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Cost and risk assessment for spacecraft operation decisions caused by the space debris environment☆

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ABSTRACT

Space debris is a topic of concern among many in the space community. Most forecasting analyses look centuries into the future to attempt to predict how severe debris densities and fluxes will become in orbit regimes of interest. Conversely, space operators currently do not treat space debris as a major mission hazard. This survey paper outlines the range of cost and risk evaluations a space operator must consider when determining a debris-related response. Beyond the typical direct costs of performing an avoidance maneuver, the total cost including indirect costs, political costs and space environmental costs are discussed. The weights on these costs can vary drastically across mission types and orbit regimes flown. The operator response options during a mission are grouped into four categories: no action, perform debris dodging, follow stricter mitigation, and employ ADR. Current space operations are only considering the no action and debris dodging options, but increasing debris risk will eventually force the stricter mitigation and ADR options. Debris response equilibria where debris-related risks and costs settle on a steady-state solution are hypothesized.

1. Introduction

The presence and creation of debris due to human operations in orbit is an ongoing problem. It is recognized that the continuation of current trends in launches and long orbital lifetimes of satellites will only increase the density of debris in both Low Earth Orbit (LEO) and High Earth Orbit (HEO) regimes, such as geosynchronous (GEO) [1–4]. This has led to increased use of passivation techniques to avoid on-orbit break-ups, improved spacecraft shielding against small object impacts, and the mitigation guidelines of a 25-year lifetime rule for LEO and sub- or super-synchronous graveyard orbit for GEO. Active Debris Removal (ADR) has also been suggested, and widely studied, as a possible method for reducing debris density. However, ADR techniques considered in the literature, such as robotic re-orbiting [5–8], electrodynamic tethers [9,10], laser ablation [11–14], ion shepherd methods [15–18], tethered tugging of large LEO debris [7,19–24], harpoons or nets to capture debris [7,25,26], and electrostatic tractors [27–30], are economically costly, technically challenging to develop, and often overshadowed by political hurdles [31,32]. More recently, Just-in-time Collision Avoidance (JCA) concepts are discussed where the orbit of a large debris object is nudged with an intercept mission to avoid collisions with operating assets or other debris objects [33]. Such technology could be more cost effective than ADR, but requires highly accurate debris tracking and leaves the debris in orbit.

There are many important research papers discussing the projected growth of space debris in the near Earth environment, such as the often cited studies by Liou

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published in References [1] and [2]. Here, the LEO debris population greater than 10 cm in size is modeled for the next 100–200 years, showing that even with an optimistic 50% mitigation compliance rate, the LEO debris population could double over 200 years. Reference [34] shows the debris doubling over 100 years if no mitigation methods are implemented. While such figures are alarming to space debris researchers and experts who understand that these results represent mean trends, the worst-case scenarios could be much more severe. Convincing the general public, policy makers, and research funding agencies that action is required now to control this debris hazard remains a challenge. For example, operators today are able to fly satellites in their desired LEO or HEO orbits with only minimal concern regarding space debris avoidance. When asking unmanned satellite operators how often they need to make an additional maneuver to avoid debris, the common answer is that this almost never happens. If there is a warning of a possible conjunction, the uncertainty of the miss distance is often so large that the warning is ignored, or the conjunction is accounted for in regular orbit maintenance maneuvers, thus not expending additional fuel. Therefore, considering that space debris strikes have had a minimal documented impact on current satellite operations, doubling or tripling debris-related risk – especially 100–200 years in the future – is unlikely to convince policy makers or operators to demand strong space debris mitigation and remediation policies over the next decade. There are significant on-going efforts to better attribute many anomalies and failures of unknown cause to their trigger.[1] some of these anomalies may have been caused by non-trackable debris, the true current space debris threat has not yet been captured or communicated.

Reference [35] discusses the need to consider near-term ADR (remediation) developments and stronger end-of-life disposal guidelines (mitigation). The complexity of considering LEO space debris risks is shown by how the fragment sizes and orbit types impact the risk to the space operator. Vance proposes in Reference [36] an economic metric by which competing debris removal methods are evaluated for the highly populated sun-synchronous orbit regime. However, this orbit-specific analysis only considers cost due to the economic value of the satellite, and the environmental cost if the satellite experiences a fragmentation collision. Risk costs of the de-orbit maneuver, costs incurred by precision tracking of the debris to be removed, and political cost considerations are not included.

Thus, this paper investigates a means to bridge the divide between space debris researchers that support near-term action (begin ADR within a decade) to control the space debris population, and most space operators that are successfully operating satellites without demanding stronger mitigation and remediation methods. In particular, this study highlights the complex decision logic that space operators face when considering the total space debris-related cost. The available debris response options during a mission are classified under one of the following categories:

1. Make no mission changes in response to space debris.
2. Respond to conjunction warnings by dodging close-approach debris or using JCA.
3. Follow current or more stringent end-of-mission *mitigation* guidelines.
4. Begin active debris removal or *remediation* in the orbit regime of interest.

Currently only elements of options 1 or 2 are employed in the operator community. Implementing shorter post-mission orbital lifetimes (element of option 3) can have a significant impact on the commercial viability of launch operation if it is not uniformly adopted. Elements of option 4 are discussed and researched, but economically viable and proven solutions are at least a decade away from being flight ready. The natural question arises: At what point is the total space-debris-related cost large enough to warrant options 3 or 4? This paper considers a high-level decision logic from an operator's point of view on how to respond to a space debris threat including not only direct mission-related financial considerations, but also indirect costs such as tracking or debris avoidance analysis, environmental and political considerations. While earlier studies focus on the overall space debris growth, the impact to the individual space operator can vary by orders of magnitude depending on where the satellite is flown, the mission duration, and the mission objectives (e.g., high-value commercial communication satellite versus low-cost CubeSat technology demonstration).

The paper outline is as follows. First, the present-day status of the LEO and GEO debris environment is reviewed. Next, the overall space debris costs and associated response decision factors are discussed, illustrating how these can vary drastically across mission types. A mission scenario case study illustrates how different mission types are impacted very differently by space debris, leading to the current range of operator responses to debris-related risk. This is important when trying to bridge the divide between space debris researchers and operators/policy makers. A fundamental question is asking whether common mitigation guidelines for all LEO operators make sense. Another important aspect to consider is what happens if stronger mitigation or ADR measures are implemented. In particular, would these ADR efforts continue indefinitely, or could the debris control methods stabilize to new operational equilibriums? Finally, the possible operator responses and costs to the debris threat are reviewed and discussed.

2. Present day space debris congestion

LEO is the most studied orbit regime for orbital debris – this is because it is the most densely populated regime (using spherical shell densities), as illustrated in Fig. 1, and many commercial, government, and military satellites are in this regime. GEO has the next largest spherical density, while Oltrogge states that its volume density can be as critical as

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[1] http://www.integrity-apps.com/events/scaf/.