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Preliminary Design of an End-of-life ADR Mission for Large Constellations

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Abstract

Since the beginning of the space era, the amount of debris generated in low Earth orbit has been steadily increasing. Recently, the rise of plans for large satellite constellations in low-Earth orbit (LEO) means that the number of satellites in key orbits will increase at a much higher rate than today.

OneWeb, for example, will be launching a constellation of over 600 satellites to provide global commercial broadband service from an altitude of 1,200 km. In addition to designing their satellites to be deorbited under their own power at EOL, OneWeb is working with industry to develop and standardize ADR-related technologies for the benefit of the entire industry.

This paper considers the design of a potential ELSA-OW (End of Life Services by Astroscale – OneWeb) mission, funded under ESA's Project Sunrise. ELSA-OW will rely on heritage from ELSA-d, Astroscale's first end-of-life servicing mission due to launch in the early 2020 timeframe. ELSA-d will demonstrate technologies for rendezvous and proximity operations (RPO) by launching a chaser satellite attached to a small target satellite, which will then repeatedly separate and dock in orbit. The chaser is equipped with rendezvous guidance, navigation, and control (GNC) technologies and a magnetic docking mechanism, whereas the target has a docking plate (DP) which serves as a capture interface. These RPO technologies will be further developed in the ELSA-OW mission, which will be designed to capture a OneWeb satellite equipped with OneWeb's standard grappling fixture interface.

This paper will broadly provide an overview of the concept of operations (CONOPS) and key aspects of the preliminary mission design. The ELSA-OW concept presented would be the first commercial time active debris removal (ADR) is being tested in space, in LEO, with a representative constellation customer.

Keywords: end of life, active debris removal, ELSA-OW, OneWeb, rendezvous proximity operations

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1. Introduction

Since the beginning of the space era, the amount of debris generated in low Earth orbit has been steadily increasing. Recently, the rise of plans for large satellite constellations in low-Earth orbit (LEO) means that the number of satellites in key orbits will increase at a much higher rate than today.

OneWeb, for example, will be launching a constellation of over 600 satellites to provide global commercial broadband service from an altitude of 1,200 km. In addition to designing their satellites to be deorbited under their own power at EOL, OneWeb is working with industry to develop and standardize ADR-related technologies for the benefit of the entire industry.

The ESA Sunrise programme for OneWeb (OW) – the focus of this paper – provides an opportunity for Astroscale (AS) to work with OW, a representative customer, to work towards development of an ADR service for constellations (under the development name ELSA-OW), and in the first step an IOD (in-orbit demonstration) mission. The project addresses many different aspects:

- Business case development & customer analysis.
- Mission architectural trade-off.
- Initial mission & systems design (including CONOPS) and initial subsystem analysis.
- Supply chain and procurement analysis.

The work programme is crafted in this fashion, because AS has three business cornerstones it feels are necessary for a successful ADR business: developing the technology & capability, maturing the business case, driving regulation, policy (norms and standards) & insurance domains. [9 - 11] complement this paper by considering Astroscale's involvement in aspects of regulation and policy for the ADR business.

The wide variety of work in this project thus differs from conventional projects which usually only consider technical design aspects. In addition, for AS, a comprehensive business analysis is needed as a pre-cursor to even understand what satellite needs to be developed to begin with. Only then, in conjunction with CONOPS development, can one understand how a service is to be offered.

The paper begins in Section 2 setting the scene with business analysis and architectural trade-off. In Section 3, we analyse the design of the mission CONOPS. In Section 4 we analyse mission capabilities and innovations. In Section 5 we examine supply chain (including external services like SSA). Finally, the paper concludes in Section 6.

2. Business Analysis & Architectural Trade-off

The business analysis part of the Sunrise project is comprehensive. In this paper we only assess the Business & Mission Analysis Tool, its purpose and outcomes. [7] complements this paper to offer Astroscale's perspective on aspects of customer selection, market analysis, value proposition of a debris removal service to end-users.

In order to design an ADR service many questions have be answered; some key ones include:

- What clients (targets) need removal? – e.g. client altitude, mass, inclination.
- What service is being offered e.g. do you target customer clients one at a time, or sweep multiple clients up at once, and how often?
- What launch solution is being used for the servicer (chaser)?

Analysis of customer groupings that conform to varying client altitude, mass and inclination sets, yields a business envelope for which a servicer vehicle can be designed to, to accommodate the maximum number of clients.

Thus, OW is just a representative customer, and the servicer is designed for an array of different clients and needs.

2.1. Business & Mission Analysis Tool

The business and mission analysis tool is designed to come up with different architectures based on an input set of client target properties. Considerations include: (a) single or multi-client service, (b) altitude of servicing and altitude of commissioning, (c) altitude of deorbiting or drop-off altitude, (d) varying propulsion types e.g. mix of chemical and electric propulsion. The designed tool is a simplified form of a CDF (concurrent design facility) and based on its trade-offs, which it performs autonomously, it can yield an "approximate" servicer design on completion e.g. overall servicer mass, fuel tank sizing, reaction wheel sizing, etc.

It does this by using ELSA-d [1 - 6] as a baseline for estimating core equipment, scaling the system as necessary, and in some cases "choosing" equipment from an equipment database (based on supplier data) to come up with a very initial concept of a mission. In no way does the tool design a full mission baseline – it only provides high level analysis to infer key aspects of a mission.

The tool, also containing both non-recurrent and recurrent satellite and business costs models, can also then be used to examine price points for the servicer vehicle, full service and to the business.

A key driver in providing a service to constellation providers is to achieve an attractive price point that is profitable to AS but acceptable to our customers. Constellation providers expect a low price point, compared to conventional missions. The trade-off tool is thus important to AS's business in being able to infer mission solutions that are at the lower price points. AS can also work with launch providers to examine opportunities for price reduction (especially if there are a large number of servicers) and examine supply chain investment to bring down the overall cost of the supply chain and thus final mission cost.

Analysis with the tool has yielded that a 3-client removal service is optimal for AS, and is the case being studied in this paper. However, as key business criteria (e.g. customers, suppliers) are constantly evolving, this does not mean that this is a final design that AS has selected to move forward with.

3. Mission CONOPS

As part of ELSA-OW development activities AS are considering both the design of a Full Service Mission (FSM) and an in-orbit demonstrator (IOD). The FSM is the final service that would be offered to a customer. The IOD is a demonstrator that is needed as a bridge between ELSA-d (designed to mature key capabilities) and the FSM. It is planned to use the same servicer vehicle, where possible, between the FSM and IOD. Therefore, the vehicle needs to be capable of providing a lean ADR service, yet also being able to perform demonstrations necessary in the IOD.

The key differences between the IOD and FSM are thus as follows:

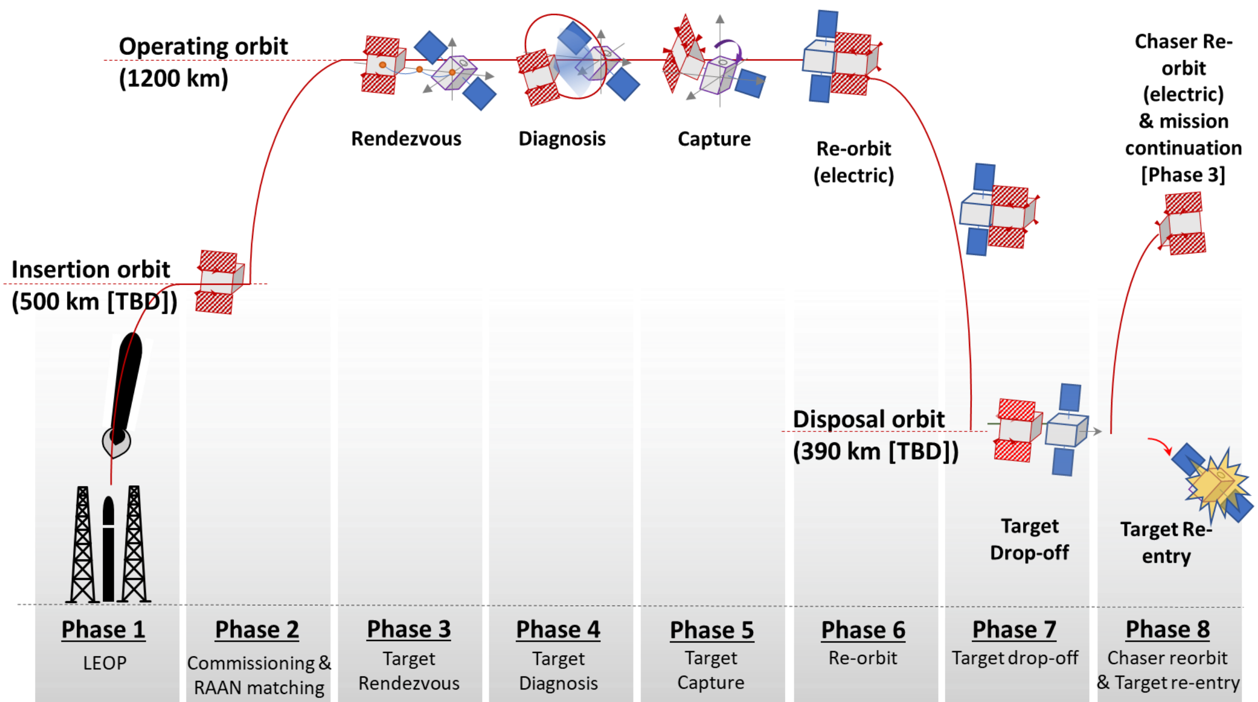

Figure 1 – Mission CONOPS

- The FSM operates at the customer operating orbit (likely 1200 km). The IOD is likely to be undertaken at the 500 km.
- The FSM intends to removal actual customer clients. The IOD will use a representative customer constellation satellite client for demonstration purposes only and may not proceed to de-orbit the client.
- The FSM would execute a multi-client removal in a lean approach. The IOD will instead use the available fuel to re-test demonstration sequences from ELSA-d to solidify confidence in RPO with the representative customer client.

The mission CONOPS for the ELSA-OW Full Service Mission (FSM) can be seen in Figure 1; the IOD mission CONOPS are not considered in this paper.

In this scenario we consider a multi-client scenario for 3 clients at 1200 km, with initial insertion at 500 km. Here, the servicer is inserted at the insertion altitude, raises to the operational altitude, captures a client, brings to down to a lower altitude and drops it off (for uncontrolled re-entry) and increases orbit again to go after another target. The servicer is designed to repeat this process for up to 3 clients before it finally de-orbits itself.

The mission CONOPS is subject to change and designed in a fluid manner that give operators the final decision in spacecraft operations, and making up-to-date decisions about undertaking demonstrations based on satellite health and performance.

Phase 1 to 2: Launch, LEOP and Commissioning

The servicer is deployed at a low insertion altitude of around 500 km (TBD). The low insertion altitude ensures that in the unlikely event that the servicer is inoperable following insertion, its orbit will naturally decay causing it to re-enter Earth's atmosphere within 25 years in the worst case.

Following separation form the launch vehicle the spacecraft autonomously performs initial switch on and booting of the primary Bus OBC. Following initial contact with the ground segment, the commissioning phase commences checking out the subsystems critical to the safe operation of the platform.

Due to the difference in altitude between the insertion and operational orbit (where the client is), it is expected that the ascending node (RAAN) of the servicer orbit will drift with respect to that of the client at a rate of approximately 0.07°/day in Westerly direction (TBD) following orbit insertion. The servicer spacecraft will need to perform RAAN matching in order to ensure rendezvous with the client is in the correct plane. Based on these orbital assumptions, the duration of this RAAN drift phase is just short of 7 months per plane.

The servicer performs orbit raising to reach the operational orbit with the client. At the conclusion of the orbit raising phase, the servicer reaches the "First Aim

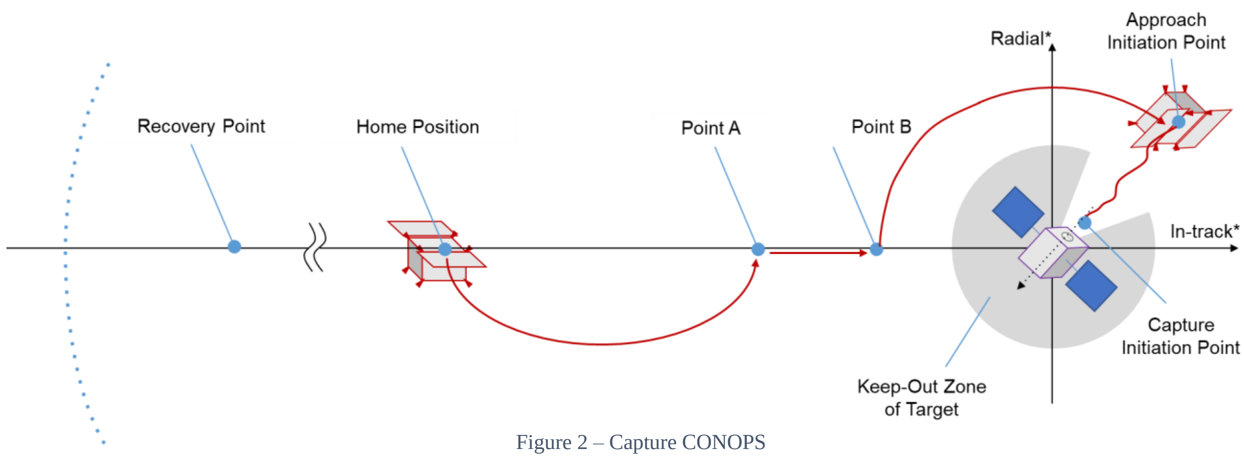

Figure 2 – Capture CONOPS

Point", which is the staging point for the subsequent manoeuvres required to achieve latter rendezvous.

Phase 3: Client Rendezvous

In Phase 3, the servicer performs RPO (rendezvous and proximity operations) with the client to the point where the servicer is operating under relative navigation with the client.

Firstly, on reaching the "First Aim Point", the servicer performs a sequence of operations that gradually brings the servicer closer to the client using absolute navigation until it is within the range of the servicer's long-range sensors

The key to long-range approach is determining the client orbit with a sufficient degree of accuracy. The manoeuvres are planned from the ground using orbit data from an SSA provider (see later) and the servicer's on-board GNSS receiver.

On client acquisition, the servicer transitions to angles-only navigation (AON). Manoeuvres then take place to align the orbits of servicer and client and a handover to relative on-board navigation takes place which allows the servicer to position itself at a predefined waypoint at close range to the client.

Phase 4: Client Diagnosis

The servicer performs a fly-around in day to inspect the client. Client inspection is a key capability where the operators will analyse the client and make a go/no go decision on capture. Several key aspects of the client's condition must be examined including: tumble rate (compared to apriori SSA-based estimates), physical damage to the client, status of the docking plate, analysis of residual client functions.

Phase 5: Client Capture

This phase is dynamically complex and is where full tumbling capture is performed. The capture process is the same as ELSA-d using Astroscale's magnetic capture system [1, 2, 6] and a docking plate (see later).

The key parts of the capture are shown in Figure 2. The servicer has the ability to position itself at set distances behind the client, which are defined as specific holding points (these include for example Home Position, Point A, Point B).

Firstly, analysis is done on the client attitude rate. Downloaded sensor data is processed on ground by the Image Processing System (IPS) and the Flight Dynamics System (FDS) in the Mission Operations Centre (MOC) to determine the projected target attitude and tumble rate.

In the principal capture stages, the servicer goes in for capture utilising the docking plate on the client for guidance. There are several sub-phases of the final capture including: client tracking; target marker acquisition; velocity, position and roll synchronisation.

Finally, before the magnetic docking, the go / no go status of servicer is checked by the operators. For "go", the servicer is commanded to go for final approach. The servicer then approaches the client via an approach corridor (a half-cone boundary extending out from the docking plate) arriving at the Capture Initiation Point. Once a successful grab has been confirmed, the capture mechanism is autonomously commanded to firmly hold the client.

Phase 6 to 8: Re-orbit, Drop-off & Continuation

In Phase 6, the servicer performs a re-orbit manoeuvre to reduce the client altitude. In the multi-client scenario, this is point at which the client is dropped off for an uncontrolled re-entry (Phase 7). Following release of the client, the servicer performs a short impulsive burn to separate itself from the client and to avoid risk of collision with the client.

Finally, in Phase 8, the servicer will re-raise its orbit to a nominal altitude (e.g. 550 km) in order to mitigate the increased atmospheric drag encountered at low altitudes and to manage the rate of RAAN drift. From there it can proceed to the next client (Phase 3 onwards again).

4. Mission Capabilities & Innovation

Some of the key innovations, which enable active debris removal sequences to be performed, include:

4.1. Capture System

Astroscale's capture system enables magnetic capture of tumbling objects using a specialized capture mechanism. The technology improves on the shortcomings of both tethered systems (tether dynamic issues, complexity / jamming of a reeling mechanism, difficulty in controlling client attitude) and robotic systems (degree of complexity, cost). The system has a set of small concentric permanent magnets which are extended and retracted using a mechanism to allow connection with the docking plate on the client. Once it attaches to the docking plate, the capture system can also release when desired using an internal mechanism that slowly pushes the docking plate away. This enables repeated docking and undocking cycles.

4.2. Docking Plate

The DP is part of Astroscale's rendezvous suite, providing a point of contact on the client for a magnetic capture system, and also provides an optically controlled surface for GNC. The DP turns the capture into a semi-cooperative case, compared to the more complicated uncooperative case. It provides distinctive features that make a defunct satellite easier to identify, assess, approach, capture, and de-orbit, thus minimising future costs of removal. Specific characteristics of the Astroscale DP which facilitate navigation and capture include: optical markers for guidance and navigation in proximity operations, a flat reflective plane for precise distance and attitude measurement, and ferromagnetic material suitable for magnetic grappling concepts.

5. Supply Chain & External Services

This section will address aspects of supply chain and procurement for the planned missions.

5.1. Supply Chain and High-Volume Analysis

Astroscale presently is planning to develop a European supply chain towards facilitating the high-volume production of servicing vehicles. The scale of the supply chain, and the number of servicers to be produced is a complex factor of the future failure rate of constellation satellites. From [7], initial approximations show that the accessible ADR market is upwards of 6,000 satellites in the next decade. At an average failure rate of between 4.3% and 15.6%, there are an estimated 20-100 satellites per year that could be removed from orbit by end-of-life services by Astroscale. Even at the lower end of estimates, AS must prepare for high volume production and ensure its suppliers are ready for that level of demand.

Suppliers must also be chosen to comply with geo-return considerations, so in-depth analysis is required to consider supplier country in mission development.

5.2. External Services

This mission requires an array of external procurements including launch, ground stations, SSA providers. AS believes SSA / SST services are a fundamental part of on-going services, like ELSA-OW. The need for SSA stems from the requirement to have the following services:

1. Pre-services e.g. tumbling rate estimation, failure detection from ground.
2. Initial approach & contact observation (providing target altitude / attitude / uncertainty ellipse).
3. Independent monitoring for transparency for external entities (e.g. government) & international confidence and trust building measures.
4. External advisory for CAMs including during de-orbit phases.

6. Conclusion

This paper has examined key aspects of the ELSA-OW mission premise, including business analysis and architectural trade-offs, CONOPS development, mission innovation and supply chain.

ELSA-OW (End of Life Services by Astroscale – OneWeb), under the ESA Sunrise programme, is a concept for future active debris removal servicing with a representative large constellation entity, designed for addressing a wide range of future customers. ELSA-OW extends the capabilities of ELSA-d (due to launch in 2020) towards multi-client ADR.

The ELSA-OW mission would be the first commercial time active debris removal (ADR) is being tested in space, in LEO, with a representative constellation customer.

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