Turning the Tables: Modeling the Fight against Space Debris

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Abstract

As commercial space development policies gain traction in the United States and elsewhere, commercial schemes for the disposal of dangerous orbital debris have become increasingly common policy suggestions. We have developed an analytical model incorporating data and models of both the space industry's value and the risk posed by orbital debris to determine the viability of commercial approaches to debris mitigation.

We consider the risk posed by space debris in terms of the risk it poses to revenue-earning commercial satellites. First, a scheme for determining both the average value of satellites in Low Earth Orbit (LEO) and the rate at which that value changes due to economic growth is developed. This value-change model is combined with the European Space Agency's Meteoroid and Space Debris Terrestrial Reference model, which provides worst-case predictions for the quantity of space debris present in LEO for the next fifty years. Finally, a Poisson-Distribution model of collision dynamics is used to evaluate the collision risk for spacecraft operating in LEO.

This price-risk model is employed to evaluate the potential profitability of three classes of debris removal technologies: ground-based laser systems, space-based laser systems, and space-based debris capture satellites. The debris removal efficacy and cost of each of these systems per year is modeled, providing both cost and debris-removal functions as a function of time. Additionally, a relationship between the value of space debris removal versus the density of space debris in LEO is presented, allowing for the evaluation of other debris mitigation technologies as they become available.

Our model concludes that some types of debris removal methods may be profitable under optimistic assumptions in the next five to ten years. A framework for calculating the profitability of future mitigation systems is presented, and the results of modeled systems and their implications for the success of a commercial venture are discussed. Ultimately, our model recommends a staggered approach to space debris mitigation, wherein mitigation technologies are implemented as risk collisions and the market grow to levels that would support them.

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1. Background of the Problem

1.1. Collisions, Kessler, and Risk

Objects orbiting around the earth speed along at ground-relative speeds ranging from one to nine kilometers per second. At these speeds, virtually any object—lost gloves, Mylar insulation, paint chips—carries enough kinetic energy to damage or destroy active spacecraft [5]. At the same time, few mechanisms exist to remove debris; in orbits far outside the reach of the Earth's atmosphere, debris objects can remain aloft virtually indefinitely, creating a sustained risk of not only damaging other spacecraft but also creating more debris.

The problem of space debris and the possibility of a catastrophic "debris cascade" was first identified by NASA engineer Donald Kessler in 1978 [6]. Using simple population models, Kessler revealed the principal mechanics and methods behind space debris formation and longevity. Debris, according to Kessler, springs both from negligent littering during space launch and operations, and from collisions between debris. As the quantity of debris increases, so too does the quantity of collisions between debris, creating a self-reinforcing feedback loop that, if not stopped, would render space unusable.

As the quantity of debris increased throughout the early space age due to accidents and negligence, so too did our dependence on space-based infrastructure. Today, $122.9 billion dollars worth of space-based services are provided commercially [7]. At the same time, government applications of space, including GPS, which provides the timing data all credit and debit purchases rely on, have also expanded tremendously. The United States Air Force, which runs the Joint Space Operational Command (JSpOC) responsible for tracking both spacecraft and debris, has identified Space Domain Awareness—the monitoring of satellites and debris partly to identify collisions before they occur—as a key technology development area, underscoring the risk posed by space debris.

1.2. The Present Debris Environment

Debris objects range from pieces of paint less than a centimeter in diameter to entire defunct, nuclear-powered cold war relics leaking their coolant. The Joint Space Operations Command estimates that of the roughly 22,000 tracked space objects, only five percent ($\sim$1,100) are active satellites. The other ninety-five percent is debris of various national origin [8]. With such a significant presence of debris in orbit it is imperative to provide tracking for as many objects as possible, in order to prevent debris collision with active satellites. Between late March and July, 2015, the International Space Station (ISS) had to shift its orbit twice to avoid debris. On another occasion, crew members had to take emergency shelter when an old satellite fragment passed in close proximity to the station [9]. Whether or not debris can be tracked and the potential collision risk is related to its size. Four standard size-classes of debris are itemized in Table 1.

Satellite-based shielding can readily withstand the majority of small untrackable debris. Large, untrackable debris presents an issue, as these objects carry enough energy to be dangerous but are not large enough to be tracked individually; instead, combinations of radars can track their general distributions such that satellites can best avoid regions of high collision probability. Objects larger than 10 cm can be tracked, which is convenient because an impact with any object this size or larger would result in complete fragmentation, also termed a "catastrophic" collision. The fragmentation from a catastrophic collision of a 10

ton satellite has the potential to double the amount of current debris in LEO. For example, the explosion of Fengyun-1C and the Iridium-Kosmos collision resulted in a 45% increase of trackable debris an produced on the order of one hundred thousand untrackable pieces [10]..

Classification	Size	Collision Effect
small untrackable	< 1 cm	none – minor
large untrackable	1 cm – 10 cm	medium – high
small trackable	> 10 cm and < 100 cm	catastrophic
large trackable	> 100 cm	catastrophic

Table 1: The classification of orbital debris. Shielding can withstand most small untrackable debris. A "catastrophic" collision results in complete fragmentation.

Presently, major space-faring nations have instituted design rules and regulations to prevent the formation of additional space debris. Data on the number of space objects added to tracking databases between 1996 (when multiple major rules were implemented) and 2006 suggests that these policy changes greatly slowed the accumulation of debris [10]. However, fears exist within the debris monitoring community that many orbital belts are already "super-critical," and will remain extremely risky for spacecraft operations for the foreseeable future, including many high-use polar orbits [11].

For an object in a stable orbit, an impulse Δv imparted to the object will change its orbital trajectory. A retrograde impulse ($-\Delta v$) will decrease the altitude of the orbit. An object will deorbit if the perigee, or point of the orbit closest to the Earth, comes within an altitude of 100 km. This is known as the Karman Line, which is the formal separation between the atmosphere and outer space. In practice, there is still enough atmosphere at 200 km that an object orbiting at that altitude will deorbit in a matter of days to a week. Therefore, for an object orbiting at a given radius there is a well-defined Δv needed to deorbit it. Of major interest are orbits in the following ranges:

- Low Earth Orbit (LEO): 200 km to 2,000 km
- Medium Earth Orbit (MEO): 2,000 km to 35,786 km
- Geostationary Earth Orbit (GEO): 35,786 km to 35,986 km
- GEO Graveyard Orbit: 40,000 km

The altitude of an orbit can help us to decide on how best to dispose of debris in said orbit – namely deorbiting the object or pushing it outwards into a 'graveyard orbit'. For example, due to the large altitude of GEO objects, it is more feasible to move debris into a graveyard orbit just outside of GEO than to expend the immense amount of Δv required for atmospheric reentry.

The active satellite population is almost exclusively found in LEO or GEO. We further refine our attention by focusing on LEO satellites, for the following reasons:

- nearly half of all debris larger than 1 cm is found in this region [10]
- the number of GEO collisions in the next 200 years is only 1.6% that of LEO collisions [12]

- having the satellites and debris within a belt in GEO reduces the risk of collision from debris on other orbital inclinations.

See the appendix for a discussion on the ramifications of our decision to solely consider objects in GEO.

1.3. The International Environment

Due to the fundamental dynamics underlying orbital motion, the near-Earth orbital environment is inherently shared without respect for national boundaries. While this opens up many uses for space, it also creates what economists would describe as a "Tragedy of the Commons" problem. Actors wishing to exploit this environment have virtually no short-term economic incentive to reduce the quantity of debris they contribute, in the same way that rational actors will happily spoil public grazing meadows to increase the size of their own flock.

This economic problem is compounded by the vagarities of international politics. Most international cooperation on space usage to date has focused on demilitarization, and treaties therein refer only to the governance of "space objects". Indeed, there is no widely-accepted international definition of debris. According to Article XIII of the Outer Space Treaty, all nations retain ownership over their launched space objects (including debris) indefinitely; in this legal framework, active debris removal efforts would be not only discouraged but could be made punishable by international law. Even still, there is a growing consensus in the space community on the dangers of space debris. Formal talks on changing the Outer Space Treaty have not begun, but recent legislation in the United States does appear to oppose several sections of it [13]; and, as the push for broad-strokes commercialization of space moves forward, so too will efforts to allow international debris removal efforts.

1.4. The Promise of Commercial Space

In spite of debris fields, meagre markets, and the traditionally pseudo-military status of space development, a new generation of forward-facing space development companies has sprung. NASA, the largest civilian space agency on Earth, has turned to private companies like SpaceX and Orbital-ATK to ferry its astronauts and supplies into near-Earth space; at the same time, commercial entities like Planet Labs and Facebook are turning to smaller spacecraft made viable by technical advances to create billion-dollar capabilities on million-dollar platforms.

The success of markets at solving difficult problems is a long-proven truism that has come to define efforts in social and environmental fields in addition to commercial ones. The success of the United States' cap-and-trade policies towards reducing acid rain bespeaks the underlying promise of market-based methods towards reducing structural or externality-based problems [14].

A commercial venture, whose aim and principal means of profit is the removal or mitigation of space debris, appears at once to be a viable undertaking that would both enrich its owners and solve one of the great environmental crises of our time. However, this proposal requires the answers to a number of questions before its viability can be assured, namely:

1. What is the economic value of space debris removal? What potential profits justify investment in such a commercial venture?

2. What techniques or technologies provide the best return-on-investment for eliminating the debris problem? Can they do so profitably, given the answer to the above question?
3. What risks does such a venture entail, both on orbit and on the ground?
4. Should this venture be found non-viable, how should the problem of debris be addressed?

Unfortunately, the difficulties associated with tracking space debris, the sheer magnitude of the problem, and the chaotic nature of collision fragmentation results in a computational expense that prevents direct overall modeling attempts. To answer these questions, we combine traditional business-analysis techniques fed by existing data on the debris problem with orbital mechanics models to analyze the nonlinear behaviors inherent to the problem at hand.

2. Revenue Modeling

2.1. Valuing Risk

Our model begins by examining the value of an individual commercial satellite on-orbit. According to the Satellite Industry Association, the space-based services sector—i.e. the sector of companies who profit by selling services related to satellites, like imaging or telecommunications—was worth $122.9 billion US in 2014 [7]. As we will be predicting into the future, we start by assuming that this value will continue to grow every year. The SIA cites annual growth rates for the space industry ranging from 10% in 2009 to 4% in 2014 [7]. Our model makes the conservative assumption that the satellite services industry falls in line with historical global growth trends since the Second World War, and grows for the next forty years at an average of 2%. This assumption is consistent with the idea that space-based services are becoming an increasingly regular part of the day-to-day economy; as the global economy grows, so too will the need for satellite-based services. The value of the satellite services industry is given by the simple growth rate formula,

$$V_{\text{new}} = V_{\text{old}}(1 + g), \tag{1}$$

wherein V_{new} is the current year's industry value, V_{old} is the previous year's industry value, and g is the annual growth rate (assumed to be 0.02).

Next, we use this growth model to predict the number of commercial satellites in orbit. Because the space debris problem is primarily a threat to spacecraft in LEO, we first determined the fraction of spacecraft in LEO as compared to the total. According to data released by the Union of Concerned Scientists, 48 out of the 603 commercial spacecraft currently in orbit reside in LEO, with an average expected lifespan of 8.13 years[1]. Simultaneously, our model recognizes that the revenue of LEO spacecraft is typically lower than that of GEO spacecraft. Data from the UCS Satellite Database suggests that the typical yearly revenue produced by a spacecraft operating in LEO is $77.56 million USD. We assume that companies are re-investing the revenue from these spacecraft over their operating lifespans in

[1]Satellite data is compiled in the UCS Satellite Datebase, provided at www.satellitedebris.net

accordance to the law of compound interest. Using this, we can account for the revenues generated by a spacecraft as an annuity and calculate its future value FV to a company,

$$FV = A_{\text{in}} \frac{(1+i)^t - 1}{i}, \tag{2}$$

where $A = \$77\text{M USD}$, $i = 2\%$, and t is the number of compounding periods.

We will assume moving forward that the average satellite on orbit presently is halfway through its lifespan, such that its owner can expect to eventually receive the value of four additional years of service and compound interest from its operation. With this, the remaining future value is held fixed at FV_{rem}. Actuaries price risk C_{risk} by a deceptively simple formula,

$$C_{\text{risk}} = V_{\text{asset}}\, r, \tag{3}$$

which accounts for both the probability that a risk will occur (an asset's "risk exposure" r) and the value of that asset V_{asset}. In our case, the risk exposure is the probability that a satellite will have a collision with a piece of debris within a year, and the value of the asset is the future value of the satellite, FV. The primary use of this formula is to determine how much a firm should invest in risk reduction, i.e. the expected annual "cost" of the risk. In a competitive market, firms will attempt to adjust their risk downward so long as they can do that at a price less than the annual risk cost.

The financial viability of a space-debris removal company depends on the annual risk cost to satellites in LEO remaining higher than the price of space debris removal. Such a company would earn its keep by decreasing the risk exposure of space assets, effectively arbitrating between the price that space-service providers should be willing to pay and the cost of debris removal. The viability of such a venture is dependent on the margin between those two values.

Importantly, this model does not account for specifics of policy implementations that would foist this cost concretely upon companies, such as cap-and-trade schemes or taxes on spacecraft to fund debris-reduction efforts. This is a model of the pure "economic benefit" to be had by reducing the risk to an asset posed by space debris strikes.

Additionally, we assume that each spacecraft in orbit is owned by a separate firm, and that the profitability of each satellite is equal such that the revenues for the space-services sector can simply be divided by the number of spacecraft. This assumption is effectively an extension of the efficient market hypothesis, which states that given perfect competition and information transmission, the prices of goods will approach their marginal cost; in our case, each firm has made its satellite equivalently useful at the lowest possible cost already. This allows us to calculate the value of an individual satellite in LEO as follows,

$$n_{\text{sat}} = \frac{V_{\text{ind}}}{6A_{\text{LEO}}}, \tag{4}$$

where n_{sat} is the number of satellites in LEO and A_{LEO} is the annual profit generated by a satellite in LEO. We assume further that no new uses for LEO are found, and that LEO satellites continue to be launched in a proportion and with an annual return consistent with current trends. By using Eq. 3, we find the formula to price the risk per satellite as

$$PR_{\text{risk}} = FV_{\text{rem}} r. \tag{5}$$

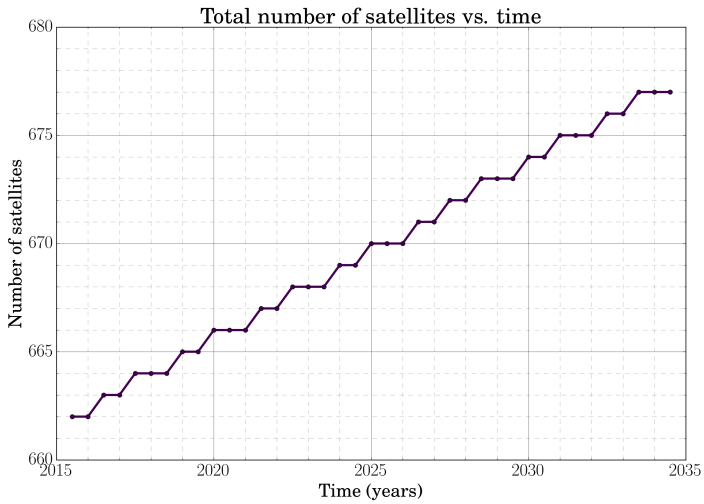

Figure 1: The population of satellites in LEO predicted by our model from 2015 to 2045.

It is furthermore reasonable to assume that the risk posed by space debris is shared evenly by any spacecraft in LEO. As such, each firm in LEO will evaluate the same risk price, and attempt to spend their mitigation dollars accordingly. This allows the total economic value of a reduction in space debris to be calculated as

$$PR_{\text{total}} = \sum_{\text{satellites}} (PR_{\text{satellite}}) = \sum_{\text{satellites}} (FV_{\text{rem}} \cdot r) = n_{\text{sat}} \cdot FV_{\text{rem}} \cdot r. \tag{6}$$

Any space debris mitigation firm will effectively act as an arbitrator of risk. Revenues for such a firm will come from the economic value created by reducing this level of risk (and therefore the risk's associated cost burden). The net profits of this company are therefore based upon the reduction in risk $(r_1 - r_2)$ the venture can achieve, the cost associated with that reduction in risk, and the fraction of that economic improvement that can be captured by the venture. This relationship is represented by the equation,

$$P = k \cdot n_{\text{sat}} \cdot FV \cdot (r_1 - r_2) - C(r_1, r_2). \tag{7}$$

In this expression, the function $C(r_1, r_2)$ represents the cost of performing the associated risk-reduction, i.e. the cost to run a satellite removing debris. This is based on the technologies involved, and is discussed later in this paper.

In the bounding case of $k = 1$, the proposed commercial venture would capture the entire economic utility of the reduction of risk; as such, we will perform most of our analyses with $k = 1$ to justify the raw economic utility of each debris-removal method, before discussing the potential profits to be had for such a venture. Using this model, we calculated the number of new (i.e. filling new roles, rather than replacing older spacecraft) launched per year for the next twenty years, cf. Fig. 1.

3. Collision Risk Modeling

3.1. Debris Growth Models

Crucial in the profit model outlined above is a model for the time-dependent risk of a satellite colliding with space debris. A-priori, it is intuitive that the quantity of debris will increase with time, as both new debris is created during both regular launch and operational activities and during collisions between debris and other debris or satellites. We sought a model that incorporated these interactions, and which provided us with both

1. how the quantity of debris will behave over time, and
2. how the quantity of debris in orbit relates to the risk of collision for active spacecraft.

Due to the importance of predicting space debris collisions and the general trend of the debris problem, a variety of modelling efforts have been undertaken to characterize the threat–present and future–posed by space debris. While public records of large, trackable debris objects can be found readily through JSpOC, models and records of smaller debris are typically less open-source. This is problematic, since initial estimates of the quantity of debris in the damaging-but-not-trackable range (1 cm - 10 cm) are high, on the order of hundreds of thousands of debris items. We felt that ignoring these items would dramatically understate risks to spacecraft.

The European Space Agency's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model provides a standard and readily usable reference for the quantity of debris present on-orbit for the next fifty years. MASTER uses semi-deterministic analyses and prediction techniques to propagate measurements and estimates of the current debris environment forward over three separate trajectories:

1. Business As Usual: No or minimal debris mitigation
2. Moderately Mitigated Environment: Satellites are required to deorbit within 25 years and steps are taken to prevent on-orbit explosions.
3. Mitigated Environment: In addition to the above, debris is actively removed by parties.

These pre-built scenarios provide us with readily available, comparable predictions of the debris environment under various combinations of policy changes. We take the business-as-usual case to be the most likely given recent increases in space debris, and the rise of international tensions. However, both of the mitigation environments potentially provide grounds to test our business model in lower-debris environments. Due to time constraints and issues in obtaining access to these large data sets, examination of our model's predictions in these debris mitigation environments is left as future work.

Unfortunately, due to the closed-source nature of MASTER, we are not able to simulate how our debris reduction efforts feed-back into the growth or decline dynamics of the space debris problem. This directly limits our model's ability to simulate large companies or coordinated efforts at removing debris.

This feed-forward behavior is instead approximated by reducing the total amount of future debris by the amount removed in a given year. More specifically, using the debris density data from MASTER we apply our removal methods by means of filters, described later in the paper, and propagate the effects through the static future data. This kind of approximation assumes that the implementation of one debris-removal system would not substantially impact the underlying dynamics at play when discussing space debris.

3.2. Collision Risk Model

To determine the risk of collisions between any given object and a piece of debris, we utilize the Poisson distribution method, a derivative of statistical mechanics [15]. As illustrated in Fig. 2, the outline of an object moving at a constant[2] speed v_o will trace out a volume from its path in a time Δt. This volume V is a product of the projected area A of the object and the length of the path $v_o\,\Delta t$. We assume that the debris is uniform in spatial density at a certain radius from Earth R, that the motions are seemingly random overall, and that there are minimal interactions between the objects. Essentially, we treat the debris cloud like an ideal gas. Under this assumption, the number of "particles" found in the volume of the satellite's path in Δt is the number of encounters N_{enc} during that time; the following equation,

$$N_{\text{enc}}(R) = \rho(R)\, v_o(R) A\, \Delta t, \tag{8}$$

gives the number of encounters for a satellite orbiting at radius R in a time Δt. From this, we can apply a Poisson distribution to get the probability of collision,

$$P_c(R) = 1 - e^{-N_{\text{enc}}(R)}. \tag{9}$$

If we define the timescale to be $\Delta t = 1$ year, then the P_c would be the probability that a satellite will collide with a piece of debris within the year.

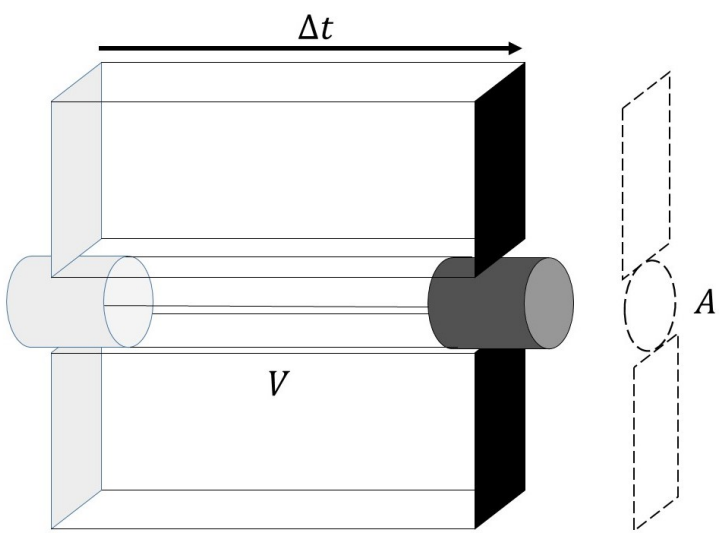

Figure 2: The cross-sectional, or projected, area A traces out a volume V by its path over a time Δt.

3.3. Modeling Strengths and Shortfalls

Combining the profitability, economic growth, and collision risk models outlined above provides us with an estimate of how the market will price the risk of space debris. Our approach has a number of advantages; chiefly, it uses industry-standard approaches towards

[2]Since we are primarily focused on Low Earth Orbits and Geostationary Earth Orbits and they are relatively circular, the orbital speed can be assumed to be constant.

modeling both risk and the quantity of space debris, and incorporates real-world data to predict growth trends in the space industry. . In a sense, our assessment of the economic viability of space debris removal does not depend on the actual threat of debris, but on the threat of debris perceived by commercial actors.

With that being said, the number of assumptions made to develop this model presents an issue when compared with the duration we are modeling over. As evidenced by the 2007 Chinese anti-satellite weapon test or the 2009 Iridium/Kosmos collision, the quantity and location of debris on-orbit is extremely sensitive to unpredictable "black-swan" style events that make long-term trends difficult to gauge.

This assumption is compounded by our orbit-agnostic approach towards modeling the probability of a collision. We make no distinction between the various bands of spacecraft and debris in LEO; objects in polar orbits are considered to have the same collision probabilities as objects in equatorial orbits, for example. In reality, the debris is distributed most tightly within commonly used bands, such as polar or sun-synchronous orbits.

Our model could be improved by more tightly specifying the orbital volumes occupied by both spacecraft and debris. However, doing so with certainty would require much more detailed data on both the positioning of active spacecraft and the positions of debris objects. While some of the data to support analysis on this problem exists, we did not have the computational resources to run such an analysis.

4. Predictive Cost Modeling for Active Debris Removal

4.1. Defining Debris Mitigation

Profits made from space debris mitigation are fundamentally the result of decreasing the probability that an active spacecraft will collide with a debris object, thereby "mitigating" the threat posed by debris. Industry studies have identified a number of options for accomplishing this, but all methods boil down to either moving active satellites out of the way of debris (or vice-versa), or by reducing the quantity of debris on-orbit (which is proportional to the probability of a collision.)

Two proposed methods to accomplish the former method of risk mitigation include ground-based lasers, which would exploit radiation pressure to nudge threatening objects out of the paths of active satellites or vice-versa (to save propellant), and clouds of dense gas which could be released on notice of a potential debris threat. At present, the literature seems to favor ground-based laser systems [1]; the cited cost-per-impact-avoided for gas-based systems approaches $50M [5]. As such, we have chosen to analyze ground-based lasers in the framework of our pricing model below.

At the same time, modern predictions of the near-future debris environment show that active debris removal will be needed to prevent further growth in the quantity of space debris on-orbit, even without additional space launches [16]. Technologies for active debris removal mitigate the risk of debris collisions by lowering the present and future densities of space debris in a given orbital environment. Two broad categories of approaches are presented by the literature: approaches which use space-based lasers to shoot down debris by again applying focused radiation pressure to them, and approaches which directly capture or

grapple debris objects and boost them into disposal orbits. We will investigate the quantity of debris removed by each system (and therefore its risk-reduction and profitability) and the projected setup and operating costs of such systems.

There are a host of proposals for this type of mitigation. Some involve plans to grapple the debris, such as the ElectroDynamic Debris Eliminator (EDDE), discussed below [17, 18, 19]. Other ideas include attaching solar sails or electrodynamic tethers to large debris objects to use solar "winds" or the Earth's geomagnetic field to provide the Δv to deorbit debris [20, 21]. Another direct contact approach involves expanding a huge ball of foam to catch incoming satellites and deorbit them [22]. Complications, such as rapidly spinning debris, often makes direct contact difficult. Non direct contact approaches involve using space-based laser impulse coupling to deorbit debris, discussed below as well [4, 23]. There are also plans for a "shepherd" satellite to orbit just in front of a debris object, spraying it ion beams to deorbit it [16, 24].

The ideal characteristic for any method is one in which operation lifetime is as long as possible while providing for relatively safe, effective, and cheap debris removal. We have chosen one collision avoidance method and two strategies for active debris removal, involving both direct and non direct contact, for rational analysis.

4.2. Ground-Based Laser Impulse Coupling

4.2.1. Qualitative Assessment

The use of photon momentum as a source of propulsion has been studied since 1962 [1]. Lasers, as high-coherence sources of photons, are a commonly proposed means of mitigating space debris hazards. Ground-based laser sites have a number of qualitative and quantitative advantages over space-based approaches that have driven us to include them in our model. Ground-based laser sites are first and foremost much less expensive by nature than any space-based method, by virtue of not needing to be launched into orbit—a process which brings up system design measures that further increase costs beyond simple launch vehicle costs. Remaining ground-based means that operating organizations can readily perform maintenance on malfunctioning components or expand the functionality of the system, allowing for a high degree of scalability.

Atmospheric attenuation of ground-to-space lasers remains a performance drain, and limits the usage of ground-based lasers to mitigating debris in Low Earth Orbit [1]. At the same time, the lasing geometries provided by ground-based lasers prevent these systems from removing debris; instead, ground-based lasers mitigate collision risk in advance of detected collisions. This limits the usage of lasers to preventing identified collisions between small trackable objects and active spacecraft, rather than working towards reducing the net amount of debris in orbit.

The ground-based nature of lasers also means they have a limited number of targeting opportunities. To provide true global coverage, sites at various latitudes are required to ensure all orbital trajectories can be accessed. The four chosen sites are listed in Table 2. According to the Air Force Research Laboratory, these four sites would provide adequate coverage over LEO to prevent about 28% of potential collisions either between debris and active spacecraft or between two small trackable debris objects [1]. These locations were specifically selected on the basis of minimizing atmospheric interference and the benefit of an existing facility.

4.2.2. Quantitative Model

When an object in orbit rises above the horizon and comes into view of the ground-based laser system, the targeting procedure is begun. Once the appropriate positioning information has been ascertained by the targeting system, the laser focuses the beam on the object for approaching half of the target's pass, cf. Fig. 3. Each target would be hit for approximately 103 minutes per day. Due to the time it takes objects to pass, it may be possible for one laser to target up to 10 objects per day. Several factors influence the efficacy of the laser, such as reflectivity of the target, cross-sectional area of the target, mass of the target, beam width, and atmospheric turbulence. The average probability of orbit change by installing a 5 kW laser system at the four facilities is presented in Table 2. These probabilities are based on simulations involving each station targeting 100 LEO objects. There is current interest in installing a 5 kW IPG single mode fiber laser with a wavelength of 1060 nm at each of the four locations [1]. Notably, this method does not obtain geometries versus space debris that are favorable to deorbiting them (ideally Δv should be applied opposite to their orbital direction); instead, ground-based lasers would be used to gently nudge debris that is expected to collide with active satellites out of their way. This accomplishes two things; it both prevents the risk of collisions with active satellites, and prevents the debris resulting from those collisions form forming.

Station	50 m/day	100 m/day	200 m/day	500 m/day	1000 m/day
PLATO, Antarctica	18%	13%	30%	8%	5%
AMOS, Hawaii	17%	8%	1%	2%	2%
Eielson AFB, Alaska	19%	7%	1%	2%	2%
Mt. Stromlo, Australia	7%	0%	1%	3%	0%

Table 2: The average probability for each station to change the orbit altitude of a small trackable LEO object by 50, 100, 200, 500, and 1000 m per day based on a simulation of 100 LEO objects. Based on Ref. [1]

A straightforward analysis shows that such a system would not be viable for the active removal of space debris. The highest density of tracked debris occurs at 871 km [25]. We separately simulated 4,000 small trackable objects radially and normally distributed around 871 km with a standard deviation of 150 km and applied the probabilities of orbit change per day by each station. With one thousand trials for each of the thousand debris objects, we determined the average number of objects that all of the stations together can deorbit (bring below 200 km) in a given time. Since all of the stations together would only be able to deorbit one piece of debris every 3.55 years, we decided that it was not a feasible application for this system and only focused on collision mitigation further.

Ground-based laser systems are still the cheapest option for collision avoidance. The price per Watt of a laser appears to decrease by a factor of 10 over approximately a decade, further reducing the construction cost if one desired to postpone construction for a more opportune time [26]. Accurate data for the operating costs from the different facilities was difficult to ascertain. Hence, we assume that the cost of the AMOS facility to be comparable to the other three. The price for the AMOS ground-based laser system would be [1, 27]:

Ground-Based Laser System:	
Laser cost	\$0.8 million
Targeting Systems Cost	\$5 million
Facility Cost per year	\$18 million
Electrical Cost per year	\$0.014552 million
Total Cost	\$5.8 million + (\$18.014552 million/year)
Total Cost×4	\$23.2 million + (\$72.058208 million/year)

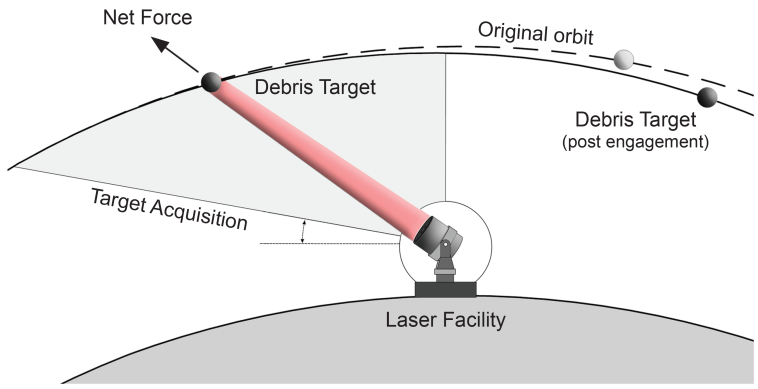

Figure 3: In order to provide negative impulse to the debris object, the laser only targets it during half of the pass. Taken from Ref. [1]

4.3. Space-Based Laser Impulse Coupling

4.3.1. Qualitative Assessment

Proposals also currently exist to use high-power lasers to fight space debris on its home turf—orbit [23, 4]. Space-based laser systems present a number of attractive advantages over ground-based systems, albeit at the expense and risk of placing such a system on a spacecraft. Historical precedent for such a system lies in the heat of the cold war, wherein both the United States and the Soviet Union designed space-based laser systems for missile defense (or offense) purposes. By basing an anti-debris laser in space, issues with atmospheric attenuation of the laser beam are eliminated, allowing for substantially increased range and power. At the same time, the orbit-to-orbit geometry allows such a system to directly change the velocity—and thus the trajectory—of debris objects, including large untrackable debris.

Unfortunately, such a system by nature incorporates the high-risk, high-cost issues associated with basing anything in space. While launch and systems engineering costs are discussed in the next section, something is to be said for the inherent debris risk present with large, propellant-laden spacecraft. Many pieces of debris on-orbit stem from propellant tank explosions or spacecraft that shut down due to technical issues before they could deorbit; despite a space-based laser's intentions, many precautions must be taken to prevent it from creating additional debris [10].

The history of spacecraft development shows several issues with this type of debris removal technique. First and foremost, spacecraft are historically very expensive to design, manufacture, and launch, on the order of \$350 million dollars for a typical communications

satellite[3]. This large initial investment must be re-made every several years as the debris removal bus runs out of propellant and must deorbit itself. At the same time, many issues are fundamentally implicit with attempting to shine high-power lasers at pieces of debris too small to be tracked. Beam-pathing, and therefore the system's attitude control, would need to be designed to avoid pointing the beam on paths that intercept active satellites to reduce the risk of damaging or incapacitating other satellites.

4.3.2. Quantitative Model

The primary advantage to a space-based laser is that it would be able to remove large untrackable debris in the 1 cm - 10cm range [4]. The fact that the laser system would itself be in LEO provides the opportunity to track incoming debris from orbit and impart the Δv without the need for long-term tracking. In order to provide such a large Δv to deorbit the debris as fast as possible, the International Coherent Amplification Network (ICAN) plans to use a 100 kW fiber laser on-board the ICAN Debris Sweeper. With a scan radius of $r_{\text{scan}} = 6.1$ km and a scanning range of $L_{\text{scan}} - L_{\text{max}} = 300$ km $- 170$ km $= 130$ km, it has a tracking zone of about 15,200 km^3 and a shooting zone of 11,690 km^3, cf. Fig. 6. For the most effective ICAN Debris Sweeper, the laser would need to operate with 100,000 fibers and fire a 1000 nm wavelength beam at a 1 kHz repetition rate. Under these conditions, simulations show that the Debris Sweeper orbiting near 800 km is capable of eliminating 56,000 large untrackable debris objects (1cm – 10cm) in a single year [28, 4]. To implement this in our model, we simply removed 56,000 objects throughout a year's duration, for each year that the satellite is in service.

Since the laser would be space-based it would be subject to launch costs, which contribute a large percentage to the overall cost of the endeavor. Due to the continual growth of the space industry, the launch cost has steadily decreased over time, cf. Fig. 4. Currently, the cheapest option is on board the Falcon 9v1.1 launch vehicle provided by SpaceX at $4109 per kilogram. The estimated mass of the satellite is based on the 3,600 kg mass of the 100 kW IPG fiber laser. A fiber laser with a 4 kW operating power is able to provide a 100 kW shooting power. Assuming a 30% efficiency for the laser, the input power would need to be 13.3 kW. If the solar system also operates at 30% efficiency, then the solar input power would need to be 44.3 kW. The mass per kW for a space solar array is at most 20 kg/kW, which translates to a solar array mass of 886 kg. A heat sink is required to handle the 31 kW heat waste, which, at 10 kg/kW, contributes a heat sink of 310 kg. The telescope and optics system has a mass of 400 kg. We are expecting a mission lifetime around 15-20 years, for which we estimate 2000 kg of propellant. This calculation follows that in Ref. [4]. With such a massive satellite, there will be an appreciable amount of mass surviving reentry, about 10-40% of the mass. Therefore, it will need to have a highly controlled reentry, account for such a large amount of propellant budgeted.

We bring the total cost of the satellite up to 9492 kg for far above average shielding. A catastrophic collision with this satellite would be expected to nearly double the amount of debris, and due to the fact that it will intentionally be seeking out debris trajectories, it is imperative that the shielding be able to withstand impacts of objects with a radius of

[3]UCS Satellite Database

near 1 cm. The cost of the physical laser itself is $40 million. We assumed that the stature of the project is comparable to the Hubble Space Telescope, and so we estimated that the manufacturing cost would be roughly the original Hubble cost projection [29]. The yearly operating cost of Hubble is about $98 million [30]. Based on this cost, we expect the Debris Sweeper to be more active, thus we estimate the yearly operating cost to be $100 million. to cost around $100 million/year. Overall, the 100 kW ICAN Debris Sweeper is projected to cost:

Space-Based Laser System:	
Laser Cost [31]	$40 million
Manufacture Cost	$500 million
Launch Cost [2]	$39 million
Operating Cost per year	$100 million
Total Cost	$581 million + ($100 million/year)

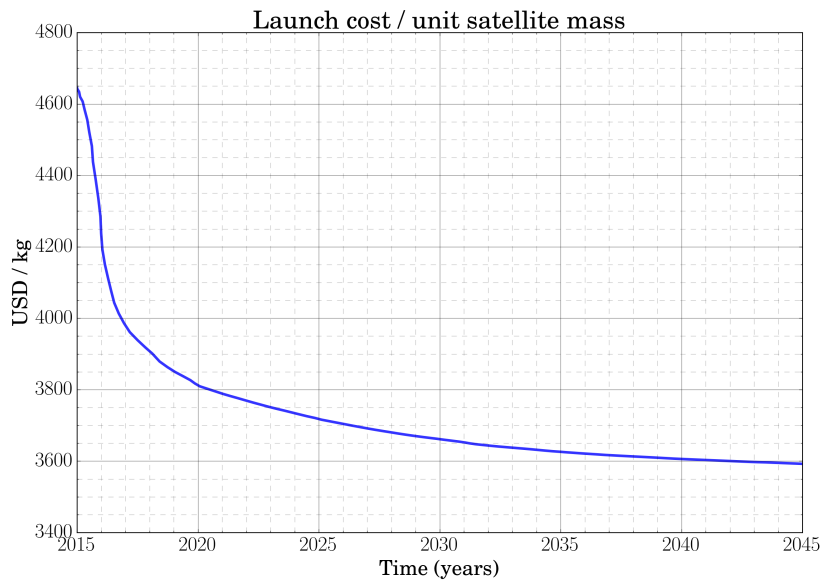

Figure 4: The projected cost per kg to launch a payload to LEO up to the year 2050 [2].

4.4. Billion-Dollar Garbage Trucks: Space-based capture methods

4.4.1. Qualitative Description, Benefits, and Risks

A classically proposed method of removing space debris is to send up a purpose-built spacecraft to dock with one or more debris objects and deorbit them using thrusters. This class of solutions is defined by flexibility, both in terms of their design and their potential capabilities. Space-based collectors could be designed to act in any of the near-Earth environments, and deal with any size of debris–for a price.

These solutions work by docking with pieces of debris and applying thrust to modify their orbit. In doing so, the debris-removal spacecraft typically must then thrust again to raise its orbit out of the removal zone. While many concepts involving spacecraft that grapple

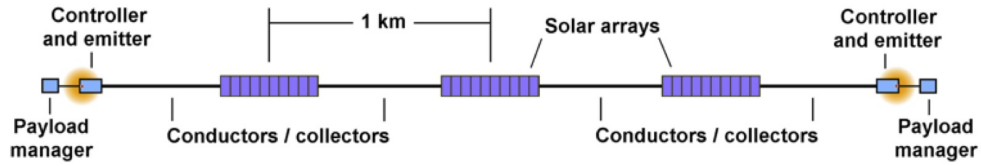

Figure 5: Components of the ElectroDynamic Debris Eliminator (EDDE). Taken from Ref. [3]

onto debris objects, a survey of the attitude states of debris reveals that many are actually tumbling chaotically, sometimes at very high speeds. This means that ideally, space-based methods should actually avoid contact with targeted debris, and instead apply their thrust through an intermediary medium, such as an ion-beam. Unlike lasers, these technologies are extremely early in their development, making exact modeling difficult. Our modeling effort instead chooses to categorise these separate but similar proposals under the realm of debris capture satellites.

A common strength of these methods is their flexibility in the location of the debris they can target. As large spacecraft, it is possible to design DCS systems that can target debris in LEO, GEO, or intermediate altitudes if needed; if properly designed, the differences between each system would only be their propellant loading and launch vehicle.

While such systems would be able to target debris in any orbit, the size of debris these systems could tackle is typically limited to rather large pieces of trackable debris, which is again thought to account for only a small fraction of the debris on orbit [10]. However, large objects are a potent source of both catastrophic collisions which generate large sources of dangerous debris, a-la the Kosmos/Iridium collision of 2009. According to several studies, removing just a handful of these objects per year could be enough to halt the debris problem [16]. Finally, as space-based systems, DCS systems are also constrained by the same set of risks described for the space-based aspect of space-based lasers.

The most critical risk for deorbiting an object is the chance that a percentage of it can survive re-entry and may impact the Earth's surface, causing damage to property and/or people. Debris Capture Satellites are typically designed to dispose of large pieces of debris by either deorbiting them or removing them from active LEO bands; in the deorbit case, between 10%–40% of a given object's original mass can be expected to survive intact through reentry [32].

While reentering space debris has caused property and personal damage, the probability of such an event is low. In fact, only one person was ever recorded to have been hit by debris and she sustained no injury [32]. As only 29.2% of the planet's surface is land and only 3% of that land is urbanized, there is a 0.876% change of a piece of debris even impacting an urban area.

For the small trackable objects there should still be a very low risk of a debris reentry threat; however, for the large trackable objects there is an appreciable chance of a damaging impact if a reentry is not controlled, i.e. carefully placed to land in the ocean or desert.

4.4.2. Quantitative cost model

Out of the many Debris Capture Satellites proposed over the several decades of space exploration, the ElectroDynamic Debris Eliminator (EDDE) proposed by STAR Industries.

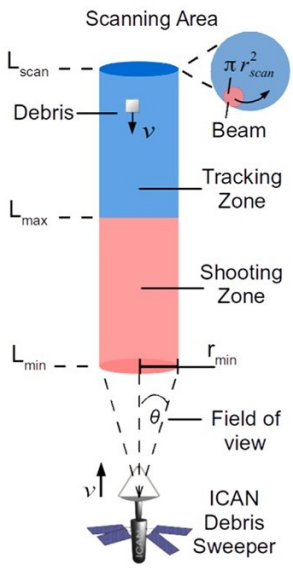

Figure 6: The tracking and scanning zone for the debris removal procedure of the ICAN Debris Sweeper. Taken from Ref. [4].

This solution involves direct contact for acquisition of large trackable debris objects via nets launched from the payload manager, cf. Fig. 5. The true benefit of EDDE is that its operating costs are rather low compared to other DCS proposals. Rather than supplying the Δv to move itself and other objects by chemical or ion engines, EDDE is able to generate an impulse by interacting with the Earth's natural geomagnetic field [18, 19**?**]. It is well known that a particle with charge q moving through a magnetic field $\mathbf{B}$ feel a force governed by the Lorentz Force equation,

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}, \tag{10}$$

where $\mathbf{v}$ is the velocity of the particle. The electrons in the current generated through EDDE's centerline are affected by the Lorentz force as they are passing through the Earth's geomagnetic field. This force is large enough to provide an impulse to move itself along with objects with masses far surpassing its own mass [19]. The solar panels generate the energy needed to sustain the current. Hence, the operating life is not restricted by the amount of propellant. The only drawback to this method, is that movement is restricted to LEO since the geomagnetic field is not strong enough past 2000 km to provide effective Δv.

It is projected that a fleet of 16 EDDE vehicles can remove 2,000 tons of debris in a period of 16 based on simulations [17]. This implies that a single EDDE vehicle can remove 13.89 tons in a year. Assuming that EDDE is put to work right away towing the large, possibly multi-ton, objects then we are removing 5 - 10 large objects per year. This reduction per year is predicted to stabilize the current debris problem and prevent the natural exponential growth [16]. To implement this in our model, we stabilized the growth of debris after one year of an EDDE unit being launched. At the end of the allotted time, the difference between the risk of the stabilized debris amount and the unmitigated debris amount is the change in risk from which the revenue is derived.

One of the largest sources for any space-based project cost is the launch cost. Luckily,

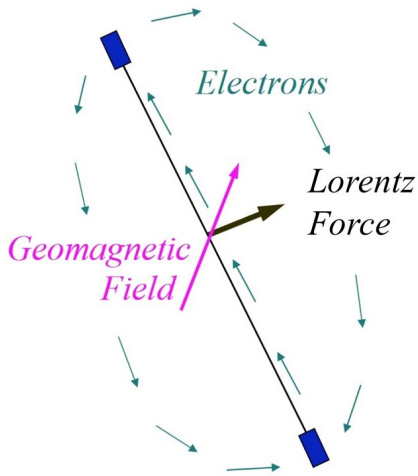

Figure 7: The propulsion of EDDE via the Lorentz force. Modified from Ref. [3].

EDDE weighs only 100 kg [17]. As it fits easily into the secondary payload slots on Atlas V and Delta IV launch vehicles, it would only take a single launch to put 12 EDDEs in orbit [18]. This also helps to further reduce launch costs as secondary payload slots may be cheaper depending on the main payload. However, for our model we assume that standard launch costs apply. Overall, the upfront and yearly cost of a single EDDE unit comes to:

EDDE System:	
Development Cost [33]	\$1.9 million
Manufacture Cost	\$15 million
Launch Cost [2]	\$0.4109 million
Operating Cost per year [19]	\$84 million
Total Cost	\$17.3109 million + (\$84 million/year)

Lastly, since propellant is not a problem for EDDE, large pieces of debris, like spent rocket stages and old satellites, can be carefully positioned for a safe reentry. Another viable option is to start a new graveyard orbit just beyond LEO [18]. The benefit of this option is that in addition to reducing the reentry risk to zero, there may be valuable metals on the debris that could be salvaged at a future time.

Due to its low weight and lack of propellant, EDDE in many ways represents the "ideal" Debris Capture Satellite. This factor—combined with our extreme pessimism over the viability of debris removal from an economic perspective—motivated us to select it as our Debris Capture Satellite representative.

5. Business Models and Sensitivity Analyses

5.1. Single-System Mitigation Strategies

This section outlines the results of our model in predicting the profitability of the systems discussed above from an assumed implementation date of May 1st, 2009 to May 1st, 2045, under a "business-as-usual" prediction of debris densities. This environment provides the

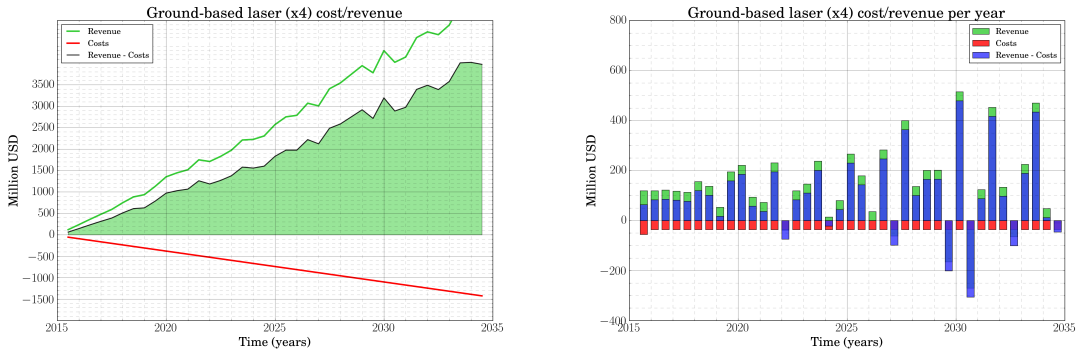

Figure 8: The (a) cumulative and (b) yearly cost, revenue, and profit of a ground-based laser debris collision avoidance system consisting of four ground-based lasers, the minimum number of stations required to attain a collision avoidance rate of 28% in the preset day.

most optimistic business outlook for a prospective debris-removal corporation, although not for peaceful use of space.

Figure 8 shows the cost and profitability of a set of ground-based laser sites at the locations described in the previous section. This system is profitable virtually from its construction, only becoming more profitable as time goes on and the risk it is capable of reducing by a fixed percentage increases. This occurs due to our assumption that such a system would reduce the risk of debris collisions by a fixed percentage, regardless of the quantity of risk involved. As such, the profitability of the system as modelled increases exponentially with time as the debris quantity goes up. While a time-dependent collision avoidance rate is much desired, we were not able to ascertain how the ground-based laser systems would perform as the debris density increased.

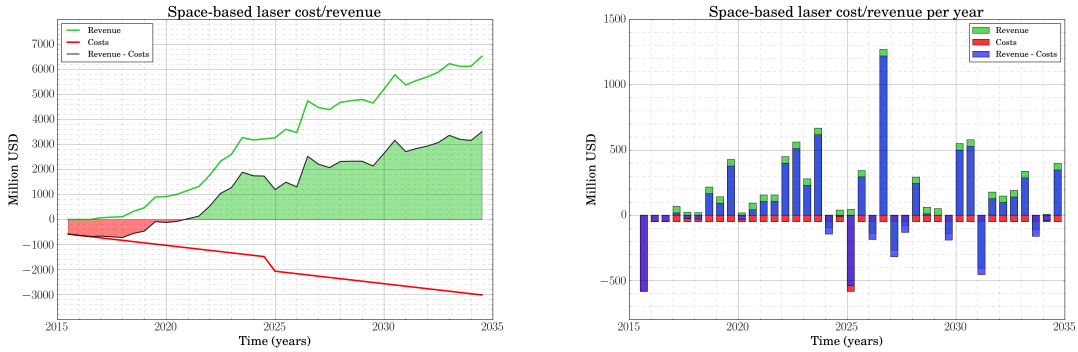

Figure 9: The (a) cumulative and (b) yearly cost, revenue, and profit of a space-based laser debris clearing satellite, with a new satellite being deployed once every ten years.

Figure 9 shows the profitability of a space-based laser system launched in 2015 and re-launched in 2025. These plots indicate that a space-based laser system would not be profitable in the near-term, but would become profitable around 2020 as the LEO debris density increases and the number of commercial spacecraft at risk grows.

Finally, Figure 10 shows the profit/loss ratio for a single orbital debris removal satellite modeled on the predicted performance of EDDE. Our model shows that this class of debris

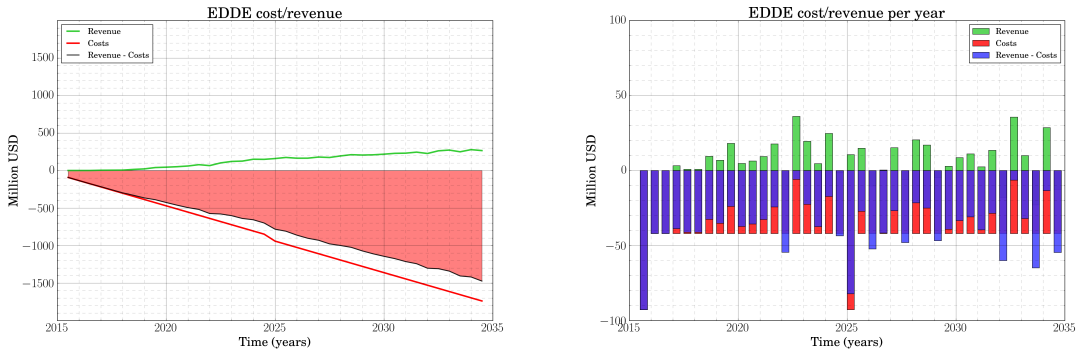

Figure 10: The (a) cumulative and (b) yearly cost, revenue, and profit of a single EDDE debris removal satellite, with a new satellite being deployed once every 10 years.

mitigation system will not be profitable to construct or operate within the time-frame considered by our model, despite the high-debris operating environment and ideal performance provided by an EDDE type system.

These individual-system results allow us to immediately write off the value of a debris capture satellite system for debris removal. Both the ground-based laser system and the space-debris laser removal satellite appear potentially profitable within the assumptions of our model.

5.2. Multi-System Profitability Analysis

While our model can be readily extended to analyze the performance of systems based upon composites of different debris-removal techniques, the results outlined in the previous section degrade the value of such analysis. With this being said, the systems examined here do appear to qualitatively compliment each-other. Ground-based lasers can provide low-cost risk reduction to LEO spacecraft; space-based lasers can eliminate small debris that the ground laser cannot effectively target, and bring it out of orbit; direct-removal satellites provide a means of removing hazardous large debris objects. Selecting any one option will address only one aspect of the debris problem, with no guarantee that the others will sort themselves out in turn.

From a profit-oriented perspective, both classes of laser system have clear advantages and disadvantages. Ground-based lasers appear to be consistently profitable, earning a rough average of $100M USD per year. On the other hand, space-based systems have the potential to be enormously profitable–on the order of $500M to $1bn USD per year, but much less consistently due to its high operating costs.

These results suggest that a savvy operator will implement a mix of ground-based sites to provide steady, reliable income and laser satellites to eliminate small debris on-orbit. Interestingly, many papers suggest that such a combination will not actually reduce the total quantity of debris at any given time, which would be accomplished by direct contact satellite systems like EDDE; we treat this result as an issue with Capitalism rather than our model.

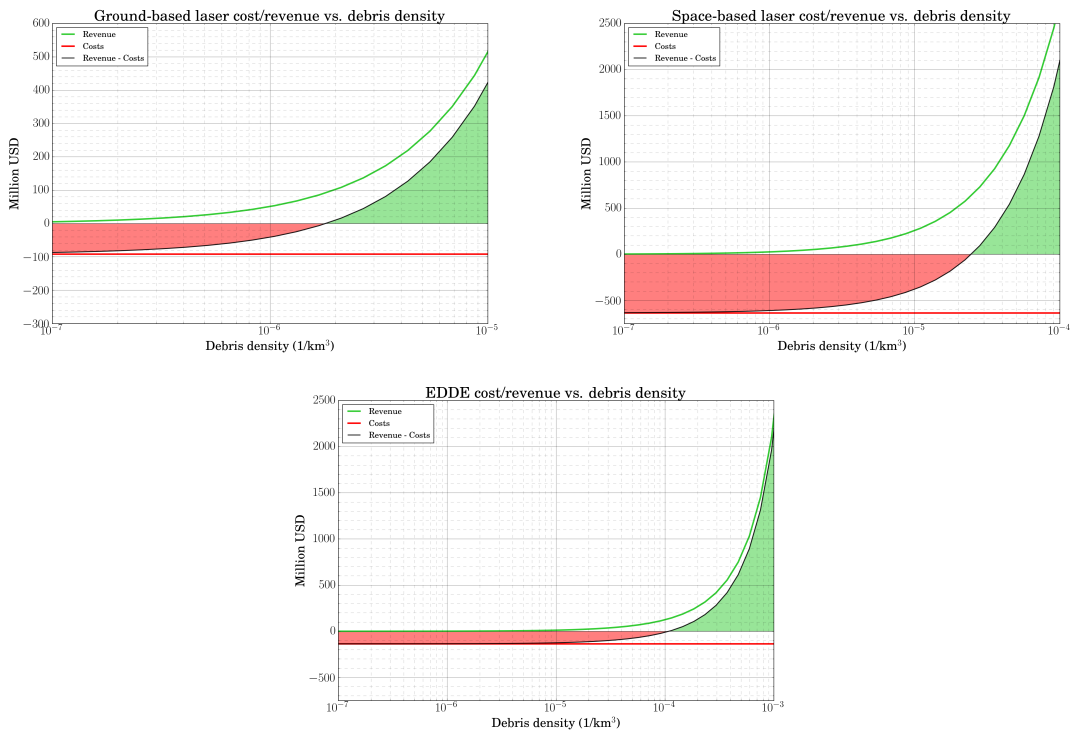

Figure 11: Break even points for (a) ground-based laser, (b) space-based laser, and (c) EDDE debris removal systems, with respect to the density of debris in any given orbit.

5.3. Break-Even versus Debris Density

To determine the cost-effectiveness of each system as it relates to the density of debris in LEO, each system was evaluated using its quantitative model over a range of debris densities. The profit quantities shown above are assumed to have occurred over a single year. From this, we note that each system breaches its break-even at a different debris density in the following order:

1. Ground-Based Laser
2. Space-Based Laser
3. Debris Capture Satellite

Because the quantity of space debris in an unmitigated scenario increases over time, this order should be the order of economic feasibility for future systems.

6. Conclusions

6.1. Commercial Viability Statement

Our model shows that space debris removal, as a commercial venture, is viable under regimes of high debris density and continued growth within the space industry. Based on the quantitative results of our model presented in Sec. 5, we predict that such ventures will likely be restricted to ground-based and space-based lasers for the foreseeable future, as such methods reduce large amounts of risk as quantified in our model for their operating cost.

In addition, we have derived relationships that show the density of space debris required at modern satellite values for space-debris mitigation systems to become effective. Commercial ventures will likely first implement ground-based laser sites to move away large pieces of debris that are predicted to intercept active satellites in the near term (next 5 years), while a handful of space-based laser systems will become profitable in the long term to reduce the quantity of debris on-orbit. Because both of these systems will become profitable to operate in the near-term, debris capture satellites may never become profitable to operate, as the requisite debris densities will never be reached; laser systems will reduce levels of debris before a profitable level for debris capture systems is reached.

From these results, our model recommends the immediate implementation of ground-based laser systems to nudge debris out of collision trajectories, which will be profitable even in today's debris environment. Should the debris environment continue to worsen, space-based lasers would be the next most profitable system to implement. It is only at apocalyptic debris densities that it becomes profitable to operate debris capture satellites, even in EDDE's idealized case.

Because of this, we suspect that any business model for the removal of space debris will never actually eliminate the debris problem. As debris is removed, the threat of a collision is reduced, and so there is less incentive to further reduce the quantity of space debris. This is a sensible approach to resource allocation; it is only worthwhile after all to do something if its marginal benefit exceeds its marginal cost. Our analysis suggests that the typical marginal cost of removing space debris is typically very high, while low collision risks dictate that the marginal benefit is, well, marginal.

6.2. Proposed Alternative Strategies

6.2.1. Risk Sharing

Our analyses reveal that all space-debris removal methods tend to have extremely large setup and operating costs, but are typically fairly effective at dealing with debris. This effectiveness, in turn, reduces the amount of debris that can be cost-effectively removed, leading to a downward spiral of both cost and debris. These quantitative behaviors indicate that a space debris market would likely create a monopoly, as the first firm to effectively remove space debris would quickly remove enough debris that no other firm could profit.

Because of this, our model appears to indicate that the best option for an organization to remove space debris is not strictly free-market commercial, but instead a joint venture, either between companies or at the international level, funded by dues paid by any spacecraft operating organization in LEO. This would effectively accomplish the risk-pooling we assumed in Sec. 2.1, while not encountering the problem of market monopolies; should the governments or corporate adventurers decide that debris removal is no longer profitable, they could simply disband the venture.

6.2.2. Debris Tracking Services

One mitigation strategy we did not address is the improvement of "Just In Time Avoidance" methods. These mitigation strategies focus on improving the technologies that track debris and spacecraft, and provide spacecraft with warnings such that they can maneuver out of the way of incoming debris.

Today, this is the only existing means of avoiding debris strikes; however, the extremely nonlinear behavior of space debris objects on orbit makes predicting future strikes extremely difficult and computationally intensive. At the same time, performing on-orbit maneuvers uses propellant, which in turn reduces the lifetime of satellites, if they have propellant at all.

Commercial companies have already been founded whose intention is to provide "commercial space situational awareness," which includes debris monitoring services. A proliferation of debris-monitoring sites and stations could greatly improve the tracking and prediction of space debris, which could be used to reduce the risk of collisions with active satellites. We take the existence of commercial companies in this area to be a sign of its commercial viability, including industry giants like AGI incorporated (comspoc.com).

6.3. Future Work

The modeling effort outlined above provides an initial estimate of the costs and potential benefits involved in space debris removal from an economics perspective. Our approach incorporates real-world data and industry standard models. However, a number of aspects of our model could be improved upon or extended to provide additional fidelity and certainty.

Chief among these improvements is the development of physics-based models of the debris environment and our mitigation strategies. As outlined above, our model provides no means for simulating the impact of the debris mitigation methods on the long-term trends in space debris. Developing a physical simulation of the debris environment would allow us to model how the implementation of active debris removal methods will slow the growth of the debris problem–which, in turn, will reduce their profitability. We predict that such a simulation would show a steady-state level of debris mitigation effort that maintains the debris population at a certain level and produces a corresponding and moderate profit for its operators.

In addition, while we do feel that our system models are representative of the classes of active debris removal systems discussed, additional work could be done in both modeling additional debris removal systems and in adding additional fidelity toward the systems described here. Of particular note should be efforts to model the economic benefit of space debris tracking services, which as mentioned above have already started as commercial responses to the space debris problem.

Appendix A. Discussion of selected assumptions

1. **All market values continue their predicted trend.** While this necessarily leads to an exponentially increasing net value in the satellite market, in the short term such a trend is generally valid, as evidenced by its appearance in most, if not all, other market sectors in the short-term.
2. **Each spacecraft in orbit is owned by a separate rm, and the protability of each satellite is equal.** This pair of assumptions leads directly to the conclusion that it would be economically unreasonable for any one company to invest in their own debris-mitigation solution. In reality the distribution of satellites to firms, as well as their values, varies, making it such that a firm with (for example) 25% market share may find it in their best interests to invest in one of our proposed solutions.

3. **The average satellite on orbit presently is halfway through its lifespan.** In reality the lifetimes of satellites can range from one ten years, depending on their construction and launch date, as well as whether or not they encountered/avoided any unforeseen debris collisions. However this distribution of satellite lifetimes is not easily obtainable, owing to the randomness of the debris collision/avoidance process.
4. **The risk posed by space debris is shared evenly by any spacecraft in LEO.** One might posit that the debris density in LEO is non-uniform, with higher densities being found along the orbits of current/past large objects, and that owing to this the risk posed to individual satellites varies wildly. However, projections by Wright [10] show that over the course of a few years the debris cloud formed by a large debris collision, which was initially quite clustered, will distribute itself almost uniformly along a range around the original objects' orbits. We use this analysis to justify our use of an angularly-uniform debris cloud that varies only with radius and time.
5. **The base annual revenue is $77.59 million for each LEO satellite and $322.06 million for all GEO satellites.** The total worth of the satellite services industry was $122.9 billion in 2015. The ratio of LEO satellite revenue to GEO satellite revenue is 1:5 (UCS Satellite Database). There are 264 LEO satellites and 318 GEO satellites. The total revenue of each region of space was divided the number of satellites in the region, giving the average value for each satellite.
6. **The value of all LEO satellites hold a value based on 4.06 remaining years of operation; 7.16 years remaining for GEO satellites.** The average lifespan for a LEO satellite is 8.12 years, and the lifespan for a GEO satellite is 14.32 years. Current ages of satellites are spread out over a range of years, hence the assumption that on average the satellites are about halfway through their lifespan.
7. **Using the debris density data from MASTER we apply our removal methods by means of filters, and propagate the effects through the static future data.**
8. **Orbits are circular and orbital speed is constant.** The latter follows from the former since orbital speed is only dependent on the instantaneous orbit radius. Orbits are circular if they have an eccentricity of 0. Since the average eccentricity is 6.89×10^{-4} for GEOs and 2.07×10^{-3} for LEOs, it is reasonable to assume that the orbits are circular.

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Team 46655 Executive Summary

Problem B

Our modern world is increasingly built upon space-based infrastructure. From the imaging satellites that inform farmers about their crops' health, to the GPS that guides you to the bakery, to the satellite television that sedates you after a stressful day of proletarian labor, many core components of daily life are dependent on the usage of near-Earth orbit.

However, this increased dependence has also driven a dramatic increase in the quantity of orbital debris—objects in orbit that are no longer useful, but which remain in orbit. The extremely high energies associated with orbital motion allows even small pieces of debris—such as paint flecks—to disable or destroy active satellites. Each collision will create additional debris fragments, creating the possibility of a runaway debris catastrophe that renders space too expensive or risky to use.

Because of the economic threat posed by space debris, the prospect of a market-based solution to the debris problem seems promising. Our organization developed a modeling framework to analyze various space debris removal schemes, their costs, and the potential profits involved to gauge whether a commercial solution to the debris problem is feasible. Ultimately, our modeling approach showed that there is a clear economic benefit to removing space debris in periods of high space industry growth and in the face of increasing debris threats.

To assess whether or not a commercial solution to the space debris problem exists, we developed a model that incorporates both the economic benefit to be gained by decreasing the risk to active satellites posed by debris and the rate at which the quantity of debris will change as time goes on.

This revenue model is based upon current estimates of the size and profitability of the space industry, and upon the European Space Agency's MASTER debris growth simulator. We price the estimated risk per year posed by space debris to an active satellite proportionally to both the value of that satellite and the risk that the satellite would be destroyed by space debris. Notably, our analysis excludes risk-reduction profits for government and military systems, and instead focuses on threats to valuable commercial satellites which publish their value.

We studied three proposed debris-mitigation technologies which we felt were representative of the classes of proposed debris mitigation technologies as a whole: ground-based laser systems (popularly referred to as "laser brooms"), space-based systems which targeted small debris objects, and space-based systems targeting large debris objects such as defunct satellites.

Each class of system was judged on a set of standard criterion: that system's implementation cost, operating cost, and ability to reduce the risk posed to spacecraft by debris.

While developing our model, we found several core issues with the space debris modeling problem that limited our fidelity:

1. <u>GEO Debris remains uncharacterized:</u> Due to the extreme distance of geostationary orbit, surveys of this belt have been limited to relatively large debris items, on the order of 1 meter. A survey of small but no less deadly debris would enable better estimates for the cost efficiency of GEO-facing systems.
2. <u>Closed-Source Modeling:</u> Because many debris tracking suites can also be used for military purposes, most—including the model we used—do not allow end-users to make modifications to their simulations. The development of debris prediction modeling is both computationally intensive and time-consuming due to the complexities involved; the development of open-source debris modeling suites would enable more accurate predictions of the benefits associated with active debris removal.

3. Slow Timescale, High Nonlinearity: Debris growth due to collisions happens on the order of tens of years. However, current state-of-the-art orbit propagators are not trustworthy over these timescales, bringing into question how much debris predictions can be trusted over the timescales involved. As evidenced by the 2007 Chinese ASAT test and the Iridium/Kosmos collision, generation of space debris is heavily dependent on low-probability, high-risk "black swan" events, further complicating modeling efforts. These complications reduce our ability to quantitatively model the risks associated with space debris.

Because of these issues, we will focus on the *qualitative*—rather than quantitative—predictions of our model, which does show that space debris removal can be profitable if the following assumptions can be met:

1. International Space Law must change: Addressing the debris problem via the active removal methods we studied requires a standard definition of space debris and a transparent guideline for debris-removal practices at the international stage.
2. The debris population continues to grow: Our model assumes a pessimistic outlook for conventional debris mitigation methods. This means that the quantity of debris, and therefore the risk of collisions, is large—consistent with debris growth trends in the last five years.
3. Spacecraft operators recognize the risk, and pool resources: Due to the high startup costs of the mitigation methods we investigated, no single commercial company will find it profitable to reduce their own debris risk.

With these assumptions, it becomes economically beneficial to remove space debris with large-debris removal satellites and ground-based lasers within the next ten years. While we did not explicitly test our model with mitigated debris growth levels resulting from policy changes, the small operating margins our model predicted leads us to conclude that **active debris removal is only feasible in high-debris environments.**

Importantly, our model shows how incentives to remove debris change over time. Based on projected debris mitigation efficiencies, **a small number of debris-removal systems may reduce the threat of debris enough to make it uneconomical to address further**. From this, we assert that the debris-removal market would be "winner take all;" the first company to consolidate the market would also be able to capture all of its profits.

In effect, our model predicts that—because of the high entry costs and limited number of systems needed to halt the debris problem—**any debris-removal market would rapidly become a (profitable) single-entity monopoly**. As such, the space debris environment is not amicable to the kinds of market-based environmental solutions practiced in other public-goods markets on Earth, such as cap-and-trade or punitive taxation.

Instead, we propose that pooled-resource approaches—such as a multi-national entity funded by taxes on spacecraft operators, or a joint commercial venture between large satellite operators—represents the most economical means of implementing active-debris removal systems.

The results of our model recommend ultimately a proportional mitigation response by a pooled-resources venture. New types of debris mitigation methods should be implemented only when the debris density is such that they can be operated profitably, and no sooner. Companies will ultimately recoup their expenditures in taxes or dues to support such a company in the reduced replacement costs for their spacecraft.