Space Situational Awareness (SSA) activities explored through the ELSA-d mission

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Abstract

Astroscale's ELSA-d mission, the world's first commercial demonstration of an end-of-life (EOL) capability is be used to demonstrate the core technologies necessary for debris docking and removal. The uniqueness of the mission objectives and its operations provide an exclusive opportunity to explore both the Space Situational Awareness (SSA) demands on future Rendezvous and Proximity Operation (RPO) missions, as well as potential uses of the demonstration technologies to support SSA services.

The ELSA-d mission consists of two spacecraft, a servicer and a client, stacked together during launch and orbit insertion. The servicer is equipped with proximity rendezvous technologies and a magnetic docking mechanism, while the client has a ferromagnetic plate which enables the docking. The servicer will repeatedly release and dock with the client in a series of technical demonstrations proving the capability to find and dock with debris. Demonstrations include client search, client inspection, client rendezvous, and both non-tumbling and tumbling docking.

Because of the controlled nature of this specific mission - Astroscale has direct command and control of both spacecraft - ground-truth instrumented data, including accurate time-dependent state-vectors and spacecraft dynamics, are readily available. This enables evaluation of the use of SSA services during the key phases of the mission. This paper seeks to assess SSA requirements including orbit propagation and determination of both spacecraft, attitude analysis (state and evolution rate), approach analysis and collision avoidance. By evaluating these needs during and post-mission, it is hoped that a better understanding of what services are either essential or desirable for future RPO missions, whether they be Active Debris Removal (ADR), EOL, In-orbit Inspection or Life Extension (LEX).

As well as assessing SSA needs, ELSA-d also offers the prospect of considering how bespoke RPO technologies onboard the spacecraft could be used to support other SSA mission objectives. The ELSA-d spacecraft has several sensors designed for close-proximity analysis and inspection which could potentially be used to explore In-situ SSA application. This includes, for example, small-debris characterisation in LEO and large object identification in GEO. This paper seeks to explore some of these activities and consider the results from these on-orbit experiments, as well as draw some preliminary conclusions on the efficacy of these types of systems.

1. INTRODUCTION

Astroscale is a commercial venture with a focus on space sustainability. Our mission is to develop innovative technologies, advance business cases, and inform international policies that reduce orbital debris and support the long-term, sustainable use of space. Our vision is to ensure a safe and sustainable development of space for the benefit of future generations.

SSA plays an important role for Astroscale in two distinct ways. First, SSA is essential to meet our mission goals. We need comprehensive SSA data that allows us to accurately interpret and characterize the activity of spacecraft, improve operational safety and reduce the risk of collisions by increasing ability to recognise abnormal or off-nominal behaviour. The focus is therefore on identifying mission SSA needs, determining how to meet those needs, and considering cost effective options for those requirements.

In addition, as we continue to develop our technologies and mission capabilities, Astroscale are keen to see how we might contribute to SSA technologies, missions and operations. In the near-term, this includes leveraging current Astroscale mission plans and technologies to support SSA provision and development. In the longer-term, we wish to consider specific technology developments and missions that might directly support SSA provision.

2. ASTROSCALE MISSIONS

Astroscale are in the process of developing a range of complex missions supporting different facets of In-Orbit Servicing (IOS). These missions are not only underpinned by the need for comprehensive SSA capabilities, but they also offer the opportunity to explore and develop SSA technologies, applications, and future services.

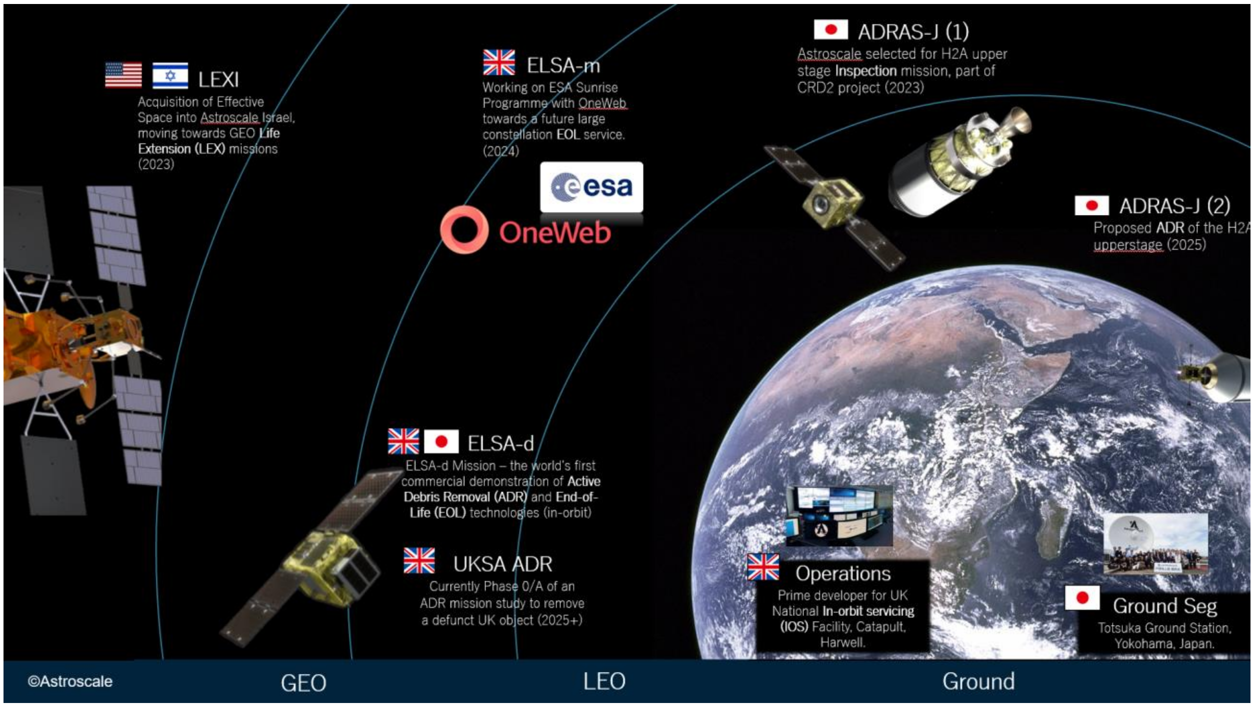

Figure 1: An illustration of Astroscale's current missions and activities around the world

2.1 ELSA-d

With the goal of being the world's first End-Of-Life demonstration mission, proving end-to-end debris removal technologies, ELSA-d (End of Life Service Demonstrator) was successfully launched from Baikonur Cosmodrome on 22nd March 2021 [1]. The mission, consisting of two initially docked spacecraft - a 180kg servicer and a 20kg client – is designed to explore the full phases of operations that would be necessary for a full EOL service. This includes client search, inspection, capture, re-orbit and de-orbit, and lends itself both to identifying SSA requirements for future RPO missions as well as supporting future SSA capabilities.

2.2 ADRAS-J

The JAXA Commercial Removal of Debris Demonstration project (CRD2) consists of two mission phases to achieve one of the world's first ADR mission of a large object, the first phase of which has been awarded to Astroscale. Phase One, involving comprehensive inspection of the object is due to launch in 2023.

2.3 ELSA-m

ELSA-m is being developed as a multi-client ('m') EOL servicer which aims to build on the heritage of the technology from ELSA-d. It is planned to be equipped with rendezvous guidance, navigation, and control (GNC) technologies, as well as a magnetic docking mechanism specifically designed to be compatible with the docking plates on future commercial satellites.

2.4 LEXI

Life Extension (LEX) services in GEO are under development in the form of a servicer spacecraft which docks with the client and provides station-keeping and attitude control for the joint stack. Expected launch for the first Astroscale LEX mission is 2023.

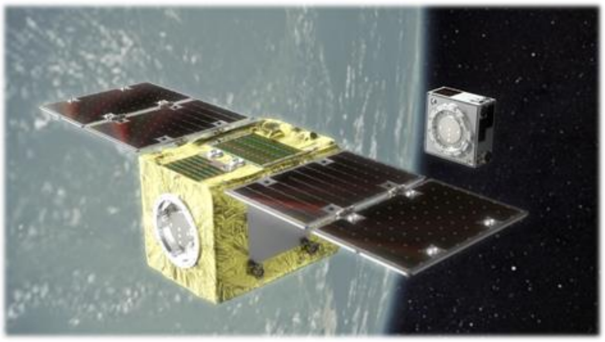

Figure 2:Illustration of ELSA-d, the End-of-Life (EOL) Services by Astroscale demonstration mission

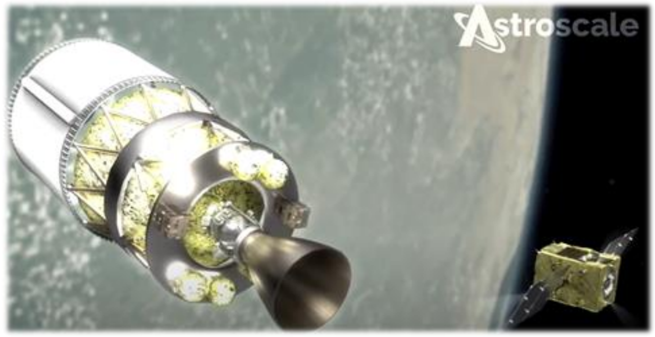

Figure 3: Illustration of *ADRAS-J, the JAXA Commercial Removal of Debris Demonstration project*

3. UNDERSTANDING SSA REQUIREMENTS

Recent work [2] has sought to define and quantify the expected SSA requirements for an RPO mission. Planning for the ELSA-d mission has helped to highlight key needs and different mission phases. These requirements are closely tied to the operational phases of the mission [1]., which are illustrated in Figure 4, and are described in the subsequent section

3.1 ELSA-D CONOPS

As with all missions, SSA is required for **pre-launch**, particularly for Launch Collision Avoidance (LCOLA) to ensure the safety of initial insertion. RPO missions may also require additional client analysis, including assessed tumble rate and anomalous motion to ensure a viable and safe mission. During LEOPs (**Phase 1** on Figure 4) servicer acquisition requires SSA measurements to be correlated with the spacecraft telemetry, as with all non-RPO mission.

During and after commissioning (**Phase 2** onwards), in addition to appropriate Collision Avoidance (COLA) and planned manoeuvre support, client fault and failure analysis may be undertaken through SSA services. If, for example, the client is tumbling in a specific way, or has unusual trajectory motion, this might indicate a GNC or propulsion failure.

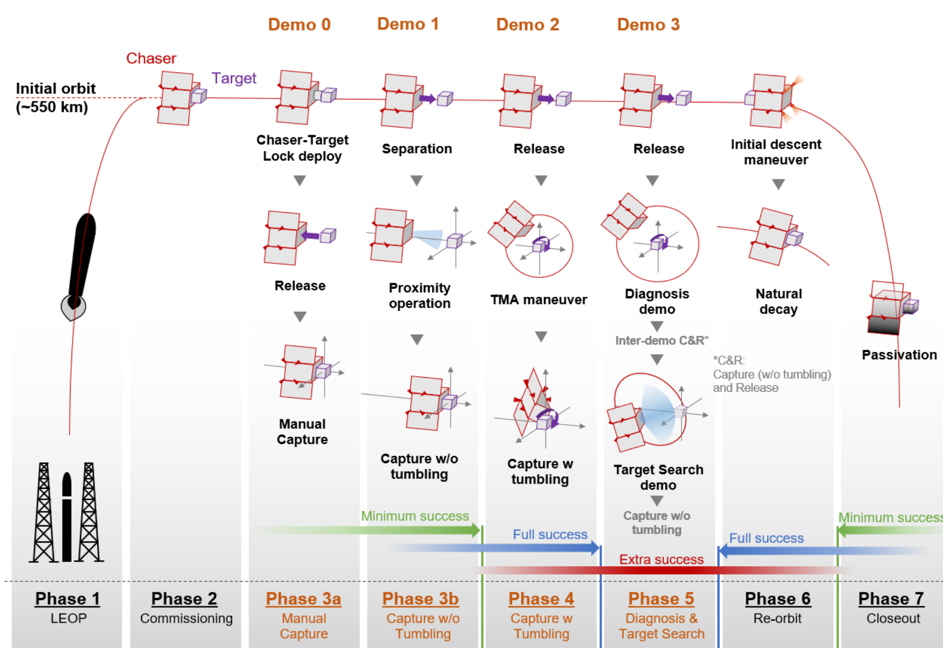

Figure 4: Illustration of ELSA-d CONOPS

Phases 3,4 and 5 of the ELSA-d missions are indicative of the operations that future RPO missions are likely to perform. Because of the unique nature of ELSA-d - both the client and servicer have onboard relative and absolute navigation sensors, as well as frequent telemetry down/uplink via the large network of ground-stations – the mission provides a rare opportunity to explore SSA capabilities to meet future RPO mission needs (this is discussed in detail in §3.2) Search and approach for ADR and EOL missions, cannot assume any onboard client capabilities, and so precision SSA services, in space but particularly in time, are needed. In addition, COLA operations involving two spacecraft in close-proximity require not only SSA service provision but appropriate support to identify efficient and safe risk mitigation.

Finally, re-orbit and de-orbit (**Phase 6 and 7**) involve typical SSA support that are needed for all missions, as well as bespoke input for more complex RPO missions. This may include, for example, multi-client de-orbit operations where defunct objects are manoeuvred into a short end-of-life trajectory whilst the service would then manoeuvre to a new transfer orbit.

3.2 DEFINING RPO SSA NEEDS

By considering the operational requirements of ELSA-d, needs for more general RPO mission SSA support, including ADR, EOL, in-situ inspection, refueling and other IOS mission types, can be defined. The ELSA-d mission is uniquely placed due to the planned close proximity between two well-characterised objects. This offers a rare opportunity for SSA service providers to observe the activity and behaviour of the two interacting ELSA-d spacecraft, and then compare these observations and analysis with the 'ground-truth' data (that is, the data directly provided by the ELSA-d spacecraft via telemetry or other high precision measurements).

There are several reasons in which this may be of use to SSA service providers or support organisations. The ground-truth data can be used to calibrate existing SSA/SST systems against measurement bias, as well as help to quantify accuracy and precision of their systems. Having data for two objects will enable unique assessment of their system's capabilities.

In addition, new and novel sensors (for example, low-cost ground-based cameras) can use the information to validate their capability, test the limits as to what their systems can discern (both in time and space), assess their ability to characterise the objects that are being observed (for example, tumble-rate using light-curve data) and provide insight into what level of operational support such systems might be able to provide. Finally, more mature SSA providers can use the information to build upon their current processes and capabilities to support future RPO missions, enhancing space-safety services such as COLA.

Table 1: Description of key SSA data requirements that are required for mission involving RPO

SSA capability	Data requirement
Servicer state (standard/RPO)	Position/velocity, element set and uncertainties/covariances
Client state (standard/RPO)	
Client attitude rate	Attitude or information to infer attitude (e.g. light curve data) with associated analysis.
Servicer GPS calibration	Analysis to compare GPS data to SSA state data to calibrate use of SSA to support mission operations
COLA (standard)	Screening against catalogue for provided ephemeris (standard or EP maneouvre)
COLA (EP manoeuvre)	Conjunction data messages (CDMs)
COLA (RPO)	To account for proximate client
L-COLA	OD information for rocket upper stage for launch window and Launch COLA screening
Space Weather Analysis	High energy particle flux
De-orbit and re-entry support	Analysis of servicer re-entry

Table 1 provides some of the key SSA data requirements for RPO missions, including those for operational support, space safety and more general needs, such as environmental data. Currently Astroscale are attempting to understand the fidelity of these needs, quantifying and bounding the accuracy and frequency of data. Figure 1 illustrates how some of these needs might relate to the example of ELSA-d and the mission phases (right-hand side). By using ELSA-d ground-truth data (top left box) alongside SSA measurements (bottom right box) it is hoped that Astroscale can support the validation of novel systems, calibrate sensors and help develop new SSA capabilities that can support RPO missions.

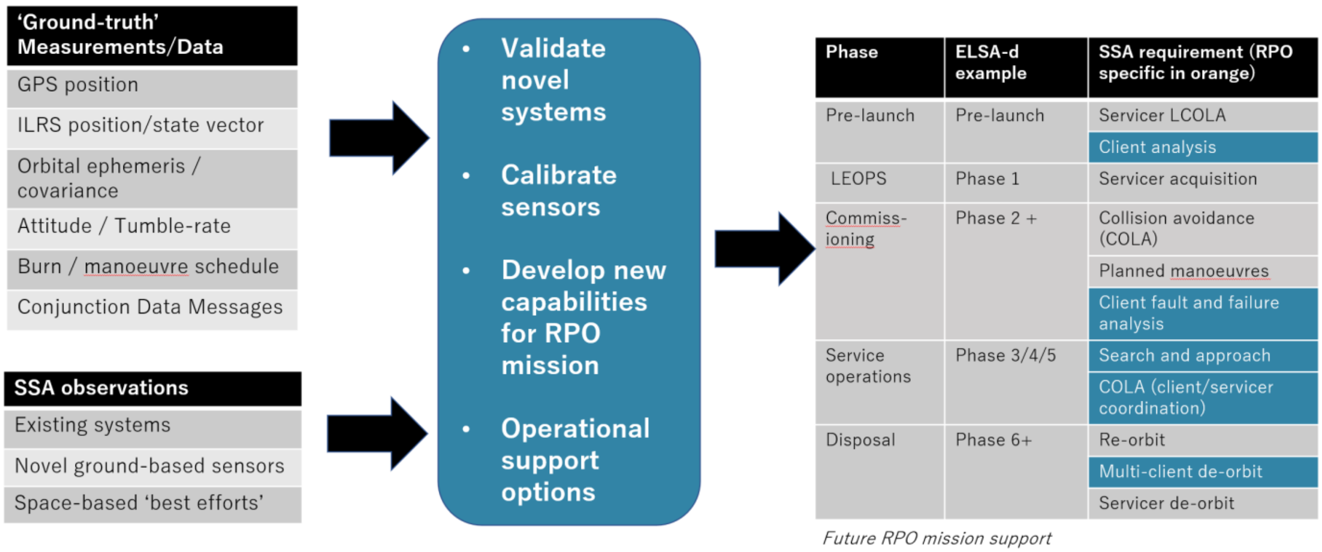

Figure 5: Illustration of how ground-truth data from ELSA-d can be combined with SSA observations to perform a number of vital SSA developments. The goal is to ensure that robust, reliable SSA capabilities are understood and available for future RPO missions.

4. LEVERAGING THE ELSA-d MISSION

Since launching from Baikonur Cosmodrome in March this year, we have been endeavoring to understand as much as possible about the SSA capabilities, both to support ELSA-d operations, but also to determine how the SSA needs of future missions can be met. Through a number of collaborations with SSA service providers, we have been examining ground-based capabilities, including ground-based radars, active and passive optical systems, and space-based optical systems.

4.1 GROUND-BASED TRACKING OF ELSA-d AND COLA

The ELSA-d mission is currently backed by a number of SSA service providers to ensure space-safety. The 18SPCS, ESA Space Debris Office and SpaceNav constitute direct support to ensure collision avoidance and distribution of space-safety information such as ephemeris and covariances. Astroscale has also had several coordination discussions with other spacecraft operators, including NASA. In addition to this, ELSA-d is being used to understand the accuracy and robustness of SSA services for future missions. Data from LeoLabs, AGI/ComSpoc, 18SPCS and the International Laser Ranging Service (ILRS – see §4.2) are being ingested and compared to ELSA-d telemetry (see Figure 6) . During the demonstration phases, when two objects in close proximity are manoeuvering, this information will be vital in assessing how SSA services can support operations, both nominally or in the case of anomalies.

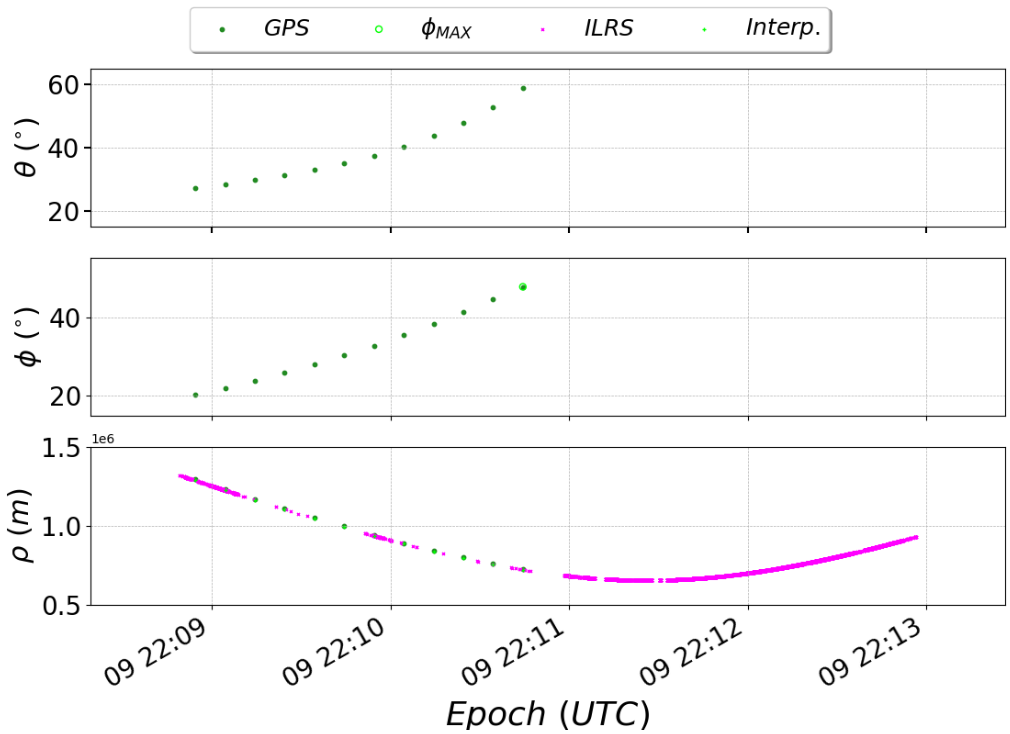

Figure 6: Example of a comparison GPS (dark Green), interpolated radar measurements by LeoLabs (light green) and ILRS observation during a pass over Graz.

4.2 GROUND-BASED OPTICAL OBSERVATIONS OF ELSA-d

Ground-based optical observations include use of active sensors such as Satellite Laser Ranging (SLR), and passive sensors to measure the magnitude of the object as it passes the camera FoV (photometry).SLR is of interest for two reasons. Firstly, laser-ranging can offer the highest positional accuracy of objects in space, greater than that of typical ground-based active RF systems as well as onboard telemetry using GNSS signals. This is both of operational importance during the ELSA-d demonstration phases to provide redundant accurate data should telemetry be unavailable, but also of use when considering SSA capabilities available for future missions. ADR missions, for example, will not have telemetry on the target object, and this may be the case for failed spacecraft which required de-orbiting as well. For these missions, accurate ephemeris would be required should relative navigation be unavailable from the servicer spacecraft. Secondly, laser ranging can potentially provide attitude state data [3]. This is particularly the case for failed spacecraft equipped with retro-reflectors, and may also be feasible for debris targets or those without retro-reflectors. To explore this further, Astroscale have been working with the ILRS, as well as directly with the Austrian Academy of Sciences (AAoS) at Graz. Recent SLR data of ELSA-d is illustrated in Figure 7. It is hoped that comparisons with ELSA-d telemetry will enable us to assess its operational use for future missions.

Also of interest is the use of photometry, specifically to determine the attitude state of the object [4,5]. This includes the rate of tumble, rotation axis and stability. Because of the well characterised nature of the ELSA-d servicer and client objects, in terms of both the telemetry as well as the dimensions and composition, it is hoped that observations can used to assess how photometry can be used to assess future ADR or EOL client objects. In addition, because of the unique nature of the mission, involving two objects separating and moving apart in a well conditioned stable state, it is of interest to understand what photometry can tell us about the RPO manoeuvres. Both AAoS at Graz and ShareMySpace are both currently making observations of ELSA-d (see Figures *Figure 8* and *Figure 9*). In the future it is hoped that the need for this data, supported by these activities, will lead to the development of commercial services able to provide this data to the in-orbit servicing community.

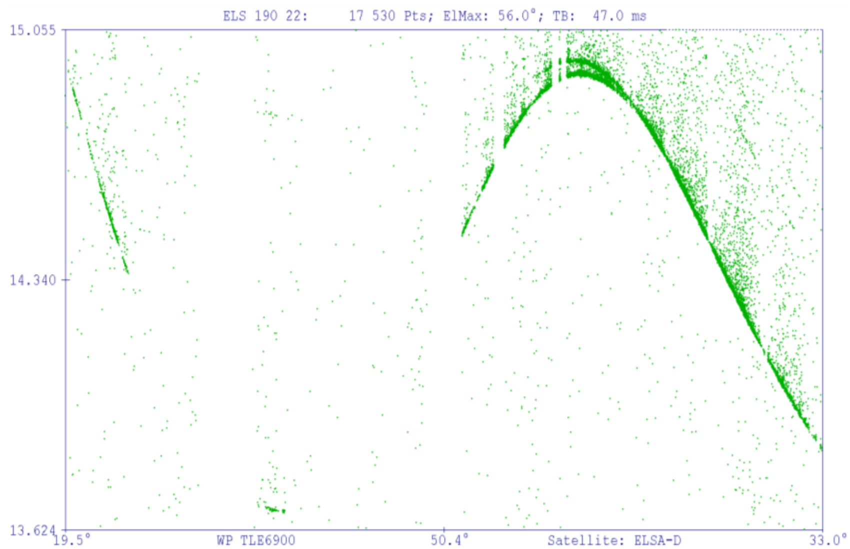

Figure 7: Example ILRS raw data provided by AAoS during a pass over Gra (courtesy Austrian Academy of Sciences)

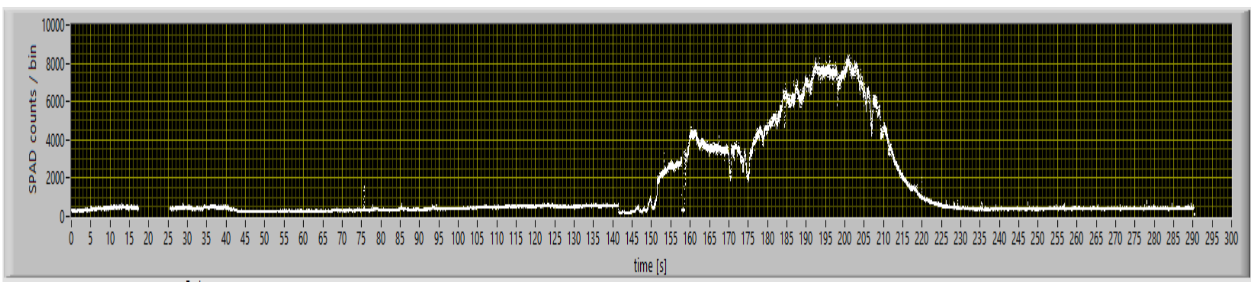

Figure 8: Example light-curve photometry provided by AAoS during a pass over Graz. There is limited large scale structure due to the current stable attitude of ELSA-d (courtesy Austrian Academy of Sciences)

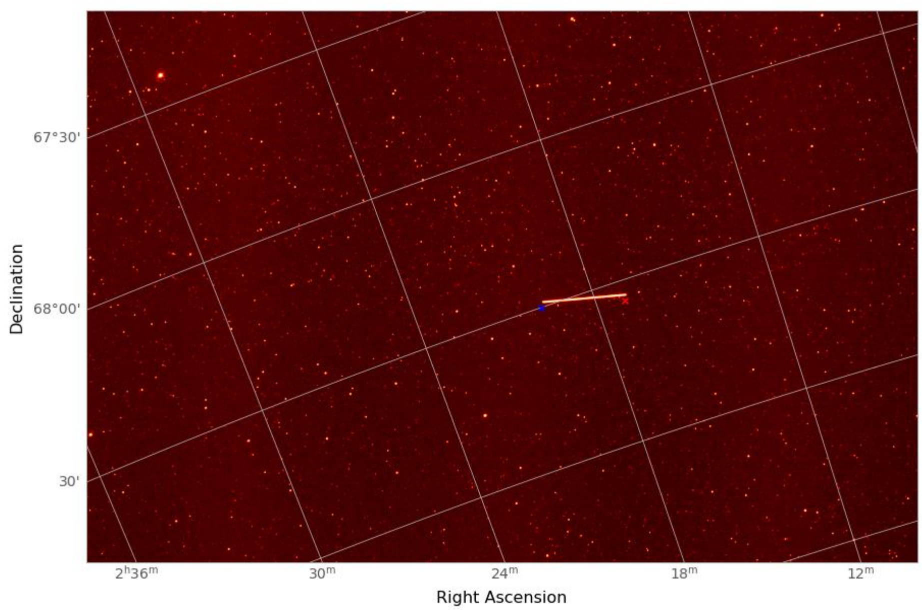

Figure 9: Passive optical imagery of ELSA-d on night of 18-19th July (courtesy ShareMySpace)

4.3 SPACE-BASED OPTICAL OBSERVATIONS

Resolved imagery of objects in orbit is of interest to missions like ELSA-d, as well as RPO missions in general. Resolved imagery can provide useful information about a potential ADR debris targets, such as the condition of the vehicle, attachment structures, potential risks in removal and possibly the dynamical state of the object. This is useful for mission planning or assessing objects during operations. Ground-based imagery is problematic due to atmospheric effects and large stand-off distances which limit the imaging resolution of orbiting objects. HEO Robotics are currently working with Astroscale to perform fly-by inspection of ELSA-d to explore the capabilities for future ADR missions [6]. In addition to providing mission information, resolved imagery is useful for operational transparency and confidence building measures, something that will be essential as RPO missions between international commercial organisations become more commonplace. *Figure 10* illustrates simulated imagery of a potential close-approach fly-by during one of the later demonstration phases of the ELSA-d mission.

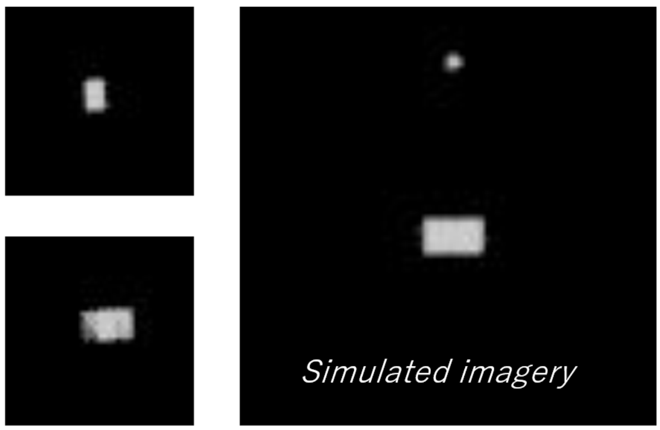

Figure 10: Simulated images of ELSA-d, showing undeployed/deployed chaser (left) and RPO manoeuvre during demonstration phase.

4.4 IN-SITU SSA USING ELSA-d

In addition to using the ELSA-d mission to support SSA development, it is of interest to explore how the onboard sensors can be used to directly support SSA. ELSA-d is equipped with optical sensors, or visual cameras, called 'VISCAM'. These are for the proximity visualisation of the client object to perform ultra-close inspection and assess the motion of the client. However, it is also of interest to understand how well these sensors might perform for direct SSA uses.

In collaboration with ESA, Astroscale will test the VISCAM for this purpose during the ELSA-d mission. The experiment objective will be to investigate the (re-) use of wide-field space-based small camera for monitoring the situation in high altitude orbits. The aim will be to improve image processing methods as risk reduction for future dedicated space-based optical payloads or missions.

5. SUMMARY

Astroscale recognise the importance of SSA to future RPO missions, including IOS missions such as ADR and EOL. To support the needs of Astroscale and other mission operators, we are currently developing SSA requirements for future missions and intend to use the recent successful launch of ELSA-d to help support this. It is expected that ground-truth data from ELSA-d will be helpful in the development of current and future SSA service capabilities can underpin RPO-type missions. As Astroscale are one of the first users of SSA for this specific application, our unique customer-side insight helps ensure we can drive SSA provision in support of these missions. We are continuing collaborations with a number of partners, exploring the use of ground-based and space-based observations to help better understand SSA capabilities for future Astroscale missions.

In addition to understanding mission SSA needs, future Astroscale missions also offer the chance to investigate novel SSA applications and opportunities. Preliminary work to understand applications and benefits of In-Situ SSA, for example, are underway. This includes the future use of the VISCAM/NAVCAM onboard ELSA-d mission to explore their capabilities

6. REFERENCES

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