SYNERGY OF DEBRIS MITIGATION AND REMOVAL

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ABSTRACT

At the beginning of the twenty-first century there was considerable effort made using evolutionary models to assess the effectiveness of post-mission disposal (PMD) and other mitigation measures to stabilise the growth of the debris population in low Earth orbit (LEO). Subsequently, this activity led to the recommendation of a “25-year rule” for the post-mission disposal of spacecraft and orbital stages intersecting the LEO region. At the time, it was anticipated that the 25-year rule, together with passivation and suppression of mission-related debris, would be sufficient to prevent the continued growth of the LEO debris population. However, in the last decade both the LEO debris environment and the debris modelling capability have seen significant changes. In particular, recent population growth has been driven by a number of major break-ups, including the intentional destruction of the Fengyun-1C spacecraft and the collision between Iridium 33 and Cosmos 2251. State-of-the-art evolutionary models now indicate that mitigation measures alone are insufficient to stabilise the LEO debris population. Consequently, this has led to considerable interest in the remediation of the debris environment and, especially, in debris removal. Yet there is a reluctance to revisit the role of PMD within the wider goal of remediation even though it does not provide the solution that was expected. Thus, there is a risk that the approach to remediation will follow a sequential, “over-the-fence” philosophy, which tends to deliver costly, and less than optimal solutions. In this paper, we present a new and large study of debris mitigation and removal using the University of Southampton’s evolutionary model, DAMAGE, together with the latest MASTER model population of objects > 10 cm in LEO. Here, we have employed a concurrent approach to remediation, whereby changes to the PMD rule and the inclusion of other mitigation measures have been considered alongside multiple removal strategies. In this way, we have been able to demonstrate the synergy of these measures and to identify aggregate solutions to the space debris problem. The results suggest that reducing the PMD decay rule offers benefits that include an increase in the effectiveness of debris removal and a corresponding increase in the confidence that these combined measures will lead to the stabilisation of the LEO debris population.

1. INTRODUCTION

Space debris is now understood to represent a significant risk to operational spacecraft due to the collision hazard it represents. As the population of debris continues to grow, the probability of further collisions will consequently increase.

At the beginning of the 21st Century there was considerable effort made using evolutionary models to assess the effectiveness of post-mission disposal (PMD) and other mitigation measures to stabilise the growth of the debris population in low Earth orbit (LEO). Subsequently, this activity led to the recommendation of a “25-year rule” for the post-mission disposal of spacecraft and orbital stages intersecting the LEO region. In 2007, the Inter-Agency Space Debris Coordination Committee (IADC), the inter-governmental forum created to discuss the technical issues associated with space debris, published this 25-year rule within a set of debris mitigation guidelines aimed at reducing debris-related risks (available from http://www.iadc-online.org). Subsequently, the United Nations (UN) General Assembly adopted resolution 62/217, endorsing the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (COPUOS). These voluntary guidelines outline key measures for the planning, design, manufacture and operation of spacecraft and launch vehicles that are encapsulated within seven mitigation guidelines:

1. Limit debris released during normal operations
2. Minimize the potential for break-ups during operational phases
3. Limit the probability of accidental collision in orbit
4. Avoid intentional destruction and other harmful activities
5. Minimize potential for post-mission break-ups resulting from stored energy
6. Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low Earth orbit region after the end of their mission
7. Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous region after the end of their mission

The qualitative, high-level UN COPUOS space debris mitigation guidelines follow the more detailed and technical IADC guidelines. Broadly speaking, the first five guidelines are aimed at preventing the generation of debris in the short-term, whereas the last two guidelines focus on reducing debris generation in the long-term by limiting the lifetime of defunct spacecraft and launch vehicle stages in key altitude regimes used by operational spacecraft. For example, the penultimate guideline is the ‘higher-level’ version of the so-called, 25-year rule.

Based on the results of computer simulations conducted ten years ago, it was anticipated that the 25-year rule, together with passivation and suppression of mission-related debris, would be sufficient to prevent the continued growth of the LEO debris population. However, the LEO population has changed significantly in the last decade, with growth driven by a number of major break-ups, including the intentional destruction of the Fengyun-1C spacecraft and the collision between Iridium 33 and Cosmos 2251. In addition, the computer codes used to make such long-term, future projections of the debris environment have progressed beyond their 20th Century counterparts. Simulations conducted in the last four years using these new codes have suggested that the current debris population in LEO has reached a sufficient density at some altitudes for collision activity there to continue even in the absence of new launches [1]. The rate at which new debris is generated by these collisions will likely exceed the rate at which it is removed by atmospheric decay, leading to a net growth of the space debris population in LEO. Whilst the debris mitigation measures described above will help to limit the rate of growth, spacecraft will continue to be launched and major, unexpected break-ups will continue to occur.

There is a reluctance to revisit the 25-year PMD rule even though it does not provide the solution that was expected when it was first introduced. This reluctance stems, in part, from the adoption of the 25-year rule (or similar) within national standards and regulations, and the momentum that has been established by the compliance of satellite operators. Instead, substantial interest has been shown in the remediation of the debris environment and, especially, in debris removal. Concepts for the removal of large, intact objects from critical altitudes, where high levels of collision activity are expected, are now being considered to stabilize the population growth.

Simulations of Active Debris Removal (ADR) have demonstrated, in principle, that the LEO debris population can be stabilized by the removal of a relatively few, selected debris targets in addition to the widespread adoption of mitigation guidelines [2][3]. However, if the limitations of post-mission disposal are overlooked there is a risk that the approach to mitigation and remediation will follow a sequential, "over-the-fence" philosophy, which tends to deliver costly, and less than optimal solutions.

In this paper, we present a new and large study of debris mitigation and removal using the University of Southampton's evolutionary model, the Debris Analysis and Monitoring Architecture for the Geosynchronous Environment (DAMAGE), together with the latest Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model population of objects > 10 cm in LEO. Here, we have employed a concurrent approach to mitigation and remediation, whereby changes to the PMD rule and the inclusion of other mitigation measures have been considered alongside multiple removal strategies.

2. THE DAMAGE MODEL

The DAMAGE debris model is a three-dimensional computational model of the full LEO to GEO debris environment. It is supported by a fast, semi-analytical orbital propagator, a breakup model and a fast, pair-wise collision prediction algorithm based on the 'Cube' approach adopted in NASA's LEO-to-GEO Environment Debris model (LEGEND) [4]. Projections into the future of the debris population ≥ 10 cm are performed using a Monte Carlo (MC) approach to account for stochastic elements within the model and to establish reliable statistics.

Within this collision risk algorithm in DAMAGE, the collision probability of an object i with a second object j in a small cubic volume element dU over a short time interval dt is computed as [5]

$$dP_{i,j}(t) = s_i s_j v_{ij} \sigma \, dU \, dt \,, \tag{1}$$

where s_i and s_j are the residential probabilities (also spatial densities) of objects i and j in the cube dU, v_{ij} is the velocity of object j relative to object i, and σ is the combined cross-sectional area of both objects measured in a plane normal to the relative velocity. The integration of (1) for all objects $j \neq i$ over a relatively long projection period (e.g. decades or centuries), and over the volume of near-Earth space provides an estimate of the cumulative collision probability, $P_{i,j}(t)$, for objects i and j. In practice, $dP_{i,j}(t)$ is calculated at discrete time intervals only for cases where two objects occupy the same cubic volume element. A uniformly distributed random number is generated and compared with $dP_{i,j}(t)$ to determine whether a collision between objects i and j at time t actually occurs. If so, DAMAGE makes use of the NASA Standard breakup model [6] to generate fragmentation debris.

[INSERT FIG.1 ABOUT HERE]

The semi-analytical propagator in DAMAGE includes orbital perturbations due to Earth gravity harmonics, J_2, J_3, and $J_{2,2}$, luni-solar gravitational perturbations, solar radiation pressure and atmospheric drag. The drag model assumes a rotating, oblate atmosphere with density and density scale height values taken from the 1972 COSPAR International Reference Atmosphere (CIRA). Projected solar activity is described in DAMAGE using the pseudo-sinusoidal model in fig. 1.

3. INITIAL POPULATION AND LAUNCH DATA

The population of debris ≥10 cm residing or passing through the LEO regime on 1 May 2009 was used as the initial reference population. These objects were derived from the MASTER 2009 reference population. Whilst being part of the MASTER population, objects assumed to have been generated by the de-lamination of multi-layer insulation or fragmentation and having high area-to-mass ratios were excluded. In addition, an eight-year traffic cycle, based on launches from 2001 to 2009, was used to generate future launch traffic.

4. METHOD

A 200-year future projection from 1 May 2009 was used by DAMAGE as the basic scenario for this investigation (Table 1). This scenario incorporated key elements of the UN COPUOS and IADC space debris mitigation guidelines, including post-mission disposal to limit the lifetime of spacecraft and launch vehicle orbital stages in the LEO region. These objects were moved to decay orbits with remaining lifetimes of either 25, 20, 15, 10, 5 or 0 years, or LEO storage orbits (above LEO) depending on the delta-v. As the storage orbits were above LEO, objects placed here were no longer processed in the simulation. PMD measures were implemented from the start of the future projection and were applied to 90% of all eligible objects. In addition to the PMD measures, it was assumed that no explosions occurred during operational phases, and all spacecraft and upper stages were passivated at end of mission. That is, no explosive break-ups occurred in the projection period. Further, some intact objects not already subject to PMD measures were removed through the implementation of ADR at a rate of either 1, 2, 3, 4 or 5 objects per year, starting from the year 2020.

[INSERT TABLE 1 ABOUT HERE]

Intuitively, it makes sense to target objects for ADR based on their contribution to future collision activities. Thus, the probability of an object being involved in a collision, and the number of fragments added to the environment if a collision does occur, are key factors used to define criteria for ADR. For example, [3] used the criterion

$$R_i(t) = m_i \sum_{j \neq i} P_{i,j}(t), \tag{2}$$

to rank objects for removal, where m_i is the mass of object i, which plays an important role in the NASA standard breakup model for determining the number of collision-induced fragments [6]. The estimation of the cumulative probability over all objects $j \neq i$ for use in this removal criterion is made outside the normal environment projection and is achieved using an integration of (1) over 200 ‘snapshots’, at the start of each ADR year. In addition, the following eligibility requirements for removal were used:

1. The object must be intact (i.e. a payload, launch vehicle upper stage or mission-related debris),
2. have an orbital eccentricity < 0.5,

3. have a perigee altitude < 1400 km, and
4. must not already be subject to PMD measures.

The combination of six PMD lifetime ‘rules’ and six, yearly ADR removal rates (including no removals) led to an investigation comprising 36 separate scenarios. In order to minimise computational effort, each study was restricted to 50 MC runs. Each run was performed on a quad-core PC, generating outputs describing the number of objects and the cumulative number of collisions, amongst others.

The growth in the LEO population from 1 May 2009 to 1 May 2209, expressed as a proportion of the initial population, was used as the key metric to understand the effectiveness of the PMD and ADR measures. In addition, the proportion of MC runs demonstrating an increase in population provided a measure of confidence. An Effective Reduction Factor (ERF), introduced by [3], was calculated to quantify the effectiveness of the runs employing ADR, where

$$ERF(t) = \frac{N(t) - N_S(t)}{CN_R(t)}, \tag{3}$$

$N(t)$ is the effective number of objects ≥ 10 cm in the no ADR scenario at time t, $N_S(t)$ is the effective number of objects ≥ 10 cm in the ADR scenario at time t, and $CN_R(t)$ is the cumulative number of objects removed through ADR at time t. The effective number is defined as the fractional time, per orbital period, an object spends in LEO. The ERF quantifies the reduction in the total population for each object removed through ADR. $ERF(t)$ is a function of time and can thus be calculated at any point in the projection period. Here, we report ERF values calculated at the end of the projection period.

5. RESULTS AND ANALYSIS

For simplicity and clarity, the results from the 36 scenarios are presented as surface charts, below, with red indicating a ‘poor’ performance (typically, the lower-left corner of each chart), blue indicating a ‘good’ performance (typically, the upper-right corner) and colours between the two indicating ‘mid-level’ performance.

Fig. 2 shows the growth in the LEO population measured at the end of the projection period (as a percentage of the initial population), with the percentage of MC runs providing a confidence metric (fig. 3). The ‘worst-case’ scenario, featuring a 25-year decay rule and no removals (red line in fig. 4), resulted in an average population of 20,442 objects and a growth of 19.5%, with 78% of the MC runs ending with an increased debris population. As expected, decreasing the PMD rule and/or increasing the yearly ADR removal rate improved the debris environment, such that the ‘best-case’, featuring a 0-year decay rule and five removals per year (blue line in fig. 4), resulted in the debris population shrinking, on average, by 29.8% to 12,009 objects and only 2% of the MC runs ending with a population larger than on 1 May 2009. However, scenarios that did not include ADR consistently demonstrated a population growth in over 72% of the MC runs, regardless of the PMD decay rule employed. ‘Mid-level’ cases typically resulted in a slight increase or slight decrease in the debris population. For example, the scenario featuring a 15-year PMD rule and two removals per year (green line in fig. 4) resulted in an average 1.8% growth to 17,414 objects with the population increasing in 58% of the MC runs.

[INSERT FIG.2 ABOUT HERE]

[INSERT FIG.3 ABOUT HERE]

[INSERT FIG.4 ABOUT HERE]

The results shown in Figs. 2 and 3 reveal:

- The LEO population will continue to grow without ADR even with good compliance with PMD mitigation measures and even if the PMD rule is reduced.

- For a 25-year PMD rule, between three and four removals per year are required to prevent the growth of the LEO debris population. For a 90% confidence-level (i.e. 90% of MC runs showing a decrease in the LEO debris population) more than five removals per year are required.
- The growth of the LEO debris population can be prevented with 90% confidence by as few as two removals per year, if the PMD rule is lowered from 25-years.
- On average, a reduction in the PMD rule by 5.7 years has an effect equivalent to removing one object through ADR.

The total number of ‘critical’, catastrophic and non-catastrophic collisions generating fragments ≥10 cm is shown in fig. 5, for each scenario. Here, there is a consistent, beneficial effect of PMD and ADR, such that for a reduction of the PMD rule by one year there is a corresponding decrease, by 0.53 on average, and for every object removed by ADR there is a corresponding decrease, by 2.94 on average, in the number of critical collisions. In other words, moving to the right, or moving up, by one grid cell in fig. 5, has approximately the same effect in terms of reducing the number of critical collisions. In absolute terms, the ‘worst-case’ scenario resulted in an average of 50.2 fragment-generating collisions, compared with an average of 23.4 in the ‘best-case’ scenario.

[INSERT FIG. 5 ABOUT HERE]

Fig. 6 shows the impact of different ADR removal rates on the ERF, for each of the PMD decay rules. In-line with previous results, the ERF values demonstrate that a greater benefit is obtained for the first object removed, compared with subsequent removals. This arises because objects are ranked according to their contribution to the future collision environment (2), with the first object removed contributing the greatest risk (and, therefore, resulting in the greatest benefit once removed from the environment). Thus, the most ‘cost-effective’ ADR scenarios are characterised by relatively few removals per year. From the 36 scenarios studies, the highest ERF value (16.7) was obtained for one removal per year, and a PMD decay rule of five years. This scenario resulted in the LEO population shrinking by 6.1% (although 26% of the MC runs resulted in a population growth). The lowest

ERF value (5.7) was obtained for five removals per year and a 25-year PMD decay rule. Here, the LEO population decreased by an average 12.1% (with only 18% of the MC runs showing an overall growth).

[INSERT FIG.6 ABOUT HERE]

If the ERF results are presented as a function of the PMD decay rule (fig. 7) then an important synergistic effect emerges. That is, the effectiveness of ADR is enhanced by reducing the PMD rule from 25-years. The effect is most pronounced for fewer removals and is in addition to the benefit obtained by reducing the lifetime of intact objects by lowering the PMD decay rule alone. For example, the ERF for a removal rate of one object per year was found to be 2.64 times greater for a 5-year PMD rule (*ERF* = 16.7) compared with a 25-year rule (*ERF* = 6.3). This means that for every object removed through ADR at this rate, the population at the end of the projection was reduced by a further 10.3 objects by limiting the time spent by spacecraft and rocket bodies in the LEO region to five years after the end of their operational life.

[INSERT FIG.7 ABOUT HERE]

The synergistic effect remains when the ERF values are averaged over all the removal rates considered in this study (fig. 8). On average, the ADR ERF for a 0-year PMD rule was found to be 9.35, and 1.43 times greater than the value for a 25-year PMD rule (*ERF* = 6.56). Using linear regression, applied to the data in fig. 8, we find that the average ADR ERF increases by 0.124 for each reduction in the PMD decay rule of one year (correlation coefficient = 0.79).

[INSERT FIG.8 ABOUT HERE]

If a target-based approach is taken, whereby the aim is to stabilise the LEO population such that there is no net growth over the projection period, for example, then the synergistic effect allows the target to be met in a cost-effective manner by reducing the PMD rule and cutting the ADR removal rate to one or two objects per year. There is, of course, a cost involved in reducing the PMD rule, in terms of additional propellant required to lower the perigee of the decay orbit. However, the simulation results suggest that increasing the delta-v by 10% from the level required for the 25-year rule would be sufficient to reduce the decay orbit lifetime to five years, on average. An increase of 45% in delta-v would be sufficient to achieve a 0-year rule. A greater increase in delta-v may be required for some cases.

6. DISCUSSION

In absolute terms, the results presented above are, of course, dependent upon the assumptions made about future traffic and the future solar flux, amongst other factors, as well as the methods used within the DAMAGE model and the number of MC runs used. For example, lower solar activity in the future would lead to an increased rate of growth whereas higher solar activity would result in slower growth, or even a decline in the LEO debris population. However, it is anticipated that the relative differences between the scenarios and the overall trends would remain irrespective of these assumptions. That is, reducing the PMD rule and increasing the rate at which objects are removed from the environment will lead to greater benefits, in terms of reducing the hazards posed by space debris. In addition, whilst these results suggest that a 25-year PMD rule is no longer sufficient to constrain the future debris population growth, and that reducing the PMD lifetime provides increasing benefits with respect to ADR, the widespread adoption of this mitigation measure does have a substantial, positive effect on the debris environment. The “25-year rule” is an integral component of space debris mitigation guidelines that work to prevent a much more significant growth of the debris population, as seen in previous “business-as-usual” simulation results. As such, it is important to maintain, and even improve, compliance with this measure.

The emergence of a synergy between this key mitigation practice and ADR does, however, lead to a recommendation that proposals aimed at the remediation of the debris environment should also take account of debris mitigation measures and address both in a holistic fashion. This approach would avoid the sequential and individual optimisation of mitigation and remediation practices, which may lead to a sub-optimal and costly solution when aggregated into an overall mitigation-remediation package. In practice, there are many challenges, including legal and political, which would need to be addressed in order for such a holistic approach to be successful.

The results from this initial effort to demonstrate and investigate a holistic approach provide some evidence that a range of aggregate solutions are possible, each providing similar and desirable outcomes. For example, a scenario featuring a 25-year rule and four removals per year, and a scenario featuring a 5-year rule and two removals per year, are equivalent in terms of constraining the LEO population growth (both show a ~10% reduction in the number of objects) and the confidence level (~75% of the MC runs from both scenarios show a population decline). This adaptability – to adjust mitigation and remediation practices and still achieve the desired goal – may offer some resilience if future unanticipated changes in the environment (such as major fragmentation events or a change in thermospheric density [7]), modelling capability or technology innovations (such as advances in propulsion), for example, should occur.

7. CONCLUSIONS

Using the University of Southampton’s debris model, DAMAGE, a new, concurrent approach to remediation has been simulated, whereby changes to the PMD rule and the inclusion of other mitigation measures have been considered alongside multiple removal strategies. The results from 36 separate scenarios have demonstrated the synergy of these measures and identified common, aggregate solutions to the space debris problem. Through this synergistic effect, the effectiveness of ADR (as measured by the ERF) is improved by 0.124, on average, for every year removed from the PMD decay “rule”. The results also show that reducing the PMD decay rule and/or increasing the rate at which objects are removed from the environment increases the confidence that these combined measures will lead to the stabilisation of the LEO debris population. Further work, within the European Union Framework 7 Alignment of Capability and Capacity for the Objective of Reducing Debris (ACCORD) project, will seek to identify and quantify other synergies that may exist within commonly adopted space debris mitigation guidelines.

Due to the emergence of this synergy, it is recommended that remediation proposals, such as active debris removal, are considered in conjunction with existing mitigation practices, such that optimal guidelines and measures can be identified in a holistic fashion. In addition, efforts to improve the resilience of mitigation- and remediation-related guidelines should be considered. The results of this study show that remediation goals can be met through a variety of different approaches, providing the adaptability required for such resilience. However, the challenges related to these recommendations are recognised by the authors and, until they can be addressed, we encourage continued or improved compliance with existing methods to tackle the space debris problem.

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TABLES

Table 1. Description of the basic scenario.

Parameter	**Value**
Projection period	1 May 2009 to 1 May 2209
Traffic model (2009-2209)	Repeat 8-year (2001-2009) launch traffic
Post-mission disposal (2009-2209)	Move spacecraft and rocket bodies to decay orbits (90% success rate and 1 year tolerance)
Active debris removal (2029-2209)	Rank objects according to (2) and remove immediately on 1 January in each ADR year
Future explosions (2009-2209)	No explosions
Time-step	5 days
Minimum object size	10 cm
Collision prediction: cube size	10 km
Manoeuvres	No station-keeping or collision-avoidance

FIGURE CAPTIONS

Fig. 1. F10.7 cm solar flux projection used in DAMAGE.

Fig. 2. Average percentage LEO population growth from 1 May 2009 to 1 May 2209

Fig. 3. Percentage of MC runs showing population growth.

Fig. 4. Effective number of objects in LEO for three mitigation-remediation scenarios.

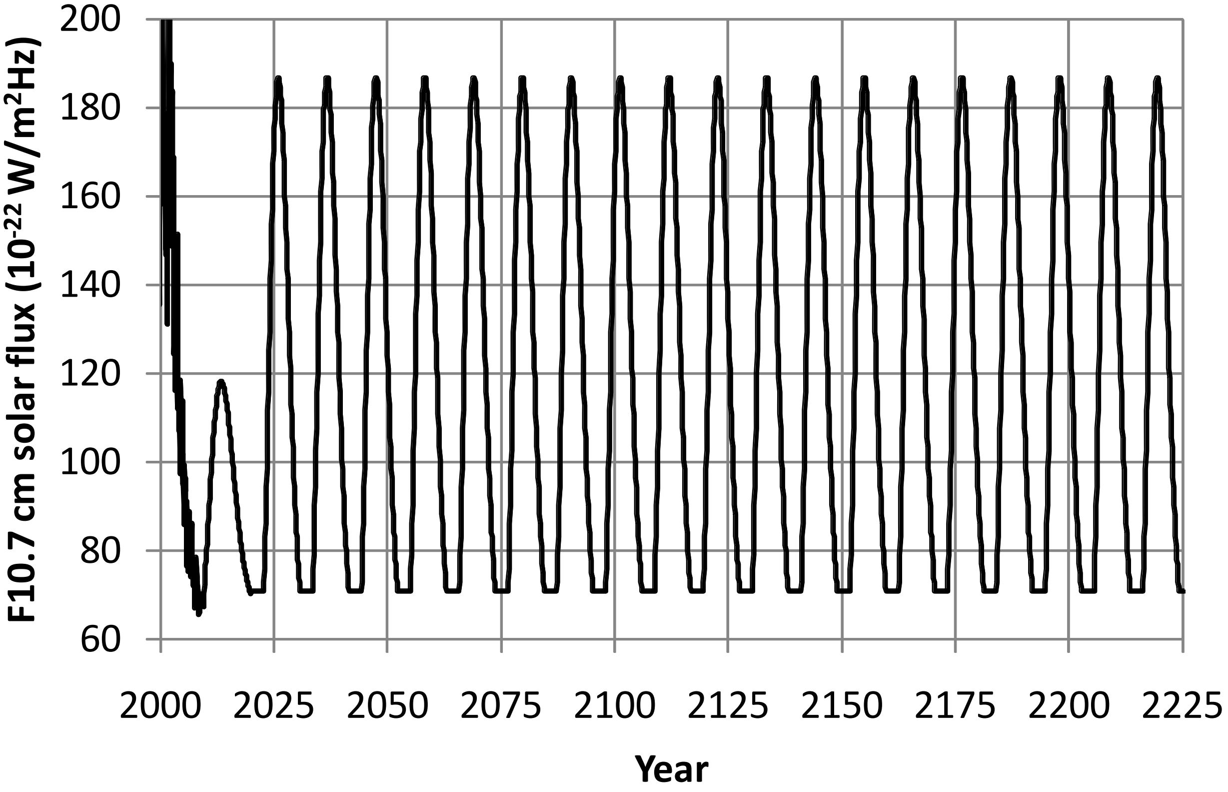
Fig. 5. Number of catastrophic and non-catastrophic collisions generating large fragments in the projection period.

Fig. 6. The impact of different removal rates on the Effective Reduction factor for each PMD decay rule.

Fig. 7. Effective reduction factor as a function of the PMD decay rule

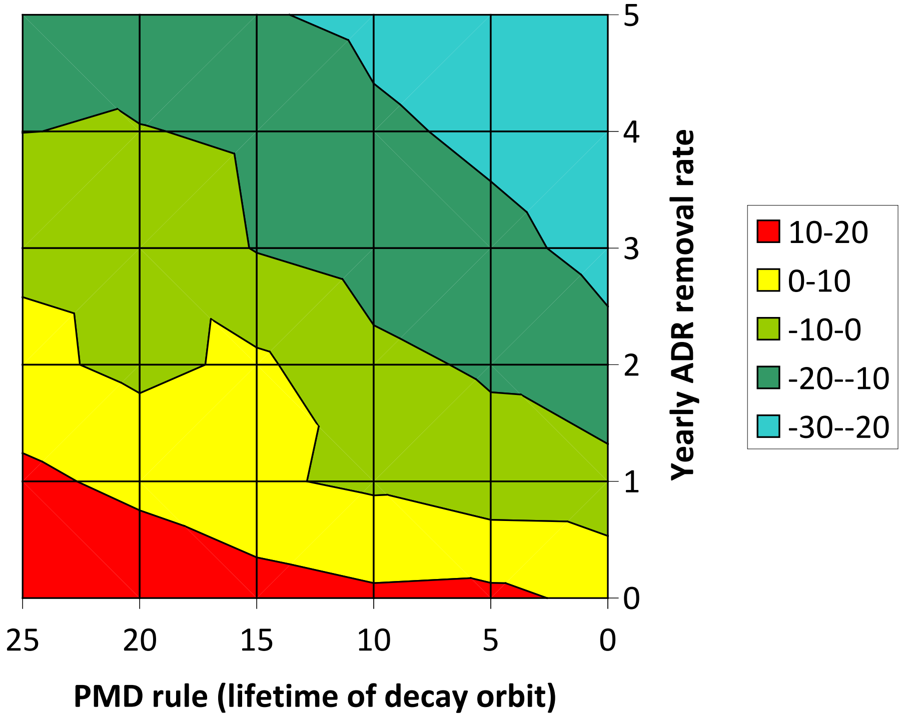
Fig. 8. Synergy of PMD and ADR.

Figure 1



200
180
160
140
120
100
80
60
F10.7 cm solar flux (10^-22 W/m^2Hz)
2000
2025
2050
2075
2100
2125
2150
2175
2200
2225
Year

Figure 2



25
20
15
10
5
0
PMD rule (lifetime of decay orbit)
5
4
3
2
1
0
Yearly ADR removal rate
🟥 10-20
🟨 0-10
🟩 -10-0
🟩 -20--10
🟦 -30--20

Figure 3

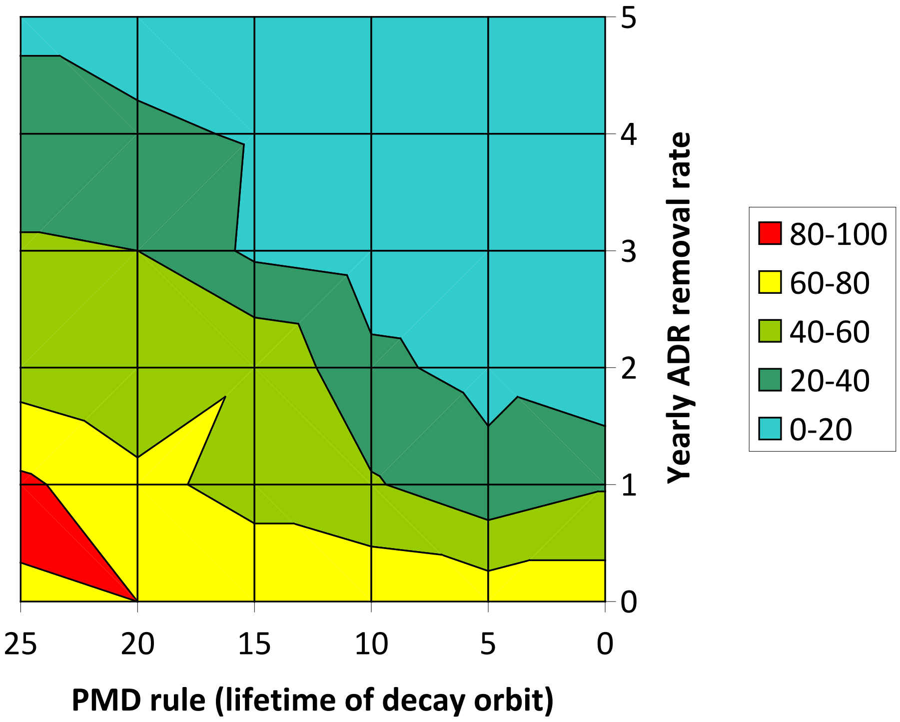

5
4
3
2
1
0
25
20
15
10
5
0
PMD rule (lifetime of decay orbit)
Yearly ADR removal rate
80-100
60-80
40-60
20-40
0-20

Figure 4

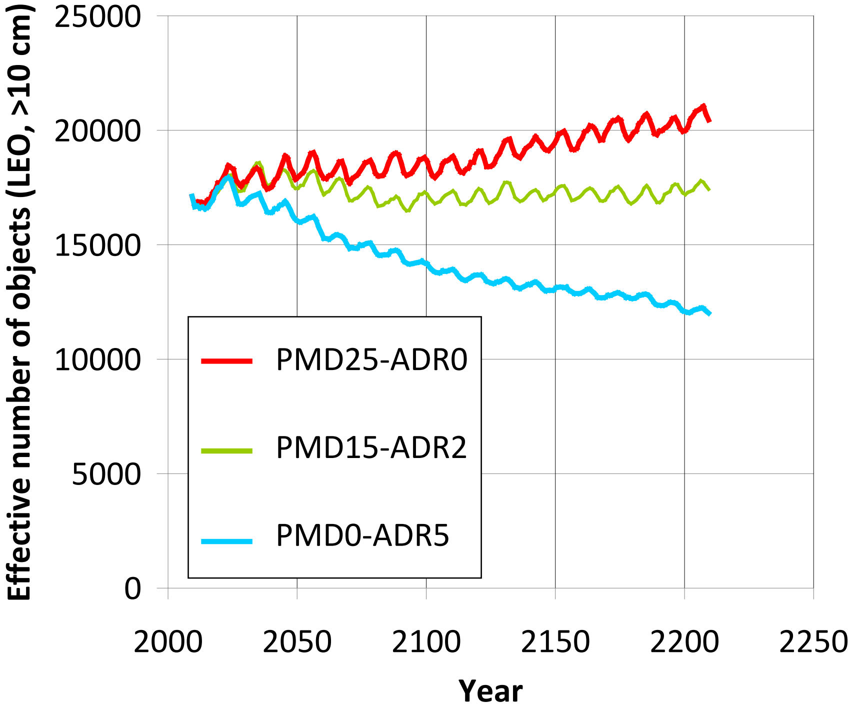
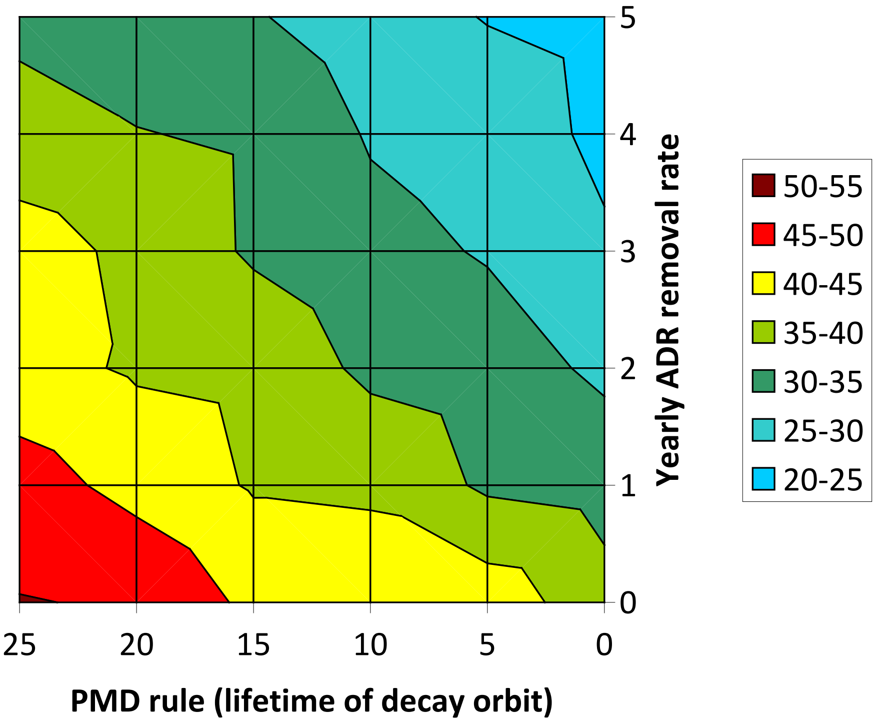
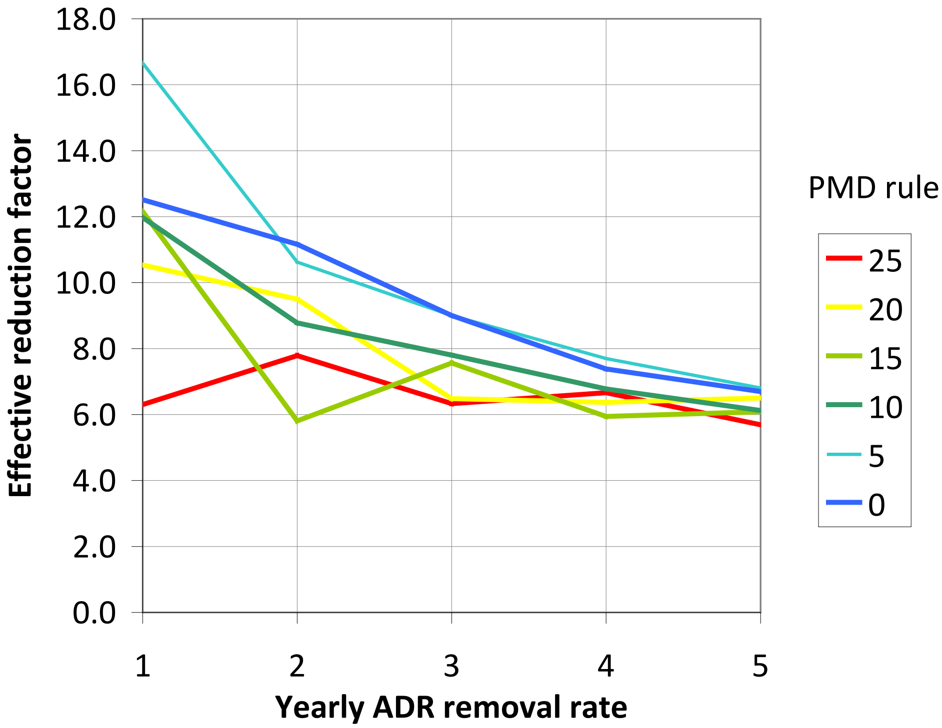

Effective number of objects (LEO, >10 cm)
25000
20000
15000
10000
5000
0
2000
2050
2100
2150
2200
2250
Year
PMD25-ADR0
PMD15-ADR2
PMD0-ADR5

Figure 5



5
4
3
2
1
0
25
20
15
10
5
0
PMD rule (lifetime of decay orbit)
Yearly ADR removal rate
50-55
45-50
40-45
35-40
30-35
25-30
20-25

Figure 6



18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Effective reduction factor
1
2
3
4
5
Yearly ADR removal rate
PMD rule
25
20
15
10
5
0

Figure 7

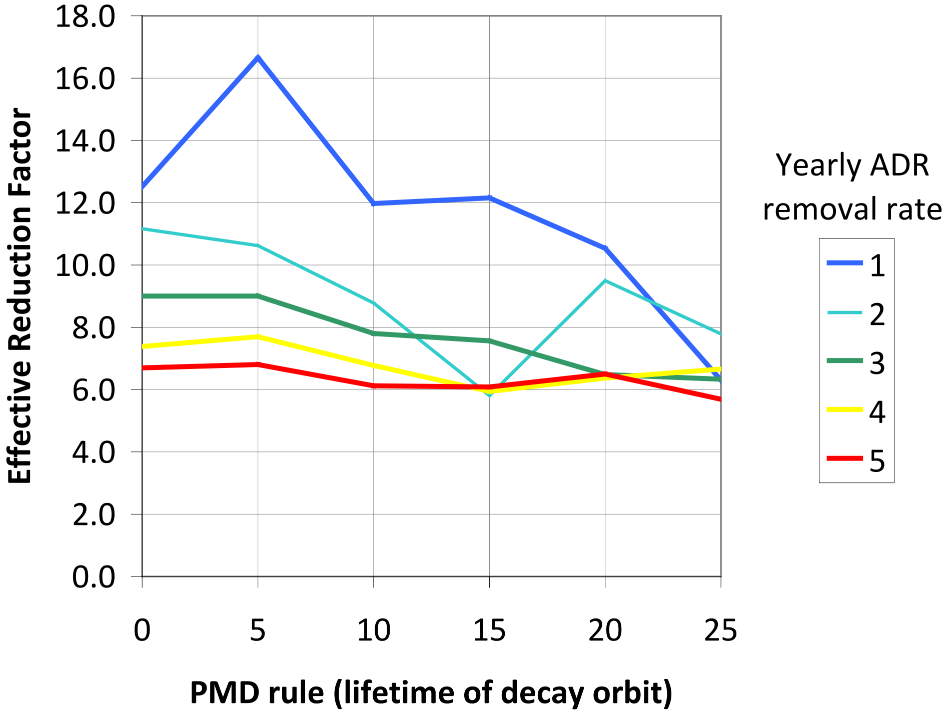
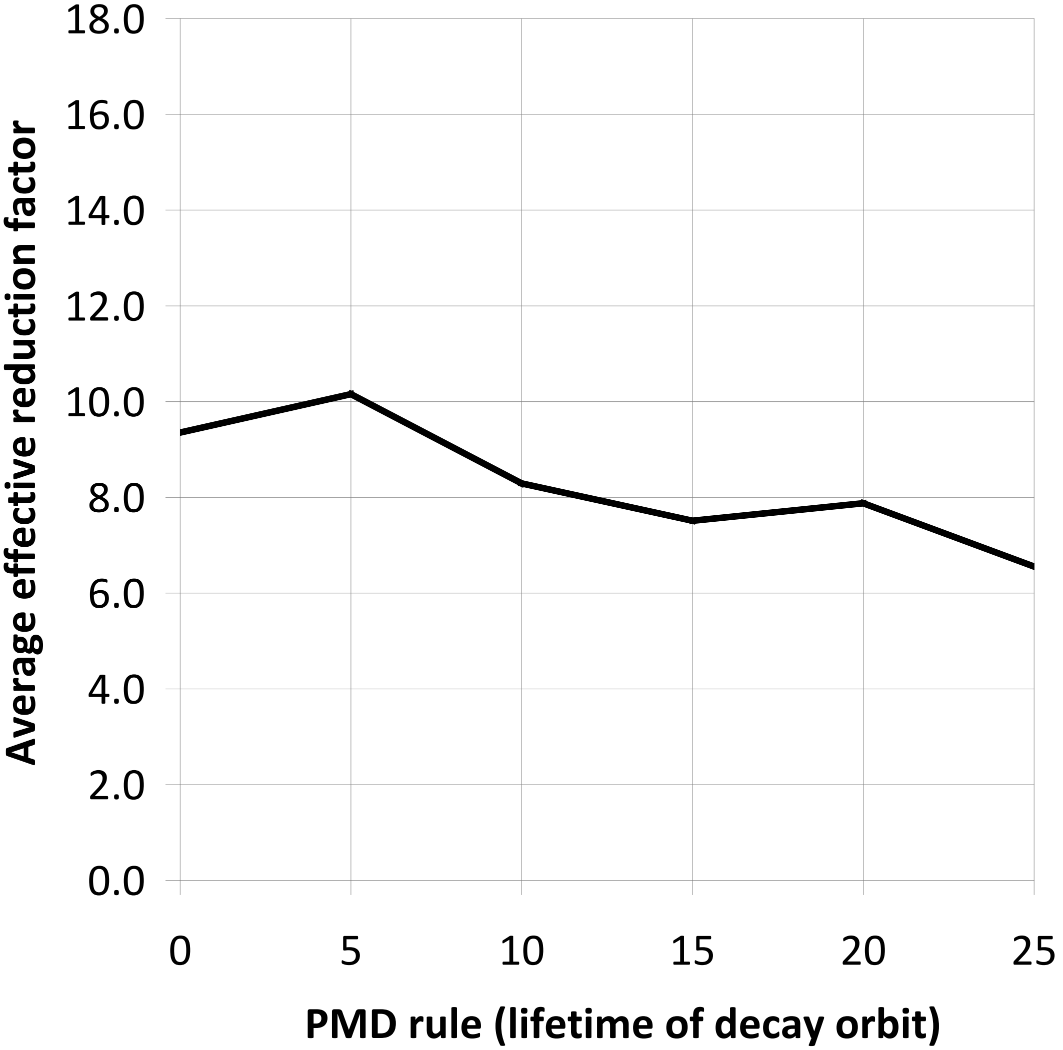

18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Effective Reduction Factor
0
5
10
15
20
25
PMD rule (lifetime of decay orbit)
Yearly ADR removal rate
1
2
3
4
5

Figure 8


18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Average effective reduction factor
0
5
10
15
20
25
PMD rule (lifetime of decay orbit)