Methods of Space Debris Removal in LEO

Alexander Berthelot[1]
University of Tennessee, Knoxville, Tennessee, 37996

This paper analyzes modern disposal methods for human-made debris in low Earth orbit (LEO). Since the first space race, debris from varying spacecraft has been continuously filling LEO at an exponential rate. Space debris moving at extreme velocities poses a major threat to spacecraft, for pieces as small as 1 mm in diameter can completely compromise functionality on collision. Modern spacecraft have countermeasures for this since pieces smaller than 10 cm cannot be tracked from the ground, and collision is often unavoidable. Even with state-of-the-art ground tracking and avoidance methods, debris will only increase as satellite mega-constellations begin to emerge and space missions become more frequent. Space debris will remain in orbit indefinitely unless it descends low enough into the atmosphere to burn up; therefore, efficient and reliable disposal methods must be readily available and applicable. This paper will discuss and analyze the challenges of space debris disposal missions, past and current concepts that were institutionally researched to overcome these challenges, and future research applications and mission structures designed to efficiently remove debris from LEO.

I. Nomenclature

LEO	=	Low Earth Orbit
ESA	=	European Space Agency
LODR	=	Laser Orbital Debris Removal
4S	=	Space Sweeper with Sling-Sat
GA	=	Genetic Algorithm
SRP	=	Solar Radiation Pressure
ACS3	=	Advanced Composite Solar Sail System

II. Introduction

Since the Soviet Union launched Sputnik in 1957, deploying satellites into Earth's orbit has become a focal point of many aerospace engineering and astronautical programs. From globally inclusive projects like the International Space Station to the ambitions of private aerospace companies such as SpaceX's Starlink mega-constellations; satellites have been constant tools for research and are starting to see more commercial applications. With the exponential rise of satellites in LEO, collisions have become inevitable. With the average speed of a satellite in LEO being 7 km/s, the impact of two satellites at hyper-velocities results in an explosion that shatters both bodies [1]. This explosion is unlike most observed on the ground since the objects move through each other faster than the external shock waves can travel. Internal shockwaves shatter the satellites, and the resulting fragments are set on separate orbital paths [2]. Mathematical models already prove the possibility of the Kessler Syndrome, a phenomenon where orbital collisions will cause chain reactions, producing enough space debris to make space operations impossible [3]. This process can be slowed down through human intervention, but despite continuous engineering advancements in satellite technology, an energy and cost efficient method to remove debris from LEO has yet to be put into application.

This paper will describe the challenges that come from removing space debris from LEO and current solution methods. These solutions, derived from current aerospace technology, will be analyzed to determine the most effective and efficient method to remove space debris in the future.

---

[1] Undergraduate Student, University of Tennessee Knoxville, AIAA Member 1605464

III. Brief History and Cost Analysis of Space Debris

In the span of history, about 19,590 artificial satellites have been put into Earth's orbit. Nearly 70% of those satellites are still in space. In 2009, the first major incident involving two satellites was observed when Cosmos-2251 and Iridium-33 collided. This collision produced over 1,800 pieces of trackable debris, which are classified as being at least 10 cm in diameter [2]. An estimated additional 200,000 debris pieces were reported to be between 1 and 10 cm. Subsequent collisions have resulted in approximately 22,400 pieces of trackable debris in LEO and millions more un-trackable pieces less than 10 cm and down to millimeters in diameter [2]. Despite being miniscule in size, these fragments pose a significant threat to functioning spacecraft. Modern technology has allowed for avoidance of trackable pieces of debris, however there is still the risk of collision between large debris or non-functioning satellites as well as the surface degradation or destruction of spacecraft due to un-trackable pieces.

The two parameters that will be considered for removal methods are cost-effectiveness and energy efficiency. When analyzing cost-effectiveness, the primary measurement is the ratio between cost and risk reduction [4]. As the majority of proposed methods to completely remove space debris are significantly less cost-effective than current tracking and mitigation methods, there are a handful of proposed remediation methods that have more comparable cost-benefit ratios. As shown in Figure 1, a highly cost-effective mitigation method is the quick deorbiting of orbital spacecraft after completion of their missions [4]. Certain U.S. regulatory agencies and the European Space Agency (ESA) are already aiming to implement a 5-year limit to deactivated spacecraft [4].

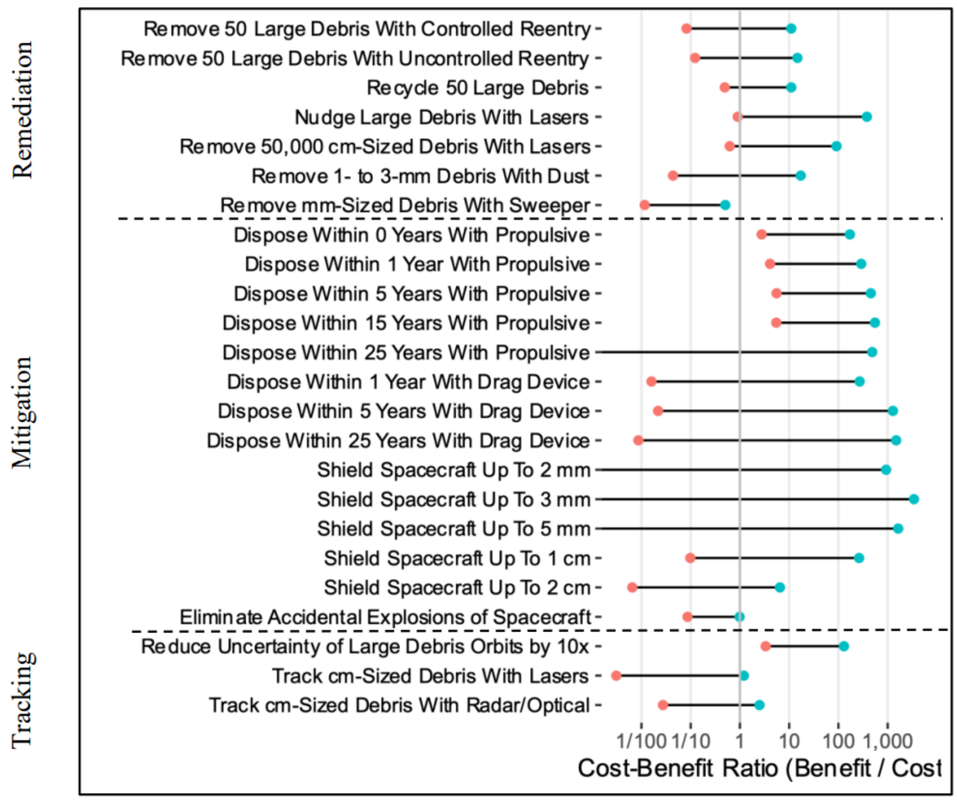

Fig. 1 Table of Cost/Benefit Ratios for Debris Solutions [4].

IV. Methods of Space Debris Removal

A. Ground-Based and Space-Based Lasers

The most cost-effective proposal to remediate orbital debris is ground and space based pulsed lasers [4]. Laser orbital debris removal (LODR) would be able to dispose of small debris pieces (between 1 and 10 cm in diameter) by ablation due to a pulsed beam, which will slightly change the orbital trajectory and cause the debris to lower into the atmosphere to burn [5]. High intensity pulsed lasers are the ideal method since a continuous beam can cause surface melting on debris pieces, instead of a clean plasma jet, which will further contribute to the debris problem [5]. Pulsed lasers are ideal for small debris since the required momentum loss to deorbit is significantly smaller than larger pieces. A ground based laser with a minimum of 75 kW of power and a pulse rate of 10 Hz can cause the deorbiting of small debris pieces within one pass [5]. Since a more powerful laser can also be used to redirect or eventually deorbit larger debris pieces, a 300-500 kW solid state laser is assumed in the applied cost models [5,6]. A space based laser, which would originate from satellites, would be able to precisely target debris and continually remove objects from orbit [6]. Cost models have been made for both ground and space based laser systems. The main factors taken into consideration for ground based systems are development/production, technical support, technical evaluation, and project management [6]. The costs for these categories are based on historical data from various ground and ship based laser weapon systems [6]. The total cost for a ground based laser system with an operation life of 5 years was estimated to be $725 million [6]. The cost model for space based lasers including bus systems with the same 5 year operation life were estimated to have a total cost of $1.146 billion [6]. In 2025, Cottrill et al., conducted a simulation of one month of operations for both ground and space lasers [6]. After subtracting the cost from the model, the simulation for space lasers showed the greatest net benefit between altitudes of 400 and 1,400 km [6]. For ground based lasers, the most net benefit was found to be at locations between -50 and 50 longitudes [6]. The gradient of profit shown in Figure 2 and 3 is in terms of money saved due to risk reduction (in $M) after subtracting the cost.

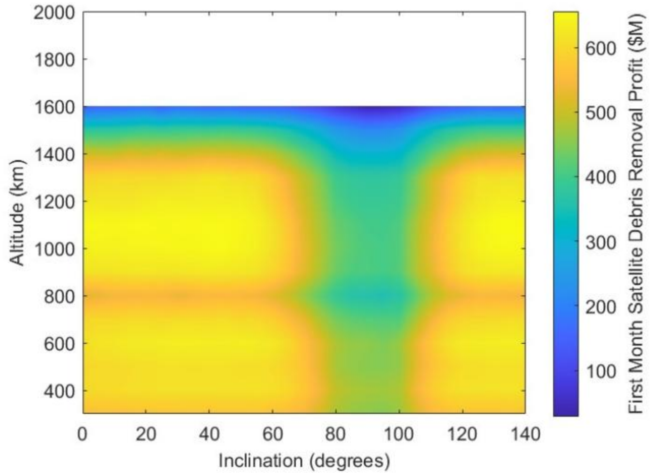

Fig. 2 Space-Based Laser Debris Removal Profit for One Month [6].

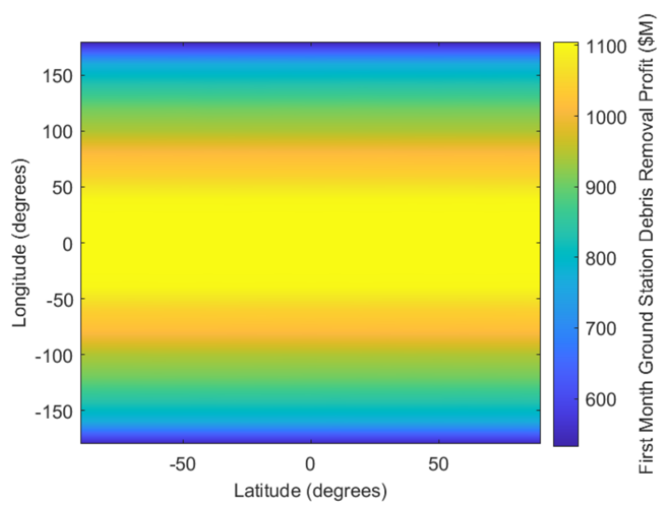

Fig. 3 Ground-Based Laser Debris Removal Profit for One Month [6].

B. Space Sweeper with Sling-Sat

In 2013, Missel J. and Mortari D. proposed a mission structure to capture and release space debris called Space Sweeper with Sling-Sat (4S). The satellite they designed would be able to capture debris and steal its momentum to achieve a change in velocity without using fuel [7].

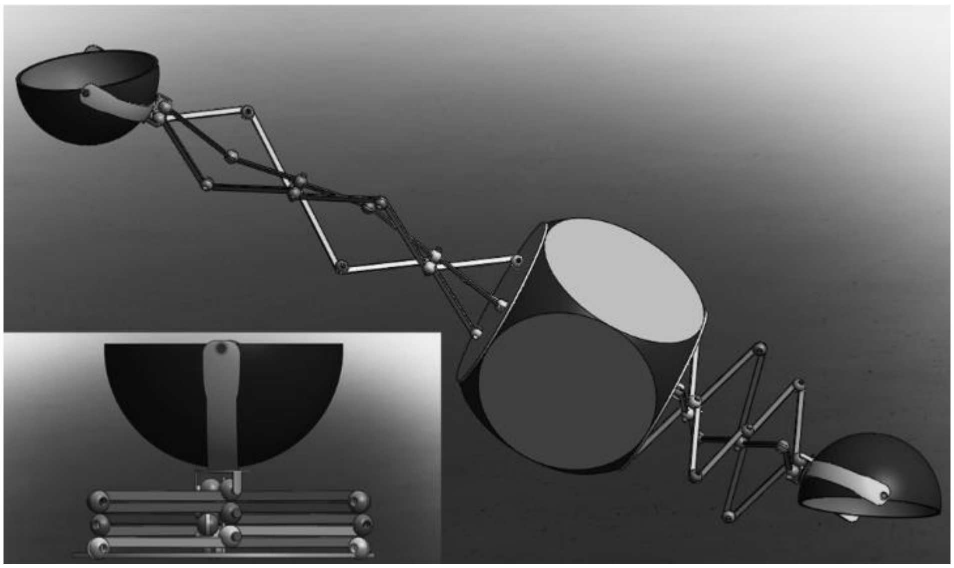

Fig. 4 Design Concept for Sling-Sat [7].

Sling-Sat can also perform timed ejections of debris to achieve another fuel efficient maneuver as well as prevent the on board mass from becoming too great [7]. The main technological challenges with this method involve precise orbital mechanics and solving nonlinear control problems [7]. The design of Sling-Sat is that of a center module with two extended arms of variable length, as seen in Figure 4 [7]. It is designed to spin when it captures a piece of debris, and extending or retracting the arms will change the angular velocity and thus the speed of the debris when ejected [7]. Since the mass of individual pieces of debris are essentially unknown, 4S will have to make adjustments to remain on course by identifying the change in the satellite's center of mass [8]. There were also structural concerns due to the nature of the plastic collisions the debris makes with the collectors, so constraints were put into place on the collectors' tangential velocity to conform to the speed of debris on impact [7]. To test path optimization, a simulation was run using a 50 generation Genetic Algorithm (GA) and was constrained to the Iridium-33 debris cloud [8]. Each simulation spanned one day (mission time) and accounted for 3 debris interactions [8]. Statistical data from 1,700 runs was used to determine that a mission time of 51 days and an on-board fuel supply capable of a total velocity change of 4.3 km/s, and can capture and eject 153 objects [8]. Further analysis also found that if the mission time is extended, fuel efficiency increases as more trajectories become possible and lead to more efficient paths [8]. Compared to a traditional mission structure where the velocity for each piece of debris has to be matched with on-board fuel, 4S can accomplish the same results while only using 60% of the fuel [8]. As for effectiveness in debris removal, 81% of debris interactions resulted in the pieces burning up in the atmosphere due to their new trajectories, while the remaining percentage of interactions resulted in a significant decrease in perigee [8].

C. Debris Removal using a Solar Sail

Another proposed mission for debris removal in LEO involves the use of a solar sail. This sail will be able to harness solar radiation pressure (SRP) from the sun as a source of thrust as opposed to using on-board fuel [9]. The mission structure begins when the sail has established a "parking orbit," targeted at 550 km [9]. The sail will then increase its semimajor axis to reach a targeted debris orbit up to 1,200 km, perform a capture sequence on the selected piece of debris, and return to the parking orbit to release the debris into the atmosphere [9]. Since the lift gained by SRP is minimal, the application of a solar sail is optimized to be used on small satellites and target debris of a similar mass [9]. While discussing the transfer between orbits, circular orbits and the instantaneous adjustment of the sail's attitude are assumed [9]. The initial ascent from the parking orbit to the debris orbit is split into two phases. In the first phase, the sail has to rapidly increase its semimajor axis to the point where atmospheric drag is negligible, at approximately 1,000 km [9]. Only the semimajor axis is controlled during the first phase, so the remaining orbital parameters need to be adjusted to match the debris orbit during the second phase [9]. Throughout the first phase, the sail is able to adjust its attitude relative to the sun for the optimal acceleration of its semimajor axis [9].

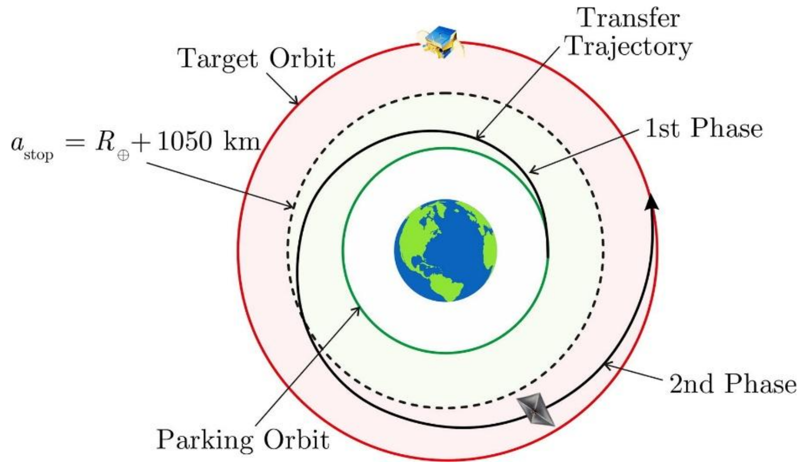

Fig. 5 Ascending Trajectory of Solar Sail [9].

Figure 5 shows a simplified trajectory of the solar sail during the first part of the mission. The dotted line represents the altitude where phase one ends, and the equation represents the threshold value of the sail's semimajor axis [9]. A simulation was run using a 50 generation GA to find the optimal control variables for the remaining parameters during phase two [9]. This study focuses on the orbital mechanics of the ascending and descending parts of the mission structure and not on a specific capture method used on a piece of debris. Part two of the mission involves the descent of the sail to the initial parking orbit in order to dispose of the debris. Since there aren't any time dependent parameters to match, the duration of this part is not constrained [9]. The same optimization of the sail attitude is used during the descent, although simulated flight times were considerably longer than the initial ascent, most likely due to the added mass of debris. This mission is executed without the use of chemical propellant, after the initial launch sequence, which greatly reduces airbus costs due to the reduced mass on the spacecraft [9]. The total simulated mission time with a high performance solar sail at minimum solar activity is close to 500 days [9].

V. Current Work and Future Research Applications

The active removal of debris from LEO is imperative to all future operations in space. The biggest challenge for future applications is overcoming the steep cost and energy requirements to put these removal methods into practice. Ground based lasers are currently the most cost efficient method to remove small space debris [4]. The restraints of this method are the large amounts of energy required to run these operations and current technology allows a maximum range of 650 km [6]. Space-based lasers can cover higher altitudes up to 2,000 km at the cost of a more expensive deployment and operational cost [6]. If LODR systems are to be used for this purpose in the future, international cooperation will need to be established for the reassurance that it is not a weapon system [5]. Currently, the most practical way to dispose of large debris pieces is through the use of a chaser satellite that attaches to the debris and uses a chemical propellant to descend back into the atmosphere, destroying itself along with the debris [10]. This method is very expensive and inefficient because of the high mission cost that is required for each piece of debris. To mitigate collisions with large debris, current space operations rely on avoidance maneuvers [5]. However, LODR systems would be capable of assisting with mitigation by "nudging" large debris out of its current orbital path to prevent a collision [4]. Large satellite remnants up to one ton can theoretically be deorbited by LODR systems with the assistance of a large mirror, although this method would take close to 4 years to completely deorbit one piece [5]. This fact alone validates the importance of continued research on LODR systems for the purpose of stabilizing debris fields in LEO.

Although the 4S mission structure was never pursued for real-world application, the simulation results showed that it would be a reliable method for targeting specific debris clouds [7]. Without the need for as much on-board fuel as traditional satellites or a large enough energy source to support a space-based laser system, 4S is a very cost and energy-efficient method for removing debris in LEO. It would be worth researching similar methods in the future with more computationally competent hardware for more accurate trajectory optimization. Mission structures using solar sails could completely bypass the need for on-board propellant, which drastically reduces launch costs [9]. Although these sails make it possible to perform multiple de-orbits, the simulated flight time for each cycle is significantly longer than other methods discussed. To maximize efficiency of a solar sail, missions need to be executed during times of high solar activity [9]. Solar activity is difficult to predict, but developing a high performing sail will allow this method to be used during times of minimal solar activity, while also decreasing flight times in ideal conditions. On April 23, 2024, NASA launched a mission called Advanced Composite Solar Sail System (ACS3) that uses carbon fiber composite booms for quick deployment with minimal storage requirements [11].

VI. Conclusion

The increasing threat of space debris is an issue that needs to be urgently addressed in the modern space age. To prevent the unusable state of Earth's orbit described by the Kessler Syndrome, a cost and energy-efficient method of debris removal needs to be implemented in the near future. A LODR system is a proposed remediation method with one of the highest cost-benefit ratios out of those analyzed in this study. The net benefit of any remediation method is measured in dollars saved due to risk reduction. The 4S mission structure has been proven through simulation that it can dispose or mitigate up to 153 pieces of debris over 51 days, which is about 1/3 of the Iridium-33 debris cloud. This concept is higher performing than the proposed solar sail, although missions such as ACS3 have seen active deployment and use of a lower performing solar sail. This technology is still in development; however, it's a great start for the future of potential remediation methods of debris in LEO, which is indispensable to the safety of all astronauts and any future space missions.

Acknowledgments

Thank you to Dr. Damiano Baccarella for his support and advice on the content of this paper. Thank you to Mason Roddy for his mentorship and advice throughout the writing of this paper.

References

[1] Morimoto, D., Takahashi, H., Sugiyama, Y., Otsuka, K. Ohtani, K., Hasegawa, S., and Makihara, K., "Support Vector Machine Framework for Detecting Ambiguous Contours of Space Debris Cloud," *Journal of Spacecraft and Rockets,* published online 22 Oct. 2024, Available: https://doi.org/10.2514/1.A35927

[2] Johnson, N. "The Collision of Iridium 33 and Cosmos 2251: The Shape of Things to Come," *60th International Astronautical Congress,* JSC-CN-18971, 2009, Available: https://ntrs.nasa.gov/citations/20100002023

[3] Wilhelm, C., and Kannan, H., "Fundamentals of Mega-Constellation Resilience," *AIAA SCITECH 2022 Forum,* AIAA 2022 1468, Jan. 2022, Available: https://doi.org/10.2514/6.2022-1468

[4] Locke, J., Colvin, J. T., Ratliff, L., Abdul-Hamid, A., and Samples, Colin., "Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris," NASA Office of Technology, Policy, and Strategy, May. 2024, Available: https://ntrs.nasa.gov/citations/20240003484

[5] Phipps, C. R., Baker, K. L., Libby, S. B., Liedahl, D. A., Olivier, S. S., Pleasance, L. D., Rubenchik, A., Trebes, J. E., George, E. V., Marcovici, B., Reilly, J. P., and Valley, M. T. "Removing orbital debris with pulsed lasers," *AIP Conference Proceedings*, Vol 1464, 2012, pp. 450–462, Available: https://photonicassociates.com/documents/LODR.pdf

[6] Cottrill, L., Tiscareno, A., Park, L., Bardaji, J., and Abdul-Hamid, A., "Cost and Benefit Analysis of Removing Small Debris Using Space-Based and Ground-Based Laser Systems," *AIAA SCITECH 2025 Forum,* AIAA 2025-1161, Jan. 2025, Available: https://doi.org/10.2514/6.2025-1161

[7] Missel, J., and Mortari, D., "Removing Space Debris Through Sequential Captures and Ejections," *Journal of Guidance, Control, and Dynamics,* Vol. 36, No. 3, pp. 637-903, May. 2013, Available: https://doi.org/10.2514/1.58768

[8] Missel, J., and Mortari, D., "Optimization of Debris Removal Path for TAMU Sweeper," *Advances in the Astronautical Sciences,* Vol. 143, No. 1, 2012, pp. 935–945; also AAS Paper 12-167, Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=8b36307bb05ee36f555620a2cccb8279fe6db935

[9] Bianchi, C., Niccolai, L., Mengali, G., and Ceriotti, M., "Preliminary design of a space debris removal mission in LEO using a solar sail," *Advances in Space Research,* Vol. 73, No. 8, pp. 4254-4268, April. 2024, Available: https://doi.org/10.1016/j.asr.2024.01.024

[10] Bonnal, C., Ruault, J., and Desjean, M., "Active debris removal: Recent progress and current trends," *Acta Astronautica,* Vol. 85, pp. 51-60, April-May. 2013, Available: https://doi.org/10.1016/j.actaastro.2012.11.009
[11] Wilkie, K., and Fernandez, J., "Advanced Composite Solar Sail System (ACS3) Mission Update," *The 6th International Symposium on Space Sailing*, NASA Langley Research Center, June. 2023, Available: https://ntrs.nasa.gov/citations/20230008378