ACTIVE REMOVAL STUDY FOR ON-ORBIT DEBRIS USING DAMAGE

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ABSTRACT

Recent debris modelling results have indicated that the debris density at some Low Earth Orbit (LEO) altitudes has reached a critical level such that the LEO debris population will continue to grow even in the absence of new launches. These simulations have provided a basis for recent investigations of debris environment remediation and Active Debris Removal (ADR). This ongoing work has established the benefits of ADR as a method of stabilising the future LEO debris environment but no consideration has yet been given to the means by which debris would be removed. Hence, with a new study of debris removal using the University of Southampton's DAMAGE model, we show the consequences on the LEO debris environment of additional launch activity to attach and deploy devices to remove existing large debris from orbit. The projection period covered the years 2009 to 2109 and the simulations included removal rates of two and five debris objects per year, starting in the year 2020, with debris selected for removal based on criteria including mass and collision probability. Only launches of debris removal systems plus associated upper stages were modelled and we assumed that these new launches comply with current debris mitigation guidelines. The results confirm the effectiveness of ADR and, within the constraints of this initial study, suggest that launch activities associated with ADR may have only a small impact on the efficacy of future remediation efforts.

1. INTRODUCTION

In the last three years, computer simulations have suggested that the current debris population in Low Earth Orbit (LEO) has reached a sufficient density at some altitudes for collision activity there to continue even in the absence of new launches [1]. Whilst mitigation strategies being implemented now – the Inter-Agency Space Debris Coordination Committee (IADC) space debris mitigation guidelines, for example – aim to address the generation of new debris arising from ongoing launch activities, these simulations suggest that it might be necessary to remove large, intact objects from critical altitudes where high levels of collision activity are expected [2]. The results of these simulations have thus provided a driver for recent reviews of debris environment remediation and Active Debris Removal (ADR) technologies, such as the study by the International Academy of Astronautics [3]. They have also prompted new computer simulation work by the National Aeronautics and Space Administration (NASA) Orbital Debris Program Office, which has demonstrated that, in principle, ADR is an effective method of stabilising the future LEO debris environment even if relatively few debris are targeted [4].

The aims of the work by NASA were to demonstrate the effectiveness of ADR and to introduce a simple selection criterion for targeting objects for removal. Under this premise, consideration of the technical means of ADR, including launch aspects and the method by which objects are removed, was unimportant compared with the need to promote ADR as a necessary step and to stabilise the future environment. It is also timely to initiate discussions between space agencies, industry and academia. Clearly, however, the technical issues related to ADR will play a significant role in shaping practical solutions of the remediation of the debris environment and, hence, their efficacy. In this new study using the University of Southampton's Debris Analysis and Monitoring Architecture for the Geosynchronous Environment (DAMAGE), a key objective was to address some of the technical issues associated with ADR, in particular the criteria that should be used in choosing which objects to remove, so that we can begin to understand their impact on its effectiveness.

The future, spontaneous growth of the LEO debris population will be driven by sustained collision activity involving intact, massive objects already on-orbit. Future launches to place new systems into near-Earth space will most likely exacerbate the collision hazard and add to this growth. Intuitively, it makes sense to target objects for removal based on their contribution to these 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 factors likely to be used to define a removal criterion. The collision probability of an object i with a second object j over a short time interval dt can be expressed as [5]:

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

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where s_i and s_j are the residential probabilities (also spatial densities) of objects i and j in a small volume element 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 Eq. (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 intersected by the orbits of all objects provides an estimate of the cumulative collision probability, $P_i(t)$, for object i. The removal criterion [4],

$$R_i(t) = P_i(t) \times m_i, \tag{2}$$

where m_i is the object's mass – a key factor in determining the number of collision-induced fragments [6] – is consistent with the intuitive approach to selecting objects for removal. In practice, the estimation of $P_i(t)$ for use in the removal criterion is made outside the normal environment projection and is achieved using an integration of Eq. 1 over a relatively short time interval (days), at the start of each ADR year [7]. Consequently, the effectiveness of the removal criterion may be less than optimal, as there is the potential for some encounters between objects to be missed. A second objective of this new study with DAMAGE was thus directed at understanding the importance of the removal criterion to the success of ADR.

The aims of this study are, therefore, threefold: to confirm the effectiveness of ADR, to investigate different removal criteria, and to start to address some of the technical issues of ADR, in particular those associated with the launch of dedicated removal systems.

2. METHOD

The University of Southampton's debris model, DAMAGE, is a three-dimensional model that was initially aimed at simulating debris within the geosynchronous orbital regime but has since been upgraded to allow investigations of the full LEO to GEO debris environment. As with other evolutionary models, DAMAGE is able to simulate the historical and future debris populations ≥ 10 cm using a Monte Carlo approach, whereby multiple projection runs are performed to establish reliable statistics on the outcome.

Projections covering the historical period from October 1957 to December 2008 (inclusive) and employing launch and fragmentation information from ESA's Database and Information System Characterising Objects In Space (DISCOS) were used to establish a LEO population for the epoch 1 January 2009. The historical (and future) fragmentation events were simulated using the NASA Standard Breakup Model [6].

A 'no new launches' scenario (described in Tab. 1) was used by DAMAGE as the benchmark "no ADR" scenario for this investigation. This type of scenario has been used in recent studies to understand the stability of the current LEO debris population and has the advantage that the uncertainty arising from estimations of future traffic does not impact upon future projections. Given the focus of this study, on the existing debris population, the scenario provides an appropriate method of investigating the remediation of the debris environment. The projection period covers the years 2009 to 2109 and all objects ≥ 10 cm were propagated forwards using a semi-analytical orbital propagator that includes Earth's J_2, J_3, $J_{2,2}$, luni-solar gravitational perturbations, solar radiation pressure (with cylindrical Earth shadow) and atmospheric drag. Collision probabilities (Eq. 1) were estimated using a fast, pair-wise algorithm based on the 'Cube' approach adopted in NASA's LEO-to-GEO Environment Debris model (LEGEND) [8].

Table 1. Description of the basic "No ADR" benchmark scenario.

Parameter	**Value**
Projection period	1 Jan 2009 – 1 Jan 2109
Traffic model (2009 – 2109)	No new launches (except for ADR)
Future explosions (2009 – 2109)	No explosions
Time-step	5 days
Minimum object size	10 cm
Collision prediction: cube size	10 km

Seven ADR and one "No Collisions" scenarios were used (Tab. 2) and are described below. The eligibility requirements for the removal of objects in the ADR scenarios were:

1. The object must be intact (i.e. a payload, rocket body or mission-related debris),
2. have an orbital eccentricity < 0.5,
3. have a perigee altitude < 1400 km, and
4. must have been launched before 1 Jan. 2009.

For an object which met these eligibility requirements, the nominal criterion in Eq. 2 was adopted, where collision probabilities were calculated using the procedure described above.

An Effective Reduction Factor (ERF), introduced by Liou and Johnson [4], was calculated to quantify the

Table 2. Description of the DAMAGE scenarios.

Scenario	Description
No ADR	As Tab. 1
No Collisions	As Tab. 1, no collisions allowed after 1 Jan. 2020
ADR 2	As Tab. 1, 2 objects removed immediately per year (on 1 Jan.) from 2020, using $R_i(t)$ criterion
ADR 5	As ADR 2, except 5 objects removed per year
ADR 5 Random 1	As ADR 5, except using $R_i^{(1)}(t)$ criterion
ADR 5 Random 2	As ADR 5, except using $R_i^{(2)}(t)$ criterion
ADR 5 Random 3	As ADR 5, except using $R_i^{(3)}(t)$ criterion
ADR 5 Launch 1	As ADR 5, 1 payload & 1 rocket stage inserted for each object removed
ADR 5 Launch 2	As ADR 5, 1 payload & 1 rocket stage inserted for every 5 objects removed

effectiveness of the ADR scenarios investigated in this study, using the “No ADR” scenario as a benchmark:

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

where $N(t)$ 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 at time t. $ERF(t)$ is a function of time and can thus be calculated at any point in the projection period. In addition, the average ERF calculated from the year 2021 to the end of the projection period describes the cost-effectiveness of an ADR strategy, as it quantifies the average reduction in the total population for each object removed through ADR. However, some caution needs to be taken when interpreting the ERF parameter, as not all objects removed contribute equally to future collision activities [4]; after removing objects with the highest $R_i(t)$ values, the effectiveness of any subsequent removals will be reduced. In other words, removing fewer objects will appear to be more cost-effective than removing more objects, even though the overall aim of stabilising the environment (typically, by preventing collisions) may not have been met. We introduce a Normalised Effective Reduction Factor (NERF) to address this issue.

The NERF takes account of the remediation goal by including a *target* number of objects, $N_T(t)$, and is defined as:

$$NERF(t) = \frac{N(t) - N_S(t)}{N(t) - N_T(t)}. \tag{4}$$

For this work, we took the target to be the effective number of objects ≥ 10 cm at time t determined from a no new launches scenario that also did not allow collisions after the year 2020 (“No Collisions”). Inspection of Eq. 4 reveals that $NERF(t)$ is the ratio of $ERF(t)$, for an ADR scenario, to the ideal $ERF(t)$ value calculated from the “No Collisions” scenario, assuming that the number of objects removed is the same as for the ADR scenario and that these removals result in no collision activity in the future projection after 2020. As with the ERF, an average NERF value can be calculated over the projection period to provide a single, quantitative assessment of the effectiveness of each ADR scenario.

2.1 Case study 1

The objective of case study 1 was to verify the effectiveness of ADR as a method for stabilising the growth of the LEO debris population. In this study, $R_i(t)$ values were calculated at the start of each year beginning in 2020, and objects with the $n \in \{2, 5\}$ highest $R_i(t)$ values were removed from the environment immediately.

2.2 Case study 2

Three additional criteria for removal were defined to investigate the importance of the $P_i(t)$ and m_i terms in selecting objects to remove:

$$R_i^{(1)}(t) = r_i(t) \tag{5}$$

$$R_i^{(2)}(t) = r_i(t) \times m_i \tag{6}$$

$$R_i^{(3)}(t) = P_i(t) \times r_i(t) \tag{7}$$

where $r_i(t)$ was a uniformly distributed random number in the range $[0, 1]$. In case study 3, objects with the five highest $R_i^{(k)}(t)$ values, where $k \in \{1, 2, 3\}$, were removed from the environment immediately. Therefore, selection for removal was either wholly random (Eq. 5), based on mass (Eq. 6), based on collision probability (Eq. 7), or based on the product of mass and collision probability (Eq. 2).

2.3 Case study 3

In this case study, the aim was to investigate the impact of launches to deploy debris removal systems on the effectiveness of ADR. The removal criterion used for case study 1 (Eq. 2) was used to identify objects with the five highest $R_i(t)$ values each year from 2020. In addition, two launch scenarios were considered. In the first scenario, one spacecraft and one rocket body (described in Tab. 3) were inserted into the environment for every object removed by ADR. In the second launch scenario, one spacecraft and one rocket body were inserted for every five objects removed through ADR. Objects targeted for removal using Eq. 2 were then removed from the environment immediately and the newly launched spacecraft and rocket bodies were transferred to 25-year decay orbits, in compliance with current debris mitigation practices. All newly launched objects were considered in the collision risk algorithm, so could contribute to future collision activity, but were not considered for ADR. Further, it was assumed that the spacecraft would carry sufficient propellant to rendezvous and de-orbit all five debris objects in the second scenario.

Table 3. Description of the spacecraft and rocket bodies used in case study 3.

	Spacecraft	**Rocket body**
Mass (kg)	1,000	2,000
Area (m^2)	10	20

3. RESULTS AND DISCUSSION

The averages of 40 MC runs for selected environment parameters and for each scenario are shown in Fig. 1 to Fig. 8. Effectiveness measures for each scenario are shown in Tab. 4.

3.1 "No ADR" and "No Collisions" Scenarios

The effective number of objects in LEO over the projection period for the benchmark "No ADR" scenario is shown in Fig. 1. After an initial decrease, the lack of remediation results in a slight rise in the population as a result of sustained collision activity throughout the projection period. In contrast, the "No Collision" scenario demonstrates the ideal situation, whereby all collision activity is halted after the year 2020 and the population at the end of the projection has fallen to half the number seen at the 1 January 2009 epoch. Without ADR, therefore, the LEO space debris population is likely to increase due to random collisions between existing on-orbit debris, even in the absence of new launch activities.

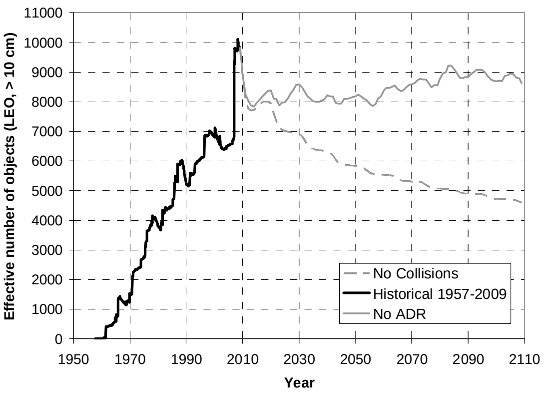

Figure 1. DAMAGE-simulated LEO debris populations between 1957 and 2109 for the "No Collisions" and "No ADR" benchmark scenarios.

3.2 Case study 1

When objects targeted using the criterion in Eq. 2 are removed from the environment at the start of each projection year, beginning in 2020, there is an immediate and beneficial effect on the LEO population (Fig. 2). In the "ADR 5" scenario the cumulative number of intact objects removed by ADR at the end of the projection period is 445, but the average number reduced compared to the benchmark "No ADR" scenario is 3005. Therefore, the Effective Reduction Factor at the end of the projection period is 6.75 (Fig. 3). However, the average ERF over the ADR period is 10.0. That is, for every object removed through ADR, a total reduction of 10.0 objects results, on average, compared with the benchmark scenario.

Inspection of the time-history of the ERF for both ADR scenarios in this case study reveals that ADR is most cost-effective in the first 20 years, due to the removal of objects that make a substantial contribution to future collision activity. Subsequent removals are not as cost-effective but are essential for maintaining the beneficial impact on the LEO population over the projection period, as shown by the time-history of the Normalised Effective Reduction Factor (Fig. 4).

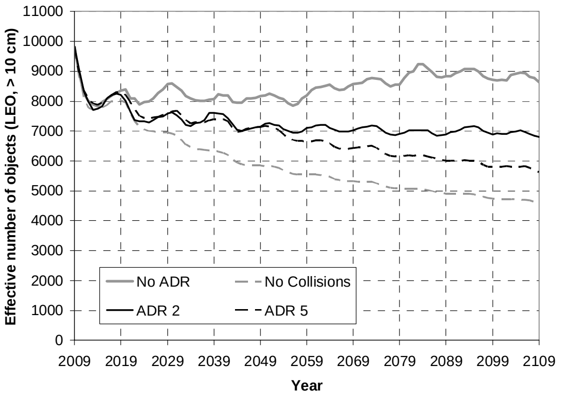

Figure 2. DAMAGE-simulated LEO debris populations between 2009 and 2109 for the benchmark, "ADR 2" and "ADR 5" scenarios.

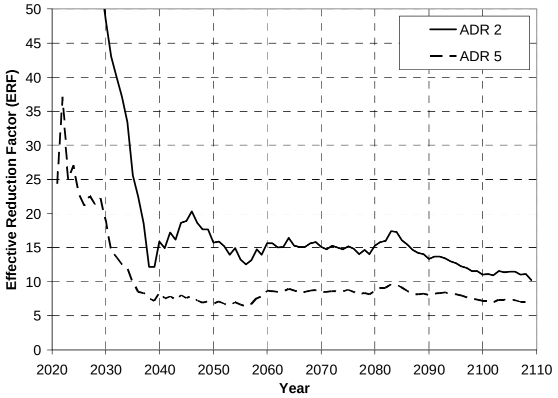

Figure 3. Effective Reduction Factor (ERF) between 2021 and 2109 for the benchmark, "ADR 2" and "ADR 5" scenarios.

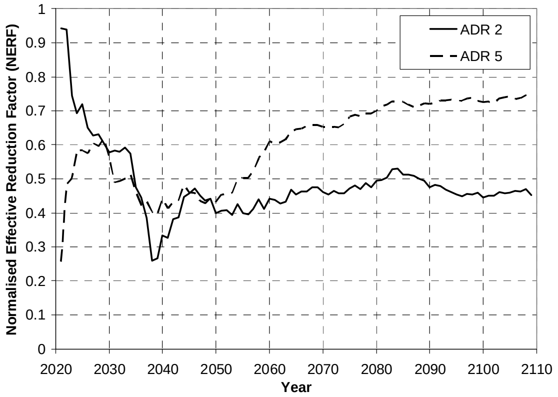

Figure 4. Normalised Effective Reduction Factor (NERF) between 2021 and 2109 for the benchmark, "ADR 2" and "ADR 5" scenarios.

The average NERF calculated for the "ADR 5" scenario is 0.6. In other words, this ADR scenario is 60% as effective as a strategy that successfully halts all collisions after 2020 (the ideal, "No Collisions" scenario). On the other hand, the average NERF value for "ADR 2" is only 0.48, indicating that removing only two objects per year does not have the same beneficial impact on the environment as removing five objects per year. Fig. 4 also suggests that removing only two objects per year will not stabilise the environment in the long-term, as the NERF for this scenario actually decreases during the last 25 years of the projection period.

3.3 Case study 2

Work reported by Lewis *et al.* [9] suggested that future encounters between objects in LEO could be represented by a complex network with disassortative properties. In a disassortative network, most vertices (representing objects in the debris environment) are connected to (have encounters with) relatively few others, but some vertices are highly connected. This property makes the network, and, hence, would make the debris environment, relatively robust to the random removal of vertices. However, if the highly connected vertices of the network are targeted for removal, then the network can be destroyed quite rapidly. Verification of the disassortative characteristic of the debris environment, and the merit of a random approach versus a targeted approach to removal, were provided by the results of case study 2. Here, selecting objects to remove based on a purely random approach (using the criterion in Eq. 5) had some benefit, but was only half as effective (Av. NERF = 0.3) as the targeted approach to removal based on the product of mass and probability (Fig. 5 and Fig. 6). This finding is important, from the perspective that identifying appropriate and robust selection criteria for removal will be a key part of any ADR campaign.

When object mass was used as a selection criterion, without the involvement of collision probability (Eq. 6), the effectiveness of ADR was similar (Av. NERF = 0.36) to the removal strategy that employed purely random selection. Conversely, when the criterion in Eq. 7 was used, the effectiveness was close (Av. NERF = 0.54) to that of the nominal ADR strategy (Fig. 6). These results imply that object mass is not as important as collision probability when targeting objects for removal. This, perhaps surprising, conclusion can be understood if we consider that relatively few objects actually contribute to future collision activities compared to the total number of objects eligible for removal. A removal criterion based on mass alone has a small chance of selecting an object that also has a high collision probability, so we see some improvement over a purely random criterion. However, most of the

Table 4. Effectiveness measures for the DAMAGE scenarios.

Scenario	No. Objects Reduced (2109)	Cum. No. Cat. Collisions Reduced (2109)	Av. ERF/NERF (Objects)	Av. ERF/NERF (Cat. Collisions)
No ADR	-	-	-	-
No Collisions	4031	8.6	-	-
ADR 2	1825	2.7	24.6 / 0.48	0.024 / 0.32
ADR 5	3005	4.4	10.0 / 0.60	0.012 / 0.46
ADR 5 Random 1	1805	2.8	4.7 / 0.30	0.008 / 0.29
ADR 5 Random 2	1859	2.3	6.8 / 0.36	0.007 / 0.24
ADR 5 Random 3	2824	3.2	9.6 / 0.54	0.009 / 0.30
ADR 5 Launch 1	2204	3.3	8.4 / 0.46	0.012 / 0.40
ADR 5 Launch 2	2755	4.1	7.7 / 0.52	0.011 / 0.40

removal effort goes towards removing objects that play no role in future collisions.

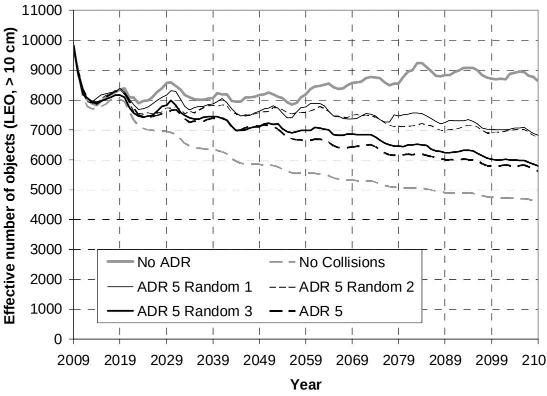

Figure 5. DAMAGE-simulated LEO debris populations between 2009 and 2109 for the benchmark scenarios and the new removal criteria.

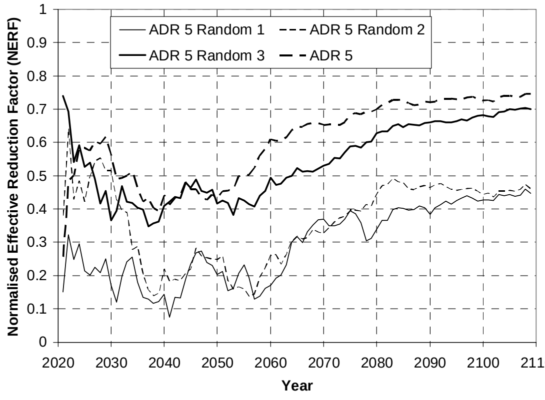

Figure 6. Normalised Effective Reduction Factor (NERF) between 2021 and 2109 for the benchmark scenarios and the new removal criteria.

3.3 Case study 3

Fig. 7 and Fig. 8 show that the insertion of new spacecraft, designed to remove existing debris, and their associated rocket bodies may have only a small impact on the effectiveness of ADR. Plainly, removal systems that can rendezvous with and de-orbit several debris objects ("ADR 5 Launch 2") will be more cost-effective than systems that can only remove one debris object ("ADR 5 Launch 1"), and this is highlighted by the differences in the NERF values for these scenarios (Tab. 4).

The results for the "ADR 5 Launch 1" scenario in case study 3 also demonstrate the effectiveness of a guideline on post-mission disposal (PMD). In this scenario, which applied the IADC 25-year rule to all new launch objects, the number of new objects added to the environment was twice the number removed by ADR, yet there was a reduction of 2,204 in the overall number of objects compared with the benchmark "No ADR" scenario (Fig. 7).

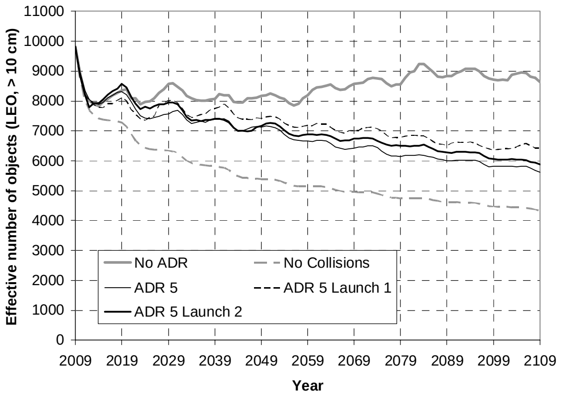

Figure 7. DAMAGE-simulated LEO debris populations between 2009 and 2109 for the benchmark and launch scenarios.

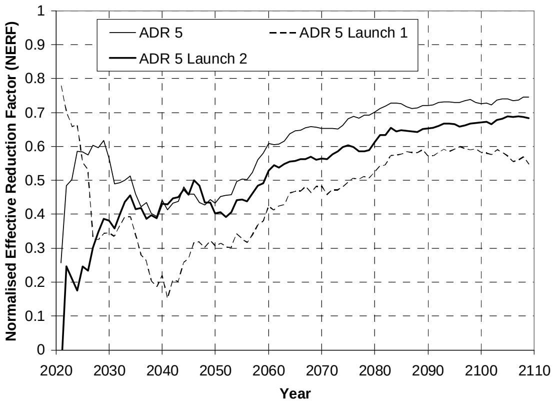

Figure 8. Normalised Effective Reduction Factor (NERF) between 2021 and 2109 for the benchmark and launch scenarios.

4. CONCLUSIONS

The modelling results presented here and in other, recent work have shown that the LEO space debris population is likely to increase due to random collisions between existing on-orbit debris, even in the absence of new launch activities. Remediation of the environment through an Active Debris Removal campaign, whereby existing, intact objects are removed, presents a possible solution to this problem. By following such a strategy, the spontaneous growth of the existing LEO population can be prevented by removing relatively few objects per year. This study demonstrated that this could be achieved by five removals per year, beginning in the year 2020. A lower removal rate may be insufficient to control the growth of the LEO population.

Identifying robust removal criteria is a fundamental component of the ADR process, because removing objects at random has only a small beneficial effect due to the disassortative nature of encounters in the debris environment. Targeted removal, based on a criterion that includes collision probability, can be up to twice as effective but is still sub-optimal owing to the deficiencies in the methods used to calculate collision probability. Further work to establish reliable removal criteria and involving the use of complex networks is ongoing.

Technical issues associated with ADR will affect the effectiveness of remediation efforts. This study focused on the impact of the new launches required to deploy spacecraft able to rendezvous with and remove intact debris objects. Under the particular assumptions of mass and area made for the new launches in the study, the results showed that the beneficial impact of ADR remains, even as new intact objects are added to the environment.

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