QUANTIFYING THE BENEFITS OF ACTIVE DEBRIS REMOVAL IN A RANGE OF SCENARIOS

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ABSTRACT

Long-term space debris modelling studies have suggested that the ≥10 cm low Earth orbit debris population will continue to grow even with the widespread adoption of mitigation measures recommended by the Inter-Agency Space Debris Coordination Committee. However, a number of recent studies have shown that, with additional removal of a small number of debris objects, it is possible to prevent the growth of debris in LEO. These modelling studies were based on assumptions constraining future launch and explosion rates, solar activity and mitigation, amongst others, to a limited number of cases. As a result, the effectiveness of Active Debris Removal (ADR) has only been established and quantified for a narrow range of possible outcomes. Therefore, the potential benefits of ADR, in practice, remain uncertain and there is a need to investigate a wider range of potential future scenarios to help establish ADR requirements.

In this paper, we present results of a study to model and quantify the influence of four essential assumptions on the effectiveness of ADR: (1) launch activity, (2) explosion activity, (3) solar activity and (4) compliance with post-mission disposal. Each assumption is given a realistic range based upon historic worst-case data and an optimistic best-case. Using the University of Southampton's Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) tool, these assumptions were modelled randomly from their permitted range in Monte Carlo projections from 2009 to 2209 of the ≥5 cm LEO debris environment. In addition, two yearly ADR rates were investigated: five and ten objects per year.

The results show an increase in the variance of the mean LEO debris population at the 2209 epoch. The uncertainty is such that, in some cases, ADR was not sufficient to prevent the long-term growth of the population, whilst in others ADR is not required to prevent population growth.

1. INTRODUCTION

Space debris represents a significant collision risk to operational satellites as well as a threat to the long-term sustainability of outer space activities. Guidelines, practices, codes of conduct, and standards have been, and are being, developed to limit the expected future growth of the debris population. However, whilst the widespread adoption of mitigation measures, like those outlined in the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines, will restrict this predicted growth, it is unlikely to stop the long-term debris population in low Earth orbit (LEO) from increasing [1]. In fact, some simulation results suggest that the current debris population in LEO has reached a sufficient density at some altitudes for collision activity to continue, even in the absence of new launches [1].

Such results have led to the consideration of Active Debris Removal (ADR) to remediate the debris environment. Modelling of ADR, such as studies by NASA [2] and the International Academy of Astronautics [3], has shown that it may be possible to reduce or stop the growth of the LEO population by removing a select number of target debris objects alongside widespread compliance with IADC guidelines. These studies indicate that a removal rate between 5 [2] and 15 [4] objects per year may be sufficient to stabilise the LEO population ≥10 cm, although

> *"The 'removing five objects per year can stabilize the LEO environment conclusion' is somewhat notional. It is intended to serve as a benchmark for ADR planning."* [5]

These studies typically operate sets of assumptions that constrain the projected future launch and explosion activity, solar activity and mitigation compliance [2][3]. As a result, the effectiveness of ADR has only been quantified for a narrow range of possible futures, thus the effects and benefits of ADR for a wider range of possible futures remain uncertain. There is therefore a need to model these possible futures to help establish ADR requirements in a wider context.

In this work, four assumptions that may lead to uncertainty in long-term LEO debris predictions were investigated. These are as follows launch activity, solar activity, compliance with post-mission disposal (PMD) and explosion activity.

Whilst past simulation studies have investigated variations in these assumptions (e.g. launch activity [6], solar activity [7], PMD compliance [8] and explosion

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activity [9]), none has been considered simultaneously and in conjunction with ADR activities.

To investigate these assumptions, with respect to the effectiveness of ADR, the University of Southampton's evolutionary model, DAMAGE (the Debris Analysis and Monitoring Architecture for the Geosynchronous Environment) was used to simulate the future ≥5 cm LEO space debris population.

All four assumptions were implemented simultaneously; the range of each assumption is derived from historic worst-case data and an optimistic best-case. At the beginning of each Monte Carlo (MC) simulation, four uniformly distributed random numbers are generated. These numbers dictate future launch rate, magnitude of solar activity, compliance with PMD and the future explosion rate for that particular MC simulation. Throughout the MC simulation, the value of each assumption remains fixed. Each simulation contains a different set of future conditions throughout its projection period representing a possible future outcome.

Alongside this, to demonstrate the effectiveness of ADR, two ADR scenarios and a baseline scenario with no ADR were investigated. To capture a wide variety of possible futures 200 MC simulations were projected for each scenario.

2. METHOD

A 200-year future projection from 1May 2009 to 1 May 2209 for the effective LEO space debris population was used by DAMAGE. The description of this study is shown in Tab. 1. Three scenarios were investigated: the removal of five objects a year (**ADR5**), the removal of ten objects a year (**ADR10**) and one scenario with no ADR (**ADR0**). Each scenario is referred henceforth by its acronyms in bold.

2.1 The DAMAGE Model

DAMAGE is a three-dimensional computational model capable of predicting the evolution of the full LEO to GEO space debris environment. It is supported by a fast, semi-analytical orbital propagator, with a time step of five days, which includes orbital perturbations due to Earth gravity harmonics, $J2$, $J3$, and $J2,2$, 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.

Collisions are predicted using a fast, pair-wise collision prediction algorithm based on the 'Cube' approach adopted in NASA's LEO-to-GEO Environment Debris (LEGEND) model [10]. The cube size for this collision prediction was 10 km^3. The NASA standard break-up model [11] is applied when collisions and explosions are detected. Catastrophic collisions occurred when the specific impact energy between two objects exceeded 40 J/g.

Projections into the future are performed using a MC approach to account for stochastic elements within the model.

2.2 Population Size

The majority of recent long-term modelling studies have considered only objects sized ≥10 cm. Such objects are, for the most part, well observed and tracked in LEO and represent approximately 98% of the total mass in orbit. Further, fragmentation events between objects ≥10 cm typically result in catastrophic breakups that lead to the generation of a high number of additional fragments. Whereas collisions between smaller objects are less likely to generate significant numbers of fragments that globally affect the evolution of the debris environment. Limiting consideration to this size regime restricts the number of propagated objects to the tens of thousands, thus allowing reasonable computational times.

This study simulates the LEO population ≥5 cm, allowing approximately twice the number of object to be propagated allowing a greater number of object interactions. The Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) 2009 reference population for the ≥5 cm regime was used as the initial population of debris residing in (or passing through) the LEO regime on 1 May 2009. Whilst included in the baseline 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.

Table 1. Summary description of the study.

Parameter	Value
Initial population	≥5 cm MASTER-2009 population
Sources included	Satellites, rocket bodies, mission related debris, explosive and collision fragments
Sources excluded	Reusable launch systems, space stations, new solid rocket motor slag (Al_2O_3), new sodium potassium droplets (NaK), ejecta and paint flakes
Satellites	The operational lifetime of satellites was set to eight years, no station keeping or collision avoidance manoeuvres occurred
Post-mission disposal	Spacecraft and rocket bodies are moved to orbits that decay within 25 years (1-year tolerance) or re-orbited above LEO and taken out of the simulation

2.3 Launch Activity

The number and position of future launches is an essential component to the future collision rate and the evolution of the debris environment [6]. Predicting the number, size and position of future launches is a source of uncertainty that depends upon future demand, mission requirements, technologies, politics and economics. Two approaches to simulating future launch activity have been used by debris models, repeatable launch traffic cycles based on historical launch data or mission-based models that estimate the future trends of space and technology.

In this study, the maximum (129) and minimum (36) yearly launch rates of the last 50 years (1962-2012) were used to define the boundaries of the possible future rates. A uniformly distributed random number between zero and one, $X_L = U(0,1)$, was generated for each MC simulation. The yearly launch rate, L, was then found using

$$L = 36 + 94X_L \quad (1)$$

where 94 is the range between the maximum and minimum launch rates. The launch rate was rounded down to the nearest integer and remains fixed for the simulation, and the process is repeated for each subsequent simulation.

Fig. 1 illustrates the possible launch rates for each simulation (shaded region), bounded by the minimum and maximum launch rates for each simulation (solid line). The dotted line shows the historic launch rate.

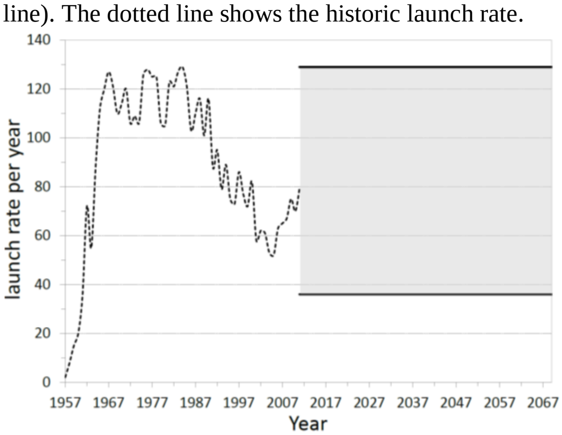

Figure 1. Historic (dotted line) and possible future launch rates for this study (shaded region).

Launch statistics and information was acquired from ESA's Database and Information System Characterising Objects in Space. The initial orbital elements, mass, area and size of launched objects was fitted to the same distribution of the last eight complete years of launches (2004-2012).
This then reflects the current trend of launch activities.

2.4 Solar Activity

The variance in solar activity drives the upper atmospheric density and influences the lifetime of debris. Solar irradiance, especially at ultraviolet wavelengths, is a key driver of mass density change in the thermosphere. The F10.7 cm radio flux values (or F10.7) are often used to link solar activity and upper atmospheric density. Studies, such as [7], have shown the interaction between the space debris population and solar activity.

Here the maximum solar amplitude was varied. The minimum F10.7 value and the duration of each solar cycle remained fixed. This maximum F10.7 cm amplitude, F, was derived from the peak F10.7 values for the last 50 complete years. This varied between the highest peak ,260 10^{-22} W m^{-2} Hz^{-1}, and the lowest peak, 148 10^{-22} W m^{-2} Hz^{-1}. This information was obtained through the National Oceanic and Atmospheric Administration National Geophysical Data Centre.

A uniformly distributed random number, $X_s = U(0,1)$, determined the maximum F10.7 value for each simulation

$$F = 148 + 112\, X_s \quad (2)$$

Fig. 2 shows this; the dotted line shows the monthly historical F10.7 cm values from 1957-2012. From 2013, the shaded region indicates the possible solar cycles. Solid lines show the boundaries of these cycles.

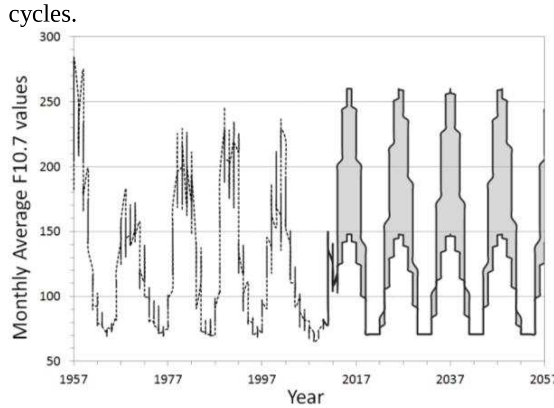

Figure 2. Historic (dotted line) and possible future monthly F10.7 values for the study (shaded region).

2.5 Compliance with Post-mission Disposal

The effectiveness of PMD has been demonstrated ([9]) since the development of mitigation measures. Some recent studies have used a 90% PMD compliance with the '25-year rule in LEO [2][3]. However, based on early data, in 2010 less than 14% of spacecraft reaching their end-of-life in the critical altitudes of 600-1,400 km reduced their altitude to comply with IADC guidelines. Since the completion of this work this value of 14% has been re-evaluated to 8% [12].

In the current study, the compliance with PMD was set between 14-90% for rocket bodies and satellites. This reflects the compliance in 2010 and an optimistic future case. The fraction of objects complying with PMD, P, for each simulation is calculated using a uniformly distributed random number, $X_p = U(0,1)$ such that

$$P = 0.14 + 0.76X_P \tag{3}$$

this value remained fixed for the duration of the simulation, until the process was repeated. To comply with PMD objects were re-orbited to orbits that decay within 25 years (1-year tolerance) or re-orbited above LEO and taken out of the simulation.

2.6 Explosion Activity

Like PMD, the effect of passivation on the long-term debris population has been well-documented [9]. To model the variation in explosion activity, the highest (4 explosions) and the lowest (no explosions) yearly observed explosion rate were taken from the past 50 years. A uniformly distributed random number, $X_E = U(0,1)$, determines the yearly explosion rate, E, between these two values

$$E = 0 + 5X_E \tag{4}$$

the explosion rate was rounded down to the nearest integer and remained fixed for the simulation.

2.7 Active Debris Removal

The ADR target selection used by DAMAGE, $R_i(t)$, implemented by [11], was

$$R_i(t) = P_i(t) \times m_i \tag{5}$$

where m_i is the mass of object i and $P_i(t)$ is the total collision probability of object i a specific time t. Objects with the highest mass-collision probability were removed at the beginning of each year after 2020. As well as this criterion, the object to be removed must be intact, removed immediately from the simulation, have an orbital eccentricity < 0.5 and perigee altitude < 1,400 km.

2.8 Performance Metrics

An Effective Reduction Factor (ERF) [11], was calculated to quantify the effectiveness of ADR. The ERF is defined as the number of debris objects reduced in the environment over a period t using ADR divided the number of removed objects

$$ERF(t) = \frac{N(t) - N_s(t)}{CN_R(t)} \tag{6}$$

where $N(t)$ is the effective number of objects ≥ 10 cm in a scenario with no ADR, $N_s(t)$ is the effective number of objects ≥ 10 cm for an ADR scenario, and $CN_R(t)$ is the cumulative number of objects removed for the ADR scenario. The ERF was measured as the end of the simulation.

The LEO population ≥5 cm, as well as the cumulative number of collisions (catastrophic and non-catastrophic) was recorded and analysed for each MC simulation.

3. RESULTS

Fig. 3 displays a histogram of all individual MC simulations LEO debris population ≥5 cm after 200 years. Each bin, of size 5,000 objects, represents the number of MC simulations that had a particular debris population at 2209. This therefore illustrates the distribution of debris populations for each scenario.

For each removal scenario, the debris population after 200 years varied by almost a factor of ten. The shaded portion of this figure indicates all simulations where the population had grown in comparison to the initial population (expressed as a percentage in Tab. 2). It is clear from Fig. 3 and Tab. 2 that introducing ADR (or increasing the removal rate), on average, reduces the population. However, doubling the removal rate (from five to ten objects a year) has a diminishing return of effectiveness; as demonstrated by the ERF values in Tab. 2.

Table 2. Summary of average results for each scenario at the end of the 200 year simulation for objects ≥5 cm.

Scenario	Percentage of MCs pop. > initial pop.	Avg. ERF	Mean pop.	Median pop.	Standard Dev. of pop.	Avg. Cum. Number of collisions	Avg. Proportion of collisions that are Non-catastrophic		Catastrophic	
							<10 cm	≥10 cm	<10 cm	≥10 cm
ADR0	70	-	48,364	45,389	16,703	77.6	40.7%	24.9%	4.5%	29.9%
ADR5	51	18.3	30,844	29,919	11,367	40.3	38.9%	18.9%	5.5%	36.5%
ADR10	32	11.9	25,697	24,683	10,817	31.3	38.4%	19.3%	5.7%	36.5%

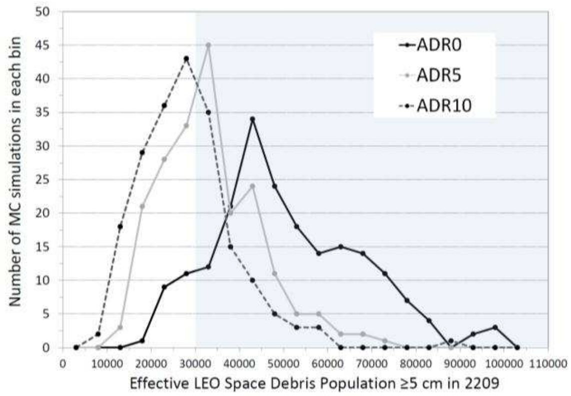

Figure 3. Histograms of the effective LEO debris population ≥5 cm of each MC after 200 years. Bin size equal to 5,000 objects.

The overlap of histograms in Fig. 3 shows where two or more scenarios have given the same result. All scenarios have a considerable overlap indicating that, introducing or increasing ADR has not had any additional benefit. The overlaps between scenarios were as follows, 52% overlap between ADR5 and ADR0, 36% overlap between ADR10 and ADR0 and ADR5 overlaps between ADR10 by 58%.

The distribution of debris populations after 200 years in Fig. 4 fits a log-normal distribution. Using the data in Fig. 4, a log-normal probability density function as a function of total number of objects, $f(N_t)$, can be estimated as

$$f(N_t) = a \times e^{-\frac{\left(\frac{ln(N_t)-b}{c}\right)^2}{2}} \tag{7}$$

where a, b and c are coefficients of the distribution for a bin size of 5,000 objects. These coefficients for all three scenarios in addition to all three scenarios combined are shown in Tab. 3. The coefficient of determination (R^2), indicating the fit of each distribution as well as the statistics of each distribution is also shown.

To give an indication of the effect each assumption and the removal rate has on the total number of objects multiple linear regression was used. The total number of objects ≥5 cm after a 200 year projection, N_t, can be approximated as

$$N_t = k_1 + k_2 L + \ k_3 F + k_4 P + k_5 E + k_6 N_R \tag{8}$$

N_R is equal to the number of objects removed by ADR each year. Each assumption (launch traffic, solar activity etc.) has been normalised to enable the coefficients of multiple linear regression, k_1 through k_6, to show the population difference between the worst and best-case (Tab. 3). This type of analysis is a coarse estimation of the total number of objects, as it assumes each variable is independent and linear and no other factors that contribute to the population. The effect of PMD compliance however will be dependent upon the launch activity. Yet, R^2 values associated with these regressions (Tab. 3) show a reasonable fit, good enough to approximate the effect of each assumption.

3.1 Comparing the <10 cm and ≥10 cm Populations

The average effective LEO debris populations for each scenario (i.e. the arithmetic average of 200 MC simulations per scenario) is presented in Fig. 4 for both ≥10 and ≥5 cm. ADR has a much greater effect at reducing the number of objects between 5-10 cm compared with ≥10 cm.

Whilst removing five objects a year stabilises or reduces 83% of MC simulations for objects ≥10 cm, only 49% of simulations for objects ≥5 cm were stabilised. Similarly, removing ten objects stabilises 94% of simulations for objects ≥10 cm and 68% for objects ≥5 cm.

Table 3. Coefficients of log-normal distributions for objects ≥5 cm, their correlation coefficients and statistics.

	a	b	c	R^2	Mean	Mode	Median	Standard dev.
ADR0	0.13	10.69	-0.34	0.88	46,528	39,120	43,915	16,288
ADR5	0.19	10.26	-0.35	0.93	30,371	25,273	28,567	10,964
ADR10	0.2	10.1	0.39	0.91	26,226	20,973	24,343	10,512
Combined	0.14	10.27	-0.44	0.96	31,659	23,820	28,795	14,468

Table 4. Coefficients of multiple linear regression for objects ≥5 cm and their correlation coefficients.

Scenario	k_1	Launch activity (k_2)	Solar activity (k_3)	Compliance with PMD (k_4)	Explosion activity (k_5)	ADR (k_6)	Correlation coefficient (R^2)
ADR0	60,563	4,767	-39,820	-2,241	16,204	-	0.52
ADR5	33,743	6,047	-23,555	-3,987	18,189	-	0.67
ADR10	29,089	6,066	-23,846	-3,090	18,172	-	0.71
Combined	52,498	5,401	-28,727	-3,664	17,093	-21,839	0.74

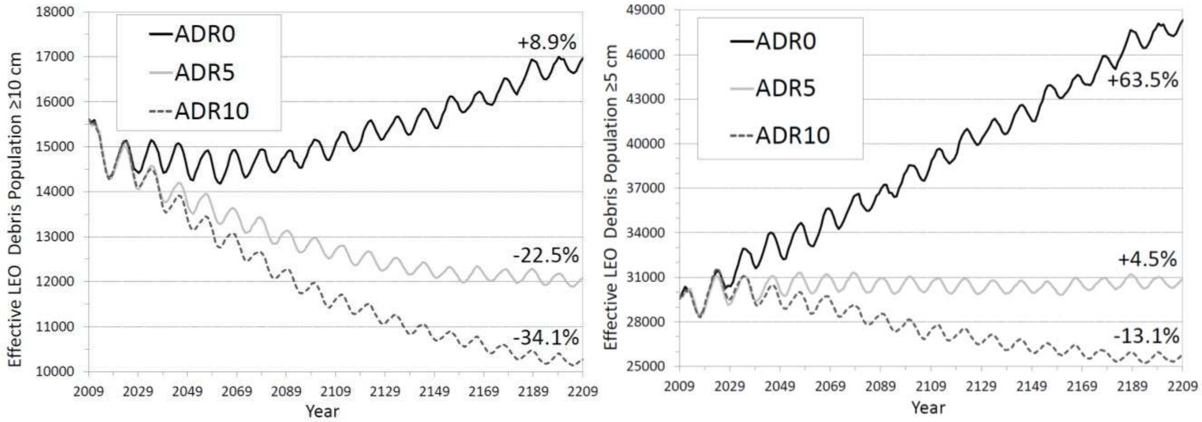

Figure 4. Average effective number of objects in LEO over a 200-year project for (LEFT) objects ≥10 cm and (RIGHT) objects ≥5 cm. Percentage values indicate the percentage increase of decrease from initial population in 2009.

The average number of collisions for each scenario (Tab. 2) follows a similar trend as the total number of objects. Approximately 40-50% of collisions involved at least one object < 10 cm in size. There was double the number of non-catastrophic collisions involving objects < 10 cm than objects ≥ 10 cm. Conversely, there were approximately seven times more catastrophic collisions occurred with objects ≥10cm compared with objects < 10 cm.

3.2 Validating the Number of Monte Carlo Simulations

To determine if 200 MC simulations were reliable enough to establish the trends and distributions of the results, a sub-sampling technique was applied, introduced by [13]. This technique was modified to allow the standard deviation to be analysed instead of the arithmetic mean. In doing so, this allows the statistical dispersion between simulations to be analysed. The procedure for this analysis was

- Starting with Z=1, randomly select Z number of MC simulations (out of 200 MCs)
- Calculate the standard deviation of the debris population at the end of the simulation for the selected MCs
- Repeat the previous two steps with the same value of Z, 200 times
- Repeat the previous three steps incrementing Z by one until Z=100

Fig. 5 illustrates this process for the ADR0 scenario. The x-axis represents the values of Z between 0-100. At each Z value, 200 individual values are plotted. Each point represents the standard deviation from a random selection of Z samples. The 200 MC standard deviation and 20% from this deviation (dark solid lines) are shown.

Both ADR5 and ADR10 scenarios show a very similar trend to Fig. 5. To achieve a standard deviation within 20% of the 200 MC "true" mean difference nine out of ten times, 71 MC simulations must be run for ADR0, 69 for ADR5 and 66 MCs for ADR10. Beyond 80 simulations, the improvements start to become insufficient. Thus 200 MCs for each scenario, in this case gave an acceptable result.

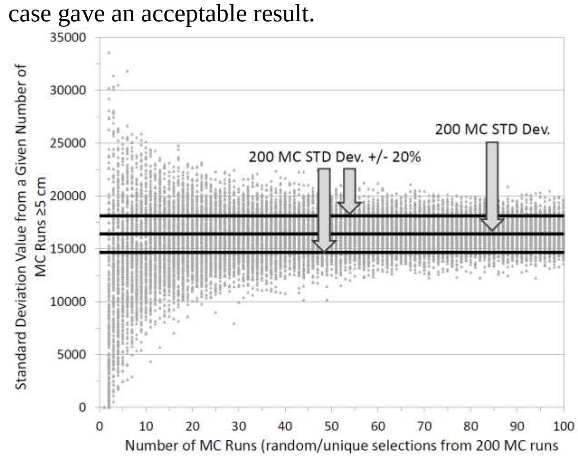

Figure 5. Sub-sampled standard deviations from 200 MC projections of the ≥5 cm LEO debris populations in 2209.

4. DISCUSSION

There are three methods to model assumptions relating to the future, using: (1) a fixed value, (2) best and worst-case values or (3) a multitude of values between a best and worst-case value. The third method, adopted in this paper, allows a much wider picture of possible futures to be examined than either (1) or (2), at the expensive of greater computational demands. In order to balance the computational demands and accuracy of results it is important to complete a number of simulations that allow reasonable statistics to be generated. The number of MC simulations completed in this study has shown to be enough to deduce the statistical trends of the four assumptions.

4.1 Key Results

The debris populations in each scenario vary by almost a factor of ten. Results show it is not possible to rely, with 100% confidence, on removing ten objects a year to stabilise the ≥5 cm population. Despite ADR being an effective measure at reducing the debris population, launch activity, solar activity, compliance with PMD and explosion activity can offset or have a larger influence on the population in LEO. This can be seen with the 36-58% overlap between scenarios in Fig. 3. These percentage values illustrate the proportion of MC simulations where introducing or increasing ADR has not had any additional benefit.

Despite modelling the assumptions in such a way that all values between the worst and best-case are equally possible, the debris population results (Fig. 3) best fit a log-normal distribution. With the fitted distributions in Tab. 3 it is possible to obtain the mode of the data, something that is not possible from the data itself due to the small sample size (200 MC). It is important to ascertain the mode value as it represents, in this study, the most likely future population. The mode of these distributions were 15-25% lower than the arithmetic mean of the population. This is a positive result as it suggests, in this case, designing ADR requirements based on the arithmetic mean of modelling results is a more conservative approach than designing for the mode.

4.2 The Impact of the 5-10 cm Population on the results

It is statistically likely that more removals are required to stabilise the ≥5 cm sized population than in the ≥10 cm population. Previous ADR studies have focused efforts on modelling and determining ADR rates that will stabilise the ≥10 cm population [2][3]. It is expected that approximately half the collisions in LEO will involve a 5-10 cm object, i.e. increasing the total number of collisions by a factor of two compared with just modelling the ≥10 cm population. Whilst only 10-15% of these collisions are likely to be catastrophic, there will be a non-negligible effect on the total number of fragments generated.

4.2 The Impact of the Modelled Assumptions on the results

Whilst the linear regression in Equation (8) is approximate, it is possible to establish what assumptions have the greatest effect on the LEO population ≥5 cm by comparing linear regression coefficients.

The solar activity (k_3) followed by ADR (k_6), explosion activity (k_5), launch activity (k_2) and finally PMD compliance (k_4). This appears to be a direct contradiction of results in [9], which has shown that PMD compliance has a greater effect on the LEO debris population than explosion activity. The probable reasons for this is because [9] was run with a population size ≥ 10 cm and explosion cycle between 2001-2009, compared with this study's ≥5 cm population and explosion activity between 0 and four explosions a year. Furthermore, according to this study the overall effectiveness of PMD compliance will vary dependently on the launch activity in a given simulation.

As a caveat, the current work has assumed that the four assumptions were equally likely to be between an optimistic best-case and historic worst-case in each simulation. In the future, it can be argued that, the growing momentum and further implementation of guidelines, standards and legal practices, the expected number of objects that will comply with PMD guidelines will increase and the number of orbital explosions will decrease.

4.2 Ensuring Population Stability

In some simulations, removing ten objects per year is not enough to achieve population stability and in others, no removals are required to achieve stability. To ensure a stable LEO population, given the significant variance in the results, one method, (implemented by [14]), is to react and adapt to the evolution of the debris environment. That study ([14]) showed that, by monitoring the behaviour of each MC simulation and adjusting at regular intervals the ADR rate, it is possible to decrease the overall population variance and increase the probability of achieving a desired population. Often this approach is more efficient (increasing the ERF), thereby requiring fewer removals than a removal rate that remains fixed. It is the author's recommendation that this approach be considered and investigated by the debris community.

5. CONCLUSION

The purpose of this paper was to highlight some of the assumptions and their variation and effect whilst modelling the long-term evolution of the LEO debris environment. The University of Southampton's DAMAGE tool has been used alongside variable launch activity, solar activity, explosion activity and PMD compliance with a population size ≥5 cm, to develop on previous ADR studies investigating effectiveness of ADR.

The results have shown a population difference of over a factor of ten can be seen after 200 years when implementing the above assumptions. Active debris removal has a positive effect on reducing the population but can be offset by other assumptions. Including the 5-10 cm population in this study has shown that it is likely more removals are required to stabilise the population than with a population ≥ 10cm.

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