Assessing Debris Removal Services for Large Constellations

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ABSTRACT

The amount of orbital debris generated in low Earth orbit has been steadily increasing. Recently, deployments of large satellite constellations in low-Earth orbit (LEO) mean that the number of satellites in key orbits will increase at a much higher rate than seen historically, raising concerns over the sustainability of future space activities.

This paper reports the results of a study using the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) evolutionary model to investigate collision risk for different satellite constellation deployments under a range of active debris removal strategies.

The first phase of the study assessed the implications of two different satellite constellations in the absence of active debris removal (ADR). Results indicate that large satellite constellations operating at low altitudes can have a substantial effect on spaceflight safety when the constellation is active and being replenished, whilst satellite constellations at high altitudes have an additional enduring effect on the orbital environment. The second phase of the study used DAMAGE to investigate the effectiveness of different active debris removal strategies, informed by the preliminary mission requirements of Astroscale's future commercial services. The ADR strategies considered include removing sufficient failed satellites to maintain a pre-defined post-mission disposal (PMD rate) and removing all failed satellites that would take longer than 5 years to passively re-enter.

1 INTRODUCTION

The deployment of large constellations of satellites into Low Earth Orbit (LEO) to provide global communications and broadband internet services is being undertaken by several operators. These constellations, and several that have been approved for future deployment, represent a substantial change to our use of this orbital region. This has led to a broad debate about the space debris mitigation measures that may be required in the constellation design and operational practices adopted by these space systems to avoid harmful impacts on the space environment (e.g. [1-5]). Although key measures have been implemented by some of the operators, such as targeting a high reliability of post-mission disposal systems or through the selection of orbits with short residual lifetimes, some potential issues remain.

In general, results from computer models of studies into large constellations in LEO have indicated that there may be two distinct impacts on the LEO orbital object population, related to the sustainability of space activities over the long-term, and the safety of spaceflight over the short-term. Firstly, it seems unlikely that reliability levels will be able to reach those suggested in a recent National Aeronautics and Space Administration (NASA) study [6], which indicated a 99% post-mission disposal reliability would be needed by constellations to prevent long-term debris generation when deployed to relatively high LEO altitudes. Satellites failing to de-orbit in line with these requirements could induce an increase in the debris population due to collisions. Secondly, deploying large numbers of satellites to relatively low LEO altitudes will increase the need for vigilance against collisions with other users of that particular LEO region [7], adding to the burdens on many other operators and a nascent space traffic management regime. Several operators have proposed that the region of LEO below 600 km altitude could be used to accommodate large constellations of spacecraft. At these low altitudes the atmospheric density is such that spacecraft can decay within a few years, thereby meeting the requirement that they are removed from the LEO region quickly even if the spacecraft were to fail. Nonetheless, this region is home to many other satellites, including the International Space Station, and the added constellation traffic will lead to a substantial increase in the number of close approaches and collision avoidance manoeuvres [8].

These results suggest that additional measures may be need to address both the long-term sustainability and short-term safety concerns. In particular, the removal of failed constellation satellites is proposed as a specific measure to prevent the accumulation of failed constellation satellites in high LEO orbital regions and the subsequent increase in the long-term collision risk. At the same time, the targeted removal of failed constellation satellites in low LEO regions may also

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enhance spaceflight safety, despite the relatively short orbital lifetimes of the satellites there.

It is important to note that this study only considers objects larger than 10cm in size. We do not assess the impact of or risk from smaller debris objects that remain undetectable but capable of catastrophic damage. As such, these results do not capture the full impact that satellite constellations pose or the full risk that they face in the orbital environment.

2 METHOD

2.1 DAMAGE

The Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) is a semi-deterministic, three-dimensional computational model of the full LEO to Geosynchronous Earth Orbit (GEO) debris environment. DAMAGE is supported by a fast, semi-analytical orbital propagator, a breakup model [9], and several collision prediction algorithms including a method based on the cube approach adopted in the LEO-to-GEO Environment Debris model (LEGEND) [10].

The process used in DAMAGE to build and subsequently replenish constellations is based on a launch schedule comprising the number of launches per year, the number of satellites on each launcher, and the duration over which the build and replenishment are to take place. If an electric propulsion option is selected, a low altitude deployment from the launcher can be specified and the DAMAGE orbital propagator will compute the ascent trajectories for the constellation satellites, incorporating a user-specified thrust level. Throughout this period, the user can indicate whether the satellites are capable of collision avoidance. Satellites launched via the replenishment schedule replace the corresponding satellites in the constellation, and the older satellites are retired even if they have not reached the end of their service lifetime, following the user-specified post-mission disposal behaviour. Once in service, the satellites maintain their within-plane spacing and inter-plane spacing subject only to Earth zonal gravity perturbations.

The Concepts of Operations (ConOps) for all spacecraft in the simulation are constructed from a set of waypoints, which identify orbital elements and times from orbital injection through to passivation (failures can occur at any point throughout this period). For spacecraft in the large constellations simulated in this study, the ConOps featured low-thrust manoeuvres and a post-mission disposal process divided into two distinct elements, all encapsulated by six waypoints for the period when the spacecraft was under active control. In general, it was assumed that the spacecraft were deployed at relatively low altitudes (~450 km), post-mission disposal success rate for all constellation spacecraft was 95%, collision avoidance was 98% successful throughout all phases of the mission when the spacecraft were active (i.e. including the descent from the mission altitude for disposal). The spacecraft disposal was separated into two stages: an initial descent to a circular staging altitude followed by the lowering of the perigee altitude to achieve an eccentric orbit with the perigee at an altitude of 250 km and the apogee at the staging altitude.

For simulations including the removal of failed constellation satellites, DAMAGE employed a new approach based on look-up tables to quickly calculate the residual orbital lifetimes of all active and inactive constellation satellites, and their collision probability over their remaining lifetime (or a maximum of 35 years, whichever was shorter). This approach enabled the compliance with post-mission disposal (PMD) to be computed for every constellation satellite, and for each satellite to be ranked in terms of the collision risk it posed. We define the PMD rate to be as follows:

$$\mathrm{PMD(t)} = 1 - \frac{\mathrm{UNC(t)}}{\mathrm{A(t)}} \tag{1}$$

Where, UNC(t), means the number of non-compliant satellites in orbit at that time with a passive decay time of greater than 25 years, and A(t) is the number of active satellites in orbit at a given time. Consequently, DAMAGE could implement different removal strategies based on the constellation's overall PMD success rate or collision risk, and the difference in these quantities from user-defined target levels.

Failed satellites targeted for removal were assigned individual "servicer" spacecraft, which followed a particular ConOps, defined through the use of waypoints, to climb to each client, capture, lower and release it at a low altitude, to quickly re-enter. Each servicer was capable of removing multiple clients by repeating the sequence of waypoints and manoeuvres. While undertaking their missions, servicer spacecraft can avoid collisions but the simulation also includes the possibility that removal missions will fail. In such instances, DAMAGE permits the failed servicer spacecraft to be targeted for removal.

DAMAGE also has the ability to simulate multiple scenarios at the same time. This approach enables the analysis of the background orbital object population, constellations and removal services, independently and all within the same Monte Carlo simulation run. Consequently, the results show the direct impact of constellations and of any removal measures on the space environment, with high reliability (no uncertainty) and without the need to perform complex and probabilistic analyses.

2.2 Reference Scenario

The analyses were based on comparisons of long-term projections of the LEO orbital object population ≥ 10 cm, under a variety of constellation scenarios, with a reference scenario comprising the following set-up:

The basic simulation parameters used for this study correspond to the parameters used for the current reference case adopted by the IADC:

- A 1 February 2018 epoch with an initial population corresponding to all objects ≥ 10 cm residing within or crossing the LEO protected region;
- Launch traffic was assumed to be represented by the repetition of recent launches (taken from 1 January 2010 to 31 December 2017) with small random adjustments made to the exact launch date and orbital parameters to avoid artificially enhancing the likelihood of collisions on launch;
- New spacecraft and rocket upper stages in the non-constellation traffic were assumed to achieve a 90% success rate with respect to post-mission disposal, targeting an uncontrolled re-entry within 25 years. No collision avoidance maneuvers were implemented.
- Vehicle passivation was assumed to be 100% successful such that no explosions were permitted within the projection period.
- A 100-year projection period from 1 February 2018 through 1 February 2118.

2.3 Constellation Cases

Two constellation cases were assessed in addition to the background population; one smaller constellation operating at a higher altitude, and one larger operating at lower altitudes.

Table 1. Constellation Parameters

	Constellation A	Constellation B
# Satellites	696	3,220
Altitude (km)	1200	Varies: 590-630
Inclination (degrees)	87.9	Varies: 28, 36, 34
Satellite Lifetime (years)	8	8
Satellite Mass (kg)	150	200
Satellite Area (sq. m)	2.24	2.99

A full description of these constellations and the assumptions made can be found in the Appendix. These constellations, whilst not an exhaustive list, cover a wide trade-space of different constellation parameters and allow us to understand the effects of different constellation parameters, particularly satellite size, altitude, and number.

For each of the baseline scenarios, the following assumptions were used:

- 10% failure rate
- 98% successful collision avoidance
- Constellations active (and replenished) for first 40 years then all active satellites de-orbited
- Constellation build-up phase from 1 Jan 2018
- Constellation replenishment phase from 1 Jan 2021 to 1 Jan 2065 (40 years)
- Immediate de-orbit of rocket bodies
- No explosions

2.4 Debris Removal Services

This study explores the effect of debris removal services and how they can mitigate the impact of a satellite constellation on the orbital environment. The following assumptions are made for all debris removal strategies:

- Failed satellites are removed using a multi-client servicer that is deployed to 500 km, collects and de-orbits a single failed satellite and repeats multiple times. More information about Astroscale's multi-client servicer can be found in [11]. This is representative of future Astroscale multi-client servicer, although this is still in development.
- The number of removals that each servicer can perform varies depending on the constellation client. Failed satellites are removed in sets of 3 for constellation A, and sets of 4 for constellation B.
- Servicer failure and collision avoidance success rates (10% and 98% respectively) are consistent with those assumed for the constellations studies.

These assumptions allow us to study realistic debris removal strategies and ensure that servicer failure will not have an unintended negative impact on the orbital environment.

We consider how these debris removal strategies will affect the impact of different satellite constellations on the orbital environment, using the metrics described in Section 3.1.

3 RESULTS

We consider the impact of the constellation on the LEO orbital object population as separated into two components: **{1} operational phase (2025-2065):** the period during which the constellation is operational, maintained and actively replenished, and **{2} the enduring phase (2075-2115):** in which operational satellites are removed from orbit through post mission disposal and the longer-term impact of remaining failed satellites is assessed.

We first consider the impact of the satellite constellations on the orbital environment under two scenarios: in the absence of any debris removal strategies, and with debris removal whereby failed satellites are removed using a multi-client servicer that is aligned with the development of end-of-life services by Astroscale (ELSA).

In section 3.1 and 3.2, we consider a debris removal strategy whereby all satellites that take more than 5 years to naturally decay are actively removed with a third-party debris removal service under the assumptions presented in Section 2.4. In Section 3.1 we consider the additional number of debris objects > 10 cm as a direct result of the satellite constellation, including failed satellites and other debris, with and without debris removal.

We find that Constellation A (smaller constellation at higher altitude) has a measurable impact on the orbital environment during its operational phase, but that this impact continues to increase during the enduring phase, even once all active satellites are removed from orbit. This residual impact is a result of the failed satellites that remain on orbit. We find that Constellation B (larger constellation at lower altitude) has a larger measurable impact on the orbital environment during its operational phase, placing additional collision avoidance operational burden on themselves and other operators. However, the impact on the orbital environment in the enduring phase is limited as objects passively decay.

Table 2. Summary of Constellation Impact

	Constellation A	Constellation B
Operational Phase	Measurable impact during operational phase.	Greater measurable impact, placing burden on themselves and other satellite operators.
Enduring Phase	Impact continues to increase, even once constellation ceases operations.	Limited impact as objects passively decay.

In Section 3.2 we consider the impact of Constellation A on spatial density, and in Section 3.3, we assess different debris removal strategies with an objective to measure when to intervene with debris removal.

The results presented in the following sections show the results for both constellations with (in green) and without (in orange) the debris removal strategy in place. In sections 3.1 and 3.2, we consider a single debris removal strategy whereby all failed satellites that take more than 5 years to naturally decay are considered clients for debris removal. Different debris removal strategies are considered in Section 3.3. As a result, we are able to directly assess how debris removal can mitigate the impact of satellite constellations across the orbital environment.

3.1 Additional Debris Objects > 10cm

The following results illustrate the difference in the number of objects (between the constellation and no-constellation scenarios), excluding the operational satellites. The difference in the number of objects is therefore showing the increase in debris objects larger than 10 cm in orbit that are directly attributable to the additional debris considered for that constellation. The number of objects changes over time in different ways depending on the constellation considered.

For a smaller constellation at higher altitudes such as Constellation A (see Fig 1a. below), the number of debris objects in orbit continues to increase, albeit at a slower rate, when the constellation is no longer operational or maintained.

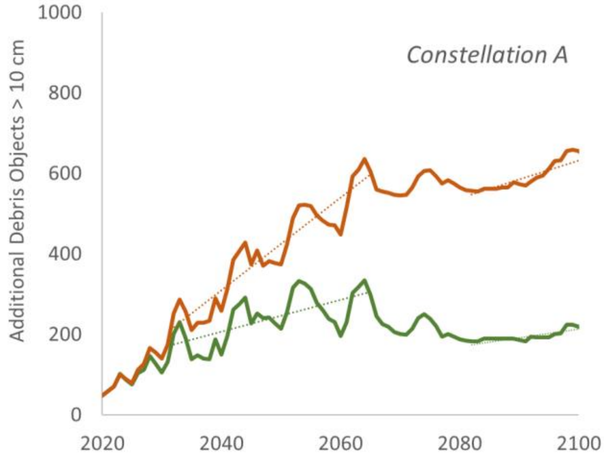

Figure. 1a - Number of Additional Debris Objects > 10cm without debris removal (orange) and with debris removal (green) for Constellation A.

For Constellation A, in the absence of debris removal, as illustrated in the orange lines, the number of debris objects in orbit continues to increase during the operational phase, at a rate of 11.5 per year. By the end of the operational phase, there are 604 debris objects in orbit, which is comparable to the size of the constellation in operation. The number of debris objects continues to increase in the enduring phase, although at a slower rate and results in an additional 687 debris objects >10cm in orbit by the end of the simulation. Debris removal, as illustrated in green, slows the growth rate of debris objects by 65% during the operational phase and almost halves the number of debris objects that remain on orbit by the end of the operational phase. By the end of the simulation, there is a 65% reduction in the number of debris objects that remain on orbit.

In contrast, for satellite constellations at lower altitudes, for example, (see Fig. 1b below), there is a growth in the number of debris objects whilst the constellation is maintained but these debris objects passively decay bringing the difference in objects down to a negligible number by the end of the 100-year simulation.

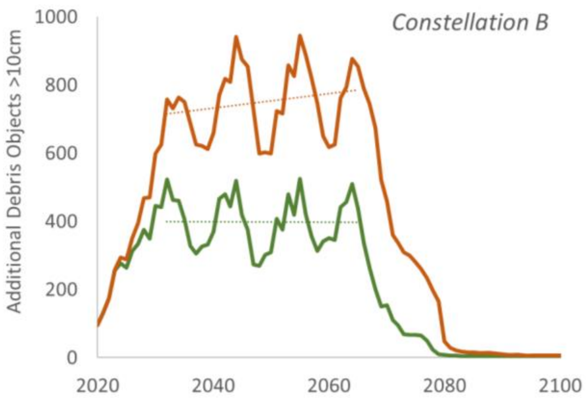

Figure. 1b - Number of Additional Debris Objects >10 cm without debris removal (orange) and with debris removal (green) for Constellation B.

For Constellation B, in the absence of debris removal, as illustrated in the orange lines, the debris objects in orbit is markedly higher, with around 600-900 additional debris objects in orbit whilst constellation is operational, and a growth rate of 2.1 additional objects per year. The peaks in the cycles that are most prominent for Constellation B correspond to solar minima in the projection of solar activity. The rate of decay of the failed satellites is affected by solar activity and this ultimately is driving the oscillation; it is not substantially related to the replenishment of the constellation. There is limited residual effect in the enduring phase as the satellites passively decay. Debris removal, as illustrated in green, results in a 48% reduction in the number of additional debris objects during the operational phase and stops the growth of debris objects during this period.

These results are summarised in the table below. The values in orange represent the results from the additional constellation, with the values in green including debris removal. As such, we can clear see the impact that debris removal strategies have on each of these metrics.

Table 3. Additional Debris Objects > 10cm

	Constellation A	Constellation B
Gradient in Operational Phase (/yr)	11.5 (4.0)	2.1 (0)
Objects at end of Operational Phase	604 (333)	854 (438)
Gradient in Enduring Phase (/yr)	4.7 (2.1)	0 (0)
Objects at end of Enduring Phase	687 (238)	0 (0)

3.2 Impact on Spatial Density

In this section, we evaluate the change in spatial density as a result of Constellation A's deployment and operations, with and without the debris removal strategy in place. Whilst the figures presently show the percentage increase in spatial density; the absolute changes in spatial density are also consistent with these results. In the following figures, we see that the spatial density of objects in orbit is primarily impacted at the constellation's operational altitude. This means that the additional debris objects > 10cm identified in Section 3.1 remain in the direct vicinity of the constellation's active fleet – posing a direct risk to operational service of the constellation.

During the operational phase, there is a ~140% increase in spatial density at the constellation's operational altitude (due to active satellites and debris), both relatively and in absolute terms. This can be reduced down to ~100% as a result of debris removal. The residual spatial density increase is largely operational and manoeuvrable constellation satellites.

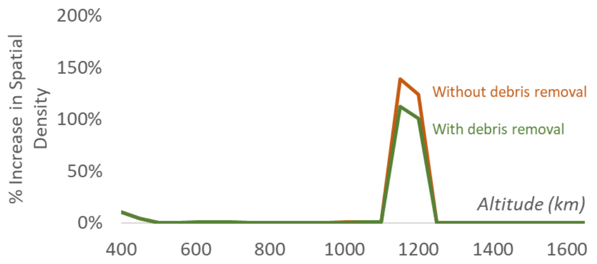

Figure. 2a – The percentage increase in spatial density without debris removal (orange) and with debris removal (green) for Constellation A during the operational phase.

Continuing on to the enduring phase whereby constellation satellites are no longer being deployed, there remains an ~60% increase in spatial density at constellation altitude. This is almost completely mitigated by the debris removal service, as shown in Fig. 2b.

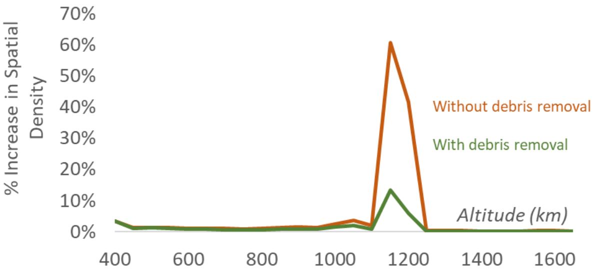

Figure. 2b – The percentage increase in spatial density without debris removal (orange) and with debris removal (green) for Constellation A during the enduring phase.

3.3 Assessment of Different Debris Removal Strategies

As the technology for debris removal services matures, so must considerations for how these services can be used by satellite operators. In this section, we consider different debris removal strategies with an objective to measure when to intervene with debris removal services.

We consider two different debris removal strategies:

- **RemoveAll5** – all satellites that take more than 5 years to naturally decay are considered clients for debris removal.
- **PMD Maintenance** - When the effective PMD rate reaches a pre-determined threshold, debris removal servicers are deployed to remove failed satellites. In this paper we use 95% PMD as the threshold.

As introduced in Section 2.1, the PMD rate is defined in equation (1) in order for DAMAGE implement removal strategies based on the constellation's overall PMD success rate.

We assume that the constellation is being maintained and replenished to a pre-determined level. In the example of Constellation A, 696 operational satellites are maintained on orbit: if satellites fail or are de-orbited at their end of life, then further satellites are launched to replenish the constellation to this same level. The number of uncontrolled non-compliant satellites increases as more satellites fail and remain on orbit for more than 25 years, and therefore the PMD rate continues to decline over time, in the absence of active debris removal.

The following figure shows the PMD under three different scenarios.

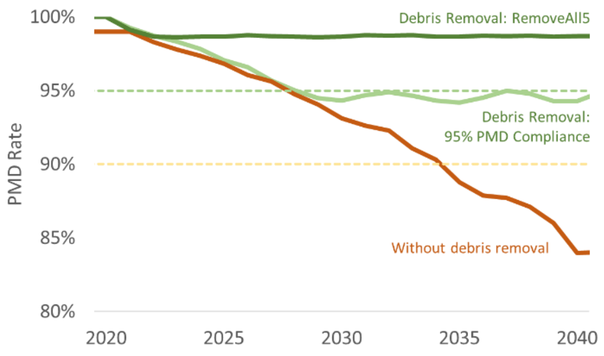

Figure. 3 – The effective PMD Rate without debris removal (orange) and with debris removal strategies (green) for Constellation A during the operational phase.

In the absence of debris removal services, the PMD rate continues to declines over time. Using the RemoveAll5 strategy (all failed satellites with a passive decay time greater than 5 years are actively removed) – in dark green – a PMD rate of ~99% can be maintained throughout the constellation's operational phase. The PMD rate can also be used to determine debris removal intervention. The pale green line in Fig. 3, illustrates how the PMD rate can be maintained at the pre-determined threshold of 95%.

Here we demonstrate that metrics such as post mission disposal rate can be used to determine debris removal intervention, as well as be used as a measurement of debris removal impact. Compliance with such metrics, including PMD rates, are considered as a proxy for the reduction of risk and in the following figure we assess the impact of the number of additional debris objects >10cm from the the three debris removal strategies.

Compliance with a PMD measure needs to demonstrate the reduction of risk as well. The following figure considers the additional number of debris objects > 10cm in the absence of debris removal (in orange) and for the two debris removal strategies presented.

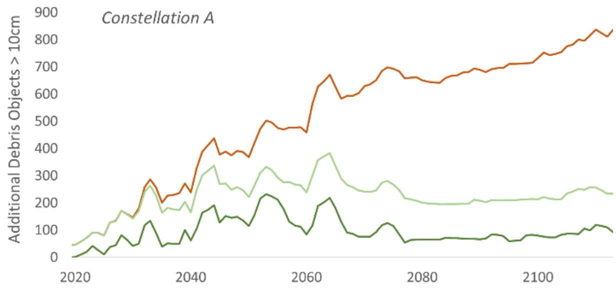

Figure. 4 – The additional number of debris objects > 10 cm without debris removal (orange) and with debris removal strategies (green) for Constellation A.

The number of debris objects > 10cm continues to increase, even once the constellation is no longer being maintained and replenished, in the absence of debris removal. Both debris removal strategies have a measurable improvement on the number of larger debris objects in orbit. The RemoveAll5 strategy is more favourable than the 95% PMD maintenance both in terms of the number of debris objects and the PMD rate presented in Figure 3.

4 CONCLUSIONS

We find that debris removal services can measurably improve the impact that satellite constellations have on the orbital environment. The value of debris removal services is demonstrated in both the operational and enduring phases of satellite constellation lifetimes.

For a constellation at higher altitudes, debris removal slows the growth rate of debris objects by 65% during the operational phase and results in 65% fewer debris objects remaining on orbit during the enduring phase.

For a larger constellation at lower altitudes, debris removal results in a 48% reduction in the number of additional debris objects during the operational phase and prevents the growth of debris objects during this period.

By considering the spatial density we find that these debris objects remain at the constellation's operational orbit. The increase in spatial density at constellation altitude can be mitigated by debris removal services, providing immediate and enduring benefits to satellite constellation operations.

Through the consideration of post mission disposal, we demonstrate in Section 3.3 how debris removal services can ensure operator compliance to pre-determined metrics and assess different debris removal strategies to evaluate risk reduction for different operators.

These results do not capture the full risk that satellite constellations pose or face. It is important to note that this study only considers objects larger than 10cm in size. We do not assess the impact of or risk from smaller debris objects that remain undetectable but capable of catastrophic damage. Over 99% of mission-terminating collision risk is attributable to lethal non-trackable (LNT) objects for LEO satellite operators [12]. Only by incorporating these smaller objects between 1 and 10cm - into these assessments can the full risk be revealed. As such, these results do not capture the full impact that satellite constellations pose or the full risk that they face in the orbital environment.

These results suggest that additional measures may be needed to address both the long-term sustainability and short-term safety concerns. Such measures will be more effective if considered now [13]. In particular, the removal of failed constellation satellites is proposed as a specific measure to prevent the accumulation of failed constellation satellites in high LEO orbital regions and the subsequent increase in the long-term collision risk. At the same time, the removal of failed constellation satellites in low LEO regions may also enhance spaceflight safety, despite the relatively short orbital lifetimes of the satellites there.

5 ACKNOWLEDGEMENTS

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