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Controlling the growth of future LEO debris populations with active debris removal

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ABSTRACT

Active debris removal (ADR) was suggested as a potential means to remediate the low Earth orbit (LEO) debris environment as early as the 1980s. The reasons ADR has not become practical are due to its technical difficulties and the high cost associated with the approach. However, as the LEO debris populations continue to increase, ADR may be the only option to preserve the near-Earth environment for future generations. An initial study was completed in 2007 to demonstrate that a simple ADR target selection criterion could be developed to reduce the future debris population growth. The present paper summarizes a comprehensive study based on more realistic simulation scenarios, including fragments generated from the 2007 Fengyun-1C event, mitigation measures, and other target selection options. The simulations were based on the NASA long-term orbital debris projection model, LEGEND. A scenario where, at the end of mission lifetimes, spacecraft and upper stages were moved to 25-year decay orbits, was adopted as the baseline environment for comparison. Different annual removal rates and different ADR target selection criteria were tested, and the resulting 200-year future environment projections were compared with the baseline scenario. Results of this parametric study indicate that (1) an effective removal strategy can be developed using a selection criterion based on the mass and collision probability of each object, and (2) the LEO environment can be stabilized in the next 200 years with an ADR removal rate of five objects per year.

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1. Introduction

Fifty years after the launch of Sputnik 1, satellites have become an integral part of human society. Unfortunately, the ongoing space activities leave behind an undesirable byproduct: orbital debris. As of 1 June 2008, more than 17,000 objects were tracked by the US Space Surveillance Network (SSN). The majority of them, approximately 12,000, have their orbital elements maintained in the US Satellite Catalog. The cataloged objects are approximately 10 cm and larger. Other than the 800 or so active payloads, this population is dominated by breakup fragments, spent upper stages, and retired payloads.

The growth of the orbital debris populations has been a concern to the international space community for decades. Many policies and procedures are established to address the issue. A good example is the adoption of the space debris mitigation guidelines by the United Nations in 2007 [1–2]. However, recent numerical studies have shown that the debris environment in low Earth orbit (LEO, defined as the region up to 2000 km altitude) has reached a point where the debris populations will continue to increase even if all future launches are suspended [3–4]. The driver for the increase is mutual collisions among orbiting objects, a phenomenon

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predicted by Kessler and Cour-Palais [5]. In reality, the population increase will be worse than the "no future launches" prediction because satellites will continue to be launched and major breakup events, such as the Fengyun-1C (FY-1C) breakup [6] and Briz-M explosion [7], may continue to occur. Even with a full implementation of the commonly-adopted mitigation measures, the LEO population growth appears to be inevitable. To better preserve the near-Earth environment for future space generations, additional remediation measures must be considered.

The concept of active debris removal (ADR) is not new, although there are major difficulties in the removal technique and the high cost associated with the actual implementation. Other issues, such as ownership, policy, and liability, also prevented ADR from being seriously considered in the past. However, the recent assessments of the LEO debris environment warrant a reconsideration of the option. From a modeling perspective, it is a straightforward task to examine the effect of ADR, and that is precisely the objective of the present study. The goals are to use the most recent NASA orbital debris evolutionary model to (1) develop simple, reliable, and objective ADR object selection criteria, (2) quantify the effectiveness of different ADR scenarios, (3) explore ADR strategies needed to stabilize or even reduce the future debris environment, and (4) provide guidance for the development of removal technology.

The ADR modeling study was initiated by the NASA Orbital Debris Program Office in late 2006. The first effort was focused on the object selection criteria. A non-mitigation (sometimes referred to as the business-as-usual) scenario was used as the baseline for comparison. The main conclusion of the study was that the product of the mass and collision probability of each object was an excellent removal selection criterion (see also Section 2.2). Numerical simulations based on this criterion showed most objects in the critical inclination and altitude regimes were identified and removed, and the LEO debris population growth, using the non-mitigation scenario as a benchmark, was significantly reduced. These results were presented at the 2007 International Astronautical Congress [8]. The present study differs from the previous one in the following areas: (1) the tracked FY-1C fragments were added to the initial environment for future projection, (2) a more realistic scenario, where the commonly-adopted mitigation measures were implemented for future launches, was selected as the benchmark, and (3) the focus was on what would be needed to stabilize (*i.e.*, no growth beyond the current levels) the future LEO debris environment.

2. Modeling tool

The LEO-to-GEO Environment Debris (LEGEND) model is capable of simulating the historical and future debris populations in the near-Earth environment [9,10]. For this study, the historical component in LEGEND covers the period from 1957 to 2007. The model adopts a deterministic approach to mimic the known historical populations. To accomplish this, launched rocket bodies, spacecraft, and mission-related debris (rings, bolts, etc.) are added to the simulated environment based on a comprehensive NASA Orbital Debris Program Office internal database.

Known historical breakup events are reproduced and fragments are created with the NASA Standard Breakup Model, which describes the size, area-to-mass, and velocity distributions of the breakup fragments [11]. The only exception to this process is the FY-1C breakup in January 2007. Since fragments from this event are very different from those of a typical breakup, their distributions are derived from the SSN tracked data [12].

The simulations described in this paper were completed in February 2008. Based on the catalog data available at that time, a total of 1536 FY-1C fragments had both good orbital elements and area-to-mass ratios derived from their orbital element histories and were estimated to be larger than 10 cm in size. Only these objects were included in the simulations. Although more catalog data became available later and additional 10 cm and larger FY-1C fragments were identified, the difference should not affect the overall outcome of the present study in any significant manner.

2.1. Benchmark scenario

The future projection component of LEGEND covers 200 years from the end of the historical simulation. Future launch traffic was simulated by repeating the 1999-to-2006 launch cycle. The following postmission disposal (PMD) mitigation measures were implemented. Rocket bodies, after launch, were moved to 25-year decay orbits or to LEO storage orbits (above 2,000 km altitude), depending on which option required the lowest change in velocity for the maneuvers. In most cases, the 25-year decay orbit was the preferred choice for vehicles passing through LEO. The mission lifetimes of future payloads were set to 8 years. At the end of the mission lifetime, each payload was moved to either the 25-year decay orbit or to an LEO storage orbit. The PMD success rate was set to 90%.

No explosions or deliberate breakups were allowed for future rocket bodies and payloads. Collision probabilities among objects were estimated with a fast, pair-wise comparison algorithm in the projection component. Only objects 10 cm and larger were considered for potential collisions. This size threshold is historically the detection limit of the SSN sensors, and more than 95% of the debris population mass is in objects 10 cm and larger. A total of 100 Monte Carlo (MC) simulations were carried out for future projection, and the averages were calculated for comparison.

2.2. ADR scenarios

The first step for ADR simulations was the development of target selection criteria. The following objects were not considered for removal since they did not significantly contribute to the growth of future LEO debris populations: objects smaller than 10 cm in size, objects with perigee altitudes above 2000 km, and objects with eccentricities greater than 0.5. In addition, operating payloads (assuming a nominal lifetime of 8 years) and breakup fragments were excluded from removal consideration.