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An active debris removal parametric study for LEO environment remediation

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Abstract

Recent analyses on the instability of the orbital debris population in the low Earth orbit (LEO) region and the collision between Iridium 33 and Cosmos 2251 have reignited interest in using active debris removal (ADR) to remediate the environment. There are, however, monumental technical, resource, operational, legal, and political challenges in making economically viable ADR a reality. Before a consensus on the need for ADR can be reached, a careful analysis of its effectiveness must be conducted. The goal is to demonstrate the need and feasibility of using ADR to better preserve the future environment and to explore different operational options to maximize the benefit-to-cost ratio. This paper describes a new sensitivity study on using ADR to stabilize the future LEO debris environment. The NASA long-term orbital debris evolutionary model, LEGEND, is used to quantify the effects of several key parameters, including target selection criteria/constraints and the starting epoch of ADR implementation. Additional analyses on potential ADR targets among the existing satellites and the benefits of collision avoidance maneuvers are also included.
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Keywords: Orbital debris; Modeling; Active debris removal

1. Introduction

The 2009 collision between Iridium 33 and Cosmos 2251 highlighted the orbital debris problem – a side effect of more than 50 years of space activities. This problem was first recognized by Kessler and Cour-Palais (1978), and then by other researchers. For over a decade, the international space community collaborated to develop the commonly-adopted mitigation measures in the hope of alleviating the problem. However, recent studies on the instability of the debris population in the low Earth orbit (LEO, defined as the region below 2000 km altitude) indicate that the environment has reached a point where collisions among existing objects will force the LEO population to increase, at least in the next 200 years, even without any new launches (Liou and Johnson, 2006, 2008). In reality, the situation will be worse than this "no future launches" scenario since satellite launches will continue and unexpected major breakups may continue to occur. Therefore, to better preserve the environment for future generations, active debris removal must be considered (Liou and Johnson, 2009a; Liou et al., 2010).

Active debris removal (ADR) involves removing objects from orbit above and beyond the currently-adopted mitigation measures. By this definition, lowering the orbit of a satellite at its end of life to force the satellite to naturally decay within 25 years ("the 25-year rule") or raising its orbit to a graveyard region are not considered active debris removal. The idea of ADR is not new, but it has never been widely accepted as necessary or feasible, primarily due to the tremendous technical challenges and cost involved. In addition, there was a lack of modeling tools to quantify the benefits of debris removal. The recent instability studies and the collision between Iridium 33 and Cosmos 2251 have certainly reignited interest in using ADR to remediate the environment. In December 2009, the first International Conference on Orbital Debris Removal was cohosted by NASA and DARPA near Washington, D.C., followed in

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April 2010 by the Debris Mitigation Workshop, organized by the International Science and Technology Center in Moscow, and then in June 2010, by the First European Workshop on Active Debris Removal, organized by CNES in Paris. This trend was further highlighted by the latest National Space Policy of the United States of America, released on 28 June 2010 by the White House, in which the President explicitly directs NASA and the Department of Defense to "Pursue research and development of technologies and techniques,..., to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment" (Obama, 2010).

This paper's intent is to further advance the ADR simulations and analyses from previous studies to explore different factors that might significantly affect the benefits of ADR. The focus of this study is on environment remediation modeling only. Issues such as cost, removal technology, ownership, legal and liability, guidelines, and policy are outside the scope of the paper and will not be addressed. Section 2 provides a short review summary of the historical and current debris environment, including key information relevant to ADR simulations. Section 3 contains the main part of the parametric study. It is organized, in logical order, into a "Top 10 list" format. Results from the parametric study are analyzed to address the questions and to quantify the differences between different test scenarios.

2. Growth of the historical debris population

Fig. 1 illustrates the monthly increase of objects in Earth orbit as cataloged by the US Space Surveillance Network (SSN). The detection limit of the SSN sensors is approximately 10 cm. The total population is represented by the top curve and the population breakdown is represented by the four curves below it. Almost from the beginning, the environment is dominated by fragmentation debris. The majority of the 203 known historical breakups between 1957 and 2010 were explosions. However, two recent on-orbit collisions – the anti-satellite test on the Fengyun-1C (FY-1C) weather satellite conducted by China in 2007 and the collision between Iridium 33 and Cosmos 2251 in 2009, dramatically changed the landscape of the LEO environment. Fragments generated by these two events more than doubled the population below 1000 km altitude (Fig. 2). The collision of Iridium 33 and Cosmos 2251 is of particular interest. The event signaled a well-accepted trend that the future environment will be dominated by fragments generated via similar accidental collisions, not explosions.

Currently, in terms of mass, there are about 5900 tons of material in Earth orbit (not including the International Space Station), and more than 40% of the total (~2500 tons) resides in LEO. As shown in Fig. 3, there are three mass concentrations in LEO – around 600, 800, and 1000 km altitudes. Rocket bodies (R/Bs) and spacecraft (S/Cs) represent about 97% of the mass in the region. The former dominates the 800 and 1000 km peaks, whereas the latter dominates the 600 km peak. Figs. 2 and 3 define the two key parameters of future collision activities in the environment. Additional discussions on the implication of these two parameters for ADR are described in the sections below.

3. The top 10 list

This parametric study focused on 10 cm and larger objects because approximately 99% of the total mass in

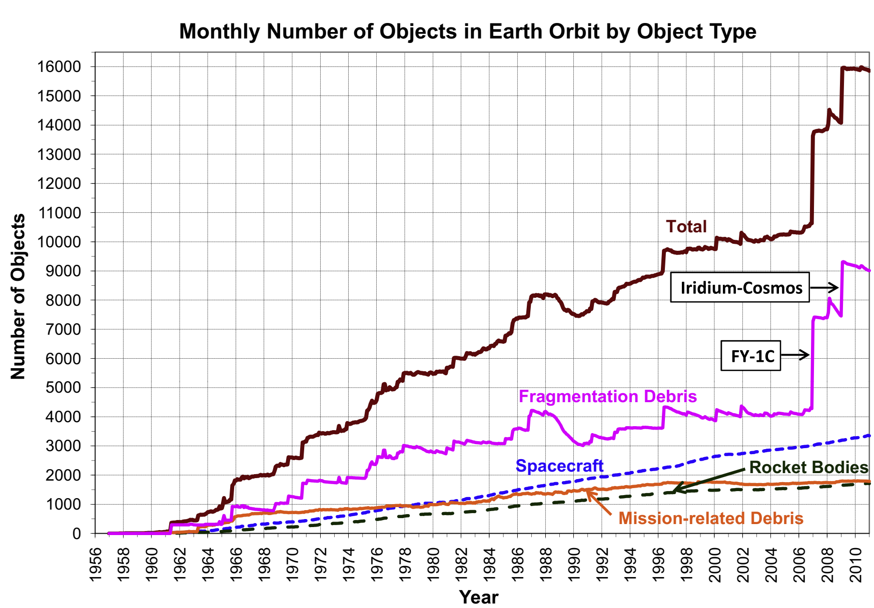

Fig. 1. The monthly increase of objects as cataloged by the US Space Surveillance Network (SSN). The FY-1C ASAT test and Iridium 33/Cosmos 2251 collision fragments are responsible for the two recent major spikes.

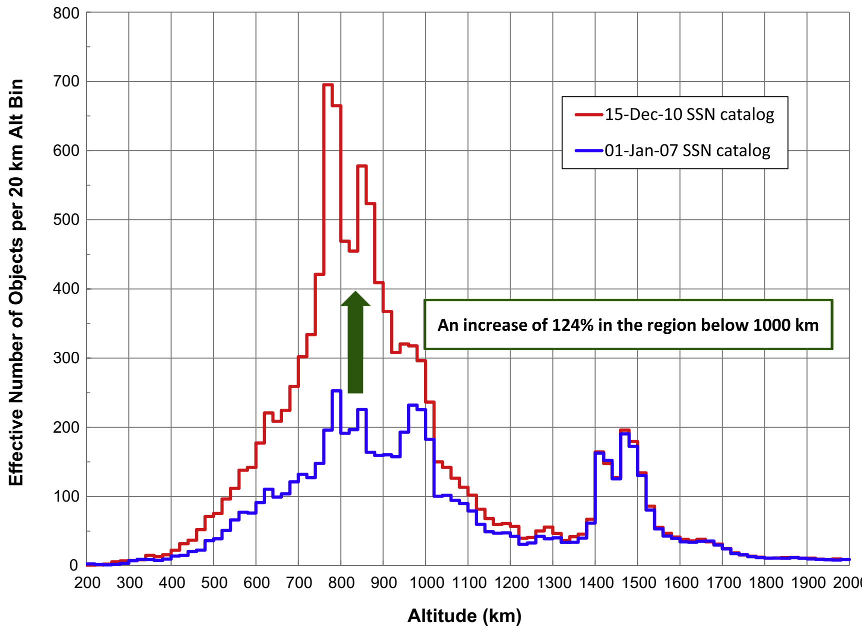

Fig. 2. Distributions of the SSN catalog objects in LEO at two different snapshots. The FY-1C ASAT test and Iridium 33/Cosmos 2251 collision fragments contribute to the majority of differences between the two curves.

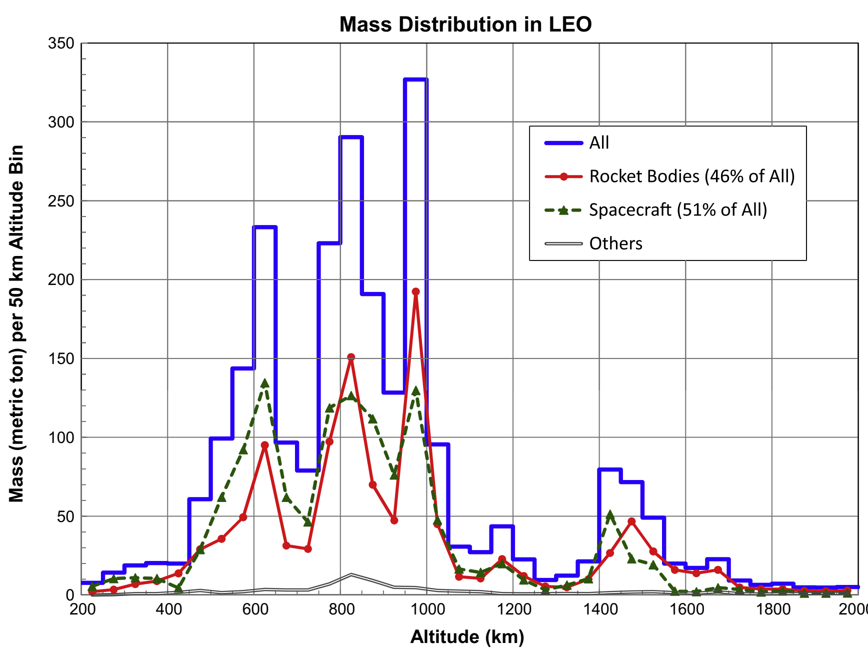

Fig. 3. Mass distribution in LEO. About 97% of the total mass is in rocket bodies and spacecraft. The ISS (~350 tons) is not included in the distribution.

orbit belonged to objects in this size regime. Numerical simulations were carried out using NASA's orbital debris evolutionary model, LEGEND (an LEO-to-GEO environment debris model). Descriptions of the model can be found in Liou et al. (2004) and Liou (2006). The future environment projection was limited to 200 years. This choice was somewhat subjective, but 200 years appeared to be a good balance between too short-sighted and too impractically long for this environmental study. The first half of the Top 10 list covers questions that have been addressed before (Liou and Johnson, 2009a; Liou et al., 2010). However, it is important to provide updated simulation results since the LEO environment was significantly altered after the FY-1C ASAT test and the collision between Iridium 33 and Cosmos 2251 (see also Figs. 1 and 2). These updated results also pave the way for discussions about the remaining topics on the list.

3.1. Which region has the fastest projected growth rate and the highest collision activities?

The projected growth of the near-Earth debris environment, based on a "non-mitigation" (also known as the "business-as-usual") scenario, is shown in Fig. 4. The region between 35,586 and 35,986 km altitudes (i.e., within 200 km from the geosynchronous orbit) is defined as GEO. The region between LEO and GEO is defined as the medium Earth orbit (MEO). The three curves are averages from 100 Monte Carlo (MC) simulations. Error bars are the one sigma uncertainties of the averages. This scenario assumes no mitigation measures are applied to any current or future satellites. In essence, the projected growth of the debris populations under this assumption represents the worst-case scenario. It can be seen that the LEO population would follow a rapid non-linear increase in the next 200 years. This is a well-known trend that was the motivation for developing the currently-adopted international and various national mitigation measures over the last 15 years. The projected growth in MEO and GEO, on the other hand, is very different from that in LEO. Even under this worst-case scenario, the growth is moderate. Only a few accidental collisions between $\geqslant$10 cm objects are predicted in MEO and GEO in the next 200 years. The currently-adopted mitigation measures, such as the end-of-life maneuvers in GEO, will further limit the population growth in these two regions. Therefore, by comparison, active debris removal is not a priority in MEO or GEO. When resources are limited, the focus of ADR should be on LEO.

3.2. Can the commonly-adopted mitigation measures stabilize the future LEO environment?

The study by Liou and Johnson (2006) indicated that the LEO debris population had reached a point where the environment was unstable and mutual collision would force the population to increase even without any future launches. Fig. 5 shows the result of an updated simulation where the historical environment was extended through the end of 2009, followed by a 200-year future projection under the same "no future launches" assumption. The major difference in the historical component between the new (dashed curves) and the 2006 (solid curves) simulations is the inclusion of fragments generated from the FY-1C breakup and the Iridium 33/Cosmos 2251 collision. The total population reflects the balance between source and sink. The former includes fragments generated by new breakups while the latter includes the natural decay of objects. Overall, the net impact of the FY-1C breakup and the collision between Iridium 33 and Cosmos 2251 is an increase of about 2500 objects (including fragments generated via collisions induced by fragments from these two events) for the next 200 years. The short-term decrease in the total population before 2030 is caused by the rapid decay of high area-to-mass ratio objects, such as multilayer insulation, solar panel, or lightweight composite debris in the FY-1C and Iridium 33 fragment clouds (Liou, 2009; Liou and Johnson, 2009b).

The projected total populations from the two simulations (the top two curves in Fig. 5) follow a similar trend. In other words, even without any future launches the population will not decrease. Rather, fragments generated from mutual collisions among existing objects will force the population to increase over time. In reality, the situation will be

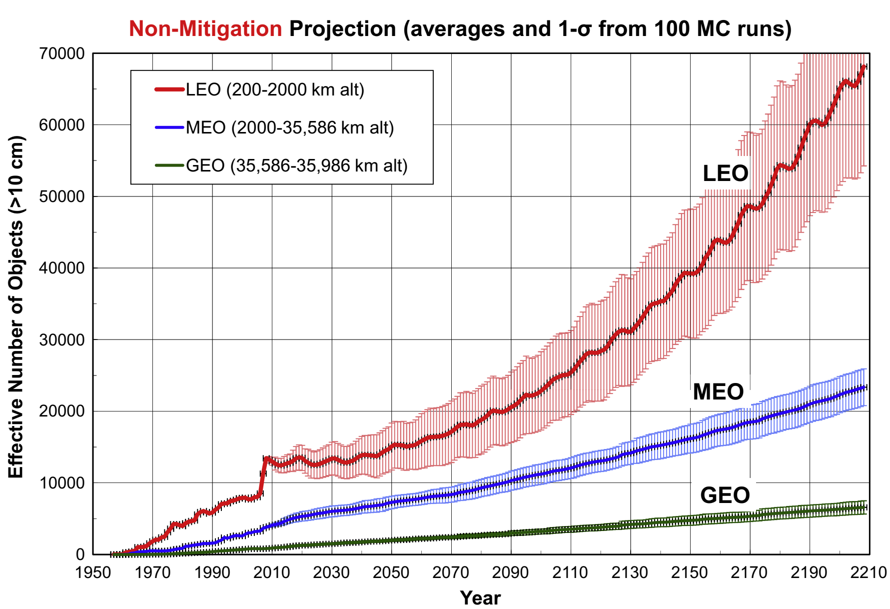

Fig. 4. LEGEND-predicted population growths in LEO, MEO, and GEO, based on the non-mitigation scenario. Each curve is the average of 100 Monte Carlo runs. One sigma standard deviations are also included.

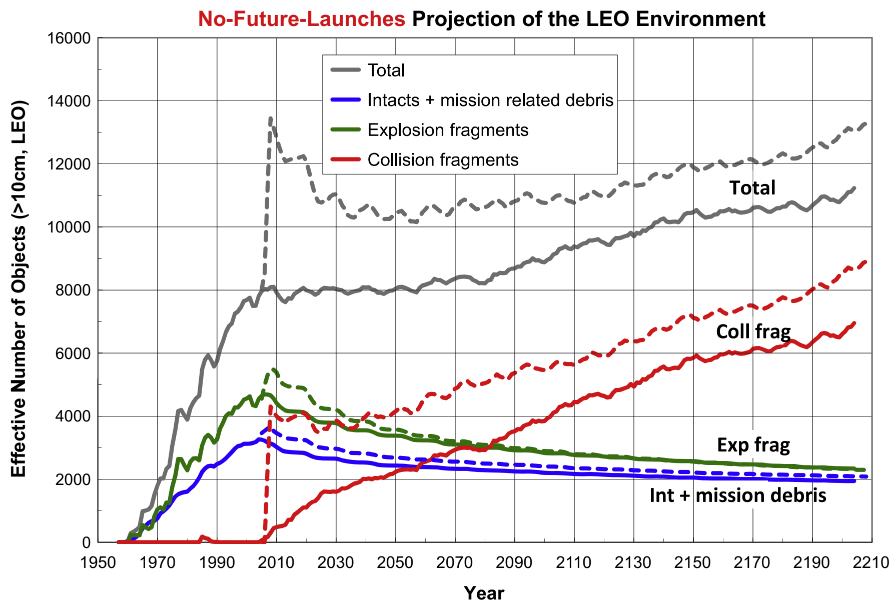

Fig. 5. LEO population growth based on the no-future-launches scenario. Solid curves are from a simulation where the historical component ended in 2006. Dashed curves are from another simulation where the historical component ended in 2009.

worse than the "no future launches" scenario because satellite launches will continue and unexpected major breakups may continue to occur. Postmission disposal, such as the 25-year rule, will help, but will be insufficient to prevent the debris self-generating phenomenon from happening. To preserve the near-Earth space for future generations, ADR must be considered.

3.3. What are the objectives of ADR?

The development of ADR technologies and the implementation of ADR are driven by top-level mission objectives. A well-thought-out strategy and a balanced, long-term roadmap are needed to ensure the best possible outcome for the environment. Common mission objectives should include maximizing the benefit-to-cost ratio and following practical/operational constraints in altitude, inclination, class, or size of the target objects. Specific mission objectives to be evaluated may include, for example, controlling the population growth ($\geqslant$10 cm or others), limiting collision activities, mitigating short- or long-term risks (damage, not necessarily catastrophic destruction) to selected payloads, mitigating risks to human space activities, and so on. These different mission objectives will lead to different requirements and the development of different technologies and techniques.

If, for example, the objective is to reduce the short-term impact risks to the US modules of the international space station (ISS), then the targets for removal are in the small size regime. The US modules on the ISS are equipped with protection shields strong enough to withstand hypervelocity impacts by orbital debris smaller than about 1.4 cm in size (Hyde et al., 2010). Currently the number of objects larger than 1.4 cm with orbits crossing that of the ISS is about 1200. Since the debris population follows a power-law size distribution, the great majority of the 1200 objects, about 800 of them, are between 1.5 and 3 cm. Therefore, to reduce 50% of the ISS-crossing orbital debris in this size regime (1.5–3 cm) will require the deployment of a debris remover/collector with an area-time product on the order of 1000 km^2 year. If this is the requirement, then resources must be allocated to develop supporting technologies. In addition, the potential negative impact of the remover/collector to the environment, including increased risks to active satellites in the region, must be carefully evaluated.

3.4. How can effective ADR target selection criteria for environment remediation be defined?

The future debris environment is likely to be dominated by accidental collision fragments. This phenomenon is popularly known as the "Kessler Syndrome" after the pioneer work by Kessler and Cour-Palais (1978). If the ADR objective is to reduce the population growth and address the root cause of the long-term debris problem, then the effort should focus on limiting accidental collision fragments. The best ADR strategy to meet this objective is to (1) select objects with the highest collision probabilities and (2) select objects with the potential of generating the greatest amount of fragments upon collision. Based on this simple physical argument, an effective environment remediation ADR target selection criterion, R_i, can be defined as:

$$R_i(t) = P_i(t) \times m_i, \quad (1)$$

where m_i is the mass of object i, and $P_i(t)$ is its collision probability at time t (Liou and Johnson, 2009a). In addition to this selection criterion, objects on highly eccentric

GEO-transfer orbits should not be considered for removal because they only spend a small fraction of time below 2000 km and, consequently, contribute very little to the LEO collision activities. Breakup fragments should be excluded as well because their overall mass is small compared with those of rocket bodies and spacecraft (see Fig. 3). The uncertainty in estimating the mass of individual fragments also makes it difficult to apply a mass-dependent selection criterion. Various numerical simulations based on these selection criteria have been conducted and the results indicate that, indeed, these selection criteria are very effective in limiting the population growth in LEO (Liou et al., 2010).

3.5. What are the keys to remediate the future LEO environment?

Fig. 6 summarizes the results of an ADR simulation where fragments from the FY-1C breakup and the Iridium 33/Cosmos 2251 collision were included in the historical environment. All three test cases assumed future launches could be represented by the traffic cycle from the last 8 years. Commonly-adopted postmission disposal (PMD) measures, including the 25-year rule, were applied to R/Bs and S/Cs with a 90% success rate. The two ADR scenarios further assumed a routine yearly ADR was implemented, starting from the year 2020, and criteria described in Section 3.4 were used to prioritize objects for removal. The comparison clearly shows that to maintain the LEO population at a level comparable to the current environment requires (1) a successful implementation of the commonly-adopted mitigation measures and (2) a removal rate of about five objects per year. This scenario, demoted as "Reg Launches + 90% PMD + ADR2020/05" in the figure, is referred to as the "benchmark scenario" and is used for additional comparisons with other test cases in the following sections.

The predicted collision activities of the three scenarios are shown in Fig. 7. The top three curves are the cumulative numbers of "all collisions" – catastrophic and non-catastrophic collisions. The bottom curves depict the cumulative numbers of catastrophic collisions only. A catastrophic collision occurs when the impact energy to target mass ratio exceeds 40 J/g (Johnson et al., 2001). The outcome of a catastrophic collision is the total fragmentation of the target, whereas a non-catastrophic collision only results in minor damage to the target and generates a small amount of fragments. On average, the PMD-only scenario indicates a total of 24 catastrophic collisions in the next 200 years. With the addition of ADR of two objects per year and five objects per year, the numbers of catastrophic collisions reduce to approximately 17 and 14, respectively, in the next 200 years. The breakdown of the collisions, in terms of intact–intact, intact–fragment, and fragment–fragment, is summarized in Table 1.

The "mass in orbit" and "mass removed" distributions from the three test cases are shown in Fig. 8. Under the 90% PMD scenario, the mass in LEO is actually kept at a constant level. However, apparently this level is above the threshold of instability. The removal rate of five objects per year, based on the target selection criteria outlined in Section 3.4, leads to an average of 6.8 tons of mass being removed from orbit every year.

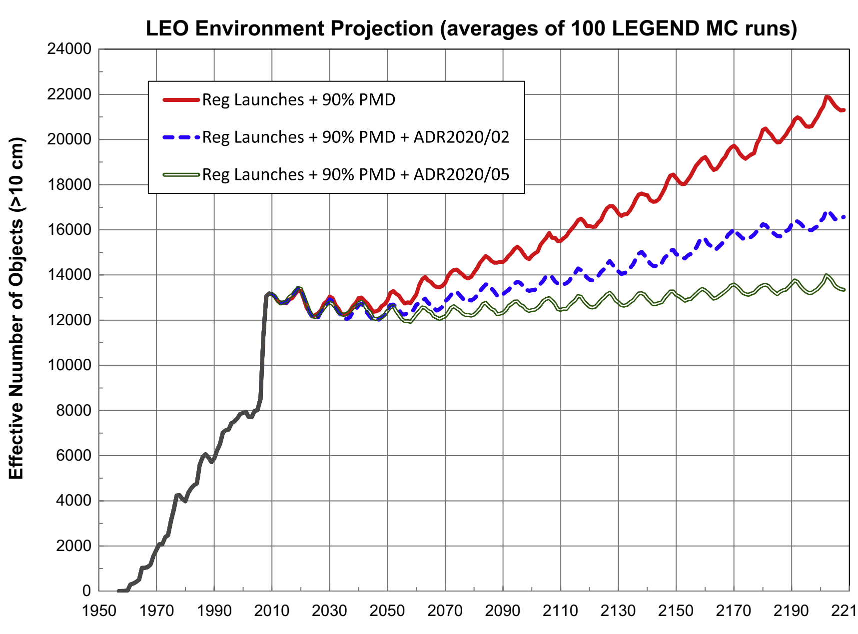

Fig. 6. Simulated LEO population growth as a function of time. ADR2020/02 means active debris removal starts from the year 2020 and the removal rate is two objects per year. ADR2020/05 means active debris removal starts from the year 2020 and the removal rate is five objects per year. To maintain the future LEO population at the current level requires a good implementation of the mitigation measures and an ADR removal rate of about five objects per year starting from the year 2020.

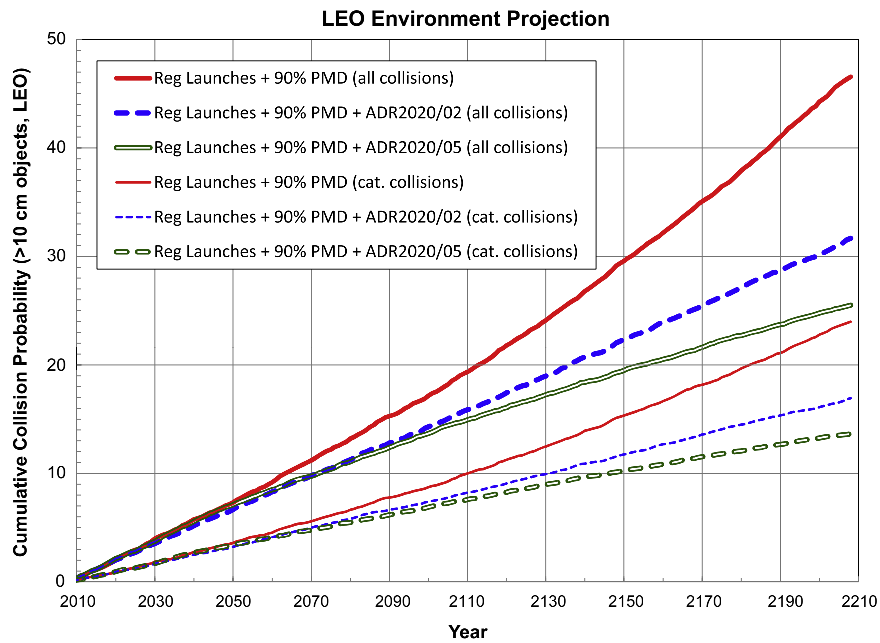

Fig. 7. Predicted collision activities in LEO from three different scenarios. The top three curves show the total numbers of "all" collisions – catastrophic and non-catastrophic collisions. The bottom three curves show just the catastrophic collisions.

Table 1
Predicted LEO collision activities in the next 200 years. Collisions are separated into three categories – those involving two intact objects (i–i), those involving one intact and one fragment (i–f), and those involving two fragments (f–f). The number of catastrophic collisions is indicated by the first number. Non-catastrophic collision is indicated by the second number.

	i–i Collisions cat./non-cat.	i–f Collisions cat./non-cat.	f–f Collisions cat./non-cat.	Total cat./non-cat.
PMD	10.2/0.0	10.9/20.8	3.0/1.6	24.1/22.4
PMD + ADR2020/2	8.2/0.0	7.0/13.2	1.9/1.3	17.1/14.5
PMD + ADR2020/5	6.5/0.0	5.5/10.5	1.8/1.2	13.8/11.7

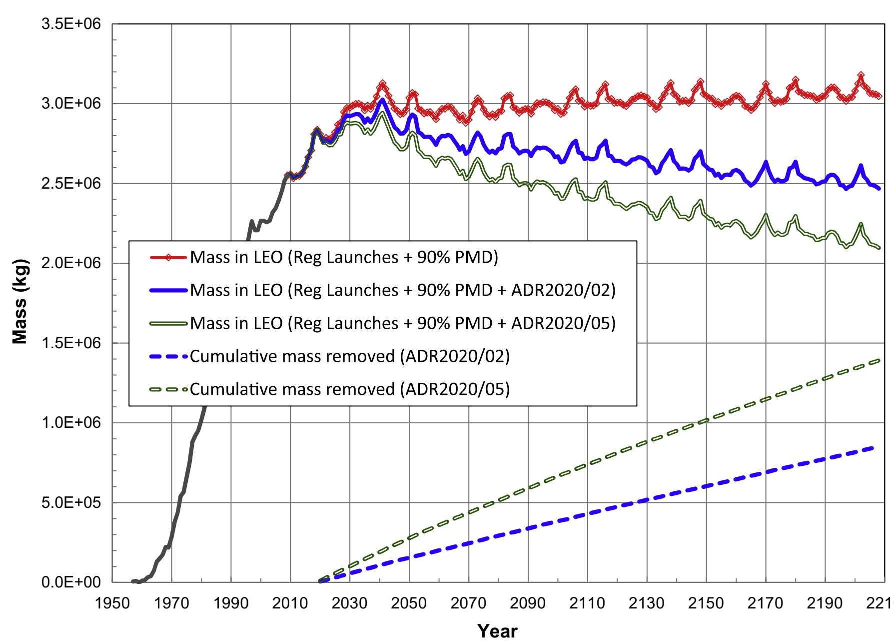

Fig. 8. The top three curves depict the masses in LEO from the three different scenarios. Each LEO-crossing object's mass is weighted by its time residing between 200 and 2000 km altitudes. The bottom two curves show the cumulative masses removed from the two ADR scenarios.

3.6. What is the best timeframe for ADR implementation?

From the projected increase of the future LEO debris population, a common-sense approach would argue for a timely implementation of ADR for environment remediation. However, the expectation that matured technologies will be available to allow for routine ADR operations as early as 2020 may be too optimistic. A simple comparison study was made to quantify the effect of different ADR implementation timetables. The results are summarized in Fig. 9. The middle curve is the projected population growth based on an ADR rate of five objects per year, starting from the year 2060. The average numbers of collisions predicted by the three scenarios, from the top to the bottom curves, are 47, 32, and 25, respectively. The comparison indicates moving ADR implementation from 2020 to 2060 would lead to 7 more collisions and about 2000 more objects in the environment for the next 200 years. How significant these differences are, and whether they are acceptable depend on many factors. To reach a consensus on a reasonable ADR implementation timeframe will require detailed tradeoff studies to balance the negative impacts to the environment (including risks to operational satellites) and the time needed to develop cost-effective ADR technologies.

3.7. What is the effect of practical/operational constraints?

In addition to the criterion of Eq. (1), the nature of ADR operations is likely to favor the selection of removal targets in specific altitude, inclination, right ascension of the ascending node, or size regimes. Vehicle type/class may need to be considered as well. These additional, but necessary, constraints will have some negative impact on the effectiveness of an ADR strategy solely based on Eq. (1). Fig. 10 shows the altitude versus inclination distributions of the currently existing R/Bs and S/Cs with masses above 50 kg. Crosses and open circles represent the apogee and perigee altitudes, respectively, for the same objects. The majority of the current on-orbit R/Bs and S/Cs are concentrated in about 10 narrow inclination bands over 3 altitude regions (see also Fig. 3). To analyze the effect of additional selection constraints in altitude and inclination, a special LEGEND simulation was performed where ADR targets were limited to objects (1) with the highest mass and collision probability products, (2) with inclinations between 82.5° and 83.5°, and (3) residing between 900 and 1050 km altitudes. The spatial density distributions at the end of 200-year future projection simulations, based on three scenarios, are compared in Fig. 11. As expected, limiting ADR targets to a specific altitude will not address the population growth in other regions, such as those around 800 km or 1450 km altitudes. In addition, limiting ADR targets to a narrow inclination band may not be the most efficient way to control the population growth in the same altitude region. This is because vehicles in the same altitude region, but with different inclinations, may also contribute significantly to collision activities in the environment. Comparison of the projection LEO population growths from the three scenarios is shown in Fig. 12.

3.8. What are the collision probabilities and masses of objects in the current environment?

Of all the R/Bs and S/Cs in the current environment, those with the highest (top 500) mass and collision probability products are shown in Fig. 13. The prograde region is

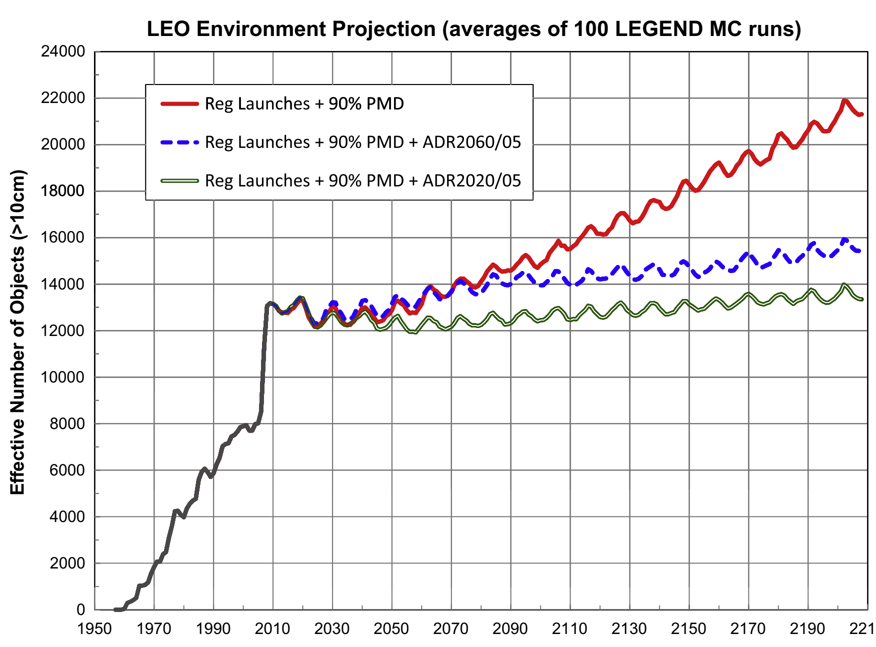

Fig. 9. Simulated LEO environment from three test scenarios. ADR2020/05 means active debris removal starts from the year 2020 and the removal rate is five objects per year. ADR2060/05 means active debris removal starts from the year 2060 and the removal rate is five objects per year.

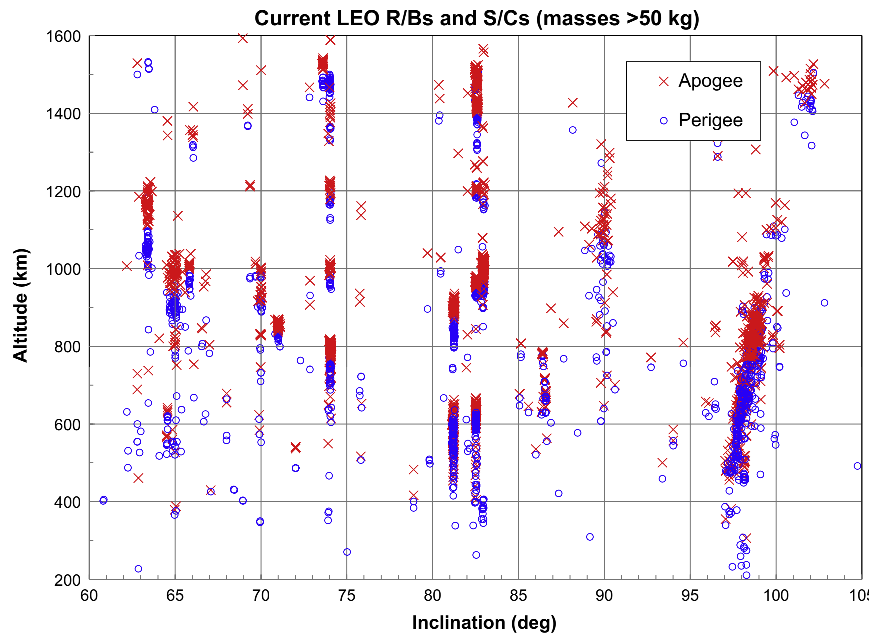

Fig. 10. Apogee altitude (crosses) and perigee altitude (open circles) versus inclination distributions of the current LEO R/Bs and S/Cs. Only those with masses above 50 kg are shown. Additional selection constraints in inclination (82.5–83.5°) and altitude (900–1050 km) are applied to ADR targets for the special comparison.

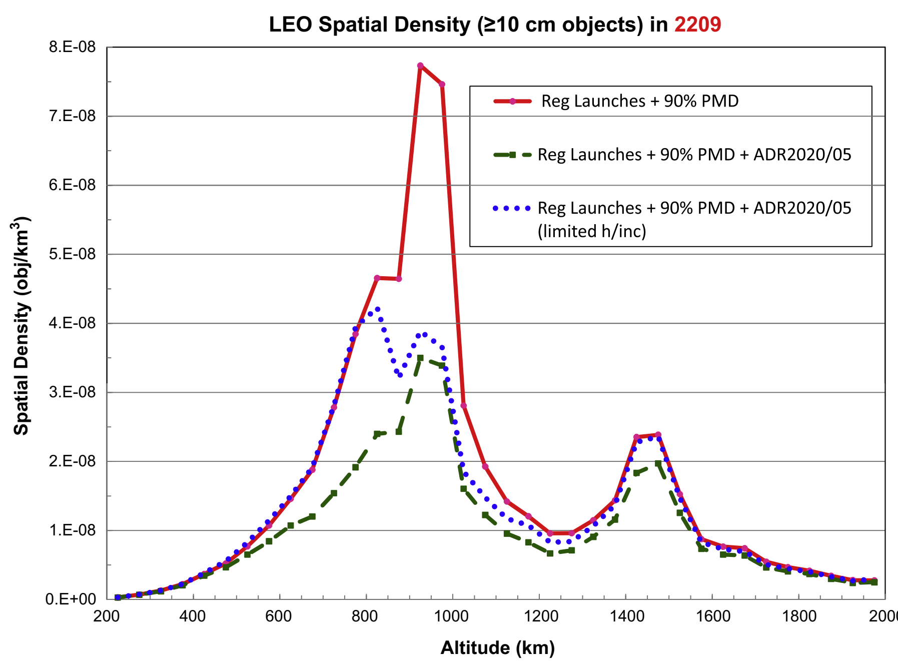

Fig. 11. Object spatial density distributions at the end of a 200-year future environment projection. The middle curve shows the results from the special LEGEND run where additional constraints are applied to targets selected for removal.

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. Objects in the retrograde region are more diverse. They include, for example, Ariane R/Bs (1700 kg dry mass), CZ-series R/Bs (1700–3400 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

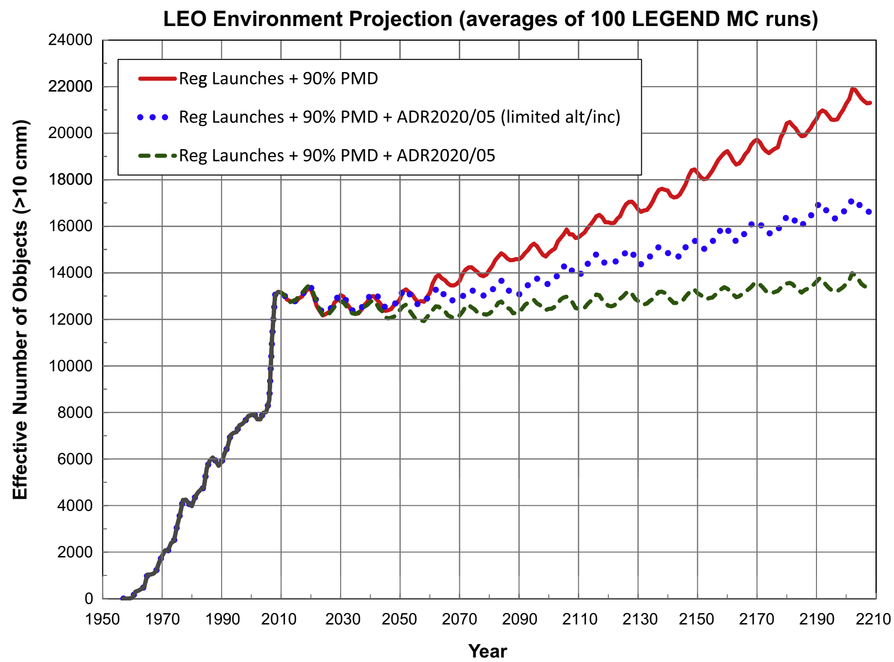

Fig. 12. Projected LEO population growth based on three different scenarios. Limiting ADR target selection to a narrow inclination and altitude range decreases the efficiency of remediation.

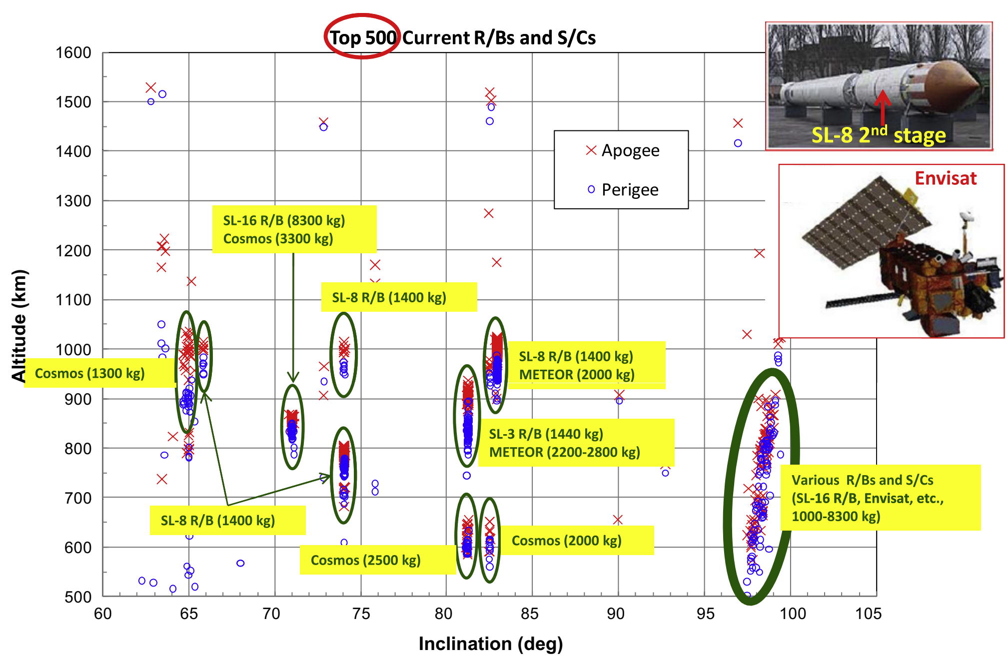

Fig. 13. Apogee altitude (crosses) and perigee altitude (open circles) versus inclination distributions of the existing LEO R/Bs and S/Cs that have the highest mass and collision probability products. Only the top 500 are shown.

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, objects in Fig. 13 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 Fig. 13). 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. New ground-based observations on these objects are needed in the near future to identify their spin and tumble states. If the majority of these non-cooperative targets have very fast

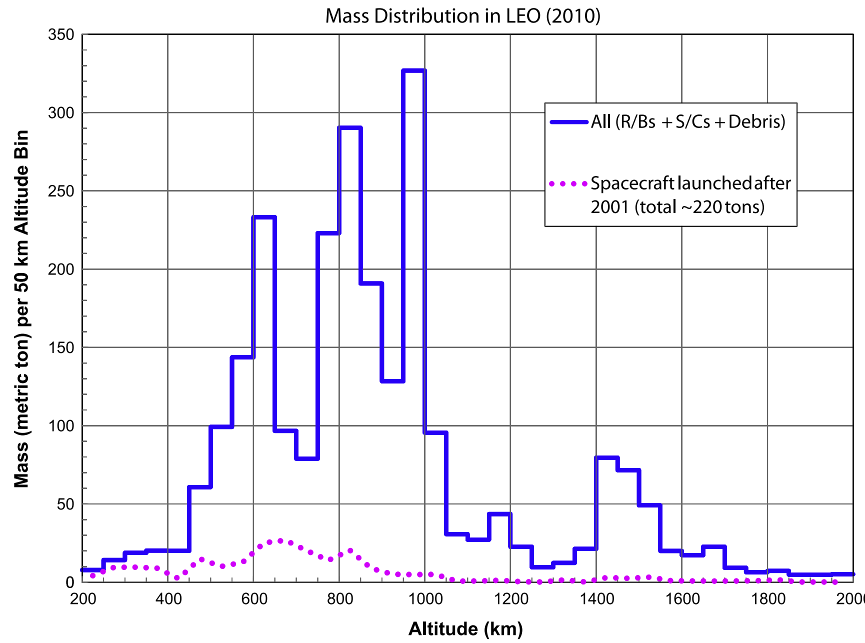

Fig. 14. Mass distribution of all objects in LEO (histogram) and the mass distribution of "active" S/Cs (bottom curve).

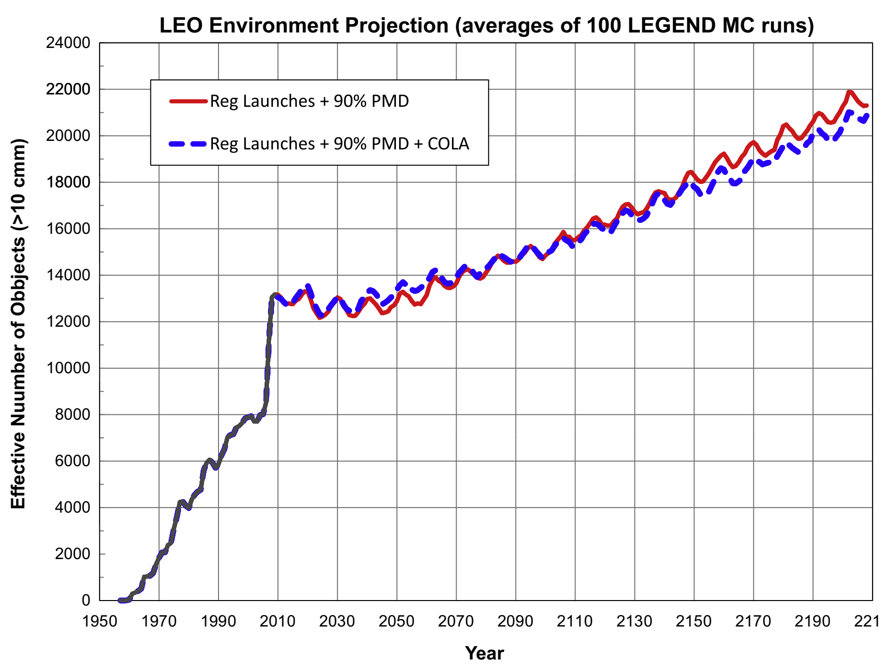

Fig. 15. Projected future LEO debris populations from two test scenarios. The top curve is the benchmark scenario. The bottom curve represents a special LEGEND simulation where "active" S/Cs were excluded from collision consideration.

spin/tumble rates, then new technologies or techniques to slow down their motion will be needed before any proximity and/or capture operations can be successfully conducted. Some of the R/Bs may also 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.

3.9. *What are the benefits of collision avoidance maneuvers?*

Since the collision between Iridium 33 and Cosmos 2251, the US Department of Defense's Joint Space Operations Center (JSpOC) has been conducting conjunction assessments for all active S/Cs and providing this information to the operators or owners of the involved vehicles.

Approximately 80% of active S/Cs in LEO have maneuvering capability. Certainly collision avoidance (COLA) maneuvers can prevent S/Cs from colliding with objects tracked by the SSN and limit the generation of collision fragments. The long-term benefit of COLA in reducing the LEO population growth, however, is less clear and is evaluated below.

The first step to quantify the benefit of COLA to the environment is to identify active S/Cs with maneuvering capabilities. Since it is very difficult to develop a complete list, a good way to envelop the problem is to assume all S/Cs with lifetimes less than 9 years are active and have COLA capability. Based on this assumption, the mass distribution of the identified active S/Cs, as of 2010, is compared with the total mass distribution in LEO in Fig. 14. The total mass of the "active" S/Cs only accounts for about 9% of the mass in the environment. This comparison shows that "active" S/Cs do not represent a major mass reservoir in LEO. A more quantitative comparison is shown in Fig. 15. As illustrated, a LEGEND simulation where all "active" S/Cs (less than 9 years old at any point in time) were excluded from collision consideration in future projection was conducted. The result was compared with the benchmark case. The difference between the two curves is not very significant.

One footnote on COLA – it does not protect operational S/Cs from un-tracked objects. Debris smaller than the detection threshold of the SSN sensors (approximately 10 cm) can still cause serious damage to any active S/Cs. Therefore, the LEO population growth is a concern to every satellite operator/owner.

3.10. What are the challenges ahead?

Orbital debris is a problem for all space-faring nations. The international community must first reach a consensus on the instability problem of the LEO debris environment. The next step is to determine if there is a need to adopt ADR for environment remediation, and then establish a balanced timetable for implementation. Just because the population will increase by 60% in the next 200 years does not mean ADR is imminent. The cost of losing and replacing one operational satellite approximately every 15 years may be affordable and the resulting damage to the environment may be acceptable in the short-term. Once a decision to move forward with ADR is made, then detailed trade-off studies must be conducted to examine feasible options for the implementation. During the process, the involved parties must commit necessary resources to support innovative ADR research and technology development.

An end-to-end ADR operation includes, in general terms, launch, propulsion, guidance, navigation, control, precision target tracking, rendezvous, stabilization (of the spinning/tumbling targets), capture/attachment, and deorbit of the targets. Some of the technologies involved do exist, but the challenge is to make them more cost effective. Other technologies, such as ways to stabilize a non-cooperative, fast spinning/tumbling target and techniques to capture or attach devices to a large and massive upper stage, are new and will require major development efforts. Once a feasible concept operation is defined, viable options for each component (e.g., space tug versus drag-enhancement devices, solid/liquid propulsion versus tethers, ground-based versus space-based tracking) must be explored and evaluated. In addition, policy, ownership, legal, and other non-technical issues also represent major challenges for ADR implementation.

4. Concluding remarks

This paper provides an updated assessment of the current and future orbital debris environment and shows, quantitatively, the justification to consider ADR for environment remediation. Key questions are addressed and LEGEND simulations are used to illustrate and support various arguments. The goals of the study are to highlight the complexity of active debris removal, to demonstrate the types of analyses that would be needed to gain a better understanding of the difficulties involved, and to potentially guide the development of viable ADR technologies. As the beneficiary of the space age and related technologies for half a century, it is our responsibility to preserve the near-Earth environment for future generations. Analogous to efforts to fix other major environment problems, however, it will require major contributions, collaboration, and cooperation at national and international levels to move forward with ADR for debris environment remediation.

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