Impact on Collision Probability by Post Mission Disposal and Active Debris Removal

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ABSTRACT

The collision probabilities of debris objects with and without Post Mission Disposal (PMD) and Active Debris Removal (ADR) are evaluated and discussed. A debris evolutionary model named NEODEEM was jointly developed by Kyushu University and JAXA for use in predicting future debris populations and calculating collision probabilities. The collision probability in each altitude bin is initially compared with and without PMD or ADR. Then a case involving a large satellite constellation is also discussed. The effective number of debris objects at each altitude for the PMD success rates of the large constellation and the collision probability at each altitude are calculated. The collision probability per unit time will increase when a small satellite utilizes a drag augmentation sail or a tether as a PMD device, but the dwell time will be greatly reduced. A collision with a sail or tether will be non-catastrophic collision. Therefore, the use of such devices will reduce the cumulative collision probability and expected number of debris fragments.

1 INTRODUCTION

A debris evolutionary model is used to predict future debris populations, and such debris mitigation measures as Post Mission Disposal (PMD) and Active Debris Removal (ADR) are shown to be effective in suppressing increases in the overall number of debris objects. Given the different situations at each orbital altitude, however, more detailed investigations are needed to discuss which orbital region requires ADR and how many more debris objects can be added. PMD and ADR are both effective, but in some cases will increase the short-term collision probability. For example, many satellites may deorbit from their operational orbits, where the currently low collision probability is predicted to increase in the future, to the disposal orbit where orbital lifetime is short enough, but collision probability is higher. The collision probability per unit time will increase when a small satellite utilizes a passive deorbit device, such as a drag augmentation sail or an electrodynamic tether (EDT). However, the low mass per unit area of such devices result in non-catastrophic collision with the sail or tether, while they can greatly reduce the dwell times. Thus, both short-term risk and long-term sustainability must be considered in order to take appropriate measures. In this paper, the overall effective number of debris objects and the collision probabilities at each altitude are investigated. This paper first introduces the collision probability and debris evolutionary model, and then discusses the changes in collision probability using PMD and ADR. The collision probability in the case of a large constellation of satellites, and the impact of PMD using a sail and tether are also discussed.

2 DEBRIS EVOLUTIONARY MODEL AND COLLISION PROBABILITY

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. NEODEEM simulates the trajectories of all objects larger than 10 cm, and considers the perturbations caused by air drag as calculated using the Jacchia-Roberts model, Earth’s gravitational potential (4 orders and degrees), gravitation forces of the Sun and the Moon, and solar pressure. Collisions are determined by considering the error spheres around those objects (Fig. 1). A collision will occur when two objects exist in the overlapping volume of two error spheres, and the collision probability can be calculated with the following equation [1].

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

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. When two objects have diameters of d_1 and d_2, effective collision area, A_{12} can be calculated as shown in Fig. 2.

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

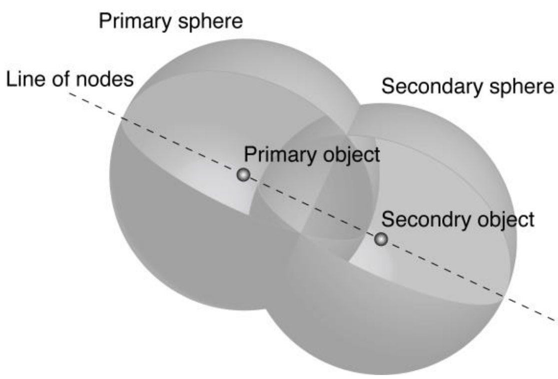

Fig. 1. Error spheres around two objects that can collide

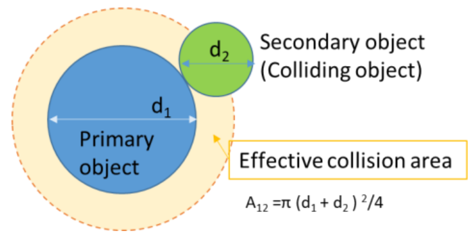

Fig. 2. Effective collision area

A random number generator is used to simulate an expected debris collision, with debris fragments being generated according to NASA's standard breakup model [2]. When relative kinetic collision energy is larger than 40 J/g, a collision is considered to be catastrophic; otherwise, it is considered non-catastrophic. Because a catastrophic collision produces many fragments, it is important to avoid catastrophic collisions in order to preserve the space environment.

The equation above gives a collision probability between two objects, and we can get the collision probability of one specific object by integrating all collision probabilities with other objects that can collide. And because the collision probability will change according to its orbital change due to perturbations, particularly a decrease in altitude caused by air drag, the cumulative collision probability is calculated by integrating all collision probabilities each time. It is also possible to integrate the total collision probability of all objects in each altitude band in order to investigate the different situations at each altitude.

3 EFFECTS OF PMD AND ADR

Debris mitigation guidelines such as those stipulated by the Inter-Agency Space Debris Coordination Committee (IADC) recommend PMD to shorten the orbital lifetime to less than 25 years [3]. If future space missions adapt this 25-year rule, the debris evolutionary model shows that the effective number of debris objects will be suppressed (Fig. 3). It assumes a repeat of recent eight-year launches and 90% of future missions to conduct 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. However, even with 90% compliance of the 25-year rule, future debris populations are expected to increase [4]. Is this increase acceptable or not? Fig. 4 shows the effective number of objects in each altitude bin. It indicates that the effective number of objects in some regions such as around an altitude of 1000 km will increase, but whether such an increase is acceptable or how many objects can be added remains unclear.

ADR is also shown to be effective in suppressing increases in the effective number of debris objects in the future as shown in Fig. 5. The effect of limiting debris targets is discussed in [5], but it is unclear why ADR is effective with some limitations, such as regarding the orbit or debris type. Fig. 6 shows the collision probabilities in each altitude band in the case of 90% PMD, without ADR. This figure shows the average of 100 Monte-Carlo (MC), and that the collision probabilities at 800 to 900 km and 700 to 800 km are currently high. The total collision probability in these altitude regions is about 0.1, meaning that one collision every 10 years is predicted in these regions. However, these values will maintain the same level and not dramatically increase in the future. The collision probability at 700 to 800 km is indicated as increasing in about ten years from now as many fragments at 800 to 900 km will fall. At

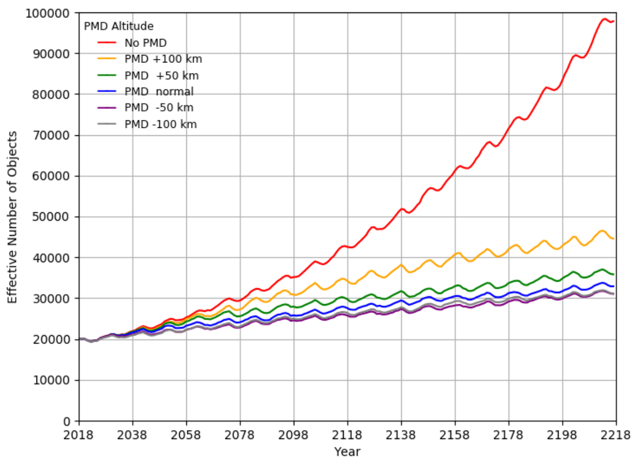

Fig. 3. Effective number of objects with PMD

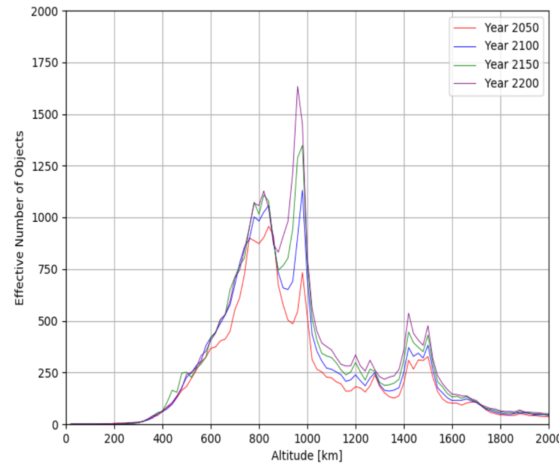

Fig. 4. Distributions of orbital altitude

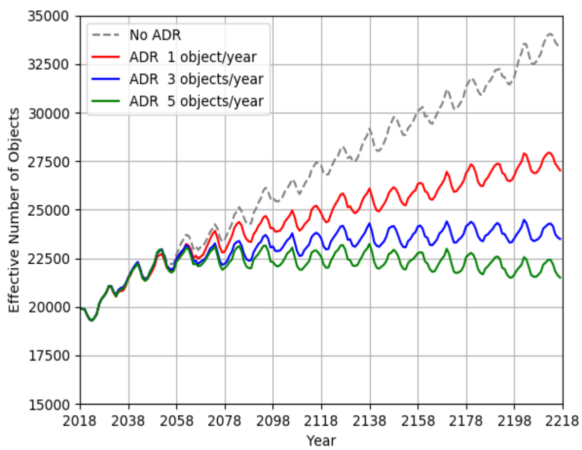

Fig. 5. Effect of ADR

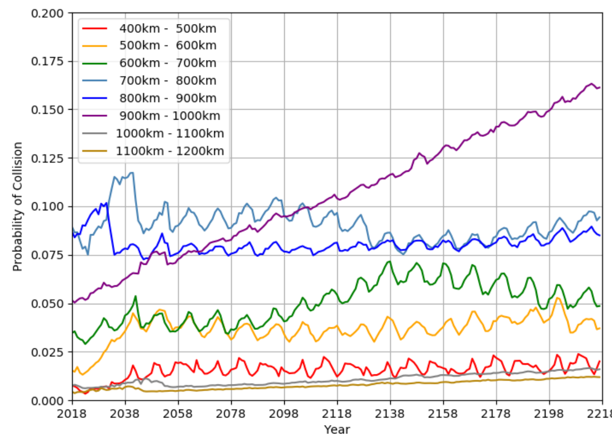

Fig. 6. Collision probability of each altitude band with 90% PMD, and no ADR

present, many fragments generated from recent collision events at 800 to 900 km will reenter Earth's atmosphere within several tens of years due to their high area-to-mass ratio.

The current collision probability at 900 to 1000 km is conversely lower than that at 700 to 900 km, but is predicted to increase in the future. The air drag is quite small at these altitudes, and many objects remain in this altitude region for a long time. Fig. 7 and Fig. 8 shows a case without any launch in the future. It also shows that the collision probability at 900 to 1000 km will increase, and that existing debris objects in this region are the main cause of the increase. In the future, collision probabilities below 900 km are expected to decrease, thus making the mitigation of future missions important in both regions.

It should be noted that NEODEEM can predict the population of debris objects larger than 10 cm, but a large amount of smaller fragments are generated by collisions and explosions. Debris objects larger than 10 cm can be observed from the ground and tracked for collision avoidance. The increase of unavoidable smaller debris objects is a more critical issue for sustainable space development, as such smaller objects are difficult to observe and their modeling must still be investigated.

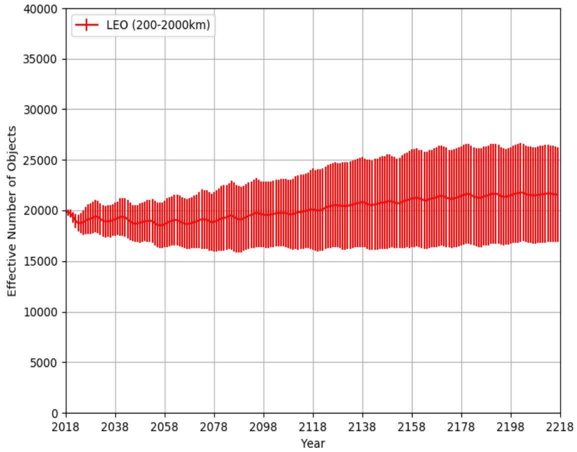

Fig. 7. Effective number of objects (no new launch)

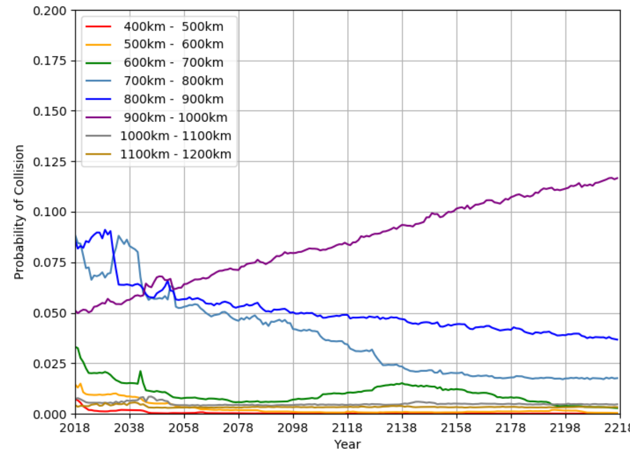

Fig. 8. Collision probability of each altitude band with no new launch, and no ADR

As shown in Fig. 5, the effective number of objects can be decreased with ADR. Several debris objects are chosen based on a debris index such as collision probability multiplied by mass, and the highest objects in the index are moved into the disposal orbit at an altitude of 650 km, where the orbital lifetime is about 25 years. Fig. 9 and Fig. 10 show the collision probabilities in case of ADR of one object per year and five objects per year, respectively. ADR of even one object per year will suppress the increase of collision probability in the 900 to 1000 km region. When five objects are removed every year, collision probabilities at 500 to 700 km will be higher than those at other altitudes, but will not increase drastically even if a collision occurs in that altitude region when no fragments are accumulated thanks to air drag.

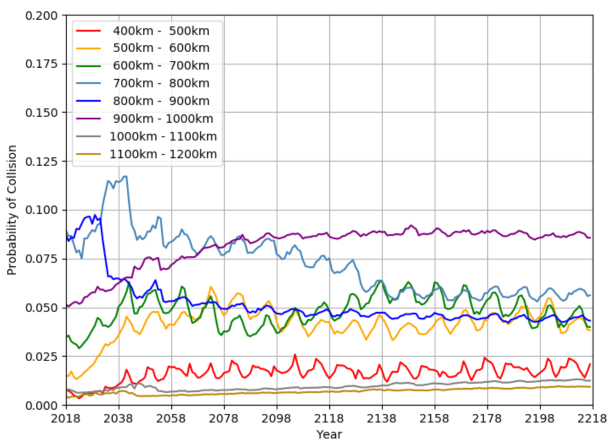

Fig. 9. ADR of one debris object per year

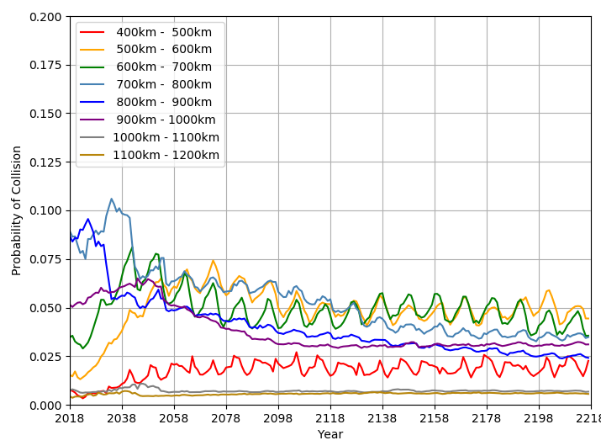

Fig. 10. ADR of five debris objects per year

4 EFFECT OF A LARGE CONSTELLATION

The deployment of a large constellation of satellites will drastically change the orbital environment. Fig. 11 shows the case of a constellation consisting of 1000 satellites at an altitude of 1200 km. Details can be found in [6] and [7]. A high PMD compliance rate is essential for a large satellite constellation. Fig. 12 to 14 show the effective number of objects at each altitude. These figures show that the effective number of objects at the operational orbit altitude will increase when the PMD success rate is low, and that the effective number of objects in the disposal orbit will increase when the PMD success rate is high. Fig. 15 and Fig. 16 shows the collision probabilities in each altitude band in the case with a large constellation. Fig. 17 and Fig. 18 show the cumulative collision probabilities for a satellite at about 1200 km and 650 km.

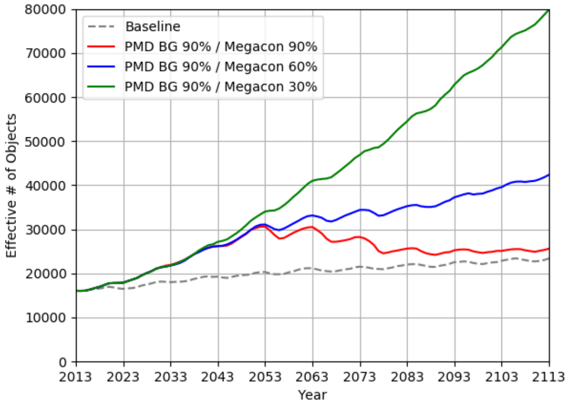

Fig. 11. Effect of PMD compliance rate for a large satellite constellation

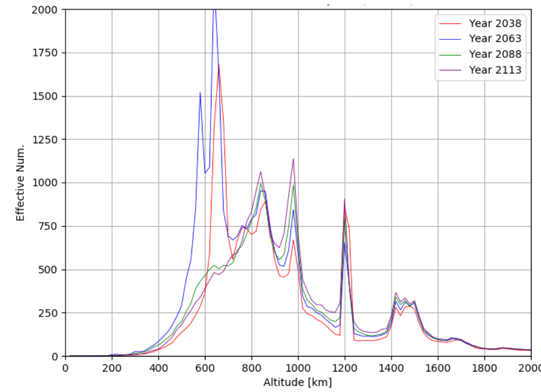

Fig. 12. Effective number of objects at each altitude for a large constellation with 90% PMD

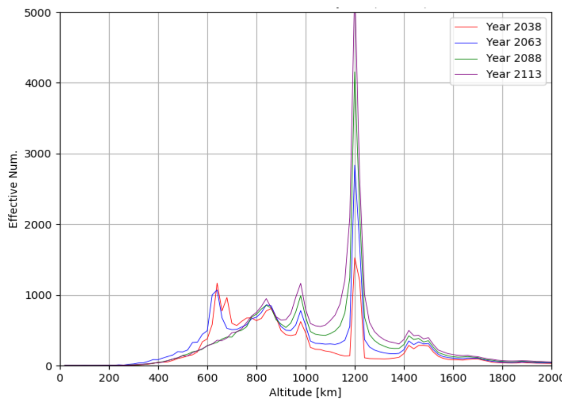

Fig. 13. Effective number of objects at each altitude for a large constellation with 60% PMD

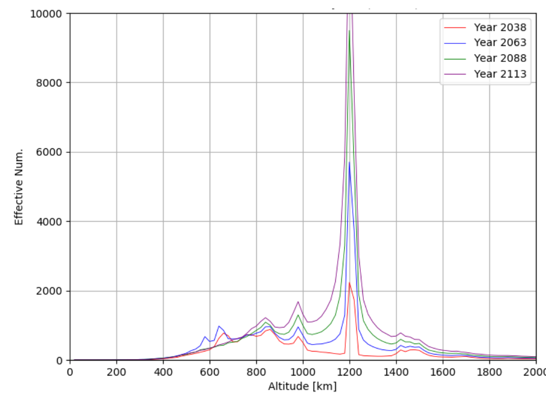

Fig. 14. Effective number of objects at each altitude for a large constellation with 30% PMD

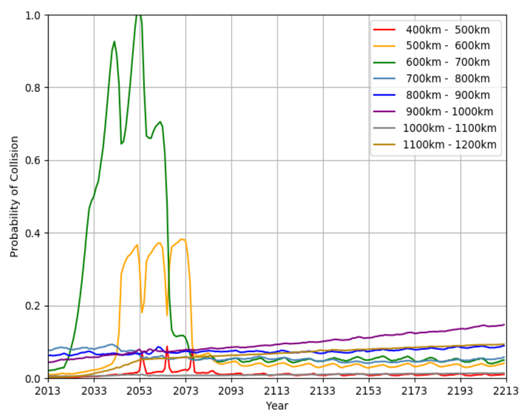

Fig. 15. Collision probability at each altitude (with a large constellation, 90% PMD)

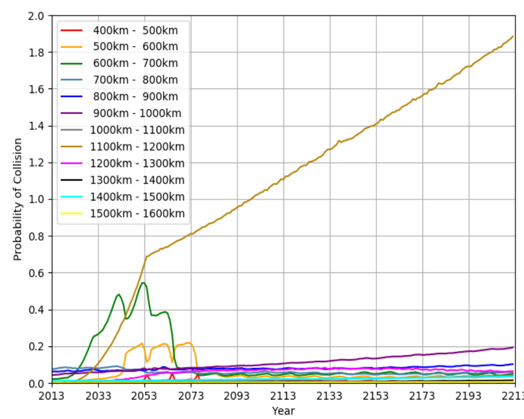

Fig. 16. Collision probability at each altitude (with a large constellation, 60% PMD)

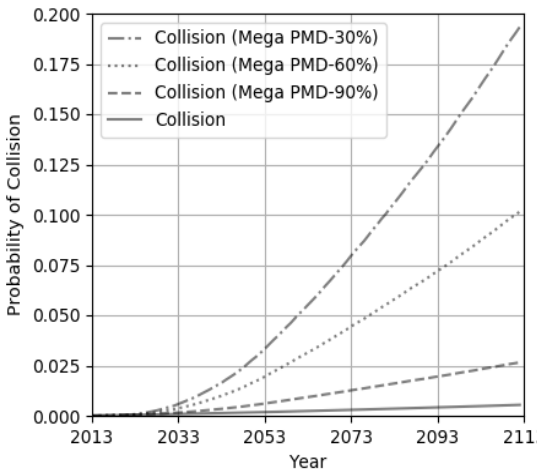

Fig. 17. Cumulative collision probabilities for a satellite at about 1200 km

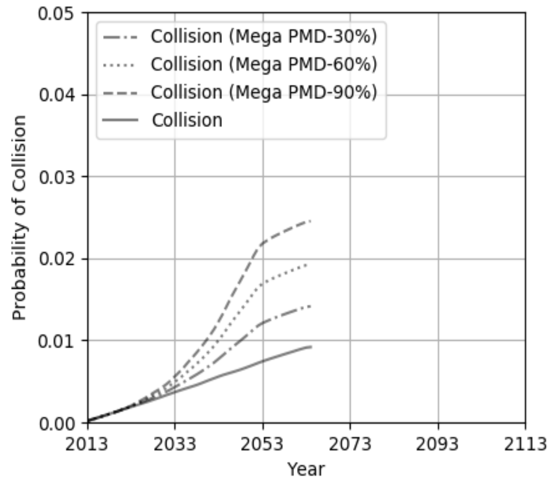

Fig. 18. Cumulative collision probabilities for a satellite at about 650 km

5 EFFECT OF PMD DEVICES SUCH AS DRAG SAIL AND TETHER

Passive PMD devices such as a drag augmentation sail and an electrodynamic tether (EDT) are proposed for a small satellite with limited resources and reliability. These devices can deorbit small satellites without any operation by utilizing air drag or induced voltage generated by interaction with the geomagnetic field. A high PMD success rate is expected when such devices are deployed automatically using a timer or similar mechanism, even in case of failure. However, the use of these devices will increase the short-term collision probability, although a collision with a sail or tether will be non-catastrophic [8] and such devices are effective in suppressing the long-term increase of the effective number of debris objects [9]. The Handbook for Post-Mission Disposal of Satellites Less Than 100 kg [10] compares several PMD methods for a small satellite. However, the collision probabilities are calculated using simplified methods, and consequently are not accurate. The collision probabilities and effects of these PMD devices are thus investigated using NEODEEM.

5.1 Drag Sail

When a small satellite deploys a drag sail N times larger than that of the original area, the air drag will become N times larger and the expected orbital lifetime will be decreased about the N-th part of the original orbital lifetime. However, the collision probability with surrounding debris objects will not become N times larger, considering the size of colliding debris objects (Fig. 19). The debris flux of each size can be calculated using a debris environment model such as NASA's ORDEM and ESA's MASTER. Total collision probability (*Pc*) can be calculated as follows:

$$Pc = \Sigma(E(x)*diff\_flux(x)) \quad (3)$$

where *E(x)* is the effective collision area for an object whose diameter is *x*, and *diff_flux(x)* is the differential debris flux of size *x*.

Table 1 lists the results when the debris flux at 800-km Sun Synchronous Orbit (SSO) in 2018, calculated by MASTER2009 is used. It shows that when the size of the satellite increases, collision probability × relative lifetime will decrease because the expected collision probability is smaller than the value proportional to the size of the satellite, whereas the relative orbital lifetime is inversely proportional to the size of the satellite. But because the debris flux actually changes when its orbital altitude changes, the cumulative collision probabilities are calculated using NEODEEM. Four test cases cited in the handbook [10] are calculated: 3U CubeSat with mass of 5 kg at 650-km altitude, and a 100-kg small satellite in 700-km SSO, 800-km SSO, and at an altitude of 1000 km with 90 deg inclination. Fig. 20 shows the cumulative collision probabilities in case of a 100-kg small satellite in 800-km SSO, as an example. The orbital lifetime is about 250 years without PMD, and the cumulative collision probability is about 0.0106. If this satellite deploys a sail with area of 12 m^2, the orbital lifetime will be shortened to about 45 years. (Although orbital lifetime of 25 years is expected as per the handbook, but it become 45 years due to different models such as the atmosphere model used for calculation in this paper.) During the deorbit phase by the sail, the cumulative collision probability for the sail is 0.0095, or slightly smaller than that of the case without a sail due to the size of the colliding debris. Note that the collision probability is calculated for the sail with area of 12 m^2, while half of this area (6 m^2) is used for calculating the air drag, assuming random tumbling as a severe case. Cumulative collision probability for the satellite itself is about 0.0023, which may be a catastrophic collision. It shows that the probability of a catastrophic collision could be greatly decreased by using a sail. The collision with sail is assumed to be non-catastrophic collision in this study, but the actual design such as booms for supporting the sail should be considered in the future study. The expected number of fragments to be generated by the small satellite can also be reduced from 7.65 to 2.13, as shown in Fig. 21. This expected number of fragments includes not only fragments generated from the small satellite itself, but also those from the colliding objects. In fact, Ref [9] showed that the long-term environment can be stabilized by using sails or tethers. However, the short-term collision probability becomes larger and gives the impact of a collision avoidance maneuver for operating spacecraft in the near orbit, as the collision may damage the spacecraft, although it may result in a non-catastrophic collision. Collision with the sail also means that PMD failed on the way if the sail is damaged by the collision. Collision avoidance maneuver (CAM) using such PMD devices had been studied [11] and CAM is recommended if possible. It should also be noted that the insertion of those small satellites to the lower altitude (such as below 600 km) is more effective in reducing the number of future collisions and number of generated objects [1]. Table 2 lists the results of other test cases.

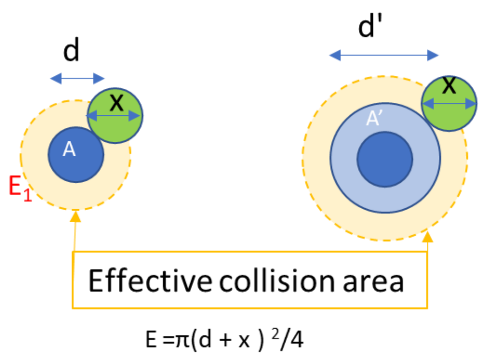

Fig. 19. Effective collision area not proportional to the primary object area considering the colliding object size

Table 1. Collision probability × relative lifetime for each size of satellite

Satellite size	Expected collision probability	Relative orbital lifetime	Collision probability x relative lifetime
d=0.1m	1.508e-5 /year	1	1.508e-5
d=1m	3.68e-5 /year	0.01 (=1/100)	3.68e-7
d=3.5m	1.9e-4 /year	0.0008 (=1/35/35)	1.58e-7

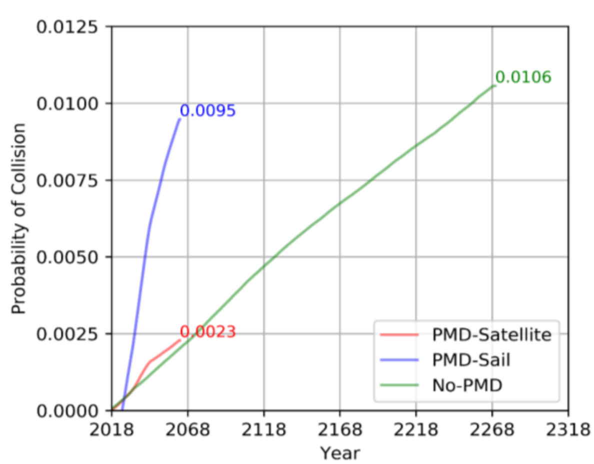

Fig. 20. Collision probability of 100-kg small satellite in 800-km SSO with and without sail

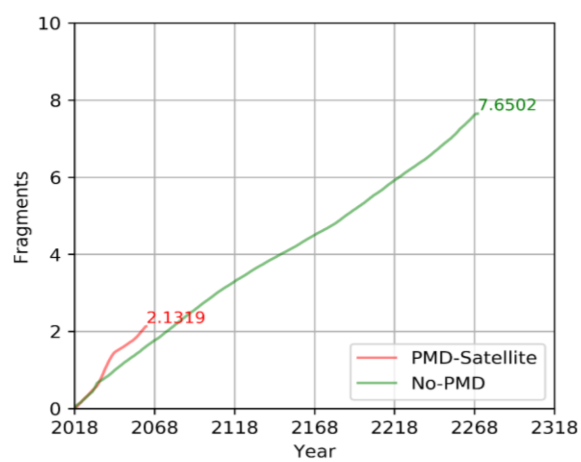

Fig. 21. Expected number of debris fragments with and without sail

Table 2 Effect of sail for the four testcases

	Case		Sail Size	Orbital lifetime	collision probability	Expect # of Fragments
3U @700km, 65deg	NO PMD		---	120 year	0.0021	2.1932
	PMD	Sat.	$0.25m^2$	40 year	0.0006	0.6324
		Sail			0.0007	
100kg @700km, SSO	NO PMD		---	75 year	0.0027	2.5529
	PMD	Sat.	$4m^2$	27 year	0.0010	0.9422
		Sail			0.0016	
100kg @800km, SSO	NO PMD		---	250 year	0.0106	7.6502
	PMD	Sat.	$12m^2$	45 year	0.0023	2.1319
		Sail			0.0095	
100kg @1000km, 90deg	NO PMD		---	>1000 year	>0.0357	>9.6550
	PMD	Sat.	$81m^2$	35 year	0.0015	1.4674
		Sail			0.0357	

5.2 Electrodynamic Tether (EDT)

A tether is also proposed as a PMD device for a small satellite. When a conductive tether is used, electrodynamic force generated by interaction with the geomagnetic field in addition to air drag will shorten the orbital lifetime, and such a tether may be applicable for higher altitudes where the atmosphere is thin [12]. A tape tether is often used for a small satellite to get larger air drag and electron collection from the surrounding plasma. A bare tether (a conductive tether without insulation) can collect electrons and ions directly from the ambient plasma by electromotive force. Electrons are collected at a positive electrical potential part of the tether, and ions are collected at a negative electrical potential part, as well as the emission of photoelectrons. However, ions are hard to collect as they are heavier than electrons; thus, an electron emitter can be installed on the satellite to get larger electric current (active EDT). It is also possible to collect more electrons by applying electric voltage to the tether for a faster deorbit. The passive EDT is simpler and more cost-effective because no operation is required after tether deployment. The active EDT has larger thrust than the passive EDT, but has to deorbit within one or two years as satellite operation is needed.

A collision with the tether will not be catastrophic, but the tether will be cut and the deorbit stopped, whereas an end-mass attached to the other end of the tether for deployment or stability of the tether might cause a catastrophic collision. The mass of the end-mass is assumed to be 1 % of satellite. The effective collision area for a tether with length of L and width of w is calculated as a severe case as follows (Fig. 22):

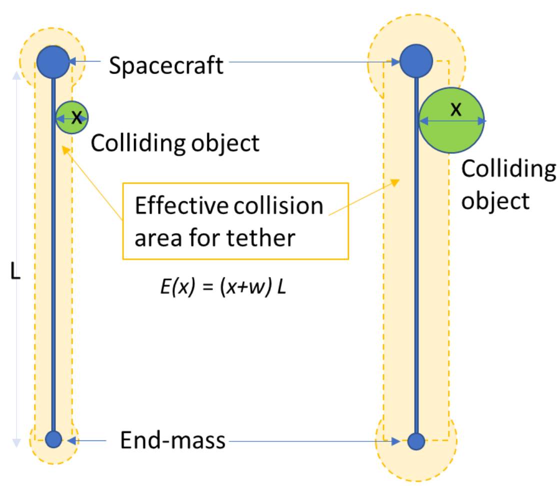

Fig. 22. Effective collision area for a tether

$$E(x) = (x+w)L \quad (4)$$

The four test cases cited in the handbook are also calculated for a tether. The available thrust of the EDT depends on orbit and such tether specifications as tether length and width, but here the values described in the handbook are used and constant altitude change is assumed. Only the passive EDT that deorbits within 25 years is assumed in the handbook, but the active EDT that deorbits within two years is also calculated. Fig. 23 and Fig. 24 shows the cumulative collision probabilities and the expected number of fragments with and without active EDT which deorbit within two years, as an example. The results, Table 3 shows that the collision probabilities and expected number of fragments can be reduced, although the short-term collision probability of the tether is large. Note that only collision with objects larger than 10 cm is calculated. Tether design such as a tape tether or a net tether is required for surviving impacts with smaller debris.

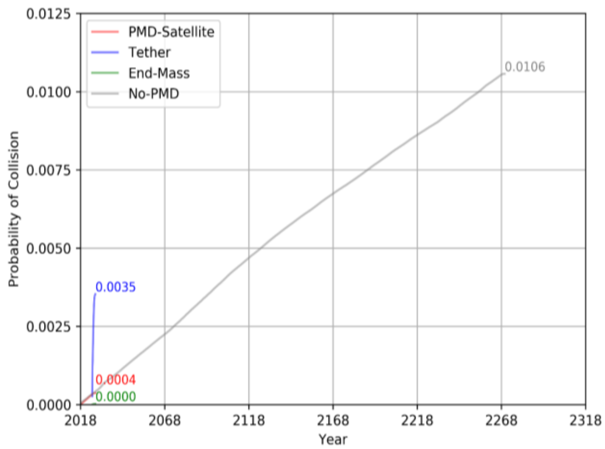

Fig. 23. Collision probability of 100-kg small satellite in 800-km SSO with and without active EDT

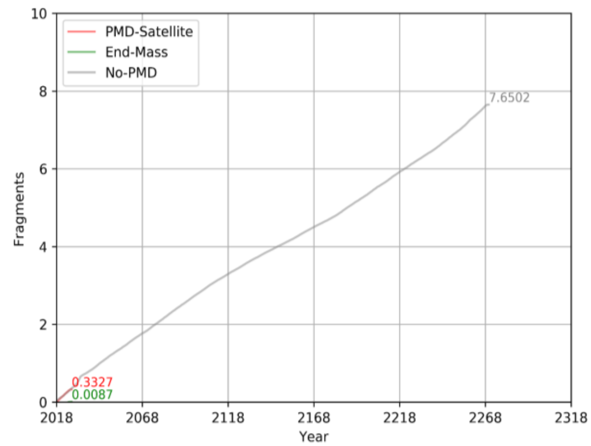

Fig. 24. Expected number of debris fragments with and without active EDT

Table 3 Effect of passive EDT and active EDT for four test cases

Case	PMD		EDT Size	Orbital lifetime	collision probability	Expect # of Fragments
3U @700km, 65deg	No PMD		-	120 year	0.0021	2.1932
	PMD (passive)	Sat. + EM	12m x 10mm	25 year	0.0004+0.0002	0.3970+0.0042
		Tether			0.002	
	PMD (active)	Sat. + EM	30m x 50mm	2 year	0.0001+1.8E-5	0.1242+0.0003
		Tether			0.0003	
100kg @700km, SSO	No PMD		-	75 year	0.0027	2.5529
	PMD (passive)	Sat. + EM	120m x 25mm	25 year	0.0007+0.0003	0.7374+0.0964
		Tether			0.0121	
	PMD (active)	Sat. + EM	300m x 100mm	2 year	0.0003+1.9E-5	0.2312+0.0067
		Tether			0.0021	
100kg @800km, SSO	No PMD		-	250 year	0.0106	7.6502
	PMD (passive)	Sat. + EM	320m x 25mm	25 year	0.0009+0.0003	0.8850+0.1260
		Tether			0.038	
	PMD (active)	Sat. + EM	320m x 200mm	2 year	0.0004+2.5E-5	0.3329+0.0087
		Tether			0.0035	
100kg @1000km, 90deg	No PMD		-	>1000 year	>0.0357	>9.6550
	PMD (passive)	Sat. + EM	340m x 100mm	25 year	0.0009+0.0004	0.9429+0.1543
		Tether			0.0531	
	PMD (active)	Sat. + EM	1000m x 200mm	2 year	0.0003+3.1E-5	0.2603+0.0115
		Tether			0.0124	

6 CONCLUSIONS

This paper discussed collision probability in order to evaluate the orbital environment as well as the effective number of debris objects. In particular, the changes in collision probability caused by PMD or ADR were shown using NEODEEM, a debris evolutionary model. The total collision probability at each altitude was investigated in order to discuss which altitude regions are in a critical situation and how many additional satellites can be added, and so on. The collision probability at 700 to 800 km or 800 to 900 km is currently high, but that at 900 to 1000 km is expected to increase in the future. The effect of a large constellation of satellites was also investigated, and the change in collision probability at each altitude with different PMD rates was shown. The effects of such PMD devices as a drag sail and an electrodynamic tether were also investigated, and these devices were shown to increase the short-term collision probability, but also to decrease the long-term cumulative collision probability and expected number of fragments.

The results presented in this paper may change relative to different launch traffic and different assumptions. It should also be noted that the collision probability with smaller debris objects is very important for sustainable use of the space environment, and that further studies are required for a proper discussion.

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