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The ELSA-d End-of-life Debris Removal Mission: Preparing for Launch

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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. Founded in 2013, Astroscale's mission is to provide reliable and cost-efficient spacecraft retrieval services to satellite operators in order to secure long-term spaceflight safety and achieve orbital sustainability for the benefit of future generations. Astroscale is one of the few com-panies in the world proposing to aid in the removal of orbital debris through the provision of two services: end-of-life (EOL) targeting the LEO constellations, and active debris removal (ADR) targeting existing larger space debris.

The ELSA-d (End of Life Services by Astroscale-demonstration) mission is late in its assembly, integration and test (AIT) stages and due to launch in the early 2020 timeframe. ELSA-d will demonstrate technologies for rendezvous and proximity operations (RPO) by launching a servicer satellite attached to a small client satellite, which will then repeatedly separate and dock in orbit. The servicer is equipped with rendezvous guidance, navigation, and control (GNC) technologies and a magnetic docking mechanism, whereas the client has a docking plate (DP) which enables it to be captured.

This paper will initially provide an overview of each phase of the concept of operations (CONOPS). Whereas existing space missions have performed rendezvous with cooperative clients either manually or semi-autonomously, ELSA-d will demonstrate semi-autonomous capture of both non-tumbling and tumbling clients; the latter being novel in the space environment. ELSA-d will also demonstrate client search and inspection capabilities validating key RPO capabilities such as passively safe trajectories and absolute-to-relative navigation handover. The paper also provides an overview of the general mission design, including capabilities and technologies, ground segment, and elements of mission production as the project progresses through AIT and Astroscale finalizes the vehicle for its upcoming launch.

The ELSA-d mission promises to be a major step forward in demonstrating RPO capabilities applicable to future debris removal services.

Keywords: end of life, debris removal, ELSA-d, rendezvous proximity operations, AIT, launch

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. 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.

1.1. Past Papers & Updates

The ELSA-d mission has been described in past papers [1 - 5], but this paper provides the latest mission updates. Compared to the original mission design [5], the mission has been augmented with deployable double solar panels and re-routing of thrusters for higher fuel efficiency.

1.2. Mission Overview

The ELSA-d mission is an in-orbit demonstration that aims to test several capabilities and technologies needed for future services (e.g. see constellation mission considered in [6]). The servicer and client can be seen in Figure 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. The key features of the mission are summarised in Table 1.

Table 1 – **ELSA-d: Mission Features**

Entity	**Property**	**Value**
Servicer	Structure	~ 0.6 × 1m
	Mass	~180 kg
	GNC (command)	GNC OBC, GNC sensor handling unit
	GNC (sensing)	star trackers, gyros, magnetometers sun-sensors, accelerometers, GPS
	GNC (actuation)	reaction wheels (pyramid), magneto-torquers
	GNC (RDV)	night cameras, day cameras, laser ranging device, radiometric ranging device, illuminator
	Capture	magnetic capture system
	Comms	S-band, X-band
	Power	deployable double solar array, PCDU system, flight battery
	Propulsion	green propellant chemical propulsion system
	C&DH	BUS OBCs, CAN bridge, spacewire router
	Other	retro-reflector, client separation mechanism & activation unit
Client	Bus	~20 kg satellite with OBC, EPS, S-band COM, AOCS
	Docking plate	DP mounted on client
	Other	retro-reflector, camera, illuminator

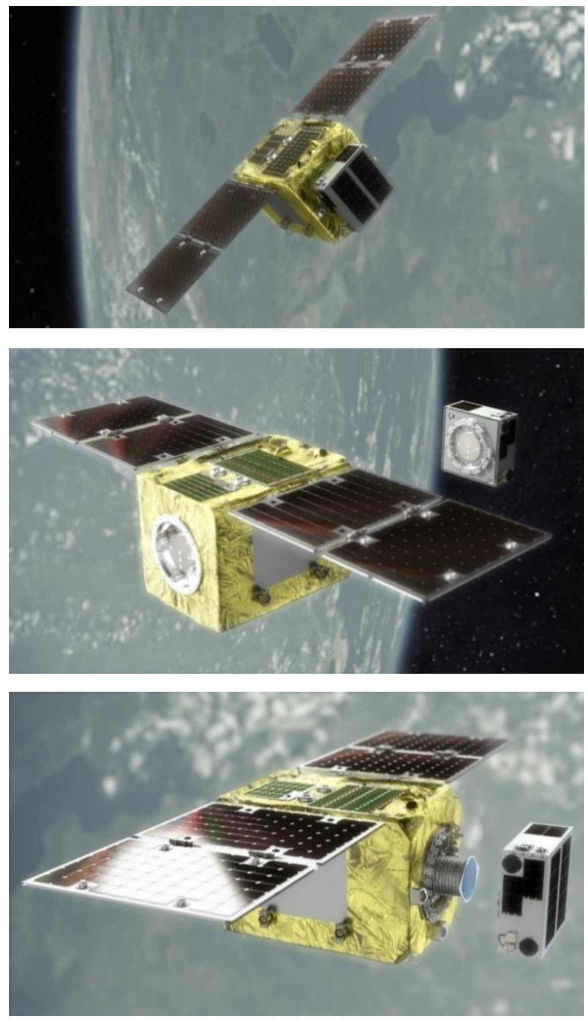

Figure 1 – **ELSA-d: Servicer and Client**. Top: servicer with attached client. Middle: release of client for a capture demonstration. Bottom: recapture of client with servicer capture system extended.

1.3. Paper Structure

Section 2 examines the mission CONOPS. Section 3 explores mission capabilities and innovations. Section 4 considers the mission ground segment and operations. Section 5 shows the latest efforts in AIT towards launch. Finally, Section 6 concludes.

2. Mission CONOPS

The mission CONOPS are shown in Figure 2 and are divided into 7 phases. 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.

A video demonstrating the sequences can be seen here: https://youtu.be/HCWxdK7l0hI.

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 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.

During the phase, inter-demo C&R (capture and release) is an available option to "pause" demonstrations by quickly recapturing (most likely in non-tumbling capture methology) if an operator so desires.

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

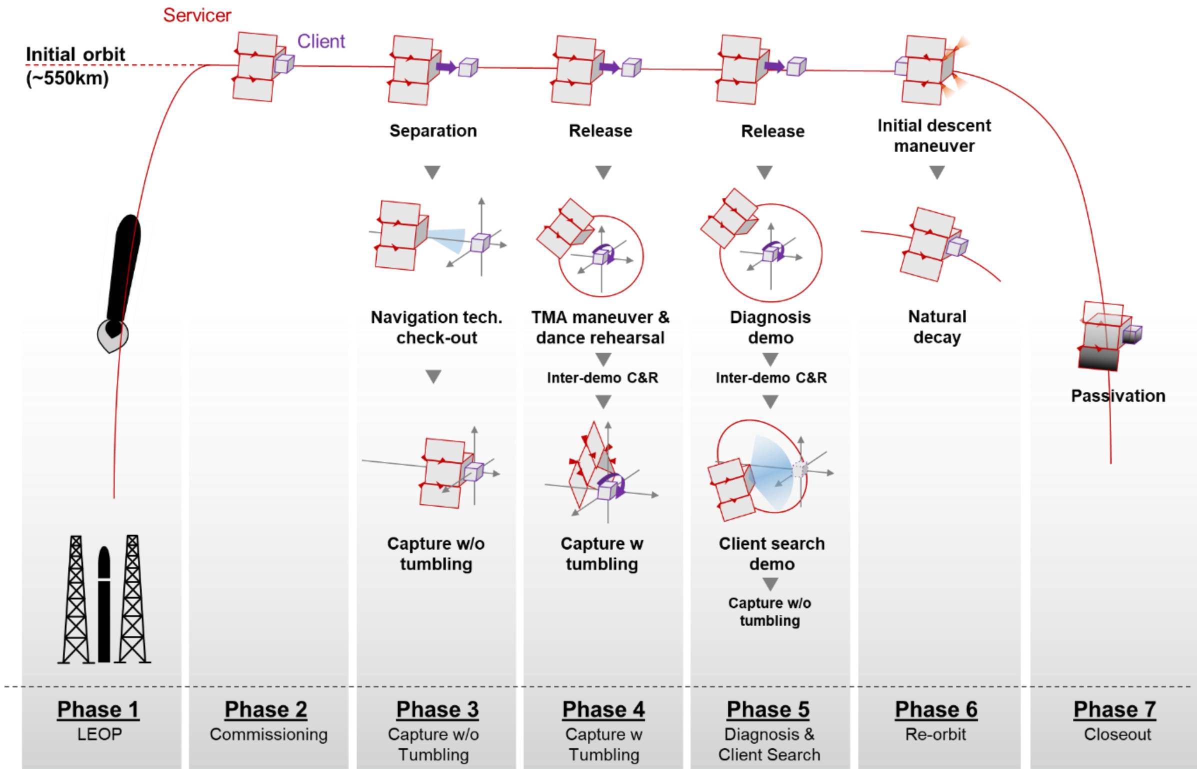

Figure 2 – **Mission CONOPS**

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 & Innovations

ELSA-d has a series of 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. End-to-end 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. In a full service mission, 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. ELSA-d performs parts of this demonstration as explained in the CONOPS section.

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.

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. Future missions will also make use of electric propulsion for orbital manoeuvring.

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):

- Safety evacuations and passively safe trajectories (passive / active aborts, predefined evacuation point, protected safety ellipse insertion)
- Collision avoidance maneuvers
- Ground segment and operator oversight during critical phases (including manual experimental abort)
- Protected critical mission functions (including reversion to higher levels of hardware and software authority)
- Safety critical computing (including multi-level FDIR, one fail-safe architecture)
- Architectural redundancy (some units are semi-hot redundant, some cold redundant)
- High-fidelity ground-based simulation (of key operational sequences before execution)

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. Please see later sections.

4. Ground Segment & Operations

ELSA-d utilises the National In-orbit Servicing Ground Segment Facility hosted at the Satellite Applications Catapult (UK) and developed by AS (prime) with Catapult, RHEA, GMV, SciSys subcontracts. The facility has been developed as a multi-mission facility with a long-term view to provide capability for a variety of IOS missions.

4.1. Ground Segment Architecture

The control centre has, at its core, a Mission Control System for the servicer spacecraft and one for the client spacecraft. The centre interfaces to a number of external entities including Astroscale's own ground station in Totsuka (Japan), external ground stations for contact with the servicer and client, and a ground support centre in Tokyo. It is built in the virtualised environment of a CEMS cloud infrastructure. Satellite communications are based on CCSDS standards and a core suite of ESA software tools are part of the system. The main components are as follows:

1. Mission Control System (MCS)

The MCS is responsible for controlling and monitoring the spacecraft. It is based on ESA MICONYS SCOS-2000 framework. The Mission Database (MIB) is considered a sub-component of the MCS. The MCS relies on the File Based Operations (FBO) approach which guarantees improved reliability on command sequences, bandwidth optimisation, file compression, and use of standard file formats.

2. Flight Dynamics System (FDS)

The FDS determines both the position and the orientation of satellites, and enables the planning and execution of required manoeuvres. It is responsible for LEOP calibrations, planning docking and orbit maintenance, conjunction avoidance manoeuvres with other resident space objects, de-orbiting and re-entry planning, and station-keeping operations. Classical functionalities, such as orbit and attitude determination, use advanced filtering techniques to fuse multiple measurements sources and absolute/relative navigation features. In addition, the FDS provides IOS specific functionalities such as diagnosis trajectory optimization, active abort manoeuvre reconstruction, safety orbit planning and capture trajectory optimisation. A 2D/3D visualisation tool is built-in to the FDS.

3. Image Processing System (IPS)

The IPS is in charge of the estimation of the docking plate attitude information from a live stream of images taken by the servicer spacecraft. It includes advanced feature detection capabilities that allow the servicer to estimate the docking plate attitude information even when it is not directly visible.

4. Mission Planning System (MPS)

The MPS is used to plan activities and use of resources (e.g. data budget). The MPS receives data from the FDS, the MIB, and the Mission Operations Preparation Tool (MOIS Preparation) to construct a coherent schedule, which can then be uplinked to the satellite, executed and verified by telemetry. The MPS is able to automatically negotiate passes with the ground stations providers based on the user needs. In addition to classical MPS functionalities, it automatically manages passes over ground stations in order to have (when possible) an uninterrupted stream of telemetry when switching from one ground station to the other.

5. Automation System (MOIS)

The automation system is responsible for the automatic execution of schedules produced by the MPS and preparation system. It also provides validation and test harness components which can be used for testing before going operational, and a validator component which can be used alongside the MCS to validate that correct procedures are being executed.

6. Ground Station Control System (GSCG)

The GSCG is based on the ESA SCOS2000 NIS component. It is used to interface the MCS and ground stations conforming to the CCSDS SLE standard.

7. Simulator (SIM)

The simulator is implemented using the ESA SIMULUS Simulation framework. It provides an end-to-end simulation of both the servicer and client spacecraft. The simulator includes a highly realistic servicer model that emulates the OBCs. This feature not only allows AS to run faster-than-real-time simulations but also to run on-board software in a plug-and-play fashion. The purpose of the simulator is testing and validation of operational procedures and databases, support the training of operators, and execution of simulation campaigns. Moreover, the simulator is used for testing and validating the on-board software in an operational environment.

4.2. Operations

The mission will be split into four main phases with respect to operations: LEOP, commissioning, critical phases, non-critical phases. Docking and rendezvous will be performed during critical phases, and the mission will be continuously operated. Astroscale will be fully responsible for conducting all the operations for the servicer and client at the control centre in Harwell.

The control room has several operator desks; each desk includes a thin client for remotely connecting to the data centre. As all the MCC systems are running in a virtualised environment inside of the data centre, the positions and roles of the desks are flexible. The data centre will be replicated in two different locations in order to ensure the reliability of the MCC. In addition, every system will be composed of a primary and backup server, where data is replicated in near real-time across servers and data centre locations. The control centre and associated communication channels are designed with data encryption in mind.

5. Towards Launch

As the design stages have progressed, some adjustments to the mission baseline have occurred since past papers [5] as described earlier.

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.

Figure 3 shows the STM (structural model) in the clean room. This model underwent vibe mechanical testing as part of the EVT flow.

ELSA-d is also progressing through the mission licensing process, with on-going discussion with the UKSA (see [9]). This is part of the wider exercise of Astroscale involving itself in regulatory, policy and insurance discussions to grow the ADR market [8 - 11].

6. 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 servicer (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.

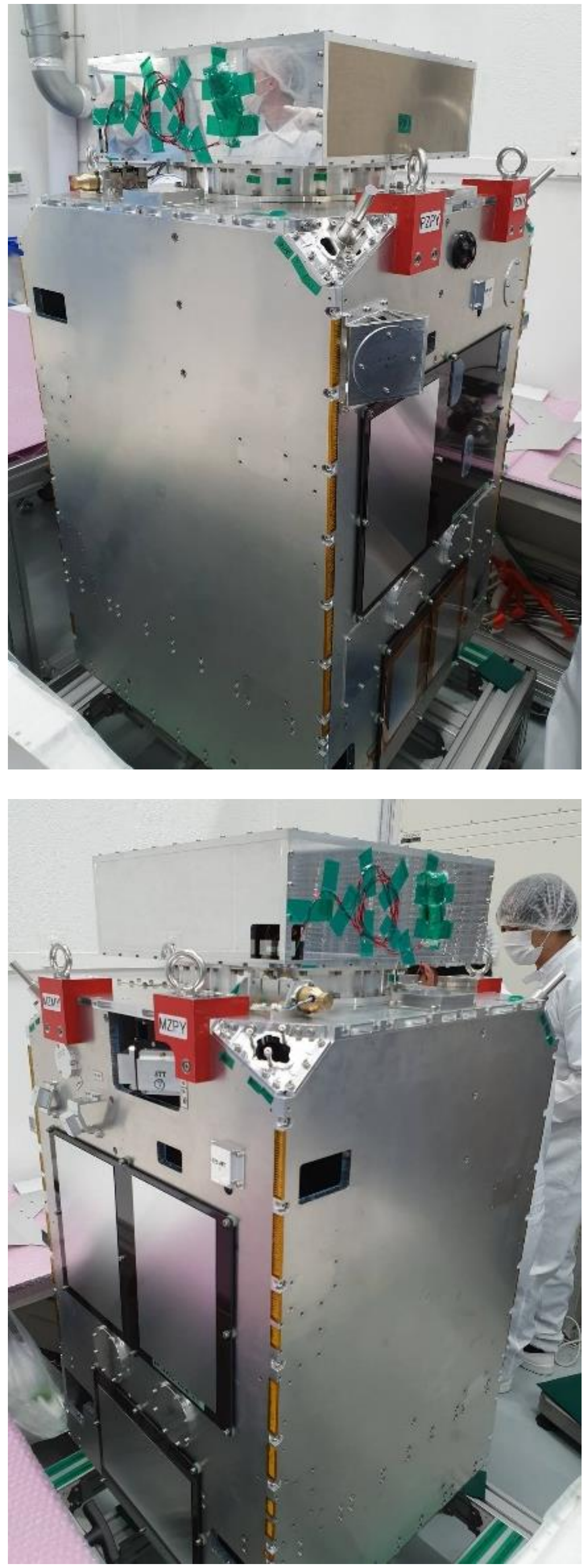

Figure 3 – **ELSA-d: AIT**. Assembly, integration and testing for the STM (ELSA-d structural model).

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