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Beyond ELSA-d – Developing Commercial Viability of Multi-Client Servicing with ELSA-M

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Abstract

Large commercial satellite constellations in low Earth orbit (LEO) provide essential services but increase the number of objects in key orbits. This raises the risk of further debris creation and could ultimately make these orbits unusable for future generations. Commercial services for post-mission disposal are widely encouraged through government and agency policies (such as ESA's Zero Debris policy) to maintain the safe use of LEO orbits for the benefit of humankind.

Astroscale launched its End-of-Life Services by Astroscale – Demonstrator (ELSA-d) mission in March 2021 to perform in-orbit demonstrations of core Rendezvous and Proximity Operation (RPO) capabilities necessary to achieve debris removal. The successor Multi-Client mission, ELSA-M, will build upon ELSA-d to develop a service which can remove multiple clients. It involves sequentially moving to clients, docking with them via a prepared docking plate interface, lowering their orbits, and facilitating their uncontrolled re-entry before moving on to the next client. ELSA-M is commissioned and developed by Astroscale Limited in the Sunrise Public-Private Partnership Project, part of the European Space Agency's (ESA) Advanced Research in Telecommunications Systems (ARTES) programme and based on funding provided to Eutelsat OneWeb by the UK Space Agency via ESA. The programme has been in development since 2018 and is currently progressing towards Critical Design Review.

This paper explains the critical technical developments (space segment and ground segment) that have been required to mature from ELSA-d to the ELSA-M commercial servicer. Details are provided on the following mission enabling elements: a concept of operations to realise the capture of a OneWeb client spacecraft; the RPO sensor suite to support short-range and long-range RPO manoeuvres; Guidance Navigation and Control and Computer Vision algorithms essential for supporting closed-loop RPO manoeuvres; Astroscale's magnetic capture system to ensure safe docking and compatibility with client spacecraft; supporting ground segment capabilities, such as the Flight Dynamics System to determine the position and the orientation of satellites; and the operations support required to plan and execute manoeuvres in-orbit.

This paper provides further details on how Astroscale has approached enabling services, such as insurance, regulation, and policy, which in some instances are being addressed for the first time for debris removal services.

The ELSA-M in-orbit demonstration is planned to launch in early 2026 and will be the world's first prepared satellite debris removal mission conducted with a full-sized representative constellation customer in OneWeb.

Keywords: End of Life, Active Debris Removal, ELSA-M, Rendezvous Proximity Operations, In-Orbit Servicing

Acronyms/Abbreviations

CAM	Collision Avoidance Manoeuvre
CAPSYS	Capture System
CoM	Centre of Mass
CONOPS	Concept of Operations
CP	Chemical Propulsion
CV	Computer Vision
ELSA	End-of-Life Services by Astroscale
ELSA-d	ELSA – Demonstrator
ELSA-M	ELSA – Multi-Client
EoL	End-of-Life
EP	Electric Propulsion
FOS	Flight Operations System
GNC	Guidance Navigation and Control
IOD	In-Orbit Demonstrator
IOS	In-Orbit Services
LEOP	Launch and Early Orbit Phase
LIDAR	Light Detection and Ranging
LRF	Laser Range Finder
RPO	Rendezvous and Proximity Operations
SQM	Structural Qualification Model
SSA	Space Situational Awareness
TMA	Target Marker Acquisition
VISCAM	Visible-Range Camera

1. Introduction

Since the dawn of the space era, the number of debris generated in Low Earth Orbit (LEO) has been steadily increasing. Recently, plans for large constellations in LEO mean that the number of satellites in key orbits will increase at an unprecedented rate. In 2022, a record 2,409 new tracked payloads entered orbit and currently, over 30,000 individual pieces of space debris larger than 10 cm have been identified, with more than half of them in LEO [1].

The dangers posed by human-created orbital debris are well documented, and there is broad consensus that, if left unchecked, such debris poses a significant threat to the future of space activity. Even if no further launches occur, collisions between existing space objects will continue to drive the growth of the debris population, unless services to remove debris from orbit are implemented (see Figure 1).

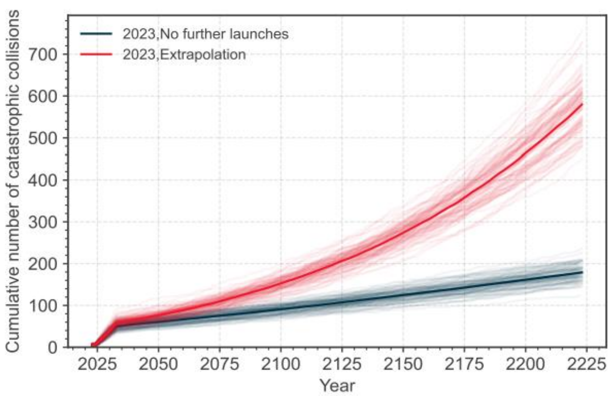

Fig. 1. Number of cumulative collisions in LEO (<2,000 km) in the simulated scenarios of long-term evolution of the environment. Credit: ESA [1].

The growth of large LEO constellations, shown in Figure 2, is a significant contributor to the object population in LEO. The companies that own and operate these constellations are highly incentivised to keep their orbits safe and clear, as a single collision could have significant impact on the operation of the constellation and greatly increase the number of Collision Avoidance Manoeuvres (CAMs).

Astroscale was founded in 2013 with the vision to ensure the safe and sustainable development of space for the benefit of future generations. The global team is dedicated to remediating the space debris problem with commercial In-Orbit Services (IOS) such as active debris removal, end-of-life removal, life extension, refuelling, in-space transportation, in-orbit assembly, and manufacturing, which can be realised utilising common capabilities and technologies.

1.1 Mission Premise

Astroscale's ELSA-M (End-of Life Services by Astroscale – Multi-Client) mission provides an End-of-Life (EoL) IOS to de-orbit inactive LEO spacecraft fitted with a ferromagnetic docking interface. The client spacecraft would nominally perform de-orbit manoeuvres independently upon mission completion. However, a proportion of these spacecraft will fail during their lifetime and be unable to do so. In these instances, an ELSA-M servicer will dock with the client spacecraft and remove it from congested orbits where they pose a space debris risk to other spacecraft. This service improves the sustainability of space operations, benefiting all users and particularly large LEO constellation operators who may have hundreds or thousands of assets in the same orbit as a failed client.

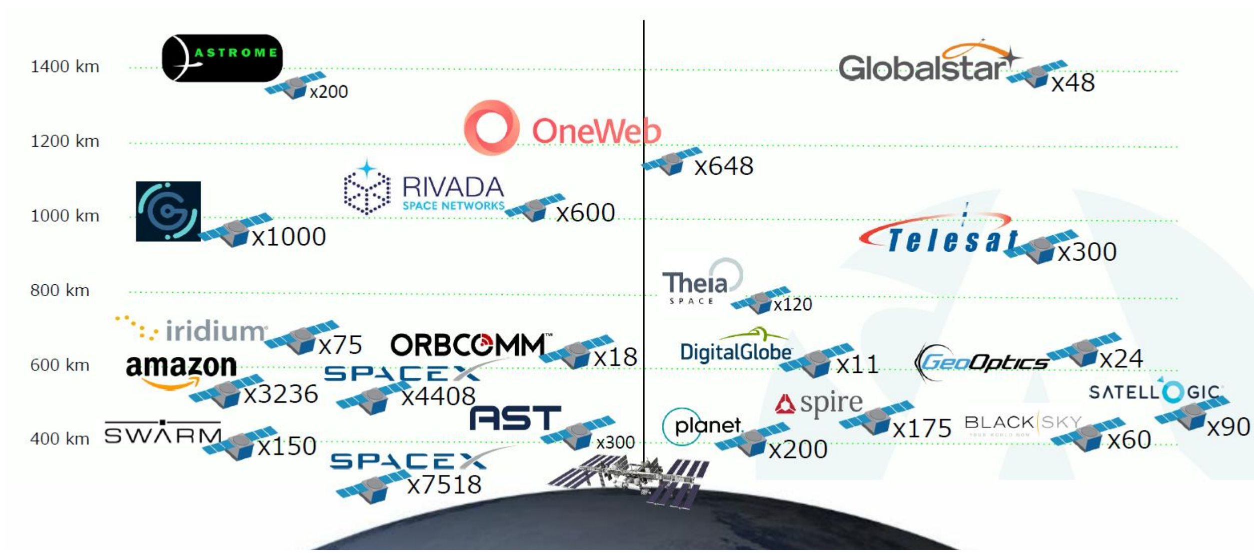

Fig. 2. Constellation growth in LEO

ELSA-M builds on the heritage of the ELSA-d mission. The ELSA-d stack was launched from Baikonur on 22 March 2021 to an approximately 550 km, circular sun-synchronous orbit. It consisted of two spacecraft: the servicer demonstrator and its mock-client. Initially, the two were attached, and once commissioned on-orbit, the client was released and re-captured as part of an in-orbit demonstration of autonomous Rendezvous and Close Proximity Operations (RPO). More details on the ELSA-d mission can be found in J. Forshaw 2022 [2].

ELSA-M expands on the technological development of ELSA-d and will be the world's first EoL service for a full-sized commercial end customer. The first ELSA-M will rendezvous with multiple satellites, capture a client that has reached its end of life, lower its orbit, and ensure timely atmospheric re-entry. Subsequent ELSA-M services will be capable of removing multiple clients in a single mission.

1.2 Partnership for Commercial Sustainability

ELSA-M is commissioned and developed by Astroscale Limited (Astroscale UK) in the Sunrise Public-Private Partnership Project, part of the European Space Agency's (ESA) Advanced Research in Telecommunications Systems (ARTES) programme and based on funding provided to Eutelsat OneWeb by the UK Space Agency via ESA. OneWeb, a large constellation provider with 648 satellites in LEO, has satellites both in need of servicing and equipped with a ferromagnetic docking plate interface to enable capture.

By preparing its spacecraft with docking interfaces, OneWeb has signalled its commitment to being a responsible space operator. This preparation greatly simplifies the servicer needed to remove them from orbit, reducing both the risk and cost of the service compared to an unprepared client, which would require a more complex capture mechanism.

The first ELSA-M mission, for which the Structural Qualification Model (SQM) is shown in Figure 3, is planned to launch in early 2026. This mission will break new ground in EoL technologies by removing a OneWeb client at its end of life, rather than a demonstrator object. This mission will establish Astroscale's commercial EoL offering and positions the company to lead the global effort toward sustainable space operations, making satellite servicing a standard operation in the near future.

1.3 Paper Structure

This paper starts by explaining the critical design differences between ELSA-d and ELSA-M, highlighting the added complexity of a multi-client mission and how the mission design is driven to ensure commercial viability. Further details are then provided on the specifics of the ELSA-M concept of operations (CONOPS) and some of the major space and ground segment elements: the RPO sensor suite, the Guidance Navigation and Control (GNC) and Computer Vision (CV) architecture, the capture system, operations, and relevant Space Situational Awareness (SSA) services.

Conclusions are provided, commenting on the next steps toward commercial viability and the further exploitation of technology and capabilities to develop new IOS concepts.

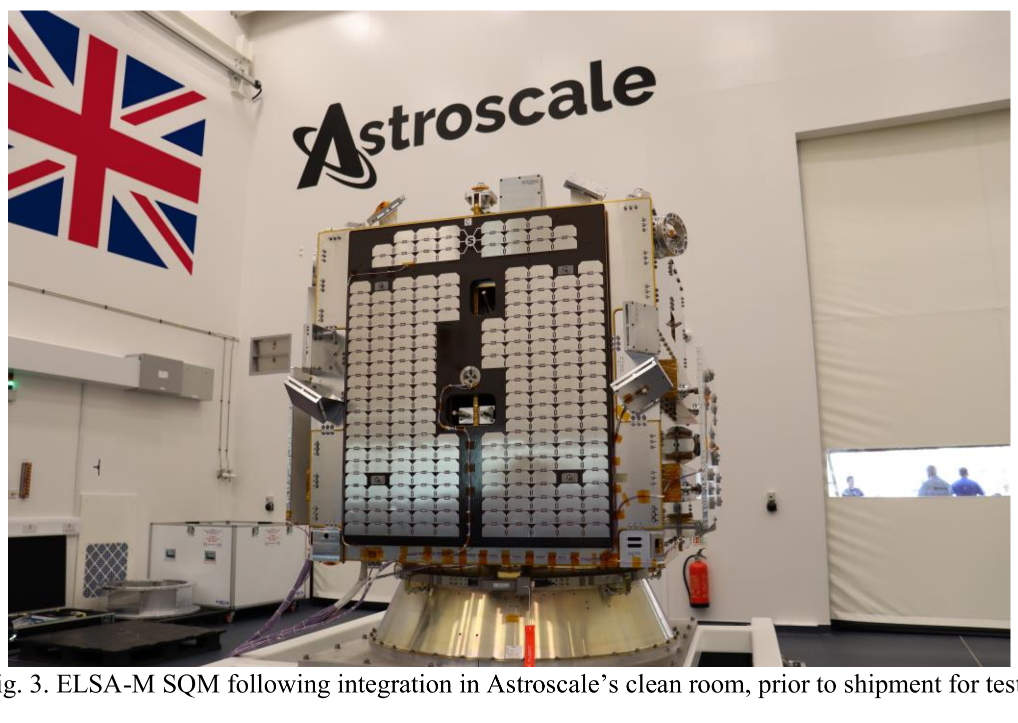

Fig. 3. ELSA-M SQM following integration in Astroscale's clean room, prior to shipment for testing

2. From Demonstrator to Multi-Client Mission

2.1 ELSA-d Overview and Key Accomplishments

ELSA-d, shown in Figure 4, had a servicer mass of 175 kg and was launched attached to a mock-client (seen on top in this stacked configuration) with a mass of 17 kg. ELSA-d was launched in March 2021 by Soyuz from Baikonur to a ~550 km orbit to ensure the demonstration mission's safety. This mission was internally funded by Astroscale and delivered with a range of partners, including space and regulatory agencies, and was licensed by the UK Space Agency.

Fig. 4. ELSA-d under environmental testing with the client stacked on top of the servicer.

Despite experiencing challenges due to thruster failures, as discussed in J. Forshaw 2022 [2], ELSA-d achieved the following key accomplishments:

- Successful development of regulatory and insurance considerations, laying the groundwork for future IOS activities.
- Successful in-flight validation of Astroscale's magnetic capture mechanism.
- Successful closed-loop control and station keeping using on-board relative navigation sensors.
- Ability to undertake a long-range approach and rendezvous even under contingency conditions with reduced propulsive capability.
- Successful transition from absolute navigation to relative navigation operating regimes.
- Successful operations over multi-ground station consecutive (dual and triple) passes with minimal gaps in commandability.
- Synchronized operations of two spacecraft while in simultaneous communication with the spacecraft team in Astroscale Japan, SSTL spacecraft team in London, and multiple ground station providers.

2.2 Proving the Commercial Business Case

Despite developing and verifying key enabling capabilities and technologies, ELSA-d did not demonstrate how EoL services could be commercially provided. To achieve this next step, Astroscale developed ELSA-M, driven by key business case requirements. ELSA-M targets the growing population of large LEO constellations as the first-adopter customer base for EoL services, due to their vested need in maintaining clean and operational constellation orbits.

It must be noted that whilst the first ELSA-M mission will be conducted in partnership with OneWeb to remove one of their satellites, it is designed with a broader set of clients in mind. From certain points of view, other clients drive the design requirements, rather than OneWeb.

LEO constellation clients are much larger than the mock-client used in ELSA-d (17 kg). To encompass the clients assumed in the business case, ELSA-M has been upgraded to handle prepared clients up to 800 kg in mass. Additionally, ELSA-M is designed to achieve multiple de-orbits in a single mission. Both factors result in an increase in platform mass, but also in its capability to deliver a commercially viable service.

ELSA-M is required to travel to much higher altitudes than ELSA-d to meet the demands of the business case. The ELSA-M servicer will need to move across altitudes from low LEO drop-off altitudes up to high LEO (1,200 km+). As such, ELSA-M must be designed for higher radiation exposure and longer mission lifetimes.

To achieve a robustly designed ELSA-M mission, at a price point suitable for the EoL market, Astroscale must develop a strong supply chain while progressing with its first mission. The ELSA-M supply chain is primarily European, with a UK focus, and Astroscale's procurement team has worked with key partners to provide supply assurance for the delivery of the commercial business case.

Further details on the ELSA-M design are provided in the following sections, highlighting the critical technical developments that enable the mission.

3. ELSA-M CONOPS

Several factors constrain the platform design and the concept of operations for an EoL commercial mission that aims to service multiple client satellites. The most challenging part of the mission is the RPO. During this phase, the servicer must generate enough power to support the intensive use of its GNC sensors and propulsion system. In addition, the servicer must be able to downlink visual information about the client and receive commands from the ground station before capture.

To ensure a successful capture without damaging the servicer or the client, and to avoid amplifying the tumbling motion of either spacecraft, the servicer's centre of mass must be controlled precisely, and the inertial properties of both satellites must be known. After capture, the client could potentially shadow the servicer's solar arrays during de-orbit, which is another power-intensive operation. Balancing servicer mass is crucial, requiring the right balance of chemical propulsion (CP) for high impulse operations (such as matching the tumble rate and orientation of the client or detumbling the servicer–client stack) and low impulse operations (such as orbit changes), while also minimising the total service time. This type of mission profile is highly constrained and the CONOPS solution that Astroscale is developing is discussed here.

When describing the CONOPS for ELSA-M, it should be noted that the first ELSA-M mission will be conducting demonstrations in-orbit before capturing the full-sized client, making it non-standard compared to the CONOPS of future ELSA-M servicers. The first mission has the following main phases:

- Phase 1: Launch and Early Orbit Phase (LEOP)
- Phase 2: Commissioning and Checkout
- Phase 3: Phantom Fly-around (Demo 0)
- Phase 4: RAAN Matching and Orbit Raising
- Phase 5: Demos 1-3 with Client 1
- Phase 6: Orbit Raising
- Phase 7: Capture of Client 2
- Phase 8: Orbit Lowering
- Phase 9: Client 2 Release and Servicer Passivation

These phases can be seen in Figure 5 detailing the mission CONOPS. An initial version of the CONOPS was presented at IAC in 2021 [3]. As depicted, the first ELSA-M servicer will interact with two OneWeb clients. The servicer will perform a series of demos with an active OneWeb satellite, Client 1, in preparation for the capture of Client 2, a OneWeb Gen 1 satellite at its end of life. These demonstrations are crucial for building customer confidence and paving the way for commercial viability.

3.1 Detailed Description of First ELSA-M CONOPS

3.1.1 Phases 1-4

Phases 1-3 start with the ELSA-M servicer being injected into a 480 km circular orbit at an inclination of 87.5° (corresponding to the inclination of Client 1). Following the full commissioning of the ELSA-M servicer, the first demonstration (Demo 0) will be performed. This demonstration involves validating

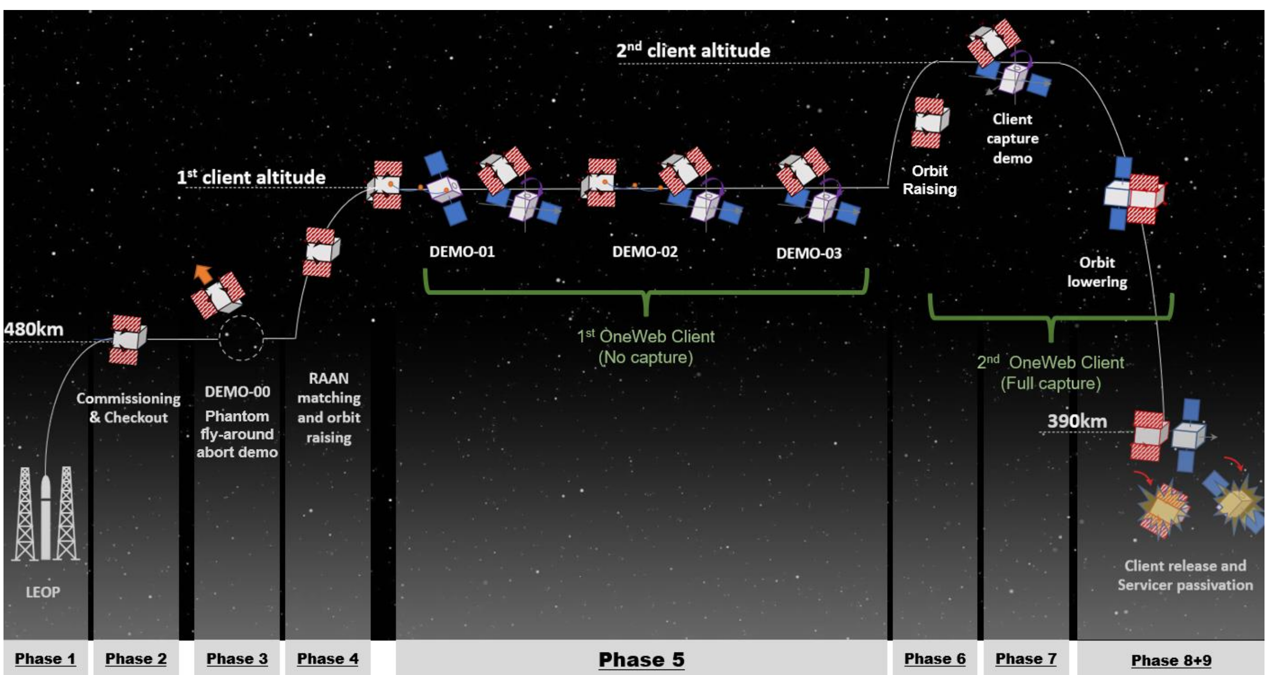

Fig. 5. ELSA-M Servicer Concept of Operations

safety-related abort capabilities early in the mission by performing an abort around a phantom client. In Phase 4, the ELSA-M servicer will first perform RAAN matching and then perform its first orbit raising to 580 km, where Client 1 is located.

3.1.2 Phase 5 – Demos with Client 1

Phase 5 then commences as the ELSA-M servicer initiates Demo 1 with Client 1. The servicer will perform rendezvous and bring itself to 30 m behind the client at a point called Home Position.

For Demo 2, Client 1 will be controlled to a fixed attitude state in a nadir orientation, eliminating the need for tumble rate assessment. The ELSA-M servicer will directly proceed with proximity operations until the final approach. Once the servicer has partially completed the final approach trajectory, it will trigger a retreat manoeuvre, moving to a position 10 m behind the client, concluding the second demo.

For Demo 3, Client 1 will adjust its attitude slightly to an off nadir pointing (= nadir + offset). To validate the servicer's inspection manoeuvre capabilities, the servicer will perform a fly-around manoeuvre, maintaining a 10 m radius around the client's centre of mass (CoM). During this manoeuvre, the servicer will assess the client's state by taking pictures and providing inputs for further operations. After the fly-around is complete, the servicer will again perform proximity operations, starting with Target Marker Acquisition (TMA) where the Servicer will have to align itself with Client 1.

The servicer will then start the dance procedure, maintaining alignment with Client 1 as the client remains in LVLH + offset and then performs a slew manoeuvre. After a few minutes of dance, ELSA-M will autonomously trigger a planned active abort, moving away from Client 1.

3.1.3 Phases 6-9 – Capture of Client 2

Following the success of the in-orbit demonstrations with Client 1, Phase 6 commences. The ELSA-M servicer will perform a second orbit raising to match with Client 2, a OneWeb Gen-1 satellite equipped with a compatible Altius DogTag docking plate.

The servicer will then start Phase 7 which involves the full capture service: performing rendezvous with Client 2, conducting a fly-around to inspect and confirm the client's serviceability, conduct further pose estimation, and perform proximity operations until the client is captured.

Following docking, Phase 8 will start as the servicer lowers the orbit to 390 km while attached to the client. Once this orbit is reached, Phase 9 commences as the client will be released. At this point, the ELSA-M servicer will have completed its mission and will be passivated before performing an uncontrolled re-entry scenario.

The full duration of this first ELSA-M mission is expected to be around 21 months, achieving the world's first prepared satellite debris removal mission with a full-sized representative constellation customer, OneWeb.

Future ELSA-M servicers are expected to deorbit several clients in a single mission, which is critical to achieving commercial viability and meeting customer price expectations. The CONOPS for a future ELSA-M servicer mission is explained in the following section.

3.3 Future CONOPS for a Multi-Client Mission

Future ELSA-M missions are designed to service multiple clients. The number of clients a single mission can service depends on factors such as the relative operational orbits and client characteristics such as mass, volume, and tumbling rate. As an example, the CONOPS for a future 3-client mission is shown in Figure 6.

Similar to the first ELSA-M servicer, this future mission would start with Phase 1, focusing on LEOP and commissioning of the servicer. Phase 2 will follow

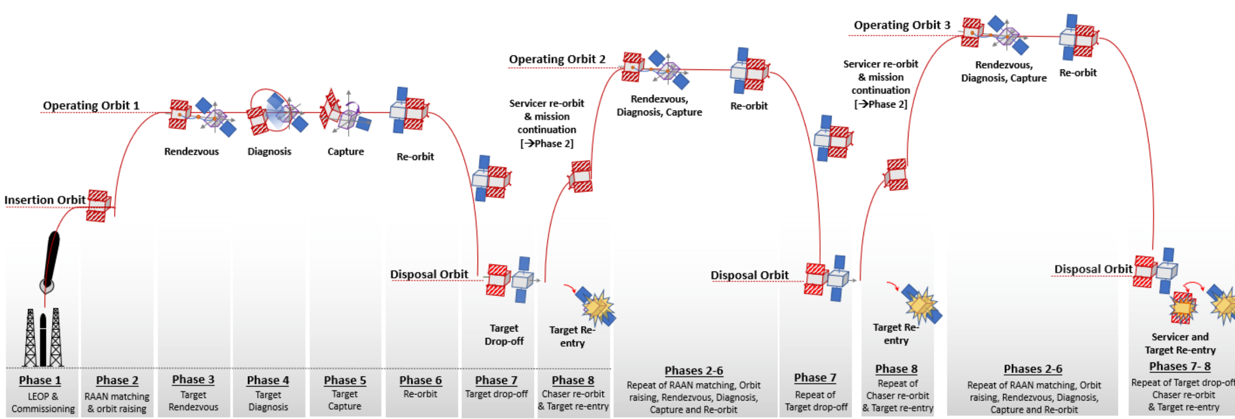

Fig. 6. CONOPS for an ELSA-M type mission with three clients

as the servicer will match the RAAN of its first client and will perform orbit raising. Phases 3-5 will focus on rendezvous, diagnosis, close proximity operations, and capture of the client. In Phase 6, the servicer will re-orbit the client before dropping it off in Phase 7.

Phase 8 signals the end of the first mission cycle, as the first client starts its re-entry while the servicer starts chasing the second client, repeating Phases 2-8 two more times. On the final de-orbit of a client, the servicer will remain in an orbit that allows rapid re-entry into Earth's atmosphere.

4. Docking Interfaces and Capture System

4.1 Docking Interfaces

To maximise Astroscale's share of the EoL market, the capture system on the ELSA-M servicer must be compatible with existing and future docking interfaces on client spacecraft. Without a prepared interface on the client, docking in a safe manner is more difficult and requires additional considerations. Historically, satellites have not been designed with IOS in mind, thus making potential servicing more complex and costly. Incorporating a docking plate into satellite designs is a low-cost and minimally intrusive method of preparing for and simplifying future servicing, whilst aligning with international best practices and guidelines.

To this end, Astroscale is currently developing its Gen 2 Docking Plate (Figure 7) which comes in three off-the-shelf heights (70 mm to 160 mm). All height variants can be easily integrated on future client spacecraft and, although fully compatible with the Astroscale servicer, the simple and lightweight design (less than 500 grams) is also compatible with an array of docking techniques, including robotic and magnetic capture, making it servicer agnostic. This interoperability provides clients with options and removes perceived barriers to adoption. The Docking Plate is designed with a flight lifetime of over 15 years to meet EoL servicing timelines.

Fig. 7. The Astroscale Docking Plate showcasing its three off-the-shelf heights

While the Astroscale Docking Plate is intended to be the future standard client interface for the ELSA-M capture system, the OneWeb client in the first mission uses a different docking interface, namely the Altius Dog Tag (Figure 8). The ELSA-M capture system is therefore designed to be compatible with both the Astroscale Docking Plate and the three client variants that use the Altius Dog Tag. The key difference between these variants in terms of interface with the capture system is the clearance between the docking plate and a nearby thruster.

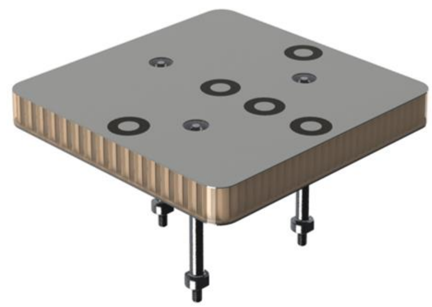

Fig. 8. Altius Dog Tag. Credit: Altius Space Machines Technologies [4]

4.2 The ELSA-M Capture System

The current Magnetic Capture System (CAPSYS) on ELSA -M consists of a mechanical unit component (CAP-M) and an electronics unit component (CAP-E). The CAP-E, designed and built by Astroscale, contains all electronic components to drive and provide logic to the operation of the motor actuators in the CAP-M. It will ensure that once brought within the capture range of the client spacecraft, the magnetic capture plate engages and holds the ferromagnetic docking plate affixed to the client and that the quality of the contact can be accurately and reliably determined. It will retain hold of the client to form a servicer-client entity during detumble and all subsequent re-orbit and collision avoidance manoeuvres, again monitoring the quality of the contact during these operations. Following the required operations, the CAPSYS safely releases the client and accurately detects the moment of release so that the servicer can manoeuvre away and continue with its mission.

Due to the safety-critical nature of several of the CAPSYS operations, particularly those that trigger the release of the client spacecraft, it is essential to ensure that power loss, spurious telecommands, or incorrectly formatted telecommands cannot inadvertently cause the mechanism to move.

Firstly, both mechanisms within the CAPSYS have 'power to release brakes', ensuring that in the case of power loss to the subsystem, no mechanism movement (and therefore no release of the client) will occur. Incidentally, this same braking scheme provides the

Launch Lock. Secondly, the CAPSYS employs an 'arm and execute' telecommanding scheme, requiring two telecommands to be issued in the correct order before a mechanism movement is executed by the CAP-E. This applies to all mechanism movements, not just those that are safety critical. Finally, the release of the client depends on the correct mechanism sequences being performed in the correct order, adding a further layer of safety against an accidental release.

The capture system on the ELSA-M is currently under development and will undergo validation testing as part of the flight qualification campaign.

5. Space Segment Developments

The space segment platform (Figure 9) is divided into two main parts:

- ELSA-M Payload: Contains the capture system.
- ELSA-M Bus: Contains the rest of the units that enable the mission and payload operation, such as GNC sensors, communication subsystem, propulsion, and solar panels.

5.1 GNC Subsystem Description

The GNC subsystem on ELSA-M has two parts:

- Subsystem components needed to maintain safe attitude and orbit control functions, excluding client-related operations.
- Sensor units required for RPO.

The control side of the ELSA-M GNC system consists of a standard hardware selection meant to enable inertial estimation and control of the spacecraft.

Fine attitude estimation is achieved through star trackers and gyros. Coarse attitude estimation is enabled by measurements from sun sensors, magnetometers, and gyros. This method of attitude estimation is less accurate due to the nature of the sensors and because none of them directly measure attitude. Coarse attitude estimation will be approximately one order of magnitude less accurate than fine estimation. The reason for having a dual-method approach of inertial attitude estimation is because the estimate from fine estimation is not always available due to star tracker blinding.

The actuators selected for the spacecraft attitude control are reaction wheels and magnetorquers. In addition, the ELSA-M platform uses a combination of Electric Propulsion (EP), and CP. CP is needed for the more energetic position changes during RPO, while EP is used for orbit raising and lowering. Hardware performance, mounting tolerances, and fuel consumption will mean that the thrust vectors do not perfectly align with the centre of mass, but it should be within the capabilities of the attitude actuators to cancel the disturbances induced from these effects.

5.2 Rendezvous and Proximity Operations Sensor Suite

There are three types of sensors used for the navigation solutions that are required throughout the RPO phases:

- VISCAMs (Visible-Range Cameras)
- LIDAR (Light Detection and Ranging)
- LRFs (Laser Range Finders)

The combination of GNC sensors has been selected to provide the necessary accuracy in the rendezvous, close approach, and proximity operations. Not all

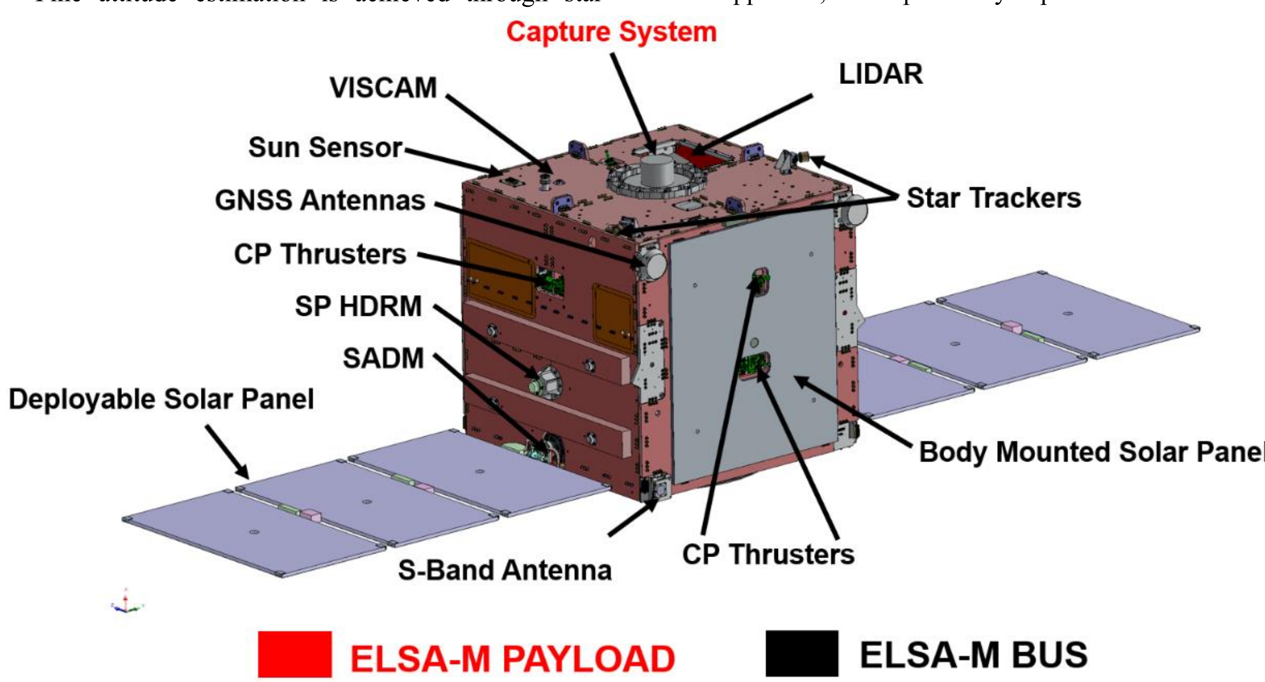

Fig. 9. ELSA-M space segment

sensors are used simultaneously, as their effectiveness depends on the distance to the client. Figure 10 provides an overview of the sensors used in each mission phase, while Figures 11-12 show the VISCAM and LIDAR units.

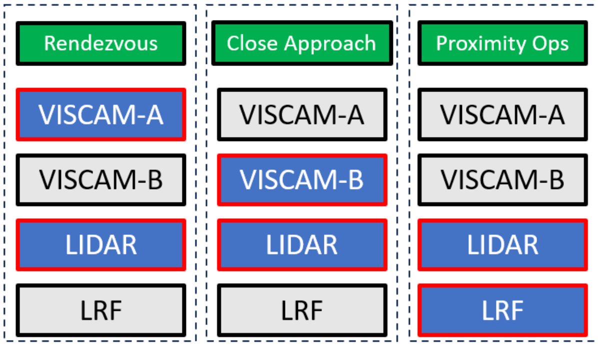

Fig. 10. Overview of sensors used in each mission phase (highlighted in red)

The *Rendezvous* phase happens several km away from the client, while the *Close Approach* happens in the range of hundreds to tens of meters. *Proximity Operations* unfold within a few meters of the client. Before any sensor-based navigation is implemented, the ELSA-M servicer will make use of SSA and GPS data to navigate in the vicinity of the client.

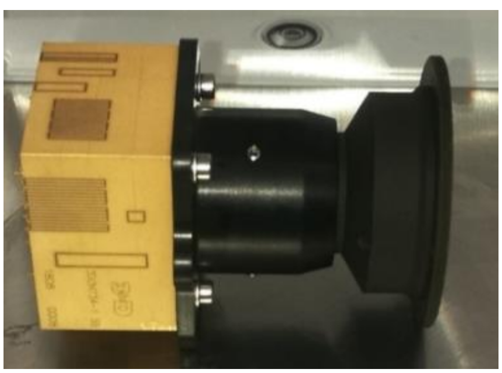

Fig. 11. Image of the VISCAM unit. Credit: APC Technology Group [5]

A LIDAR unit is used at close range within the constraints of a mission such as ELSA-M where the docking distance is minimal. Some of the operational constraints of the LIDAR unit are as follows:

- Close proximity on docking: when the servicer is docked to the client, the distance between the two closest panels is in the order of 100s of millimetres. As the LIDAR will also be at this distance, it must provide a navigation solution with a limited amount of the client features in its field of view, rather than the entire silhouette.
- Customer agnostic: as the service should be applicable to various customers, the LIDAR must be capable of identifying distinct features/shapes within the field of view at close range, regardless of the specific client spacecraft, while staying compliant with the navigation requirements.

The LIDAR system will be used for rendezvous, close approach, and proximity operations. The selected LIDAR is the Jena Optronik RVS3000-X (Figure 12) and has a point cloud density of 16000, a detection range of 0 – 1500 m for an uncooperative client, an FOV of 40° x 40° and a 2 Hz sample rate.

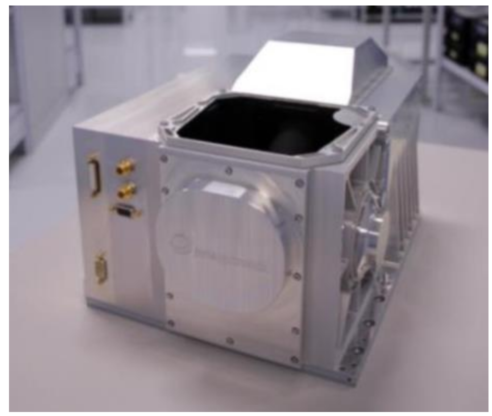

Fig. 12. Image of the LIDAR system. Credit: Jena Optronik [6]

It is a known feature of LIDARs that the range information that accompanies each point in the point cloud has noise in the order of 1 cm. It is important to note that range resolution may vary depending on the surface material properties of the client, which can mostly impact the LIDAR's attitude estimation capability.

5.3 Computer Vision Algorithms Constraints

The GNC Payload also hosts a CV algorithm that will allow 6 degrees of freedom (6-DoF) pose estimate of the client from LIDAR images on board. The images are taken from a space LIDAR unit, and the CV algorithms should start to work out relevant pose information from a distance where the LIDAR returns are sufficient to do so.

The ability of the servicer to achieve the navigation performance requirements depends on both the hardware selected and the computer vision software developed for it. Several factors affect the ability of the computer vision software to be compliant to the navigation requirement. On the hardware side, these factors include the density of the LIDAR point cloud as well as the field of view (FOV), minimum range, and sampling rate of the LIDAR. On the software side, these factors are the number and size of distinct features within the FOV of the LIDAR and the sources of spurious lighting reflections within the FOV of the LIDAR.

The CV algorithms will require the following to perform as required:

- A powerful enough on-board processor and sufficient memory to execute the algorithm programs.
- LIDAR images to be acquired in a relatively clean manner without significant blur and motion blur.
- Coordinate transformation between the LIDAR unit and the entire servicer to be known.
- CAD model provided to the CV algorithms to match the coarse geometry of the client with sufficient accuracy.

The CV tasks will differ depending on the distance between the servicer and the client's LIDAR unit. In developing the ELSA-M CV algorithms, four different range modes are used from Long Range to Short Range.

6. Ground Segment Developments

6.1 Ground Segment Design Overview

The ELSA-M Ground Segment will provide secure ground-based facilities to support the operations of the Astroscale ELSA-M servicer. It will support the entire lifecycle of the service and therefore must support multiple servicer spacecraft. Figure 13 presents a high-level system context view of the complete ground segment.

The approach taken for the ELSA-M ground segment design emphasizes the pragmatic re-use of the ELSA-d design where possible. The ELSA-d Ground Segment, as a demonstrator for follow-on programmes, has been designed with future re-use in mind, making it a logical baseline for the ELSA-M design.

Whilst the ELSA-d and ELSA-M spacecraft differ, the ground segment concept and design can be effectively reused, reducing both risk and cost to the overall programme. The alternative—is to design a new ground segment from scratch which would be less desirable.

The Ground Segment is composed of three high-level major systems:

- The Ground Communications System: provides the communication between the spacecraft and the ground-based operations. This consists of a network of Ground Station terminals (antennae) distributed around the Earth. These receive RF data from the spacecraft, passing it through as baseband telemetry to the FOS, and transmitting telecommands received from the FOS to the spacecraft in RF.
- The Flight Operations System (FOS): provides the main functionality to operate the spacecraft. It includes the various components to manage the spacecraft effectively and securely from ground. This includes monitoring and control, planning and scheduling, orbit and attitude monitoring, and various other elements to ensure the operations of the spacecraft. It also includes the ground-based systems to support the image processing, rendezvous, and capture of the client spacecraft.
- The SSA system: provides the ground-based observations for space debris, as well as active

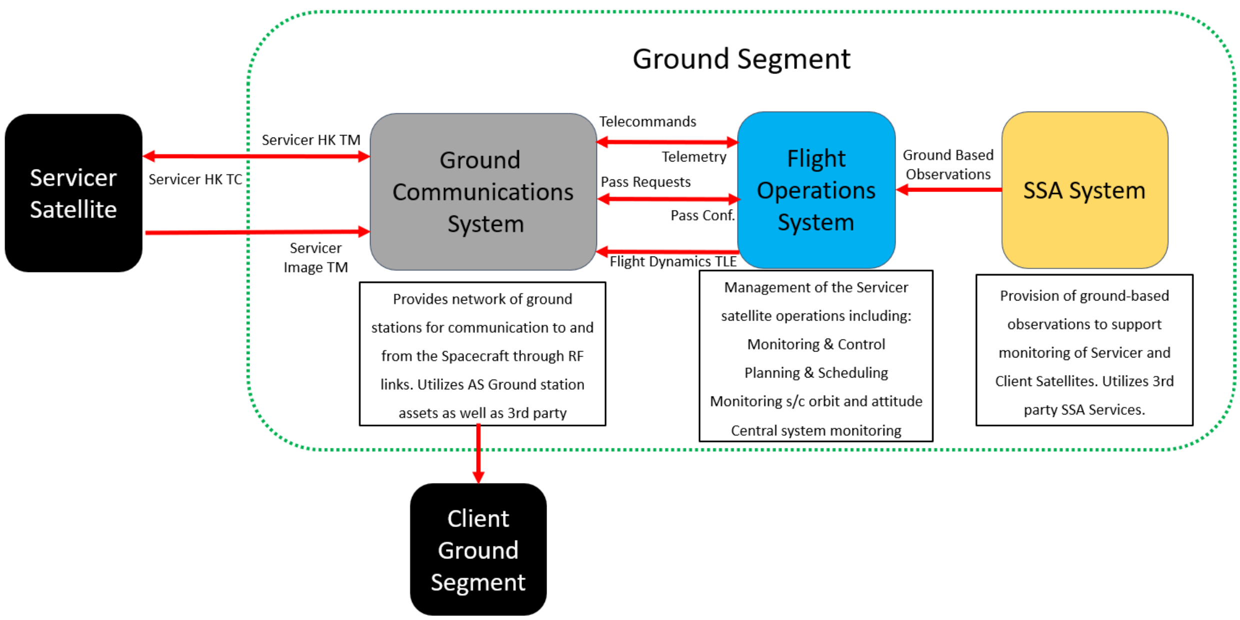

Fig. 13. ELSA-M Ground Segment High-Level System Context

spacecraft (servicer and client) to the FOS to support spacecraft control.

At a component level, changes are required to the ground segment due to differences in mission objectives. These must be addressed in the ELSA-M ground segment design. For instance, the ELSA-d servicer was not intended to perform far-out proximity and rendezvous with the client spacecraft, as both the servicer and client were launched together. In contrast, the ELSA-M ground segment must support both far-out proximity operations and closer proximity and capture operations. Two additional subsystems including the Visual Image Processing System and the AON and Pose Estimation System, are included within the ELSA-M Ground Segment design. Also, the ELSA-M concept requires support for multiple servicer spacecraft in orbit concurrently, whereas ELSA-d only considered one servicer and one client.

6.2 Future Ground Segment Developments

Based on the developments of the ELSA-M mission, Astroscale is planning to expand its operations and ground segment capabilities to allow for the operation of several concurrent missions. A priority in this expansion is the re-use of elements from the operation of the ELSA-d and ELSA-M missions to keep the costs of End-of-Life services provided by Astroscale competitive.

Two types of operations are defined for scaling up the ground segment operations:

- Critical Operations: LEOP, RPO, client release, servicer decommissioning, and servicer anomaly resolutions.
- Non-Critical Operations: all other nominal operations.

Given Astroscale's ambition to service several clients simultaneously and operate multiple servicers, the ground segment and operations configurations are being developed to allow non-critical operations to be automated and conducted for tens of missions simultaneously. In addition, when launching and operating numerous servicing missions, critical operations will need to be conducted for multiple spacecraft in parallel.

To support this expansion, Astroscale UK has established a new Mission Control Centre at its facility in Harwell, UK (Figure 14). Astroscale UK is also investigating utilising the IOS Control Centre in Harwell as a back-up and surge capacity facility for future operations. This was developed as a joint project between Astroscale UK and the Satellite Applications Catapult.

The concept utilises a UK-based cloud-based infrastructure, with a physical data centre hosted within the Zeus premises. The baseline is to use AWS cloud-based services to provide virtual hosted environments for all Ground Segment Software systems. AWS will host these services in the UK, offering complete support. Astroscale will design the virtual environments to ensure data redundancy, failover, and availability requirements. Through integration with the AWS environment, the Ground Segment is designed to be easily scalable, and it enables remote spacecraft operation.

Fig. 14. Astroscale UK Mission Control Centre

7. Conclusion

As this paper demonstrates, Astroscale UK has made significant technical advancements in developing ELSA-M, working toward delivering the world's first commercial solution for solving orbital debris. The development of an RPO-capable craft that can achieve the service at an achievable price point for large constellation providers is a non-trivial objective.

With ELSA-M, Astroscale takes a significant step toward its vision of the safe and sustainable development of space for the benefit of future generations.

The development of such technologies and capabilities, particularly in the provision of RPO services, positions Astroscale well (either independently or through partnerships) to unlock other in-orbit servicing concepts, such as refuelling, in-space logistics, and in-orbit assembly.

References

[1] ESA Space Debris Office, ESA's Annual Space Environment Report, GEN-DB-LOG-00288-OPS-SD, Issue: 7.0, 12th June 2023, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf (accessed 07.09.23)

[2] J. Forshaw et al., Operational Progress Update on the ELSA-d Debris Removal Mission, IAC-22 A6.5x69288, 73rd International Astronautical Congress, Paris, France, 2022, 18-22 September.

[3] J. Forshaw et al., Towards Commercial ADR Services: The ELSA-M Mission, IAC-21 A6.6.3.x64394, 72nd International Astronautical Congress, Dubai, United Arab Emirates, 2021, 25-29 October.

[4] Altius Space Machines Technologies, Technologies – Altius Space Machines (altius-space.com) (accessed 13.09.23)

[5] 3DCM739 3P Plus Space Camera Module, APC Technology Group, 3DCM739 - 3DCM734 (apctech.com) (accessed 13.09.23)

[6] RVS 3000 Data Sheet, Jena Optronik, 2022, RVS 3000-3D - LiDAR - Jena Optronik (jena-optronik.de) (accessed 13.09.23)