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An adaptive strategy for active debris removal

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Abstract

Many parameters influence the evolution of the near-Earth debris population, including launch, solar, explosion and mitigation activities, as well as other future uncertainties such as advances in space technology or changes in social and economic drivers that effect the utilisation of space activities. These factors lead to uncertainty in the long-term debris population. This uncertainty makes it difficult to identify potential remediation strategies, involving active debris removal (ADR), that will perform effectively in all possible future cases. Strategies that cannot perform effectively, because of this uncertainty, risk either not achieving their intended purpose, or becoming a hindrance to the efforts of spacecraft manufactures and operators to address the challenges posed by space debris.

One method to tackle this uncertainty is to create a strategy that can adapt and respond to the space debris population. This work explores the concept of an adaptive strategy, in terms of the number of objects required to be removed by ADR, to prevent the low Earth orbit (LEO) debris population from growing in size. This was demonstrated by utilising the University of Southampton's Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) tool to investigate ADR rates (number of removals per year) that change over time in response to the current space environment, with the requirement of achieving zero growth of the LEO population.

DAMAGE was used to generate multiple Monte Carlo projections of the future LEO debris environment. Within each future projection, the debris removal rate was derived at five-year intervals, by a new statistical debris evolutionary model called the Computational Adaptive Strategy to Control Accurately the Debris Environment (CASCADE) model. CASCADE predicted the long-term evolution of the current DAMAGE population with a variety of different ADR rates in order to identify a removal rate that produced a zero net growth for that particular projection after 200 years.

The results show that using an adaptive ADR rate generated by CASCADE, alongside good compliance with existing mitigation measures, increases the probability of achieving a constant LEO population of objects greater than 10 cm. This was shown to be 12% greater compared with removing five objects per year, with the additional advantage of requiring only 3.1 removals per year, on average.

Keywords: Space debris; Orbital debris; Remediation; Active debris removal; Adaptive; Strategy

1. Introduction

Space debris is a threat to the safe operation of near-Earth satellites and the long-term sustainability of outer space activities. In the last decade, modelling studies, such as Liou and Johnson (2006), have predicted 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 any new launches.

Indeed, in 2009, the Inter-Agency Space Debris Coordination Committee (IADC) initiated an Action Item (AI 27.1) to determine the stability of the future LEO space debris environment (IADC, 2013); and as such establish whether measures such as active debris removal (ADR)

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Nomenclature

$\dot{C}$	intact object collision rate (#/year)
CN_R	cumulative number of objects removed in an ADR scenario
$\dot{D}_c$, $\dot{D}_e$, $\dot{D}_i$	drag rates for collision, explosion and intact objects (#/year)
$\dot{E}$	explosion rate (#/year)
F	a scaling factor implemented within the NASA standard breakup model
h	altitude band number
$k_1, \dots k_4$	collisions coefficients
$\dot{L}$	launch rate (#/year)
L_c	the minimum characteristic length of a fragment (m)
m_{avg}	the average mass of an intact rocket body or satellite $\geqslant 10$ cm in size (kg)
m_i	mass of an intact object i (kg)
N	number of objects $\geqslant 10$ cm in CASCADE
N_A	number of objects $\geqslant 10$ cm in a scenario with no ADR
N_B	number of objects $\geqslant 10$ cm in an ADR scenario
Nc, Ne, Ni	number of objects $\geqslant 10$ cm for collision, explosion and intact objects
N_D	number of objects $\geqslant 10$ cm in a DAMAGE projection
N_p	growth of the CASCADE population compared to the initial DAMAGE population
n_s	number of explosion fragments generated per explosion
n_c	number of explosion fragments generated per collision
$\dot{P}$	PMD compliance rate (#/year)
P_i	collision probability of object i
R^2	coefficient of determination
$\dot{R}$	rate of objects removed by ADR (#/year)
S	Scaling factor to replicate the effect of solar activity on atmospheric drag
t	current projection time (year)
t_s	time at end of a projection (year)
T_i	DAMAGE target selection criterion for ADR
t_0	time at beginning of a projection (year)
Δt	time step (days)

should be investigated further. In doing so, optimistic levels of mitigation (90% future level of compliance with a 25-year post-mission disposal (PMD) rule and 100% passivation of satellites and rocket bodies) and potentially optimistic levels of launch and solar activity were used. Despite these optimistic values, using six agencies' modelling tools, a consensus was reached that confirmed the current $\geqslant 10$ cm LEO debris population was still likely to grow. A key conclusion of the report was that:

> "…to stabilize the LEO environment, more aggressive measures, such as active debris removal, should be considered".
>
> (IADC report, Stability of the Future LEO Environment, IADC-12-08, Rev. 1, page 17, January 2013)

Recent ADR modelling studies, completed by the International Academy of Astronautics (Klinkrad and Johnson, 2010), the National Aeronautics and Space Administration's (NASA's) Orbital Debris Program Office (Liou et al., 2010), the University of Southampton (Lewis et al., 2012), and others have all demonstrated the effect of ADR. Results have shown that it may be possible to prevent the expected growth of the $\geqslant 10$ cm LEO population by removing in the order of three (Lewis et al., 2012) to 15 (Klinkrad and Johnson, 2010) well-chosen debris objects per year alongside widespread compliance with IADC Space Debris Mitigation Guidelines (IADC, 2007).

These ADR studies have taken some reasonable, although arguably optimistic assumptions, concerning the future, that constrain parameters such as launch, explosion, solar and mitigation activity, to a limited number of cases. As a result, amongst other reasons, current removal rates are proposed only to serve as a guide for the further development of high-level ADR requirements. Liou stated that,

> "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".
>
> (J.-C. Liou, Presentation at the 2nd European Workshop on Active Debris Removal, CNES HQ, France, slide 19, June 2012)

The way we utilise near-Earth space, and the way the space environment behaves in the long-term future will directly affect the number of debris objects required to be removed. New space technologies, increasing numbers of space-faring nations, developing policies and political motivations will affect launch and mitigation activity, and thus the size of the LEO population, potentially threatening the sustainability of outer space activities. These future values remain unknown. Results from White and Lewis (2014) have shown that modifying values for launch, explosion, mitigation and solar activity, as well as looking at objects down to sizes of five cm can significantly effect on the sustainability of space activities, even whilst utilising ADR of five and ten removals per year.

Fig. 1 highlights the difference between debris population of optimistic and non-mitigation scenarios from the