(Preprint) AAS 11-254

ACTIVE DEBRIS REMOVAL – A GRAND ENGINEERING CHALLENGE FOR THE TWENTY-FIRST CENTURY

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The collision between Iridium 33 and Cosmos 2251 in 2009 has reignited interest in using active debris removal to remediate the near-Earth orbital debris environment. A recent NASA study shows that, in order to stabilize the environment in the low Earth orbit (LEO) region for the next 200 years, active debris removal of about five large and massive (1 to more than 8 metric tons) objects per year is needed. To develop the capability to remove five of those objects per year in a cost-effective manner truly represents a grand challenge in engineering and technology development.

INTRODUCTION

The growing orbital debris problem has been known to the debris research community for decades. However, the public was, in general, unaware of the problem until the anti-satellite test (ASAT) conducted by China in 2007 and the collision between Cosmos 2251 and the operational Iridium 33 in 2009. The latter event, in particular, underlined the potential of an ongoing collision cascade effect, commonly known as the Kessler Syndrome in the environment (Reference 1). A 2006 NASA analysis of the instability of the debris population in the low Earth orbit (LEO, the region below 2000 km altitude) shows that the environment has reached a point where the debris population will continue to increase in the next 200 years, even without any future launches (Reference 2). The increase is driven by fragments generated via accidental collisions among existing objects in LEO. In reality, the situation will be worse than this prediction because satellite launches will continue and unexpected major breakups may continue to occur. Mitigation measures commonly adopted by the international space community (such as the 25-year rule) will help, but will be insufficient to stop the population growth. To better preserve the near-Earth space environment for future generations, active debris removal (ADR) should be considered.

The definition of ADR is to remove debris beyond the guidelines of the currently-adopted mitigation measures. Therefore, lowering the orbit of a satellite at its end of life to force it to naturally decay within 25 years ("the 25-year rule") or raising the satellite's orbit to a graveyard region are not considered ADR. Although the idea of ADR is not new, due to the monumental technical, resource, operational, legal, and political challenges associated with removing objects from orbit, it was not widely considered feasible. However, recent major breakup events and environment modeling efforts have certainly reignited interest in using active debris removal to remediate the environment. This trend is further highlighted by the National Space Policy of the

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United States of America, released by the White House in June 2010, where NASA and the Department of Defense are directed to "pursue research and development of technology and techniques…, to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment."

TARGETS FOR ACTIVE DEBRIS REMOVAL

Currently, there are close to 6000 tons of materials in Earth orbit, and more than 40% of the total (~2,500 tons) resides in LEO. In terms of number, the U.S. Space Surveillance Network (SSN) is tracking more than 22,000 objects larger than about 10 cm. Additional optical and radar data indicate that there are approximately 500,000 debris larger than 1 cm, and more than 100 million debris larger than 1 mm in the environment. Because of the high impact speed between orbiting objects in LEO (typically 10 km/sec, but could reach up to 15 km/sec), debris as small as 0.2 mm poses a realistic threat to Human Space Flight (EVA suit penetration, Shuttle window replacement, etc.) and other critical national space assets.

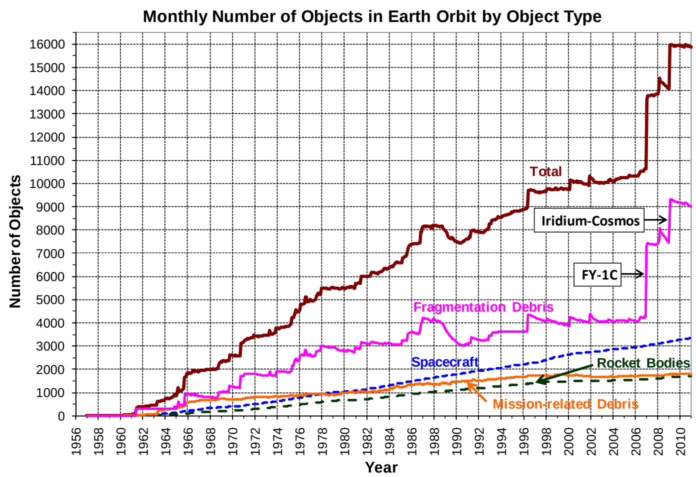

Figure 1. Growth of the Historical SSN Catalog Population.

Figure 1 shows the growth of the historical SSN catalog population. The SSN is tracking about 22,000 objects, but approximately 6000 of them have yet to be entered into the catalog. The top curve represents the total population and the four curves at the bottom represent the population breakdown. The two recent jumps were due to fragments generated from the ASAT test and the collision between Iridium 33 and Cosmos 2251. Fragmentation debris have dominated the environment from the very beginning. Before the ASAT test, fragmentation debris were almost all explosion fragments. Today, the ratio of collision fragments to explosion fragments is about 1:1. It is expected that the future environment will be dominated by fragments generated via accident collisions between satellites.

The two key elements for successful and effective ADR operations for environment remediation are to focus on regions where the debris problem is the most critical and to target objects that have the greatest potential of contributing to the future debris growth. A recent study on the environment projection shows that the debris population growth in the geosynchronous (GEO) region and in the medium Earth orbit (MEO, between LEO and GEO) region is moderate, with just a few accident collisions predicted in the next 200 years (Reference 3). The environment in LEO, on the other hand, is very different. Even with a good implementation of mitigation measures commonly-adopted by the international space community, the population will continue to increase. Therefore, the focus of ADR in the near future should be on LEO.

In general, small debris are generated from the breakup or degradation of large and massive upper stages or payloads. For small debris that are generated below about 1000 km altitude, the atmospheric drag will force them to decay over time. How fast each object decays depends on its ballistic coefficient. In other words, the small debris environment in LEO is very dynamic. For long-term environment preservation, it may not be very efficient and effective to target small debris for removal. The solution for long-term environment remediation is to address the root cause of the problem – large and massive spent upper stages and retired payloads.

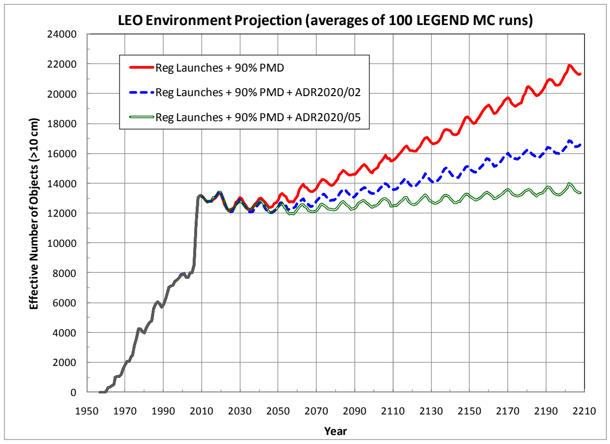

Figure 2. Projected Growth of the LEO Population Based on Three Different Scenarios.

A 2009 modeling study by the NASA Orbital Debris Program Office indicates that, in order to maintain the LEO debris population at a constant level for the next 200 years, an active debris removal of about five objects per year is needed (Reference 4). Figure 2 shows the predicted trend in the next 200 years. The results are averages from 100 Monte Carlo simulations based on the NASA long-term debris evolutionary model LEGEND (References 5 and 6). The scenario for the top curve assumes a regular launch cycle and a 90% success rate of the commonly-adopted postmission disposal (PMD) measures in the next 200 years. The scenarios for the middle and bottom curves further assume an ADR implementation starting from the year 2020, with the removal rates of two objects per year and five objects per year, respectively. It is clear that the LEO debris population can be maintained at an approximately constant level with an ADR of about five objects per year. If more than five objects are removed per year on a routine basis, the future LEO environment can actually be better than what it is today.

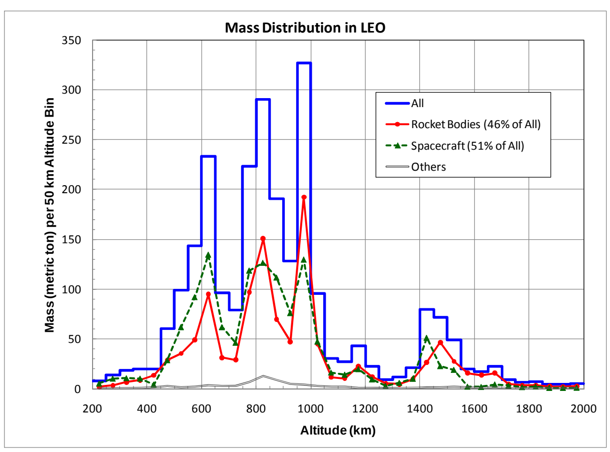

Figure 3. Mass Distribution in LEO.

The objects identified for removal in the simulations described above are those with the highest mass and collision probability products in the environment. The justification for this selection criterion is that the best way to limit the generation of collision fragments in the future is to remove objects which have (1) the highest collision probabilities with other objects in the environment and (2) the potential of generating the greatest amount of fragments upon collision. Analyses from the study indicate that, in general, these objects are spacecraft (S/Cs) and rocket bodies (R/Bs) at least several meters in dimensions, with masses ranging from one to more than eight metric tons. This is not surprising because these objects dominate the three mass concentrations in LEO (Figure 3). In particular, the peaks around 800 and 1000 km altitudes are the sources of future collision activities. Note the 350 ton International Space Station (at 350 km altitude) is not included in the figure.

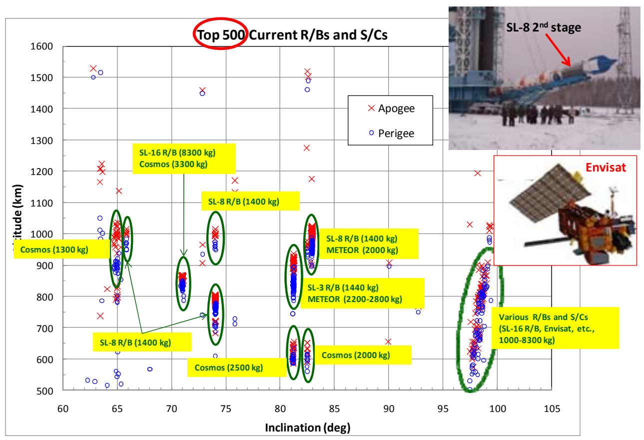

Figure 4. Potential LEO Objects for Removal.

Figure 4 shows the R/Bs and S/Cs with the highest (top 500) mass and collision probability products in the current environment. Each object is represented by two points – apogee (cross) and perigee (circle). These objects reside in several altitude regions up to about 1000 km (see also Figure 3), and concentrated in seven narrow inclination bands. There is no obvious concentration in their right ascension of the ascending nodes. The prograde region is dominated by several well-known classes of vehicles: SL-3 R/Bs (Vostok second stages; 2.6 m diameter by 3.8 m length; 1440 kg dry mass), SL-8 R/Bs (Kosmos 3M second stages; 2.4 m diameter by 6 m length; 1400 kg dry mass), SL-16 R/Bs (Zenit second stages, 4 m diameter by 12 m length; 8300 kg dry mass), and various Meteor-series and Cosmos S/Cs (masses ranging from 1300 to 2800 kg). Below 1100 km altitude, the numbers of SL-3, SL-8, and SL-16 R/Bs on nearly circular orbits are 39, 211, and 18, respectively. The corresponding mass totals for SL-3, SL-8, and SL-16 R/Bs in this region are approximately 56, 295, and 149 tons, respectively. They account for 20% of the total mass in LEO. Objects in the retrograde region are more diverse. They include, for example, Ariane R/Bs (1700 kg dry mass), CZ-series R/Bs (1700 to 3400 kg dry mass), H-2 R/Bs (3000 kg dry mass), SL-16 R/Bs, and S/Cs such as Envisat (8000 kg) and meteorological satellites from various countries. The total mass in the retrograde region is about 220 tons, with approximately equal contributions from R/Bs and S/Cs.

If ADR is to be implemented in the near future as a means to stabilize the LEO environment, objects in Figure 4 should be high on the priority list for removal. In general, R/Bs should be considered first because they have simple shapes/structures and belong to only a few classes (see the two sample R/B and S/C images at the upper-right corner of Figure 4). In addition, R/Bs do not carry any sensitive instruments, so it will be easier to achieve an international agreement on selecting them as removal targets. However, some of the R/Bs may still carry leftover propellant in pressurized containers. Any capture operations of those R/Bs will have to be carefully conducted to reduce the possibility of explosion.

TECHNOLOGY AND ENGINEERING CHALLENGES FOR ACTIVE DEBRIS REMOVAL

To remove five of the objects described above in a cost-effective manner on a yearly basis truly represents a grand challenge in engineering and technology development. An end-to-end debris removal operation includes, in general terms, launches, propulsion, precision tracking, guidance, navigation and control, orbit rendezvous, stabilization (of the tumbling motion), capture/attachment, and deorbit/graveyard maneuvers of the targets. Some of the technologies involved in the operations do exist, but the difficulty is to make them more cost effective. For example, an ADR system deigned to remove just a single object is probably cost-prohibited. A system designed for multiple-object removal that can be launched as a secondary payload to other missions is the preferred approach.

Table 1. Components of ADR Operations

Operations	Technology Challenges
Launch	Low cost
Propulsion	Solid, liquid, tether, plasma, laser, drag-enhancement devices, *etc.*
Precision Tracking	Ground or space-based
GNC and Rendezvous	Autonomous, non-cooperative targets
Stabilization (of the tumbling targets)	Physical or non-physical (how)
Capture or Attachment	Physical (where, how) or non-physical (how)
Deorbit or Graveyard Orbit	When, where, reentry ground risks

Table 1 outlines the general challenges and some potential options associated with ADR operations. The technology readiness levels (TRLs) of the listed options are all different. Some are more mature than others. For example, electrodynamic or momentum-exchange tethers have been proposed as a promising propellant-less system to provide propulsion for debris removal. However, the TRL of the technology is very low. It will require major efforts to make it a mature and reliable system. Detailed trade studies must be performed to evaluate the pros and cons, including cost, of different operational approaches. For example, large-area drag-enhancement devices, such as a balloon or a solar sail, can be used to deorbit a spent R/B from as high as 1000 km altitude, but the large cross-sectional areas of the devices will increase the impact risks to other vehicles in the environment.

New technologies will also be needed because of the new challenges associated with the ADR operations. One such challenge is the handling of the tumbling motion of a non-cooperative ADR target. Many of the large R/Bs and S/Cs may have non-trivial tumble rates (on the order of 1 rpm or more). This will cause a major problem for proximity operations, including orbit rendezvous and capture or attachment operations. To better characterize the tumble states (and how they change over time, if any) of the potential ADR targets, new ground-based radar and optical data will be needed. This knowledge will then drive the necessary development of new innovative techniques to stabilize large, massive, and fast-tumbling targets for any ADR operations that will require physical contact with the objects.

CONCLUSION

This paper provides an assessment of the current debris environment and outlines the need of using ADR to preserve the future environment. It is shown that the debris population in LEO can be maintained at a constant level by a good implementation of the commonly-adopted mitigation measures and an ADR of about five objects per year. However, the objects identified for removal are large and massive upper stages and payloads. Many of them may have fast tumbling rates and at least some of the upper stages may have leftover fuels stored in pressurized containers. The end-to-end operations of removing five such objects on a yearly basis in a cost-effective manner will certainly require major innovation in engineering and technology development. Cooperation, collaboration, and coordination at the national and international levels will be needed to develop a strategic plan for ADR operations and to identify appropriate resources to support development of the needed technologies and techniques. In addition, policy, ownership, liability, and other non-technical issues will have to be addressed before ADR can be implemented for environment remediation.

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