[1]MAXIMIZING POST MISSION DISPOSAL OF MEGA CONSTELLATIONS SATELLITES REACHING END OF OPERATIONAL LIFETIME

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ABSTRACT

Emerging plans for low Earth orbit (LEO)-based constellations featuring large numbers of satellites (the so-called “mega constellations”) pose a potential risk of threatening orbital sustainability. Therefore, systematic spacecraft end-of-life (EOL) management strategies assuring post-mission disposal (PMD) are required to maintain utility of all LEO assets. Founded in 2013, ASTROSCALE’s mission is to secure long-term spaceflight safety, and to become a key provider of reliable and cost-efficient spacecraft retrieval services to satellite operators. The company is planning its first semi-cooperative spacecraft retrieval technology and capability demonstration mission (ELSA-d) in the first half of 2019. ELSA-d is comprised of two spacecraft: “Chaser” and “Target.” Chaser is equipped with sensing instruments for proximity operations and a capture mechanism, whereas Target has a docking plate (DP) mounted on its surface, which makes Target easier to identify, approach, and capture. Similarly mounting a small, light-weight, and minimally-intrusive DP on mega constellation satellites will benefit both constellation players and EOL service providers to minimize the cost of retrieval services.

1 INTRODUCTION

1.1 Orbital Environment and ADR

Our present space environment consists of no less than 23,000 large (> 10 cm diameter) trackable resident space objects (RSOs). Of these, 1,400, or approximately 5%, are active satellites. The remaining 95%, along with the estimated millions more which are too small to be tracked, are inactive objects commonly known as space debris [2, 3]. The abundance of space debris combined with their high velocities – reaching 8 km/s in Earth orbit – threatens space assets and the safety of satellite missions.

The cumulative probability of collision experienced by an RSO is a direct function of the total number of objects in space. As the density reaches a critical level where the creation of new space debris objects occurs much faster than their natural decay into the atmosphere, a chain reaction known as the Kessler syndrome may occur [4]. As a result, the number of space debris will exponentially increase, further elevating the risk of collision for existing satellites.

To this end, studies show that even if we adopt selective active debris removal (ADR) for future debris sources, the debris population only stabilizes if 90% of all future launches comply with current debris mitigation guidelines [5]. Over the last decade, the international community has started to adopt voluntary policies on post mission disposal (PMD) [6]. Almost all PMD guidelines require a payload or upper stage to be removed from orbit within 25 years after its operational lifetime [1].

This goal is relatively easy to accomplish on new spacecraft by utilizing existing propulsion systems or by installing a device to lower its orbit sufficiently so that it re-enters within the 25-year limit. Few objects already in orbit, however, have such capabilities. Consequently, simulations show that on-orbit breakups alone are sufficient to increase the number of space debris objects even with 100% compliance with PMD guidelines [7]. Therefore, ADR of existing threats in orbit is required to control the growth of RSOs.

1.2 Mega Constellations and EOL

The use of satellites and other space-based services is becoming a greater part of our everyday lives. This trend is slated to accelerate as several plans have emerged for low Earth orbit (LEO)-based broadband communication constellations featuring a large number of satellites (so-called “mega constellations”). Table 1 summarizes those currently under consideration. These constellations are made possible thanks to recent innovations in the space industry such as mass manufacturing of satellites with low per-unit cost, frequent multi-payload launches, automation in orbit operations, and overall high satellite reliability. Most will operate in 1,000 to 1,400 km altitude orbits with thousands of satellites so as to offer high-speed broadband services worldwide.

The deployment of mega constellations, however, will bring with it the potential risk of threatening orbital sustainability. Although new payloads are expected to install a deorbiting mechanism of some sort so that they

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Table 1. List of major proposed broadband communications mega constellations.

Name	Apogee [km]	Perigee [km]	# of sat
Boeing (Ph 1)	1200	1200	1,396
Boeing (Ph 2)	1000	1000	1,560
Iridium NEXT	780	780	72
Leosat	1430	1430	108
OneWeb	1200	1200	2,600
Samsung	1400	1400	4,600
SpaceX	1100	1100	4,425
Total			**14,761**

may comply with the aforementioned PMD international guidelines, there is always risk of severe anomalies due to exposure to the strong particle radiation environment at these altitudes as well as generic malfunctions due to random failures. Consequently, a certain rate of the fleet will permanently fail before the completion of its planned service life.

Therefore, systematic spacecraft end-of-life (EOL) management strategies which are independent from constellation players are required for continued compliance with PMD international guidelines, and consequently, the sustainability of the LEO environment as a platform for space-based services.

1.3 ADR vs EOL

With respect to ADR, all of the major space agencies and private space companies face regulatory issues. Without a clear and globally defined set of rules, ADR missions to remove existing debris will be difficult to implement. EOL service missions, on the other hand, are relatively easier to accomplish in many aspects. The differences between an EOL service and an ADR mission is summarized in Table 2. Most importantly, EOL services will retrieve defunct satellites reaching end of operations using technologies for semi-cooperative rendezvous and docking. As such, the technical difficulty of providing such a service is reduced compared to the non-cooperative approach required for ADR, resulting in more reliable and affordable solutions. Furthermore, EOL services will be conducted under the framework of a business contract with the satellite operator plus mission licensing from the launching state. Thus, they can avoid the controversial legal issues embedded in ADR regarding international liability and cost-sharing.

1.4 ADRAS to ELSA

Over the past two years, Astroscale had been developing a satellite called "First Active Debris Removal by Astroscale" (ADRAS-1) planned for launch in the first half of 2018 [8]. The objective of this mission was to demonstrate a scalable, innovative, and cost-effective ADR solution. In light of the emergence of more than 40 proposed satellite constellations around the globe, however, we concluded that a proper implementation of EOL services from both a technical and regulatory standpoint will contribute to the development of a practical mechanism for international collaboration on ADR. Consequently, Astroscale halted development of ADRAS-1 to shift resources on the "End-of-Life Service by Astroscale" (ELSA) project.

While heritage from ADRAS-1 may be leveraged to accelerate development of ELSA, the key technological difference between EOL and ADR is that EOL may be approached as a semi-cooperative rendezvous and docking problem by pre-installing a so-called "rescue package" component on the satellites of potential customers. The rescue package is a small, light-weight, minimally-intrusive component that can be readily placed on the outer surface of a customer's satellite. Key functions of the rescue package are to help the ELSA satellite identify distance, attitude, and relative motion with respect to the target satellite, as well as securely capture and grapple the target. The rescue package can reduce the number of sensors on ELSA satellite for proximity operations, simplify navigation algorithms during rendezvous, and alleviate uncertainty regarding capture dynamics; all contributing to a dramatic reduction in service price.

2 ELSA-d MISSION OVERVIEW

In order to provide independent EOL services for mega constellations as noted above, Astroscale must develop satellites in a similar fashion to the constellation players themselves: i.e., with mass production, multi-payload launches, and autonomy in mind. In addition to technical know-how, these programmatic requirements represent a quantum leap in our company's capabilities. As such, the first step in the ELSA program, which we refer to as "ELSA-**d**" for "**d**emo," is an on-orbit demonstration of common core technologies for EOL missions. Demonstration priorities include:

Guidance, Navigation, and Control (GNC) for Proximity Operations

- Target diagnosis and relative state estimation (e.g., appearance status check, attitude determination, capture point identification, etc.)
- Autonomous rendezvous and docking sequence
- Absolute and relative orbit maneuvering using a propulsion system
- Post-docking spacecraft mass property estimation and attitude control

Table 2. Comparison of end-of-life services and active debris removal.

	End-of-Life Service (EOL)	Active Debris Removal (ADR)
Target Objects	Satellites reaching end of operational lifetime	Environmentally critical objects
Mass	50 kg – 500 kg	500+ kg
Rationale	Retrieve satellites allowing for timely resumption of constellation operations	Remove space debris to improve on-orbit safety
Key technologies	Semi-cooperative approach and capture	Minimally-cooperative approach and capture
Value proposition	Orbit sustainability, maximizing revenue, mitigating collision risk	Long-term sustainability
Regulation / Authorization	B2B commercial contract following mission approval from launching state	Requires international consensus

Target Capture Mechanism

- Mechanical and thermal interface for docking
- Capability to autonomously infer docking state and retry rendezvous as necessary

The success criteria of the ELSA-d mission are in Table 3. The priorities outlined here ensure that our mission meets the expectations of Astroscale's stakeholders, provide confidence to our potential customers, and build business value for Astroscale through engineering expertise and availability of mission-ready systems.

2.1 Mission Concept of Operations

The ELSA-d concept of operations (ConOps) is illustrated in Figure 1. The mission consists of seven mission phases and two system segments: the space and ground segments. The space segment is further divided into two elements which we will hereafter refer to as Chaser and Target. The Chaser is equipped with relative GNC instruments for rendezvous and docking, a capture mechanism using magnets and a secondary force for redundancy, and a propulsion system for attitude and orbit maneuvering. The Target is equipped with the so-called "rescue package," which is a specific docking plate (DP) for the mission. The DP is made of a ferromagnetic material that will enable the Chaser to secure the Target via magnetic force. In addition, it provides optical references (or "markers") for the Chaser to identify and estimate the attitude of the Target.

The seven mission phases of ELSA-d are briefly described below.

Phase 1: Launch This phase spans launch to orbit injection. The Chaser and Target will be mechanically combined and launched together on board a launch vehicle as a primary or secondary payload. Launch and orbit injection will be performed by the launch supplier.

Phase 2: Initial Operations Once the Chaser and Target are placed in a LEO trajectory, the ground station will initialize and commission the two spacecraft. After the Chaser is separated from the launch vehicle, the Chaser will be turned on. Following the Chaser's initial check, the Chaser will then turn on the Target via commands from the ground station; only then will we proceed with commissioning the Target alongside the Chaser.

Phase 3: Separation After we nominally commission the Chaser and the Target, the Target will be separated from the Chaser so that it may become an independent free-flying spacecraft. The separation mechanism will be required to impart only a small impulse on either spacecraft. A subsequent detumbling sub-phase is planned such that relative attitude motion is attenuated prior to proceeding to the next mission phase.

Phase 4: Proximity Operations Upon receiving a command from the ground segment, the Chaser will initiate a sequence of GNC operations aimed to estimate and evaluate the Target condition and state. Steps will include appearance status check of the Target, relative attitude estimation, and capture point identification. The operational timeline can be broken up further into three sub-phases: Home Position Acquisition, Diagnosis, and Target Attitude Rough Estimation. Refer to the subsequent sections for details.

Phase 5: Capture Based on relative state estimates. the Chaser will match the attitude motion of the Target – thus of the DP – and begin its final approach and capture (contact + grab + hold) sequence. Refer to the subsequent sections for details. All operations are expected to be autonomous in this phase. Furthermore, the on-board GNC algorithms designed for the Capture phase will hinge solely on the existence of the DP for

Table 3. Success criteria for ELSA-d.

Success Lvl	Criteria
Minimum	• To capture the target with little to no relative attitude motion
Medium	• To release the Target and retry the capture sequence
Full	• To capture the target undergoing torque-free attitude motion
Extra	• To estimate spacecraft mass properties and control attitude after capture • To re-orbit the spacecraft after capture

Target detection and state estimation. It cannot be applied to approach or dock with a non-cooperative Target.

Phase 6: Thrust Vector Alignment When the Chaser and the Target are physically linked and thus may be treated as a single rigid body, the attitude state of the combined system will drastically change from that pre-capture. As such, the attitude and mass properties of the combined system will be re-estimated. Only then shall the combined Chaser + Target spacecraft be able to adjust the direction of its thrust vector so that it is aligned not only with the desired re-orbit ΔV direction but also with the new center of mass of the coupled system. Thus, this step will envelop maneuver planning for the Re-Orbit phase. Note that, unlike prior to capture, any and all attitude sensors and actuators on the Chaser will be available to the combined system.

Phase 7: Re-Orbit Although the ultimate goal of the ELSA program is to deorbit defunct satellites, as the ELSA-d mission is expected to be launched at an altitude where the combined system will naturally deorbit due to atmospheric drag in a much shorter timeframe than the 25 year EOL guideline, we plan to only demonstrate ELSA's ability to safely change the combined system's altitude so as to reduce overall system mass at launch. We will ensure that our re-orbit maneuver will not result in a conjunction with another RSO, and post maneuver, will continue to monitor ELSA-d's ephemerides.

As Phases 4 and 5 are directly related to the technology demonstration goals of the mission, we provide further details on their sub-phases below.

2.1.1 Proximity Operations Sub-Phases

Home Position The Chaser will first establish a "home position," where the Chaser will be as close to the Target as possible while still allowing the probability of collision between the Chaser and the Target to be independent of either spacecraft's attitude state. Effectively, the distance between the Chaser and the Target will be constrained such that it is much larger than both Target's hard body radius and the Chaser's navigation uncertainty. The Chaser will place itself in the in-track direction of the Target's orbit so that the relative position between the two spacecraft are fixed. The relative orbit state will be refined on the on-board navigation filter that takes both range and optical measurements as inputs. The attitude control subsystem will ensure that these sensors are pointed toward Target at all times.

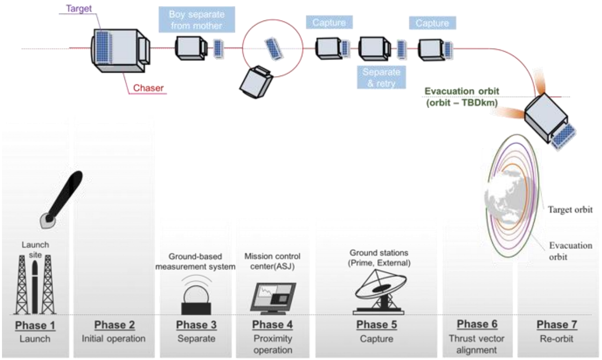

Figure 1. Concept of operations for ELSA-d.

Diagnosis Next, the Chaser will conduct a maneuver to go into a "football" orbit in the Hill frame, which is a periodic trajectory such that Chaser circumvents the Target in the same time as the Target's absolute orbital period. During this time, the Chaser will actively control its attitude so that its cameras point toward the Target, and take low-resolution images of the Target. These images will be downlinked to Earth at a later time, where ground operators will inspect the health of the Target with a particular focus on the status of the DP. It will be crucial to ascertain that the DP has sustained no physical damage during launch as the entire Capture operations will hinge upon the DP. Ground operators may additionally look for punctures and damage to other critical the Target components and the Target structure. Finally, at the end of this sub-phase, the Chaser will return to its Home Position.

Target Attitude Rough Estimation Prior to the Chaser further approaching the Target, the attitude of the Target will be estimated so as to accurately assess the probability of collision between the Chaser and the Target, to point GNC sensors so that the Target remains in their fields of view, and thus to enable the on-board computer to make abort decisions only when appropriate. When the Home Position of the Chaser is once again established, the Chaser will take high-resolution images of the Target so as to conduct image-based attitude determination at ground segment. The moment of inertia of the Target will also be updated at this time. As these algorithms will not be run on-board, this sub-phase will drive the requirement for high-speed communications between the Chaser and the ground segment. As in the Home Position sub-phase, additional ranging information will assist the Chaser in maintaining distance from the Target.

Critical events in the Proximity Operations phase will be the maneuvers that occur in between each sub-phase. In case any of these maneuvers fail to execute as planned, an abort sequence will be prepared to mitigate the risk of collision between the Chaser and the Target. Again, throughout the Proximity Operations phase, the separation between the two objects will be such that collision risk is only a function of the distance. As such, a predetermined maneuver will be executed should the distance between the Chaser and the Target reach some lower bound, or should the Target move outside of the GNC sensors fields of view.

2.1.2 Capture Sub-Phases

Final Approach Information from ranging and imaging sensors will be fed into the navigation and guidance algorithms to ensure a controlled approach to the DP in terms of both translation and rotation. Note that multiple cameras with different fields of view will be installed on the Chaser so that the navigation markers will remain in image frame as the Chaser approaches the Target. Nonetheless, should the GNC sensors lose sight of the DP or Chaser's attitude motion is no longer in sync with the Target, an appropriate abort maneuver will be executed to prematurely end and force a retry of the Capture phase. Furthermore, a maximum approach velocity will also be set to avoid any serious damage to either the Chaser or the Target. A handoff to the capture mechanism will be made when the Chaser reaches some predefined "closest approach" distance, which will ensure that the Chaser and the Target will not touch so long as the Chaser's attitude is maintained to within spec. When the Chaser reaches the "closet approach" distance, the Chaser will send a signal to start the Contact sequence.

Contact The capture mechanism will physically extend its contact surface toward the DP on the Target. At this time, there is a possibility that the contact surface is not parallel with the DP due to attitude determination and control error, forcing the contact surface to stick with the DP at an angle. We will accommodate for such an event by adding a flexible mechanism as a part of the capture mechanism. In addition, mechanical sensors will enable ground operators to judge whether the capture mechanism has stuck to the DP nominally.

Grab During grab, contact with the DP will be secured by a backup instrument on the capture mechanism. If, for instance, the contact area between the capture module and DP is too small for the Chaser to securely hold onto the Target, the Chaser will release the DP.

Hold An even greater bonding force than in the previous two subphases is required to ensure that the Chaser and Target act as a single rigid body during the re-orbit maneuver. As such, additional forces will be applied to the DP.

2.2 Programmatic Design Constraints

The biggest challenge for EOL services is mission efficiency. Given system failure rates of constellation satellites, plus launch costs and necessary mass for the ELSA chaser spacecraft, Astroscale identified three programmatic design constraints to be incorporated into ELSA-d so as to pave the way for reliable and cost-effective EOL solutions for our potential customers.

Bus size Considering that the majority of mega constellation players plan to develop relatively small satellites (< 500 kg), we concluded that a microsatellite bus (50 – 100 kg) is the optimal size that will enable us to reduce launch costs yet still deliver capabilities required for EOL.

Modular design ELSA-d will be comprised of three independent mission modules: capture, GNC, and propulsion. Such a modular approach not only will allow us to reduce development time but also to readily adapt to the needs of future customers. The ability to swap bus systems as needed will enable Astroscale's EOL solutions to operate wherever the customer is operating.

Redundancies To maximize system reliability, we plan to embed redundancies in the functions of ELSA-d critical to mission safety. By safety, we are most interested in 1) collision avoidance between the Chaser, Target, and other RSOs, and 2) reliable passivation of both spacecraft in partial or complete mission failure. Thus, these features will act as the rationale to identify certain features as critical and to add redundancy to relevant subsystems, such as communications, power, controls, propulsion, and capture. Note that, as the Target is expected to be passive by design, we plan to imbue more redundancy in the Chaser than the Target.

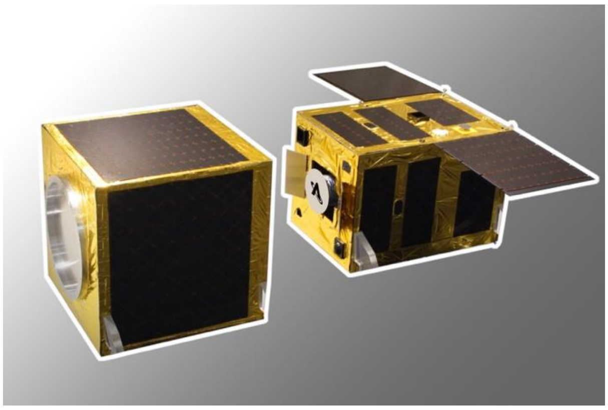

Figure 2. Conceptual drawing of space segment configuration for ELSA-d.

2.3 ELSA-d Segment Configuration

Given the mission success criteria, design requirements, constraints, and ConOps described above, Figure 2 is a conceptual drawing of one proposed space segment configuration for ELSA-d. A summary of key specifications are in Table 4. Again, we stress that system design for ELSA is still ongoing and that any specifics described in this section are one of many potential solutions being considered by Astroscale.

Chaser The Chaser will be a microsatellite whose size is approximately 600mm × 600mm × 1000mm and whose mass is approximately 100 kg. As previously described, the Chaser will be equipped with a capture mechanism using magnets and a redundant secondary force to capture and grapple the Target. In addition, GNC sensing instruments (optical cameras and radiometric ranging sensors) and a green propellant propulsion subsystem will be mounted on the Chaser so that it may identify and safely approach the Target.

Target The Target will be a microsatellite whose mass is approximately 30 kg (TBD). The Target will have basic satellite bus functions except for a propulsion system. Such a design will simplify the post-mission disposal process of the Target during nominal operations as well as reduce the risk of an explosive breakup should a conjunction occur between the Target and Chaser. The mission module equipped on the Target will be a DP rescue package. The Target will be mechanically bound to the Chaser at launch, and will separate from the Chaser after orbit injection.

Table 4. Key specifications of space segment configuration for ELSA-d.

	Specs
Size [mm]	**Chaser**: 600× 600× 1000 **Target**: 12U-18U cubesat equivalent
Mass	**Chaser**: 100 kg **Target**: 30 kg
AOCS sensors	**Chaser**: Star tracker, sun sensor, magnetic sensor, gyro sensor, GPS, accelerometer **Target**: Sun sensor, magnetic sensor, gyro sensor, GPS, accelerometer
Actuator	**Chaser and Target**: Magnetic torquer and reaction wheel
Communication	**Chaser**: S+X bands **Target**: S band
Propulsion	**Chaser**: Green propellant system **Target**: None
Mission modules	**Chaser**: Optical cameras, radiometric ranging sensors, capture mechanism **Target**: Rescue package

Ground Segment The ELSA-d Ground Segment will consist of tracking stations, conjunction assessment systems, and the Mission Control Center (MCC), which will encompass the satellite control system as well as analysis software for mission operation. The Ground Segment is in charge of the following operational functions:

- Commissioning and initialization of both spacecraft
- Telemetry monitoring and command management
- Initiating all mission phase transition events prior to Capture
- Spacecraft parameter estimation beyond kinematic states, including but not limited to:
  - Image-based Target diagnosis
  - Image-based Target attitude estimation
- Chaser-Target combined moment of inertia estimation
- Operational planning and decision-making

Ground operators will continuously monitor both the Target and Chaser throughout the mission, with the capability to override autonomous safety mechanisms on the spacecraft and abort the current mission phase in an emergency situation.

The Ground Segment will be physically located both at Astroscale's facilities and those of external service providers. For the ground stations, Astroscale plans to construct two ground stations in Japan. These stations assure redundancy in that they will each have an S- and X-band radio, and are geographically separated by approximately 1000 km. We also plan to incorporate an external network of antennas (e.g., KSAT) for both initial and mission operations to increase coverage during critical events. We will similarly work with commercial space surveillance networks and orbit analysts to ensure that our planned maneuvers pose minimal risk of conjunction with other RSOs.

3 CONCLUSIONS

In this paper, we discussed Astroscale's near-term strategic shift to prioritize the development of satellite end-of-life (EOL) services for mega constellation operators. Looking ahead, by nurturing regulatory and technological know-how for EOL, we may proceed with active debris removal under a robust international framework. We also outlined our strategy for delivering reliable and cost-efficient EOL service to satellite operators. We proposed the “rescue package” concept, where a small, light-weight, and minimally-intrusive docking plate (DP) component will be pre-installed on constellation satellites. The DP will help our spacecraft to identify, approach, capture, and deorbit defunct spacecraft, as well as allow satellite operators to significantly reduce costs on post-mission disposal.

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