Active Debris Removal and the Challenges for Environment Remediation

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Recent modeling studies on the instability of the debris population in the low Earth orbit (LEO) region and the collision between Iridium 33 and Cosmos 2251 have underlined the need for active debris removal. A 2009 analysis by the NASA Orbital Debris Program Office shows 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. The targets identified for removal are those with the highest mass and collision probability products in the environment. Many of these objects are spent upper stages with masses ranging from 1 to more than 8 metric tons, residing in several altitude regions and concentrated in about 7 inclination bands. To remove five of those objects on a yearly basis, in a cost-effective manner, represents many challenges in technology development, engineering, and operations. This paper outlines the fundamental rationale for considering active debris removal and addresses the two possible objectives of the operations – removing large debris to stabilize the environment and removing small debris to reduce the threat to operational spacecraft. Technological and engineering challenges associated with the two different objectives are also discussed.

Key Words: Orbital Debris, Modeling, Active Debris Removal

Nomenclature

GEO	:	geosynchronous orbit
LEO	:	low Earth orbit
MEO	:	medium Earth orbit
M	:	mass
σ	:	standard deviation
P_c	:	collision probability

1. Introduction

After more than 50 years of space activities, the near-Earth environment is populated with orbital debris. This environmental pollution is creating problems for robotic and human space programs. On average, two Shuttle window panels are replaced after every mission due to damage by micrometeoroid or orbital debris impacts. More than 100 collision avoidance maneuvers were conducted by satellite operators in 2010 to reduce the impact risks of their satellites with respect to objects in the US Space Surveillance Network (SSN) catalog. Of the four known accident collisions between objects in the SSN catalog, the last one – collision between Cosmos 2251 and the operational Iridium 33 in 2009, was the most significant. It was the first ever accidental catastrophic destruction of an operational satellite by another satellite. It also signaled the potential collision cascade effect in the environment, commonly known as the "Kessler Syndrome," predicted by Kessler and Cour-Palais in 1978[1].

Fig. 1 shows the historical increase of objects in the SSN catalog. The SSN sensors are capable of tracking objects 10 cm and larger. As of April 2011, the total of the tracked population exceeds 22,000. However, approximately 6000 of them have yet to be entered into the catalog. The population is dominated by fragmentation debris throughout history. Before the anti-satellite test (ASAT) conducted by China in 2007, the fragmentation debris were almost all explosion fragments. After the ASAT test and the collision between Iridium 33 and Cosmos 2251, the ratio of collision fragments to explosion fragments was about one-to-one. It is expected that accidental collision fragments will further dominate the environment in the future.
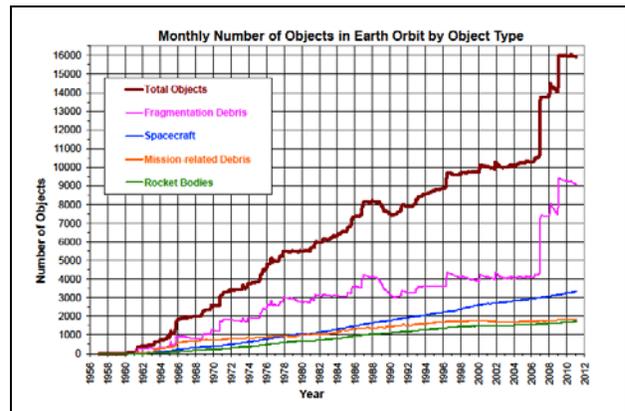

Fig. 1. Increase of the historical SSN catalog population through April 2011. The number of operational spacecraft is only about 1000, which represents a small component in the environment.

The debris population does not stop at 10 cm. Additional radar data indicate that at the 1 cm level the total is at least several hundred thousand. At the 1 mm level, the population is estimated to be on the order of hundreds of millions. Due to the high impact speed in space, objects as small as 0.1 mm pose certain safety concerns to satellite operators. The well-shielded U.S. modules of the International Space Station (ISS) are protected against debris smaller than 1.4 cm. For a typical

operational spacecraft, however, hypervelocity impact by debris 5 mm and larger is likely to lead to mission-ending damage.

Fig. 2 depicts the historical increase of the mass of objects in orbit. Unlike the curves in Fig. 1, which are heavily influenced by major breakups, the mass increase is relatively steady over time. The total mass is dominated by rocket bodies (R/Bs) and spacecraft (S/Cs). They combine for approximately 96% of the mass in orbit. Although more than half of the catalog objects are fragmentation debris, they only account for less than 3% of the total mass in space.
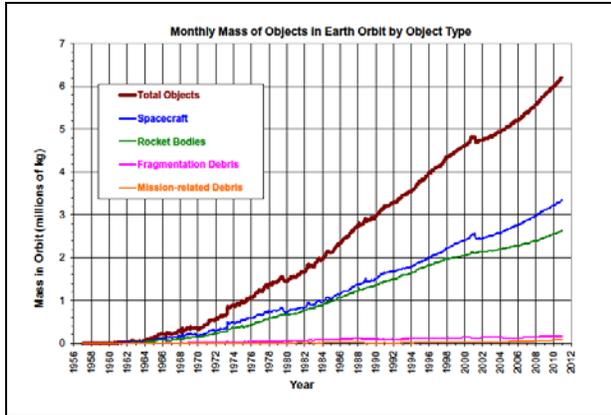

Fig. 2. Historical mass increase of objects in Earth orbit. Variations due to Shuttle missions are not included. More than 99% of the total mass is in 10 cm and larger objects.

The projected growth of the future debris environment is shown in Fig. 3. It is a summary of a recent study based on the LEGEND model developed by the NASA Orbital Debris Program Office. The study assumed nominal launches in the future, but no mitigation measures were implemented. In essence, this is a worst-case scenario. The environment is divided into three zones. Low Earth orbit (LEO) is the region below 2000 km altitude. The geosynchronous (GEO) region is 200 km within the geosynchronous altitude. Finally, the region between LEO and GEO is defined as medium Earth orbit (MEO). Each projection curve is the average of 100 LEGEND Monte Carlo (MC) simulations. The 1-σ standard deviation for each curve is also included in the figure.

The rapid increase of the debris population in LEO is a well-known trend[1]. It was the motivation for the development of the mitigation measures, such as passivation and the 25-year rule, by the international community in the last two decades. However, recent analyses have shown that the commonly-adopted mitigation measures will not be sufficient to stabilize the environment[2,3]. Therefore, to better limit the growth of the debris population in LEO, active debris removal (ADR) must be considered[4]. (The definition of ADR is to remove debris beyond the mitigation guidelines currently adopted by the international space community.)

The projected population growths in MEO and GEO over the next 200 years are not as severe as that in LEO. Even under the worst-case, non-mitigation assumption, the increase is very moderate. When postmission disposal (PMD) options are
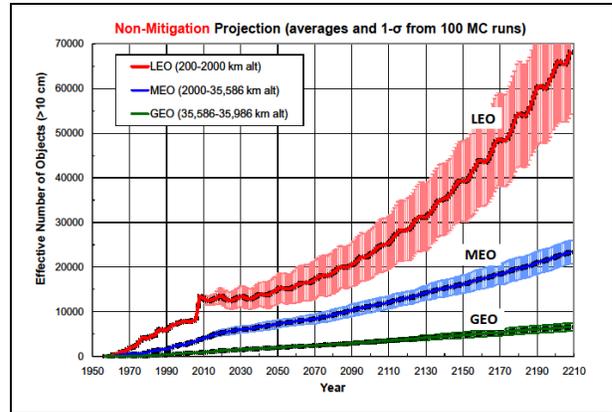
implemented, such as maneuvering satellites at the end of life

Fig.3. Projected growth of the ≥10 cm populations in LEO, MEO, and GEO for the next 200 years. The simulations assumed nominal launches, but no mitigation measures were implemented in the future.

to the graveyard orbit region, the increase will be further reduced. Since there is no atmospheric drag to clean up the environment in MEO and GEO, the long-term build up of debris will continue. However, there is no urgent need to consider ADR in MEO and GEO in the near future.

2. Active Debris Removal

Removing debris from orbit is far more complicated than launching satellites. Several key questions must be addressed at the beginning of any ADR planning. They include 1) where is the most critical region for ADR, 2) what are the short- and long-term mission objectives, 3) what objects should be removed first, 4) what are the benefits to the environment, and finally, 5) how to carry out the operations. The answers to these questions will define the top-level requirements, drive the necessary technology development, and guide the implementation of the ADR operations. In addition, non-technical issues, such as policy, coordination, ownership, legal, and liability, will also influence the direction of ADR planning and implementation.

Based on the projection curves shown in Fig. 3, it is obvious that any environment remediation in the foreseeable future should focus on ADR operations in LEO. Mission objectives will set the measures for success. Common mission objectives, such as maximizing the benefit-to-cost ratio and following practical mission constraints (in altitude, inclination, class, size, *etc*.) are always applicable to any ADR concepts. Specific mission objectives, on the other hand, are very diverse and will lead to very different forward paths. These objectives include, for example, controlling the LEO population growth (≥10 cm or others), limiting collision activities, mitigating short- or long-term risks (damage, not necessarily catastrophic destruction) for selected payloads, or mitigating risks for human space activities. Once a specific mission objective is selected, it needs to be further quantified (*e.g.*, limiting the population growth or reducing mission-end threat to a pre-set level) to define the mission requirements.

What debris objects should be removed first depends on the specific mission objective. The cumulative size distribution, plotted at the half-decade points, of the LEO-crossing objects in 2011 is shown in Fig. 4. The populations at 10 cm and larger come from the SSN catalog. The populations at 5 mm, 1 cm, and 5 cm are estimated from the Goldstone, Haystack, and HAX radar data[5]. The populations below 10 cm roughly follow a power-law size distribution – meaning there are far more smaller debris than larger ones. This means the main mission-ending threat for operational S/Cs in the environment comes from debris just above the threshold of the vehicle's impact protection shields. Since S/Cs all have different configurations and designs, the "critical debris size" varies from S/C to S/C. For most operational S/Cs, any impact by debris between 5 mm and 1 cm is likely to cause mission-end damage. The chances of similar damage diminish if the S/C is impacted by smaller debris.

Based on the size distribution of Fig. 4, debris in the 5-mm-to-1-cm regime represent about 80% of all objects larger than 5 mm. Therefore, if the mission objective is to reduce the mission-ending threat for operational S/Cs, then the ADR operations should focus on the 5-mm-to-1-cm objects. If the mission objective is to limit the growth of the debris population or to reduce the catastrophic collision activities in the environment, then the ADR operations should focus on the root cause of the problem – the massive and large (at least several meters in dimension) R/Bs and S/Cs[4]. Analyses of these two different objectives are described below.
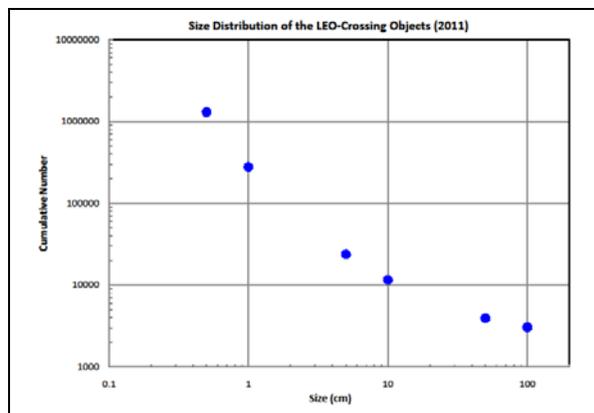

Fig. 4. Cumulative size distribution, between 5 mm and 1 m, of the LEO-crossing objects in 2011.

2.1. Targeting the main threat for operational spacecraft

The main challenges for removing 5-mm-to-1-cm debris from LEO are related to the dynamic nature of the small debris and the huge number of their presence in the environment. The former is illustrated in Fig. 5, where the simulated evolution of the 5-mm-to-1-cm Cosmos 2251 fragments between 2009 and 2019 is shown. The initial fragments were generated via the NASA Standard Breakup Model[6]. Individual fragments were then propagated forward in time, including Earth's J_2, J_3, J_4, solar-lunar gravitational perturbations, solar radiation pressure, and atmospheric drag. NOAA's solar flux F10.7 projection was combined with the

Jacchia 1977 atmospheric model for the drag calculation[7].

Small debris tend to have high area-to-mass ratios (A/Ms). For those with perigees below about 1000 km altitude, they are subject to strong atmospheric drag perturbation. What the curves in Fig. 5 show is that, at any given altitude below 1000 km, the 5-mm-to-1-cm debris rapidly decay toward lower altitudes. At the same time, the region is rapidly replenished by debris spiraling down from higher altitudes on a yearly basis. The environment is highly dynamic, and could have strong short-term (*i.e.*, monthly to yearly) episodic variations.
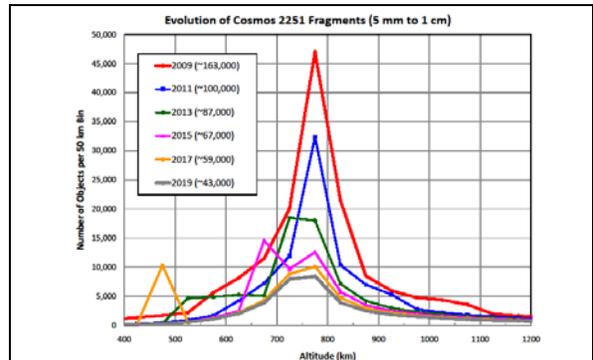

Fig.5. Altitude distributions of the 5-mm-to-1-cm Cosmos 2251 fragments between 2009 and 2019. Numbers in the parentheses indicate the total number of objects still in orbit.

The ISS example provided below outlines the analyses needed and the technical challenges for removing small debris to reduce the threat for a critical operational spacecraft. The ISS is constructed with the best micrometeoroid and orbital debris impact protection in history. The U.S. modules of the ISS are equipped with bumper shields that could withstand hypervelocity impacts by orbital debris 1.4 cm or smaller[8]. The U.S. Joint Space Operations Center (JSpOC) conducts conjunction assessments for all operational spacecraft, with respect to objects in the SSN catalog, and provides the information to the operators/owners of the vehicles involved for each conjunction. (Based on the conjunction data, the ISS has conducted 12 collision avoidance maneuvers since 1999.) Therefore, the main threat to the ISS comes from objects between 1.5 and 10 cm. In 2010, the number of objects in this size range, and with orbits crossing the altitude of the ISS (330 to 360 km), was approximately 1200. Since these objects follow a power-law size distribution (see also Fig. 4), about 800 of them are between 1.5 and 3 cm. If the ADR objective is to reduce the threat to the ISS by removing, for example, 50% of the debris in this size range, then trade studies must be conducted to investigate various options for removal.

Large-area debris collectors made of different materials and designed with different configurations have been proposed for small debris removal. The technology readiness levels (TRLs) for the commonly-mentioned capture mechanisms (*e.g.*, using low density materials) are relatively mature. The key difficulty for the collector is in the large area-time product that will be needed to remove any meaningful amount of small debris. Based on the estimated 1.5-to-3-cm debris flux at the ISS altitude in 2010, it will require a collector with an area-time

product on the order of 1000 km²·yr to remove 400 debris in this size range. For a one-year operation at the ISS altitude, the concept of a 1000 km² cross-sectional area collector is simply not practical. In addition, as illustrated in Fig. 5, the near ISS environment will continue to be replenished by debris decaying from higher altitudes. Any ADR operations of small debris, even if they are technically feasible and economically viable, will have to be carried out continuously for as long as the ISS remains active. To remove 5-mm-to-1-cm debris at higher altitudes to better protect the majority of the operational S/Cs will be even more challenging because the demand for the area-time product will be significantly higher.

A ground- or space-based laser system is another concept being proposed for the removal of mm-to-cm-sized debris. The unique technical challenges for this approach are the power required for the system, tracking capability for small debris, and the pointing accuracy of the laser system. Because of the concern for space weapons, this concept faces more non-technical issues than others.

2.2. Targeting the root cause of the population growth

The future debris population growth will be driven by fragments generated from accidental collisions involving large and massive intacts (R/Bs or S/Cs). Therefore, the most effective way to limit the population growth is to remove the major "debris generators" for such events. Major "debris generators" are those that have the highest collision probabilities with other objects in the environment, and when they do collide with other objects, they have the potential of generating the greatest amount of fragments. The latter is a function of mass. Hence, the mass, M, and collision probability, P_c, of each object can be used as a selection criterion for removal[9,10]. Numerical simulations have shown that, indeed, $[M \times P_c]$ is an effective target selection criterion for environment remediation in LEO[4, 9-11].

Fig. 6 shows what will be needed to stabilize the LEO population with ADR based on the mass and collision probability criterion. The historical environment, shown as the gray curve, included fragments from the ASAT test and the collision between Iridium 33 and Cosmos 2251. Each projection curve is the average of 100 LEGEND MC simulations. The scenario for the top curve assumed nominal launches and a 90% compliance of PMD for all R/Bs and S/Cs. The middle curve shows that if an ADR of two objects per year was implemented after the year 2020 (denoted as ADR2020/02 in the figure), the population growth could be reduced approximately by half. If the ADR was increased to five objects per year (bottom curve), the population could be maintained at a level similar to the current environment. It will require an even higher annual ADR rate if the objective is to reduce the future LEO population to a lower level.

The simulation results shown in Fig. 6 are intended to serve as a guide to illustrate the effectiveness of using $[M \times P_c]$ as a target selection criterion, to quantify how many objects need to be removed, and to show the benefits to the environment by targeting the root cause of the population growth. The conclusion that "removing five objects per year can stabilize the LEO environment" is somewhat notional. A key

assumption in the simulations is the nominal launches during the projection period. It is a common practice to repeat launches from the last 8 years for future environment simulations. If future launches are very different from the repeated cycle, including launch frequency, mission orbits, and vehicle masses, then the required ADR rate will be different. Another assumption in the simulations is the immediate removal of objects from the environment. If that is not the case, then the required ADR rate will be somewhat higher. Other factors, such as the compliance of the mitigation measures and the long-term solar activity projection, will also affect the number of ADR objects needed to stabilize the environment.
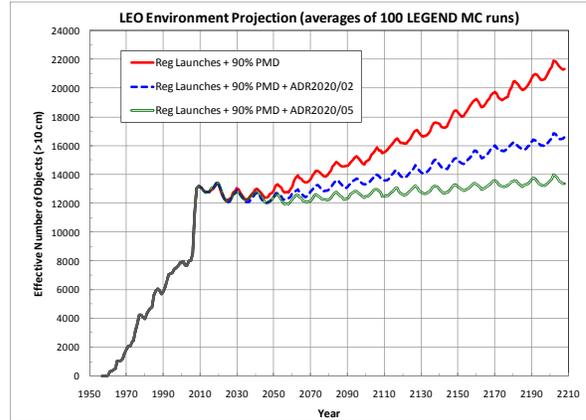

Fig.6. Projected increases of the future LEO populations (objects ≥10 cm) based on three different scenarios. Each projection is the average of 100 LEGEND MC simulations.

If the same $[M \times P_c]$ criterion is applied to objects in the current LEO environment, potential targets for future ADR operations can be identified. Fig. 7 shows their apogee/perigee altitudes and inclinations. It can be seen that many of the potential targets fall into several well-defined classes of vehicles between 600 and 1050 km altitudes, and in seven narrow inclination bands. These R/Bs and S/Cs have masses between 1 and 9 metric tons, and sizes up to more than 10 meters. The challenges for removing five such objects in a cost-effective manner, on a yearly basis, are monumental.
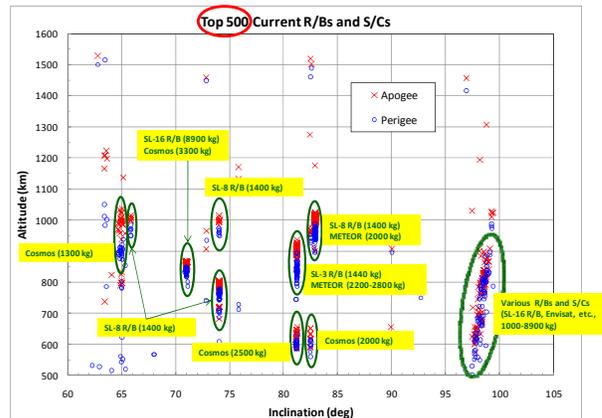

Fig.7. Altitude versus inclination distribution of potential ADR targets.

An end-to-end ADR operation includes many components – launch, propulsion, proximity operations, rendezvous, contact (capture or attachment), and finally, deorbit or graveyard maneuver. From the cost perspective, multiple ADR systems per launch or secondary payload design are preferred. Options for propulsion, both for the ADR system vehicle and for the debris targets, are more diverse. The space tug concept based on solid or liquid propellants is a mature technology, but the propellant mass and the operational cost may be too high for a routine operation. Plasma propulsion has low TRL, but may turn into a good alternative. The concept of using electrodynamic tethers as a means of removing large orbital debris was first suggested in the early 1990s[12]. Once the technology is mature and demonstrated, it could provide a promising propellant-less option to deorbit ADR targets and to maneuver the ADR system from target to target. However, the collision risks of a long tether to other vehicles in the environment remain an open issue.

Attaching a drag enhancement device, such as an inflatable balloon or a thin-film sail, to a massive debris object is another potential low-cost option to deorbit ADR targets. The effectiveness of this concept is illustrated in Fig. 8. The orbital lifetime of an SL-8 second stage, with a mass of 1400 kg and a 950 km altitude, is more than 200 years. The addition of a lightweight and large-area device will increase the total A/M of the system and cause it to decay more rapidly over time. For example, a balloon with a diameter of about 27 m can deorbit the second stage in 25 years. If the size of the balloon is increased to 100 m, then the orbital lifetime of the target can be reduced to just 2 years. The dimensions of the balloons, or equivalent thin-film sails, are not that unreasonable. However, as the system decays toward lower altitudes, its collision risks to other satellites in the environment will need to be evaluated as well.
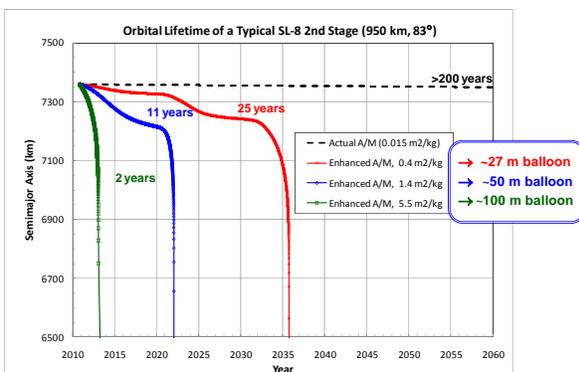

Fig.8. Effectiveness of deorbiting a typical 1400 kg SL-8 R/B from a 950 km altitude with a drag enhancement device. A lightweight balloon (or an equivalent sail) with a diameter of 100 m can force the R/B to decay in just 2 years.

Proximity operations (including guidance, navigation, and control), rendezvous, and contact (capture or attachment) of the ADR targets require new technologies as well because the targets are non-cooperative. The major challenge, however, is in the handling of the potential rapid spin/tumble motion of the targets. Limited data seem to suggest that many of the

potential ADR targets have tumble rates above 1 rpm. Ground-based radar or optical observations will be needed to survey the potential ADR targets to better characterize their tumble states and determine how these states might change over time. This is another area where new technologies will be needed to stabilize the target if physical contact with the target is required during the removal operations.

Once a target is captured by the ADR system or is attached to a device, there are only two possible outcomes. For some ADR concepts, it is possible to maneuver the target to the graveyard orbit above 2000 km altitude. This option really is not a solution. The cumulative debris mass eventually will create a new environment problem in the graveyard orbit. The best end result for an ADR operation is to bring the target down. However, the reentry risks of any large and massive R/B or S/C must be evaluated. If it is necessary to include a controlled reentry at the end, it will severely limit the ADR operational options and will increase the overall cost significantly.

3. Conclusions

The orbital debris problem is facing a critical point. The commonly-adopted mitigation measures will not be sufficient to fully control the debris population growth in LEO. As the international community gradually reaches a consensus on the need for ADR, the focus will shift from environment modeling to completely different challenges – technology development, system engineering, and operations. As the community takes on these new challenges, a long-term strategic plan must be established first. Mission objectives must be clearly defined to drive the forward path. If the goal is to remediate the environment, then four critical "Cs" will be needed at the international level. The first "C" stands for the consensus on ADR. The second "C" is for cooperation – the removal target may belong to a different country. The third "C" is for collaboration – it is highly unlikely that any single organization or country can accomplish the goal by itself. The last "C" stands for contributions – cost-sharing will be the key for using ADR to preserve the environment for future generations.

References

1) Kessler, D. J. and Cour-Palais, B. G.: Collision Frequency of Artificial Satellites: The Creation of a Debris belt, *JGR*, **83** (1978), pp.2637-2646.
2) Liou, J.-C. and Johnson, N. L.: Risks in Space from Orbiting Debris, *Science*, **311** (2006), pp.340-341.
3) Liou, J.-C. and Johnson, N. L.: Instability of the Present LEO Satellite populations, *Adv. Space Res*., **41** (2008), pp.1046-1053.
4) Liou, J.-C., Johnson N. L., and Hill, N. M.: Controlling the Growth of Future LEO Debris Populations with Active Debris Removal, *Acta Astronautica*, **66** (2010), pp.648-653.
5) Xu, Y.-L., Horstman, M., Krisko, P. H., Liou, J.-C., Matney, M., Stansbery, E. G., Stokely, C. L., and Whitlock, D.: Modeling of LEO Orbital Debris Populations for ORDEM2008, *Adv. Space Res*., **43** (2009), pp. 769-782.
6) Johnson, N. L., Krisko, P. H., Liou, J.-C., Anz-Meador, P. D.: NASA's new breakup model of EVOLVE 4.0, *Adv. Space Res*., **28**, 9 (2001), pp.1377-1384.
7) Jacchia, L.G.: Thermospheric Temperature, Density, and

Composition: New model, Smithsonian Special Report SAO 375 (1977).

8) Hyde, J. L., Evans, H. J., Hoffman, K. D., Christiansen, E. L., Lear, D. M., and Prior, T. G.: International Space Station Micrometeoroid and Orbital Debris Integrated Threat Assessment 12, NASA JSC-65837 Rev. A, (2010).

9) Liou, J.-C. and Johnson, N. L.: A Sensitivity Study of the Effectiveness of Active Debris Removal in LEO, IAC-07-A6.3.05, (2007).

10) Liou, J.-C. and Johnson, N. L.: A Sensitivity Study of the Effectiveness of Active Debris Removal in LEO, *Acta Astronautica*, **64** (2009), pp.236-243.

11) Lewis, H. G., Swinerd, G. G., Newland, R. J., and Saunders, A.: Active Removal Study for On-orbit Debris Using DAMAGE, Proceedings of the Fifth European Conference on Space Debris, ESA SP-672, (2009).

12) Portree, D. S. F., and Loftus, J. P.: Orbital Debris: A Chronology, NASA-TP-1999-208856, (1999).