IAC-22-A6.9.8

SSA observation campaign of the ELSA-d mission

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Abstract

Astroscale's ELSA-d mission, the world's first commercial demonstration of end-of-life (EOL) debris remediation capabilities, was successfully launched in March 2021. ELSA-d is being used to demonstrate the core technologies necessary for future active debris removal (ADR), including rendezvous and capture. The uniqueness of the mission provides an exclusive opportunity to explore both the Space Situational Awareness (SSA) demands as well as the associated operational safety and orbital coordination aspects of Rendezvous and Proximity Operation (RPO) missions.

ELSA-d consists of two spacecraft, a Servicer and a Client, initially attached together using a ferromagnet docking mechanism. The mission comprises a series of demonstrations, which started in August 2021. These demonstrations include the separation, manoeuvring and capture of the Client by the Servicer through use of remote tele-commanding and autonomous on-board GNC software. The unique nature of the demonstration and availability of telemetry for both spacecraft make this an excellent opportunity to explore Space Surveillance and Tracking (SST) capabilities for spacecraft in close proximity. To maximise the benefit of this, several space agencies and commercial SSA service providers performed observations and measurements of the spacecraft during their activities.

This paper first considers the ELSA-d demonstration from an operator perspective, starting with details of the demonstration activities and operations. The observations performed from ground-based SST assets tasked to observe the demonstrations are then discussed. SSA products from a variety of sources and using several instruments, such as radar and optical telescopes, were involved in the observation campaign. An analysis of the observations and data, including fusing data sources and comparing to ground-truth data provided from ELSA-d telemetry are presented. Finally, conclusions on key areas of future SSA development that are essential to support future RPO missions, and underpin developing in-orbit servicing missions, are then considered.

Keywords: proximity operations, low earth orbit, LEO, SSA, SST, tracking

Nomenclature

Δr – relative position, of Servicer relative to the Client or third-party ephemerides of each w.r.t. Astroscale's reference trajectory. Typically given in RIC frame.

r_S, r_C – osculating Cartesian positions of the Servicer and Client, respectively.

Δu – relative argument of latitude of Servicer w.r.t. Client.

M_S, M_C – mean anomalies of the Servicer and Client, respectively.

ω_S, ω_C – true anomalies of the Servicer and Client, respectively.

S_{dBsm} – signal strength in dBsm (dB per square metre)

Acronyms/Abbreviations

18SDS: 18th Space Defense Squadron

CA: Collision Avoidance

EU SST: European Union Space Surveillance and Tracking

FG: fragmentation service of EU SST

GNSS: Global Navigation Satellite System

IOD: In-orbit demonstrator

IOS: In-orbit servicing

RCS: radar cross-section

RE: re-entry service of EU SST

RIC: radial, in-track, cross-track (reference frame)

RPO: Rendezvous and Proximity Operations

RSO: Resident Space Object

SATAM: System for the Acquisition and Trajectography of Aircraft and Ammunition (radar)

SSA: Space Situational Awareness

SST: Space Surveillance and Tracking

TIRA: Tracking & Imaging Radar

1. Introduction

Astroscale's ELSA-d is an exceptional mission, involving two spacecraft acting in close proximity to one another. This affords a unique opportunity to understand how one can observe and analyse such a mission, often referred to as Rendezvous and Proximity Operation (RPO) mission, using remote sensing techniques. To do so is of benefit to many groups. For example, de-risking future commercial in-orbit servicing (IOS) missions can be performed by understanding to what degree Space Situational Awareness (SSA) is able to support critical operations. Defence organisations can also see benefit by assessing the ability to characterise RPO activities by accessing ground-truth data and ground-based SSA observations.

To support critical mission safety operations, Astroscale have several SSA service provides on contract or contributing through other agreements. This includes the US 18th Space Defense Squadron (SDS), ESA, LeoLabs [*] and SpaceNav [†]. However, as part of the mission, other SSA service providers have also been encouraged to observe and analyse the activities of ELSA-d, particularly during the key events such as separation and close-approach (see Section 4 for details). This includes programmes such as EU SST [2] and the commercial SSA company ShareMySpace [3]. This paper seeks to explore how SSA data from these observations compare to ground-truth data from the mission, and what can be learnt from this.

1.1 Astroscale

Astroscale is a global commercial venture with a focus on space sustainability.

SSA plays an important role for Astroscale – like in any space mission, it is essential to meet mission objectives safely and successfully. Astroscale needs comprehensive SSA data that allow accurate interpretation and characterisation of spacecraft activity, improvement of operational safety, and reduction of the risk of collisions by increasing the ability to recognise abnormal or off-nominal behaviour. An important aspect is to determine whether current commercial and institutional SSA services are sufficient for future IOS mission types. This is the principal reason for orchestrating an SSA observation campaign of ELSA-d.

In addition, as technologies and mission capabilities are constantly being developed, Astroscale are keen to see how it might contribute to the SSA ecosystem, and to specific missions and operations. This includes leveraging spacecraft and their sensors as a possible way to augment or provide independent in-space SSA (ISSA) capabilities.

1.2 EU SST

EU Space Surveillance and Tracking (EU SST) is the European Union's operational capability for safeguarding space infrastructure and contributing to global burden-sharing in the domain of Space Situational Awareness and Space Traffic Coordination/Management (STC/M). Implemented by a consortium of seven EU member states in cooperation with the EU Satellite Centre, EU SST serves nearly 40 user organizations with free services, such as Collision Avoidance (CA) for over 280 satellites.

EU SST operates a growing sensor network, which currently includes 50 assets distributed world-wide and comprising radars, telescopes, and lasers. These remain under the authority of the member states and rely on contributions of both civilian and military stakeholders, thereby reflecting the dual nature of the SSA provision. In a unique multilateral approach to SSA data sharing, measurements and orbit data from the contributing sensors are shared through a dedicated platform, the EU SST Database, and will be used to populate what will become a forthcoming European Catalogue of orbiting satellites and space debris.

Under the EU Space Programme, EU SST matures into a fully-fledged programme component maintaining its particular governance model, transitioning from seven to 15 member states, and therefore, enhancing the global commitment of Europe with the space sustainability. EU SST is understood as the "operational capability of the European Space Traffic Coordination and Management system", and it is also exploring additional services and synergies to enhance the current added value within the context of European and global STC/M.

[*] https://platform.leolabs.space/

[†] https://www.space-nav.com/

In this context, EU SST has cooperated with Astroscale as a system demonstration on SSA needs for future RPO and IOS missions. The idea behind was to analyse how EU SST sensors, data processing layer and services can currently contribute, and future evolve for the benefit of space sustainability, seeking synergies with the three existing services (CA, RE and FG) and the evolution of those.

The goal of this joint exercise with Astroscale was to work with international partners in the development of the understanding of future SSA capabilities at the service of new space and missions.

1.3 ShareMySpace

Share My Space is a private company providing SSA and SST services. Since 2020, a network of observatories has been developed to offer a service of on-demand observations for tracking and characterisation of space objects using astrometric and photometric data. Currently, two observatories are operational in the North and South of France, fully automated and equipped with RASA telescopes, with respective apertures of 203 and 356 cm. The latter is capable of tracking objects of approx. 10 cm diameter at altitude of 500 km.

Share My Space was working with Astroscale during the ELSA-d demonstration mission to understand the needs of future ROP and IOD missions, in order to be able better to support them in the future.

2. ELSA-d Mission

ELSA-d has been designed as an in-orbit demonstration (IOD) of key technologies needed for future active debris removal (ADR) and end-of-life (EOL) missions. The two types of missions are different – in the former, the ADR target is unprepared and uncooperative while for EOL, the client is at least prepared to be removed from orbit by a dedicated servicer spacecraft. For example, EOL-prepared spacecraft are typically fitted with a docking plate and guidance markers that can be used during the final approach just prior to docking.

This section gives a brief overview of the ELSA-d spacecraft, the mission concept of operations (CONOPs) and its timeline.

2.1 ELSA-d spacecraft

ELSA-d mission consists of two spacecraft: a 175 kg Servicer and a smaller (17 kg) Client, which were launched stacked together. The physical dimensions of the two craft are respectively 0.5x0.5x0.2 and 0.7x0.6x1.1 m. Note that this ignores Servicer's deployable solar arrays.

The Servicer is equipped with proximity rendezvous sensors and a magnetic capture mechanism, whereas the Client carries a docking plate, which enables it to be captured (see Figure 1). 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 tumbling and non-tumbling Client capture.

ELSA-d is operated from the UK's National In-orbit Servicing Control Centre Facility, with support being provided by Astroscale's Japan office, where the mission was designed, and the Servicer built. The Client's prime contractor was SSTL, who also provide engineering support during mission operations.

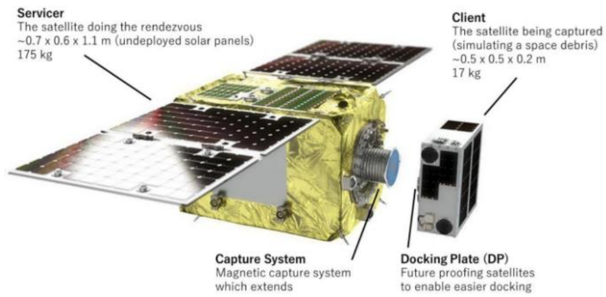

Figure 1: ELSA-d space segment overview.

2.2 Mission demonstration sequence and event timeline

The ELSA-d stack was launched from Baikonur on 22 Mar 2021 to an approximately 550 km, circular sun-synchronous orbit. Following the launch and early-phase (LEOP) part of the mission, the Client was first released and immediately re-captured by the Servicer on 25 Aug 2021.

More in-orbit checkouts and calibration followed, leading to the next Client release on 25 Jan 2022. This time, the Servicer moved to a "Home position" 30 metres behind the Client (negative in-track separation) and maintained this formation for several hours.

An anomaly was detected during this demonstration, which resulted in the Servicer performing an active abort burn and thus departing from the Client. By the time the issue was understood and resolved, the Servicer had drifted to more than 1600 km ahead of the Client. A sequence of approx. 40 manoeuvres was then performed, which ultimately took the Servicer to 159 m from the Client on 7 Apr 2022 after which the two were allowed to drift apart again. The timeline of this mission phase and of the events that transpired are described in more details by Forshaw et al. [1], while this paper focuses on the SST-related experiments and findings, particularly around the closest approach between the Servicer and the Client.

2.3 ELSA-d orbit determination

Different sizes of the two craft mean that the ability of ground-based SSA to detect and track them, as well as the accuracy of the resulting ephemerides vary. Figure 2 and Figure 3 show respectively the Servicer and the Client observed by a 356 cm aperture Share My Space

RASA telescope. The particularly bright streak of the Servicer saturated the camera while the smaller Client was less visible. For reference, at a phase angle of 112 degrees, magnitude of 13 was measured for the Client with a signal-to-noise ratio of about 4. A comparable metric for the Servicer cannot be estimated without adjusting the sensor gain or exposure settings to avoid saturation. This was not yet attempted but adjusting the settings on a per-object basis is part of the on-going work.

In order to cope with this varying tracking accuracy, both craft carry GNSS receivers and laser retroreflectors. The GNSS position fixes and International Laser Ranging Service (ILRS) measurements are fed into Astroscale's orbit determination (OD) process, which is used to generate operational ephemerides. These orbital solutions include planned as well as past Servicer manoeuvres (the Client does not have a propulsion subsystem and cannot manoeuvre).

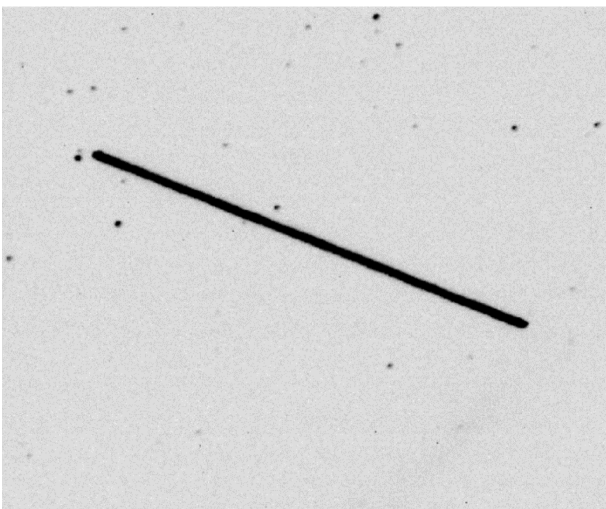

Figure 2: Servicer passage in the field of view of a telescope, obtained with an exposure time of 800 ms and maintaining the sideral tracking

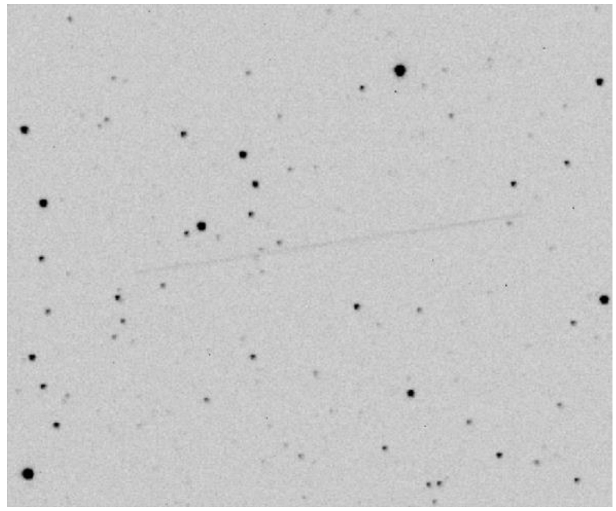

Figure 3: Client passage in the field of view of a telescope, obtained with an exposure time of 800 ms and maintaining the sideral tracking

3. Mission timeline from the SSA perspective

This section presents the above ELSA-d mission timeline from the active abort manoeuvre conducted on 25 Jan 2022 until the closest approach on 7 Apr 2022. A timeline of these and other key events of the mission is overlaid on a plot of the relative distance between the two craft in in Figure 4. The relative distance ρ was computed from the osculating positions of the Servicer (r_S) and Client (r_C) as:

$$\rho = |\overrightarrow{r_{CHS}}\text{-}\overrightarrow{r_{TGT}}|. \quad (1)$$

Figure 5 and Figure 6 illustrate the same time interval but respectively show the angular separation between the two spacecraft, Δu, and the relative position in Client-centric radial, in-track, cross-track (RIC) reference frame. These have been computed as:

$$\Delta u = u_S - u_C = (\omega_S + M_S) - (\omega_C + M_C), \quad (2)$$

$$\Delta r = r_S - r_C. \quad (3)$$

Note that mean (M), rather than true anomaly (ω) was used to compute Δu as proposed by Aardens et al. [4].

These figures were created by ex-post analysing all the Astroscale OD solutions and creating reference trajectories from them that best fit the raw GNSS (GPS in this case) data and ground-based observations. Note that they were not available during the operations for manoeuvre planning etc. but can be regarded as truth data.

Besides these reference trajectories (denoted as COMB-20220806T09 in the figures), the following third-party ephemerides are also shown:

- SP – special perturbation state vectors from the 18th SDS (SP_VEC) at their respective epochs,
- LEO – LeoLabs state vectors at their epochs,

- 47944, 51288 – TLEs generated by the 18th SDS for respectively the Servicer and the Client, at element set epochs.

By and large, all the ephemerides follow the same trend as Astroscale reference trajectories – the Servicer first departed from the Client on 25 Jan 2022, drifted ahead of it at a lower altitude, then raised the altitude, drifted backwards, equalised the altitude, and made repeated close approaches to the Client.

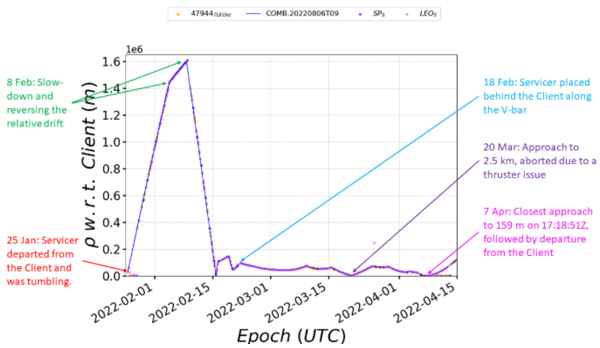

Figure 4: Relative Euclidean distance between the Astroscale ephemerides of the Servicer and Client, indicating key events during the mission. Other ephemerides (TLEs and SP_VECs from 18th SDS, and LeoLabs state vectors) shown as dots at their respective epochs.

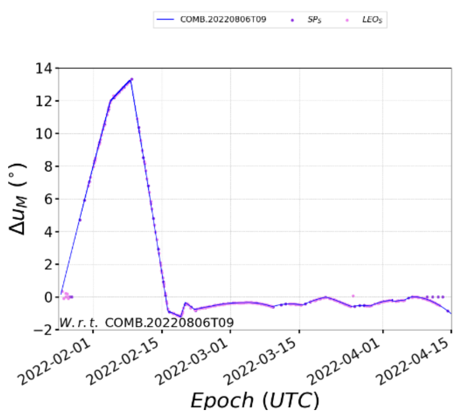

Figure 5: Relative argument of latitude between the Astroscale ephemerides of the Servicer and Client. Other ephemerides (TLEs and SP_VECs from 18th SDS, and LeoLabs state vectors) shown as dots at their respective epochs.

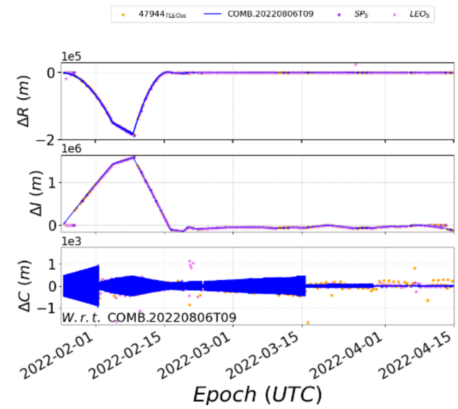

Figure 6: Relative position between Astroscale ephemerides of the Servicer and Client in Client-centric rectilinear RIC frame. Other ephemerides (TLEs and SP_VECs from 18th SDS, and LeoLabs state vectors) shown as dots at their respective epochs.

4. SSA events of interest

Figure 7 shows the relative range between the two craft just like Figure 4 but indicates events relevant not as much to the mission timeline itself but to the tracking of the two craft. This section analyses each of them in closer detail.

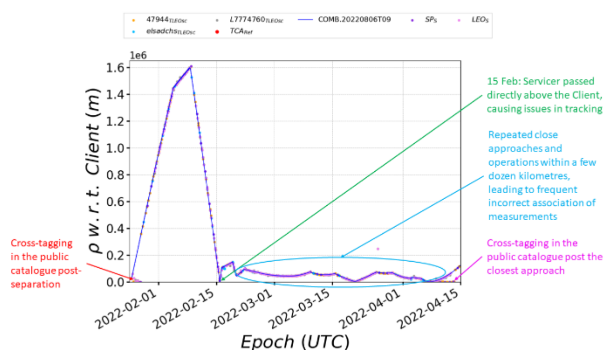

Figure 7: Relative Euclidean distance between the Astroscale ephemerides of the Servicer and Client, indicating key SSA-related events that occurred during the mission. Other ephemerides (TLEs and SP_VECs from 18th SDS, and LeoLabs state vectors) shown as dots at their respective epochs.

4.1 Servicer/Client separation and cross-tagging (25 Jan)

As described by Forshaw et al. [1], the Servicer performed an active abort manoeuvre and departed from the Client on 25 Jan 2022, and subsequently drifted ahead of it at a lower altitude while tumbling. The magnitude, direction and epoch of this abort manoeuvre were not immediately known by Astroscale, and so it was impossible to reflect them in the orbit determination. The unexpected and unknown ΔV, and the loss of attitude quickly rendered absolute navigation solutions from before the manoeuvre unreliable. So much so that the time offset values of consecutive ground station passes had to be constantly adjusted to maintain communication with the spacecraft. Ultimately, the Servicer's attitude was recovered, orbit determination updated, and the relative drift stopped. This incident is shown in Figure 8 and Figure 9, which illustrate how third-party ephemerides are located w.r.t. the ex-post determined Astroscale reference trajectories.

Shortly after the separation, 18th SDS incorrectly determined or assumed that the Servicer remained in its former orbit and that it was the Client which was drifting ahead. This is to say that the 18th's ephemerides were behind (negative in-track separation) the actual trajectory of the Servicer, and ahead of the trajectory of the Client. This phenomenon is visible as orange and purple dots (TLEs and SP_VECs, respectively) diverging from Astroscale's Servicer trajectory in Figure 8. Likewise, the pink and green dots diverge from the reference Client trajectory in Figure 9. At the time, LeoLabs were not yet tracking the Client spacecraft because it had just separated from the Servicer. However, their ephemerides of the Servicer also indicated the Servicer in place of the Client. This was subsequently understood to have been caused by the reliance of LeoLabs on the catalogue of the 18th SDS for observation scheduling, which has since been improved.

This incident demonstrates that, for a period of time, the two spacecraft were swapped in the public catalogue, or "cross-tagged". As soon as this situation was confirmed by Astroscale, 18th SDS was contacted and the cross-tagging resolved – the first correctly-associated TLEs appeared late on 27 Jan, and SP_VECs on 28 and 29 Jan for the Client and Servicer, respectively.

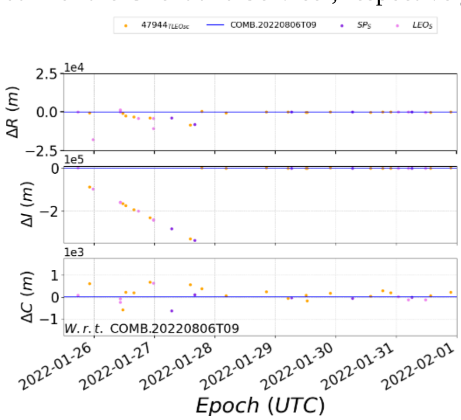

Figure 8: Relative position between Astroscale Servicer reference trajectory and other ephemerides in Servicer-centric RIC frame shortly after the departure from Client on 25 Jan 2022.

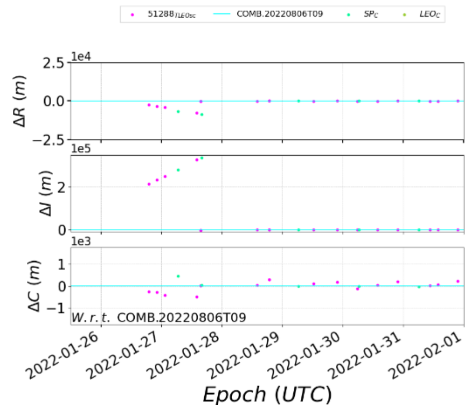

Figure 9: Relative position between Astroscale Client reference trajectory and other ephemerides in Client-centric rectilinear RIC frame shortly after the departure of the Servicer on 25 Jan 2022

4.2 Closest approach and cross-tagging (7 April)

The two spacecraft approached to within 159 metres from each other in the afternoon on 7 Apr 2022. Once a valid relative navigation fix had been established, a deliberate abort manoeuvre was conducted, which had caused the Servicer to depart from the Client. Unlike in case of the 25 Jan incident, this departure ΔV had been planned by Astroscale and did not give rise to any operational issues. However, the close approach caused a cross-tagging between the Servicer and the Client in the 18th's catalogue, as shown in Figure 10 and Figure 11 (orange and purple, and pink and green dots diverge from Servicer and Client reference trajectories, respectively).

Unlike before, LeoLabs were able to maintain custody of the Servicer throughout and after the close approach, which is demonstrated by the pink dots in Figure 10 remaining consistent with the reference trajectory. It is, therefore, interesting to observe that LeoLabs tracking of the Client (yellow-green dots in Figure 11) were falling behind the trajectory of the Client, just like the ephemerides of the 18th. This is analysed in more detail in the next section.

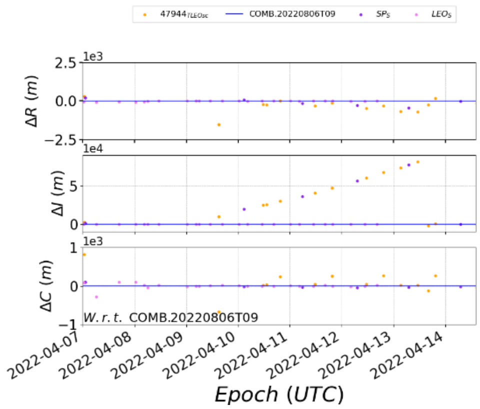

Figure 10: Relative position between Astroscale Servicer reference trajectory and other ephemerides in Servicer-centric rectilinear RIC frame shortly after the closest approach on 7 Apr 2022.

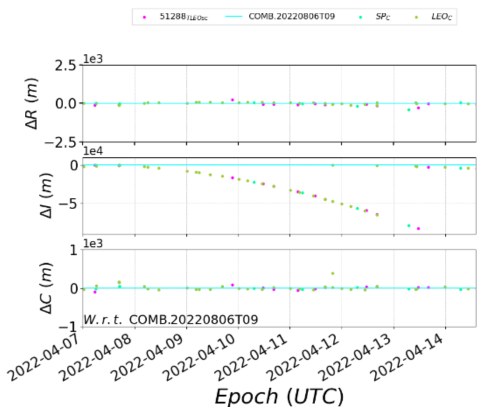

Figure 11: Relative position between Astroscale Client reference trajectory and other ephemerides in Client-centric rectilinear RIC frame shortly after the closest approach on 7 Apr 2022.

4.3 Repeated mis-associations of Servicer and Client observations

It was observed in the previous section that after the close approach, LeoLabs observations of the Client appeared to actually show the position of the Servicer, even though the Servicer's own position was determined correctly, i.e. there was no cross-tagging *per se*. This makes this situation distinct from what was observed in the data of the 18th SDS in sections 4.1 and 4.2, and necessitates a further analysis.

Figure 12 shows the same data as Figure 11 (positions of Client ephemerides w.r.t. reference Client trajectory) but at a different epoch. Here again it can be noted that LeoLabs states of the Client do not coincide with its reference trajectory. The 18th SDS was tracking the Client correctly at the time.

When contrasting Figure 12 with Figure 13, which shows the relative position of the Servicer w.r.t. Client, it can be observed that LeoLabs states of the Client overlap with the location of the Servicer. The root-cause of this behaviour was identified to lie in the LeoLabs measurement association pipeline, which would incorrectly assign raw measurements of the Servicer to the Client if the two were close enough. This would, in turn, cause the Client's OD solution to converge to the Servicer's orbit.

Similar phenomenon has been observed several times throughout the mission, typically at in-track separations less than a few tens of kilometres. Improvements in the measurement association algorithm have been made since, which is expected to alleviate the issue. Also, in most cases and certainly for ADR missions, the Servicer will be smaller than or of similar size to the Client, not vice versa as was the case for ELSA-d. In this latter case, the Servicer's radar cross-section of approx. 0.147 m^2 was an order of magnitude larger than that of the Client (0.016 m^2), which often made automated association algorithms pick up the stronger radar echo and reject the smaller object.

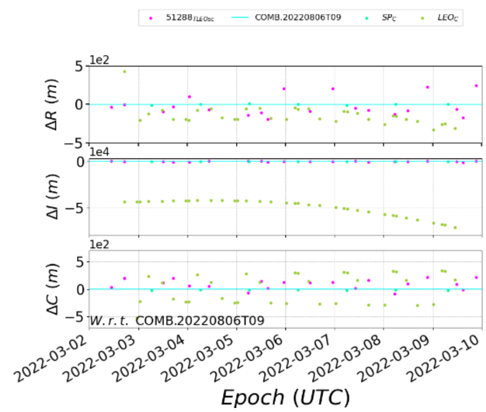

Figure 12: Relative position between Astroscale Client reference trajectory and other ephemerides in Client-centric rectilinear RIC frame shortly in early March 2022.

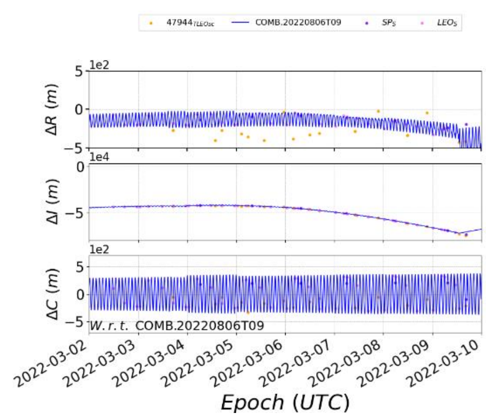

Figure 13: Relative position between Astroscale Servicer and Client reference trajectories, and other Servicer ephemerides in Client-centric rectilinear RIC frame in early March 2022.

4.4 Mis-association of measurements in EU SST observations

Given Astroscale's experience with incorrect measurement association during proximity operations that was described in section 4.3, EU SST have investigated the presence of mis-associations in their own observations. The measurements obtained around the closest approach between the two craft with the following instruments:

- GRAVES radar, France
- S3TSR radar, Spain,
- TIRA radar, Germany,
- GRAZ laser ranging, Austria,

were analysed. These were acquired between 28 Mar and 10 Apr 2022.

The residuals between the EU SST observations and Astroscale operational ephemerides have been computed. The weighted RMS of the residuals was used as Figure of Merit (FoM) for each track, based on which the association to either Servicer or Client was made (smaller FoM indicates a better fit to the given object). The weight used for each type of observable accounted for the expected sensor noise derived during calibration and a multiplying margin factor (typically 5.0).

Comparison was then made between the above association using Astroscale ephemerides, and the original associations that relied on orbital solutions solely derived from ground-based tracking. This allowed deducing any potential mis-associations that have taken place because the ex-post Servicer and Client trajectories used here contained manoeuvre information, which was not originally taken into account during measurement association done by EU SST. A comparison of the two associations in shown in Table 1.

Several mis-associations between the two ELSA-d craft have been detected. In addition to that, certain tracks show a lower FoM for other resident space objects (RSO) in a catalogue maintained by EU SST. They could, therefore, correspond to different RSOs entirely.

Even though mis-associations are present, they would typically be identified and rejected at the orbit determination stage, which was the case for the miscorrelations previously reported in section 4.3. Thus, a certain level of incorrect associations can be tolerated as long as a correct OD solution can eventually be generated.

Table 1: Summary of the original association of EU SST measurements to Servicer and Client, and the associations to Astroscale ephemerides containing manoeuvre information.

	Number of associations	
Object	**Original**	**Revised**
Servicer	31	28
Client	5	8

4.5 Cross-tagging event due to overhead fly-by (15 Feb)

While the Servicer was moving to reapproach the Client along the V-bar after the abort ΔV on 25 Jan 2022, it passed directly above the Client on 15 Feb 2022 19:43:39 (cross-track separation of 60 m, radial of 1907 m). The relative geometry of this close approach is shown in Figure 14.

This event disrupted radar tracking of the Client, which can be seen as a gap in LeoLabs state vectors in Figure 16. Nominal tracking was recovered on 17 Feb 11:28:33. Even though a certain gap in LeoLabs state vectors of the Servicer is visible in Figure 15, this only started on 16 Feb 04:56:00 after several valid state vectors had been published by LeoLabs. Therefore, this gap was likely caused by normal sensor revisit pattern rather than a close overflight.

A similar Client tracking gap was observed in EU SST radar data – the S/C was observed in the early morning on 16 Feb and then again on 22 Feb. No disruption to the Servicer tracking was observed during this interval, just like in the case of LeoLabs.

No noticeable disruption to the tracking of either Servicer or Client was detected in the 18th SDS data around this time.

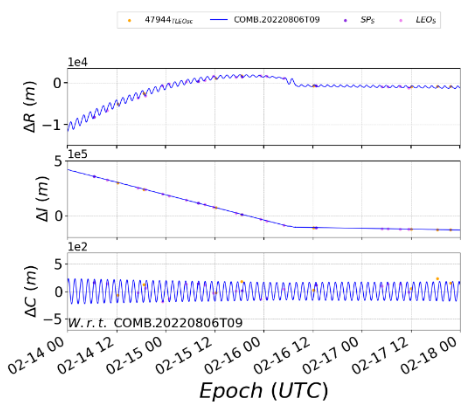

Figure 14: Relative position between Astroscale Servicer and Client reference trajectories, and other Servicer ephemerides in Client-centric RIC frame on 15 Feb 2022.

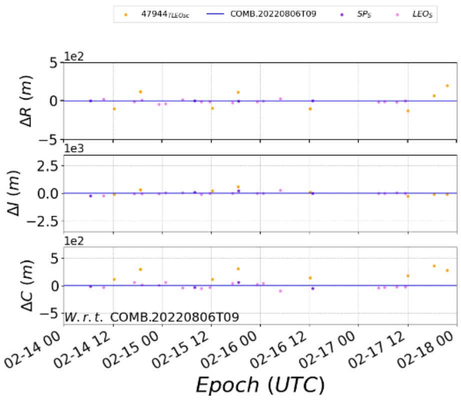

Figure 15: Relative position between Astroscale Servicer reference trajectory and other ephemerides in Servicer-centric rectilinear RIC frame on 15 Feb 2022.

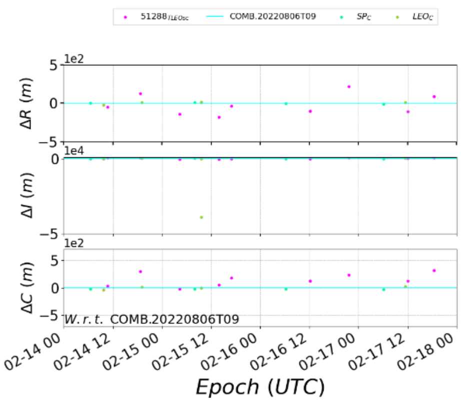

Figure 16: Relative position between Astroscale Client reference trajectory and other ephemerides in Client-centric rectilinear RIC frame on 15 Feb 2022.

4.6 Loss of attitude and its effects on the orbit

Atmospheric drag is the second dominant force in LEO after gravity [5], and the differential drag between satellites flying in the same formation should be controlled in order to maintain their relative orbits without extensive use of propulsive manoeuvres [5, 6]. This makes the differential drag one of the key factors to consider for ADR missions, especially given the unavoidable differences in the ballistic coefficients of the ADR targets and the removal vehicle.

Even attitude changes, which affect the ballistic coefficient of the satellite and thus the drag acceleration, are expected to give rise to position differences significant enough to affect ADR operations. This point is illustrated in Figure 17, which shows the relative RIC positions between two results of Astroscale OD for the Servicer together with third-party ephemerides. These trajectories were generated approx. two and five days after 01 Jun 2022 10:47:00, when the Servicer's attitude mode changed from RIC-aligned to sun-pointing.

No change in Servicer's orbit can be seen until at least 3 Jun 11:00, when the in-track drift first becomes visible in the LeoLabs state vectors. Note that this was approx. 48 hours after the attitude mode change and at least tens of metres of in-track position difference must have already been accumulated by that point [5].

When considering relative positions on this order of magnitude, one can assume that relative navigation would already be taking place and high responsiveness of the absolute navigation solutions would not be required anymore. However, this example demonstrates that even when planning more distant rendezvous manoeuvres based on absolute orbit knowledge, unexpected changes in object attitude may lead to relative in-track errors on the order of hundreds of metres or more over the course of one or two days. This can, in turn, render the manoeuvre plans obsolete and cause a risk of collision.

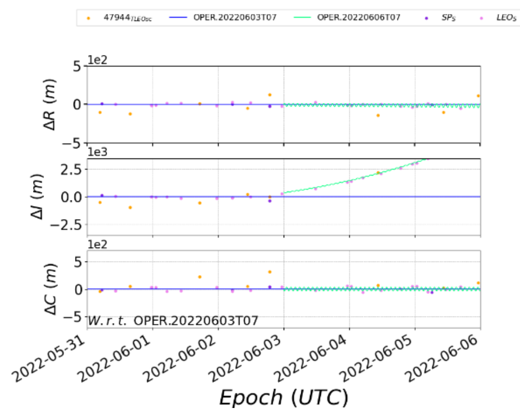

Figure 17: Relative position between Astroscale operational trajectories of the Servicer and other ephemerides in Servicer-centric rectilinear RIC frame around 1 Jun 2022.

4.7 Attitude rate estimation from ground

Section 4.6 highlighted the importance of the interplay between object attitude and position, which can have non-negligible effects when planning proximity operations. In order to investigate the possibility of estimating the attitude of potential ADR targets from ground, a series of experiments was conducted.

First, the evolution of Servicer's radar cross-section (RCS) after departing from the Client was measured on 25 Jan 2022 using the SATAM radar, and the TIRA radar on 26 Jan 2022 and 28 Jan 2022. Combining these sets of measurements, the rotation rates were estimated and compared to on-board telemetry. The qualitative behaviour of the Servicer has been identified correctly, even though the magnitude of the angular rates has been overestimated by up to a factor of two, which could have been caused by ignoring the S/C shape during the attitude estimation.

Due to spacecraft symmetry, which artificially increases the measured angular rates[‡], the metric that is actually estimated with SSA is the maximum rotational speed the spacecraft is currently experiencing. In other words, without a deeper analysis accounting for spacecraft physical properties and shape (usually unknown in general SSA analysis), the current approach allows one to find the limits of the rotational behaviour of a spacecraft rather than the actual rotation rates.

Another example of ground-based attitude determination using the TIRA radar is shown in Figure 18 and Figure 19 for two passes on 8 Apr 2022. The evolution of the RCS shows a periodic structure, with higher regions of RCS indicating stronger reflections from larger or more reflective surfaces. The periodic motion does not appear to be a simple rotation, which is indicated both by the variance in features of the RCS evolution and by the complex signature of peaks seen in the periodograms. This corresponds to the attitude motion of the Servicer at the time, which was three-axes stabilised.

These results are encouraging and suggest that this approach can be used to provide attitude estimation of both during nominal operations and in contingency situations.

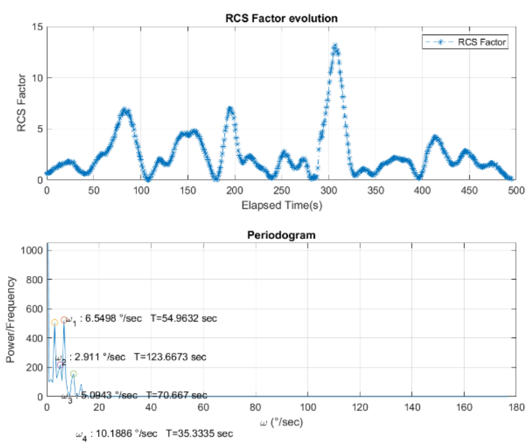

Figure 18 : RCS observed by TIRA (EU SST) on 8 Apr 2022 during the first pass.

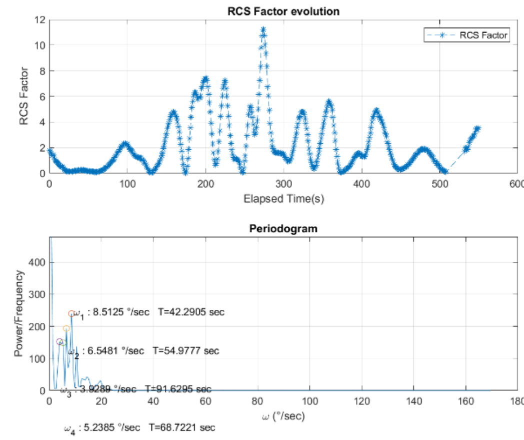

Figure 19 : RCS observed by TIRA (EU SST) on 8 Apr 2022 during the second pass.

5. Analysis and Discussion

Several distinct SST-related issues have been discovered during the ELSA-d demonstration and described herein. These predominantly include disruptions to automated tracking, measurement association and orbit determination processes that can arise when two spacecraft operate close together. While these pose challenges to operators of RPO missions by e.g. reducing the number of observations/state vectors that are available for orbit determination, it is generally possible to overcome them by the use of e.g. on-board GNSS receivers. However, when approaching a defunct spacecraft, any disruptions in its ground-based tracking could cause operational difficulties or even result in an elevated risk of collision. This highlights the importance of ELSA-d demonstration in the SSA context, as well underscores the value added by identifying SST algorithm flaws in a controlled setting.

In general, errors in automated processing are expected to be of greater importance in situations where no human operator monitors the consistency of the results due to the scale of the problem, which was not the case with ELSA-d because only two satellites were involved in the mission. The two areas that are the most likely to be affected by incorrect measurement/object association are safety of flight and defence SSA. The former can be rendered unreliable if incorrect orbits are being ingested in the conjunction screenings, while the former might not detect changes in satellite behaviour in a timely manner.

Another area that was briefly explored in this paper was ground-based attitude determination. It was shown that changes in S/C pointing can have a measurable effect on its position, which could affect RPO mission planning

[‡] For example, if a rotating plate with two identical faces is considered, a sensor will see the RCS evolving with a period that is two times lower than the actual rotation of the plate because each of the two faces will create a similar pattern.

and collision avoidance in general. Ground-based attitude estimation was demonstrated, however further improvements need to be made in the accuracy of estimating the angular rates. The output of these needs to be fed to RPO mission operators, so that they can monitor the behaviour of their targets to ensure that no sudden change in orbit is likely to occur.

6. Summary

A number of phenomena related to SST were observed during ELSA-d proximity operations phase and discussed in this paper. Based on these, certain improvements in e.g. measurement association algorithms have already been made by Astroscale's partners, and recommendations for future enhancements and areas of research have been made.

It was shown when analysing EU SST measurement mis-associations that including manoeuvre information in the association pipeline has a beneficial effect of the accuracy of the final measurement correlations. In order to increase the utility of ground-based tracking, it is therefore recommended to distribute manoeuvre plans and GNSS-based orbit estimates to the SST organisations.

A comparison was also made between ground-based and on-board attitude estimation, with promising results. Further work on this topic is crucial to enable ADR missions targeting passive, uncontrolled objects.

These multiple findings underscore the value of ELSA-d as a demonstration of not only the on-board technologies, but of the entire RPO mission system.

Acknowledgements

Astroscale would like to acknowledge the generous and valuable support of various groups that have made ELSA-d operations possible in the presence of mission-threatening in-orbit anomalies. This list includes but is not limited to the ESA Space Debris Office, 18th SDS, the ILRS community and the UK Space Command.

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