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Preliminary Mission Analysis of Active Debris Removal Service for Large Constellations

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Abstract

In the recent years, many large constellations have been announced to be deployed in Low Earth Orbit. Together with the existing space debris, the failed satellites from large constellations will pose a severe safety threat to the space environment. Driven by the strong demand to remove the failed satellites, D-Orbit and Politecnico di Milano, participate in an ESA funded programme – Sunrise – as consortium to develop an Active Debris Removal service for large constellations. To cope with different mission scenarios, two mission architectures are proposed: mothership and chaser architecture. This paper will present the mission analysis of the two mission architectures for an OneWeb-like constellation. As a preliminary study, the orbit transfer phases, which dominate the prime cost drivers of Δv budget and mission time, as well as the drag-induced de-orbiting, will be presented.

Keywords: active debris removal, large constellations, Sunrise programme

1. Introduction

In the recent years, many companies (e.g. OneWeb [1], SpaceX [2], and Amazon [3]) have made public their plans to deploy large constellations in Low Earth Orbit (LEO), to provide high-speed telecommunications services to the global Earth. Since large constellations usually contain hundreds to thousands of satellites, even a very low failure rate may lead to a large number of failed satellites, which are uncooperative and uncontrollable. If there is no intervention of the Active Debris Removal (ADR) service, the failed satellites from large constellations will remain in orbit for several months or even up to decades, posing a severe safety threat to the operational spacecraft in the already conjected LEO region.

Driven by the strong demand to remove the failed satellites, D-Orbit and Politecnico di Milano, participate in an European Space Agency (ESA) funded programme as consortium to develop an ADR service for large constellations. The ESA Sunrise programme aims to address and identify affordable ADR services compatible with LEO large constellation satellites with respect to customer's guideline, define the preliminary project baseline and, eventually, outline an industrial supply chain with a related technology development roadmap, estimating the development times and costs for the overall program. The service shall be developed considering an OneWeb-like constellation as a potential customer under ESA's technical authority but shall result in a competitive service in the international market.

The objectives of the ESA Sunrise programme are summarised below together with the major system approaches implemented to meet these objectives:

- Technology: development of the contractor's respective technologies for ADR, keeping budget constraints at the forefront during mission design in order to define a competitive service in the international market.
- Service: building a new ADR service for large LEO constellations (i.e. capable of operating with various possible configurations, in different mission scenarios and different types of spacecraft targets) able to meet the emerging request of commercial users.
- Competitiveness: creating a supply and production chain that offers a recurring service, very competitive on an international scale both technically and commercially, in terms of development time and cost.

This paper presents the preliminary analysis of ADR service design for the OneWeb-like constellation, especially focused on the orbit transfer phases, which dominate the prime cost drivers of Δv budget and mission time, and the drag-induced de-orbiting phase. The OneWeb-like constellation is composed of 12 planes at 1200 km altitude and 87.9 deg inclination; all planes are equally spaced along the equatorial plane at intervals of 15.2 deg [4]. Two different mission architectures – mothership and chaser – are proposed [4][5]. The mothership mission aims at high failure rate scenarios in which a large number of failed satellites remain in orbit. The chaser mission aims to provide a quick response service once few failures happen. The ADR servicer spacecraft is considered to be launched via a rideshare launch option with large constellation operators; for the OneWeb-like constellation, the injection orbit at 500 km altitude and 86 deg inclination [4][5].

The remaining of this paper is organised as follows. Sec. 2 and Sec. 3 present the preliminary analysis of the design for the mothership and chaser missions, respectively. Sec. 4 performs the analysis of the drag-induced de-orbiting.

2. Mothership architecture

The mission is composed of two different but dependent types of ADR servicer spacecraft – “mothership” and “kit” – one mothership hosts multiple kits. For the mothership, the mission objective is to capture one target at a time and to attach one kit to the target, and then it will move to the next target until the depletion of the kits. In the end, the mothership captures one last target and de-orbits itself together with the target. For the kit, the mission objective is to de-orbit the target. Note that the kit and target re-enter together as they are attached.

2.1 Mission steps and constraints

The major mission phases involve launch, early operation, and commissioning; orbit transfer for coarse orbit phasing for rendezvous; close-proximity operations; capture; etc. In this paper, we are focused on the orbit transfer phases of the mothership, that are, coarse orbit phasing for rendezvous and de-orbiting of the last target. The detailed orbit transfer steps are as follows.

a. Waiting in injection orbit till reaching target’s plane
b. Orbit raising towards target’s orbit and coarse orbit phasing for rendezvous with target
c. In-plane coarse orbit phasing for rendezvous with next target
… iteration of Step c till removing all targets in one plane
d. Waiting in drift orbit till reaching next plane
e. Orbit change and coarse orbit phasing for rendezvous with target
… iteration up to all kits are released
f. De-orbiting the last target to disposal orbit

Each mothership shall be compatible with a maximum Δv budget of 1 km/s and with a maximum mission time of 2 years [4].

2.2 Mission scenarios and analysis

At the stage of preliminary design, it is assumed that all motherships are launched together by a single launch vehicle; each mothership hosts 8 kits and hence can de-orbit 9 targets, recalling that the last target will be de-orbited by the mothership itself.

Two different mission scenarios are considered. In the first scenario, each plane contains 9 targets, and each mothership is responsible for one plane such that in total 12 motherships are required for the full constellation. In the second scenario, each plane contains 4 or 5 targets, and each mothership is responsible for two planes such that in total 6 motherships are required for the full constellation.

Concerning the second scenario, as depicted in Sec.*2.1*, the mothership will have to move to the next plane after it finishes cleaning the first one. To save propellant, the mothership will wait in a drift orbit to change the Right Ascension of the Ascending Node (RAAN) passively by exploiting the J_2 effect. For generating a different RAAN drift rate with respect to the constellation, three options are investigated: changing the altitude only, changing the inclination only, and changing both the altitude and inclination, as shown in Fig. 1, where Δt represents the time of drifting to an adjacent plane and Δv represents the Δv budget of orbit transfer between the drift and target’s orbits.

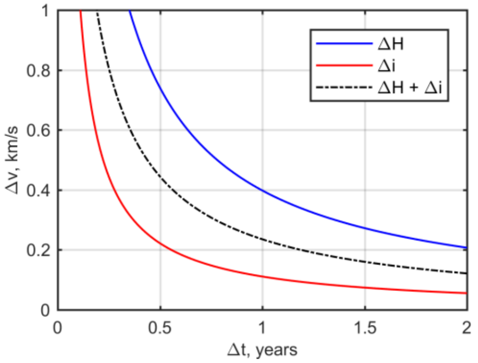


Fig. 1. Comparison of altitude-only change (blue solid line), inclination-only change (red solid line), and combined altitude and inclination change (black dash line).

It is observed from the figure that the best option is the inclination-only change, because it requires less Δt and Δv than the other two options. Note that the black dash line in Fig. 1 indicates that the ratio of the Δv budgets for changing the altitude and inclination is equal to 3, and it is used here as an illustrative example to show the cost of combined altitude and inclination change.

2.3 Simulation results and discussion

2.3.1 Scenario I

Here are the simulation results of the first scenario. The Δv budget of each mothership (for orbit transfer only) is 0.9176 km/s, less than 1 km/s and hence satisfying the Δv constraint of 1 km/s. The mission time of every mothership is listed in Table 1.

Table 1. Mission time for Scenario I

Mothership	Mission time (months)
1	1.6
2	3.1
3	4.7
4	6.2
5	7.7
6	9.2
7	10.7
8	12.3
9	13.8
10	15.3
11	16.9
12	18.4

As indicated in the table, all motherships can fulfil their respective missions within 2 years, satisfying the mission time constraint.

2.3.2 Scenario II

Through the analysis of Δv budget, the inclination of the drift orbit is designed as 87.67 deg, so that there can be enough propellant left to other mission phases such as close-proximity operations.

Here are the simulation results of the second scenario. The Δv budget of each mothership (for orbit transfer only) is 0.9582 km/s, less than 1 km/s and hence satisfying the Δv constraint of 1 km/s. The mission time of every mothership is listed in Table 2.

Table 2. Mission time for Scenario II

Mothership	Mission time (years)
1	2.2
2	2.5
3	2.7
4	2.9
5	3.2
6	3.4

As indicated in the table, none of the motherships can fulfil their respective missions within 2 years, due to the long time period of drifting from one plane to another.

2.3.3 Discussion

For both scenarios, the difference in the mission times of separate motherships is caused by the different waiting time in the injection orbit after the separation from launch vehicle.

Based on the results, we can conclude that the mothership architecture can cope with high failure rate scenarios, in which up to 9 targets are distributed in one plane or two adjacent planes, and Δv budget required by a single mothership is less than 1 km/s. In such scenarios, if one mothership takes care of one plane, the mission can be fulfilled within 2 years; however, if one mothership takes care of two adjacent planes, the mission time has to be extended to 3.4 years.

3. Chaser architecture

The mission is composed of a single ADR servicer spacecraft – “chaser” – that can capture and de-orbit one target at a time.

3.1 Mission steps, requirement, and constraints

Analogous to the mothership mission, for the chaser mission, we are also focused on the orbit transfer phases, that are, coarse orbit phasing for rendezvous and de-orbiting of target. The detailed orbit transfer steps are as follows.

a. Waiting in injection orbit till reaching target’s plane
b. Orbit raising towards target’s orbit and coarse orbit phasing for rendezvous
c. De-orbiting target to disposal orbit for target’s re-entry

… iteration of Step b and Step c till removing all targets in one plane

d. Waiting in drift orbit till reaching next plane
e. Orbit raising towards target’s orbit and coarse orbit phasing for rendezvous
f. De-orbiting target to disposal orbit for target’s re-entry

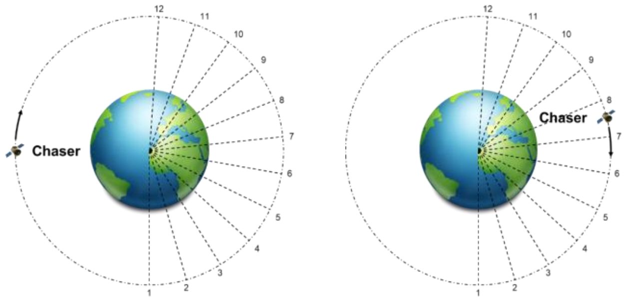
… iteration up to the depletion of propellant

The mission is required to provide 3 services in one or more planes by one chaser, and the chaser shall be compatible with a maximum mission time of 5 years [4]. Given a dry mass of 245 kg and a specific impulse of 285 s, the chaser’s real wet mass shall not be higher than the design value of 520 kg; here the fuel consumption accounts for orbit transfer only [4].

3.2 Drift orbit design

As depicted in Sec. *3.1*, in the case that targets are distributed in multiple planes, the chaser will have to wait in a drift orbit, exploiting the J_2 effect to change the RAAN passively. In this paper, we would like to emphasize the design of drift orbit, which has a significant impact on the mission time and Δv budget in the case of multiple planes.

Due to the fact that the launch is rideshare with large constellation operators, two different types of initial positioning are to be considered: the chaser’s initial RAAN slot is out of the constellation’s planes, and the chaser’s initial RAAN slot is between the constellation’s planes, as illustrated in Fig. 2 a) and b), respectively, where the constellation’s planes are numbered from 1 to 12, the RAAN is measured with the positive sense in the counter clock wise direction, and the arrow indicates the motion of the chaser relative to the constellation.



a) Type I: chaser's initial RAAN slot out of constellation's planes

b) Type II: chaser's initial RAAN slot between constellation's planes

Fig. 2. Initial positioning.

For both types of initial positioning:

- the perigee altitude of the drift orbit is fixed as 500 km, following the one of the injection orbit, to avoid the chaser deorbiting itself during the drifting, which may take several months or up to few years;
- the apogee altitude of the drift orbit is fixed as 1100 km, that is, 100 km below the constellation, to comply with safe operations criteria.

Concerning the inclination of the drift orbit, it is driven by the 5 years' mission time constraint and the worst-case scenario that takes the maximum mission time.

As shown in Fig. 3, the worst-case scenario of the first type is identified as follows.

- The first and last targets to be captured are in Plane 12 and Plane 1, respectively.
- The second target can be in any plane.
- The chaser is initially a bit behind Plane 1.

In this case, the chaser will have to wait in the injection orbit, drifting for around 180 deg with respect to the constellation, to reach the plane of the first target; after de-orbiting the first target, the chaser will have to wait in the drift orbit, drifting for another 180 deg with respect to the constellation, to reach the plane(s) of the rest targets.

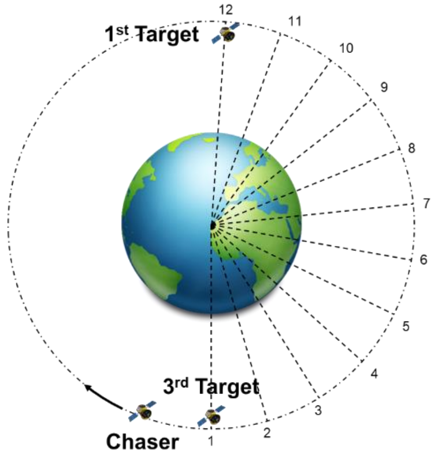


Fig. 3. Worst-case scenario of Type I.

As shown in Fig. 4, the worst-case scenario of the second type is identified as follows.

- The first and last targets to be captured are in two adjacent planes.
- The second target can be in any plane.
- The chaser is initially a bit ahead of the plane of the last target.

In this case, during the entire mission, the chaser will have to wait in the drift orbit for almost 360 deg to reach the planes of all targets.

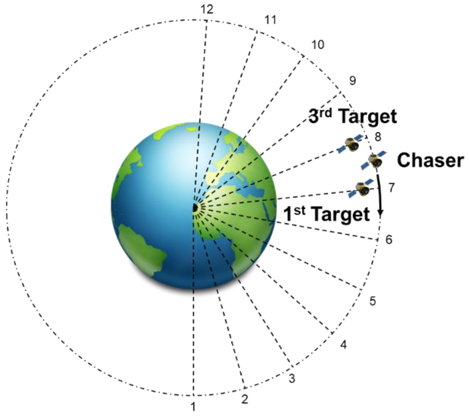


Fig. 4. Worst-case scenario of Type II.

Through the aforementioned analysis, the RAAN drift rate of the chaser, for the worst-case scenarios of the first and second types, should respectively satisfy the following equations:

$$\frac{-(360^\circ-15.2^\circ\times 11)}{\dot{\Omega}_{inj}-\dot{\Omega}_{con}}+\frac{-15.2^\circ\times 11}{\dot{\Omega}_{drift}-\dot{\Omega}_{con}}=5\text{ years} \tag{1}$$

$$\frac{-15.2^\circ}{\dot{\Omega}_{inj}-\dot{\Omega}_{con}}+\frac{-(360^\circ-15.2^\circ)}{\dot{\Omega}_{drift}-\dot{\Omega}_{con}}=5\text{ years} \tag{2}$$

where $\dot{\Omega}_{con}$, $\dot{\Omega}_{drift}$, and $\dot{\Omega}_{inj}$ represent the RAAN drift rate of the constellation, of the drift orbit, and of the injection orbit, respectively.

By solving the preceding equations, the inclination of the drift orbit for the first and second types are derived as 87.1082 and 86.5896 deg, respectively.

3.3 Simulation results and discussion

A Monte-Carlo simulation is performed, considering 3 targets are distributed in one, two, and three planes. Here are the results in terms of the mission time, Δv budget, and real wet mass.

Table 3 Simulation results for 3 targets

Number of planes	Type of initial positioning	Mission time (years)	Δv budget (km/s)	Real wet mass (kg)
1	I and II	≤ 3	1.6519	499.9141
2	I	≤ 5	1.6965	512.4969
2	II	≤ 5	1.7653	527.0289
3	I	≤ 5	1.7411	524.7717
3	II	≤ 5	1.8786	554.7926

Based on the results, the following conclusions can be drawn.

a. The 5 years' mission time constraint is respected for all cases. Especially, the mission can be fulfilled within 3 years if all targets are in one plane.
b. No matter how the targets are distributed, one chaser can provide 3 services in one plane, or 3 services in two planes for the first type of initial positioning, because the real wet mass is lower than the design value.
c. If the design wet mass can be increased by 5 kg, one chaser can also provide 3 services in three planes for the first type of initial positioning.
d. It is suggested to the ADR service supplier and large constellation operator to reach an agreement to inject the chaser into a RAAN slot out of the constellation's planes.

4. Drag analysis

To reduce the impact on space environment as much as possible, all targets are required to de-orbit within 5 years, starting with the arrival at the disposal orbit and ending with the Earth atmospheric re-entry and burn-out [4].

Two different approaches can be considered for de-orbiting: direct re-entry, or reduction of the orbital altitude to achieve natural re-entry within a given time frame due to atmospheric drag. In this work, we use the second approach which requires less Δv. The initial altitude required to achieve a fixed re-entry time is here characterised for the target. The data from this analysis will be used as inputs for evaluating the Δv budget for the ADR servicer spacecraft (kit and chaser), which need to perform manoeuvres to bring the target from the constellation operational orbit down to the disposal orbit.

The numerical simulations are performed using PlanODyn [1], a semi-analytical orbit propagator based on the single-averaged form of Gauss' planetary equations developed by Politecnico di Milano. The force models considered for the de-orbiting simulations include:

- The J_2 zonal harmonic
- Atmospheric drag. A smooth exponential atmosphere density profile fitted to the Jacchia-77 atmosphere density model is used, as described in [7].
- Solar Radiation Pressure (SRP) with a cannonball model and no eclipses. The mean solar flux at 1 AU is fixed as 1367.0 W/m^2.

Two different types of disposal orbits are considered: initially circular and initially elliptical. In both cases, the initial epoch for the simulations is January 1st, 2020, the inclination is the one of the constellation, i.e. 87.9 deg, and RAAN are arbitrarily set to zero. For the elliptical case, the altitude of apogee is fixed at 1100 km, that is, 100 km below the constellation, to comply with safe operations criteria; the corresponding initial eccentricity is then computed for each initial perigee altitude. The altitude of demise, that is, the altitude at which the re-entry is assumed to be achieved, is set to 78 km [4]. These values are summarised in Table 4.

Table 4: Initial orbital values for the drag-induced de-orbiting time analysis

Variable	Initial value
Epoch	1 January 2020
Inclination	87.9 deg
RAAN	0 deg
Argument of perigee	0 deg
True anomaly	0 deg
Apogee altitude for elliptical case	1100 km
Demise altitude	78 km

The physical characteristics considered for the target are given in Table 5. The reference values for the area-to-mass ratio A/m have been computed based on measurements from the Computer Assisted Design (CAD) model for OneWeb-like satellites.

Table 5: Physical properties of the target

Parameter	Value
Drag coefficient	2.2
Reflectivity coefficient	1.0
A/m (highest)	0.0086777 m^2/kg
A/m (mean)	0.0058721 m^2/kg
A/m (lowest)	0.0030665 m^2/kg

The evolution of re-entry time as a function of initial perigee altitude for the target in the initially circular and initially elliptical cases are shown in Fig. 5 and Fig. 6, respectively. Re-entry times up to 7 years are considered, covering the operational restriction of completing the de-orbiting within 5 years.

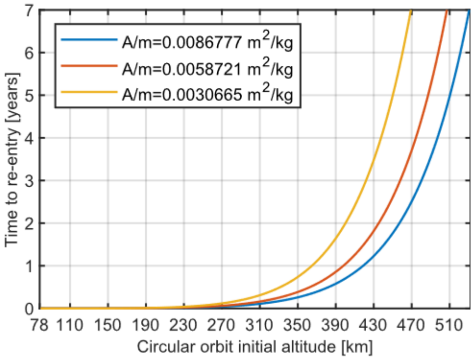


Fig. 5. Time to re-entry versus initial orbit altitude for the target, for initially circular orbit and several area-to-mass ratios.

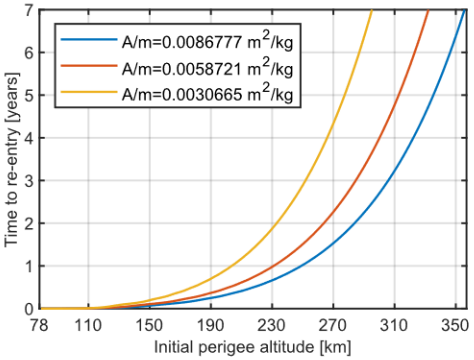


Fig. 6. Time to re-entry time versus initial perigee altitude for the satellite, for initially elliptical orbit with apogee altitude of 1100 km and several area-to-mass ratios.

In all cases, it is observed that the initially circular case leads to shorter re-entry times for the same initial perigee altitude, as expected. However, it must be noted that achieving a circular orbit with a given perigee altitude requires a higher Δv budget than reaching an elliptical orbit with the same perigee altitude. On the other hand, the time versus altitude curves for the initially circular case are slightly smoother than the initially elliptical ones, because of the eccentricity.

For these reasons, the initially elliptical case is selected for the disposal orbit. Without loss of generality, the mean area-to-mass ratio is considered for evaluating the Δv budget; the perigee altitude of the disposal orbit to re-enter in 5 years for the mean area-to-mass ratio is 312.66 km.

5. Conclusion

This paper presented a preliminary mission analysis of two ADR service architectures for an OneWeb-like constellation. In the mothership mission, one mothership can provide 9 services in one plane or two adjacent planes, within 2 and 3.5 years, respectively; the Δv budget required by each mothership is less than 1 km/s. In the chaser mission, one chaser can provide 3 services in one plane within 3 years, or two or three planes within 5 years; the real wet mass generally satisfies the constraint, noting that in the case of multiple planes, the chaser's initial RAAN slot is required to be out of the constellation's planes. In general, the mothership architecture would be suitable for high failure rate scenarios, in which up to 9 targets are distributed in one plane or two adjacent planes; while the chaser architecture would be a premium option once few failures happen, no matter where the failures are. At the end, the drag-induced de-orbiting analysis is performed, concluding that the most cost-efficient strategy for a 5 years' fixed time re-entry would be the one starting with an initially elliptical orbit.

Finally, although not presented in this paper, we would like to highlight that all orbit transfer manoeuvres have been properly designed to satisfy the Δv constraint, or wet mass constraint, as much as possible.

Acknowledgments

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