Impact Risk in LEO as a result of the Increase of Nano and Micro-Satellites

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Executive Summary

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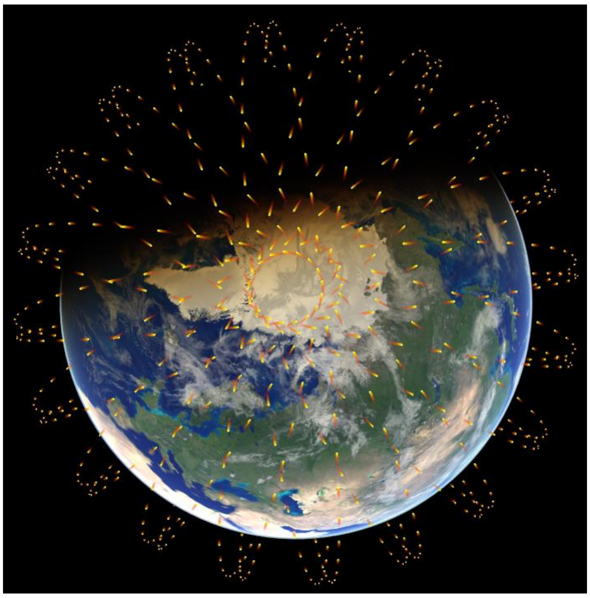

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1 Motivation

Low Earth orbit (LEO) is experiencing a renaissance thanks to increasing commercialisation of space. The opportunities provided by small satellites are enabling diminutive companies and startups, in particular, to make a significant impact on the space economy. Small satellites have played a vital role in this revolution and they have a unique ability to bring around new products and services at short timescales and for relatively low-cost. This has caused a dramatic increase in both the number of commercial actors within the space industry, to capitalise on the new opportunities, and the number of small spacecraft launched, particularly to LEO.

In 2014, two companies, OneWeb and SpaceX, announced plans to build satellite constellations in LEO to provide fast, low-cost internet services to the world. In the following years, Boeing, Samsung and others have also announced their intention to develop similar constellations. Most, if not all, of these companies are targeting altitudes between 1100 and 1400 km for their constellations.

Internet services are already offered by a number of companies with spacecraft in Geosynchronous Earth Orbit (GEO) but these suffer from high latency and, due to the complexity and resources required by the GEO satellites used, are relatively expensive. By using LEO constellations the latency can be reduced and better internet services can be offered. However, the move from GEO to lower altitudes results in the need for constellations containing an increasing number of satellites to maintain the global coverage.

Due to the rapid and significant change in launch activity that the above activities will bring, there is some concern about the effectiveness and relevance of the existing space debris mitigation guidelines.

2 Methodology

To evaluate the effectiveness of existing space debris mitigation guidelines and to understand the sensitivity of the space debris environment to a variety of small satellite and constellation parameters, the activity conducted was divided into the following tasks:

- A review of the available information and projections on small satellite populations, large constellations and long-term environment predictions,
- The implementation of a long-term debris environment simulation campaign, making use of representative traffic models for small satellite and large constellation activity and state-of-the-art space debris evolutionary models.
- An analysis of the impact of small satellites and large constellations on the LEO environment, an assessment of the most effective mitigations measures and recommendations for potential improvements which are beneficial to the environment whilst limiting the impact on industry.

Three evolutionary debris models were used to perform long-term environment projections: the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) developed at the University of Southampton, the Long-Term Utility for Collision Analysis (LUCA) developed at Technische Universität Braunschweig, and the Space Debris Mitigation long-term analysis program (SDM) developed at IFAC-CNR. The analysis was based on comparisons of long-term projections of the orbital object population, under a variety of small satellite and mega-constellation scenarios, with a reference scenario comprising:

- Initial population: all objects ≥ 10 cm with perigee < 2000 km in orbit on 1 Jan 2013 (data from MASTER)
- Future launch traffic: repeat 2005-2012 launch cycle (data from MASTER)
- Projection period: 1 Jan 2013 to 1 Jan 2213
- Post-mission disposal (PMD) of 90% of spacecraft and rocket bodies to a 25-year orbit
- No explosions
- No collision avoidance

Variations of the constellation and small satellite parameters with respect to baseline cases provided the set of simulation cases that were investigated. The variations considered for the constellation cases included mission lifetime, constellation altitude, number of satellites and spares, satellite characteristics and lifetime, and launcher behaviour, amongst others. The variations in the small satellite baseline case included the launch rate, the satellite size/form factor, the launch altitude, and post-mission disposal, amongst others.

Three categories of evaluation metrics were used in this study: (1) metrics based on averages computed over all MC runs, (2) metrics based on the statistical variability in MC runs (so-called “criticality norms”) and (3) metrics based on probabilistic assessments of the MC runs.

3 Results

3.1 Large constellations

Consistently with previous studies, the most influential aspect on the future space debris environment is the post mission disposal of spacecraft and rocket bodies. The impact of compliance below 90% for the constellation has the most substantial impact on the environment regardless of the metric used. There is substantial benefit in maximising the reliability/success of post mission disposal.

In some cases, the use of electric propulsion can be more efficient than having satellites delivered directly to the target orbit. The results of the simulations confirm that this can have a substantial effect on the environment. Importantly, it increases the robustness of the system to failures and to post mission disposal failures. It is clearly evident in the data that a low deployment altitude effectively raises the compliance with post mission disposal requirements by having both rocket body PMD failures and dead-on-arrival (DOA) failures naturally compliant with PMD guidelines. Similarly, operating a large constellation at low altitudes (e.g. below approximately 650 km) ensures high compliance rates and reduces long-term impacts on the environment, due to the action of atmospheric drag on any failed constellation satellites in this orbital regime. However, the congestion already existing at these altitudes can lead to an increase in the number of collisions involving constellation satellites and objects from the background population. Nevertheless, the long-term benefits to the environment of low altitude constellation operations are important and should be considered by constellation operators.

Whilst the use of low altitude deployment and electric propulsion for constellation satellites has been shown to reduce the impacts on the environment, satellites that use electric propulsion will require larger solar arrays to meet the relatively high power requirements of those systems, which will increase the cross-sectional area exposed to impacts and could have a negative impact on the environment. Ultimately, there is a trade off with the collision area. Indeed, the results show that low-mass constellation satellites with small cross-sectional areas are better, from an environmental perspective, than high-mass satellites with large cross-sectional areas. Certainly, the satellite cross-sectional area is one of the most important parameters in terms of the short- and long-term environmental impacts of large constellations.

The number of satellites has a significant effect. It seems possible for constellations consisting of up to 1500 satellites to have a minimal effect on the environment. In order to achieve this, an appropriate altitude must be selected, and the satellites themselves must be relatively small. The characteristics of the satellites themselves, particularly the collision (projected) area, have a high sensitivity demonstrating that an influence on the environment should be considered at the satellite design stage. Further environmental benefits can be observed from increasing the satellite lifetimes, thereby reducing the replenishment launch requirements and by reducing the lifetime of the constellation operations.

The inclination and altitude separation of the orbital planes of a large constellation can be designed to mitigate some of the potential negative impacts on the environment. In particular, lower inclinations and increased separation of the orbital planes, in terms of altitude, lead to a reduction in the number of objects and the number of collisions over the long-term. Ensuring that operational constellation satellites have the ability to perform collision avoidance and that good situational awareness is available are also important requirements if the long-term consequences of collisions are to be avoided.

Further, the benefit of Active Debris Removal (ADR) can be seen in the results, with a reasonable impact if at least 5% of failed satellites are removed. Over the constellation lifetime, this is of the order of one satellite per year, which appears feasible given the number of satellite launches. Higher impacts can be observed with higher removal rates. It is worth noting that similar benefits can be obtained by extension of the satellite lifetimes, which has the potential to be a cheaper solution, so this also provides an interesting trade-off for industry.

There is some vulnerability to the behaviour of the background population. Clearly, where operators are less compliant with space debris mitigation guidelines, the existence of a large number of operational satellites provides an increased risk, even if the constellation operators are diligent. Therefore, the impact of the constellation is increased if the compliance of the background population with mitigation guidelines is poor.

3.2 Small satellites

The most sensitive parameter in the simulations is the behaviour of the background population. Therefore, the measures which can be taken to mitigate against the impact of small satellite numbers are vulnerable to the behaviour of the general satellite population.

Of the scenarios where the background behaviour is good, it is clear that the key aspects affecting the impact of small satellites are the number of satellites, the altitudes of deployment and the size of the satellites. Where there are dedicated launches operating to deploy satellites at lower altitudes, especially where these are within the 25-year lifetime domain, a reduced impact on the environment can be observed. This consolidates the concern that unmanoeuvrable small satellites deployed at higher, more populous, altitudes can remain a source of collision risks. It is noticeable in the results that this effect (and the effect resulting from potentially long residual lifetimes) can be mitigated where the small satellites have orbit control and collision avoidance capability, and this capability would be recommended for small satellite missions at higher altitudes.

The trend towards increasing small satellite sizes in order to increase the capability of the satellites would be expected to have a significant impact on the environment according to these results. Again, collision avoidance capability has some mitigating impact. Where this propulsive system is also able to provide a de-orbit capability, increased benefit is observed. This suggests that the guidelines for the de-orbit of small satellites should be similar to other satellites if deployed at sufficiently high altitude.

4 Conclusions

A review of the literature and other sources related to CubeSats, constellation and simulation studies related to these topics has been undertaken. The review has enabled an understanding and awareness of the current state-of-the-art in these areas, and has provided some evidence about the emergence of possible threats to the safety of satellites operating in the LEO protected region and the sustainability of the space environment, and it has identified some of the technological developments that may help to mitigate these threats. The review has also helped to shape two simulation plans for the study of small satellites and large constellations

An unprecedented number of simulation cases have been investigated by the evolutionary models DAMAGE, LUCA and SDM to evaluate the impacts of large constellations and small satellites on the LEO environment. Given the large number of simulation cases investigated, a set of evaluation metrics was identified with the aim of simplifying the subsequent analysis. This set included metrics based on the average and final number of objects, the average and final number of catastrophic collisions, criticality norm metrics adopted from a previous ESA study, and probability-based metrics. The latter two types of metric were chosen to ensure that the variability in the Monte Carlo runs produced by the evolutionary models was taken into account; the criticality norm focused on the statistics derived from the Monte Carlo runs (i.e. the mean and standard deviation) whereas the probability-based metrics focused on the probabilities.

Most opportunities for risk reduction come from measures that limit exposure of the orbital object population to the constellation and small satellite traffic. Importantly, and as shown in the results, this is not simply a case of launching to altitudes that are sparsely populated. Further, only one of these exposure-based parameters is represented in existing space debris mitigation guidelines (PMD). Given the innate complexity involved in constellation design and operation, and the relatively low number of constellation proposals being put forwards (and, therefore, the low number of operators to deal with), it may be better to address the risks posed by large constellations on a case-by-case basis. In contrast, there are fewer opportunities overall to mitigate the impacts of small satellites. For the most part, this is due to the constraints on the design of small satellites, especially CubeSats. In particular, the technology needed for propulsion and/or disposal has yet to achieve any maturity, and reliability issues remain a considerable source of concern. Without the ability to perform post-mission disposal, there is currently no overlap with existing space debris mitigation guidelines; compliance with the so-called “25-year rule” is typically achieved through launch to low altitudes but this can’t always be predetermined or stipulated, given that small satellites are mostly secondary payloads on the launch. In addition, the small satellite community is large and made up of a diverse set of actors, which makes it difficult to develop a case-by-case assessment approach. Consequently, there is perhaps a need to consider additional space debris mitigation guidelines for small satellites and CubeSats given the potentially ubiquitous and negative impacts on LEO and the need to communicate responsibilities widely. However, there is a trade-off: imposing restrictions on small satellite missions could forfeit many of the advantages offered by them. In particular, the cost impact could be severe and affect the commercial viability of missions.

Nevertheless, the simulation results suggest that it is important to have regulation of the small satellite population in order to mitigate the effects on the environment. The existing space debris mitigation guidelines already include an altitude-/lifetime-based measure – the “25-year rule” – but evidence of the past decade has shown that CubeSats, small satellites and conventional/large satellites have a patchy record of compliance, at best. Enforcement, perhaps, will provide a more robust way to mitigate the impacts of small satellites on the environment.