Evaluation of Space Debris Mitigation Measures
Using a Debris Evolutionary Model

By Satomi KAWAMOTO,1) Takayuki HIRAI,1) Shiki KITAJIMA,2) Shuji ABE,2) and Toshiya HANADA2)

1)Research and Development Directorate, JAXA, Chofu, Japan
2)Kyushu University, Fukuoka, Japan

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Debris mitigation measures such as post-mission disposal (PMD) were set by considering the effects thereof using a debris evolutionary model. Many small satellites have recently been deployed in orbit and various plans are proposed for a so-called mega-constellation consisting of thousands of satellites in Low Earth Orbit (LEO). New systems such as an electric propulsion system and air drag augmentation devices are also proposed for satellite de-orbit. Therefore, the impact of them must be discussed in order to preserve the space environment. This study evaluates the debris mitigation measures taken by using the Near-Earth Orbital Debris Environment Evolutionary Model (NEODEEM) that was jointly developed by Kyushu University and JAXA. It revealed that mega-constellations have much impacts on the debris environment, and that the future environment will be affected by the PMD compliance rate and how PMD is achieved.

Key Words: Space Debris, Debris Evolutionary Model, Mega-constellation, Debris Mitigation Guideline

1. Introduction

Space debris may impose large impacts on sustainable space utilization and development activities; therefore, its effects should be studied and adequate countermeasures taken. Future environmental changes have been evaluated by using a space debris evolutionary model that considers future launch traffic, explosions, collisions, and other factors. Debris mitigation measures are set by considering the balance between impacts on a mission and the effects on the environment. For example, post-mission disposal (PMD), that is, de-orbit to the disposal orbit having an orbital lifetime of less than 25 years is recommended in many debris mitigation guidelines such as the Inter-Agency Space Debris Coordination Committee (IADC). This so-called 25-year-rule requires average spacecraft with an Area-to-Mass ratio of 0.01 m²/kg to deorbit at the altitude of less than about 630 km. This 25-year rule was developed based on certain assumptions that were considered reasonable at that time. However, with the recent drastic changes in space utilization, the sufficiency of debris mitigation measures should be re-examined. About 20 years ago when the 25-year rule was developed, less than 10000 objects of debris were catalogued, and about 100 objects were inserted annually. It was recently reported more than 23,000 cataloged objects are orbiting the Earth, as well as more small satellites. More than 100 nano/micro satellites alone are inserted every year and huge constellations, so-called mega-constellations with several thousands of satellites, are planned. Proposals for PMD also include an electric propulsion system and air drag augmentation device, which were not considered in the past. Many papers have pointed out that mega-constellations would have huge impacts on the debris environment. The purpose of this paper is to evaluate the impacts of such emerging forms of space utilization using a debris evolutionary model and to discuss which factor is important to preserve the space environment.

2. Debris Evolutionary Model

The debris evolutionary model can simulate the future debris environment by analyzing the orbit propagations of each object and considering future launch activities, explosions, collisions, and PMD. This study used the Near-Earth Orbital Debris Environment Evolutionary Model (NEODEEM) jointly developed by Kyushu University and JAXA to simulate the future environment and debris objects larger than 10 cm. Perturbing accelerations of the orbital elements due to the gravitation forces of the Sun and the Moon, solar radiation pressure, atmospheric drag, and J2, J3, J4 of the Earth are calculated with a 5-day time step to propagate the objects. The results show that even with 90% compliance of the commonly-adopted mitigation measures, the LEO debris population is expected to increase by an average of approximately 30% in the next 200 years (Fig. 1). Note that 90% compliance of PMD...
and no explosion are very optimistic assumptions. Here we should also note that the tendency of an increasing number of debris objects predicted by the debris evolutionary model is an average of many Monte Carlo runs. The debris environment is governed by collisions having a small frequency but much impact so that, for example, a mean value of 100 MC calculations is used. The number of debris objects increases immediately when an actual collision occurs, which is different from the gradual increase predicted by the evolutionary model.

Fig. 1 shows that the number of debris objects will increase with high probability, even with such optimistic assumptions as 90% PMD compliance and no explosions, and with launch traffic at almost the same level as that of today. What the evolutionary model can predict is an average of the future environment, so it is meaningless to compare the result of the evolutionary model and the actual environment. However, it is still possible to evaluate the effectiveness of mitigation measures by using the debris evolutionary model.

We should also note that the results depend on the future solar activities since air drag has large impact on the future environment.6)

3. Small Satellites and Mega-constellation Scenario

Many small satellites weighing less than 50 kg, especially CubeSats weighing less than 10 kg, have recently been launched. More than 100 nano/micro satellites were launched every year since 2014 and more than 200 are expected in the coming years7). The small satellite usually does not possess a propulsion system for de-orbit. The debris evolutionary model showed that the debris environment will be degraded by more small satellites. Ref. 8) shows that if small satellites are inserted at high altitude, the number of collisions will increase even though the satellites are equipped with a drag augmentation device for complying with the 25-year rule, because the area enlarged by such devices increases the probability of collision. Therefore, it is important to insert small satellites at lower altitude and reduce the mass of the drag augmentation device so as to avoid a catastrophic collision.

Moreover, a massive so-called mega-constellation with several hundreds or tens of thousands of satellites are planned. In the debris evolutionary model, the launch of rocket bodies, payloads, and mission-related objects was assumed to be repeated according to the 8-year cycle of the past. Some new functions have been added to NEODEEEM in order to conduct the computation of mega-constellation scenarios. At first, its launch process was revised to insert new objects in any year independent of the usual launch traffic.9)

3.1. Mega-constellation model

Table 1 lists several assumptions. The number of constellation satellites is 1000 at a constant altitude of 1200 km. Considering that the 1000 satellites should be deployed by 2020 when full service starts, the satellites are launched from 2016 at a rate of 200 satellites per year in order to reach 1000 satellites. The mission lifetime is assumed to be five years.

Table 2 lists the mass, average cross-sectional area, and orbital elements of the satellites. This study adopts the Walker delta pattern as the basic form of the constellation. Adjacent orbit planes are gapped 18 degrees at their ascending nodes and neighboring satellites are gapped 7.2 degrees. There is an initial offset angle gap of 0.36 degrees between the first satellite of an orbit plane and the first satellite of the next orbit plane.

3.2. PMD scenario

If a satellite is judged to succeed its PMD process based on the PMD compliance rate decided in each scenario, it transfers its orbit to a lower orbit. Basically, it lowers both the apogee and perigee using two impulses of chemical propulsion in order to be in a circular orbit having an orbital lifetime of less than 25 years. Other options are to lower only the perigee by one impulse, or a spiral, gradual orbital lowering by electric propulsion and so on. In Geo synchronous orbit (GEO), spacecraft will be transferred into a disposal orbit about 300 km above GEO. In LEO, regions below 2000 km are protected, but re-orbit at an altitude higher than 2000 km is not recommended, so as to avoid increased debris in the disposal orbit. Therefore, only de-orbit for LEO is considered in this paper, although less propellant will be required for spacecraft whose operational

![Image](367x296 to 486x415)

Fig. 2. Satellite constellation of Walker delta pattern simulated in the present study
altitude is higher than about 1300 km, for re-orbit above 2000 km rather than de-orbit. Re-orbit is accepted in only GEO as de-orbit from GEO is unrealistic considering the huge amount of propellant required. The 25-year rule was set by considering the balance between the merits for the environment and the cost required for the mission.

There are plans for mega-constellations to use electric propulsion for de-orbit. Today, the PMD compliance rate is about 20 to 40% for spacecraft whose original orbital lifetime is more than 25 years, while the evolutionary model mentioned above assumed 90% compliance. No explosions are assumed, although several have been observed annually in recent years.

4. Results

This section describes the results of the evolutionary model.

4.1. Effects of mega-constellation

Fig. 3 shows the evolution of the LEO population with mega-constellations. The population in LEO will further increase from 2016 to 2050 due to many launches and more collisions, compared with a baseline scenario that assumes no mega-constellation. But from 2050, the population will begin to decrease. This is due to the concentration of many collisions at 600-700 km, which suggests that satellites after PMD are responsible for most of the collisions, and that collision fragments would re-enter the atmosphere over the course of 25 years, as shown in Fig. 4 and Fig. 5. The figure shows that the disposal orbit after PMD should be dispersed so as to avoid collisions within disposal orbits. Re-orbit at an altitude higher than 2000 km is not recommended. While these are short-term effects, the PMD compliance rate has a long-term effect. Fig. 6 shows the change in the effective number for each PMD compliance rate. At a PMD compliance rate below 60%, the effective number will increase even after the operational period of mega-constellations. This is because many collisions occur in the operational orbit around 1200 km. The 1200 km altitude is high enough for the long-term presence of fragments. Fig. 7

Collision avoidance maneuvers (CAM) are assumed to be applied during the operational period.
shows that the increase can be suppressed if the operational altitude is divided into 1200 km and 1100 km. Therefore, the PMD compliance rate and disperse operational altitude are important to preserve the orbital environment.

4.2. Effects of orbital lifetime of disposal orbit after PMD

Fig. 8 shows the effects of the orbital lifetime of the disposal orbit after PMD. The orbital lifetime of the disposal orbit is as short as 0 to 15 years. It shows that the effective number during the operation period of a mega-constellation is affected by the orbital lifetime after PMD, but such effect is not long term. It also shows that a lower disposal altitude is better, but a disposal orbit having an orbital lifetime of less than 25 year seems to be low enough.

4.3. Effects of the manner of de-orbit

If de-orbit is conducted using low-thrust propulsion or a drag augmentation device, the number of collisions is expected to increase, even though these methods comply with the 25-year rule. Fig. 9 shows the effects of the manner of de-orbit, such as immediate disposal or taking one year for disposal operation 24 years after PMD. Gradual disposal takes 25 years for disposal operation. Lowering the altitude as soon as possible is important to preserve the environment.

4.4. Effects of other parameters of constellations

CAM has long term effect (Fig. 10). If satellites do not conduct CAM during operations, the number of objects increase for the long term because collisions occur in their operational altitude. Increasing the number of satellites in a constellation also has large short-term and long-term effects (Fig. 11). When 4000 satellites are considered, effective number of objects will increase more than proportional. The detail of the scenario is described in Ref. 9.

Fig. 12 shows the effective numbers when a satellite has large mass. We assume the mass of satellite to be 150 kg in the above mentioned scenario, and here mass as heavy as 450 kg is assumed. More fragments will be generated for heavier debris according to the standard breakup model developed by NASA\textsuperscript{10} but 450 kg still seems to be small enough. Conversely, area has much impact as shown in Fig. 13. If the area of a satellite is as large as 9 m\textsuperscript{2} while 3 m\textsuperscript{2} is assumed in the above scenario, more collisions will occur. Those effects should be considered when we discuss the sufficiency of debris mitigation measures.

4.5. Short term effects and long term effects

The results above reveal the importance of the following in suppressing short-term increases.
- Orbital lifetime after PMD
- CAM during disposal operations
- Dispersing disposal orbit

Conversely, the following are important in suppressing long-term increases.
- Dispersing operational orbits
- PMD compliance rate
- Immediate PMD
- CAM during operation

In order to preserve the space environment, debris mitigation measures need to be re-examined by considering them.
5. Conclusion

This paper discussed the impact of recent space systems on the orbital space environment and evaluates the debris mitigation measures. Future debris populations are predicted using a debris evolutionary model that considers emerging forms of space development and utilization activities, such as mega-constellations. It was shown that mega-constellations have much impact on the debris environment, and that the PMD compliance rate and the manner of PMD is important to preserve the space environment.

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References