RPOD Concept of Operations

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Distribution

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Executive Summary

This document provides a framework for **Rendezvous Proximity Operations** (RPO) a capability that underpins In-orbit Servicing, Assembly, and Manufacture (ISAM) within the context of the Satellite Applications Catapult's initiatives. As the space industry faces increasing challenges, including the proliferation of space debris and the need for sustainable practices, this framework aims to delineate the methodologies and operational strategies necessary for effective RPO and ISAM.

Key objectives

The primary objectives outlined in this document include:

1. Providing a foundational guide for the methods and approaches required for servicer spacecraft to locate, approach, and dock with target objects in space.
2. Informing Catapult staff and stakeholders about the intricacies of RPO, ensuring a shared understanding of operational requirements and best practices.
3. Encouraging the development of advanced technologies and strategies to facilitate effective servicing and debris removal operations.

Document structure

The document is structured into the following sections:

- **Background:** An overview of the current challenges in space operations, including the risks posed by space debris and the need for sustainable solutions.
- **Document scope:** The intended audience and purpose, emphasizing the focus on internal stakeholders involved in RPO and ISAM.
- **Existing RPO Standards:** A comparison between CONFERS, ESA, NASA, ISO and BSI standards that are already in place.
- **Types of RPO:** Classification of target vehicles and the operational approaches associated with cooperative, partially cooperative, and uncooperative targets.
- **RPO zones:** Identification of operational zones as per ESA and CONFERS guidelines, outlining the phases of approach and capture.
- **RPOD concept of operations:** A detailed examination of the operational procedures necessary for successful RPO missions.
- **Example Manoeuvres:** A series of system requirements and permissible manoeuvres that servicer spacecraft perform during an RPOD.

Future direction

The document highlights the potential for future missions, including the development of initiatives to address the growing issue of space debris, the implementation of strategies for maintaining and upgrading operational satellites, and the evaluation of proposed missions to ensure they are aligned with market demands and are economically sustainable.

1. Background

This document has been authored to provide the baseline for the methods and approaches that a servicer spacecraft will need to undertake in order to locate, approach and dock with a target. It has been produced in order to inform Catapult staff of Remote Proximity Operations (RPO) and as such, is not intended for wider dissemination.

The urgency and necessity of RPO and In-orbit Servicing, Assembly and Manufacturing (ISAM) stem from the increasing challenges posed by space debris. As highlighted in the European Space Agency's (ESA) video titled "Space Debris: Is it a Crisis?" the proliferation of satellites threatens both ground-based astronomy and the broader social and cultural functionalities of space. Other drivers for increased ISAM activity, and associated RPOD manoeuvres, include emerging requirements for space infrastructure assembly, as well as ensuring current and future sovereign capability and maintaining national security.

As other nations develop RPO capabilities, the UK needs to be aware of this field and develop capability to support and proliferate it. The development and operationalisation of RPO capabilities offer substantial benefits to national security, sovereign space capability, and the resilience of critical space infrastructure. By enabling in-orbit inspection, anomaly resolution, asset repositioning, functional augmentation, material delivery and recovery of malfunctioning satellites, RPO enhances a nation’s ability to safeguard its strategic space assets and ensure the continuity of vital services such as communications, Earth observation, and navigation. Furthermore, the mastery of RPO technologies underpins sovereign autonomy in space operations, reducing dependency on foreign providers and strengthening a country's position in the evolving geopolitical landscape of space. As space systems become increasingly integrated into defence, civil, and commercial infrastructure, RPO serves as a foundational enabler for responsive, secure, and sustainable operations in orbit.

Key points regarding the current situation include:

- ESA has set a target to achieve a debris-neutral status by 2030, mandating that all its spacecraft de-orbit within five years post-mission.
- Ongoing efforts aim to safeguard the integrity of dark and quiet skies for astronomical observation and environmental health.
- The Zero Debris community is actively engaged in tracking, monitoring, and avoiding space debris, emphasizing the need for effective Active Debris Removal (ADR) strategies.
- The impact of space debris re-entry on Earth's atmosphere is an area of intensifying research, necessitating robust solutions.
- The ultimate objective is to establish a sustainable circular economy in orbit, which will require advancements in in-orbit servicing, refuelling, and orbital recycling technologies.
- The “Earth-Space Sustainability Initiative” (ESSI) Memorandum of Principles cover the importance of safe and transparent RPO practices for in-orbit services (IOS) to human-made objects, recognising that these services aim to extend the life of space assets, remove space debris, reuse products and materials, eliminate waste and pollution and remediate the space environment.
- Large-scale space infrastructure, such as telescopes, habitats, and power stations, are being developed that require RPO to enable in-space assembly that requires the autonomous joining of modular components in orbit.

- There is a market developing for the upgrade and repurposing of existing spacecraft, enabling the insertion of new capabilities or payloads mid-mission, thus improving mission flexibility and asset longevity.

In this context, the ability to perform RPO is essential. RPO enables servicer spacecraft to interact with, repair, or decommission defunct satellites and other objects in orbit, thereby contributing to a cleaner and more sustainable space environment.

This document outlines the specific methods, requirements, and assumptions underpinning RPO, serving as a vital resource for Catapult staff involved in discussions and planning related to in-orbit proximity operations.

2. Document Scope

In order to address the above issues and develop Catapult knowledge, this document sets out a series of methods, requirements and assumptions for RPO. It is intended to be used by RPO and ISAM (In Orbit Servicing, Assembly & Manufacture) internal stakeholders as a baseline for discussions about in-orbit proximity operations.

The scope of this document includes:

- A detailed explanation of RPO, including their significance in the current landscape of space operations and debris management.
- An outline of the methodologies that servicer spacecraft will employ to locate, approach, and dock with various target types, including cooperative, partially cooperative, and uncooperative targets.
- Specifications for the technical capabilities required for successful RPO missions, such as telemetry needs, attitude control, and safety protocols.
- A clear statement of the assumptions made in the development of this document, including the absence of external engagement during its creation.

This document is tailored for Catapult’s internal stakeholders and is not intended for external distribution. It is designed to facilitate discussions and decision-making regarding in-orbit proximity operations within the organization.

Given the evolving nature of space operations and technology, it is expected that this document will undergo regular updates to incorporate new findings, technologies, and operational insights. Stakeholders are encouraged to provide feedback and insights that can enhance future revisions. By establishing a solid foundation through this document, Catapult aims to advance its knowledge base and operational readiness in the rapidly evolving field of in-orbit servicing.

Limited input from external engagement has been included in this early version, but further updates will be made during July and August 2025.

3. References

1. LEO Regulatory & Technology Testbed for IOSM – Business Case (N.Dhanji, Oct'23)
2. CONFERS Recommendations for Best Practices, Functional Requirements, and Norms for Prepared Free-Flyer Capture and Release
3. International Rendezvous System Interoperability Standards (IRSIS)
4. Removal interface operational requirements document TN_SatApps Comments.docx
5. ISO TC20/SC14 Space Systems ISO 24330 – Programmatic Principles for Rendezvous and Proximity Operations (RPO) and On-Orbit Servicing (OOS) (Behind a paywall)
6. DSIT RPO Sandbox Workshop Analysis.docx
7. ESSI - Memorandum of Principles

4. Existing RPO Standards

CONFERS, ESA, NASA, ISO, and the British Standards Institution (BSI) contribute to a growing international framework of technical, operational, and legal guidance to ensure safe and sustainable in-orbit operations.

Key elements of each set of standards are:

- **CONFERS** offers an industry-led, non-binding best practices framework, primarily focused on commercial servicing missions. It is globally accessible and supports voluntary standardisation and transparency.

- **ESA**, through ECSS standards, defines binding technical and safety requirements for European missions and contractors, with high fidelity in GNC modelling, interface protocols, and disposal planning.

- **NASA** enforces internal procedural requirements and safety standards, including proximity operations regulations for both crewed and uncrewed assets. These standards are sometimes made available internationally to guide interoperability.

- **ISO 24330** ("Space systems — Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS) — Programmatic principles and practices") and related documents aim to create a globally recognised, harmonised set of technical standards, usable by national agencies and commercial operators alike. These are consensus-driven and support interoperability and licensing coordination.

Additionally, **BSI PAS 280** ("Through-life Engineering Services (TES) Guide") is a publicly available specification that provides guidance for manufacturers, support providers, owners and end users looking to implement "through-life engineering services". It focuses on how to implement TES effectively across an asset's entire supply, operate, and support chain. PAS 280 aims to improve efficiency, reliability, and cost-effectiveness in engineering projects by promoting the proactive application of TES. It was developed with input from BAe Systems, UK MoD and Rolls Royce, sponsored by Innovate UK.

A comparison of the standards is provided in Table 1.

4.1. Regulations

While not a formal standards body, the UK Civil Aviation Authority (CAA) plays a critical regulatory role in shaping the framework within which RPO missions are authorised and conducted. As the UK's spaceflight licensing authority under the Space Industry Act 2018, the CAA applies rigorous scrutiny to missions involving close proximity to other space objects. Its approach effectively sets a high operational and safety threshold for RPO missions, particularly for those involving docking, servicing, or debris removal.

The CAA's regulatory stance influences RPO mission design and implementation through:

- **Risk-based licensing assessments**, which require operators to demonstrate robust technical and procedural controls to mitigate collision risk, unintended interference, and third-party harm.
- **Mission transparency expectations**, including the need to disclose intent, target identities, and manoeuvre plans, to support responsible behaviour and international confidence.
- **Operator competence demonstration**, requiring applicants to show that they possess the technical capability and experience to conduct complex manoeuvres such as approach, capture, and withdrawal.
- **Third-party liability insurance requirements**, proportionate to the risk profile of the RPO activity, especially for missions in GEO or involving non-consensual targets.
- **Environmental and space sustainability assessments**, in line with the UK's endorsement of debris mitigation guidelines and international best practices, such as those of the UN COPUOS Long-Term Sustainability Guidelines.

Although the CAA does not issue technical standards per se, its regulatory expectations serve as a de facto benchmark for mission assurance and responsible RPO conduct. As such, they are highly relevant to stakeholders considering operational, commercial, and legal standards for in-orbit servicing missions.

Table 1: A comparison of RPO standards

RPO Element	CONFERS	ESA (ECSS)	NASA (e.g., NPR 8715.6)	ISO (e.g., ISO 24330)	BSI (PAS 280)
Mission Planning	Promotes early coordination, transparency, and cooperation. Emphasises documentation of mission objectives and risk mitigation.	Requires detailed planning per ECSS-E-ST-10 series, including hazard analysis and compliance with EU policy.	Calls for mission assurance through risk assessments, hazard controls, and lifecycle planning.	ISO 24330 requires documented mission phases, risk controls, and mission assurance processes.	Stresses early-phase due diligence, intent declarations, and responsible mission definition.
Approach Geometry & Safety Zones	Defines safe standoff distances, approach cones, and abort paths tailored to cooperative/ uncooperative targets.	Prescribes detailed keep-out zones (KOZs), safety zones, and escape strategies (per ECSS-E-ST-70-11C).	Requires trajectory safety assessments, bounding boxes, and fly-by constraints for crewed/ uncrewed missions.	Establishes standardised definitions for approach geometries and mandatory abort scenarios.	Encourages harmonised definitions for approach volumes and trigger points for fallback modes.
Communication Protocols	Advocates for real-time, secure, and standardised data exchange, especially for cooperative servicing.	ESA requires validated comms architecture, redundancy, and autonomous fallback modes.	NASA specifies comms performance thresholds, encryption, and human-in-the-loop contact requirements.	ISO standards call for interoperable links, health-check signalling, and interface standardisation.	Recommends adoption of open comms protocols for transparency and interoperability.
Consent & Licensing	Requires prior consent from the target owner/ operator and compliance with national and international law.	Enforces compliance with national regulations and UN treaties; licensing is	NASA missions must comply with U.S. policy directives (e.g., SPD-3), FCC licensing, and DoD coordination.	ISO emphasises compliance with state-level licensing frameworks and	PAS 280 highlights ethical consent practices, licensing consistency, and transparency in intent.

RPO Element	CONFERS	ESA (ECSS)	NASA (e.g., NPR 8715.6)	ISO (e.g., ISO 24330)	BSI (PAS 280)
		coordinated via ESA member states.		operator consent protocols.	
Autonomy & Fault Management	Encourages tiered autonomy, robust FDIR (fault detection, isolation and recovery), and contingency planning.	Requires high-integrity fault management, escape strategies, and human supervision thresholds.	Calls for autonomous abort capability and multi-layered fault recovery logic.	Provides generalised fault tolerance criteria and abort path validation standards.	Advises incorporation of autonomous safety logic and fail-safe behaviours.
Relative Navigation & GNC	Supports use of RF, visual, LIDAR, and hybrid systems for redundancy; stresses real-time accuracy.	Specifies navigation accuracy thresholds, sensor specifications, and calibration standards.	Requires sensor suite certification, autonomous trajectory prediction, and GN&C simulation validation.	Defines minimum relative navigation performance and GN&C error handling strategies.	Promotes use of standardised sensor performance metrics and GN&C validation protocols.
End-of-Life and Disposal	Encourages deorbiting or relocation to a disposal orbit; documents post-mission status and passivation.	Mandates passivation, disposal per orbital regime (e.g. GEO graveyard), and reporting to ESA.	NASA follows 25-year LEO rule, disposal orbit guidelines (per NASA-STD-8719.14), and hazard mitigation. However, FCC regulations require de-orbit within 5 years of End of Life.	ISO requires operator-defined end-of-life strategy and debris minimisation.	PAS 280 aligns with UK Space Agency and UN LTS Guidelines for responsible post-mission disposal.

5. Types of RPO

RPOs can be categorized based on the operational status of the target spacecraft and the nature of the interaction required. Understanding these categories is useful for designing effective RPO missions/capabilities and ensuring the appropriate methodologies are employed for each situation. Each type of RPO presents distinct challenges and requirements that must be considered in mission planning. The types of RPO are as follows:

Cooperative Target:

The Client Vehicle (target) is operational but unable to perform end-of-life functions regarding removal from orbit. For these targets, it is assumed the satellite:

- Is prepared for capture e.g. has dedicated capture interface, rendezvous markers / navigation aids implemented
- Can provide telemetry to the mission control centre of the debris removal service provider
- Is capable to perform attitude control
- Will not hinder the capture process e.g. thrust during the final moment before Capture.

Partially Cooperative:

The Client Vehicle exhibits any one of the above features/capabilities, but not all. For example, the satellite…

- May have limited telemetry capabilities or could be able to provide partial status updates.
- Might have some degree of attitude control but may not be fully stable or responsive.

Uncooperative Target:

The Client Vehicle is non-operational (either completely or with respect to attitude control) and tumbling. For these targets, it is assumed the satellite:

- Is prepared for capture e.g. has dedicated capture interface, rendezvous markers / navigation supports implemented (it is possible that
- Is not providing telemetry on status, all information on target status is based on observations from ground.
- Is unable to perform attitude control:
  - The tumbling motion shall be assumed around any axis.
  - The characterisation of tumbling motion shall be done in orbit by the chaser or by ground-based services.

RPO with debris, or objects of unknown characteristics (mass, material, form, stored energy) are considered extremely high-risk targets and are not being considered, at this time, for RPO/ISAM/ADR.

6. RPO Zones

In the context of RPO, specific zones have been defined to facilitate safe and effective interactions between servicer spacecraft and target vehicles. These zones are crucial for ensuring that manoeuvres are conducted within operational safety limits, allowing for both successful capture and the mitigation of risks during the approach phase.

6.1. ESA RPO Zones

The ESA defined zones, which correspond to current thinking around approaching a target, are as follows:

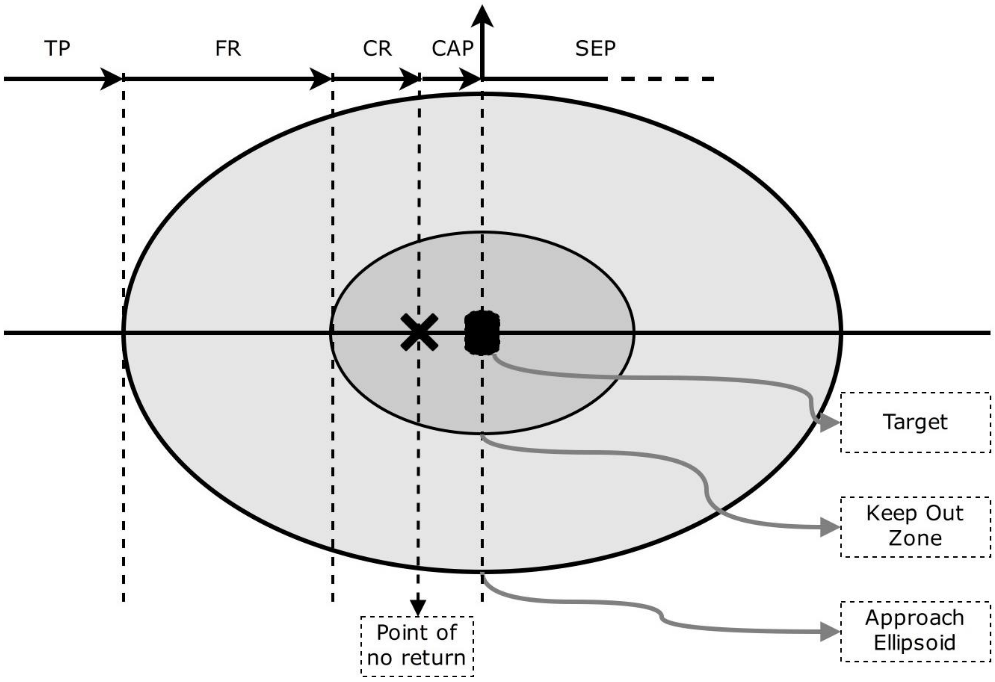

Figure 1: RPO Zones

Table 2: ESA RPOD Phasing Descriptions

Phase	Description
TP-Target Phasing	This initial phase involves aligning the orbital parameters of the client vehicle and the servicer spacecraft while remaining outside the defined approach zones. It includes all the activities performed by the chaser and on ground to prepare for capture, in particular: • Conduct functional tests to ensure all systems are operational. • Verify the integrity and functionality of sensors, processors, and actuators. • Ground operators must confirm completeness of all pre-capture activities before transitioning to the next phase. The purpose of TP is to prepare both the servicer and the target for a safe and successful approach, minimizing the risk of collision or system failure.
FR-Far Rendezvous	The servicer enters the Approach Zones and arrives at the entry point of the Keep Out Zone. This phase enables the servicer to close the distance to the target, while ensuring operational safety and readiness for further manoeuvres. Key activities of FR: • Initiate a gradual approach to the target vehicle while maintaining the ability to abort the approach trajectory if necessary. • Monitor the relative motion to ensure that the servicer can safely manoeuvre without jeopardizing the target.

Phase	Description
CR-Close Rendezvous	This phase represents a close-range approach between the Keep Out Zone and the Point of No Return. The key activities of CR are: • Conduct rendezvous rehearsals to test the handover between different sensors and systems. • Continuously assess the suitability of the target for capture, including monitoring for any unexpected changes in behaviour or status. The purpose of CR is to facilitate the final preparations for capture, ensuring that all systems are functioning correctly, and that the servicer is ready to execute the capture manoeuvre.
CAP-Capture Phase	This phase spans from the Point of No Return to the establishment of a stable stack through physical connection. The capture phase is divided into: • **Soft Capture**: Initial action of grappling in which an Active Capture System aligns with and latches to a Passive Mechanical Interface, preventing unintentional separation or unintended contact. • **Hard Capture**: Considered complete when the vehicles are constrained in all degrees of freedom and no relative motion exists following rigidizing operations. The purpose of CAP is to securely connect the servicer to the target, enabling safe handling and subsequent operations.
SEP-Separation	This phase occurs after the mechanical connection is released and prior to the first servicer thruster activity. The key activities of SEP are: • Execute controlled thruster burns to separate from the target vehicle. • Monitor the condition of the servicer and ensure all systems remain functional post-separation. The purpose of SEP is to safely disengage from the target while preparing for the next phase of the mission.
Disposal	Relevant to Removal missions, this phase involves actions aimed at permanently reducing the risk of accidental break-up and ensuring long-term clearance of protected orbital regions. The key activities of Disposal are: • Implement procedures to deorbit or reposition defunct satellites or debris. • Ensure compliance with regulatory requirements for space debris mitigation. This phase contributes to a sustainable space environment by effectively managing end-of-life satellites and debris. In the context of Removal missions, actions to permanently reduce the chance of accidental break-up and to ensure long-term clearance of protected orbital regions.

6.2. CONFERS RPO Zones

The zones defined by CONFERS depict envelopes around the target vehicle and ‘approach corridors’ (±10° cones). The zones and approach corridors are drawn from the International Rendezvous System Interoperability Standards (IRSIS):

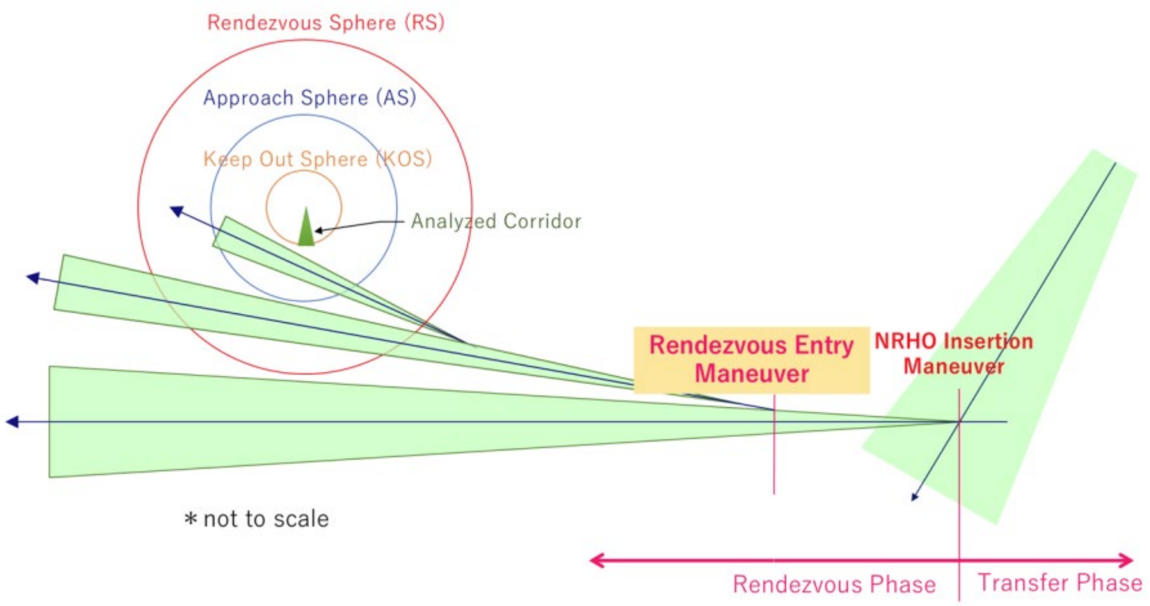

Figure 2: IRSIS/CONFERS RPOD Operational Zones & Approach Corridors

The zones are similar to those specified by ESA, but with numerical figures attached:

Zone	Description
Rendezvous Sphere (RS)	The RS is a 10 km radius sphere around the target spacecraft's centre of mass and is used to govern the Rendezvous Entry (RE) decision. A shape larger than the AS is needed to balance the risk associated with the large dispersions expected from the RE burn, to ensure target vehicle safety.
Approach Sphere (AS)	The AS is a 1 km radius sphere centred at the target vehicle centre of mass.
Keep-out Sphere (KOS)	The KOS is 200 m radius sphere centred at the target vehicle centre of mass.
Approach/ Departure Corridors	The Approach and Departure corridors are ±10° centred to the docking port axis within the KOS.

7. RPOD Concept of Operations

The concept of operations for Remote Proximity Operations and Docking (RPOD) outlines the systematic approach and procedures that a servicer spacecraft will follow to successfully find, approach, and dock with a target vehicle. This section provides an overview of the operational framework, key phases, and specific actions involved in executing RPOD missions.

7.1. Overview of Servicer CONOPS

The launch, LEOPs (Launch and Early Orbit Phase) and commissioning of the servicer spacecraft are not covered in this document, as they pertain to the spacecraft itself rather than the RPO.

Assuming the Servicer is in its standby orbit and power-safe, the following process applies for an RPOD sequence:

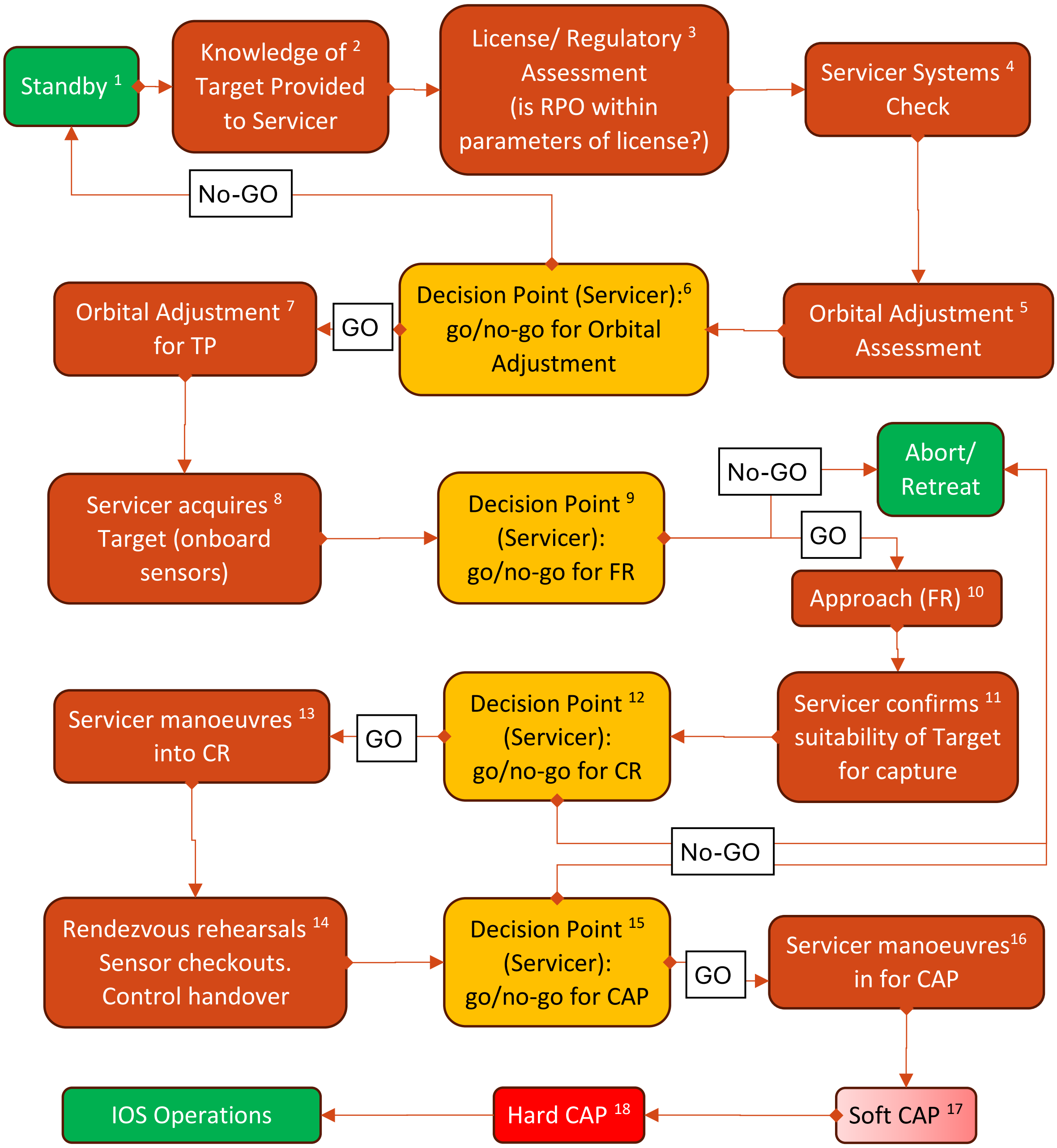

Figure 3: Typical RPOD Sequence

The pre-RPO phase involves all activities required to manoeuvre a servicer spacecraft from its parking or standby orbit (step [1] in Figure 3) into a controlled trajectory toward the target object while ensuring mission safety and orbital precision. This phase begins while the servicer is in the standby orbit and progresses until it transitions into the **close-range rendezvous phase** (step [13]). Proper execution of each step is critical to establishing a stable approach while mitigating collision risks and ensuring onboard systems operate within nominal parameters.

The first step in this phase is **mission planning and pre-approach checks**, which involve validating mission parameters, confirming the target spacecraft's orbital elements, and assessing its attitude and operational status (step [2]). This may be achieved through a combination of ground-based tracking, telemetry exchange (for cooperative targets), and passive remote sensing (for uncooperative targets).

Before any proximity operations can commence, the servicer spacecraft operator must obtain the necessary **regulatory approvals** (step [3]). In most jurisdictions, approaching another spacecraft—particularly in geostationary orbit (GEO) or medium Earth orbit (MEO)—requires prior authorisation from the relevant national space agency or regulatory body, such as the UK Civil Aviation Authority (CAA), the U.S. Federal Communications Commission (FCC), or the European Space Agency (ESA). This ensures compliance with space traffic management (STM) guidelines, minimizes the risk of unauthorized interference, and supports transparency in orbital operations. If the target is owned by another nation or entity, diplomatic and legal considerations may also influence the approval process.

> **Note:** the ability for spacecraft to manoeuvre in space is heavily scrutinised by foreign nations as such manoeuvres are not the norm for regular orbital operations. Accordingly, diplomacy and transparency are essential to avoid geopolitical tensions.

The servicer spacecraft must perform a comprehensive **health check of its subsystems** (step [4]), including propulsion, guidance, navigation, and control (GN&C), as well as its onboard sensors, docking mechanisms and assurance of communications throughout the RPO process. If the target spacecraft is cooperative, two-way communication systems will have to be checked to ensure coordinated manoeuvres can be performed (step [14]). In cases involving uncooperative targets, passive tracking and trajectory prediction techniques are employed to compensate for the lack of active telemetry and provide ephemeris data for the target.

Once the servicer has validated its own readiness, confirmed the target's orbital characteristics and sought regulatory approval, an **assessment of the orbital adjustment** is made (step [5]). This adjustment could burn more fuel that the servicer operator is willing to use, so a decision is made whether or not to implement the orbital adjustment (step [6]). If 'go', a series of orbital manoeuvres are made (step [7]) to align the inclination of the servicer's orbit to that of the target, then reduce the relative distance and align the servicer's orbit with that of the target through altitude changes and phase (RAAN) matching. These manoeuvres typically include controlled orbit-raising or lowering burns to adjust the phase angle, as well as drift correction burns to compensate for any deviations from the planned trajectory. Depending on the servicer's capabilities, these manoeuvres may be pre-planned or autonomously adjusted using onboard GN&C algorithms. The servicer must also account for perturbative forces such as Earth's gravitational harmonics, solar radiation pressure, and third-body influences (e.g., the Moon's gravitational pull) to maintain accuracy in its trajectory predictions.

When the target spacecraft is within view of the servicer's sensors (which might include RF, LIDAR, infrared or visual sensors) then the servicer is considered to be in the **Far-Rendezvous (FR) phase** (step [8]). The servicer (or its operators) will assess the target and determine if it is safe to approach (step [9]). If not, an abort/retreat is implemented. If it is safe to approach, the servicer will move from FR to **Close Rendezvous (CR)** (step [10]).

From this point on, real-time navigation updates (and thus, constant contact with the ground for non-autonomous approaches) are essential to ensure the servicer remains on a predictable and safe approach path. The transition from FR to CR must be carefully managed to ensure that all preparatory conditions have been met and the target remains safe to approach (step [11]).

If the servicer, target, and approach remain safe, the servicer enters the **high-precision manoeuvring phase** (steps [12 & 13]). Once the servicer is within an appropriate range, it will perform further sensor checkouts and initiate handover of control from target to servicer (step [14]).

Once control is established, the final decision is made whether to go for **capture (CAP)** (step [15]) or to abort. Relative navigation and precise positioning manoeuvres will become the primary focus here (step [16]), and docking operations can start in order to achieve **'Soft CAP'** (step [17]). Soft capture involves initial contact and grappling with the target. **Hard CAP** (step [18]) is the point at which the two spacecraft are joined and preparations for the In-Orbit Servicing (IOS) can start.

Decision Criteria

Before, during approach, and up to the point of docking, several elements need to be in place or determined:

1. **Target Acknowledgement**

The Servicer needs to have agreement from the operator/owner of the target to approach and attempt docking. There are many facets within international law that will govern the way an RPO can be requested and performed. Appropriate liability and insurance cover will also need to be complete.

2. **Safety Assessment**

The Servicer will need to prove that the proposed RPO is safe, including a detailed safety analysis of the RPO and servicing operations, as well as mitigating actions should anything go wrong.

3. **Appropriate license**

The Servicer needs to have the appropriate authorisations to approach a target, as determined by the licensing state of the Servicer. This will include acknowledgement of the RPO by the Target (operator and state), appropriate frequency filings, ground/ autonomous control plans, risk tolerance/ ALARP compliance, insurance, IOS certification (agreement to carry out the IOS task) and separation and retreat plans.

7.2. AOCS Takeover

Certain RPO and ISAM missions may require the servicer spacecraft to assume control of the target spacecraft's Attitude and Orbit Control System (AOCS). This process, referred to as AOCS takeover, involves the servicer using its own guidance, navigation, and control (GNC) systems to stabilise and manoeuvre the target, usually following capture when the Servicer/Target is joined as a unified stack.

(AOCS takeover is being talked about as a 'pre-docking' process too, where the Servicer is able to command the target's AOCS in order to make rendezvous & docking safer or quicker. This requires commanding over RF/communications and is further away as a technology capability.)

AOCS takeover begins once a secure mechanical and, where applicable, electrical interface has been established between the servicer and the target. In cooperative scenarios, the target spacecraft may be designed with compatible docking ports and avionics interfaces that facilitate command and data exchange. This allows the servicer to access telemetry, issue control commands, and even share attitude sensor data. In contrast, for non-cooperative or non-communicative targets, the servicer must rely entirely on passive sensing and external force-torque estimation to stabilise the stack, necessitating advanced autonomous control algorithms and robust fault tolerance.

Once control is established, the servicer assumes responsibility for attitude control, using onboard systems (“actuators”) such as reaction wheels, control moment gyroscopes (CMGs) or thrusters to orient the combined servicer-target stack. This may require dynamic reconfiguration of control laws to account for the altered mass properties and inertia. Similarly, orbital station keeping such as maintaining a geostationary position or performing deorbit manoeuvres, is executed using the servicer's propulsion system. This enables mission extension or end-of-life disposal for targets that no longer possess active propulsion capabilities.

The successful execution of AOCS takeover depends on a range of operational and regulatory factors. These include pre-mission coordination to ensure system compatibility, compliance with national and international laws governing control of space assets, and implementation of safety protocols to avoid unintended interference or collision risk. Missions such as Northrop Grumman’s Mission Extension Vehicle (MEV) have already demonstrated the feasibility of this concept, having provided full AOCS control to extend the operational life of commercial geostationary satellites. Future servicing missions are expected to rely increasingly on this capability, making AOCS takeover a critical enabler of sustainable and responsive in-orbit operations.

8. Example Manoeuvres

This section outlines example manoeuvres that servicer spacecraft may execute during RPO. These manoeuvres are essential for achieving successful docking, servicing, or decommissioning of target vehicles. Each manoeuvre is designed to ensure precision and safety, minimizing risks associated with proximity operations.

A servicer is expected to be injected into orbit and remain on its nominal orbit throughout its lifetime until there is a requirement to manoeuvre to approach a target spacecraft. These manoeuvres will have several elements to consider:

- Conjunction Avoidance capabilities
    - How fast and how much is servicer expected to move?
- Inclination changes
    - Inclination changes are very expensive in terms of the required change of velocity and as such, the propellant consumption.
    - To minimize the ΔV requirements, inclination change burns should happen at the point where the velocity is a minimum: at apogee.
        - Note: it can be cheaper (propellant-wise) to boost the spacecraft into an higher orbit, change the inclination at apogee then return the spacecraft to the desired orbit.
- Altitude changes
    - Approaches towards a target are usually considered to be either “V-bar” (where the servicer’s altitude changes (vertically) to approach and dock with the target) or “R-bar” (where RAAN is adjusted to approach the target horizontally/perpendicular to the velocity vector but at the same altitude)

8.1. Delta-Velocity (ΔV) requirements

Delta-V (ΔV) refers to the change in velocity required for a spacecraft to perform specific manoeuvres during its mission. Understanding the ΔV requirements is crucial for mission planning and execution, as it directly impacts fuel consumption and operational efficiency. Key steps include:

- Assess the current orbit of both the servicer and the target vehicle to determine initial ΔV requirements.
- Calculate ΔV needed to change the orbit of the servicer in order to approach the target. (Margins on the ΔV budget will be required to accommodate adjustments for perturbance and safety.)
- Identify the ΔV necessary for soft capture and hard capture phases, ensuring that the servicer can achieve the required velocities for a secure connection.

The ΔV required to perform sample manoeuvres are approximated below:

- A **50km** increase in altitude (Hohmann Transfer) with no inclination/RAAN change requires around **27m/s of ΔV**
- A **1°** inclination change requires around **132m/s** of ΔV
- A 50km altitude change AND 1° inclination change requires about **145m/s** of ΔV.

Propellant budgets (ΔV) should also account for propellant required to separate from the target and retreat to a safe orbit, maybe even the original 'parking orbit'.

Propellant stores should also consider multiple approaches, so the servicer is not restricted to "1-target, 1-mission" scenarios.

8.2. Prohibited Operations/Manoeuvres

Certain operations or manoeuvres may be classified as prohibited due to safety concerns, high risk of failure, or regulatory restrictions.

The operator of a servicer spacecraft will have the ability to understand how much ΔV is required to approach a target / customer spacecraft. It is their decision whether or not they wish to undertake an RPO/IOS mission based on the suitability of the target and propellant requirements. (If the propellant required to approach and dock with a target is too great, it may limit the servicer to just the 1 RPO mission, which might not be in line with their own business plan.

Rendezvous that cannot be achieved are:

Between Opposite-Orbiting Spacecraft
A servicer spacecraft cannot perform a rendezvous with a target in a retrograde orbit (opposite direction) without incurring an enormous velocity change (ΔV). For example, if a servicer in a prograde low Earth orbit (LEO) attempts to rendezvous with a retrograde satellite, it would need to cancel its entire orbital velocity (~7.8 km/s) and match the retrograde velocity in the opposite direction—effectively a ~15.6 km/s ΔV manoeuvre. This exceeds the propellant capacity of all current spacecraft and is energetically prohibitive.

Large Inclination Changes at High Altitude
Rendezvous with a target in a significantly different inclination requires a lot of ΔV and is typically not feasible. Inclination changes require ΔV that is proportional to orbital speed, which is lower at higher altitudes, but still extremely costly.

For example, changing inclination by just 10 degrees in GEO (~35,786 km altitude) requires >1.5 km/s ΔV, which is beyond the capabilities of most servicing spacecraft. Thus, a servicer must be launched into a compatible inclination, or target objects must be chosen within a narrow orbital band.

Rendezvous with Targets in Highly Eccentric Orbits
Spacecraft in highly elliptical orbits—such as Molniya orbits or graveyard disposal orbits—pose significant challenges:

- The servicer must match both apogee and perigee velocities, which vary widely in elliptical orbits
- Synchronizing time and location for rendezvous is complex and may exceed mission ΔV constraints
- For many high-eccentricity targets, a servicer launched from LEO would require multiple complex burns or lunar assists, making the mission impractical.

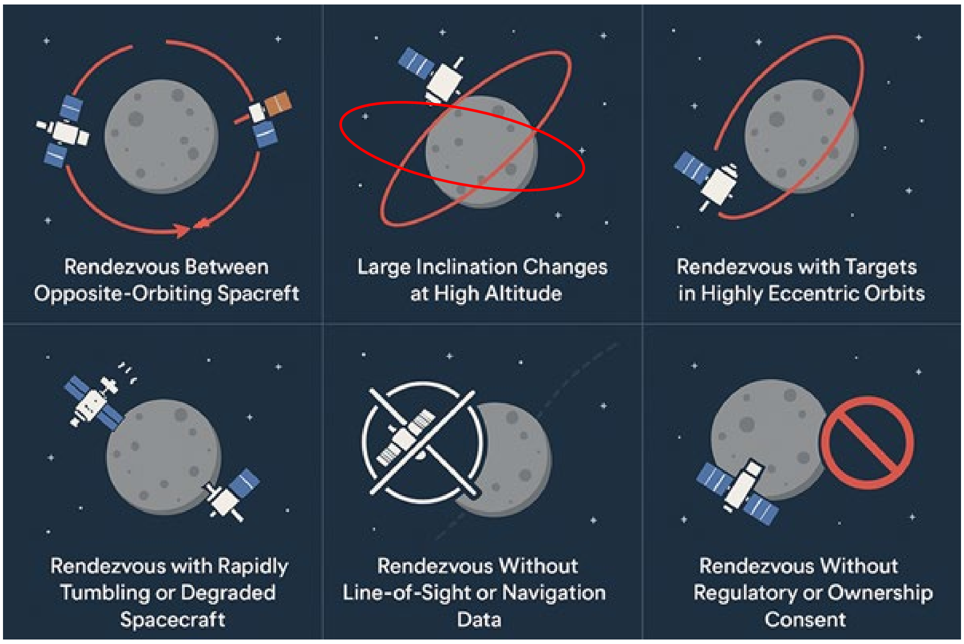

Figure 4: Examples of prohibited manoeuvres

Rendezvous with Uncooperative Targets
Although not strictly impossible, rendezvous with non-cooperative or tumbling spacecraft presents limits:

- If the target is spinning rapidly or unpredictably, a safe docking or capture may be impossible
- Without prior knowledge of the target's inertial behaviour, the servicer risks collision or system damage
- Autonomous stabilization of a target may be attempted using robotic arms or damping systems, but this requires extensive mission planning and carries a lot of risk.

Rendezvous Without Line-of-Sight or Navigation Data
Servicing missions cannot proceed without accurate relative navigation data or line-of-sight (LOS) tracking. Also, for deep space orbits (e.g., lunar or interplanetary), GNSS is unavailable.

Optical or LIDAR sensors can be blinded (e.g. by solar angle or plume obscuration) making rendezvous attempts unsafe.

Rendezvous Without Regulatory or Ownership Consent

Even if technically possible, a rendezvous cannot be legally conducted without appropriate regulatory permissions and owner consent. Under the Outer Space Treaty (1967), unauthorized interference with another nation's spacecraft is prohibited.

Unilateral approach to commercial or governmental assets may be construed as a hostile act. In most jurisdictions, this would prevent mission authorisation and insurance coverage.

8.3. Proposed Servicer Orbits

The orbital regime for a servicer mission depends on several factors, including the orbital regime of the target, launch constraints, manoeuvrability requirements, and propellant efficiency. This subsection discusses various orbital regimes and how servicer missions might be planned to achieve RPO.

8.3.1. Low Earth Orbit (LEO) – For LEO RPO Missions

500–800 km circular, near-polar Sun-synchronous orbit (SSO) or mid-inclination orbit (~51.6° for ISS compatibility).

Rationale:

- Ideal for inspecting or servicing other LEO assets (e.g., Earth observation satellites, smallsats, and space stations).
- Offers frequent ground passes for telemetry, tracking, and control.
- Lower ΔV requirements for phasing and rendezvous.
- Compatible with a wide range of launch vehicles.
- Reduced communication latency and lower fuel requirements for launches.

Drawbacks:

- Limited access to higher orbits.
- Atmospheric drag increases station keeping propellant use at lower altitudes.
- Increased space debris must be managed.

8.3.2. Highly Elliptical Orbit (HEO)

An orbit characterized by a high apogee and low perigee, allowing for extended coverage over specific areas. Super-synchronous transfer orbit (e.g., 500 km perigee / 35,000 km apogee) or Molniya-like profiles.

Rationale:

- Provides wide visibility across multiple orbital regimes (LEO to GEO).
- Suitable for servicing missions requiring extensive coverage or multiple rendezvous targets.
- Perigee passes allow low-energy burns to raise/lower apogee.

Drawbacks:

- Rendezvous timing with targets in circular orbits is complex.

- Requires significant mission planning for precise synchronization.
- Requires careful planning to maintain communication links during rapid orbital changes.

8.3.3. GEO Drift Orbit – For GEO Servicing

Suggested Orbit: GEO drift orbit (e.g., ~150–300 km above or below GEO belt).

Rationale:

- Enables rendezvous with operational satellites in GEO while minimizing risk of interference.
- Minimizes station keeping during loiter or standby periods.
- GEO servicing is a key commercial driver (e.g., refuelling, life extension).

Drawbacks:

- High ΔV required to reach GEO from LEO (unless rideshare/piggybacked on GEO-bound launch).
- Limited target diversity without large fuel reserves.
- Requires careful planning to maintain communication links during rapid orbital changes.

8.3.4. Medium Earth Orbit (MEO) – For Constellation Support

Suggested Orbit: 19,100–20,200 km (GNSS-compatible altitude).

Rationale:

- Suited for servicing navigation constellations (e.g., GPS, Galileo).
- Stable radiation environment compared to higher orbits.
- Increasing interest in MEO mega-constellations (communications, PNT services).

Drawbacks:

- High ΔV to reach from LEO; limited number of commercial targets currently.

8.3.5. Recommended Initial Orbit: High LEO (~800 km circular), ~51.6° Inclination

This orbit strikes a balance between operational flexibility, ΔV efficiency, and accessibility to future servicing missions.

Key Benefits:

- Compatible with ISS and many smallsat constellations.
- Offers flexibility to raise/lower orbit for varied rendezvous targets.
- Frequent launch options and good ground station visibility.
- Servicer can loiter safely while awaiting tasking.

Modifications:

- For GEO targets: Launch into LEO, then transfer via staged propulsion (e.g., electric or chemical).
- For a multi-regime architecture: A modular servicer bus deployable from LEO staging points could be considered.

However, it is noted that the orbit of the initial target would drive the orbital regime of a servicer. An orbit cannot be selected without knowledge of the target's orbit.

9. Fuel Estimates

Accurate fuel estimates are critical for the successful execution of RPO. This section outlines the methodologies for calculating fuel requirements for various manoeuvres, ensuring optimal operational efficiency and mission success.

Overview of fuel requirements

The fuel requirements for RPO missions depend on several factors, including spacecraft mass, desired manoeuvres, and operational scenarios. The primary considerations in estimating fuel needs include the Delta-V Budget, which is the total change in velocity (ΔV) required for each manoeuvre based on the orbital dynamics involved in approaching, docking, and manoeuvring around target objects. Additionally, the efficiency of the propulsion system, measured by its specific impulse (Isp), directly influences fuel consumption. Understanding the efficiency of the chosen propulsion technology is essential for accurate estimates.

Manoeuvre scenarios

Different manoeuvres will require varying amounts of fuel. The initial approach phase involves transitioning from a standby orbit to the vicinity of the target, with fuel estimates depending on the distance to the target and the required ΔV for trajectory adjustments. Once in proximity to the target, precision manoeuvres are necessary for alignment and docking, demanding higher fuel consumption due to the need for rapid adjustments. After successful docking, additional fuel may be required for stabilization and operational adjustments, especially if the servicer spacecraft is tasked with conducting repairs or refuelling.

Calculation methodology

Fuel estimates require a systematic methodology, including the modelling of orbital dynamics using simulation tools to predict fuel consumption for each manoeuvre. Incorporating safety margins in the fuel estimates is necessary to account for unforeseen circumstances, such as variations in target behaviour or orbital perturbations. Iterative refinement of fuel estimates based on real-time data and mission feedback enhances accuracy for future missions.

Until mission objectives (and associated manoeuvre requirements) are known, fuel estimates cannot be made. However, for reference, AstroScale's ELSA-d mission had a mass of approximately 175kg, carried 10.5kg of fuel and achieves approximately 43m/s of ΔV. (About enough for 1 Hohmann Transfer, but no inclination/RAAN changes.)

10. RPO Hardware Specifications

10.1. Space Segment

This section outlines the parameters that define the spacecraft's capabilities, ensuring it meets the operational demands and mission objectives.

Spacecraft Mass

The mass of a spacecraft significantly impacts its performance, fuel requirements, and manoeuvrability. The overall mass, including the spacecraft structure, propulsion system, payload, communications system and avionics, must be optimized to ensure efficient operation within both the targeted parking orbit and the orbits used during servicing. Mass must be balanced and distributed to maintain predictable stability and control during manoeuvres. Additionally, the spacecraft must be capable of carrying any additional equipment or payload necessary for specific missions, such as servicing tools or replacement components.

The mass of the spacecraft is highly dependent on the mission objectives, systems on board and power requirements. If the spacecraft is bound for orbits beyond LEO, physical shielding will add to the mass.

Spacecraft Integrity

As RPOD inherently involves the physical approach and contact between two spacecraft, both servicers and targets must be engineered with a degree of resilience to low-speed impact. While the objective is always to achieve a controlled, nominal docking with minimal contact force, operational realities like sensor latency, actuation errors, or target tumbling, mean that minor deviations can result in unintended low-velocity contact. Spacecraft systems, particularly structural interfaces, appendages near the docking plane, and critical subsystems, must be designed to tolerate such impacts without sustaining mission-degrading damage.

This requirement does not necessitate heavy structural reinforcement but does call for thoughtful materials selection, mechanical compliance features, robust interface design and correct positioning on the spacecraft. For instance, soft-capture mechanisms may include dampers or crushable elements to absorb residual kinetic energy, while non-cooperative targets should be assessed for vulnerable areas that must be avoided during approach. Similarly, servicer spacecraft may incorporate passive or active collision mitigation features, such as articulated bumpers or force-limited docking arms, to protect both parties during final capture. Designing for this level of physical resilience ensures operational robustness across a range of nominal and off-nominal RPOD scenarios, supporting mission success and space safety.

Payload

The payload defines the spacecraft's functional capabilities. This encompasses equipment for in-orbit servicing, such as robotic arms, inspection tools, communication devices and replacement components, each with specific integration requirements. The mass, dimensions and power requirements of the payload must be accounted for in the overall spacecraft design to ensure compatibility and integrity.

Several payloads could be specified for an RPO capable servicer. Notable options include the RAFTI interface (a refuelling interface from Orbit Fab) and the ASPIN interface (mechanical and data interface Lockheed Martin).

Communications

A servicer spacecraft conducting an RPO will have stringent communications requirements to support command, control, telemetry, payload data, and safety-critical decision-making. The communications architecture must account for mission phases, autonomy level, regulatory oversight, and potential failure modes. Below is a breakdown of key requirements:

a) Frequency Bands & Links

Band	Typical Use Case	Notes
S-band	TT&C, low-rate data	Common for LEO, robust, bandwidth limited
X-band	Payload telemetry	Used for most LEO payloads
Ka-band	High-rate comms, HD video	Preferred for detailed servicing ops or inspection imaging.
Optical comms	LOS data transfer	High bandwidth; weather-dependent; emerging capability.
UHF/VHF	Backup comms	Used for emergency or contingency commands.

b) Directional antennas

Such antennas may be required to maintain contact with ground stations during dynamic manoeuvres.

c) Pre-Rendezvous (Far-Field Operations)

- Continuous command and telemetry (TT&C) via networked ground stations or relay satellites (e.g. TDRSS, Iridium or EDRS)
- Orbit determination updates to refine targeting solution
- Secure links to receive regulatory clearance for approach
- Redundancy to guard against loss of command during manoeuvring.

d) Proximity Operations (Near-Field: <1 km)

- High-rate, low-latency links to support:
  - Relative navigation sensor data (LIDAR, optical, radar)
  - Real-time telemetry during critical manoeuvres
  - Possible operator-in-the-loop decision-making for final approach or docking
- Line-of-sight (LOS) tracking using directional antennas or optical terminals
- Autonomous fallback modes in case of comms dropouts (fail-safe procedures).

e) Docking and Capture

- Zero-latency control loops (when not fully autonomous)
- Video and telemetry for situational awareness on the ground
- Communication handoff or shared channels with the target (if cooperative).

f) Post-Capture / Servicing Phase

- If the servicer performs repairs, refuelling, or payload swaps:
  - Payload data links for health monitoring of both spacecraft.

If haptics or any other requirement for fast communications is in place, this may mean a GEO orbit may not be suitable due to signal latency.

It is feasible that ubiquitous communication will be required, implying a Ground Stations as a Service (GSaaS) approach with geographically distributed ground stations.

Live video may be required to transmit details of activities. It would be useful for satellites to have cameras onboard in order to track incoming servicers – this video shall be streamed to operators to validate telemetry from the servicer during RPOs and servicing.

g) Security & Fault Tolerance

Hacking of spacecraft is not common but is of growing concern to regulators and MoD. End-to-end encryption of command and telemetry is essential to prevent hijacking or spoofing. Authentication protocols may be required to confirm origin and validity of commands and redundant communication buses and RF chains for resilience against hardware failure.

Watchdog timers and autonomous safe modes are common in spacecraft and would be required on servicers to enable fault tolerance and mitigation strategies.

h) Coordination with Target Spacecraft

For cooperative targets, a shared communication plan must be established (e.g. time slots, protocols, encryption keys).

For non-cooperative targets, passive sensing (RF sniffing, optical tracking) substitutes for active communications, but requires a high level of GNC autonomy.

i) Ground Segment Integration

Global or semi-global ground station coverage would be required to ensure command uplink opportunities during orbit passes. Integration with space traffic management systems would also help in reporting on RPO activity and to avoid potential conjunctions.

For operations beyond LEO, satellite relay access may be required.

j) Optional Enhancements

Inter-satellite links (ISLs) could support RPOs and ISAM operations when they (the servicer/target, be they separate or as a stack) are not within sight of a ground station.

10.1.1. RPOD Sensors

When designing a servicer (chaser) spacecraft for RPO, sensor selection and performance across different approach ranges need to be considered. The approach sequence typically spans from hundreds of kilometres down to a few centimetres, and different sensor modalities are optimised for specific ranges, lighting conditions, and target cooperation levels.

At **long range** (1000 km to ~10 km), where the target may be unlit or only intermittently visible, RF-based ranging systems and Global Navigation Satellite System (GNSS) data are the primary tools. Dual-GNSS configurations (on both chaser and cooperative target) can provide accurate relative positioning when signal conditions are favourable. RF systems, such as radar altimeters or crosslink transponders, offer resilience to low-visibility conditions and provide range and velocity data, though their angular resolution may be coarse.

In the **mid-range** (10 km to ~100 m), optical tracking systems and LIDAR become more effective. Optical systems can passively track the target based on reflected sunlight or thermal signatures, but performance degrades with poor illumination or occlusion. LIDAR sensors, emitting their own signal, provide active range and bearing measurements with high precision, making them suitable for autonomous navigation in cluttered or dynamic environments.

At **close range** (100 m to ~1 m), high-resolution LIDAR, stereoscopic vision systems, and infrared or visible-light cameras are typically used in combination to enable fine relative navigation and attitude estimation. At these distances, the servicer must manage potential plume impingement, collision risk, and precise alignment for docking or capture.

Finally, in the **ultra-close** regime (sub-metre to contact), vision-based systems (including stereo cameras and pattern recognition algorithms) enable millimetre-scale precision. These systems must operate with low latency and high robustness to dynamic lighting, glint, and shadowing effects.

Designers must consider not only each sensor's optimal operational envelope, but also environmental factors (e.g. lighting conditions, Earth/space background), potential interference, and redundancy. Furthermore, a blend of sensors is often required to enable transitions between operational modes and maintain accuracy and reliability throughout the approach trajectory.

10.1.2. Mission Duration

Mission durations must be established for spacecraft design and operational planning. The expected operational lifespan of the spacecraft must align with mission objectives, taking into account factors such as fuel reserves and component degradation. The spacecraft should be designed for repeated operational cycles, accounting for periods of inactivity, active servicing, and potential mission extensions. Provisions should be made for extended mission duration in case of unforeseen delays or additional tasks, ensuring that the spacecraft remains functional and effective throughout the mission.

The duration of a servicer would depend on the missions it is targeting. If a target was known prior to launch, a servicer could be launched, approach, dock and interact with the target within 3 months.

If a target was not known, a servicer should be expected to remain capable for many years, although this might be a problem for the servicer operator’s business case!

10.2. Ground Segment

RPOs place unique demands on the ground segment infrastructure, necessitating high levels of situational awareness, operational readiness, and coordination. These missions differ significantly from conventional satellite operations due to their dynamic and time-critical nature, which requires robust ground-based systems and highly skilled personnel to ensure safe and successful execution.

10.2.1. Infrastructure

The ground segment must support **high-temporal-resolution tracking and telemetry**, particularly during close approach and docking phases. This may involve continuous or near-real-time command and control capabilities, either via dedicated ground stations or through commercial networks capable of providing global coverage. Low-latency data links are critical to enabling tight closed-loop control, especially for non-autonomous operations or missions involving uncooperative targets where situational updates are more frequent and unpredictable.

10.2.2. People

The mission control team must be trained for RPO-specific procedures. This includes real-time trajectory monitoring, anomaly resolution, and execution of pre-scripted abort or retreat sequences. Operators must interpret complex multi-sensor telemetry, assess risk in rapidly evolving conditions, and coordinate with external stakeholders such as space traffic management authorities and/or space domain awareness agencies.

10.2.3. Tools

RPO missions may demand enhanced planning and decision-support tools, capable of integrating GN&C models, sensor fusion data, regulatory constraints, and predicted conjunction assessments into an operational timeline. These tools help manage mission complexity, reduce human error, and enable fast, informed decisions during time-sensitive manoeuvres.

The availability of simulation environments and digital twins is increasingly seen as a requirement to rehearse and validate these operations prior to execution.

10.2.4. Transparency

Inter-agency and cross-border coordination can be required where the mission involves foreign-licensed spacecraft or targets in highly trafficked orbits. In such cases, the ground segment must facilitate secure communication channels, data sharing agreements, and timely notification to meet regulatory transparency obligations.

11. End-of-Life

The End-of-Life (EOL) phase is a critical component of the overall lifecycle of spacecraft operations, particularly for those involved in RPO. This section outlines the objectives, strategies, and procedures relevant to the EOL phase of a spacecraft.

11.1. Objectives of EOL management

The objectives of End-of-Life management include mitigating space debris, ensuring compliance with regulations, and promoting sustainable space operations. Mitigating space debris involves ensuring that defunct spacecraft do not contribute to the growing problem of space debris, which poses risks to operational satellites and crewed missions.

Compliance with regulations requires adherence to international guidelines (e.g. the Inter-Agency Space Debris Coordination Committee, or IADC) and national regulations regarding the decommissioning of satellites and the removal of non-functional objects from orbit. Sustainable space operations promote a sustainable approach to space usage by implementing practices that prevent long-term environmental impacts in low Earth orbit and beyond.

11.2. Strategies for EOL operations

Strategies for End-of-Life operations include controlled deorbiting, graveyard orbits, and end-of-life procedures. Controlled deorbiting involves implementing planned manoeuvres to deorbit the spacecraft safely, allowing it to re-enter the atmosphere over designated areas, such as remote ocean regions. Propulsion systems are used to reduce altitude gradually, ensuring that the spacecraft disintegrates upon re-entry.

Graveyard orbits are used for satellites in geostationary orbits, transferring defunct vehicles to designated graveyard orbits to minimize the risk of collision with operational satellites. End-of-life procedures involve conducting thorough assessments of the spacecraft's systems to determine the best approach for EOL actions and executing final operational checks to ensure systems are disabled or safely configured to prevent unintended activations.

11.3. Procedures for EOL implementation

Mission planning must include EOL strategies in the mission design phase prior to the mission's initiation, ensuring that all stakeholders are aware of the operational plans for decommissioning.

Execution of EOL manoeuvres occurs once the spacecraft has completed its mission objectives, initiating EOL procedures as planned and documenting all EOL actions and decisions for future reference and compliance verification. Post-mission analysis is conducted after the spacecraft has been decommissioned to evaluate the effectiveness of EOL strategies, gathering data to inform future missions and improve EOL practices, contributing to the ongoing development of best practices in space operations.

As an RPO servicer approaches the end of its operational life - whether due to mission completion, or system degradation - a series of decommissioning activities must be executed to ensure long-term orbital safety and regulatory compliance. (It is of course possible that the servicer itself could be serviced, refuelled, etc.) The servicer must first assess its residual capability, including available propellant, attitude control functionality, and communication health, to determine viable end-of-life options. If sufficient capacity remains, the spacecraft may be commanded to perform a controlled disposal manoeuvre. In LEO, this typically involves initiating a targeted deorbit to ensure atmospheric re-entry and burn-up within 25 years, in alignment with international orbital debris mitigation guidelines such as those from the IADC. In GEO, the servicer may perform a graveyard orbit transfer, raising its altitude by at least 235 km above the GEO belt and passivating all energy sources thereafter.

Prior to final disposal, the spacecraft must transition into a safe, non-interfering configuration. This involves powering down non-essential systems, passivating propulsion and battery systems to prevent explosion risks, and transmitting a final telemetry package to confirm compliance. The spacecraft’s final orbital state must be registered with relevant regulatory authorities, and notification provided to space traffic management entities to update conjunction assessment databases. These end-of-life activities are not only critical for compliance and insurance closure but also serve as a responsible contribution to sustainable in-orbit operations and debris mitigation.

For servicer spacecraft operating in LEO, end-of-life disposal must account for demisability - the ability of spacecraft components to fully disintegrate and burn up upon atmospheric re-entry. This requires selecting materials and structural designs that minimize the risk of surviving debris reaching the Earth's surface, in accordance with guidelines such as ESA’s DRAMA or NASA’s ORSAT criteria.

It is noted that, when properly designed, demisable spacecraft pose negligible threat to the ground and contribute minimal impact to the atmosphere; combustion byproducts - primarily carbon oxides, metal vapours, and trace particulates - are dispersed at high altitudes and constitute an insignificant addition to atmospheric pollutants when compared to natural meteoroid ablation or industrial emissions. Nonetheless, increasing re-entry traffic has prompted further study into cumulative effects, particularly the injection of aluminium oxides and other metals into the stratosphere, which may warrant future regulatory attention.

11.4. Importance of EOL in RPO context

In the context of RPO, effective EOL management is essential not only for compliance and sustainability but also for the safety of ongoing operations. By ensuring that defunct spacecraft are properly decommissioned, operators can reduce the risk of collisions in crowded orbits and maintain a safer environment for active satellites and crewed missions.

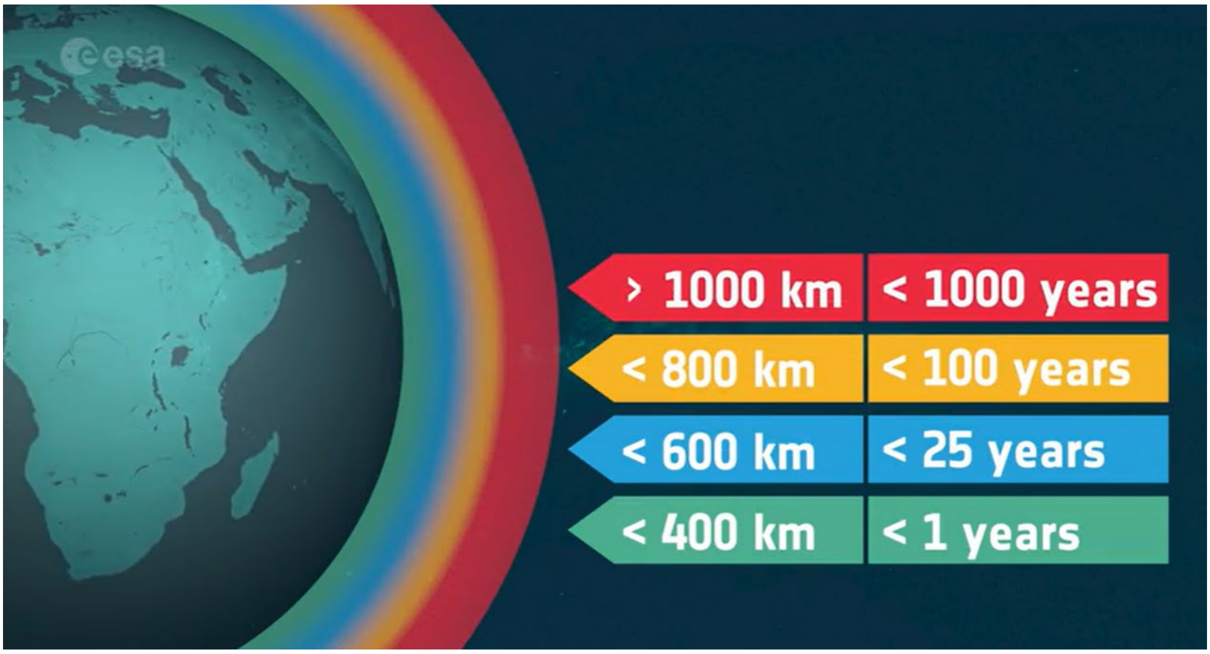

Figure 5: LEO de-orbit times (Credit: ESA)

12. Assumptions

In developing the framework for Remote Proximity Operations (RPO), the following assumptions have been established to guide the operational planning and execution:

1. It is assumed that the target vehicles fall into one of three categories: Cooperative, Partially Cooperative, or Uncooperative, as defined in the Types of RPO section. This classification will dictate the operational approach and the necessary technologies for successful engagement.
2. The operational environment is presumed to be within the designated RPO zones as identified by current ESA guidelines. This includes clear demarcations for safety and efficiency during approach and capture manoeuvres.
3. All systems and technologies employed during the RPO are expected to meet the outlined performance specifications. This includes sensors, communication systems, and capture mechanisms that are validated and operational prior to the RPO execution.
4. It is assumed that adequate telemetry data will be available from the target vehicle, particularly for Cooperative targets. For Partially Cooperative and Uncooperative targets, reliance on ground observations and onboard sensor data will be crucial.
5. Effective communication and coordination between mission control and the servicer spacecraft are assumed to be established. This includes decision-making protocols for go/no-go assessments at critical decision points during the RPO.
6. Safety protocols are assumed to be in place to manage risks associated with RPO, including provisions for aborting the approach if necessary. The servicer is expected to maintain operational safety throughout all phases of the manoeuvre.
7. The primary objective of the RPO is to conduct safe and effective captures of target vehicles for debris removal or servicing purposes. It is assumed that all stakeholders are aligned with this mission focus, ensuring that the document remains a relevant resource for internal discussions.
8. All RPO operations are assumed to comply with relevant regulatory and licensing requirements, ensuring that the missions are conducted legally within established frameworks.
9. A mechanism for feedback and continuous improvement is assumed to be in place, allowing for the adaptation of strategies based on lessons learned from each RPO mission.
10. Specifics of the servicing tasks are not provided here due to the wide variety of applications.

13. Conclusions

This document serves as a foundational resource for understanding and implementing Remote Proximity Operations (RPO) and In-orbit Servicing, Assembly, and Manufacture (ISAM) within the current landscape of space operations. The insights and strategies presented here provide a robust foundation for advancing RPO and In-Orbit Servicing initiatives. As the space environment evolves, continuous adaptation and improvement of these practices will be essential for ensuring the sustainability and safety of space activities.

Key takeaways:

1. As the number of satellites in orbit continues to grow, the need for effective servicing and debris removal strategies becomes paramount. This document highlights the importance of RPO as a prerequisite for successful ISAM missions.

2. By adhering to the existing guidelines, servicers can be designed in such a way to provide a structured approach to mission planning, execution, and assessment. This ensures that all stakeholders operate with a common understanding of objectives, risks, and operational protocols.

3. The detailed breakdown of operational phases—from target phasing to capture and disposal—offers a clear roadmap for implementing RPO missions.

4. This document fosters collaboration among various stakeholders, including industry partners, regulatory bodies, and research institutions. Such partnerships are essential for advancing technologies and methodologies in the field of remote proximity operations.