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The impact of large constellations on space debris environment and its Countermeasures

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Abstract

Large constellations have developed rapidly in recent years because of their unique advantages, but they will inevitably have a huge negative impact on the existing space debris environment. According to the existing research results, large constellations will inevitably lead to the deterioration of space debris environment. The key to mitigate the impact is the success rate and time of the post-mission disposal process. Aiming at this problem, this paper further studies the impact of large constellations on other space targets under different PMD strategies through simulation calculation, and puts forward corresponding strategies and suggestions.
According to Oneweb's large constellation launch operation plan, the dangerous intersection of large constellation with existing space targets in different stages of its life cycle is calculated by simulation. Based on this, the influence of large constellation operation on existing space targets under different time and strategy of PMD is analysed. The conclusion shows that the stage of PMD is the stage in which large constellations have the greatest impact on existing space targets; the speed of PMD and number of satellites performing PMD at the same time are the key factors to the degree of the negative impact; The faster the PMD is, the less threat it poses to other spacecraft. More results and conclusions are still being analysed and calculated.

1 Introduction

Small satellite has developed rapidly since 1995 because of its new technology, fast response, flexible application and low cost. From 2015 to now, small satellite applications have been enriched and expanded, and began to enter the systematic application stage [1] [2]. The great value of large and small satellite constellations in a series of new applications, such as space-based global communications and remote sensing, has been discovered. These applications provide new opportunities for economic development, global education, rural health care, remote services and environmental science. At the same time, small satellites have also made the cost of entering and utilizing space drop rapidly, paving the way for many new participants (big or small) who are trying to devote themselves to commercial space applications. In 2017 alone, the number of small satellites under 500 kg launched worldwide reached 312, accounting for more than 80% of the total number of spacecraft launched in that year. The world's major space powers and commercial companies have also proposed extremely large small satellite constellation launch deployment plans, as shown in Table 1 [1]. According to these plans, the number of satellites in orbit in the next few years will surge from more than 2,000 to more than 2,000. China has also proposed several small satellite constellation plans deployed at different orbital altitudes, such as Hongyun (MEO), Queqiao (LEO), Hongyan (LEO), Xingyun (LEO), CUBESAT (LEO).

Table 1 Small Satellite Constellation Launch Plan

Operator	Boeing	Cube Star	Universal Star	OneWeb	Eagle Eye 36	Iridium	SpaceX	Samsung	Orbcomm	Terra Bella

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Number of satellites	**1120**	**828**	**1008**	**100**	**100**	**100**	**40**	**720**	**6**			**71**	**1600**	**1600**	**400**	**375**	**450**	**4600**	**31**	**28**
Orbital altitude (km)	**1200**		**380**	**600**	**800**	**1400**		**1200**	**650**		**780**	**1150**	**1110**	**1130**	**1275**	**1325**	**900**		**750**	**576**
Orbital inclination (degree)	**45**	**55**	**88**	**98.5**			**52**	**87.9**	**44**	**63.5**	**97**	**86.4**	**53**	**53.8**	**74**	**81**	**70**		**45**	**97.76**
Spindle size (m)	**3**		**0.3**			**9.7**		**2**	**0.4**		**4.27**	**2**					**3**		**10.5**	**1.5**
Sub axial dimension (m)	**1.55**		**0.1**			**0.1**		**0.1**	**0.1**		**0.1**	**0.1**					**0.1**		**0.1**	**0.1**
Sub axial dimension (m)	**1.55**		**0.2**			**4.9**		**1.05**	**0.25**		**2.19**	**1.05**					**1.55**		**5.3**	**0.8**

Don Kessler pointed out that the deterioration of the space debris environment is far from being curbed even without considering the impact of large satellite constellations. According to its calculation, if there is no effective control means, the debris density will reach a critical value after 70 years, leading to the chain impact effect of debris (Kessler disaster), which makes the near-Earth space completely unavailable [4] [5]. A large number of small satellite launching plans will make the satellite density in typical orbit areas increase sharply, which will not only make the orbit and frequency resources more tense, but also lead to a significant increase in the probability of space collision, which will undoubtedly further aggravate this trend [6]. Existing space debris mitigation guidelines and related space traffic management policies do not take into account the explosive development of small satellite constellations, and it is difficult to meet its enormous challenges [7]. Therefore, in order to cope with the rapid development of large and small satellite constellations, it is urgent to introduce new measures to regulate the development of large and small satellite constellations.

This paper investigates the existing research results on debris environmental impact of large satellite constellations, and analyses the impact of large small satellite constellations on the long-term evolution of space debris environment and the impact risk faced by large small satellite constellations during deployment, operation and derailment. According to Oneweb's constellation launch plan, the threat of deployment, operation and derailment to existing space targets is analysed and calculated. On the basis of these three, the Countermeasures for large small satellite constellations are put forward.

2. Impact of Large Satellite Constellation on Long-Term Space Debris Environment

Up to now, in most debris environment evolution studies, the frequency of human space launch, as one of the important factors, is generally 50-70 times per year. This is based on past average data. Many debris mitigation policies are formulated and implemented in turn. However, the large small satellite constellation project has made the human space launch activities increase step by step, and the number of small and medium-sized objects entering orbit reaches about 100, Fig. 1, which will undoubtedly have a very significant impact on the long-term evolution of the debris environment. [8]

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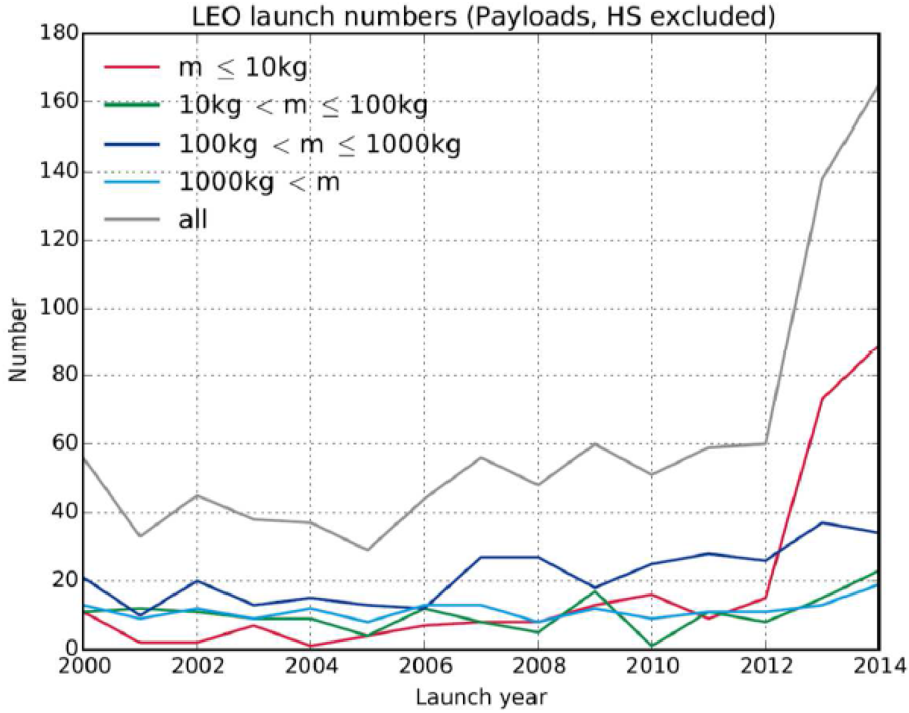

Fig. 1 LEO Launch Target Number Increase Curve [8]

In 2016, ESA studied this issue. Based on the space debris model, the long-term impact of a typical large small satellite constellation (1080 200 kg satellites distributed in 20 orbital planes with an inclination of 80 degrees at an altitude of 1100 km) with a life span of 50 years (2021-2071) on the space environment is simulated. [9] The mission process includes two-year constellation construction stage (20 launches per year, 18 satellites per time), 50-year maintenance operation stage (12 launches per year, 18 satellites per time) and post-mission processing stage. According to the research results, the launching operation of large constellations will lead to a sharp increase in LEO orbital objects and impact times in a short time; when the success rate of PMD reaches more than 90%, the number of orbital objects and impact times can slowly return to normal level after the decommissioning of constellations. And less than 90% of PDM will lead to the continuous growth of orbital objects, and the space environment will continue to deteriorate irreversibly, as shown in Figures 2 and 3.

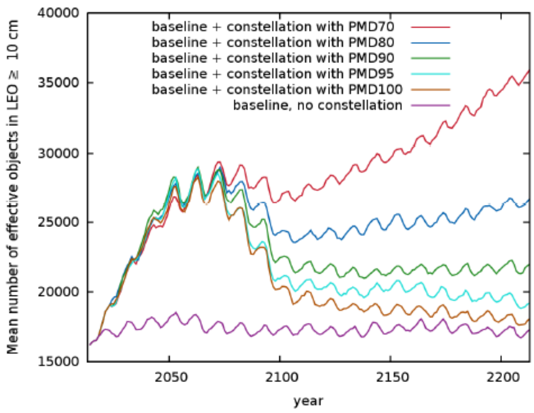

Fig. 2 The impact of constellations on the number of debris above 10 cm in LEO orbit at different PMD execution rates [9]

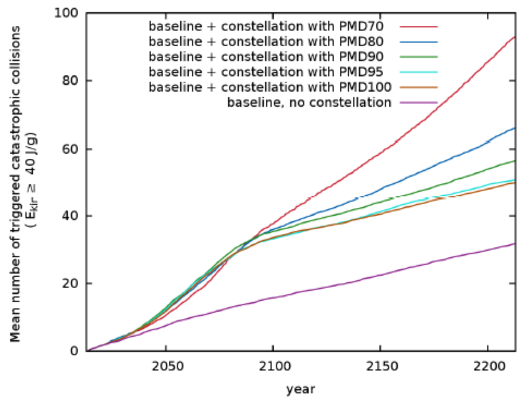

Fig.3 The impact of constellations on collision times of LEO orbital objects with different PMD execution rates [9]

They also further analysed the impact of large constellations on debris environment at 90% PMD at different times. According to the current regulations, the longest time of satellite derailment in the constellation after the mission can reach 25 years. If the time of satellite derailment is shortened, the number of objects in LEO region and the peak number of impact times will be reduced, and the speed of environmental recovery will be increased accordingly, as shown in figs. 4 and 5.

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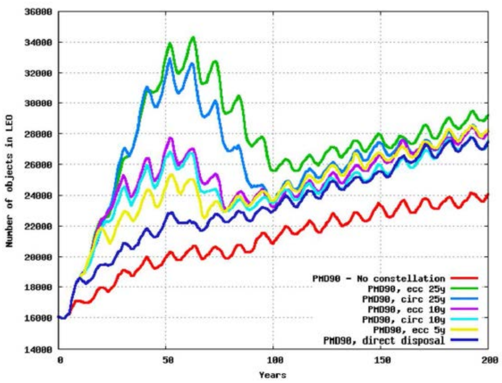

Fig. 4 The impact of constellations on the number of debris above 10 cm in LEO orbit at different PMD times [9]

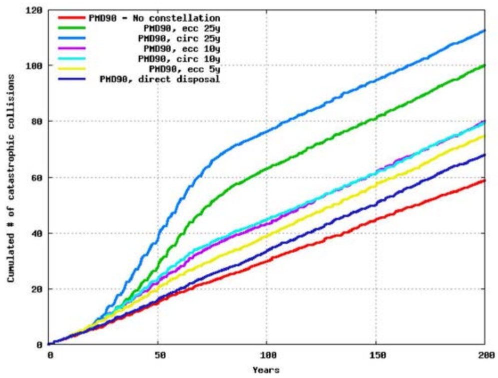

Fig. 5 The impact of constellation on collision times of LEO orbital objects at different PMD times [9]

According to its research results, the launch plan of large and small satellite constellations will undoubtedly greatly aggravate the deterioration of space debris environment, and the huge impact in the short term is inevitable. The impact on debris environment can be minimized by shortening the off-orbit time after the mission and improving the PMD success rate. However, due to the fact that the derailment time in the current mitigation guidelines is up to 25 years and the actual PMD implementation rate is far below the ideal value of 90%, the impact of large constellations on debris environment evolution will be catastrophic.

3. Impact Risk of Large Satellite Constellation themselves

According to the conclusion obtained from the long-term debris evolution model, shortening the PMD time after the large small satellite constellation mission can reduce the impact on the short-term debris environment caused by the reduction of the peak number of orbital objects caused by the launch operation of the constellation. And improving the success rate of the PMD of the constellation satellite can greatly reduce or even eliminate the medium-term and long-term impact on the debris environment. However, satellites in the constellation are also facing the risk of debris impact in the process of launching, deploying and running out of orbit. Once the impact fails, not only the functions of the satellite itself, including post-mission derailment, may be lost, but also a large number of debris will cause greater environmental hazards.

In view of this situation, CNES and NASA take Oneweb's constellation plan as an example to analyse and calculate the impact risk of large and small satellite constellations in the phase of launch deployment, operation and post-mission derailment.

According to Oneweb's constellation plan, 720 satellites will be evenly deployed on 18 orbital planes in a circular orbit with an altitude of 1200 km and an inclination of 87.9 degrees. The launch deployment time of constellation is 1 year, the operation time is 5 years, and the orbit descent time is 5 years after the mission. [10]

In the research of CNES, through the debris data of each orbit of MASTER debris model, the possible impacts can be classified into three categories: penetrating impacts, fatal impacts and disintegration impacts. [11] The penetrating impact is judged by the impact limit equation according to the size and velocity of the impact debris; the fatal impact is judged by the size of the impact debris larger than 1 cm in the penetrating impact results; and the disintegration impact is judged by the impact energy density greater than 40 J/g. According to the statistical results of several calculations, the number of penetration impacts, fatal impacts and disintegration impacts occurred in the whole operation process was 11-38, 1 and 0.06. Among them, the impact ratio is 5% in launch deployment phase, 35-60% in operation phase and 40-60% in derailment phase.

In NASA research, the fragmentation data provided by ORDEM 3.0 model are used to calculate the probability of catastrophic disintegration impact (impact energy density greater than 40J/g). [12] The calculated results are shown in Fig.6.

According to the results of CNES and NASA, the main impact risk of large constellations during their life cycle comes from the post-mission orbital phase (more than 60% impact and fatal impact probability). During the launch phase, the probability of collision is relatively low because the satellites are put into orbit in batches and the duration is short. Because the selected orbit height of 1200 km avoids the dense orbit height distributed by debris and spacecraft, the impact probability is not high. Because of its long duration, the impact probability of the descent stage is much higher than that of the first two stages because it will traverse the densely distributed area of space objects.

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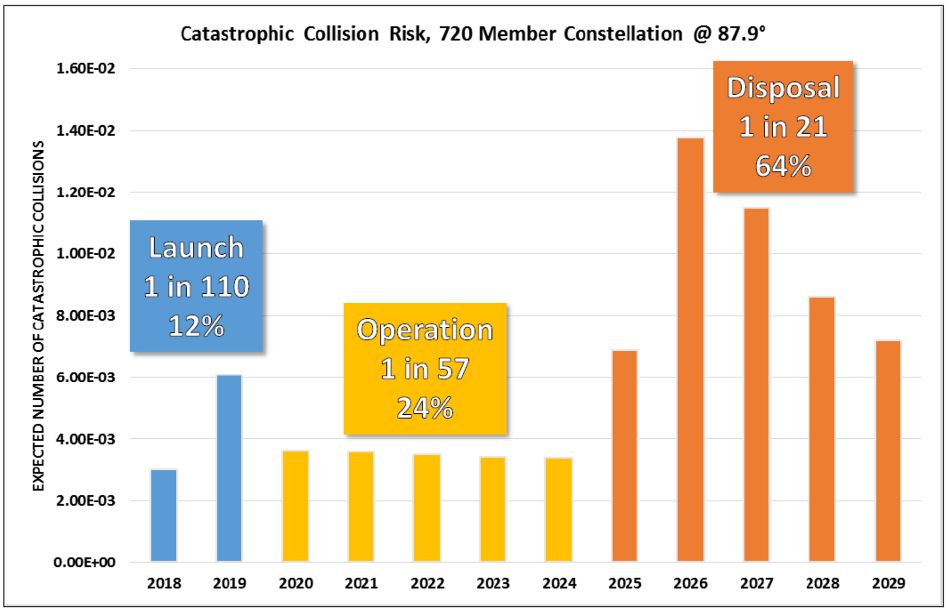

Fig. 6 Distribution of the probability of disintegration impact at different stages of Oneweb constellation [12]

4. Threats of Large Small Satellite Constellations to Existing Space Targets

According to Oneweb's constellation launch deployment plan and the analysis and calculation methods of NASA and CNES, the lifetime of constellation is divided into three stages: launch deployment, on-orbit operation and off-orbit after mission. The dangerous intersection times of spacecraft with distances less than 10 km from other space targets in three stages are calculated by simulation program to analyse the impact of its life cycle on existing orbital space targets, including spacecraft in orbit and space debris whose size is more than 10 cm on orbit which has been tracked and coded.

According to the simplified calculation method in NASA research, the orbital parameters calculated at different stages are set up. In the ascending stage, the orbital inclination is 87.9 degrees, the perigee altitude is 475 km, and the apogee altitude is 600 km, 840 km and 1080 km respectively. The ascending time of a single satellite is 60-70 days, and the total launch and deployment time is 1 year. Each orbit has 40 satellites at the same time according to the launch period and batch. The operation stage is a circular orbit with an inclination of 87.9 degrees and a height of 1200 km. It is divided into 18 orbital planes, each of which has 40 satellites, and the operation time is 5 years. In the post-processing stage, the satellites on each orbit plane descend in turn according to the perigee altitude of 1000 km, 800 km, 600 km, 400 km and 200 km, and all satellites descend synchronously for 5 years.

The calculation results are shown in Fig. 7. It can be seen that in the stage of constellation launch and deployment, due to the short time and batch deployment of satellites, the number of close-range rendezvous with existing space targets is less; in the stage of operation, the orbit is located at 1200 km altitude with fewer space targets, but the number of rendezvous increases due to the increase of constellation satellite density; in the PMD stage, because a large number of satellites pass through the LEO region with dense spatial targets at the same time, and this stage lasts for a long time, the number of intersections is obviously greater than the first two stages.

When the PMD time is five years according to Oneweb's plan, the proportion of PMD times in this stage accounts for 60.64% of the total number of PMD times in the whole life cycle, which is basically consistent with the calculation results of NASA and CNES. As shown in Figure 7, the number of intersections can be significantly reduced by increasing the speed of derailment and shortening the post-processing time of tasks; when the time of derailment is less than three years, the number of intersections in this stage is only 44% of the total number of intersections less than the number of operation stages; when the time of derailment is shortened to one year, the number of intersections decreases to only 20.94% of the total number of intersections, which is close to the number of single-year intersections in operation stage.

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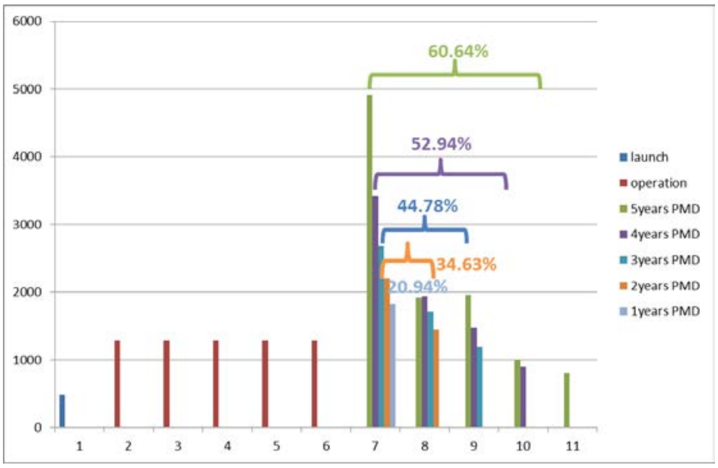

Figure 7 Number of intersections within 10 km at different stages of large small satellite constellations

5 conclusions and suggestions for measures

The results show that the deployment of large and small satellite constellations will inevitably cause adverse impacts on the space debris environment, mainly in the increase of the number of orbital objects and the number of collisions; the key to mitigate and control the adverse impacts of large and small satellite constellations lies in post-mission processing; improving the success rate of PMD can greatly reduce or even eliminate the medium and long-term impact of constellations on the space environment. Shortening PMD time can not only reduce the short-term impact of constellation on debris environment, accelerate the recovery of debris environment, but also reduce the risk of impact of constellation satellite itself, and also reduce the impact of constellation lifetime on other space targets.

Based on the above conclusions, this paper puts forward the following suggestions for future large and small satellite constellation plans from the perspective of debris environmental governance:

1) The deployment track has been fully communicated and coordinated beforehand. The large number of satellites in a large constellation will greatly increase the number of space targets deployed in the region, thus increasing the complexity of satellite operation and collision risk. Therefore, the existing high-density orbits and other large constellation deployment orbits should be avoided in large constellations.

2) Satellite orbital positions in constellations should be fully open and transparent. It includes detailed launch plan, operational orbit, derailment path and so on. It also needs to be equipped with angular reflector, automatic transponder and other devices to report the real-time position of satellite in order to reduce the difficulty of early warning processing for dangerous intersection and minimize its impact on other spacecraft.

3) Satellites in constellations should have timely and reliable post-processing capabilities. Post-mission derailment time cannot be 25 years as stipulated in the current mitigation guidelines, but should be shortened to 5 years or even shorter after the mission. The post-processing capability should be reliable enough to ensure that all satellites in the constellation have a success rate of more than 90% after the mission.

4) Satellites should ensure that the reentry process is safe and reliable. Through reasonable design and appropriate material selection, the satellite can be fully disintegrated and burned during the re-entry process, and the residual debris can be avoided from reaching the ground, or the remaining deb ris can be confined to the landing area that does not pose a threat as far as

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possible. This is particularly important for large-scale systems where hundreds or even thousands of satellites may be out of orbit every year.

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