DILUTION OF DISPOSAL ORBIT COLLISION RISK FOR THE MEDIUM EARTH ORBIT CONSTELLATIONS

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ABSTRACT

Previous studies have shown that disposal orbits for the medium Earth orbit constellations can be unstable and undergo significant long-term eccentricity growth. This can lead to repenetration of the constellations by disposed vehicles, thereby posing a collision risk. The study presented here investigated the possibility of diluting disposal orbit collision risk by exploiting long-term eccentricity growth. The Galileo constellation was selected as an example. Various disposal strategies were considered. It was found that high eccentricity growth strategies can reduce the combined constellation and intra-graveyard collision risk relative to a minimum eccentricity growth strategy. High eccentricity growth strategies also offer the option of significantly increasing the percentage of disposed vehicles that will re-enter the atmosphere within 200 years after disposal rather than remain on orbit for thousands of years. High eccentricity growth strategies thereby offer an effective and potentially inexpensive option for medium Earth orbit debris mitigation.

1. INTRODUCTION

The potential instability of disposal orbits of the Global Positioning System (GPS) was discovered by Chao (2000). The instability manifests itself as significant growth in orbital eccentricity over a timeframe of decades. The cause of this long-term eccentricity growth is a dynamical resonance condition resulting from the combined gravitational pull of the Sun, Moon, and the non-spherical gravity field of the Earth. Long-term eccentricity growth of disposal orbits will lead to penetration of the constellation by previously disposed vehicles, thereby posing a collision risk to the operational constellation members. Chao and Gick (2002) also showed that disposal orbits for Glonass and Galileo can be similarly unstable. Hence, long-term disposal orbit eccentricity growth affects all of the existing and planned satellite constellations in medium Earth orbit (MEO). Gick and Chao (2001) showed that the amount of eccentricity growth depends on the initial elements of the disposal orbit. In particular, minimization of the disposal orbit initial eccentricity, e_0, and proper selection of the initial argument of perigee, ω_0, can suppress eccentricity growth, and hence constellation penetration, over a time period of up to 200 years. The initial right ascension of ascending node (RAAN = Ω_0) and inclination, i_0, also strongly influence long-term eccentricity growth (Chao and Gick, 2002), but these orbital parameters are not easily modified during the disposal process due to the excessive amount of required ΔV. The purpose of the study presented here is to investigate the possibility of diluting MEO disposal orbit collision risk by selection of e_0 and ω_0 in order to increase long-term eccentricity growth. The Galileo constellation was selected as an example.

2. OVERALL METHODOLOGY

The study analysis flow was as follows. The long-term evolution of the expected range of constellation orbits was simulated using a mean element propagator of high accuracy to account for eccentricity growth. From the resulting data, a statistical spatial distribution model of the operational constellation was generated. Next, for each disposal strategy considered, the entire expected range of disposal orbit initial conditions was swept out, and the resulting disposal orbits were propagated over 200 years. The propagated disposal orbit histories and the constellation spatial density model were then used to generate an ensemble of time profiles of cumulative long-term collision probability, one for each disposal orbit initial condition. The total collision risk accounting for on-going disposal of satellites over time was determined by randomly selecting collision probability time profiles from the ensemble that was generated, time-shifting them to account for future disposal epochs, and then summing them together. The entire disposal sequence over 200 years is repeated 1000 times in Monte Carlo fashion.

3. LONG-TERM ORBIT PROPAGATION

The Aerospace Corporation tool MEANPROP was used to perform the long-term propagation of the constellation and disposal orbits. MEANPROP is a mean orbit element control simulation that uses the Semi-Analytic Orbit Propagator (SAOP) to perform long-term propagation. SAOP is a program developed by the Charles Stark Draper Laboratory that has undergone extensive validation (McLain, 1977). In this study, the force model included Sun-Moon gravity, a 12 × 12 WGS84 Earth gravity field, solar radiation

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pressure, and atmospheric drag. Vehicle design data on the GSTB-V2-B experimental Galileo satellite was taken from Space Daily (2004). The vehicle mass was assumed to be 523 kg, projected average cross-sectional area was assumed to be 4.53 m^2, and the reflectivity coefficient c_r was assumed to be 1.3. The MSIS-90 atmosphere model was used, the solar flux parameter F10.7 was set to a constant value of 140, the geomagnetic index A_p was set to a constant value of 10, and the drag coefficient was assumed to be 2.0.

4. COLLISION RISK ANALYSIS

A density-based method was used to compute collision risk in this study. This method is formulated from the perspective of the primary satellite as it flies through a field of secondary objects. The following formulation was used:

$$N_C(t) = A_{cc} \int_{t_0}^{t} \rho\left(r_s(\tau)\right) v \, d\tau \qquad (1)$$

$$p_C(t) = 1 - e^{-N_C(t)} \qquad (2)$$

where t is the current time point, t_0 is the propagation start epoch, $p_C(t)$ is the cumulative collision probability at time t, $N_C(t)$ is the average number of collisions at time t, r_s is the position of the primary satellite, $\rho(r_s)$ is spatial density (averaged over latitude and time) of the secondary objects at the position of the primary satellite, v is the average relative velocity between the primary and secondary satellites, and A_{cc} is the average collision cross-sectional area between the primary and secondary satellites. The implementation of this formulation and a discussion of its accuracy is described in more detail in Jenkin and Gick (2003). The average collision cross-sectional area A_{cc} was set to unity, thereby normalizing the collision probability. It is a simple matter to obtain the absolute collision probability level by scaling the normalized probabilities with actual collision cross-sections determined from design information.

5. CONSTELLATION MODEL

In order to account for the effect of eccentricity growth on the orbital configuration of the constellation, the mean elements of constellation orbits were propagated over an assumed lifespan of the satellites. It was assumed that satellite station keeping maneuvers are carried out in a way so that they do not directly change eccentricity. The propagation start epoch is assumed to be 1 January 2009. The initial semimajor axis of constellation orbits was assumed to be 29994 km, and inclination was assumed to be 56 deg (ESA, 2002). The orbital eccentricity was assumed to have an initial value of 0.008, which is taken from GPS practice (Jenkin and Gick, 2002). The nodal regression rate for the Galileo constellation due to the J_2 oblateness term of the Earth's gravitational field is 9.025 deg/year. Together, all three constellation planes will sweep out the entire 360 deg range of right ascension of ascending node, Ω, in 13.3 years. The argument of perigee, ω, may take on any value over its 360 deg range. Therefore, to generate the constellation model, the initial values Ω_0 and ω_0 were varied over the range [0,360) deg in 10 deg increments. (The notation [0,360) deg denotes the entire range from 0 deg to 360 deg, including 0 deg but excluding 360 deg because it is redundant with 0 deg.) Orbital mean element vs. time profiles for each (Ω_0, ω_0) pair were generated by propagating over a time period of 15 years using MEANPROP. This time period is based on the assumption that the maximum vehicle life is 15 years. A statistical model of the spatial distribution of the constellation satellites was generated using the formulation of satellite altitude distribution derived by Dennis (1972). These spatial density distributions were then averaged across all the propagation time points and (Ω_0, ω_0) pairs, and then prorated by the number of constellation members, which is assumed to be 30 (ESA, 2002). Figure 1 shows the resulting average spatial density distribution. It can be seen from this figure that altitude boundaries at +/- 500 km (relative to the constellation reference orbit) effectively clear the Galileo constellation most of the time.

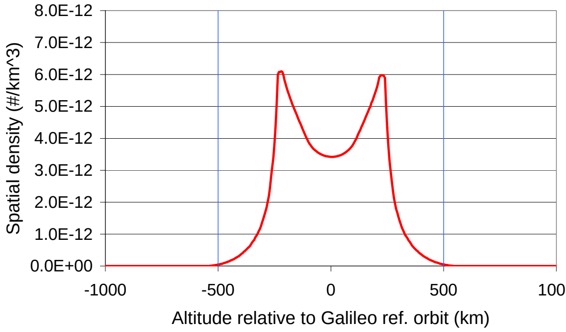

Figure 1. Variation of spatial number density with altitude (relative to the constellation reference orbit) of the Galileo constellation model used in this study. The spatial density is averaged over latitude.

6. CONCEPT OF COLLISION RISK DILUTION

In order to understand the concept of collision risk dilution, the dependence on orbital eccentricity of probability of collision posed by a sample disposed Galileo satellite was determined. The disposed satellite is assigned a semimajor axis a = 30647 km. When the eccentricity is 0.005, the perigee is 500 km above the

Galileo reference circular orbit. The collision probability posed by the disposed satellite to a secondary satellite on a circular orbit was computed as a function of the altitude of the secondary satellite (Fig. 2).

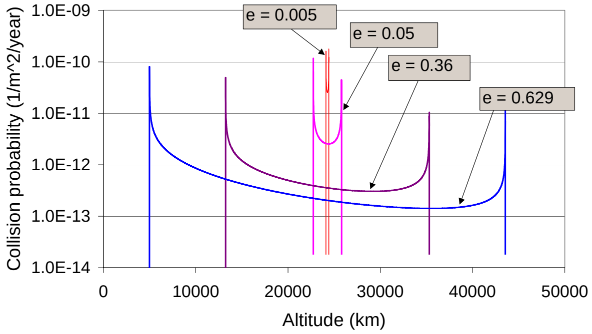

Figure 2. Collision risk posed by a disposed Galileo satellite to a target satellite on a circular orbit as a function of target satellite altitude.

The collision probability is formulated from the perspective of the secondary satellite as it flies through the spatial density field of the disposed satellite. The eccentricity of the disposed satellite is varied parametrically. As eccentricity increases, collision probability is significantly reduced for most altitudes between the apogee and perigee of the disposed satellite. The collision probability for an eccentricity of 0.36 is two orders of magnitude below the collision probability for an eccentricity of 0.005 for most altitudes. The reduction in collision probability at the altitude extremes is less substantial, especially at perigee. This indicates that, for a disposal orbit undergoing eccentricity growth, it is desirable to minimize the time spent by the disposal orbit perigee and apogee at altitudes with high population density.

7. DISPOSAL ORBIT EVOLUTION FOR e_0 = 0.005

The long-term evolution was determined for a disposal orbit strategy with e_0 = 0.005 and perigee 500 km above the Galileo reference orbit. The corresponding semimajor axis is 30647 km. Initial inclination was assumed to be 56 deg. The first disposal is assumed to occur on 1 January 2009. As in the case for the constellation propagation, Ω_0 and ω_0 were varied over the range [0,360) deg in 10 deg increments. Orbital mean element vs. time profiles for each (Ω_0 , ω_0) pair were generated by propagating over a time period of 200 years using MEANPROP. Figures 3-5 show the resulting evolution of apogee and perigee altitude for a sample set of constellation orbits with Ω_0 = 0, 120, and 170 deg, respectively. Each pair of apogee and perigee curves corresponds to a specific value of ω_0. It can be seen that values of ω_0 are available that result in either large, moderate, or small eccentricity growth, depending on Ω_0.

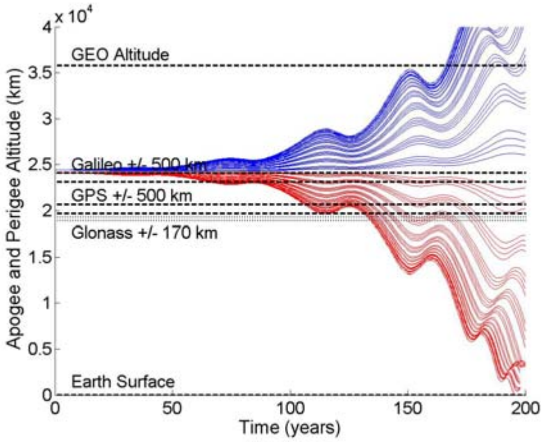

Figure 3. Apogee and perigee altitude profiles (shown relative to the Earth surface) of Galileo disposal orbits with e_0 = 0.005 for Ω_0 = 0 deg.

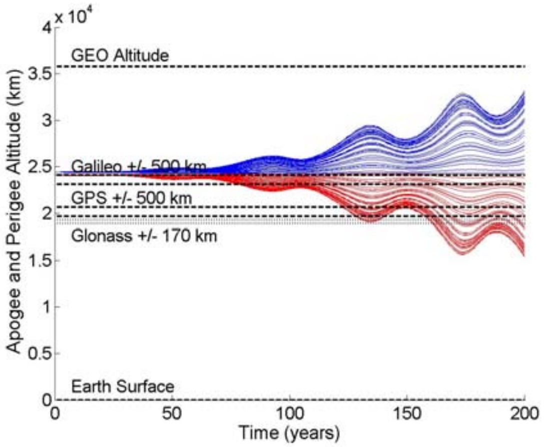

Figure 4. Apogee and perigee altitude profiles (shown relative to the Earth surface) of Galileo disposal orbits with e_0 = 0.005 for Ω_0 = 120 deg.

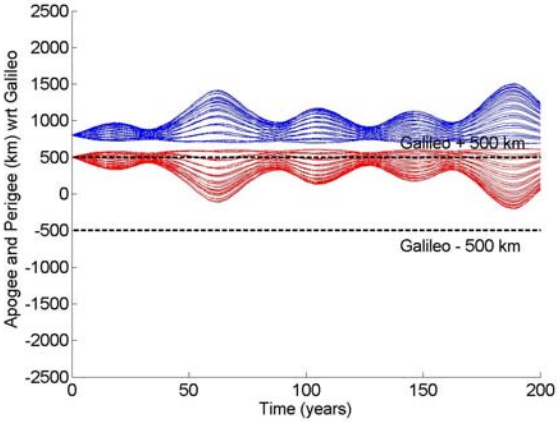

Figure 5. Apogee and perigee altitude profiles (shown relative to the constellation reference orbit) of Galileo disposal orbits with e_0 = 0.005 for Ω_0 = 170 deg.

For some of the large eccentricity growth cases, the perigee drops low enough so that the disposed vehicle reenters the atmosphere toward the end of the 200-year time period. For Ω_0 = 120 or 170 deg, there is no case where perigee drops low enough so that the disposed vehicle reenters within 200 years.

8. THE MINIMUM ECCENTRICITY GROWTH STRATEGY

Because of the strong sensitivity of eccentricity growth to ω_0, a wide variety of disposal strategies are potentially available. The strategy that has been previously proposed is to minimize e_0 and select ω_0 that minimizes eccentricity growth. This strategy can be called the minimum eccentricity growth strategy. It will minimize the number of disposed vehicles that penetrate the constellation. By selecting the disposal orbit perigee to be 500 km above the constellation reference orbit, the ΔV required to clear the constellation is minimized. There are several difficulties with this strategy. One drawback is that for small values of initial eccentricity, ω_0 becomes very sensitive to small maneuver errors, and it is difficult to accurately achieve a desired value of ω_0. Another disadvantage is that disposed vehicles will accumulate over time within a tightly confined graveyard. As a result the disposed satellites will pose a collision risk amongst themselves. In order to model the graveyard population growth, a spatial density model of the graveyard was constructed via the same technique used for the constellation model. To obtain the spatial density field that accounts for all satellites disposed up to a time t, the single satellite spatial density field was multiplied by the number of accumulated disposed vehicles at time point t. Figure 6 shows the spatial density field of the graveyard after 100 years, assuming a satellite disposal rate of 2 satellites per year. It is shown along with the spatial density field of the constellation. It is seen that the graveyard spatial density is much higher than the constellation spatial density.

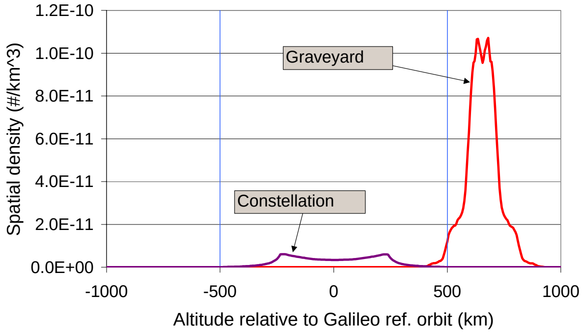

Figure 6. Spatial population densities of the graveyard and constellation after 100 years for the minimum eccentricity growth strategy.

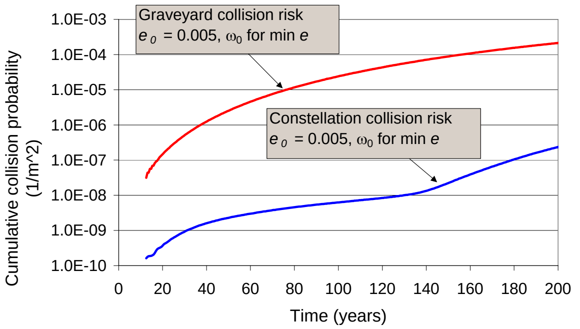

Figure 7. Cumulative collision risk over time between disposed satellites in the graveyard. For comparison, the collision probability between the disposed satellites and the operational constellation is also shown.

The cumulative collision risk between the disposed vehicles in the graveyard was computed as a function of time (Fig. 7). For comparison, the collision probability between the disposed satellites and the operational constellation is also shown. Both curves are the median profiles resulting from the Monte Carlo repetition of the disposal sequence. It is seen that, for most of the 200-year time period, the intra-graveyard collision risk is three to four orders of magnitude higher than the collision risk posed by the disposed vehicles to the constellation. If a collision occurs between disposed vehicles in a graveyard that is located near the constellation, it is very likely that debris resulting from the collision will follow orbits that penetrate the constellation. Therefore, collision risk within the graveyard poses a significant indirect risk to the operational constellation.

9. HIGH ECCENTRICITY GROWTH STRATEGIES

The option considered here is to exploit natural dilution of the intra-graveyard collision risk by increasing eccentricity growth. The strategy that is investigated here is to select (e_0, ω_0) to maximize eccentricity growth at 100 years or minimize time to reentry. The disposal orbit perigee is anchored at 500 km above the constellation reference orbit. An advantage of this strategy is that, as e_0 increases, it becomes easier to accurately target ω_0. A disadvantage is that increasing e_0 must be accomplished by raising apogee. This will cost extra ΔV, so more effort on the part of the satellite will be required in the form of propellant as e_0 is increased. An important issue to consider is that the high eccentricity growth strategy will pose a higher direct collision risk to the constellation than the minimum eccentricity growth strategy. Therefore, the tradeoff between graveyard collision risk and constellation collision risk must be considered. The high eccentricity growth strategy will also pose a higher direct collision risk to other objects external to Galileo, such as the GPS and Glonass systems and, in extreme cases, low Earth orbit and geosynchronous objects. Determination of the collision risk posed to these objects was beyond the scope of this study. However, it is expected to be low due to the dilutional effect of eccentricity growth as illustrated in Fig. 2.

Table 1. High eccentricity growth strategy cases.

e0	Perigee altitude rel. to Galileo (km)	Semimajor axis (km)	Increase in semimajor axis above Galileo (km)
0.005	500	30647	653
0.021051	500	31150	1156
0.036593	500	31652	1658
0.051649	500	32155	2161

Four levels of eccentricity were considered. Table 1 shows the corresponding disposal orbit semimajor axis and the required increase in semimajor axis above the constellation reference orbit for each level of eccentricity. This range of disposal effort was selected for this study because it is believed to be feasible with modern satellite technology.

The resulting apogee and perigee altitude profiles for e_0 = 0.005 have already been presented in Figs. 3-5. As noted before, large eccentricity growth, as well as re-entry within 200 years, can be achieved for some but not all values of Ω_0. Figures 8-9 show the apogee and perigee altitude profiles for $e_0 = 0.036593$ and Ω_0 = 290 and 170 deg, respectively. It is seen that eccentricity growth has been increased, even for Ω_0 = 170 deg. In addition, for Ω_0 = 290 deg, re-entry can be achieved as early as 120 years after disposal.

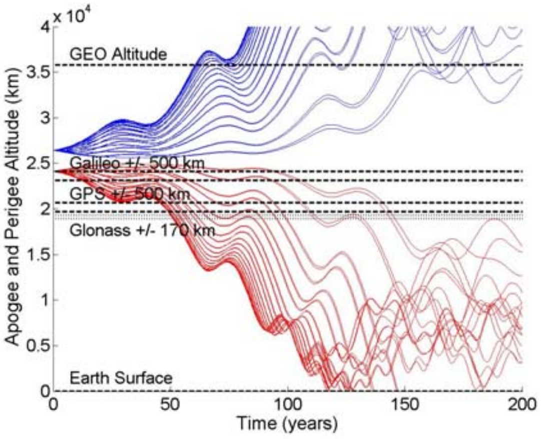

Figure 8. Apogee and perigee altitude profiles (shown relative to the Earth surface) of Galileo disposal orbits with e_0 = 0.036593 for Ω_0 = 290 deg.

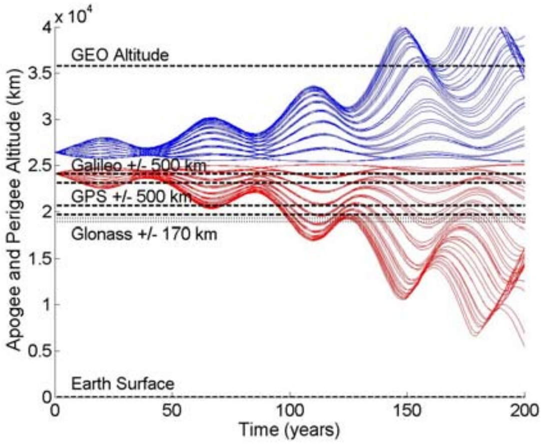

Figure 9. Apogee and perigee altitude profiles (shown relative to the Earth surface) of Galileo disposal orbits with e_0 = 0.036593 for Ω_0 = 170 deg.

Figure 10 shows the time profiles of collision risk posed to the constellation by accumulating disposed vehicles (assuming a disposal rate of two per year) corresponding to the various disposal strategies. The plot shows curves for the four high eccentricity growth cases considered, and also a strategy in which e_0 = 0.005, perigee is 500 km above the constellation reference orbit, and ω_0 is not specifically targeted but rather allowed to vary randomly among sequentially disposed satellites. From the plot, it is seen that the case with the highest collision risk is the high eccentricity growth case with e_0 = 0.005. The case with the second highest collision risk after 130 years is the random ω_0 case with e_0 = 0.005. The long-term collision risk is reduced further for the high eccentricity growth strategy cases with higher e_0. The collision risk is continually reduced as e_0 is increased, however the gains in risk reduction begin to diminish after e_0 exceeds 0.036593.

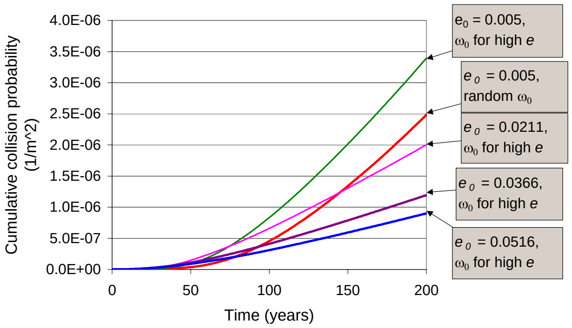

Figure 10. Collision risk posed to the Galileo constellation by various disposal strategies.

Comparing Figs. 7 and 10, it is seen that the high eccentricity growth strategies and the random ω_0 strategy result in a higher collision risk to the constellation than the minimum eccentricity growth strategy. However, the collision risk posed to the constellation by the high eccentricity growth strategies is much lower than the intra-graveyard collision risk. The intra-graveyard collision risk for the high eccentricity growth strategies was not quantified in this study. However, from Fig. 2 it is expected that these strategies will significantly reduce the intra-graveyard collision risk.

Table 2 shows the percentage of disposed satellites that will re-enter within 200 years after disposal for various strategies. The results account for the entire [0,360) deg range of Ω_0. It is seen that the re-entry percentage is significantly increased and is substantial for the high eccentricity growth cases with $e_0 = 0.0211$ and larger.

Table 2. Percentage of satellites that re-enter within 200 years after disposal.

ω_0-selection strategy	**e_0**	**% of satellites that reenter before 200 years after disposal**
Random ω_0	0.005	7.1%
High eccentricity	0.005	19%
"	0.0211	**67%**
"	0.036593	**75%**
"	0.051649	**92%**

10. CONCLUSIONS

The minimum eccentricity growth strategy minimizes the collision risk posed directly to the constellation by disposed vehicles, but it also results in a collision risk between disposed vehicles in the graveyard that is much higher. High eccentricity growth strategies increase the collision risk posed directly to the constellation, but they will significantly reduce the intra-graveyard collision risk, and therefore reduce the combined collision risk. The increase in collision risk posed to the constellation can be reversed by increasing initial disposal orbit eccentricity. It is preferable to avoid a high graveyard collision risk because potential graveyard collisions can produce untrackable debris that will penetrate the constellation and cannot be evaded by collision avoidance. High eccentricity growth strategies also offer the option of significantly increasing the percentage of disposed vehicles that will re-enter the atmosphere within 200 years rather than remain on orbit for thousands of years. This option may be desirable if the vehicles pose a low ground casualty expectation. Therefore, high eccentricity growth strategies offer an effective and potentially inexpensive option for MEO debris mitigation.

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