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Impact of high-risk conjunctions on Active Debris Removal target selection

Aleksander A. Lidtke *, Hugh G. Lewis, Roberto Armellin

University of Southampton, Southampton SO17 1BJ, UK

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Abstract

Space debris simulations show that if current space launches continue unchanged, spacecraft operations might become difficult in the congested space environment. It has been suggested that Active Debris Removal (ADR) might be necessary in order to prevent such a situation.

Selection of objects to be targeted by ADR is considered important because removal of non-relevant objects will unnecessarily increase the cost of ADR. One of the factors to be used in this ADR target selection is the collision probability accumulated by every object.

This paper shows the impact of high-probability conjunctions on the collision probability accumulated by individual objects as well as the probability of any collision occurring in orbit. Such conjunctions cannot be predicted far in advance and, consequently, not all the objects that will be involved in such dangerous conjunctions can be removed through ADR. Therefore, a debris remediation method that would address such events at short notice, and thus help prevent likely collisions, is suggested.

Keywords: Active Debris Removal; Target selection; Just-in-time collision avoidance; Collision probability; Conjunction detection; Orbital debris

1. Introduction

It is a common belief that removing uncontrolled objects from Earth orbit is necessary to halt the increase of the debris population, most of which are expected to be fragments resulting from collisions (Liou, 2011). This phenomenon was indeed predicted in the 1970s (Kessler and Cour-Palais, 1978) but more attention has been paid to it recently as the self-exciting effect of collisions generating more debris and thus more collisions has been stipulated to be inevitable even if no future launches take place (Liou and Johnson, 2008). This has sparked world-wide interest in the development of technologies to stop this potential collision cascade.

At the time being it is difficult to assert whether such an "avalanche" of collisions will take place at all – the forecasts of the number of objects in orbit 200 years from now performed using the current debris environment models vary by as much as an order of magnitude (White and Lewis, 2014). However, there are other incentives to avoid collisions in orbit and to increase the sustainability of spaceflight, for example reducing the number of collision avoidance manoeuvres performed by the active satellites. This would effectively extend spacecraft lifetimes as they would have more propellant to conduct orbit maintenance.

It is argued by many authors that measures should be taken to address the potential growth of the number of debris objects in orbit (Liou, 2006, 2011; Pas et al., 2014; McKnight et al., 2012; Furuta et al., 2014). Several

* Corresponding author.
E-mail addresses: al11g09@soton.ac.uk (A.A. Lidtke), H.G.Lewis@soton.ac.uk (H.G. Lewis), roberto.armellin@soton.ac.uk (R. Armellin).

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conceptually different approaches have been suggested over the years, ranging from reducing the number of debris added to the environment in the form of entire spacecraft or parts of thereof (mitigation) (Liou, 2006), active removal of derelict objects (Liou, 2011), or prevention of collisions between uncontrolled objects via just in time collision avoidance (JCA) (McKnight et al., 2012).

Two out of three mentioned approaches aimed at improving the sustainability of space activities require selection of objects that are to be targeted. Active Debris Removal (ADR) appears to be the most popular strategy (Liou, 2011; Pas et al., 2014; Furuta et al., 2014; McKnight et al., 2014) and it requires targets to be selected if not all the objects can be removed, e.g. due to financial or political constraints.

ADR is so popular because it ensures that mass is removed from orbit thus lowering the potential for future collisions. Due to the novelty of the technologies required to perform such removal missions and complexity of the necessary space systems, the cost of every such undertaking is expected to be high. Thus, reducing the number of removal missions by selecting the targets more appropriately becomes important.

A common option for the selection of ADR targets is ranking all the objects based on a single metric that reflects the risk a given object poses to the environment, which typically accounts for the chance of an object being involved in a collision (collision probability) with high severity (Liou, 2011; Rossi et al., 2014). Severity of collisions is said to be roughly proportional to mass because collisions of massive objects are likely to produce many new debris (Johnson et al., 2001). Performing Active Debris Removal of targets selected in this manner leads to several (at least 9.5 in a study by Liou and Johnson, 2009) objects that need to be removed to prevent a single collision, thus increasing the capital cost of ADR even further.

Removing more objects does not necessarily prevent more collisions (Liou and Johnson, 2009). This is because these targets are not necessarily the ones that *will* take part in dangerous conjunctions but rather the ones that are the *most likely* to have them. Therefore, in order to increase the confidence in the outcome of ADR using such target selection schemes, more objects need to be removed per year to reduce the probability of a collision taking place in orbit (Liou and Johnson, 2009).

Previous studies with DAMAGE (Debris Analysis and Monitoring Architecture to the Geosynchronous Environment, the evolutionary debris model of the University of Southampton) have hinted at the importance of individual conjunctions in the scope of the evolution of the entire debris population (Lewis and Lidtke, 2014). This work investigates this phenomenon in greater detail in order to show why statistical ADR target ranking metrics that ignore the individual conjunctions may not prevent all the orbital collisions if a limited number of ADR missions can be flown. It is stipulated that if these high-risk conjunctions can be predicted more accurately and addressed at short notice it is likely that more catastrophic collisions can be prevented.

This study investigates the behaviour in which collision probability, P_C, is accumulated by objects in orbit in fine spatial and temporal resolutions to examine the impact of individual high-risk conjunctions. Primarily the relative importance of different conjunctions, in terms of the collision probability that they contribute to the final collision probability of every object, was of interest. The method used to identify individual conjunctions is described first. The description of the methods used to estimate the collision probability for all the conjunction is given next. The relative importance of different conjunctions can be estimated without identifying and assessing the P_C of all the conjunctions to the best of our abilities, as long as the collision probabilities are not contrived and the frequency of conjunctions with high collision probabilities is similar to what takes place when using higher fidelity methods. Therefore, certain inaccuracies in the algorithms and the input data were acceptable because using the highest-accuracy propagators and ephemerides would increase the computational time required for the analysis. Wherever practical, however, the precision of the used numerical schemes etc. was kept high not to degrade the results further.

Once the method used to find and assess conjunctions is described, its application to the study of the debris environment is described. The results are presented, the limitations stemming from the employed method discussed, and the conclusions drawn.

2. Conjunction detection and assessment

In order to achieve the goals of this study a new debris simulation framework was developed. It uses a freeware implementation of the simplified general perturbations (SGP4) propagator (Kelso, 2000) together with Two-Line Element sets (TLEs) (Hoots and Roehrich, 1988). The predictions made with this propagator are only accurate to within several days but it allows the major perturbing forces on a satellite to be modelled while being computationally fast, which allows simulations of all the objects in orbit to be performed. TLEs are not provided with uncertainty information, therefore their covariance has to be estimated. However, these TLE uncertainty estimation methods provide only approximate accuracy of the orbital elements, not the actual covariances. Lastly, TLEs are officially said to be unsuitable for conjunction screenings. However, they do remain the only publicly available source of ephemerides. They were also used for operational collision avoidance performed by the European Space Agency (Flohrer et al., 2011) and other organisations that did not maintain their own catalogue of space objects before the US Strategic Command (USSTRATCOM) offered to issue conjunction warnings to spacecraft operators.