Policy Memorandum: The Case for Addressing the Crisis of Space Debris with Ground-Based Lasers

Nolan Hedglin
United States Military Academy, Physics and Nuclear Engineering, 745 Brewerton Rd. West Point, NY
Corresponding author: nolan.hedglin@usma.edu
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Executive Summary: The amount of space debris presents in low earth orbit (LEO) is increasing at an unsustainable rate. Without an active method for de-orbiting the more than half a million pieces of debris currently crowding LEO, we will continue to see inter-debris collision and scattering events that will eventually render LEO completely unusable. Phipps et al. (2011) proposes the development of a ground-based laser system to drastically decrease the time until debris safely reenters the atmosphere. A ground-based laser solution would come at a significantly lower price than any other removal method proposed thus far. This memorandum summarizes the cost of proposed solutions and builds upon the work of Phipps et al. by analyzing the policy implications of building a high energy laser system for the purposes of de-orbiting space debris and recommending specific policy action items.

I. A barrier of trash

In 2013, there were more than 500,000 unused or broken objects the size of a marble or larger left in low earth orbit as a result of past missions, known as space debris. Millions more of even smaller objects remained untracked.[1] Traveling at speeds of more than 28,000 kilometers per hour, even tiny objects have the potential to destroy pivotal satellites. For reference, the kinetic energy of a single aluminum object in LEO a centimeter in diameter, assuming it has nominal and uniform density, is approximately forty-six times that of a standard NATO 5.56mm combat round. According to the US National Aeronautics and Space Administration, even objects as small as paint flecks have caused “a number of space shuttle windows [to be] replaced because of damage caused by [them].”[1] As a result, many potential orbits have been rendered unusable due to the risk of collision with debris.

A decade ago, when the problem was still new, passive debris removal methods such as the de-orbiting of late-stage boosters and rules about post-mission rocket disposal were enough to ameliorate the issue at hand. However, as objects continue to collide with one another debris scatters and accumulates in potential orbits, greatly multiplying the number of unusable orbits. Passive methods of debris removal are no longer sufficient because they cannot eliminate the problem of inter-debris collision, which further destabilizes the LEO environment. Additionally, short term solutions such as maneuvering rockets out of danger cost a significant amount of money. Based on its cost-efficiency and targeting capabilities, laser orbital debris removal (LODR) provides the best chance of decluttering LEO and permitting debris-free travel for future satellites.

II. The cost of mechanical methods

One approach to minimizing space debris involves launching satellites with active tracking that use mechanical methods for de-orbiting. For example, the European Space Agency proposes using a throwing net or a robotic arm to catch the debris in orbit.[2] The cost of long term implementation for satellite removal methods can be summarized by the following equation:

$$\text{Additional Cost} = \sum_i [L_i + \sum_j E_j]$$

Each individual satellite will have an associated and launch cost, L. Even with the advent of reusable rocket stages, the cost of implementing such a system limits its feasibility because of how expensive it is to launch an object into space, (approximately $20,000 per kilogram on SpaceX's Falcon 9 in 2016).[3] This is an issue that affects only satellite-based proposals. Following that, each system has a specific energy cost, E, for operating its removal technique, which Phipps et al. predicts will cost approximately $27M per large object.[4] As this paper will later demonstrate, the LODR system could remove an entire constellation of large objects for this price.

III. Lasing the problem

As a permanent and cost-effective solution to the crisis of space debris, I propose the development of stationary laser defense systems that accelerate the rate at which debris re-enters the atmosphere. Upon reentry, the debris can safely burn up in the atmosphere. The LODR consists of two main components: a high energy short-pulsed laser and a debris targeting system.

Ground-based lasers, known as laser brooms, would sweep out large areas of space debris by heating up only one side of the object, ablating its surface and lowering the altitude of its orbital perigee by causing a thrust against the debris' direction of motion. The change in momentum of the debris object as a result of the laser system is equal to the coupling coefficient, c_m, of the debris (which varies from object to object) multiplied by the energy deposited by the laser, E_d. However, since the mass of the debris changes with each successive pulse, it becomes a function of the ablation rate, μ, and E_d. The velocity change is then characterized by: [5]

$$\Delta v = \sum_{j=1}^{n} \frac{c_m E_d}{m_j}, \qquad m_j = m_0 - \sum_{i=1}^{k} \mu E_d.$$

Following initial implementation, maintenance costs will be limited to keeping the laser system temperatures at a reasonable level while it is in use, which is a significantly cheaper upkeep cost than standard satellite maintenance. This would be a long-term, cost-efficient solution. In their 2011 paper, Phipps et al. determined that removal of objects less than one meter in diameter would cost a few thousand dollars per object, while larger objects will cost about one million dollars per object.[6] Given that there are an estimated 100 objects in orbit greater than a meter in diameter in LEO, it would cost approximately $600 million to remove all debris greater than 1cm in diameter.[1] The cost to remove the millions of debris pieces smaller than 1cm would not be significantly greater than this figure because decreasing the size of the target by two orders of magnitude general decreases the price by three orders of magnitude.[†] This is a small price to pay to protect multibillion dollar investments like the International Space Station and providing stability and commercial viability for the continued development of LEO.

Additionally, an active tracking and targeting system permits the laser to reach all points in LEO. Through a combination of adaptive optics and predictive functions, the active tracking can accurately and precisely target objects the size of a marble at a distance up to 1000 kilometers. This range is sufficient to reach most orbital debris, as NASA believes the highest concentrations of debris reside between 500-530 miles in altitude.[7] This means each individual broom would cover about 0.63% of LEO. If the LODR system were, for example, comprised of 100 brooms scattered evenly across each continent, then the system would cover approximately 63% of the Earth's atmospheric surface area. Since all objects pass through the equatorial plane twice in their respective orbits, this would sufficiently address all debris. Furthermore, due to the oblate shape of the Earth, orbits gradually precess across the Earth relative to the surface over time, providing opportunity for laser brooms to eventually sweep out debris from any LEO path.[8]

The immediate goal of the LODR would be a demonstration of its capabilities to de-orbit large-scale debris. This is because larger objects pose the biggest threat to inter-debris collision, causing an exponential increase in scattered. Due to this phenomenon known as "Kessler syndrome," Klinkrad (2009) claims that these large objects "destabilize" the debris environment and make any future space travel impossible.[11] In his report to NASA on the state of space debris, the systems would only need to deorbit 15 large objects a year in order to stabilize the debris environment and prevent further scattering of objects that hit one another.

IV. Current difficulties

A technical issue regarding the laser system is that we currently do not know much about how the atmosphere affects beam divergence, which can dissipate power quickly. Mason et al. recommends reducing the atmospheric effects by placing the LODR in high altitude locations such as the Plateau Observatory in Antarctica.[9] Furthermore, even at a power of 91kW, which is three times the power needed to destroy an unmanned aerial system (UAS), the system would not be able to deorbit larger objects that weigh over one ton on a single orbital pass.[10] While objects smaller than this account for over 99% of all debris, it does not address the issue of collisions that scatter and repopulate the surrounding region. This problem, however, is remediated by the laser's ability to maneuver a large object from its collision trajectory with another satellite. Additionally, the object can still be deorbited when targeted by multiple brooms or when making multiple passes on a single broom.

One of the most challenging policy hurdles in implementing LODR systems is fostering international agreement. If the power level of the broom were increased to a level such that it was able to shoot down a UAS conducting reconnaissance, then conflict might arise over its potential to destroy enemy systems. Lockheed Martin recently demonstrated that their 30kW defensive laser, known as ATHENA, could quickly destroy an Outlaw UAS, which implies that LODR systems are more than capable of destroying any conventional UAS.[10] A system that has the ability to deorbit a satellite or destroy a UAS from the ground at a low cost may create consternation among nations with competing space interests. However, creating a sense of shared ownership over the space debris crisis with other nations will mitigate this issue. Other countries participating in this agreement would own and have full control over their own LODR system, which would place a greater emphasis on this crisis being a global issue rather than a ploy by the United States to augment their laser defense capabilities covertly. If cooperation cannot be achieved because a nation still disagrees with the proposal, then guaranteeing a nation's compliance is sufficient.

V. A call for action

In order to facilitate the protection of satellites and promote future missions to the region, it is imperative that the United States act now to implement a LODR system as soon as possible. I propose that an initial proof of concept be developed at the High Energy Laser System Test Facility (HELSTF) in White Sands, New Mexico under the supervision of US Army Space and Missile Defense Command. The facility is currently progressing the field of directed energy defense and they have laboratories suitable for the research needed to successfully develop a prototype. Although not a military-exclusive issue, the US Army relies heavily on satellite communications for conducting missions in theatre. Furthermore, their facilities and expertise would serve as an optimal starting point for the development of a LODR system. After a prototype has been successfully demonstrated in an operating environment, the LODR could be rapidly deployed to US locations across the globe so that there could be imminent global coverage of space debris in LEO. Informed by NASA's expertise in debris tracking, I propose that this system be installed at military installations in Alabama, Alaska, Colorado, and Hawaii, and New Mexico.

Concurrently, there should be an international summit to request permission from other nations and to propose a plan for the implementation of the system worldwide because it is of international interest that LEO remains as decongested as possible. Such a meeting would increase the transparency of the policy and allow the United States to lead the charge in creating a more accessible space environment for all nations interested in LEO. This meeting would not create international gridlock over the issue because nearly every nation has or will have a vested interest in space in the future.

VII. Conclusion

LEO has become overcrowded by small objects with the potential to render certain orbits ineffective and destroy space systems currently in orbit. Through the employment of multiple high energy stationary lasers, the LODR system stands as a long term, cost-effective solution to the problem of space debris, unlike passive methods of removal or the launching of satellites to move debris by mechanical means.

After a successful demonstration of the LODR in LEO, this system could be assessed for its feasibility for removing objects in medium earth orbit and geo-synchronous orbit.

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Nolan Hedglin is an undergraduate student in Physics and Mathematics at the United States Military Academy. He also has been recently accepted into a doctoral program in electrical engineering at the Massachusetts Institute of Technology. Following graduation, he aims to continue pursuing his interests in applied physics, astrophysics, and applied mathematics as a cyber operations officer in the United States Army.

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