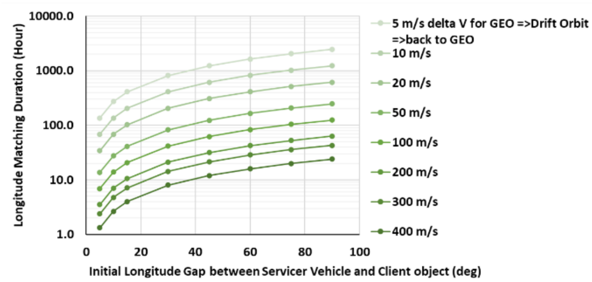


Figure 8: Relative longitude matching duration with high thrust chemical propulsion, at GEO, by delta V for approach

Table 4: Available number of longitude change, by required longitude matching duration and by delta V capacity

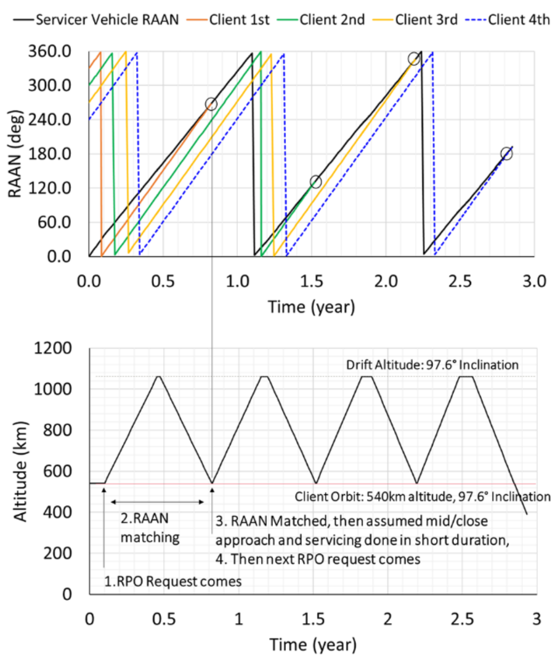
Longitude change (deg)	Longitude matching duration	Drift Orbit's SMA off-set (km)	delta V: from GEO to Drift Orbit, then back to GEO (m/s)	Number of longitude change			
				within 500 m/s	within 1000 m/s	within 1500 m/s	within 3500 m/s
90	Within 2 months (1440 hour)	117	8.5	59	117	176	410
90	Within 1 month (720 hour)	235	17.1	29	59	88	205
90	Within 1 day (24 hour)	8883	560.6	1	2	3	6

4.2.2.2 Servicer Vehicle with Low thrust EP

Another in-orbit standby option is an architecture which uses electric propulsion, which has a high Isp. With electric propulsion (EP), the amount of fuel is significantly reduced, allowing a single Servicer Vehicle to be reused to serve multiple clients, offering cost advantages. However, current electric propulsion systems have low thrust, resulting in long orbital transfer times, which makes it difficult to achieve responsive RPO.

For LEO mission:

The RAAN matching duration by initial RAAN gap between the Servicer Vehicle and the Client object is assessed here. The RAAN matching strategy is to attain a drift orbit with an off-set altitude against the Client object. The assumed thrust of electrical propulsion is 15 mN and Isp is 1500 s. Duty ratio of thrust on is 60% assuming power limitation during eclipse at LEO. The orbit of the Client object is 540 km altitude and 97.6 deg inclination. Figure 9 shows an example mission profile to provide service to 4 client objects. The initial RAAN gap between the Servicer Vehicle and the first Client object and gap among following Client objects are 30 deg. A 350 kg Servicer can provide four instances of RPO. However, as shown in Figure 10, it can take several months to a year to complete the RAAN matching for each Client object due to the low thrust of electrical propulsion. This disadvantage of electrical propulsion at LEO can be resolved by using high-thrust electrical propulsion.



Servicer Vehicle Mass for 4 Client objects	Total mass	374 kg
	Fuel mass	52 kg (Electrical propulsion) 45 kg (Chemical propulsion)
RAAN Matching duration	8.3 month	

Figure 9: Example mission profile and Servicer mass, low thrust electrical propulsion, at LEO

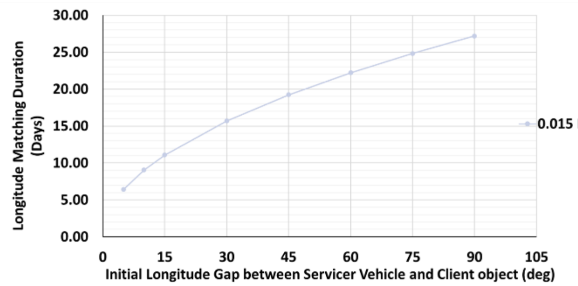


Figure 10: RAAN matching duration with low thrust electrical propulsion, at LEO

For GEO mission:

The longitude matching duration with low-thrust EP in GEO is assessed here. The assumed thrust of electrical propulsion is 15 mN and Isp is 1500 s. Even with low thrust electrical propulsion, longitude matching within 1 month is achievable. Therefore, as long as the ToF of RPO can be multiple months, a Servicer Vehicle based on low thrust electrical propulsion can offer sufficiently rapid RPO. However, if the required ToF of RPO is hours, low-thrust electrical propulsion is not a sufficient solution. This disadvantage can be resolved by high-thrust electrical propulsion.

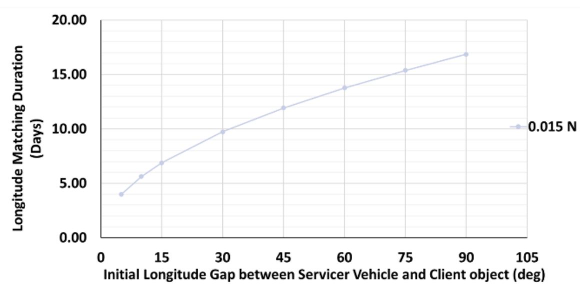


Figure 11: Longitude matching duration with low thrust electrical propulsion, at GEO

4.3 Advanced solution

In the former section, two advanced technologies are identified as key enablers to resolve the disadvantages of present existing mission architecture for responsive RPO. In this section, the effectiveness of advanced tech technologies is discussed.

- High thrust electrical propulsion
- Refueling

Expected benefits of these advanced solutions are summarized in the Table 5.

Table 5: Disadvantage of present solution and expected benefit of advanced technologies

Technology	Benefit	Disadvantages of present solution	
High-thrust Electrical propulsion	Enable months-ToF	LEO RPO with EP	Nearly 1 year ToF is needed due to low thrust
	Enable days-ToF	GEO RPO with EP	Months-order ToF is achievable with present low thrust EP. However, rapidness for days-ToF is difficult
Refueling	Enable multi RPO	LEO RPO with CP	Fall in One-shot disposal use. Difficult to reuse for multiple client
	Increase service capacity	GEO RPO with CP	Multiple service with months-ToF is achievable even without Refuel. However, number of multiple rapid service within days or hours-ToF is limited

4.3.1 High Thrust Electric Propulsion

Currently, commonly used electric propulsion systems such as Hall thrusters can only generate thrust in the range of a few mN to several tens of mN with 1 kW or less, depending on the power supply available for small satellites. However, there is growing interest in high-thrust electric propulsion thrusters to enable more agile and significant orbital maneuvers. For example, development is underway on technologies such as microwave electrothermal thrusters (MET), Magnetoplasmadynamic (MPD) thrusters using superconducting materials, and metal plasma pulse thrusters. These high-thrust electric propulsion systems aim to achieve thrust levels between 0.1 N and 1 N with low power, with specific impulses exceeding 1000 s. There is potential for these systems to deliver up to ten times the thrust of current electric propulsion technologies. The table below shows examples of ongoing development projects.

Table 6: Examples of high thrust electrical propulsion

Product, Activity	Organization	Type	Thrust [mN]	Isp [sec]
AQUAMET	URA Thrusters	MET	30 - 150	500 – 1000
Jal 5000	Bellatrix	MET	300	1050
SUPREME	Neutron Star Systems	AF-MPD	140	4660
Super Magdrive	MagDrive Space	Metal Plasma	1000 +	2000

[3],[4],[5],[6],[7]

For LEO mission:

The RAAN matching duration with high thrust electrical propulsion is shown in Figure 12. By using high thrust electrical propulsion, the RAAN matching duration is reduced to several months.

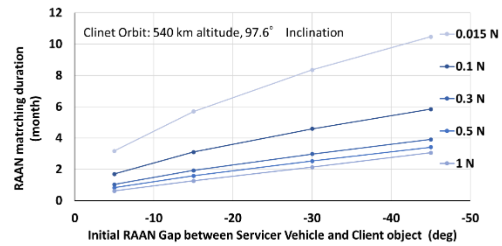


Figure 12: RAAN Matching Duration for High-thrust electrical propulsion architecture, LEO RPO

For GEO mission:

The longitude matching duration with high thrust electrical propulsion is shown in Figure 13. By using high thrust electrical propulsion, the longitude matching duration is reduced to several days.

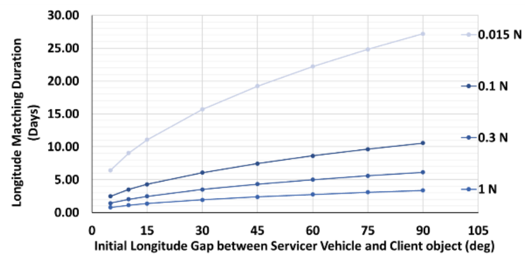


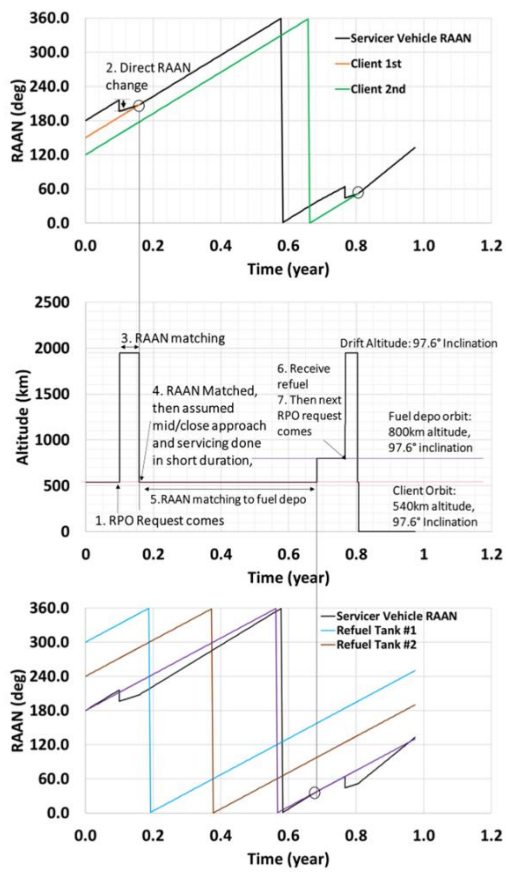
Figure 13: Longitude matching duration with high-thrust electrical propulsion architecture, LEO

4.3.2 Refueling for high-thrust chemical propulsion

In-orbit refueling is the service to supply fuel to the third-party spacecraft in orbit by using a fuel depot or refueling vehicle. When the Servicer Vehicle receives fuel to replace the consumed fuel for the 1st Client, the Servicer Vehicle can be reused to provide RPO and service for a 2nd Client.

For LEO mission:

The example mission profile for LEO SSO clients was assessed. The initial RAAN gap between Clients and Servicer is 30 deg and delta V capacity of the Servicer Vehicle is 3500 m/s. The orbit profile and spacecraft mass are shown in Figure 14.



Client	Altitude 540 km, Inclination 97.6 deg, Initial RAAN 150 deg (1st Client), 120 deg (2nd Client)	
Servicer Vehicle	Initial Altitude 540 km, Inclination 97.6 deg, Initial RAAN 180 deg	
	Delta V capacity 3500 m/s, Isp 300 sec	
Refuel Depo(s)	Altitude 800 km, Inclination 97.6 deg	

Servicer Vehicle with Refuel	Total Mass (Wet)	1400 kg
	Fuel Capacity	1000 kg
ToF of RAAN matching duration	0.4 month	

Figure 14: Example mission profile and Servicer mass, with chemical propulsion with Refuel, at LEO

For GEO mission:

If the required ToF for large longitude changes is within several months, a chemical propulsion system without refueling can still support multiple RPO and on-orbit servicing missions meeting market needs. However, for faster longitude changes—within days or hours—the number of RPOs becomes limited without refueling. In other words, chemical propulsion systems without refueling are vulnerable and less scalable for the increasing requests for fast longitude changes. Refueling can significantly increase the number of rapid longitude changes at GEO, but chemical thrusters still face lifetime constraints, such as propellant throughput or cumulative on-time. As shown in Table 7, refueling can boost the number of operations within days-hours from just 1–2 to several dozen, for 1000 m/s capacity Servicers. It is noteworthy that the Servicer Vehicles with higher delta V capacity tend to consume more fuel per maneuver, reducing the number of operations when throughput limits are considered. Therefore, smaller Servicer Vehicle may be more suitable for frequent rapid maneuvers with refueling. However, if the Servicer Vehicle is too small and receives many RPO requests in a short period, it may exhaust its fuel before it can refuel, making it unable to respond to RPO requests. Therefore, manufacturers must carefully size the Servicer Vehicle by balancing the expected number of rapid longitude change operations—based on thruster lifetime—and the number of missions it must complete without refueling. If future technologies enable in-orbit upgrading of thruster components, the optimal size of the Servicer Vehicle may shift accordingly.

Table 7: Number of rapid longitude changes operation, with Refuel

Servicer Assumption	delta V capacity	1000 m/s		1500 m/s		3500 m/s	
	Mass	363 kg		603 kg		1686 kg	
Longitude change (deg)		90					
Longitude matching duration		< 24 h	< 12h	< 24 h	< 12h	< 24 h	< 12h
delta V: from GEO to Drift Orbit, then back to GEO (m/s)		561	1264	561	1264	561	1264
Fuel (kg)		61	124	102	205	284	574
Number of longitude change, with Refuel	< propellant throughput 1000 kg	16	8	10	5	4	2
	< propellant throughput 5000 kg	82	40	49	24	18	9
Number of longitude change, without Refuel		2	1	3	1	6	3

4.3 Cost Impact for LEO mission

The potential cost impact of high thrust EP and refuel for chemical propulsion (CP) for LEO mission is assessed. The recurring cost per single Client is evaluated for each architecture. The cost includes the recurring cost for spacecraft, launch, ground system, operation, and insurance, accommodating effects of launch method difference, spacecraft size and design difference, and operations duration. Multiple analysis cases are assessed for each architecture based on different assumptions of spacecraft cost (i.e., high bus cost, low bus cost) and launch cost (i.e., fully dedicated, prime cost shared with rideshare payloads).

Then, the cost is normalized with highest cost of ground standby architecture. For advanced architectures with high-thrust electrical propulsion and chemical propulsion with refuel, the number of serviced Client objects per single Servicer Vehicle is assumed as four. The architecture with refueling includes the cost to receive refueling. The result is show in Figure 15. Compared to the present existing architectures with ground standby and in-orbit standby without refueling, advanced architectures can be potentially advantageous in cost per service cost, particularly those with high-thrust electrical propulsion, although the cost advantage of chemical propulsion with refuel at LEO varies depending on the cost to receive refueling.

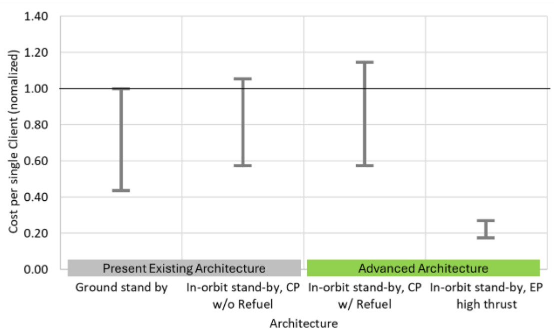


Figure 15: Normalized cost per single Client for LEO mission, by architecture

4.4 Summary of Benefits of Advanced Technologies

In this section, the disadvantages of existing architectures and the advantages of advanced architectures are summarized. In Figure 16, the position of each solution is mapped out with two aspects, achievable minimum ToF of RPO to show responsiveness, and number of RPO per single servicer, to show reusability which is related to cost advantage and flexibility of operation. Locations of market demand for commercial and defense are also mapped out.

In LEO, (a) of Figure 16, existing architectures have shortcomings such as "fast but expensive (due to limited reusability)" or "low cost but slow," making it difficult to meet commercial needs. High-thrust electrical propulsion and refuelling are potential solutions to bridge these gaps by enhancing the reusability and responsiveness.

In GEO, (b) of Figure 16, existing in-orbit standby architecture (with high thrust chemical propulsion and low-thrust electrical propulsion), can already meet with commercial demands. But advanced architecture can enhance the utility of solutions, particularly refueling enhances the number of RPOs for rapid ToF request to reduce the risk of service capacity saturation in the event of large concentrations of emergency RPO demand over a short period of time.

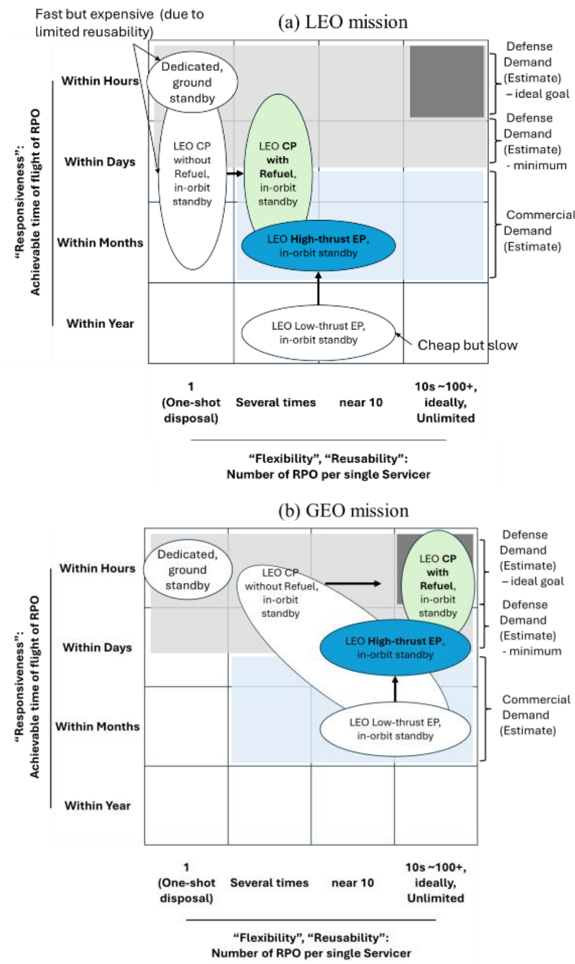


Figure 16: Position of solutions and market demand, and benefit of advanced technologies.

5. Conclusion

Responsive RPO has attracted attention in defense applications, but it also has great value in commercial applications. To avoid serious business losses or unrecoverable losses of satellite functionality, Responsive RPO is essential to provide emergency on-orbit services—such as rapid detail inspection, recovery assistance, and repair—immediately after a satellite failure occurs. Multiple satellite failures occur each year where such emergency on-orbit services would likely have been effective, indicating potential needs for responsive RPO in the commercial market. Furthermore, the ability to conduct RPO with short lead times is also beneficial for less time-critical OOS missions, such as debris removal, by improving service convenience.

The following technical issues need to be solved to realize responsive RPO: robust and versatile computer vision adaptable for arbitrary satellites, automated generation and validation of trajectory plans and operation plans, and low-cost technology, especially for commercial applications. Commercial applications may not require the same degree of responsiveness as defense applications, but instead have strict low-cost requirements. Existing mission architectures have shortcomings such as "fast but expensive" or "low cost but slow," making it difficult to meet commercial needs. High-thrust electrical propulsion and refuelling are potential solutions to bridge these gaps. High-thrust EP can offer faster RPO time-of-flight capabilities compared to low-thrust EP, while also enabling compact designs and multi-service capabilities in both LEO and GEO. Refueling, particularly in GEO, offers flexibility by reducing the risk of service capacity saturation in the event of large concentrations of emergency RPO demand over a short period of time. These technologies are effective not only in commercial applications but also in defense applications.

Accelerating the development of responsive RPO capabilities will unlock the full potential of OOS and enhance the economy and flexibility of space activities across both commercial and defense areas. Another important future effort is developing technologies that expand the application of responsive RPO, including in-orbit repair and detailed inspection.

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