Evaluation of Low Earth Orbit Post-Mission Disposal Measures

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Abstract

The substantial benefits arising from the widespread adoption of post-mission disposal in low Earth orbit (LEO) are reflected in a reduced orbital debris population and a reduced frequency of collisions. The benefits are generally seen at higher altitudes whereas some drawbacks in the form of enhanced collision risks have been predicted for lower altitudes. These drawbacks are generally expected to reduce as the post-mission disposal lifetime decreases, as less time at lower altitudes reduces collision probability. This is the rationale used by the Federal Communications Commission (FCC) for its new 5-year rule. To investigate the potential benefits and drawbacks, the DAMAGE computational model was used to investigate the effects of a variety of LEO post-mission disposal rules, including the new 5-year rule, within scenarios involving the deployment of large constellations of satellites. The results suggest substantial reductions in conjunction rates overall, as the post-mission residual orbital lifetime decreases, but indicate an increasing frequency of conjunctions and a corresponding need for risk mitigation maneuvers at low altitudes. The results reinforce the recommendation that disposal must be completed as soon as practicable following end of mission. Additionally, the results highlight the need for careful consideration and further research into post-mission disposal where a residual orbital lifetime is permitted.

1 Introduction

The Space Debris Mitigation Guidelines of the Inter-Agency Space Debris Coordination Committee (IADC) recommend that spacecraft or launch vehicle stages ending their mission in orbits passing through the low Earth orbit (LEO) region should be de-orbited immediately or maneuvered into an orbit with an expected residual orbital lifetime of 25 years or less [1]. Studies undertaken by IADC members, using computational models, have demonstrated the importance of high adoption rates amongst operators with respect to this guideline, which is commonly referred to as the “25-year rule”. For high adoption rates, e.g., of 90%, it can lead to a substantial reduction in the orbital object population compared with the case without adoption of the guideline. Whilst observations from the last 10 years show operator adoption rates have increased, it is not yet at a level where the benefits predicted in the model studies will be evident [2].

To comply with the 25-year rule, a spacecraft can transfer to an orbit with a residual orbital lifetime of less than 25 years. The transfer with the lowest delta V would typically move the spacecraft from its original, or mission orbit, to an orbit with a higher eccentricity with the perigee at a lower altitude and the apogee remaining at the mission altitude. The atmospheric drag at the new perigee is greater than at the original altitude, resulting in an increased rate of change of orbital energy and a subsequent circularization of the orbit and a reduction in its size (see Fig. 1). Hence, the residual orbital lifetime is shorter. Implementation of the 25-year rule is therefore achieved through selection of and transfer to an orbit with an appropriate perigee altitude. Reducing the altitude of both perigee and apogee to achieve the desired residual orbital lifetime is also possible but typically requires a higher delta V.

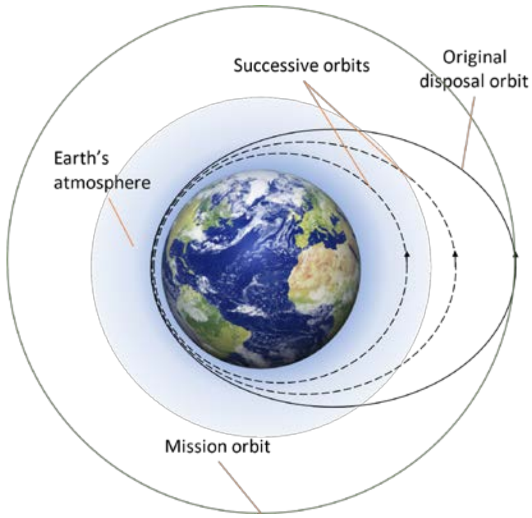

Fig. 1. Schematic showing the use of an eccentric disposal orbit to meet post-mission disposal lifetime requirements and the effect of atmospheric drag on subsequent orbits. The transfer from the mission orbit to the initial disposal orbit involves a maneuver to lower the perigee altitude. Once the satellite is passivated and switched off, atmospheric drag circularizes and reduces the size of the orbit until the satellite re-enters the atmosphere.

Computational modelling studies have shown that implementation of post-mission disposal rules (as in Fig. 1) tends to enhance collisional activity at lower altitudes even while reducing it at higher altitudes. As [3] noted in 2001, "*The act of reducing perigee of all intacts at end-of-life increases the time spent at the lower altitudes and also increases the likelihood of collision at those low altitudes.*" Results in [4] showed that adoption of the 25-year rule in the higher LEO regime led to a substantial number of catastrophic collisions that dominated collisional activity in the lower LEO altitude regime and maintained the orbital population there in dynamic equilibrium over the long-term. Nonetheless, [3] concluded that, "*Enhanced collisional activity at the lower altitudes… decreases as the PMD time decreases, since less time at lower altitudes reduces collision probability*." This insight, also supported by [4], points to the need for a change from the 25-year rule to one associated with a lower residual orbital lifetime, although neither study provided sufficient clarity on what lifetime might be needed to remove the effects of collision enhancement at low LEO altitudes.

An important factor affecting this trade-off is the deployment of large constellations of satellites in LEO. Proposals for such systems could see tens to hundreds of thousands of new satellites concentrated at some LEO altitudes, adding to the thousands that are already present [2]. Large constellation operators aspire to more stringent post-mission disposal success rates and generally ensure their spacecraft remain maneuverable throughout the disposal phase, thereby minimizing impacts on the debris environment. Nonetheless, if the deployment of a large constellation coincides with the altitude region where the enhancement of collision risks is felt (due to the broader adoption of post-mission disposal rules), there is the potential for a further and substantial enhancement, and a corresponding increase in the frequency of collision risk mitigation (collision avoidance) maneuvers and a decrease in the safety at these intersectional altitudes.

In September 2022 the Federal Communications Commission (FCC) adopted a new "5-year rule" to address the growing risks from space debris [5]. As with the old 25-year rule, operators can comply by transferring their satellites from mission altitudes to orbits that are lower (as shown in Fig. 1). An orbit with a residual lifetime of 5 years will be smaller than one with a residual lifetime of 25 years and, hence, will require a higher delta V to achieve. Whilst the FCC recognized this rule change could increase costs for the industry (e.g., for the additional propellant needed for the transfer), it argued that the benefits of the rule change in terms of reducing the likelihood of collisions and their potential consequences for the reliable provision of vital data and services outweighed any costs [5]. Setting aside the influence on lower LEO altitudes as outlined above, it is unlikely that the switch from a 25-year rule will provide a profound change in the orbital debris population. As the FCC noted (but ultimately disregarded for reasons outlined below), the results of a study using NASA's LEO-to-GEO Environment Debris (LEGEND) long-term computational model in [6] showed that reducing the 25-year rule to a 5-year rule would only lead to a 10% debris reduction in the orbital debris population over 200 years.

In combination with the uncertainty in the extent of any enhancement to the collision risk at low LEO altitudes, the results in [6] prompt some reservation over the ability of the FCC's new 5-year rule to reduce the frequency of collision risk mitigation maneuvers and potential collisional activity at low LEO altitudes. To resolve some aspects of the issue, this paper reports the results of a new study focused on post-mission disposal options and making use of the DAMAGE computational model.

2 Initial Motivations and Insights

2.1 Trolley problem and principle of double effect

As described above, the implementation of post-mission disposal rules in LEO by using transfers to orbits with reduced residual orbital lifetimes has been shown to offer broad benefits in LEO overall but at the potential cost of increased collision risks at low LEO altitudes. In engineering terms, this is a trade-off, but the problem itself is an ethical dilemma and similar structurally to the trolley problem, first described in [7]. The purpose of the trolley problem is to test intuitions, to decide what actions are morally and ethically correct.

The trolley problem describes a scenario in which a trolley is on a course leading to five people who are tied to the tracks. The driver of the trolley has the option to divert the trolley onto another track on which only one person is tied. Reference [7] questioned whether the driver should divert the trolley. A simple calculation shows that if the driver keeps the trolley on its tracks, there will be five casualties. If, conversely, the driver diverts the trolley, there will only be one casualty. It seems ethically acceptable to lose one person to save five. In this case, the outcome is justified by the principle of double effect [8], which allows actions that will produce a good effect and a bad effect provided that:

1. the objective of the action is good or at least indifferent,
2. the good effect and not the bad effect is intended,
3. the good effect is not produced by means of the bad effect,
4. there be a proportionately critical reason for permitting the bad effect, and
5. actors strive to minimize the foreseen harm of the bad effect.

The fourth condition of proportionality usually requires the extent of the harm to be determined and sufficiently offset by the magnitude of the proposed benefit. Action to assess the harm is not always taken, particularly in scenarios where it is perceived initially to be small. Additionally, it is reasonable to assume that if the harm is understood, actors will be motivated to avoid causing it or to minimize how much of it they cause.

2.2 Modelling and its limitations

A model is a conceptual tool that explains how an object or system of objects will behave, based on a mathematical description of the system. Models allow scientists and engineers to predict and understand behavior at various scales or extrapolate from a known set of conditions to another. Formulating a model is a trade-off between three important and often conflicting elements:

- *Accuracy* – the ability to reproduce the observed data and reliably predict future dynamics. Predictive models require a high degree of accuracy, e.g., to guide decisions where a trade-off exists between two or more alternative control strategies. Generally, accuracy improves with model complexity. Adding complexity is difficult because it generally requires increased computational power, a mechanistic understanding of detailed processes, and availability of necessary parameters and data. Hence, Accuracy is aways limited.
- *Transparency* – arising from an ability to understand how the various model components interact and influence the dynamics. It can be achieved by adding or removing components and building upon general intuitions from simpler models. As the number of model components increases it becomes more difficult to assess the role of each component and its interactions with the whole. Hence, transparency is often in direct opposition to accuracy.
- Flexibility – measures the ease with which the model can be adapted to new situations.

Models have two distinct roles: prediction and understanding. These roles are related to the properties of accuracy and transparency, so are often in conflict. We want models that capture the essential features of a system. Hence, a good model will be as simple as possible, but no simpler (or, conversely, as complex as necessary, but no more complex). Even the most complex model will make some simplifying assumptions.

The fact that models are imperfect representations of the real world means the results they produce are sometimes dismissed. Indeed, a commonly cited aphorism attributed to statistician George Box is that “all models are wrong,” which is sometimes expanded generously to include “some are useful.” Dismissal on such broad grounds can remove vital evidence from sometimes complex and nuanced decision-making, leading to unwanted or unforeseen outcomes. In the context of the principle of double effect, such an approach might also inhibit the understanding and assessment of potential benefits and harms. Simple models used in challenging settings are perhaps more likely to be treated in this way, even if they have an appropriate balance of accuracy, transparency, and flexibility and are suited to their purpose. For example, models used to enable predictions of the orbital debris population over the long-term may be criticized because short-term phenomena lasting seconds – the conjunctions, collisions, and fragmentations which drive the population behavior – are represented simply, often through averaged and computationally efficient approaches when propagating for hours or days at a time.

2.3 The Galton board

The Galton board, or box, was invented by Sir Francis Galton as a tool to illustrate the central limit theorem. Specifically, it shows that when the sample size is large enough, the binomial distribution closely resembles a normal distribution [9]. The Galton board is made up of a vertical board with rows of pegs that are arranged in an alternating pattern (Fig. 2). When beads are dropped from the top of the board, they collide with the pegs in subsequent layers and bounce either to the left or right. These collisions change the path taken and, ultimately, the bin they fall into at the bottom of the board. With a sufficient number of beads and rows of pegs the accumulation at the bottom approximates a normal distribution.

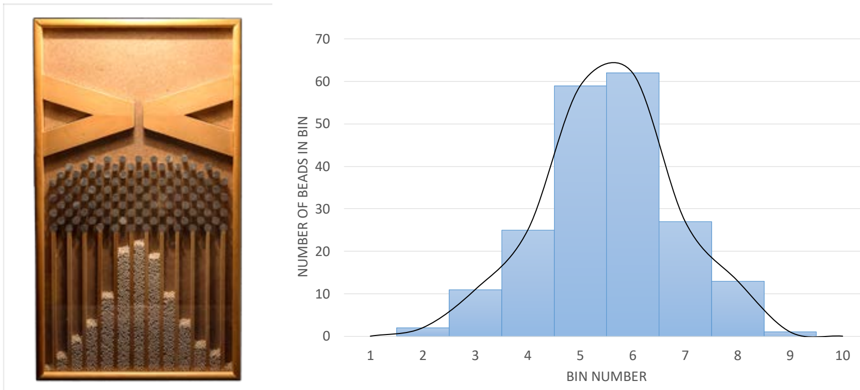

Fig. 2. A Galton box (left) showing beads in a normal distribution and (right) results from a Monte Carlo simulation using a simple model (box image credit: Matemateca (IME/USP)/Rodrigo Tetsuo Argenton).

Before the beads fall from the top of the board it is impossible to predict which beads will collide with which pegs, what the outcomes of individual bead-peg collisions will be, the path taken by each bead through the rows of pegs, or which bin each bead will fall into. However, a simple computational model of the Galton board can be created, based on the minimal premise that there is an equal probability a bead will collide with a peg and bounce either to the left or to the right, and it will be able to estimate the final bead distribution. Such a model was implemented in Microsoft Excel and used to simulate a board with 10 bins, 42 pegs in seven rows, and 200 beads. Monte Carlo simulation was used to estimate the distribution of the beads as they accumulated in the bins at the bottom of the modelled board, where each bead dropped was represented by one Monte Carlo run.

Despite being a simple model, in which the exact, high-speed physics associated with the bead-peg (and bead-bead) collisions was excluded, the resulting distribution produced by this model approximated the expected outcome – a normal distribution, as shown in Fig. 2. The result demonstrates the ability of a simple model, one with sufficient complexity, to deliver an accurate representation of the behavior of a real-world system driven by short-term phenomena. Due to its simplicity, the model also offers transparency and considerable flexibility, e.g., to increase the number and pattern of pegs, or to change the probability associated with the direction that beads take after bouncing off pegs.

3 DAMAGE Simulation

With the Galton board as inspiration, the DAMAGE model was used to investigate the effects of a variety of post-mission disposal rules over a projection period from 1 January 2020 through 1 January 2048. In the scenarios created for this study, a large constellation of satellites, comprising 36,000 satellites, embodied the pegs of a Galton board. A second large constellation of satellites, comprising 1,800 satellites at a higher altitude, represented the beads dropped through the board. No other orbital objects were included in the simulations. Given the intention of the FCC's new 5-year rule to address the rising number of conjunctions and collision avoidance maneuvers, primary outputs from the simulation were the altitude distributions of all conjunctions between BEAD and PEG satellites.

3.1 Study parameters

DAMAGE features a constellation module that enables investigations of large constellations of satellites with relatively complex Concepts of Operations (CONOPS). The process used in DAMAGE to build and subsequently replenish constellations is described in [10].

The PEG constellation comprised 36,000 satellites divided equally amongst 20 distinct orbital shells, each separated by 20 km and with the first shell at an altitude of 320 km. Satellites within each orbital shell were arranged in a Walker-Star geometry across 30 orbital planes inclined at 96°. Satellites were assumed to be 600 kg with collision and drag cross-sections of 4 m^2. Constellation deployment commenced on 1 January 2020 with the complete deployment of all satellites by the end of 2022. For this study, PEG satellites were assumed to remain operational, with no failures, for the duration of the simulation. Hence no constellation replenishment or disposal was needed. PEG satellites were injected into an initial circular orbit at 300 km before ascending to their respective mission altitudes after a 5-day checkout period. Rocket stages used to deploy the satellites were assumed to de-orbit immediately.

The BEAD constellation consisted of 1,800 satellites identical to those in the PEG constellation, deployed over the same timeframe and arranged in a Walker-Star geometry covering 30 orbital planes at 950 km and inclined at 96°. BEAD satellites were injected into an initial circular orbit at an altitude of 800 km to avoid traversing the PEG constellation altitudes. Nominally, BEAD satellites were replaced every three years for the duration of the projection period with new satellites replacing those already in orbit. The disposal of the retiring BEAD satellites had an assumed 100% success rate and occurred in two stages: an initial descent to a circular staging altitude 5 km below the shell altitude followed by continuous thrust to an eccentric disposal orbit with the perigee at a sufficiently low altitude meeting a user-specified residual orbital lifetime of 25, 10, 5, 3, or 1 year. Once in an appropriate disposal orbit, the satellites were assumed to be fully passivated and their drag and collision cross-sections were set to 30 m^2, resulting in an area-to-mass ratio of 0.05 m^2/kg. An additional post-mission disposal case was simulated to reflect actual post-mission disposal practices employed by constellation operators. In this case, continuous thrust was used to lower the perigee altitude to 300 km before passivation, essentially achieving a near-immediate disposal. Fig. 3 shows the approximate perigee altitudes needed by the BEAD satellites to achieve the required residual orbital lifetimes described above. This study setup created a steady flow of BEAD satellites descending through the layers of PEG satellites.

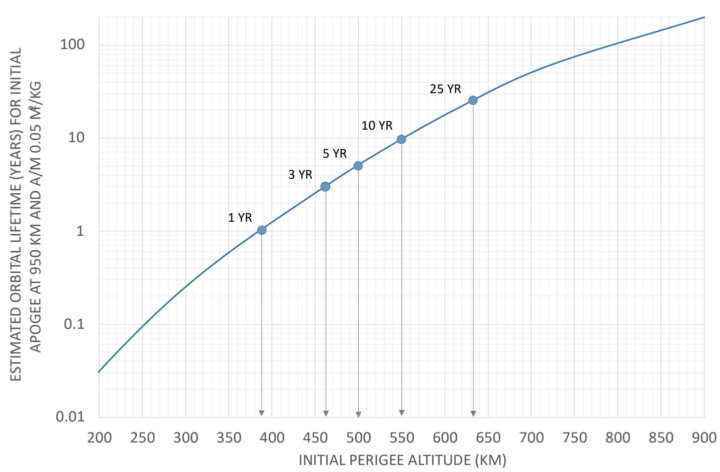

Fig. 3. Estimated orbital lifetime of objects in eccentric orbits with initial apogee altitude of 950 km.

Intra-constellation conjunctions between operational satellites were ignored but all other conjunctions were identified using a method based on the M-space approach to account for events between time-steps [11]. For the purposes of this study, simulation of collisions between satellites was not considered and only information about close approaches was used in evaluations of the post-mission disposal rules. Due to the computational load associated with the M-space approach, only one Monte Carlo (MC) run was conducted for each scenario.

3.2 M-space approach

The mean anomaly, or M-space, approach uses an analytical method to identify future close approaches (conjunctions) between satellites, with filters to enable computational efficiency [12]. If the velocity vectors of two satellites in a conjunction are linearized at the points of close approach, then lines of constant separation between the satellites are ellipses in a 2-dimensional parameter space defined by their mean anomalies. The ellipses are centered on points in this parameter space with minimum separation at coordinates (M_{PC}, M_{SC}), where M_{PC} is the mean anomaly of the primary object and M_{SC} is the mean anomaly of the secondary object at the point of closest approach. As the respective mean anomalies change because of the relative motion between the objects, the separation increases, and the corresponding ellipses are increasingly further away from this minimum. As such, it is possible to define an elliptical footprint in the parameter space containing all target and projectile mean anomalies for which two satellites are closer than a user-specified separation (assumed to be 5 km).

In M-space the primary object's mean anomaly will change linearly at n_P radians per second. Similarly, the secondary's mean anomaly will change at n_S radians per second. Thus, the combined, relative orbital motion will be a line in M-space given by,

$$M_P = \frac{n_P}{n_S} M_S + C \tag{1}$$

where M_P is the primary's mean anomaly at time t, M_S is the secondary's mean anomaly at time t and C is a constant defined by the intersection of the line with the M_S-axis.

A conjunction event will occur if the line in Eq. 1 intersects the close approach elliptical footprint at any point within the time-step (Fig. 4). The solution to this is a quadratic with the roots giving the target and projectile mean anomalies of entry and exit of the line to/from the elliptical footprint. If the target and projectile objects make more than one revolution per time-step, additional footprints at multiples of 2π are added, e.g., $(M_{PC} + 2\pi, M_{SC} + 2\pi)$ and evaluated for intersections with the line (Eq. 1).

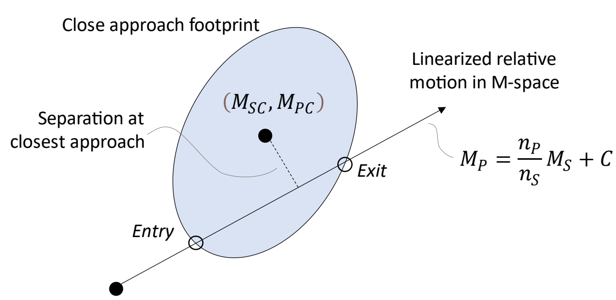

Fig. 4. Geometry of a close approach in M-space.

4 Results and Analysis

At first glance, the study results shown in Tab. 1 show a substantial difference in the number of conjunctions occurring for the 25-year rule and for the 5-year rule. The latter resulted in a 45% reduction in the number of conjunctions and anticipated maneuvers. This result supports the rationale described by the FCC for the new 5-year rule and contradicts the implication in [6] that a shift to a 5-year rule would not produce a statistically significant benefit. An even better outcome was achieved with a 1-year rule, which reduced the number of conjunctions by 90% compared with the 25-year rule. A 95% reduction was observed for the case where the PEG satellites used continuous thrust to lower the perigee to 300 km, more-or-less replicating real-world operator behavior and expected benefits.

Tab. 1. Conjunction and maneuver results for the whole PEG constellation and per satellite (calculated by dividing the "All PEG" values by 36,000). Maneuver rates were estimated to be 4% of the conjunction rates. The peak altitude is taken to be the average of all altitudes 320-700 km occupied by the PEG constellation where the conjunction rate exceeds 80% of the maximum. The "Active" case represents the use of continuous thrust to lower the disposal orbit perigee to 300 km.

Target post-mission lifetime (years)	Total # of conjunctions < 5 km Jan 2020 to Jan 2048	Average conjunction rate (#/year) All PEG / 1 PEG sat	Estimated maneuver rate (#/year) ALL PEG / 1 PEG sat	Peak conjunction altitude (km)
25	109,650,839	4,444,928 / 123.5	177,797 / 4.9	610
10	95,523,809	3,872,259 / 107.6	154,890 / 4.3	525
5	60,861,168	2,467,163 / 68.5	98,687 / 2.7	505
3	39,828,241	1,614,539 / 44.8	64,582 / 1.8	475
1	11,589,648	469,816 / 13.1	18,793 / 0.5	390
Active	5,776,751	234,175 / 6.5	9,367 / 0.3	600

However, the results in Tab. 1 also indicate a shift downwards of the peak conjunction altitude as the post-mission disposal lifetime reduces, tending to align with the perigee altitudes of the disposal orbits shown in Fig. 3. This suggests a non-uniform altitude distribution for the conjunction events, determined by the choice of post-mission disposal option – a result that supports the findings in [3]. Further inspection confirmed this, revealing a substantially different distribution in the conjunction rates for different layers of the PEG constellation at different altitudes, as shown in Fig. 5.

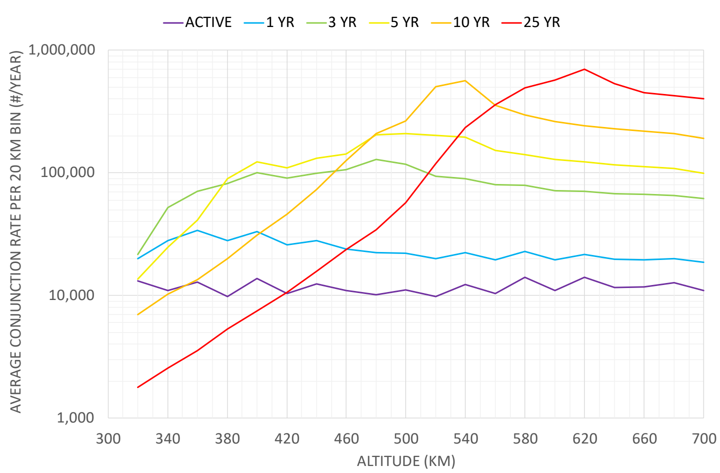

Fig. 5. Average BEAD-PEG conjunction rate as a function of PEG altitude for different post-mission disposal options.

To simplify the interpretation of Fig. 5, consider the conjunction rates for PEG satellites at 700 km, 540 km, and 400 km, which represent the approximate altitudes of Sentinel 1A, Starlink, and the International Space Station (ISS), respectively. At 700 km, PEG satellites experienced 400,000 conjunctions per year as the BEAD satellites decayed in accordance with the 25-year rule. In contrast, the PEG satellites saw only 25% of this conjunction rate if the BEAD satellites followed the 5-year rule, and less than 5% if a 1-year rule was adopted. At 700 km, therefore, a shift to a 5-year rule offered a substantial benefit, and a 1-year rule or active disposal presented even better outcomes.

At 540 km a transition occurred, whereby BEAD-PEG conjunctions occurred at approximately the same rate of 200,000 per year whether the BEAD satellites adopted a 25-year rule or a 5-year rule. At this altitude, residual orbital lifetimes of 3 years or less still offered reductions in the conjunction rates.

Finally, at 400 km, there was a complete reversal. BEAD satellites following the 25-year rule presented the lowest conjunction rate of all post-mission disposal options, with approximately 7,500 BEAD-PEG conjunction events per year. In contrast, the 5-year rule represented the worst case for PEG satellites at this altitude, with nearly 120,000 conjunctions per year – an increase by more than an order of magnitude compared with the 25-year rule. This was not simply a relative increase; in absolute terms, it wase roughly equivalent to the annual conjunction rate for the entire Iridium constellation. Hence, even though the conjunction rate results in Tab. 1 confirmed a substantial benefit to the PEG constellation arising from an *overall* reduction in the conjunction rate after adopting the 5-year rule, the elements of the PEG constellation below 540 km revealed a significant detriment in the form of highly elevated conjunction rates. Therefore, there is evidence for a double effect associated with LEO post-mission disposal, as suggested in [3]. As Fig. 5 shows, this effect occurs for all post-mission disposal options, even for those with very short residual orbital lifetimes, because reducing the perigee of the BEAD satellites at end-of-life increases the time spent at lower altitudes, as described in [3].

4.1 Analysis

It seems somewhat counter-intuitive that an orbital object decaying in 25 years from 950 km could spend less time at 400 km than the same object decaying in 5 years from 950 km, but this behavior arises because of the shape of the orbits and the effects of atmospheric drag (Fig. 1). In these eccentric disposal orbits, drag removes orbital energy predominantly at the perigee resulting in a greater rate of change of altitude at the apogee than at the perigee. Consequently, the perigee altitude remains relatively constant for a substantial proportion of the remaining lifetime even while the orbit is circularizing (e.g., see Fig. 6). In the simulations, when the initial perigee altitudes of the BEAD satellites were relatively high, the satellites did not reach the PEG altitudes until much of the circularization had occurred, at which point the decay was rapid, leading to short traversal times through the PEG constellation shells and few conjunctions. Conversely, when the initial BEAD perigee altitudes were close to the PEG altitudes, then the BEAD disposal orbits tended to overlap the PEG altitudes for a substantial proportion of the disposal lifetime, leading to long traversal times and many conjunctions.

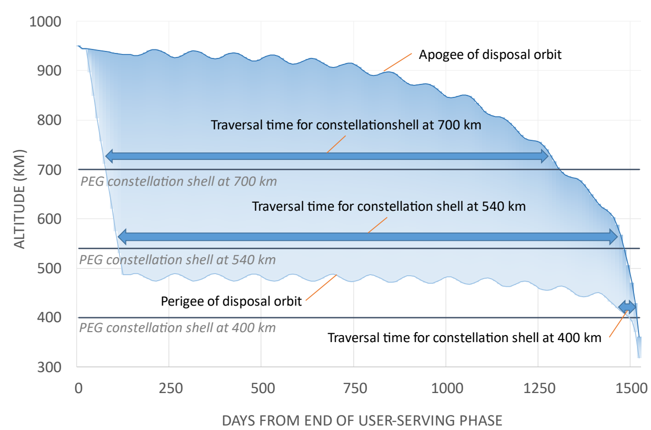

Fig. 6. Illustration of PEG constellation traversal times for a BEAD satellite implementing a 5-year rule.

5 Conclusions

Using the DAMAGE model and a simulation inspired by a Galton board, a range of post-mission disposal options was investigated, with a particular focus on an evaluation of the 25-year rule introduced by the IADC and the new 5-year rule from the FCC. Given a choice between these two options, the simulation results provide a compelling rationale for the 5-year rule, as this reduced the overall conjunction rate across the 320-700 km altitude range, although shorter residual lifetimes offered greater benefits. However, as per expectations from previous studies, adoption of a 5-year rule enhanced conjunction rates by more than an order of magnitude at altitudes coincident with the initial perigee altitudes of the disposal orbits. Analogous enhancements existed for all disposal options, to a greater or lesser degree. Hence, the choice of a post-mission disposal option is equivalent to the “trolley problem”, whereby some harm must be permitted to enable the benefits. This outcome may be justified by the principle of double effect if further work is undertaken to fully evaluate the trade-off, or other solutions may be investigated. For example, a scenario not included in the study would consider the use of circular rather than eccentric disposal orbits, as these may enable quicker traversals through all altitudes. However, circular disposal orbits would also tend to result in regions with a higher number and spatial density of derelict objects, compared with eccentric disposal orbits, as well as having greater impacts on the mission. Without a clear solution, it remains important to consider the potentially variable rate of decay of a disposal orbit and not just the overall time taken to decay. Additionally, consideration should be given to the real-world, non-uniform distribution of satellites and debris in the 320-700 km range to ensure the initial perigee altitudes of disposal orbits are not coincident with regions with high numbers of satellites (e.g., Starlink and Flock at approximately 550 km or Kuiper at approximately 600 km).

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