An exploration of opportunities to advance ground-based and space-based SSA systems through in-orbit demonstration missions

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ABSTRACT

Astroscale's core mission objectives encompass a range of Rendezvous and Proximity Operation (RPO) focussed activities, including End-of-Life (EOL) services, Active Debris Removal (ADR) capabilities, spacecraft Life Extension (LEX) and space-based 'In-situ Space Situational Awareness' (ISSA). 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.

High fidelity SSA data allows users to accurately interpret and characterize the activity of satellites, improving operational safety and reducing the risk of collisions by increasing ability to recognize abnormal or off-nominal behaviour. Astroscale continues to improve our understanding of SSA needs for its future ADR and EOL missions, further refining the specialised needs and key technical drivers for these bespoke mission types.

In addition to understanding mission SSA needs, future Astroscale pursuits also offer the chance to investigate novel SSA applications and opportunities. The imminent launch of the ELSA-d EOL technology demonstration mission, followed by the JAXA funded ADRAS-J ADR inspection mission, provide ideal platforms for this purpose. These missions offer the prospect of verifying and validating low-cost, novel ground-based and space-based sensor systems, as well as exploring the commercial-off-the-shelf (COTS) technologies re-purposed for SSA applications. These systems would be indispensable in both improving space safety as well as constructing improved and comprehensive catalogues of space debris and their distributions.

Further to expanding on the needs of SSA for RPO missions, this paper seeks to address how upcoming missions might be used to explore opportunities to advance both ground-based SSA architectures and In-situ 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.

Space Situational Awareness (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. These missions are not only underpinned by the need for comprehensive SSA capabilities, but they

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also offer the opportunity to explore and develop SSA technologies, applications, and future services.

2.1 ELSA-d

With the goal of being the world's first End-Of-Life (EOL) 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. 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 (see §4) as well as supporting future SSA capabilities (see Section §5).

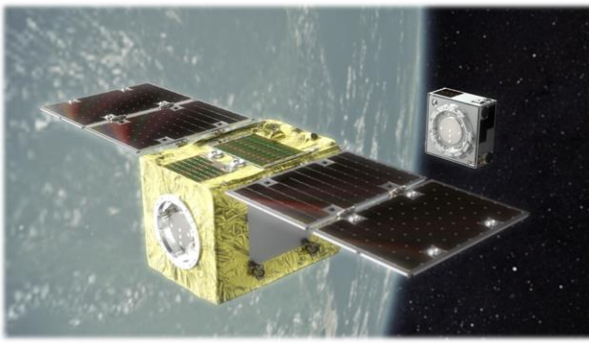

Figure 1.ELSA-d: End-of-Life (EOL) Services by Astroscale demonstration mission

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 Active Debris Removal (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.

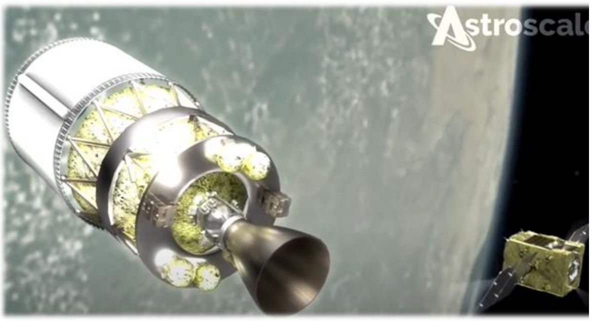

Figure 2. ADRAS-J:The JAXA Commercial Removal of Debris Demonstration project

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 3. LEXI: Life-extension services mission in GEO

3 RPO MISSION REQUIREMENTS

Recent work [1] 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, which are illustrated in *Figure* 4, and are described as follows:

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.

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 target 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). 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.

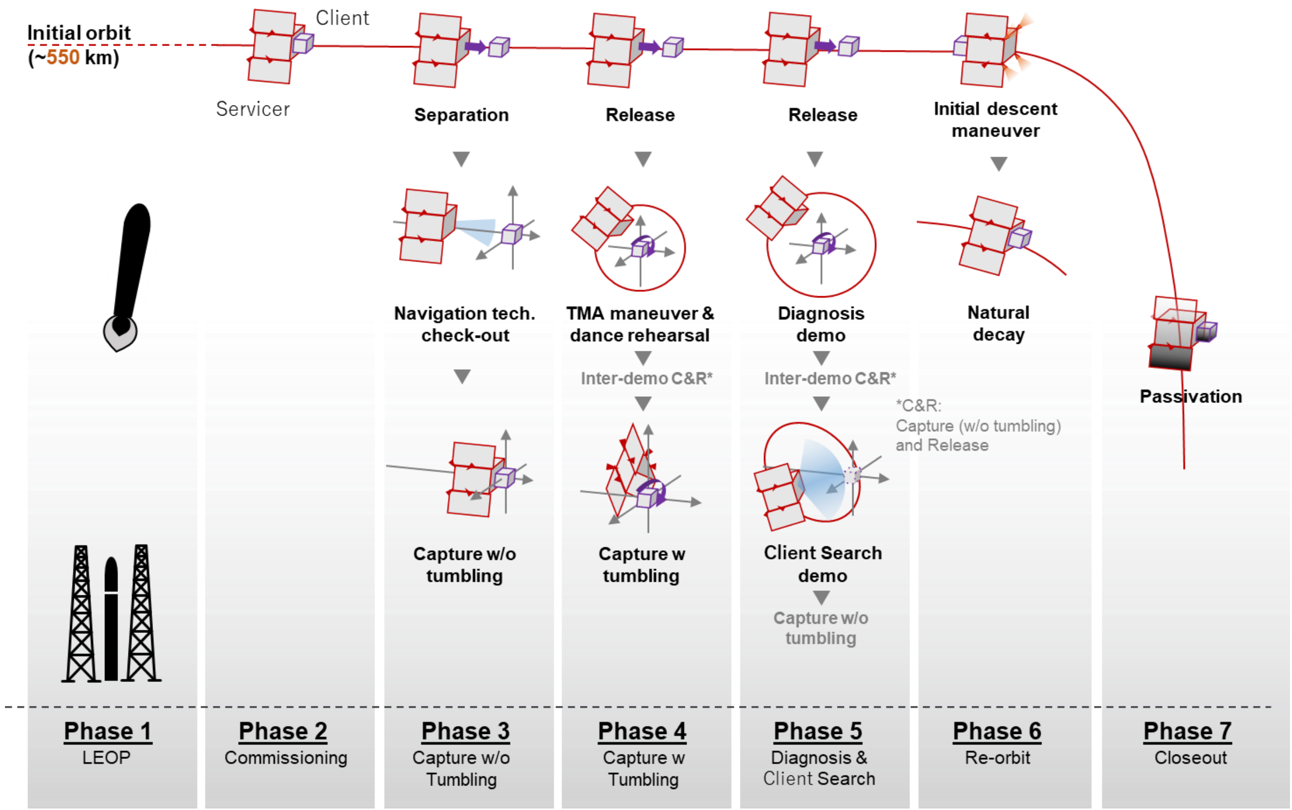

Figure 4. Illustration of ELSA-d CONOPS

4 SUPPORTING SSA DEVELOPMENT FOR RPO

The ELSA-d mission is a 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 summarises some of the measurements or data that could be used to support some of these activities.

	Measurements/Data
[1]	Manoeuvre / event schedule
[2]	Conjunction Data Messages (CDM)
[3]	Orbital Ephemeris / covariance (OEM)
[4]	GPS position
[5]	Attitude / Tumble-rate
[6]	Laser ranging position/state vector

Table 1: Overview of the different data that could be recorded/processed and used.

Astroscale are keen to explore data-sharing with SSA service providers with the goal of establishing capabilities to support future Astroscale missions. We seek to encourage validated and robust SSA capacity to meet some of the RPO-specific needs detailed in §3, including pre-launch/ through-mission client assessment, search and approach and RPO-COLA.

5 SUPPORTING SSA

As well as understanding direct SSA needs for Astroscale missions, we are also considering how the technology and operational development of these missions can contribute to the wider SSA community. One area of recent study has been exploration of Space-based or In-Situ SSA ('ISSA') which involve the use of space-borne sensors to characterise both the space environment and activities in space. With funding from the UK Space Agency, Astroscale were able to partner with Northern Space and Security (NORSS) to develop some broad understanding of the benefits and drawbacks of ISSA approaches. One of the objectives of this work is to provide some initial considerations on what a low-cost ISSA mission might look like, and what types of missions it might be able to support. For the purposes of this study, the capability of the NORSS LOCI system [1] was used as an example of what a low-cost in-orbit sensor could be capable of.

5.1 ISSA system exploration

The study began with a detailed examination of what constitutes and ISSA system, including the different types of missions and mission objectives, architectures, systems, and technologies. Much of this was assessed through extensive review of the literature on ISSA systems [2-18] Three mission objectives were defined: **Remote-survey (wide-field)**, for background profiling of Resident Space Objects (RSOs), and RSO cataloguing; **Remote-survey (narrow-field)** including surveillance, tracking and remote inspection of specific RSOs of interest; and **Close Inspection**, in which the ISSA spacecraft typically enters a near-identical orbit with the target RSO and uses onboard sensor packages to survey the object from tens of metres.

The study also considered in more detail what the mission might look like in terms of where the platforms should be located, what number and configuration they could be, and what aspects of the mission geometry (for example, where the sun is) needs to be considered. It was clear that when building an ISSA mission, the mission objectives very much affect these aspects and visa-versa when considering constraints on what the ISSA platform can do. The study sought to provide an overview of key systems and technologies that are needed, including making a clear distinction between instruments that are used for relative measurements in space and those used to make absolute measurements. Whilst there is clearly no right answer to which configuration or system for an ISSA mission is best, there are clearly preferential configurations for a given mission. For example, observation of small debris in GEO is best done from multiple spacecraft spread evenly about, the GEO belt, whilst optical cataloguing of all objects from LEO is best performed using a dawn-dusk SSO with a sensor facing away from the sun, but the field-of-view orientated so not to intersect with earth's umbral shadow.

5.2 Current and future ISSA systems

The study continued with an examination of current and future ISSA systems, both commercial and national, and consider the development of ISSA as a market. This was underpinned by an extensive review of the current literature [19-23] The preliminary conclusions of this work are now discussed.

The ISSA market is emerging and expected to mature by 2030 with several new commercial providers and a wide variety of applications. The overall ISSA market is currently driven by government and insurance claim demand, with a market size expected to be around $100-540M.

Potential future customers for ISSA include defence and commercial, such as the insurance market, GEO operators and proliferated satellite constellations. Indeed, to date the most active ISSA missions are from governments or the military (such as SBSS-1, US GSSAP and Sapphire [19]) as well as several small CubeSat missions. Future missions include a few universities and governments missions and mainly commercial missions (a dozen from 8 different countries).

Some in-orbit service providers are also looking at offering inspection services ancillary to their primary mission. In addition, several companies are preparing services for the GEO market to inspect space assets on-demand, with the aim to propose a greater image quality at a lower price than terrestrial SSA, as well as wider and more persistent coverage, unaffected by weather or light pollution.

Overall, current and future ISSA providers perceive ISSA as an enabler of new space activities as well as an augmentation to existing SSA capabilities.

5.3 Quantitative ISSA comparison

This work also considered some preliminary assessments of ISSA vs equivalent terrestrial sensors. As an example, the specifications of the NORSS LEO Optical Camera Installation (LOCI) [19] were used to define an in-orbit SSA mission. An idealised mission based on cataloguing active spacecraft in LEO was used. The ISSA mission platform was implemented in a dawn-dusk Sun-synchronous orbit at an altitude of approximately 550km and inclination of 97.5 degrees (the same as ELSA-d). Because of the orbit geometry, initially the camera was chosen to face perpendicular from the orbit plane and facing away from the sun (along the -ve W-axis in RSW orbit-frame coordinates). To perform the analysis, two simulation capabilities were used: the Brightness Analysis, Lightcurve Determination and Reproduction (BALDR) tool, developed by NORSS; and the In-Orbit Technical Assessment (IOTA) model, developed at Astroscale. For both simulations the initial population of objects to be sampled is taken from the SpaceTrack [20], and the initial epoch for all simulations was taken as midnight on 1st December 2020 (North pole winter, south pole summer).

To assess the use of an in-orbit optical camera, a number of comparison metrics have been developed, both to compare between terrestrial SSA and ISSA, and as an absolute measure of how effective an ISSA optical system might be. These include the average pass duration, the percentage of the population observed during the simulation time, the total observation time of objects within the Field-of-View (FoV) of the sensor, the average observation number (i.e. for those objects observed at least once) and the average revisit time (for those objects observed at least twice).

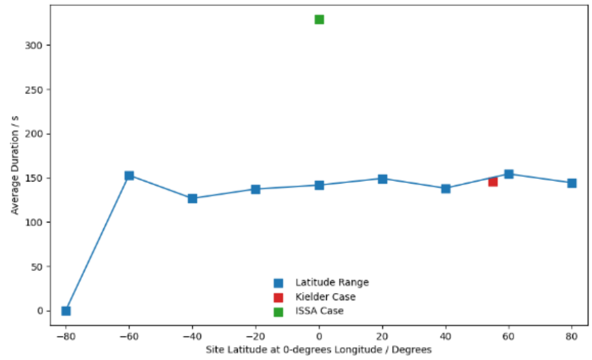

Figure 5: The average pass duration per object as a function of latitude for the ground-based LOCI system

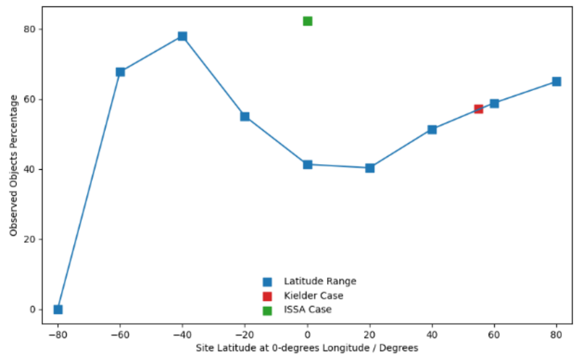

Figure 6: The percentage of the sample population that was observed during the simulation period.

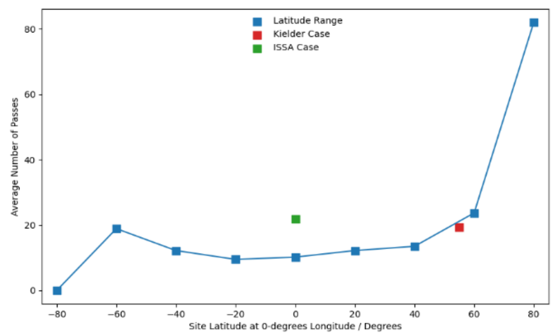

Figure 7: This graph shows, for all the objects that were observed, what the average number of observations were made per object.

Figure 5 to *Figure 7* summarise the results of a week-long simulation using BALDR for a population of 509 active spacecraft. In each figure, the blue dots represent the results of the ground-based LOCI stations at different latitudes (noting that it is winter, and therefore persistently dark at northern latitudes), whilst the green dot represents results from a single spaceborne sensor. The results suggested that there is clearly some scope for the use of ISSA platforms to provide improved coverage in comparison to ground-based optical systems using the LOCI system. This is true in terms of frequency of revisits, potentially enabling more regular follow up observations and therefore improved orbit determination. It is also the case in terms of the percentage of the population observed: space-based sensors are likely to be able to observe a large number of objects not visible to ground-based sensors, including radar. Because of the range to the objects being observed, as well as the lack of atmospheric attenuation, whilst not explicitly modelled in this study, it is also highly likely that observations would experience much better SNR, an important aspect enabling photometric analysis as well as improved orbit determination accuracy.

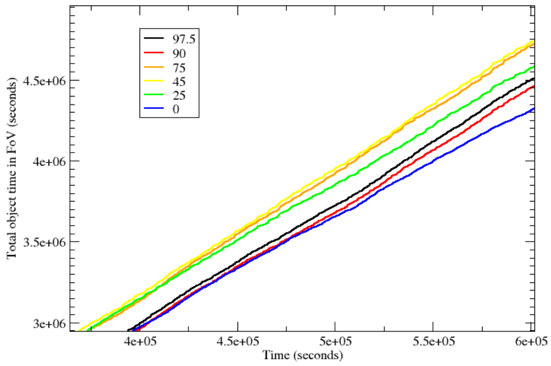

Figure 8: Total time that objects observed within the ISSA's platform FoV for six different inclinations, from SSO (97.5 degrees) to equatorial (0 degrees).

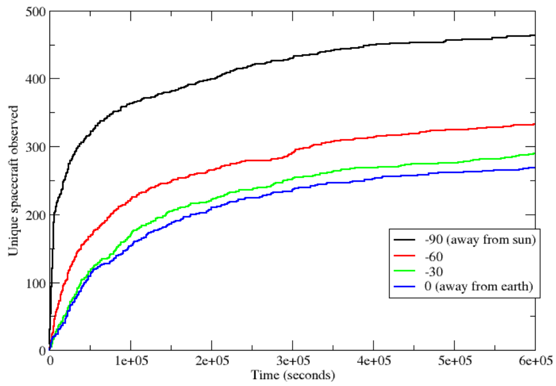

Figure 9: Total number of unique objects observed by the ISSA platform for three different camera elevations on the platform (from -90 degrees, which is perpendicular to the orbit plane).

As well as comparing to ground-based LOCI, several in-orbit LOCI variations were considered. IOTA was used to explore the impact of varying the spacecraft's orbit and camera orientation on the ability to make observations, as illustrated in *Figure 9* and *Figure 8*. These preliminary results suggest that the number of LEO objects captured is roughly independent of orbit orientation for this scenario, with a slight peak at inclinations around 45° to 75°. This is not likely to be the case when considering non-LEO objects (particularly the constrained inclination of objects in GEO). The orientation of the camera for an SSO configuration has much more significant impact. This is most likely due to the inability for the system to observe objects below the platform orbit for a radially outward facing LOCI sensor and would change with reduction in platform altitude. *Note – in these simulations the impact of earth eclipsing was not accounted for, and hence the -90° case overestimates the number of objects captured within the FoV.*

Overall, for a space-based LEO ISSA platform fielding a LOCI-type camera, an SSO orbit is preferable, with the LOCI camera orientated in such a way as to direct away from the sun and at an elevation to minimise (or remove) eclipsed objects from the field of view. For a 97.5° inclination and 40° FoV, then an elevation of around -62.5° from the outward radial would be optimal to maximise observation of LEO objects. Further work on this should be considered to refine optimal orbits for a LOCI-type sensor.

5.4 Exploration of ISSA with 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.

6 SUMMARY

Astroscale recognise the importance of SSA to future RPO missions, including 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.

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, including simulation studies and in-orbit tests, have been considered. This includes the future use of the VISCAM onboard the recently successfully launched ELSA-d mission to explore in-orbit SSA capabilities.

7 ACKNOWLEDGMENTS

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