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The World's First Commercial Debris Removal Demonstration Mission

Gene Fujii, Seita Iizuka
Astroscale Japan
1-16-4 Kinshi Sumida-ku, Tokyo, Japan 130-0013
g.fujii@astroscale.com

Carolyn Belle, Mark Muktoyuk
Astroscale U.S. Inc
525 E. Mississippi Ave, Denver CO 80210, USA; +1 720 826 9732
c.belle@astroscale-us.com

ABSTRACT

Since the launch of Sputnik in 1957, the orbital environment has become increasingly congested. Of the 5,550 satellites currently orbiting the Earth, only 2,700 are operational, and they are joined in orbit by millions of objects of space debris. Astroscale has developed a robotic servicing spacecraft and suite of technology to address this challenge by removing debris and defunct satellites from orbit; the smallsat servicer mission *End-of-Life Services by Astroscale-demonstration (ELSA-d)* launched on March 22, 2021, will demonstrate these new and innovative space debris docking and removal technologies on orbit. The *ELSA-d* mission includes both a smallsat servicer and a demonstration client vehicle. The mission will demonstrate multiple dynamic complex capture activities, testing all core sequences of end-to-end debris removal technologies, including a magnetic docking mechanism, client search, far- and short-range client rendezvous and proximity operations (RPO) using absolute to relative navigation hand-over, client inspection, and both non-tumbling and tumbling docking. While missions involving RPO and docking have been previously undertaken, none have been attempted without communication between the servicer and client spacecraft nor without a precise knowledge of the client location. The *ELSA-d* mission tests RPO capabilities and new docking technologies while facing both of these challenges as a more realistic analog to debris removal and post-mission disposal scenarios, thereby paving the way for active debris removal in the near term. In this paper, the authors share the mission design and new technologies developed to address space debris removal in the 2021 ELSA-d mission.

INTRODUCTION

Since the start of the space age in 1957, more than 11,400 satellites have been placed into orbit across ~5,500 launches.[1] The European Space Agency (ESA) and United Nations Office of Outer Space Affairs (UNOOSA) estimate that 2,700 of these remain in operation, while 2,850 are defunct but remain in orbit; the others have successfully deorbited or reorbited.[2] Yet the population of objects of human origin in space is far larger: approximately 1,950 discarded rocket stages, 21,000 observed but unidentified debris fragments, and 129 million debris fragments that are too small to observe from Earth but can be statistically modeled. These uncontrolled pieces of debris, defunct satellites, and discarded rocket stages create a risk of collision with both operational satellites (damaging and/or destroying them) or other pieces of debris (resulting in a break-up of both that creates only more debris fragments).

Satellite launch rates have increased by 931% in the last decade, and the 2020s are projected to see the launch of an additional 10,000 or more satellites as megaconstellations are deployed.[1] Many of these new satellites are designed with short on-orbit lifetimes, requiring regular replenishment and a further increase of the amount of objects on-orbit.

This combined scenario of increasing satellite launch rates and an existing debris population presents clear risk to both operational satellites and the future use of space, particularly low Earth orbit (LEO). To ensure long-term access and utilization of space, Astroscale proposes the need for industry-wide steps towards space sustainability that includes both post mission disposal and active debris removal. This objective requires the ability to safely approach, dock with, maneuver, and deorbit defunct satellites and existing debris objects.

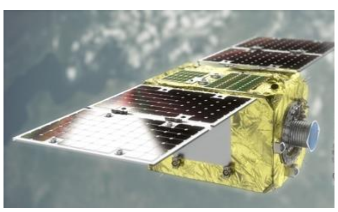
Government agencies and private companies have launched research and development and demonstration missions to address aspects of this needed capability set. The 2007 Orbital Express mission conducted by the U.S.

Defense Research Projects Agency (DARPA) and NASA demonstrated autonomous rendezvous & proximity operations (RPO) and grapple of a demonstration client via robotic arm.[3] The 2018 RemoveDEBRIS mission demonstrated net and harpoon capture of a demonstration client and deployment of a drag sail to reduce deorbit time[4]; neither of these capture approaches are reversable. Each of these missions, and others assessed elsewhere, addressed a certain aspect of post-mission disposal or debris removal. Astroscale's *End-of-Life Services by Astroscale-demonstration* (ELSA-d) mission advances the state of the art for space sustainability capabilities by demonstrating our concept of reversable prepared ferromagnetic capture and completing an end-to-end commercial RPO, capture, and maneuver campaign in multiple real-life scenarios.

MISSION OVERVIEW

The ELSA-d mission consists of two satellites: the ELSA servicer (~175 kg) and a demonstration client (~17 kg) (Table 1). The satellites were launched in a mated position on March 22, 2021 and deployed into an operational orbit at 550 km, 97.5 degree inclination. The mission is ongoing.

Table 1: On-Orbit Mission Components

Servicer	Client
	
Servicer equipped with a sensor suite, RPO technologies, and a ferromagnetic docking mechanism	A piece of replica debris/defunct satellite equipped with ferromagnetic docking plate that includes a unique fiducial pattern

The servicer will repeatedly release and dock with the client in a series of technical demonstrations, proving the capability to find and dock with defunct satellites and other debris in a variety of scenarios. Demonstrations include client search, client inspection, client rendezvous, and both non-tumbling and tumbling docking (described further in the following section). Following the demonstrations, the servicer and client will remain mated and lower their altitude with the goal to reenter within five years. While international guidelines are a 25-year reentry period, Astroscale's assessment of the orbital environment and the steps needed to ensure long-term space sustainability directed the choice of a five-year reentry period. Once the altitude is lowered, the ELSA-d servicer will be passivated – its remaining propellent expelled and its batteries drained.

ELSA-d is operated by Astroscale's mission operations team from the In-orbit Servicing Control Centre – National Facility at Satellite Applications Catapult, Harwell Campus, UK. Servicer operations are semi-autonomous, with a real-time data feed between the spacecraft and ground for critical maneuvers. The ground network consists of 16 sites across the globe, uniquely selected to provide a chain of connectivity for extended duration contact with ELSA-d from one ground station to the next.

While the client is commandable, during the demonstrations there is no direct communications between the servicer and client. This was a deliberate mission design choice to more realistically model potential future defunct satellite or debris capture scenarios.

Table 2: ELSA-d Key Features

End-to-end rendezvous solution including far-range and short-range approaches
Client search and approach from far-range with relative navigation sensors
Fly-around inspections of client with operator assessment
Docking plate to future proof satellites, enabling removal in cases of anomaly
At-night magnetic capture of non-tumbling and tumbling clients
Re-orbit, de-orbit and passivation capabilities
Safety evacuations and passively safe trajectories in mission design
Full ground segment, custom-designed for on-orbit servicing

DEMONSTRATIONS

The mission encompasses several mission phases and three unique demonstrations (Figure 1). Each one presents an additional set of complexity and demonstrates specific capabilities of the servicer and mission operations.

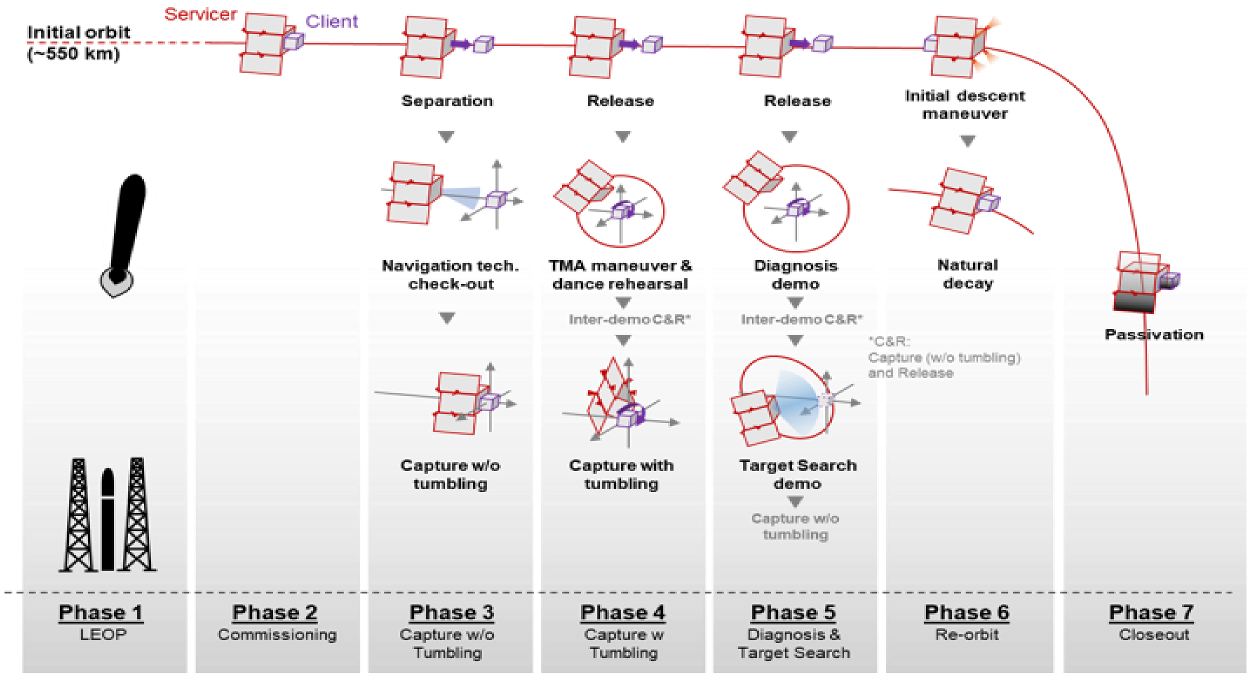


Figure 1: ELSA-d Mission Phases

Demonstration One: Capture of Stable Client

Demonstration One is the basic measure of success for the ELSA-d mission: the ability to safely approach and capture a stable, prepared client. Following LEOP and commissioning, the client is released from the servicer and demonstration one commences. The servicer positions itself at a set distance behind the client (holding point one) and performs a navigation check-out and calibration using its rendezvous sensors. Once complete, the client is commanded to hold a set orientation and the servicer gradually approaches the client by progressing through a series of holding points. Using the fiducial pattern on the client docking plate for guidance, the servicer makes its final approach, extends its magnetic capture mechanism, and captures the client. The two maneuver in a mated position before re-releasing the client for the next demonstration.

Demonstration Two: Capture of Tumbling Client

Demonstration Two presents added complexities and represents a more realistic scenario for the future defunct satellite or debris removal missions Astroscale seeks to undertake: debris and satellites that have experienced an anomaly that prevents self-deorbiting and that are likely to be tumbling. This mission phase of capture of a tumbling client demonstrates that the servicer can track the fiducial pattern on the client and can match the client's tumbling rate. In the demonstration, the client is commanded to follow a natural tumbling motion, typical of uncontrolled objects in space. The servicer records images of the tumbling client, which are processed on the ground to enable the operations team to uplink maneuver commands to the servicer. The Flight Dynamics System (FDS) aligns the servicer and client before capture using the ferromagnetic capture mechanism. This "dance" is the necessary motion and alignment needed during the tumbling capture.

Demonstration Three: Client Diagnosis, Client Search, and Capture

Demonstration Three further increases both the complexity of capture and realism of the scenario. In this phase, the client separates from the servicer and the servicer performs a fly-around in daylight to inspect the client. Client inspection and diagnosis is a key capability for future missions, in which operators must analyze a client and make a go/no-go decision on capture.

A client search demonstration follows the client diagnosis. This phase leverages a different set of sensors than previous phases to demonstrate the ability to track and approach the client from a far range. This ability to search for the client is operationally critical even in scenarios where the servicer operator has specific knowledge of client location - as the mission will reach a point when the servicer must rely on sensors to safely undertake the relative approach. In the client search 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 unprepared client as in a full-service mission. In a full mission, a combination of space situational awareness (SSA) data, including GPS and ground tracking, will be used to calculate a rendezvous trajectory for the servicer to reach the client. A "client lost scenario" is demonstrated by making the sensors lose the client at long range. The servicer then uses its sensors to re-acquire the client and make the final approach to recapture (as in demonstration one).

ENABLING CAPABILITIES

Achieving the ELSA-d mission objectives to test all core sequences of an end-to-end post mission disposal campaign leveraged a suite of technologies and capabilities developed by the Astroscale team. This includes both Astroscale's capture method (distinct from alternate capture methods tested in prior missions) as well as the supporting capabilities needed to enable ELSA-d's first-ever attempted RPO and docking without communication between the servicer and client spacecraft, without a precise knowledge of the client location, and to a tumbling client.

Low Cost and Light Weight Sensors for RPO

The ELSA-d servicer was designed within a constrained mass and volume envelope, driving trade studies on the sensor suite to balance desired capabilities with available size, weight and power demands (SWaP). The primary sensors selected to support RPO and capture were: two types of visible image cameras, a blue light device, laser range finders, and a low power radio. One visible camera is used for relative navigation in the far field alongside the low power radio, used for long distance ranging. These sensors are critical for the client search capability during Demonstration Three. Once the servicer commences close proximity operations, the second visible camera, tuned for blue light, is used in conjunction with the blue light source to illuminate the client docking plate fiducial markers to determine precise client attitude and tumble rates. During this close approach phase, multiple laser range finders are used to determine distance to the client. All three demonstration phases can be accomplished with this suite of sensors.

Docking Plate & Capture Mechanism

All prepared capture methods require a specific interface/point of contact on the client for the servicer's capture mechanisms to approach and secure. In this mission Astroscale tested its unique ferromagnetic docking plate capture method, in which the client is outfitted with a ferromagnetic docking plate and the servicer with a complementary ferromagnetic capture mechanism. The docking plate is a flat disc shape made of ferromagnetic material mounted on top of a supporting stand-off structure, designed to minimize SWaP demands on the client while ensuring a secure connection between client and servicer for mated maneuvers.

Fiducial Pattern

A unique fiducial pattern is mounted on the client docking plate, providing an optically controlled surface for the servicer's sensors to track. It provides distinctive features that make a defunct satellite easier to identify, assess, approach, capture, and de-orbit, thus minimizing future costs of removal. The fiducial pattern was uniquely designed and optimized by Astroscale to maximize the ability of the servicer's sensors to detect the client attitude and rotation rate. As the servicer approaches the client, the sensor feedback is analyzed and input to the servicer's Guidance, Navigation, & Control system to adjust close approach and capture.

Approach & Capture Algorithm

Approach and capture algorithms are unique to each servicer design, as they depend on data collected by the servicer's sensor suite; the algorithms for ELSA-d were created to use the visible-range cameras, blue lighting device, laser range finder, and low power radio to assess the range and tumbling rate of the client. The servicer then uses its reaction wheels and Reaction Control System (RCS) thrusters to correctly maneuver the servicer to match the client's tumble rate and to align the capture mechanism with the client docking plate; this positioning allows the capture mechanism to extend out and capture the client. The approach and capture algorithm does not rely on any active communication or interface with the client. The entire close approach RPO and capture operation is performed by the servicer based on awareness of the docking plate location on the client, a clear line of sight to the docking plate, and its sensor suite input.

Use of Green Propellant

ELSA-d was designed with RCS thrusters that use non-toxic, environmentally friendly green propellant. The RCS system is critical to maintain and control complex RPO servicer attitudes for successful docking demonstrations. The RCS system is also necessary for implementing abort maneuvers during close approach to avoid unplanned collisions. The use of a green propellant for ELSA-d will demonstrate that RPO missions can be accomplished with environmentally safe RCS fuel alternatives. By using a green propellant, the fuel loading operations at the launch site were less complex and easier to support, in addition to aligning with Astroscale's vision of sustainable operations.

Mission Operations

The mission operation design was a trade-off between what could be completed on-board the servicer and what demanded ground intervention – constrained by real-time ground contact times, servicer compute power, mission safety, and other factors. In complex missions, such as with cargo resupply or human transport vehicles to the International Space Station, an on-orbit relay service is used (TDRS); while this approach provides more real-time communications between the vehicle and the ground, it has limited availability, is expensive, and requires an onboard transceiver just for this link. Direct-to-ground operations is limited by the number and location of ground stations relative to the satellite's ground track, and there will always be gaps between some passes due to these geographical constraints. The ground segment was designed to optimize contact durations, seaming passes between multiple ground stations to achieve 20 to 30 minutes of near-continuous contact time (Figure 2). Ultimately Astroscale settled on a semi-autonomous mission operations approach, with some tasks and maneuvers completed on-board the servicer while others depended on ground intervention for analysis and commanding. On-board the servicer has autonomy to perform relative navigation and collision avoidance. It also has on-board various Fault Detection Isolation and Recovery (FDIR) logic to detect any unexpected failures or anomalies and autonomously react to ensure mission safety during these autonomous operations. Human-in-the-loop operations were required for the mission safety in these situations: from final approach to capture, departure and home position acquisition, and first attempt maneuvers (once a maneuver type is validated, it is no longer necessary for the mission to require continuous visibility).

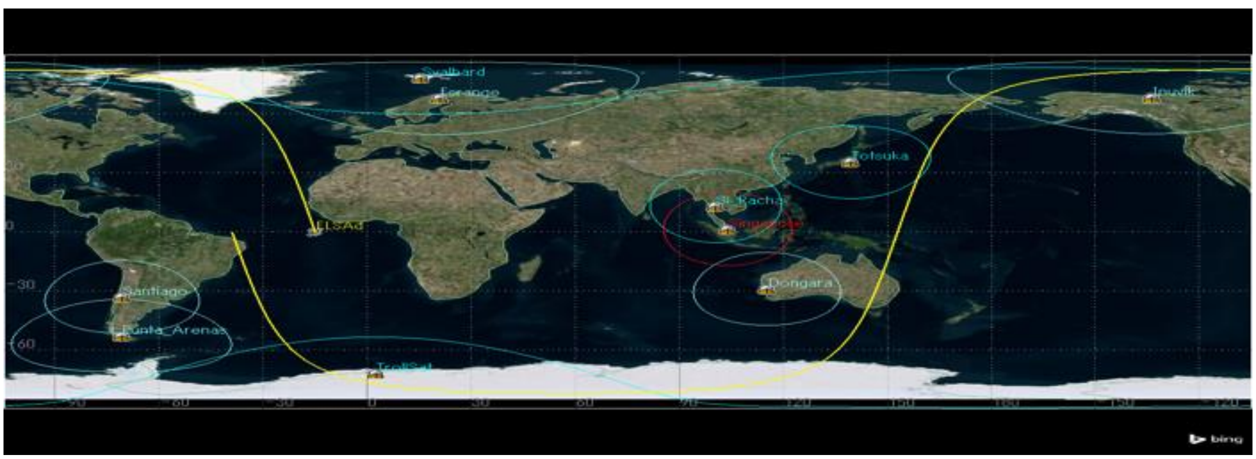


Figure 2: ELSA-d Ground Track and Ground Stations

CONCLUSIONS & DIRECTIONS FOR FUTURE MISSIONS

The ELSA-d mission represents a major stepping stone on the path to space sustainability. By demonstrating the commercial ability to rendezvous, dock with, and maneuver a client satellite without communication between the servicer and client, ELSA-d advances to TRL9 the core technologies needed for prepared end-of-life services (deorbiting) and furthers capabilities to provide active debris removal services. To further refine and develop the technologies needed to support these two applications, Astroscale has identified several areas of future study:

- Improved docking plate – refine the design of the client-side docking plate that prepares the spacecraft for servicing, including efforts to reduce cost and mass while increasing the fiduciary design for improved near- and far-range RPO activities. This would improve client satellite operator value proposition and enhance mission capabilities.
- Reusable servicer – develop and demonstrate a servicer (baselined within Astroscale as the ELSA-M vehicle) to leverage the ELSA-d capabilities to service multiple clients within a servicer's life. This would reduce per-satellite removal cost and provide a more sustainable architecture (fewer launches and fewer satellites placed on-orbit).

- Demonstrate RPO and docking with an unprepared client – removal of debris currently on-orbit demands unprepared docking (baselined within Astroscale as our ADRAS-J mission with JAXA), as none of these upper stages/satellites/satellite components were designed with servicing in mind. To achieve the targeted space sustainability goals and reduce risk of on-orbit collision this capability must be developed. This involves not only an unprepared capture technique, but also different sensors for RPO given the lack of a fiducial pattern to target. This is the extension of core ELSA-d technologies and capabilities to a new use case of active debris removal.

Alongside the technical next steps towards services to facilitate space sustainability are the industry dialogues and mindset evolution to value space sustainability activities. This encompasses wider acceptance across industry to prepare satellites for future servicing, whether via a docking plate, grappling hook, or alternate structures, so that if a critical anomaly occurs there is an alternate and cost-effective means to remove the satellite from orbit. Preparation of satellites for future servicing opens additional opportunities for satellite operators that can be further explored in tandem to deliver value and address operator challenges.

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