EVALUATION OF IMPACTS OF LARGE CONSTELLATIONS USING A DEBRIS EVOLUTIONARY MODEL FOR CONSIDERING ENVIRONMENT CAPACITY

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ABSTRACT

This paper investigates the short- and long-term impacts of large constellations using a debris evolutionary model to determine space environment capacity, that is, how many additional satellites can be inserted into orbit and still ensure the sustainable use of space. The long-term stability of orbital environments is initially investigated by comparing differences with the baseline case with no constellations. It was found that the long-term effect is acceptable when constellations are inserted at a lower altitude, but that an unstable self-cascading effect occurs when constellations are inserted into higher orbits. The acceptable level is discussed by comparing the number of objects or the cumulative collision probabilities in each altitude band. Also discussed are the effects of such initial conditions as the number of spacecraft, mass, and dispersion at corresponding altitudes. And short-term safety relative to the number of conjunctions and the collision flux of non-catalogued objects is also evaluated.

1 INTRODUCTION

A number of large constellations (LCs) is being realized or planned and the impact of them on the debris environment have been studied [1], [2], [3], [4]. How many more satellites are acceptable must be discussed, that is, how many satellites can be injected into a particular orbit while still ensuring the sustainable use of space. In a previous study, projections were made using a debris evolutionary model for a LC, and it was shown that the effective number of objects will increase more than the case without LCs [1]. However, whether such an increase is environmentally sustainable was unclear. Given the different situations at each orbital altitude, the total effective number of objects alone is not sufficient to discuss sustainability and more detailed evaluations are needed. For example, the cumulative collision probabilities at each altitude were investigated and it was shown that the cumulative collision probability between 900 and 1000 km continues to increase even though it is now smaller than that between 700 and 900 km [5]. We need to investigate the impacts of LCs added to such a background. It is also important to reveal how such LC parameters as the number of satellites, mass, and orbital dispersion at corresponding altitudes affect the orbital environment. Satellites deployed at a lower altitude will soon decay due to air drag, and thus do not have a long-term impact. However, long-term stability as well as short-term safety should also be considered, relative to the burden of collision avoidance maneuvers for spacecraft in the vicinity and the collision flux of small debris objects. The paper discusses such long-term and short-term impacts of LCs, in order to discuss space environment capacity.

2 PROJECTIONS BY DEBRIS ENVIRONMENT MODEL

2.1 NEODEEM

This study used a debris evolutionary model named the Near-Earth Orbital Debris Environment Evolutionary Model (NEODEEM) that was jointly developed by JAXA and Kyushu University to predict the future space environment. NEODEEM can calculate the trajectories of all objects larger than 10 cm in 5-day increments, including such perturbations as air drag and Earth's gravitational potential (4 orders and degrees), gravitation forces of the Sun and the Moon, and solar pressure. It simulates a collision between objects when the error spheres around them overlap as shown in Fig. 1. A collision can occur when two objects exist in the overlapping volume of two error spheres. The collision probability can be calculated with Eq. 1, where V is the volume of each error sphere, ΔV is the overlapping volume of two error spheres, p_1 and p_2 are the probabilities of objects existing within the error spheres, U_{12} is the relative velocity, and A_{12} is the effective collision area calculated by Eq. 2. When two objects have diameters of d_1 and d_2, effective collision area, A_{12} can be

$$C_{12} = \frac{p_2 \Delta V}{V}\frac{p_1}{V} A_{12} U_{12} \tag{1}$$

$$A_{12} = \pi (d_1 + d_2)^2 / 4 \tag{2}$$

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calculated as shown in Fig.2.

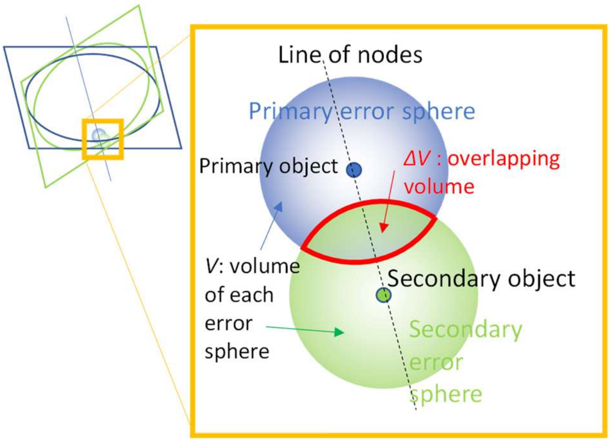


Figure 1. Error spheres around two objects that can collide

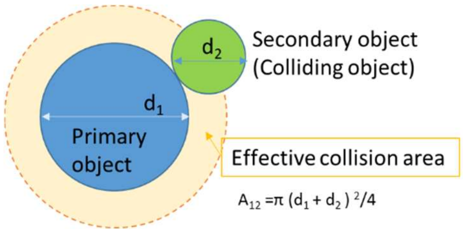


Figure 2. Effective collision area

A random number generator is used to determine whether a collision occurs, for each probability of collision between two given objects. Fragments are generated according to the NASA standard breakup model [6] (slightly modified by Kyushu University) when it is determined that a collision has occurred by using a random number value. Next, an average of 100 Monte Carlo (MC) simulations is run to show the evolution of the effective number of objects. Fig. 3 shows the effective number of objects of each MC simulation, and Fig. 4 shows the average of 100 MC runs with one standard deviation (1-σ). In Fig. 3, the results are different for each simulation run. When a collision occurs, the total effective number increases instantaneously, but when no collision occurs, said number decreases gradually due to air drag. In some cases, many collisions occur and the total effective number increases significantly as compared with the initial conditions. However, the total effective number does not increase much when only a limited number of collisions occur. The exact effective number in the future cannot be predicted because the orbital environment is dominated by collisions having a low probability of occurrence, but having high impact if collisions do occur. This paper shows that the simulation results are based on such an average, and does not show the exact predicted future. However, we can predict statistical trends if there is a statistically significant difference in the results being compared. The results presented in this paper hereafter show such an average of 100 MC runs.

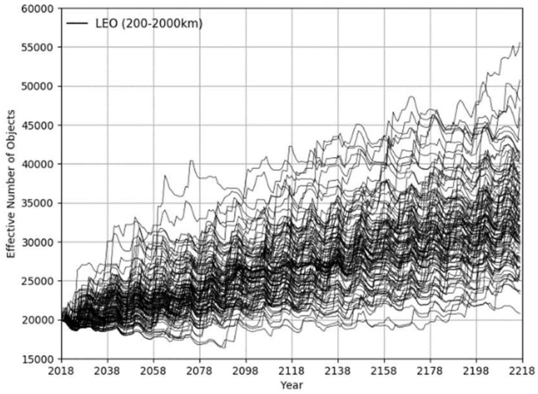


Figure 3. Change in effective number of objects for 100 MC runs

Figure 4. Average of 100 Monte Carlo simulation runs

2.2 Background Environment

Fig. 4 shows the total effective number of objects with the initial population as of 2018. Recently launched constellations such as Starlink or Oneweb are not included in the background environment in this study. It assumes a repeat of recent eight-year launches and 90% of future missions to conduct post-mission disposal (PMD) into orbit, with an orbital lifetime of less than 25 years. No explosion is assumed in the future, although several explosions occur every year, even in recent years. Even with such optimistic assumptions, the total effective number of objects in LEO is predicted to increase for 200 years due to mutual collisions between already existing objects [7]. When we investigated the situations at each altitude, we found that objects between an altitude of 900-1000 km will increase in the future [5]. Fig. 5 shows the effective number of objects in each altitude band, and Fig. 6 shows the cumulative collision probabilities in each altitude band. The cumulative collision probabilities are calculated by integrating the collision probability between two of all objects in each altitude band. Under the initial conditions, the number of objects and cumulative collision probabilities in the altitude bands of 700-800 and 800-900 km are high, due to many fragments having been generated by several collisions and explosions that occurred at around these altitudes. However, those objects will decay earlier due to atmospheric drag with a high area-to-mass ratio, as compared with intact objects. However, there is a large number of intact objects between the 900 and 1000 km altitude bands, and such objects are expected to increase in the future through mutual collisions. The number of objects at an altitude higher than 1000 km will also increase in the future without sufficient air drag at lower altitudes, but are not as large as those at lower altitudes. The following sections investigate the impacts of LCs added to such a background environment.

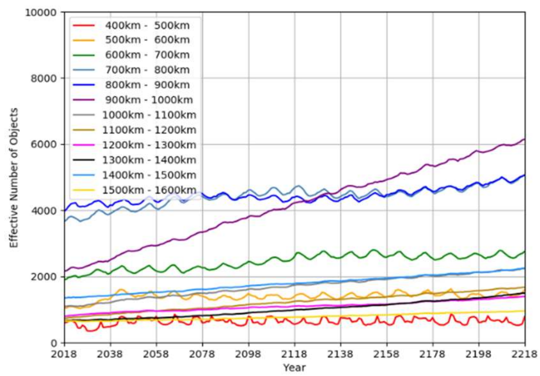


Figure 5. Number of objects at each altitude without LC

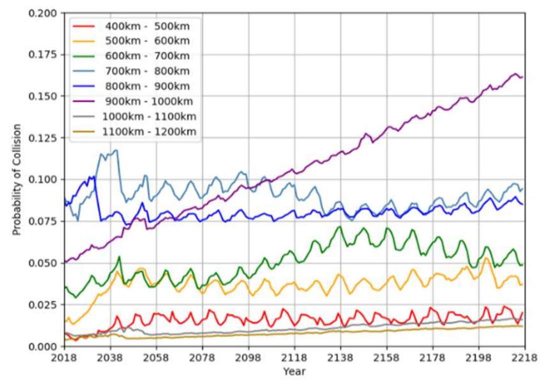


Figure 6. Cumulative collision probability at each altitude without LC

2.3 How to use NEODEEM to Evaluate the Impacts of LCs

For purposes of discussing long-term stability, we use NEODEEM to evaluate the impacts of adding LCs. Without LCs, the effective number of objects increases, as indicated by the bold black line in Fig. 7. For example, when 300 spacecraft are added to each altitude, the effective number of objects will increase more in the future. If we take the difference in the effective number of objects with and without LCs, Fig. 8 is obtained. It shows that the effect of 300 spacecraft is magnified depending on the altitude; however, this is not clear due to statistical error. In some cases, the effective number of objects decreases when LCs are added, which is unrealistic. This is because the projections of background objects are not identical with different random numbers, which are considered to be within the range of statistical error. Thus, by isolating the random number generators related to the background objects, we can isolate the background effects and evaluate the difference in LC-derived objects, as shown in Fig. 9. As this method makes

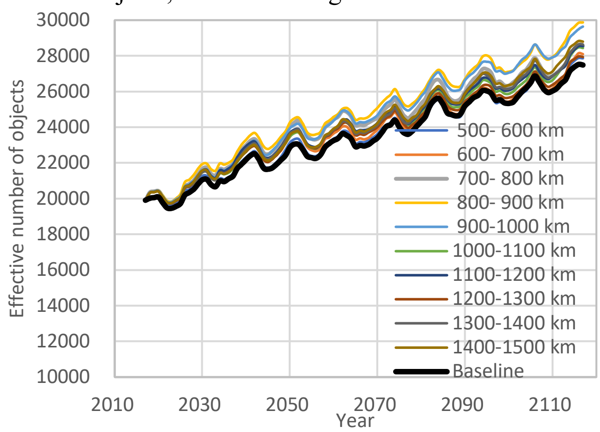


Figure 7. Effective number of objects with 300 spacecraft at each altitude

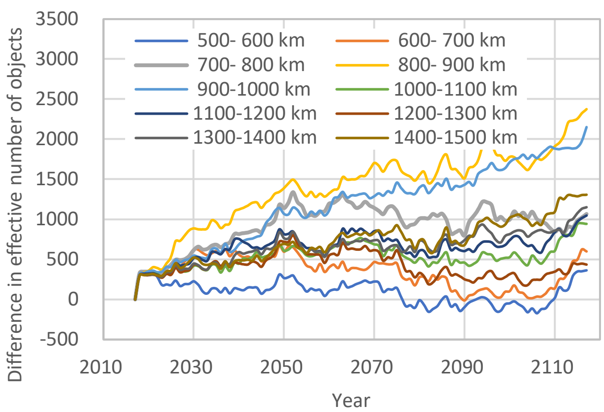


Figure 8. Difference in effective number of objects when adding 300 satellites at each altitude (without any change in random number)

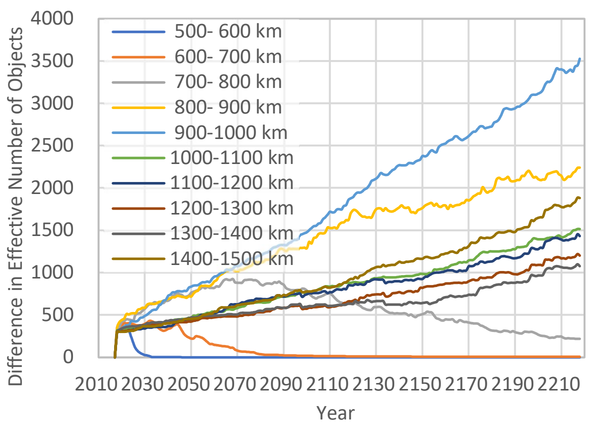


Figure 9. Difference in effective number of objects when adding 300 satellites at each altitude (with random number changes)

seeing the impacts of LCs more clearly, this paper uses this method for evaluating the impacts of LCs.

3 LONG-TERM IMPACTS OF LCs

3.1 Impacts of LCs Injected at Each Altitude

Table 1 lists the analysis conditions. The underlined values are used as the nominal values in Fig. 9. Three hundred objects left in orbit means that the PMD success rate is 90% for 3000 satellites, or a 99% PMD success rate for 30,000 satellites. The satellites are randomly distributed at each altitude with a variation of 100 km, because any failed satellites remaining in orbit would be assumed not to fail simultaneously, and with their orbits varying to some extent. For a comparison, a case where the altitudes are identical was also considered, as well as when there is a variation of 20 km. Fig. 9 shows that at low altitudes, the impact of a constellation will almost disappear within decades, whereas at higher orbits, such impact still occurs and will increase. The worst case is when a constellation is deployed at 900–1000 km because many background debris objects already exist at that altitude.

Table 1. Analysis conditions of LCs

Parameter	Value (defaults underlined)
Number of satellites	6000, 3000, 600, <u>300</u>, 100, 30
Altitude (km)	500-1500 km
Altitude width	<u>100 km</u>, 20 km, 0 km (the same altitude)
Inclination	<u>98º</u>, 85º, and 30º ± 0.25º (random)
Eccentricity	<u>0.001 ± 0.0005 (random)</u>
Right assession of ascending node	<u>6 planes every 60º ± 1º</u>
Satellite mass	<u>300</u>, 600 kg
Satellite area	<u>3</u>, 4.2 m^2
Baseline population	<u>Initial population in 2018 provided by ESA</u>

Fig.10 shows the difference in the effective number of objects when 3000 satellites are added at each altitude. More increases are observed even in projections for 100 years.

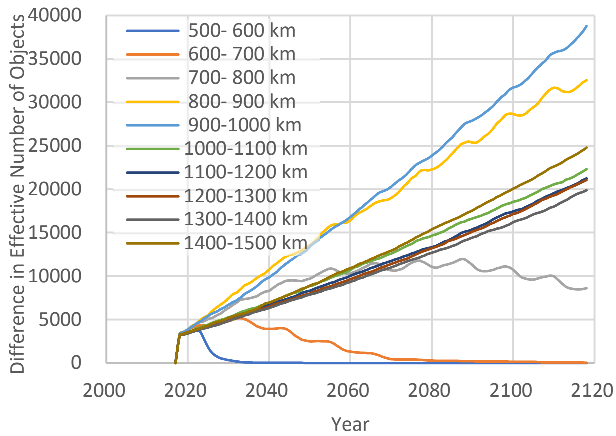


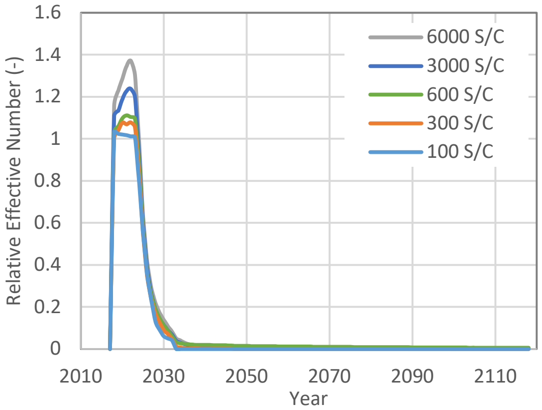
Figure 10. Difference in effective number of objects when adding 3000 satellites at each altitude

3.2 Effect of the Number of Satellites

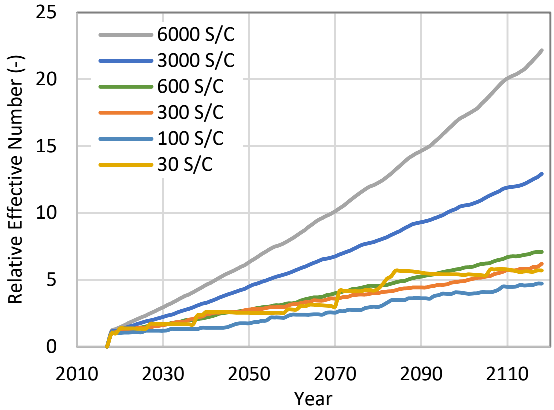
The effect of the number of satellites was investigated for each altitude. Fig. 11 compares the number of LC-derived objects per satellite at various altitudes when 6000, 3000, 600, 300, and 100 spacecraft (S/C) are inserted. At an altitude as low as shown in Fig. 11 (a), the number of LC-derived objects will slightly increase due to collisions at first, but these objects will eventually fall due to atmospheric drag, making long-term effects less likely to occur. At altitudes of 600–700 km, the effect of an impact lasts longer but eventually disappears (Fig. 11 (b)).

And the number of LC-derived objects per satellite is almost the same, regardless of the number of inserted satellites, meaning that the number of LC-derived objects is almost proportional to the number of inserted satellites. However, we should note that this depends on the method of orbital injection, satellite size, and other factors as discussed later.

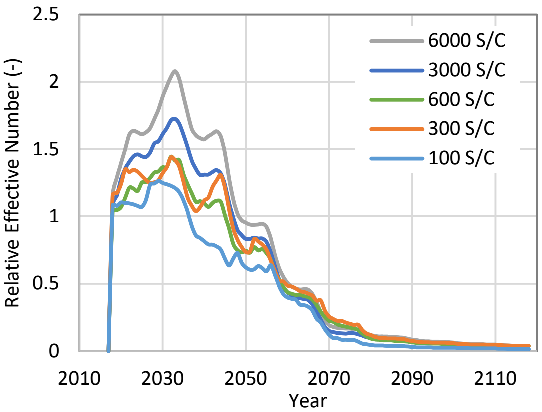
On the other hand, long-term impacts remain at high



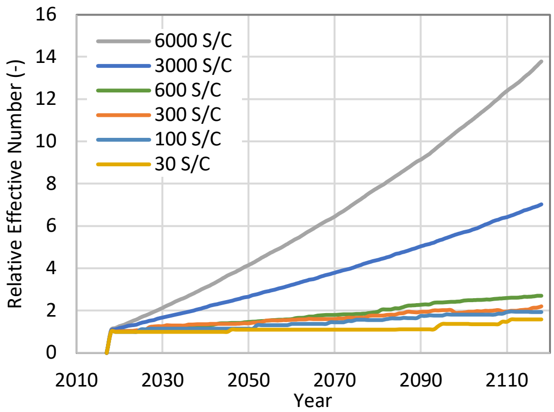
(a) Altitude: 500-600 km



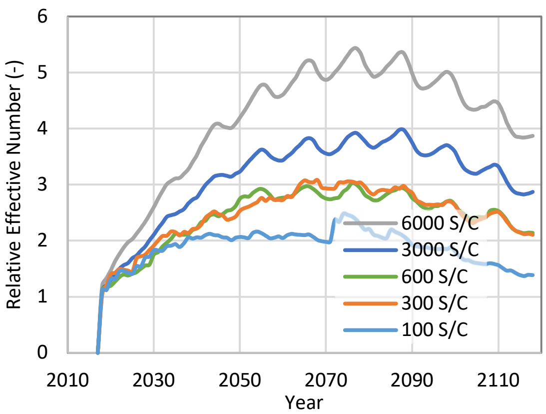
(d) Altitude: 900-1000 km



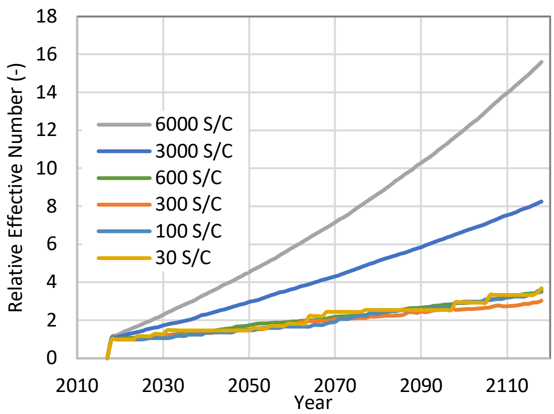
(b) Altitude: 600-700 km



(e) Altitude: 1200-1300 km



(c) Altitude: 600-700 km



(f) Altitude: 1400-1500 km

Figure 11. Relative effective number per satellite

altitudes (Fig. 11 (d) – (e)). We can see the number of impacts increase with the number of inserted satellites. If less than about 600 satellites are inserted, the number of LC-derived objects are almost proportional to the number of inserted satellites. We need to find how much of an increase is acceptable.

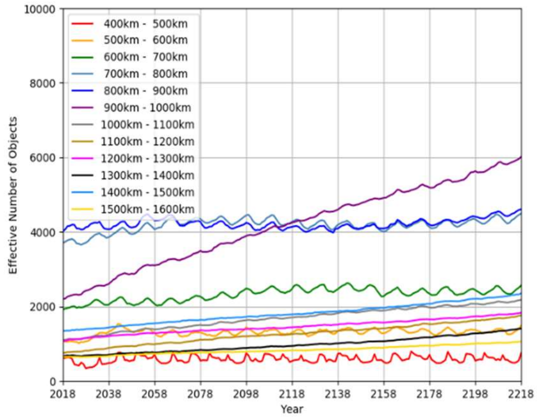
3.3 Collision Probability at Each Altitude

The impacts of LCs last longer at higher altitudes even though there are currently few background objects, because there is almost no atmospheric drag. Long-term impacts increase at a high altitude more than being proportional to the number of inserted objects, but we need to compare this finding with impacts at other altitudes. As one example, we will discuss how many spacecraft are acceptable to be injected at an altitude of 1200-1300 km, where there are currently fewer background objects than at other altitudes.

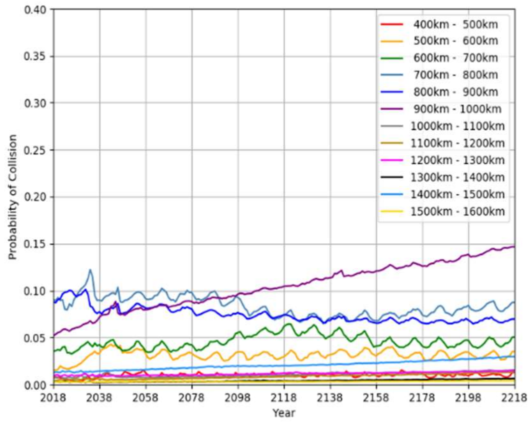
In Fig. 12, (a), (b), and (c) show the number of objects at each altitude, the cumulative collision rate, and the increase in the collision rate, respectively, when 300 satellites are deployed between altitudes of 1200–1300 km. Compared with Fig. 3, the initial number of objects increase by 300 at an altitude between 1200 and 1300 km, but it is still smaller than those between an altitude of 600 and 1000 km (Fig. 12 (a)). Cumulative collision probability at the altitude band is also small compared with those of other altitude bands, as shown in Fig. 12 (b). In order to investigate how much the cumulative collision probability increases, the normalized collision probabilities divided by the original cumulative collision probabilities at each altitude without a LC (Fig. 6) are shown in Fig. 12 (c). Cumulative collision probability at an altitude of 1200 – 1300 km is 3-3.5 times higher than that of the case without a LC, but it is not increasing. Conversely, Fig. 13 shows the case when 3000 satellites are deployed between altitudes of 1200–1300 km. The initial number of objects is almost at the same level as those at altitudes of 700 – 800 km and 800 – 900 km, but it will increase significantly in the future (Fig. 13 (a)). The cumulative collision probability at this altitude is also high from the beginning and will continue to increase (Fig. 13 (b)). The normalized collision probability will also increase in the future (Fig. 13 (c)). Such a situation is not acceptable for a sustainable environment. However, if 300 spacecraft are deployed between 1200–1300 km, the number of objects at that altitude increases slightly, but still more slowly than that at other altitudes. And the collision probability at this altitude is also low and does not increase, so it may be acceptable for the time being, although active removal of large pieces of debris will be needed in the long term future. We can accept some increase in the number of objects in GEO (geostationary orbit), where there is almost no air drag and the number of objects increases slowly. Once we decide on such an acceptable level, we can determine how many satellites can be deployed. However, we should note that the results may vary depending on the background conditions.

3.4 Differences Due to Satellite Size and Mass

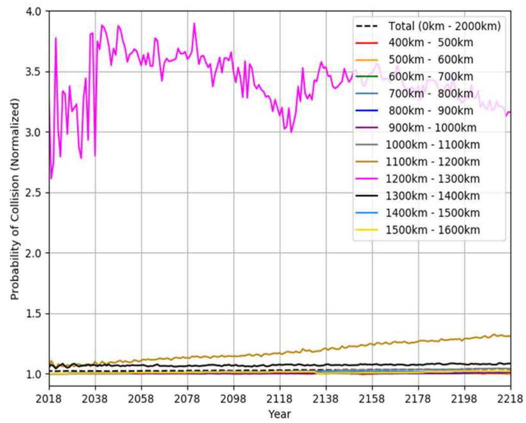
Here, the effect of the satellite size and mass was investigated. Fig. 14 shows the impacts with 300 spacecraft having a mass of 300 kg or 600 kg each. The area-to-mass ratio of the satellite is set to 0.01 m^2/kg in both cases, which means areas of 3 m^2 or 4.2 m^2 each. The heavier the mass, the more the fragments are generated at higher altitudes. At a low altitude (500–600



(a) Number of objects at each altitude

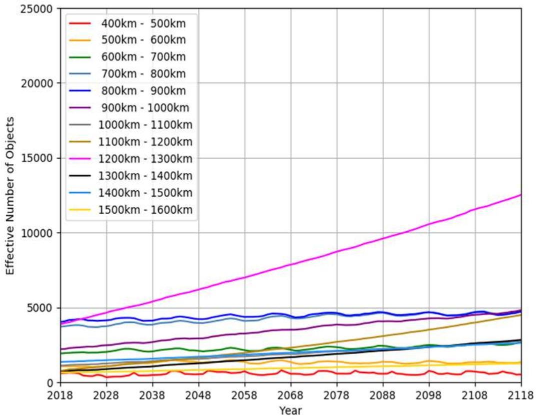


(b) Cumulative collision probability at each altitude

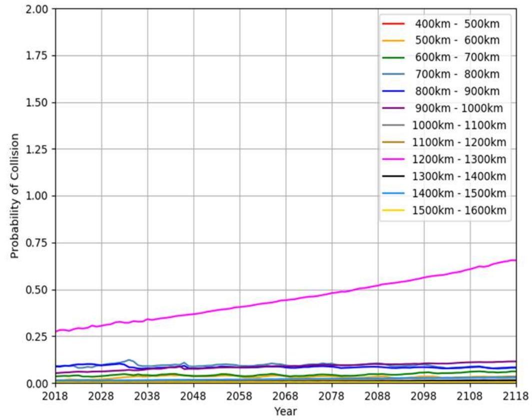


(c) Increase in collision probability normalized by the background

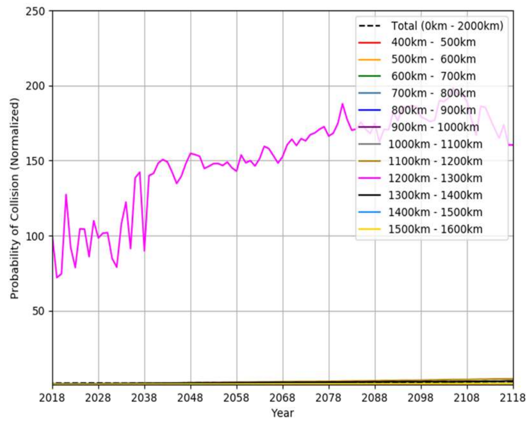
Figure 12. Number of objects at each altitude (a), cumulative collision probability (b), and increase in collision probability normalized by the background (c) when deploying 300 satellites between an altitude of 1200–1300 km



(a) Number of objects at each altitude



(b) Cumulative collision probability at each altitude



(c) Increase in collision probability normalized by the background

Figure 13. Number of objects at each altitude (a), cumulative collision probability (b), and increase in collision probability normalized by the background (c) when deploying 3000 satellites between an altitude of 1200–1300 km

km), the difference is not so clear. Figure 15 shows 3000 spacecraft deployed at an altitude of 540–560 km. We can see some difference when the mass of each spacecraft is 300 kg or 600kg, but the impact still has a short duration.

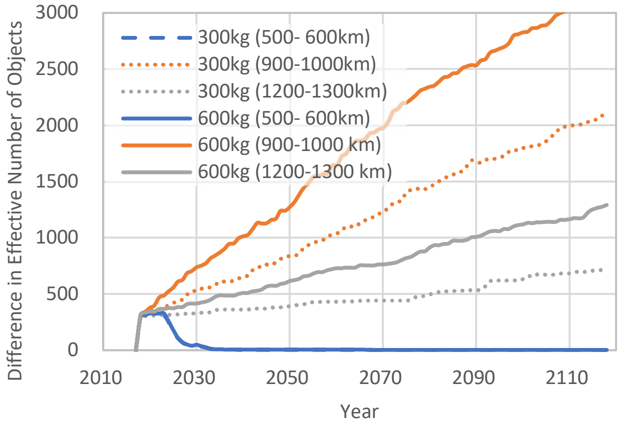


Figure 14. Effective number of objects when 300 satellites are deployed at altitudes of 500-600, 900-1000, and 1200-1300 km with a mass of 300 kg or 600 kg

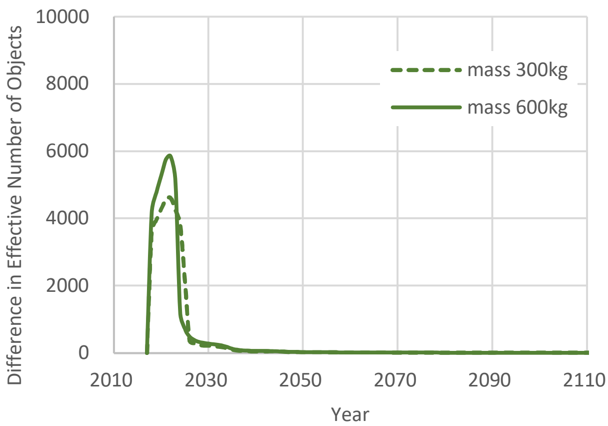


Figure 15. Effective number of objects when deploying 3000 satellites at an altitude of 540 - 560 km with a mass of 300 kg or 600 kg

3.5 Differences Due to Orbital Variability

Next, the effect of the initial satellite orbit was investigated. Figure 16 shows the impacts of LCs when 300 satellites are randomly placed between 100 km and 20 km, or 0 km (i.e., the same altitude) at altitudes of around 550 km, 950, and 1250 km. Figure 17 shows the effective number of objects when 3000 satellites are deployed at an altitude of around 550 km. It shows that the smaller the orbital range, the more the collisions between the satellites, but the impact still has a short duration at low altitude.

We need to investigate the impact of a LC with each orbit, mass, etc. to determine the capacities. We found that a constellation at a lower altitude seemed to have no lasting long-term effects. However, we also need to investigate the short-term impact next.

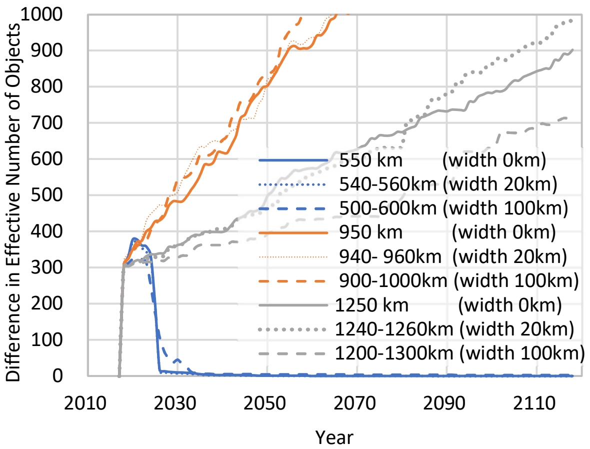


Figure 16. Effective number of objects when deploying 300 satellites at altitudes of around 550, 950, and 1250 km

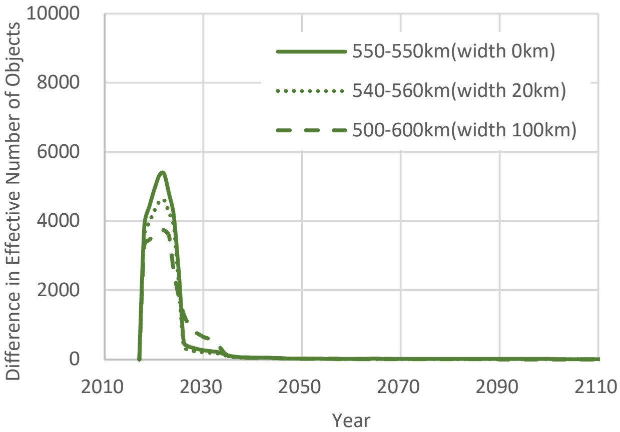


Figure 17. Effective number of objects when deploying 3000 satellites at an altitude of around 550 km

4 SHORT-TERM SAFETY

4.1 Number of Conjunctions

NEODEEM has no perigee passage time, and only evaluates the shape of the trajectory. It cannot conduct a thorough conjunction analysis, but can predict the average, statistical number of conjunctions. Fig. 18 shows the correlation between the number of conjunctions in NEODEEM and the actual number of conjunctions for several JAXA satellites as of 2018. There is a correlation between the two, and NEODEEM can evaluate the average, statistical number of conjunctions to predict the actual number of conjunctions.

We will evaluate how much the number of conjunctions will increase in the current situation for a low-altitude LC with limited long-term impact.

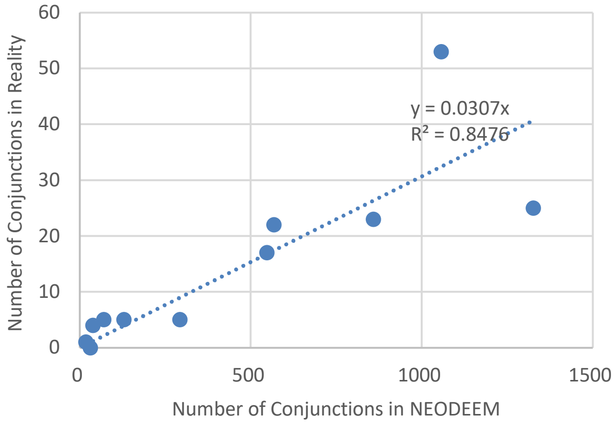


Figure 18. Correlation between the number of conjunctions (collision probability > 10-7) in NEODEEM and the actual number of conjunctions for several JAXA satellites

Fig. 19 shows the number of conjunctions relative to already existing background objects when a constellation of 3000 satellites is deployed at each altitude. It shows that the number of conjunctions relative to background objects increases significantly for some ranges in altitude, as does the number of objects, and it may be further expanded in the future for altitude. Figure 20 shows the total number of conjunctions, including inserted objects, for constellations deployed at 500–600 km. With 3000 deployed spacecraft, there will be more conjunctions than the current number in all orbits. Figure 21 shows the time

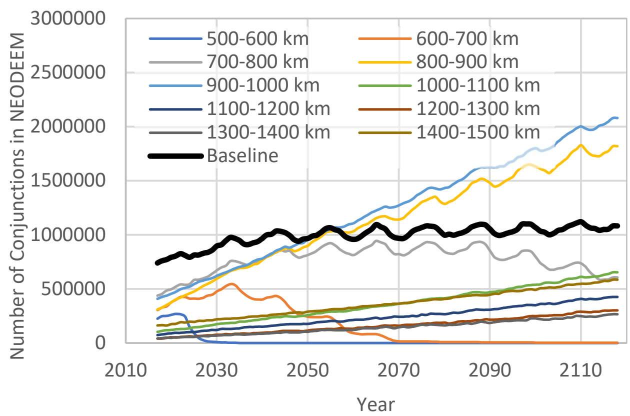


Figure 19. Number of conjunctions for background objects, with 3000 spacecraft at each altitude

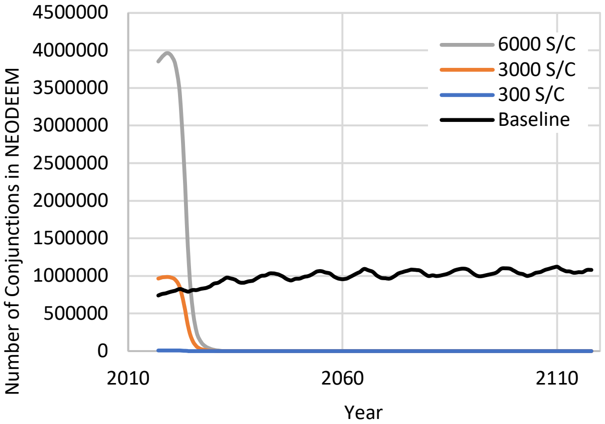


Figure 20. Number of conjunctions with each other, including inserted objects when inserting a constellation at an altitude of 500-600 km

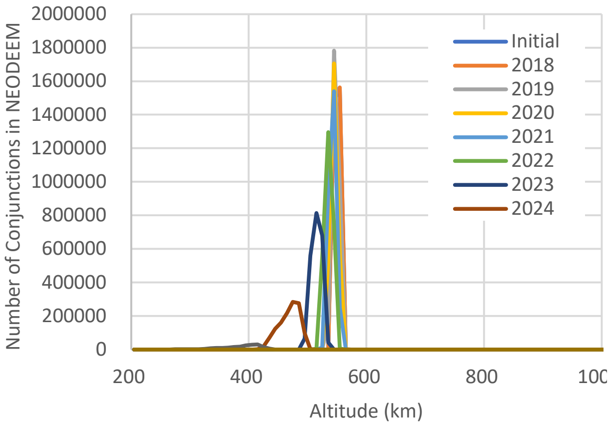


Figure 21. Time history of the number of conjunctions with 3000 spacecraft at an altitude of 540-560 km

history of the number of conjunctions with 3000 spacecraft at an altitude of 500-600 km. There will be many conjunctions around the LC altitude for several years, although the impacts disappear several years later. We need to investigate the short- and long-term impacts, and whether this situation is acceptable.

4.2 Collisions with Non-Catalogued Objects

It is also necessary to consider collisions with non-catalogued objects when discussing short-term safety. Catalogued objects larger than 10 cm have thus far been evaluated, but small size objects must also be considered because they can pose significant risk when colliding with spacecraft. Thus, fragments larger than 1 cm were generated according to the NASA standard breakup model when collisions occur. With 3000 spacecraft deployed at the 540–560 km altitude range in this case, many small objects are generated by about 11.4 collisions with the inserted spacecraft. Figure 22 shows the effective number of objects larger than 1 cm generated by collisions, and Fig. 23 shows the time history of flux of objects larger than 1 cm. The impacts are short-lived because small debris will fall quickly due to air drag and large area-to-mass ratios, but can pose significant risks to the spacecraft at low altitudes, such as the ISS. We also need to consider whether such a situation is acceptable.

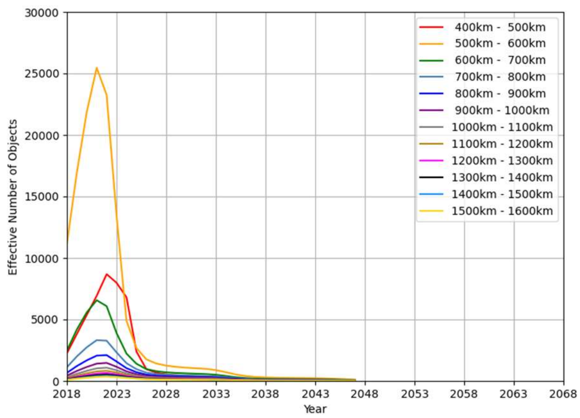


Figure 22. Number of objects > 1 cm when deploying 3000 spacecraft at an altitude of 540-560 km

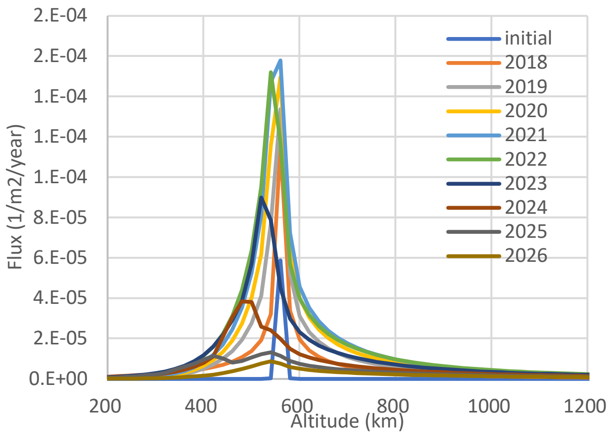


Figure 23. Time history of flux of objects > 1 cm generated by collisions when deploying 3000 spacecraft at an altitude of 540-560 km

5 CONCLUSIONS

In this study, the impacts of LCs were evaluated using the debris evolutionary model in order to discuss space environment capacity. We investigated both the long-term stability and short-term safety for a LC deployed at each altitude. The effects of such LC parameters as the number of satellites, mass, and method of orbital injection were investigated. It was shown that the long-term effect may be acceptable when constellations are inserted at a lower altitude, but that an unstable self-cascading effect occurs when LCs are inserted into higher orbits. The evolution of the number of LC-derived objects or cumulative collision probability in each respective altitude band were investigated, and the acceptable threshold was discussed.

The impact is not long-term for a constellation at a lower altitude, but short-term safety relative to the number of conjunctions and the flux of small-sized debris should also be considered.

The impacts of LCs should thus be evaluated using the actual design such as mass, size, and orbit. We should also note that the background environment changes with additional collisions, explosions, and new launches in the future. Either way, further evaluation is needed to match the actual situation.

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