Space Debris Mitigation by Passive Debris Removal in Large Constellation

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1. Introduction

Space business in recent years has reached a major turning point. One of the factors is that technological innovation has led to cost reduction and miniaturization of rockets and satellites, and the barrier to enter into space industry has been lowered. Constellation systems are attracting attention in recent years as new technologies. A constellation system is the system that achieves one mission using multiple satellites. Conventional satellite constellations have been used to deploy dozens of large satellites like GPS and Iridium, whereas recent satellite constellations for space broadband systems plan to launch 1000 or more small satellites at an altitude of 1000 km. Such a large-scale system is called a large constellation. There is a possibility that such a small satellite constellation will drastically change the way of space utilization.

When a satellite breaks up, hundreds of thousands of space debris are generated (Fig.1). They continue to drift in space because there is not much natural purification effect around 1000 km altitude, and thus debris removal for the large constellation is necessary. Removal methods are categorized into two approaches; active debris removal and passive debris removal (PDR). Active debris removal is typically used for large debris, while passive debris removal is used for small debris (Fig.2). Even small debris need to be removed because they have enough energy to destroy satellites in operation. PDR satellites reduce kinetic energy by letting them penetrate debris and remove them by forcing them into the atmosphere by reducing the orbital radius of the debris. This study investigates the effectiveness of velocity decay of debris using PDR.

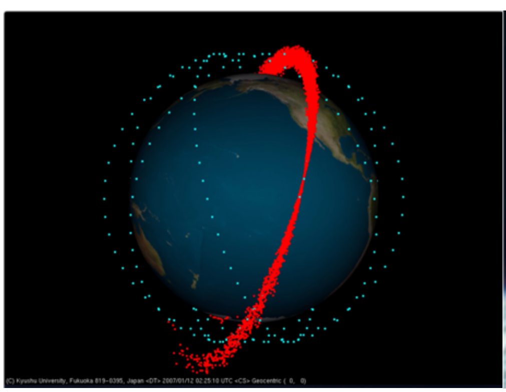

Fig. 1 Breakup satellite

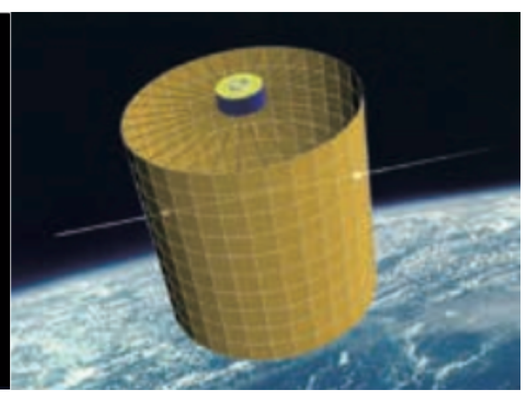

Fig.2 PDR satellite

2. **Methodology**

2.1 Research flow

First, a 150 kg satellite is assumed to be broken up in an orbit at an altitude of 1200 km, and its debris are generated using the NASA standard breakup model. Second, the small debris that may collide with the PDR satellite are found by close approach analysis. Third, the orbital element that the debris collided with the PDR satellite is decelerated from the relationship between the velocity vectors of the two objects and propagate in orbit for a year. Finally, the orbit of debris after deceleration is analyzed.

2.2 Passive debris removal

The following two calculation models are used for the deceleration effect. The parameters of the formulas are summarized in Table 1.

$$\dot{v} = -\frac{1}{2}\frac{C_D A}{m}\rho v^2 - T_s A \tag{1}$$

$$\dot{m} = -\Lambda \frac{A\rho v^3}{2Q} \tag{2}$$

Table 1 Parameters of deceleration effect

Resistance factor of debris [-]	C_D	2.0
Cross section of debris [m^2]	A	-
Density of low-density material [$\mathrm{kg/m^3}$]	ρ	1488
Tensile strength of low-density material [MPa]	T_s	350
Heat transfer coefficient [-]	Λ	0.5
Latent heat of debris [$\mathrm{J/kg}$]	Q	5.0×10^6
Debris mass [kg]	m	-
Relative velocity [$\mathrm{m/s}$]	v	-

Equation (1) expresses velocity change and Eq. (2) expresses mass change. The shape of PDR satellite is assumed to be a flat plate shape that always keeps its vertical direction with respect to the traveling direction. The Eq.(1) and (2) assume that the debris passing through the low-density material always maintains a sphere, it applies a deceleration effect depending on the relative velocity, the angle of incidence on PDR satellite, and its size.

2.3 Close Approach analysis

Close approach analysis is to evaluate the relative distance between two objects by propagating the orbit of the two objects. The collision of the two objects in the close approach analysis is not considered as a collision when the relative distance becomes 0, but a virtual size called an error sphere is provided for the size of the removal satellite and for debris. The collision probability is calculated from the two relative distances. The standard deviation indicating the position error of minute debris is set to 0.03 km. The close approach analysis period is one year.

3. **Result and discussion**

3.1 Natural purification effect at an altitude of 1200 km

The natural purification effect in one year is numerically considered, and its result is shown in Fig.3. At an altitude of 1200 km, the influence of atmospheric resistance is small, but debris is removed throughout the year, and about 90% of the debris remains in orbit. Therefore, it needs to be removed. In close approach analysis, verification is performed with debris excluding those that are naturally purified.

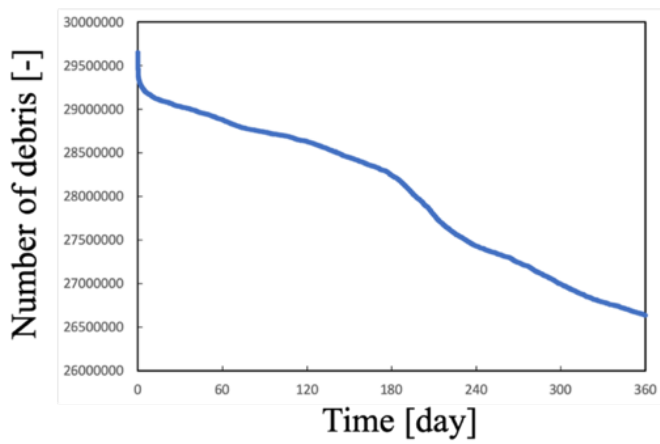

Fig.3 Natural purification effect

3.2 PDR satellite effects

Table 2 shows the deceleration effect of 1mm debris, and Fig.4 shows the debris trajectory with and without the deceleration effect. Since the orbital life is shortened by the PDR satellite, the removal effect of the PDR satellite was confirmed even at an altitude of 1200 km.

Table 2 Decelerate effect

	ΔV_x [km/s]	ΔV_y [km/s]	ΔV_z [km/s]	V [km/s]	t [days]
before	5.54	-4.37	1.77	7.27	Over 365
after	5.86	-1.69	0.88	6.17	0.01

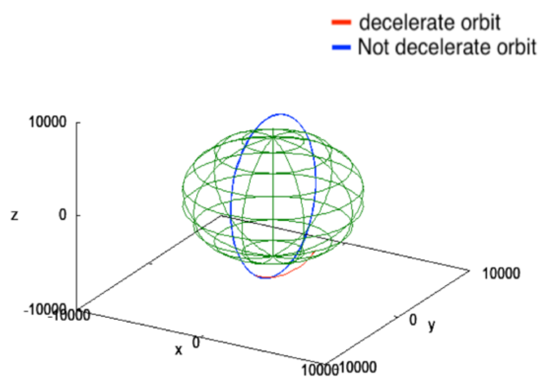

Figure.4 Debris orbit

3.3 Close Approach analysis

Table 3 shows the conditions used in the close approach analysis. The PDR satellite is put into the counter orbit for the breakup satellite. The results are shown in Figs. 5 and 6. There are many debris approaching within 10 km, but the expected number of colliding debris is small. Since the approach distance is involved in calculating the collision probability, the expected number of collisions will not be large unless the approach distance has a very small value.

Table 3 Close approach analysis conditions

	Altitude [km]	e [-]	i [deg]	RAAN [deg]
Breakup sat	1200	0.0001	75	18
PDR sat	1250	0.0001	105	162

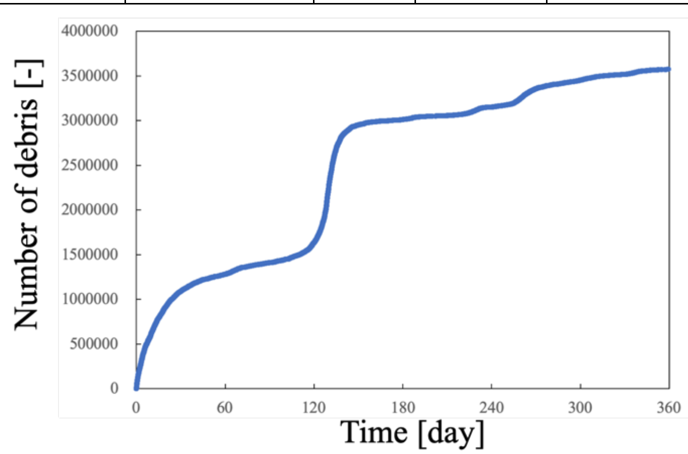

Fig.5 Debris approaching within 10km

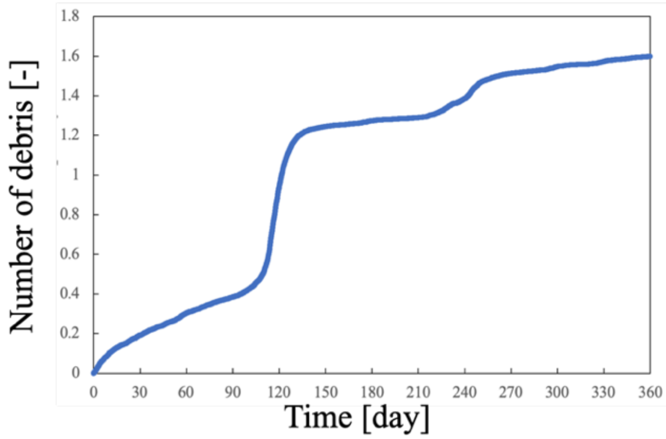

Fig.6 Expected number of collisions

Next case thus calculates by reducing the orbital distance between the fragmentation satellite and the PDR satellite from 50 km to 1 km. Figure 7 shows the expected number of colliding debris. Even if the distance between both tracks is reduced, the expected number of debris collisions does not change.

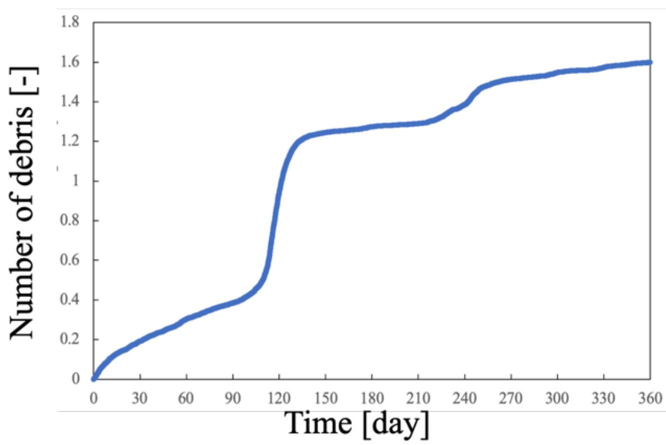

Fig.7 Expected number of collisions

Final case is examined by increasing the area of the PDR satellite. Figures 8 and 9 show the result of changing the area to $1\ km^2$ and $10\ km^2$. The number of removal debris increases because of the large area of the PDR satellite, and more debris are removed than the natural purification effect. This shows that the size of the PDR satellite has the greatest effect on the number of removals.

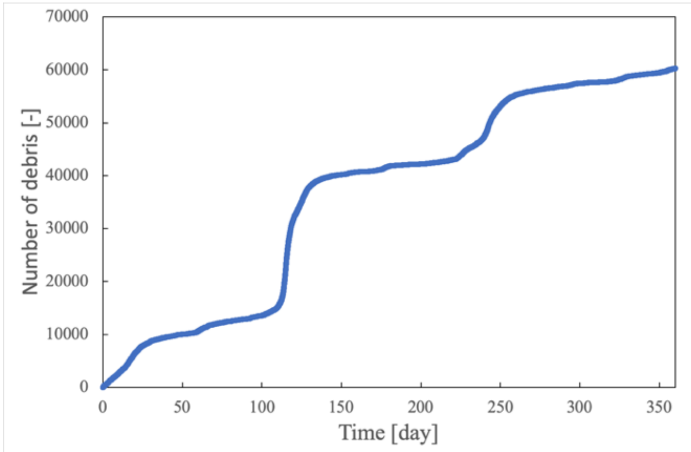

Fig.8 Expected number of collisions with 1 km^2 PDR

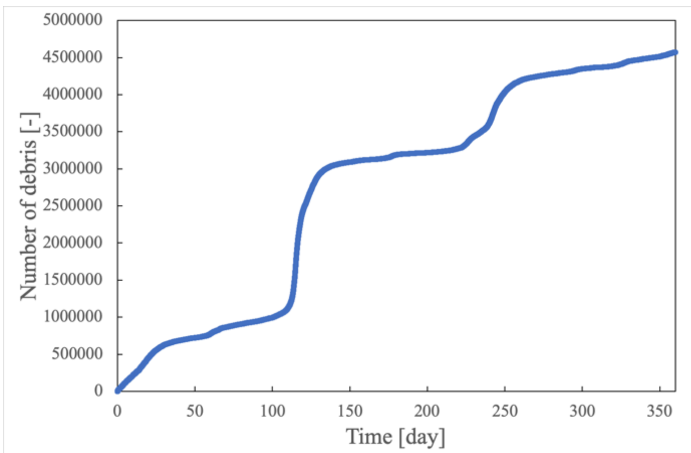

Fig.9 Expected number of collisions with 10 km^2 PDR

4. Conclusion

This paper considered the natural purification effect at an altitude of 1200 km. There are many debris with the closest approach distance within 10 km, but the number of collisions is small because the collision probability is low. More debris is removed than the natural purification effect by increasing the area of the PDR satellite. If the PDR satellite is large, however, it may collide with the satellite in operation, so it is necessary to determine a suitable size.

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