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Environmental effect of space debris repositioning

C. Bombardelli [a,*], E.M. Alessi [b], A. Rossi [b], G.B. Valsecchi [c]

[a] Space Dynamics Group, Technical University of Madrid, Pl. Cardenal Cisneros 3, 2040 Madrid, Spain
[b] IFAC-CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy
[c] IAPS-INAF, via Fosso del Cavalieri 100, 00133 Roma, Italy

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Abstract

One of the proposed measures to limit the number of near-Earth orbiting fragments to a sustainable level is to actively remove large derelict objects from crowded orbital regions. The two main removal procedures considered so far are (1) a direct targeted reentry maneuver or (2) a deorbit maneuver resulting in a predicted 25-year lifetime for the target object. We study here the viability of a third option, which consists of repositioning the target to an optimally chosen altitude according to a selected benefit/cost objective function. The objective function accounts for both the maneuver cost and the reduction of environmental criticality of the object. Numerical simulations are conducted to determine the optimal sequence of repositioning maneuvers for a given available deorbiting propellant. Results show that an optimal repositioning campaign tends to displace ton-class objects from around 900–1000 km altitude down to around 750–800 km altitude and to redistribute debris mass from altitudes around 1500 km across lower density nearby altitudes. Comparisons with a 25-year lifetime deorbiting suggest a significant performance improvement.

Keywords: Space debris; Environmental criticality; Repositioning

1. Introduction

Recent studies have shown that the environmental impact of a collision in low earth orbit (LEO) depends not only on the total mass involved but also on the *altitude* where the collision occurs Rossi et al. (2016). This fact is, mainly, a direct consequence of the exponential dependence of atmospheric density with orbit altitude and can be directly inferred by looking at the two major collision events in LEO to date: the 2009 Cosmos-Iridium collision and the 2007 Fengyun-C anti-satellite missile test. The former, which occurred at about 789 km altitude, is estimated to have 90% of its fragments to reenter the atmosphere by 2024 (Pardini and Anselmo (2011)). On the other hand, one will have to wait until about 2090 to have the atmosphere getting rid of the same fraction of fragments for Fengyun-C, generated at about 865 km altitude. This suggests that the higher the altitude of a satellite the more severe the potential threat to the environment. Indeed, several authors (Rossi et al., 2015; Yasaka et al., 2011; Utzmann et al., 2012; Kebschull et al., 2014; Pardini and Anselmo, 2016) have suggested that ballistic lifetime, together with object mass and local debris population density, should be accounted for in the definition of a criticality index for the individual Earth-orbiting objects.

In the framework of the active debris removal (ADR) challenge this aspect can be crucial for at least two main reasons. On one hand, it includes lifetime (hence orbital altitude) as an important factor in constructing priority

* Corresponding author.
E-mail addresses: claudio.bombardelli@upm.es (C. Bombardelli), em.alessi@ifac.cnr.it (E.M. Alessi), a.rossi@ifac.cnr.it (A. Rossi), giovanni@iaps.inaf.it (G.B. Valsecchi).

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lists for the objects to be removed. On the other hand, it opens up the possibility of reducing the criticality of an object by lowering its altitude by just a small amount. Once repositioned to a higher-drag and, possibly, less crowded orbital region the target can effectively get out of the priority removal list with no need to fully deorbit it.

An important advantage of the repositioning approach would apply to target debris objects whose size, material composition and structure is such to have its future uncontrolled reentry phase posing a risk exceeding the 10^{-4} human casualty probability threshold. According to international guidelines, these objects should be made to reenter in a controlled way using one or more impulsive delta-V maneuvers targeting the South Pacific Ocean Uninhabited Area (SPOUA). Crucially, impulsive controlled reentry maneuvers are much more expensive if carried out at higher altitudes: a single impulsive delta-V maneuver from a 1000-km-altitude and lowering the perigee altitude to 50 km is more than five times larger than the same maneuver carried out at 220 km as done for the reentry of MIR in 2001. This suggests that the targeted reentry of critical space debris should be initiated only when the object has reached a reasonably low altitude after the atmospheric drag has provided, for free, a large share of the deorbiting delta-V. However, large debris at altitudes well above 800–900 km pose such a prolonged threat to the environment that it is not recommended to wait until such condition is verified. Instead, it appears favorable to perform an efficient low-thrust deorbiting aimed at lowering the altitude of these objects just enough to cut down most of their environmental criticality. Atmospheric drag would do the rest of the job until a final controlled reentry phase can be carried out when the object has reached 200–250 km altitude. A dedicated platform, launched to that altitude at a later stage, would be in charge of the controlled reentry phase.

The primary goal of this article is to assess the effectiveness and benefits of a space debris repositioning approach compared to a more conventional procedure where high priority targets are deorbited until achieving a 25-year residual ballistic lifetime[1]. In addition, and unlike previous works on the subject Braun et al. (2013), it includes an assessment of the global environmental impact of a multiple debris removal or repositioning campaign.

The rationale and structure of the article is described in the following. First we review the concept of environmental criticality of a space object and the literature work on the subject in order to lay the ground for the definition of a repositioning optimization procedure. Next we introduce the concept of *fractional criticality*, as the fraction of the total criticality index of an object attributed to individual altitude shells, as a basis for our optimization analysis. From the fractional criticality we can compute the *shell criticality* and obtain an overall picture of the criticality distribution with altitude in LEO. We then move on to the definition of an objective function characterizing a single repositioning maneuver as a cost/benefit ratio accounting for both the cost of the removal maneuver and the reduction of the environmental criticality of the object. Finally, we run a numerical optimization procedure that selects, among the roughly 1400 LEO space objects larger than 500 kg and 36 repositioning destination shells, the optimum object and shell sequence leading to the highest decrease in global LEO criticality for the minimum delta-V cost. A similar optimization procedure is run for the particular case in which all objects are left inside a 550–600 km altitude shell to guarantee a residual lifetime of 25 years. The results are discussed and conclusions are drawn.

2. Measuring the environmental criticality of an object

Before considering the implementation of an active debris removal (ADR) mission it is paramount to understand the space debris environment, its current state and evolution, and what measures can be taken to improve it. Roughly speaking, one can say that the quality or "health" of the circumterrestrial space is lower the higher the risk for present and future space assets to be hit by uncontrolled objects left in orbit. As it is well known, the biggest threat in this sense comes from the population of small fragments, of 1–10 cm in size, orbiting in the LEO region Crowther (2003). These fragments, more abundant and therefore more likely to impact an active spacecraft when compared to larger objects, are large enough to fully disable a space asset (without necessarily leading to a catastrophic fragmentation) but not enough to be tracked from the ground, making it impossible to implement any avoidance maneuver. Yet the main sources contributing to the growth of these fragments are in-orbit explosions and collisions involving large and massive objects, which should be the primary target of ADR operations. Among the massive ton-class objects left in LEO, what remains to decide is what specific targets should be given priority in the removal process and in what regions they reside.

In order to perform a ranking of removal candidates it is necessary to establish a criticality index as a function of the physical characteristics of the object and its orbit. In this regard, different approaches have been proposed in the literature leading to several types of criticality indexes, which will be briefly reviewed here.

The different indexes can be conveniently grouped into two main categories:

1. Based on severity.
2. Based on risk.

[1] Note that the need not to remain in LEO for more than 25 years is a general recommendation only for recent missions (and a requirement for new ESA missions). Strictly speaking, therefore, a 25-year deorbiting would only be relevant for the ADR of relatively recent spacecraft that failed to deorbit. For simplicity, and in absence of a formal "ADR deorbiting criterion", we here consider the 25-year criterion extended to all targets.

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