

The ELSA-d End-of-life Debris Removal Mission: Mission Design, In-flight Safety, and Preparations for Launch

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ABSTRACT

The novel End-of-Life Services by Astroscale demonstration mission (ELSA-d) mission promises to be a major step forward in demonstrating rendezvous and proximity operations (RPO) capabilities applicable to future debris removal services. ELSA-d assembly, integration and test (AIT) is presently ongoing and the mission is due to launch in 2020. It will demonstrate key technologies and procedures for the rendezvous, capture, and eventual de-orbit of a client satellite.

In this paper, some of the key technologies that will be discussed are rendezvous guidance, navigation, and control (GNC) and a magnetic docking mechanism, where the client satellite will be equipped with a docking plate (DP) which enables it to be captured. While cooperative rendezvous has previously been performed either manually or semi-autonomously, ELSA-d will demonstrate the first semi-autonomous capture of a tumbling client. This will be followed by a search and capture where the client satellite will be intentionally placed outside of the field of view of the relative navigation sensors on the servicer. In the paper, we will describe the use of a walking safety ellipse, a passively safe trajectory, and sensor scanning that will be necessary to safely track and capture a client that is not in the immediate vicinity of the servicer. In the context of the described technologies, the paper will broadly provide an overview of each phase of the concept of operations (CONOPS). As ELSA-d is finalized for its upcoming launch, the paper also provides the latest updates from Astroscale Japan's clean room.

With the rise of large satellite constellations in low-Earth orbit (LEO) – the number of satellites in key orbits will increase at a much higher rate than today, raising the risk of collision. Systematic spacecraft end-of-life (EOL) management strategies assuring post-mission disposal (PMD) are required to maintain the utility of key LEO assets. The technologies stemming from ELSA-d will lead to safe and effective solutions to maintain accessibility of LEO.

1. INTRODUCTION

ELSA-d, which stands for End of Life Services by Astroscale (-demonstration), is an in-orbit demonstration (IOD) for key end-of-life technology and capabilities of future debris removal missions [1-6]. In Astroscale (AS), end-of-life (EOL) and active debris removal (ADR) have the following distinction: EOL is concerned with removal of future entities that are launched with a docking plate (DP) for semi-cooperative removal, whilst ADR is concerned with removal of existing entities in space that do not have a DP and are fully non-cooperative. ELSA-d, due for launch in 2020, consists of two spacecraft, a servicer (180 kg) and a client (20 kg), launched stacked together. The servicer is equipped with proximity rendezvous technologies and a magnetic capture mechanism, whereas the client has a DP which enables it to be captured. With the servicer repeatedly releasing and capturing the client, a series of demonstrations can be undertaken including: client search, client inspection, client rendezvous, and both non-tumbling and tumbling capture. ELSA-d is operated from the UK at the National In-orbit Servicing Control Centre Facility, developed by AS as a key part of the ground segment.

The ELSA-d mission is an in-orbit demonstration that aims to test several capabilities and technologies needed for future services. The servicer and client can be seen in Fig. 1, showing renditions for both docked and undocked configurations. For the ELSA-d mission, the client, for convenience and mass-minimisation, is smaller relative to the servicer than a future EOL or ADR mission. The client is also commandable, ensuring demonstrations can be tested in a simplified manner earlier in the mission. For example, before tumbling capture is attempted, the easier case of non-tumbling capture is attempted which requires the client to hold a set attitude. Because the client is launched with the servicer, the CONOPS can be designed such that the complexity and risk increments gradually. This compares to a full service where the non-trivial task of finding the client would be among the first mission actions. The core constituents of the mission include a rendezvous (RDV) and docking suite and a magnetic capture system. Other elements include classical bus elements, such as power, propulsion, communications and processing.

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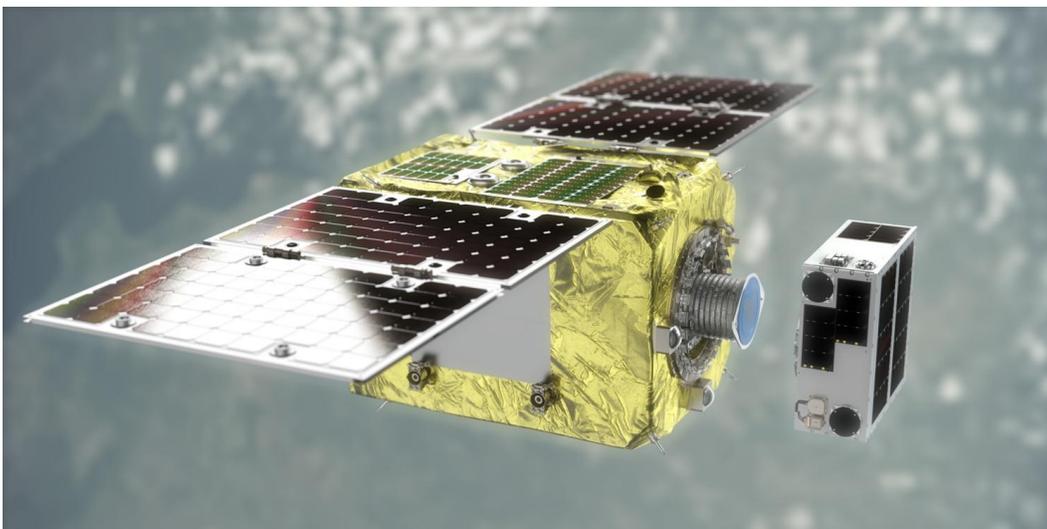
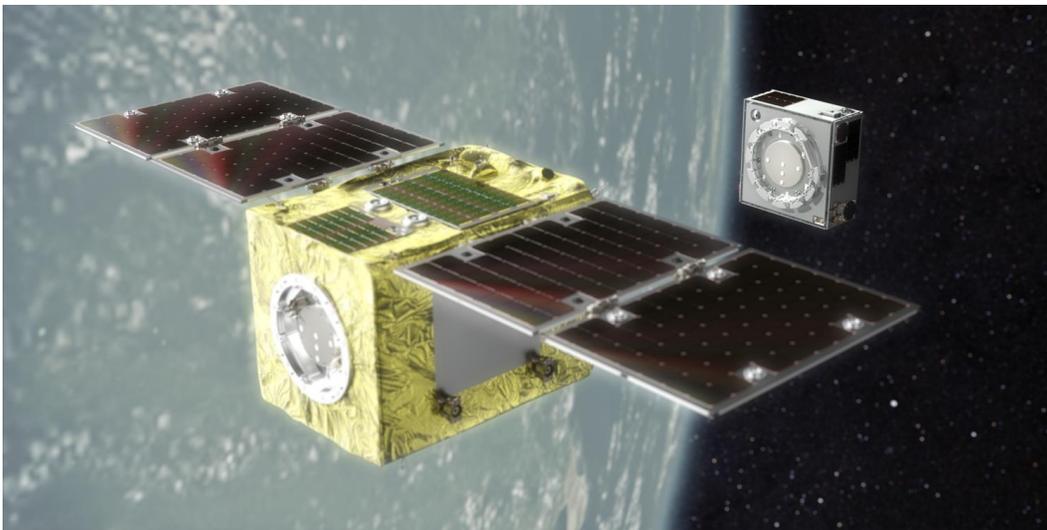
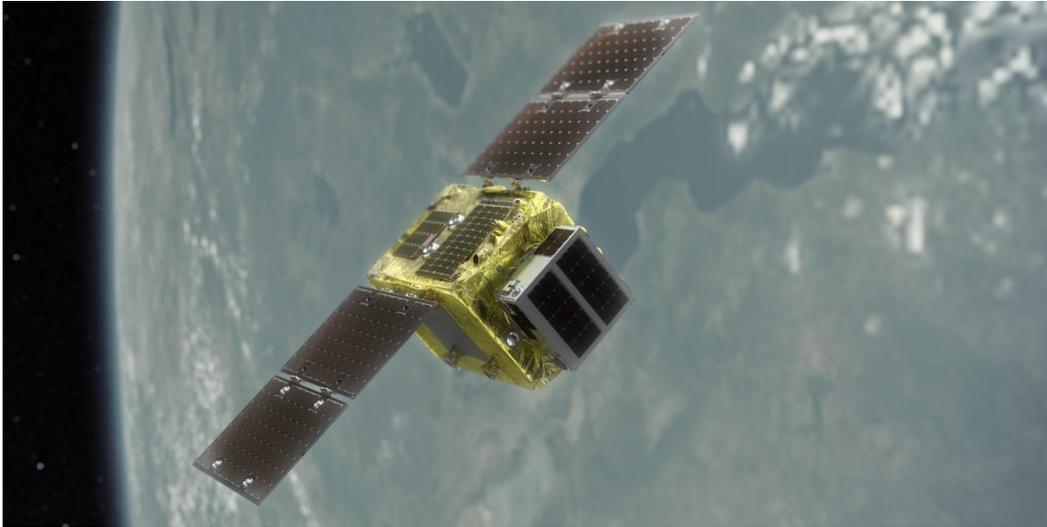


Fig. 1. **ELSA-d: Servicer and Client.** Top: servicer with attached client. Middle: release of client for a capture demonstration. Bottom: recapture of client with servicer capture system extended.

2. CONCEPT OF OPERATIONS

The mission CONOPS are shown in Fig. 2 and are divided into 7 phases as follows. Between demonstration phases, when the servicer and client are docked, they can enter a routine phase which is power and thermal safe. The phases are designed to generally increase in complexity ensuring less risky demonstrations are attempted first. 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.

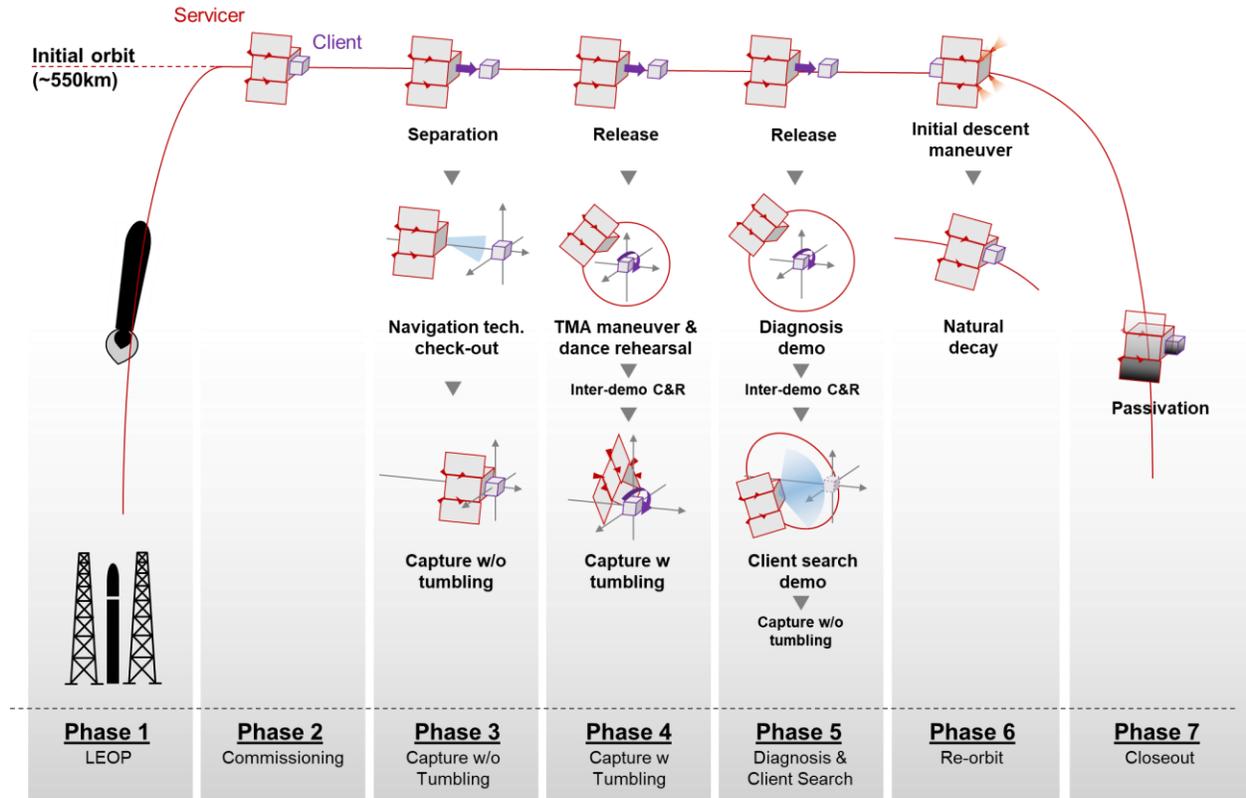


Fig. 2. ELSA-d: CONOPS

Phase 1 to 2: Launch, LEOP and Commissioning

The servicer and client are launched together into the operational orbit of roughly 550 km. The injection orbit and profile are presently in discussion with the launch provider. The servicer undergoes commissioning, testing interfaces with the ground segment, ensuring subsystems (where possible) are calibrated, and resulting in a system ready to start the demonstrations. The client is activated using the client activation unit (TAU) and undergoes the majority of its commissioning prior to separation.

Phase 3: Capture without Tumbling

A client separation mechanism (TSM) holds the client and servicer together during launch and Phase 3 is the first time the client is separated; once separated, the magnetic capture system is used to repeatedly capture and release the client, so the TSM is no longer in use. The majority of the client commissioning has already been undertaken, so any remaining commissioning is performed. 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 Point A and Point B, 10 m and 5 m behind the client, respectively). At Points A and B, the servicer performs a navigation check-out and calibration using its rendezvous sensors. This is the first time these sensors can be tested in space, since they can't be tested whilst the client is docked. Finally, the client is commanded to hold a set attitude and the servicer goes in for

capture utilizing the docking plate on the client for guidance. There are several sub-phases of the final capture including client acquisition and tracking, and velocity, position and roll synchronization, but these are easier in the non-tumbling case than the tumbling Phase 4 case.

Phase 4: Capture with Tumbling

This phase is the more dynamically complex version of Phase 3 where full tumbling capture is performed. The phase also includes a rehearsal to attempt the demonstration before finally going for the final capture. In the demonstration, the client is commanded to follow a natural motion tumbling attitude profile. The servicer performs the sub-phases of final capture listed in Phase 3. Part of the capture involves taking images of the tumbling client which are downloaded to ground and post-processed to extract client attitude. There, the FDS (flight dynamics system) in the ground segment supplies data back to the servicer to create a trajectory to move and orient the servicer with the client such that the servicer is always facing the client DP. The trajectory is executed to align the servicer and client, whereby settling is then used for final alignment before capture. The “dance” is the necessary motion and alignment needed during the tumbling capture.

Phase 5: Diagnosis and Client Search

This phase consists of two demonstrations: diagnosis, client search. In the first, the client separates from the servicer and the servicer performs a fly-around in day to inspect the client. Client inspection is a key capability for future missions, where operators will have to analyze the client and make a go/no go decision on capture.

In the second demonstration, an initial client search and approach is simulated. The servicer separates and thrusts away from the client back to a recovery point. The servicer moves into a safety ellipse, simulating first approach to an uncooperative client as in a full service mission. In a full mission, a combination of sensor data, including GPS and ground tracking, is used for the FDS to calculate a trajectory to insert the servicer on to a rendezvous trajectory with the client. In the ELSA-d mission, the FDS is still used but the demonstration is performed off-line. A “client lost scenario” is demonstrated by making the sensors lose the client at long range. The servicer then uses its sensors to reacquire the client and makes the final approach to recapture.

Phase 6 to 7: Re-orbit and Closeout

In the final phase, the servicer performs a re-orbit maneuver to reduce the client altitude. This simulates the final de-orbit in a full mission. At a lower altitude, after natural decay, the craft is passivated. Both servicer and client proceed to an uncontrolled de-orbit burning up on re-entry. The mission at all times maintains 25 year debris mitigation compliance, as the initial demonstration altitude is only 550 km. The full duration of the mission is expected to last up to 6 months, including non-demonstration (routine) phase periods.

3. CAPABILITIES & TECHNOLOGIES

ELSA-d has a series of technologies and capabilities which enable active debris removal sequences to be performed, to mature the key steps needed for a full service mission. Key technologies and capabilities include:

1. Rendezvous Suite

Astroscale have developed an end-to-end rendezvous solution for both far-range and short-range approaches. Rendezvous and docking in space is among the most complicated technical challenges. To date, only manual-docking or some limited autonomous docking (with many constraints) has ever been attempted in space (e.g. ATV, Orbital Express, ETS-7, Dragon). ELSA-d utilizes an integrated suite of technology for rendezvous and capture including both hardware (processing, sensing and control) and software (guidance and navigation algorithms, control laws), enabling these complicated scenarios to be undertaken in space efficiently and safely.

Searching for and discovering an object in space is a complex technical challenge. Astroscale’s search is performed by using absolute navigation (ground-based radar or optical methodologies plus the servicer’s GPS system) to get

within a knowledge boundary. On first acquisition of the client, relative navigation is switched to in an absolute to relative navigation handover phase. Final approach is achieved using relative navigation.

2. Fly-around Inspections

A fly-around (diagnosis) stage enables an operator to visually examine the servicer before final approach. This is useful to examine for damage to the client and may be useful if communications with the client have been lost (in cooperative docking scenarios).

3. Docking Plate

The DP is a core part of ELSA-d'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. The ELSA-d grappling interface is designed to be mounted on a client satellite and consists of a flat, disc-shaped docking plate (DP) on top of a supporting stand-off structure. It provides distinctive features that make a defunct satellite easier to identify, assess, approach, capture, and de-orbit, thus minimizing 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.

4. Magnetic Capture System

ELSA-d'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.

5. Re-orbit, De-orbit and Passivation

ELSA-d uses chemical propulsion to provide both re-orbiting and de-orbiting capability. A re-orbit to a lower altitude simulates immediate evacuation from the operating altitude, which is needed in future missions to quickly take a satellite out of harms way from other satellites in that orbit.

6. Mission Safety

Mission safety is of paramount importance to ELSA-d to ensure there is no further debris generation in space. Safety is also a large part of having a licensable mission design. The mission's range of safety features includes (but is not limited to): collision avoidance maneuvers (passive and active aborts), ability to move to an evacuation point, and ground segment oversight during critical phases.

7. In-orbit Servicing Ground Segment

Unlike a conventional ground segment, ELSA-d's ground segment is specifically designed with in-orbit servicing in mind. Features include the ability to chain and align ground station passes to service longer demonstration scenarios while providing operator-in-the-loop safety.

4. TOWARDS LAUNCH

As the design stages have progressed, some adjustments to the mission baseline have occurred since past papers e.g. [6]. This includes adjustment to the manner in which CONOPS is performed and moving to a deployable solar panel configuration.

ELSA-d assembly, integration and test (AIT) is presently ongoing in an Astroscale Tokyo clean room. A comprehensive series of both functional and environmental tests at the subsystem and system level are being undertaken. Fig. 3 shows the STM 2 (structural model) in the clean room. This model underwent vibration mechanical testing as part of the EVT flow.

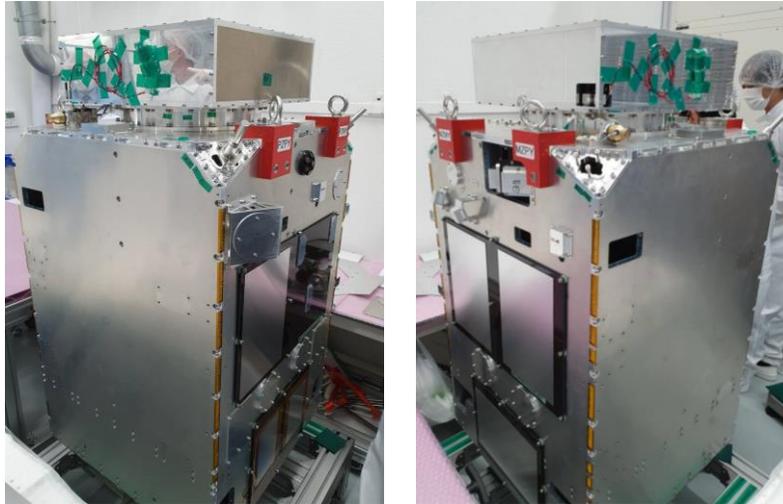


Fig. 3. **ELSA-d: AIT.** Assembly, integration and testing for the STM 2 (ELSA-d structural model)

5. CONCLUSIONS

ELSA-d, which stands for End of Life Services by Astroscale (-demonstration), is an in-orbit demonstration (IOD) for key end-of-life technology and capabilities of future debris removal missions. ELSA-d, due for launch in 2020, consists of two spacecraft, a chaser (180 kg) and a client (20 kg), launched stacked together. This paper has examined key aspects of the mission, including the several phases in the mission CONOPS that demonstrate the following capabilities: client search, client inspection, client rendezvous, and both non-tumbling and tumbling capture. The capabilities and technologies on the mission were explored such as the magnetic capture system and the Astroscale docking plate.

The ELSA-d mission is an important step towards fully operational EOL and ADR missions by maturing technologies and capabilities necessary for future services. In particular, the ELSA-d mission will not just space-prove future payload technologies but will also go through almost the full series of CONOPS expected in a full servicing mission with a demonstration client.

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