Office of Technology, Policy, and Strategy

Cost and Benefit Analysis of Orbital Debris Remediation

Authors: Thomas J. Colvin, John Karcz, Grace Wusk

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NASA Headquarters
300 E Street SW
Washington, DC 20024

Reviewers: Patrick Besha (OTPS), Bo Naasz (STMD)

Executive Summary

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Purpose

This report presents a cost-benefit analysis of various approaches to debris remediation, which refers to any action taken to reduce the risks posed by orbital debris by moving, removing, or reusing it. A thorough understanding of the near-term costs and benefits of different remediation approaches can inform decision-making regarding R&D investment and policy creation in this field.

Background

Orbital debris, including abandoned vehicle stages, non-functional satellites, and fragments resulting from collisions or explosions, hinders the use of space upon which critical infrastructure of the U.S. economy relies, such as communications, national security, financial exchanges, transportation, and climate monitoring. Debris increases the costs of space operations by requiring efforts to shield against or maneuver around it, threatens the safety of astronauts and satellites, limits the ability to launch spacecraft, and may eventually make entire orbits unusable.

The 2021 National Orbital Debris Research and Development Plan outlines three broad methods for reducing the risks associated with debris: 1) mitigate the creation of new debris; 2) improve the tracking and characterization of debris; and 3) remediate debris that has already been generated. The costs and benefits of debris mitigation and tracking are fairly well understood, but significant uncertainties exist regarding the costs and benefits of debris remediation.

In the past, motivations for performing debris remediation have been related to ensuring the safety of spacecraft conducting civilian, commercial or national security missions, fulfilling moral responsibility to other operators, or preserving the sustainability of the space environment for future generations. Although these motivations are valid, the cost of remediation is not well-known, and the benefits associated with it may not materialize for many years. Given the substantial upfront expenditures required to develop and deploy remediation capabilities and the potential delay in receiving benefits, these motivations do not appear to be sufficient to incentivize immediate action.

Therefore, we conducted a cost-benefit analysis to determine whether the near-term risks imposed by debris, summed over all U.S. spacecraft operators, are greater than the costs of remediation.

Cost-Benefit Analysis Approach

To perform this analysis, we began by estimating the costs associated with orbital debris. We created a model for economic risks imposed on satellite operators, incorporating a simplified version of a commercially available tool that estimates the number of warnings, maneuvers, and collisions a satellite will have with space debris. We also gathered cost data from discussions with spacecraft operators, subject matter experts, and the literature.

We then estimated the benefits of performing debris remediation by analyzing two scenarios. For large debris remediation, we estimated the benefits of removing the 50 statistically most-concerning derelict objects in LEO (McKnight et al. 2021), while for small debris remediation, we estimated the benefits of removing 100,000 pieces of 1-10 cm debris from 450-850 km altitude. In both scenarios, all debris is assumed to be remediated upfront, and benefits accrue over the following years. While this is not how debris would be remediated in reality, it removes the complexity of calculating benefits associated with slowly remediating debris and has little effect on the costs of remediation. Our assessments of the relative costs and benefits among remediation approaches are unlikely to change substantially if this assumption is removed.

To identify a prioritized number of approaches for debris remediation, we engaged with subject matter experts and the literature. For large debris remediation, we analyzed five approaches: removing debris by controlled reentry into the ocean; removing debris by uncontrolled reentry; moving debris with lasers or sounding rocket for just-in-time collision avoidance (JCA); and recycling debris by converting its material into propellant. For small debris remediation, we analyzed three approaches, including using ground-based or space-based lasers to nudge debris and using a physical sweeper to impact debris.

For each approach, we estimated the development and operational costs to remediate a single piece of debris and applied these per-debris costs to the debris remediation scenarios to estimate the total cost of using each approach to achieve the benefits of the scenario.

Results

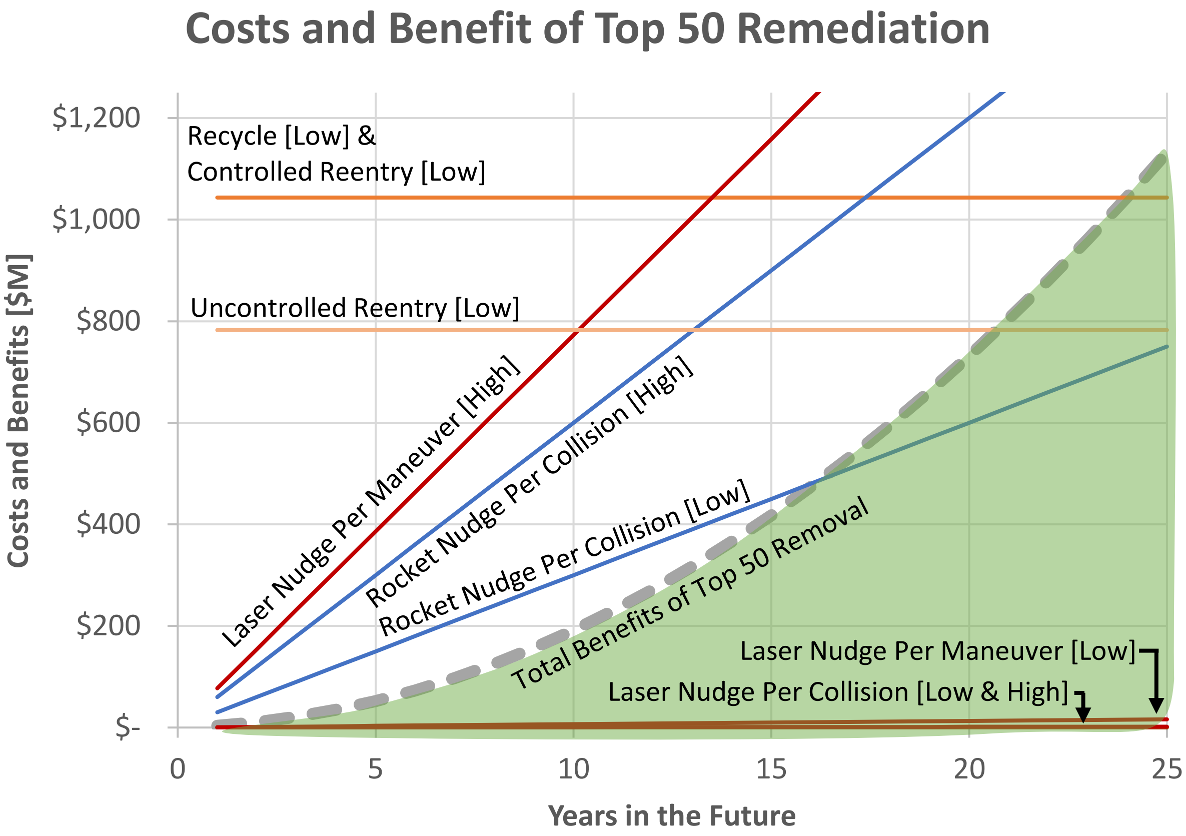

Figure ES-1. The benefit associated with removing the Top 50 objects identified by McKnight et al. (2021) grows every year after they are remediated, shown by the thick dashed line. The high costs associated with Controlled Reentry, Uncontrolled Reentry, and Recycling are not shown because they are too high to be relevant.

The costs and benefits associated with remediating the Top 50 most concerning objects are illustrated in Figure ES-1. The benefit refers to the expected reduction in risk valued at around $3.5 million in the first year after removal, as estimated by our model. The benefits compound and increase over time, as explained in the main text of this report. Our findings reveal that active and maneuverable satellites do not face significant costs from maneuvering around this debris, so there is no meaningful cost reduction associated with removing these large objects. Instead, the $3.5M value is determined by the reduced probability of debris-on-debris collisions involving the Top 50 debris. Such collisions generate significant amounts of small debris that may damage operational spacecraft, given that the debris is not currently tracked and cannot be avoided. The costs linked with removing or recycling debris are incurred once, after which the debris is permanently remediated. These costs are indicated by horizontal lines in the figure. On the other hand, remediation methods that move debris to avoid collisions incur annual costs that are paid as they are used, and they may be utilized one or more times per year. Such methods are represented by sloped lines in the figure. The intersection of the cost and benefit lines indicates the time it takes for the associated remediation method to deliver a net-positive value.

Any remediation method that costs less than this to implement will provide a net benefit in the relevant year, as illustrated by the green region below the dashed line. The figure shows high- and low-cost estimates for each remediation method. We present two options for using lasers to move debris. The first is the "per maneuver" option, where the laser moves the debris to avoid a collision if the debris will have a close approach of 1 km with another piece of debris; this is approximately the same threshold that would cause an active satellite to maneuver. The second option is "per collision," where the laser only moves the debris if it will indeed collide with another piece of debris. Collisions are so infrequent that the laser system is rarely utilized in this option. The use of a rocket for moving debris is only feasible if it is utilized on a "per collision" basis, which is not possible with current space situational awareness capabilities, but targeted ranging of debris could enable this.

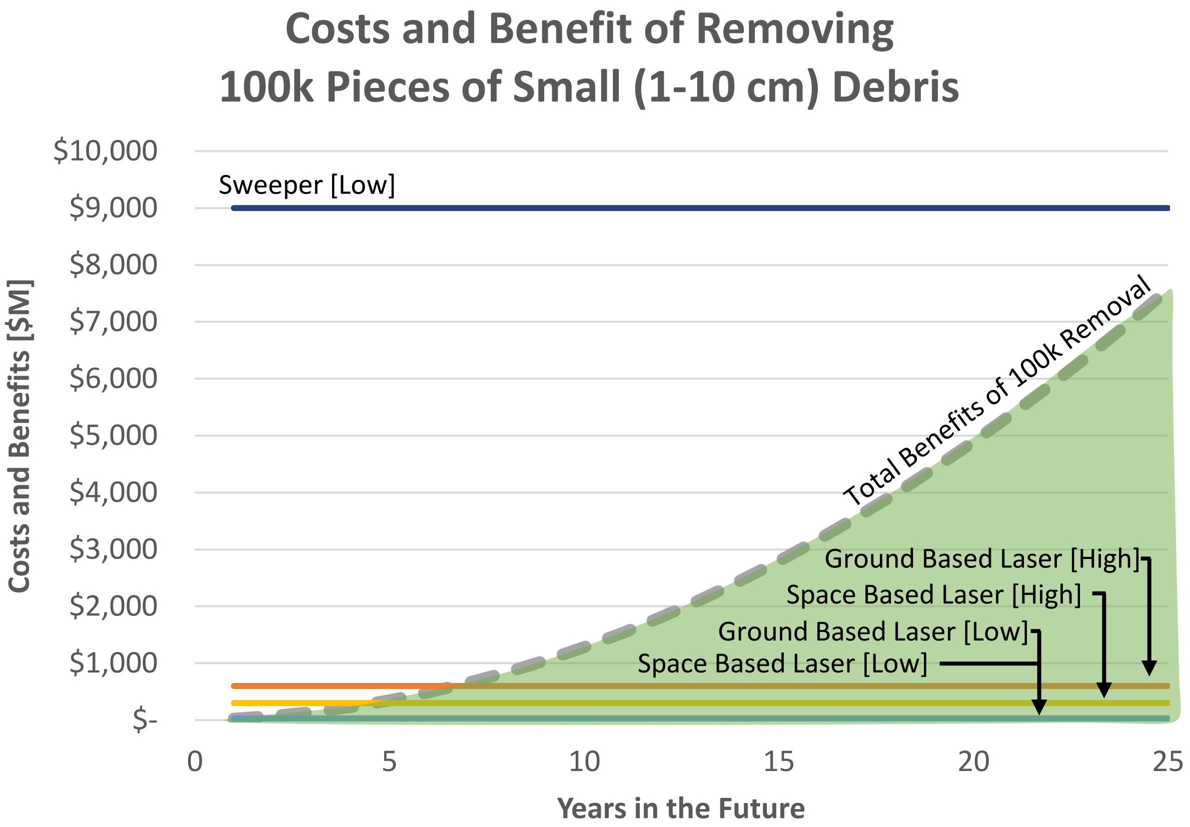

Figure ES-2. The benefit associated with removing 100,000 pieces of small debris grows every year after they are removed, shown by the thick dashed line. Any remediation method that costs less than this to implement will provide a net benefit in the associated year, shown as the green region below the dashed line. The high cost associated with a Sweeper are not shown because it is too high to be relevant.

The costs and benefits associated with removing 100,000 pieces of small debris are illustrated in Figure ES-2. In the first year after removal, the benefit refers to the expected reduction in risk valued at approximately $23 million. While this benefit is significantly greater than the benefit linked with removing the Top 50, it should not be interpreted as small debris being "worth more."

We could have achieved the same benefit as remediating the Top 50 if we had chosen to remove fewer small debris. As before, the benefits of this scenario are future risks avoided due to small debris strikes, not costs saved by spacecraft operators. Unlike before, there is no option to remediate small debris by moving it to avoid collisions; all debris must be completely removed, and thus, the cost of removal for each remediation option is incurred once, not annually.

Main Findings

Finding 1: The most effective remediation methods to reduce risks to operators are approaches for removing small debris and nudging large debris to avoid collisions.

Contrary to common concerns about the cost-prohibitive nature of remediation due to large upfront expenditures of deployment and long delays for receiving benefits, some remediation approaches may achieve net benefits in under a decade. Figure ES-3 shows the range of times to net benefit for each remediation method presented in the previous two figures. Methods for removing debris measuring 1-10 cm appear to produce net benefits quickly. Similarly, methods for nudging debris to avoid collisions have a larger range of potential costs, stretching the worst-case time to net benefit into multiple decades. However, they also have a credible path to producing net benefits almost immediately upon entering operation.

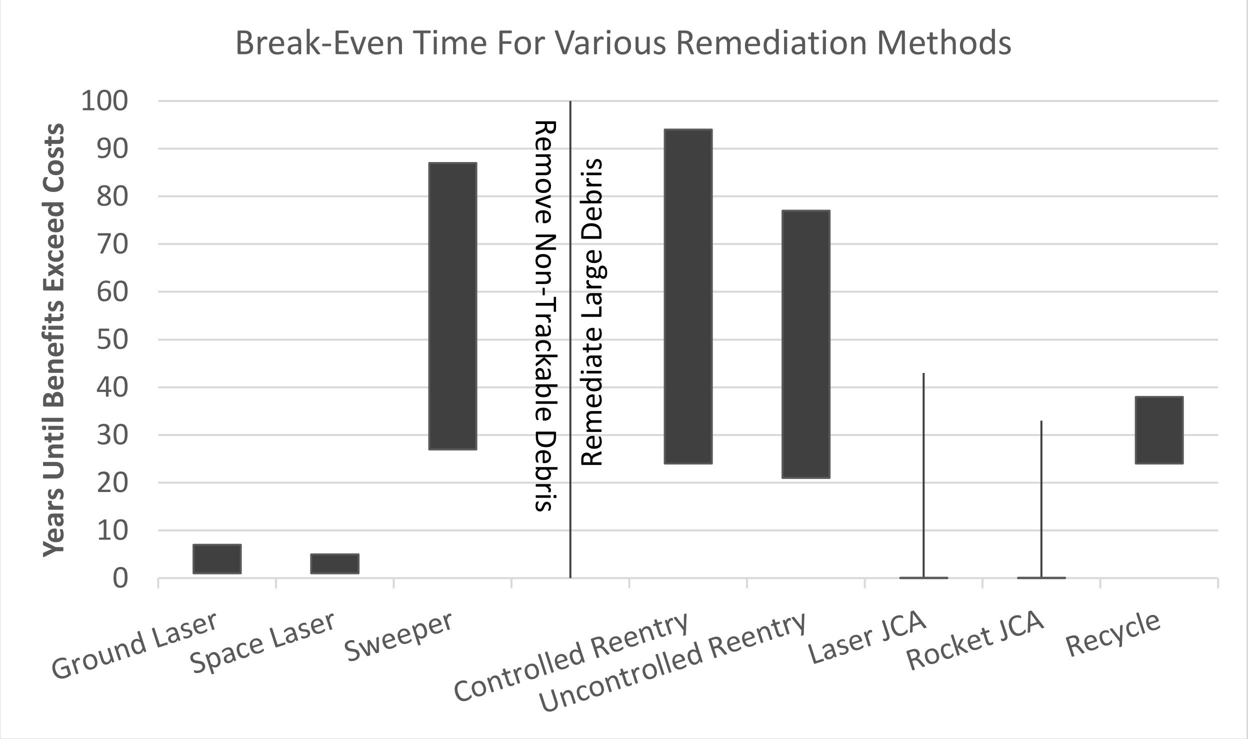

Figure ES-3. The break-even time for approaches to remove non-trackable debris [left] and remediate large debris [right]. The boxes correspond to the high and low costs associated with optimal use of each remediation approach. For the two just-in-time collision avoidance (JCA) approaches, their optimal use causes benefits to exceed costs immediately. However, a more conservative estimate of their usage is represented by the range of the whiskers.

Finding 2: Controlled and uncontrolled reentry via reusable remediation servicer may reach net benefits on timescales that are relevant to spacecraft operators.

Controlled reentry may be required for some large debris, particularly those in the Top 50, to avoid creating casualties or property damage on the ground. Contrary to the popular assumption that removal of such debris will not produce near-term benefits, we identified an approach to performing controlled reentry with a reusable spacecraft that might provide net benefits within three decades. To our surprise, this method of controlled reentry can also be adapted to provide uncontrolled reentries that are potentially cheaper than methods that use drag sails or tethers to de-orbit debris. In this case, performing an uncontrolled reentry is not much more expensive than a controlled reentry.

However, we regard this finding with caution, as we made many simplifications to develop the first iteration of our risk model, which limits its applicability to multi-decade timescales. It is not yet known whether these simplifications have led us to under- or over-estimate the benefits for debris removal. It is possible that these debris removal methods could achieve net benefit sooner than we have calculated in this report.

Finding 3: Recycling space debris has some attractive features but does not offer a clear risk advantage over other approaches.

Converting a piece of debris into aluminum propellant, for de-orbiting the remainder of the object and for sale to other in-space customers, might be the most promising approach for recycling. However, it does not yield a substantially cheaper system than remediation systems that use chemical or conventional electric propulsion. On the one hand, turning debris into propellant saves costs by removing the need for in-space refueling assets and launches of propellant. Our low-cost estimate for recycling also includes revenue from selling debris-sourced propellant to other in-space customers. However, these savings and revenue are offset by R&D costs needed to mature the capabilities to process debris into raw materials for subsequent use as propellant.

Regardless, there may be potential benefits associated with recycling debris. For example, it could remove the need for performing controlled reentries by either reusing all of the material in space or safely dividing large debris into smaller pieces that will fully burn up during atmospheric reentry. Recycling may also contribute revenue to nascent markets for in-space manufacturing and assembly if debris can be gainfully reused in space. Finally, recycling may reduce climate degradation. Reentering space debris can catalyze the creation of damaging chemicals due to atmospheric heating or deposit undesirable spacecraft materials into the upper atmosphere as the debris vaporizes. By avoiding reentries altogether, debris recycling may offer climate benefits.

Conclusions and Considerations for Next Steps

The way that risks are defined may favor certain solutions and exclude others. For instance, if the total mass of debris in space is used as a risk proxy, the only methods for reducing risks are those that involve deorbiting debris. If the time frame of interest is over 100 years in the future, debris below 800 kilometers may not factor into such risks, even though a significant number of spacecraft operate at these lower altitudes. Rather than relying on proxies for risk such as the number or mass of debris, this report aims to encourage the space community to take a holistic approach to framing the risks of space debris in terms of dollars and how debris may affect satellite operators in the coming decades.

We believe that our study is:

- The most rigorous and wide-reaching analysis in the literature, quantifying the negative effect of debris on space operators in terms of dollars.
- The first to investigate and compare the costs and benefits of a range of remediation methods, offering a framework for decision-making.
- The first to show quantitatively that certain remediation methods may yield net benefits on near-term timescales.
- The strongest evidence that direct risk analysis, rather than proxies like total mass or number of debris, should be the focus when analyzing orbital debris and its remediation.

While rigorous, our analysis provides only a high-level view of the landscape and relies on simplifying assumptions. We are planning a follow-up effort to seek community feedback, refine our risk model to incorporate mm-sized debris, reduce uncertainty in our remediation cost estimates, and incorporate additional risk-reduction approaches. In the meantime, this study provides valuable insights for government and industry to better comprehend the scope of the debris remediation challenge and inform future policy and technology development efforts.

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Background

This study attempts to quantify, in U.S. dollars, the *near-term* costs imposed by orbital debris on spacecraft operators and the benefits associated with remediating the debris. Orbital debris is defined as "any human-made space object orbiting Earth that no longer serves any useful purpose" (Space Policy Directive-3 2018). Such debris ranges in size from 9,000-kilogram upper stages down to millimeter-sized flecks of paint and metal. Debris can be created during normal launch operations, during operations of the spacecraft, when a spacecraft fails or fragments, when two objects collide, or when a spacecraft finishes a mission but is not de-orbited. Orbital debris has grown in number and total mass since the beginning of the space age, as shown in Figure 1.

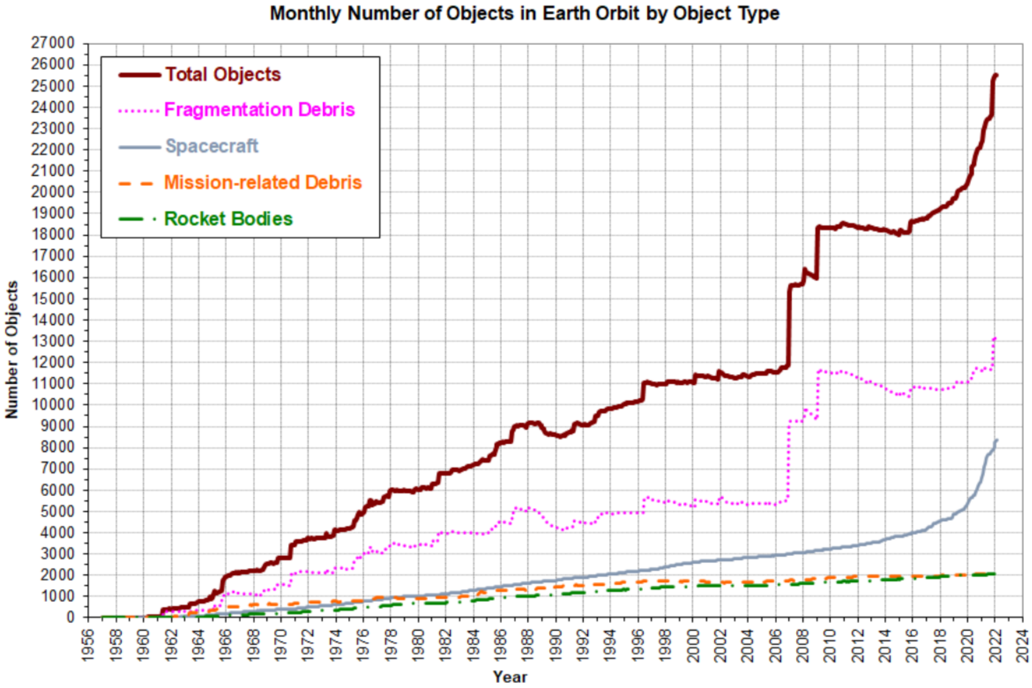

Figure 1. Trackable debris, by category, in Earth orbit since the beginning of the space age. The largest jumps in the number of objects are due to the Chinese ASAT test in 2007, the Iridium-Cosmos collision in 2009, and the Russian ASAT test in 2021. Credit: NASA's Orbital Debris Program Office (ODPO) (ODPO n.d.)

Orbital debris poses a risk to spacecraft operators. Striking active spacecraft can degrade the spacecraft or prematurely end a mission. This risk grows as the volume of both orbital debris and space traffic increases. To mitigate the risk of a debris strike, spacecraft owners use space situational awareness (SSA) capabilities to predict when a piece of debris might strike their spacecraft and then maneuver to avoid the potential collision. However, this approach works only for the 25,000 pieces of debris that are large enough (10 cm or more in diameter) to be tracked by current SSA capabilities and only for spacecraft with maneuvering capability. Of the 3,355 spacecraft in our database, about 20 percent lack the capability to maneuver.

Current SSA capabilities cannot track the estimated 300,000 to 500,000 pieces of debris that are 1 to 10 cm in diameter (Liou 2020). Figure 2 illustrates the destructive energy that a 1 cm piece of debris can deliver to a spacecraft. An impact with this energy can easily pierce a thin-walled spacecraft or upper stage, resulting in catastrophic damage and breakup if it impacts a battery or propellant tank. Pieces of debris that are 1 mm or greater in diameter may number over 100 million.

Spacecraft owners cannot maneuver to avoid non-trackable debris, but they can take measures to mitigate the damages of a strike. For example, spacecraft can incorporate shielding so that sensitive or mission-critical components are unlikely to be struck or less likely to be damaged if struck. Such approaches can protect robotic spacecraft from debris about 4 mm and below. Some human spaceflight systems may be shielded from debris up to 1 cm in diameter.

Figure 2. Impact crater from 1.2 cm aluminum sphere traveling at 6.8 km/s striking 18 cm thick block of aluminum. Source NASA ODPO.

Although most of the debris in space is in low Earth orbit (LEO), spacecraft in geosynchronous orbit (GEO) are also at risk. Historically, spacecraft in GEO were thought to be at low risk from orbital debris. For instance, one debris remediation proponent stated, “there is no problem of debris density, and no real risk of collision; in case of a collision, anyhow, the relative velocity would be relatively low (500 m/s compared to up to 15 km/s in LEO), so the effects would most probably not be ‘catastrophic’” (Phipps 2016).[1] However, new research indicates that many potential collisions in GEO could involve relative velocities higher than previously analyzed. For example, debris that is inclined by 15 degrees has a relative velocity of about 800 m/s with active spacecraft in GEO (Oltrogge et al. 2018). Oltrogge et al. (2018) also analyzed 34,000 historical close approaches in GEO and found that relative velocities as high as 3 km/s are not rare. Further, they estimate that GEO spacecraft may collide with debris 1 cm or greater every four

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[1] Phipps (2016) stated that a catastrophic collision involves more than 55 kJ/kg of specific energy. However, the space community generally uses 40 kJ/kg as the threshold, though this may still be too high (Pardini and Anselmo 2014).

years on average. In 2022, statistics from Celestrak.org indicate that 553 active spacecraft are in GEO with another 304 debris objects that are mainly defunct satellites and spent upper stages.[2] An additional 963 objects, mainly debris, transit through the GEO protected zone and can potentially cause collisions.

Events that inadvertently generate debris at any altitude, also known as fragmentation events, are relatively common. The European Space Agency (ESA) estimates that about 12 fragmentation events have happened every year for the past two decades (ESA 2022). Although fewer than 5 percent of fragmentation events are caused by collisions, many fragmentation events have an unknown cause (see Figure 3); some of these fragmentations might have been caused by collisions with small debris.

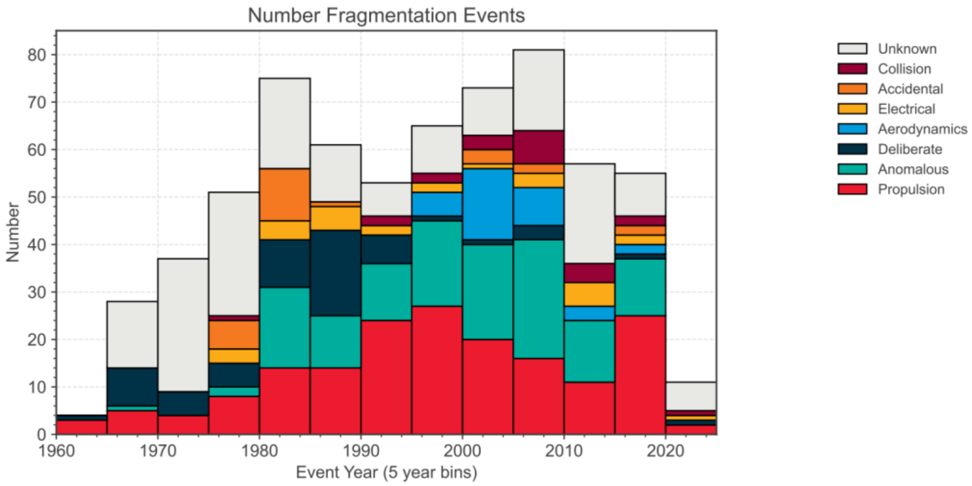

Figure 3. Source of fragmentation events over time (ESA 2022)

This characterization of fragmentation events raises two points for orbital debris remediation. On the one hand, collisions with debris have been a lower risk to spacecraft than most other hazards. On the other hand, no single method to stop fragmentation events exists, and as debris continues to increase in number and volume, the risk to spacecraft increases as well. Managing the risks posed by orbital debris requires a balanced approach that incorporates a portfolio of methods for risk reduction.

A Balanced Approach

The challenge of orbital debris requires a whole-of-nation—possibly global—approach based on three strategic pillars: mitigate the creation of new debris, improve the ability to track and characterize debris, and remediate debris that has been generated. The National Science and

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[2] https://celestrak.org/NORAD/elements/ shows 553 active satellites in the GEO protected zone (GEO altitude plus/minus 200 km), 857 total objects in the GEO protected zone, and 1,820 objects inside or transiting through the GEO protected zone.

Technology Council (NSTC) recently released three strategic documents with guidance on this balanced approach: a National Orbital Debris Research and Development Plan (NSTC 2021), a National Orbital Debris Implementation Plan (NSTC 2022-OD), and an In-Space Servicing, Assembly, and Manufacturing National Strategy (NSTC 2022-ISAM). We briefly summarize the three strategic pillars and additional considerations below.

Mitigation

Debris mitigation is any activity performed by a spacecraft to reduce the amount of new debris it generates, whether on purpose or by accident. These activities include reducing the deliberate release of debris, improving the reliability of critical spacecraft subsystems to reduce on-orbit failures, choosing spacecraft materials to reduce the likelihood that a failure leads to a fragmentation, shielding the spacecraft to protect it from small debris strikes, having sufficient maneuvering capability to avoid collisions with debris or active spacecraft, and employing a reliable method for self-disposal of the spacecraft at the end of its lifetime. Mitigation efforts have been the focus of most orbital debris policy in the United States. For example, the recent U.S. ban on destructive direct-ascent anti-satellite weapons tests will reduce the creation of new debris.

Tracking and Characterizing

Tracking debris is the ability to first detect that a piece of debris exists, then determine the parameters of its orbit to sufficient precision for predicting the trajectory of the debris, and then finally re-observe the debris periodically to update the orbital parameters, ensuring its location is approximately known at all times.

Characterizing debris is the ability to understand other features of a piece of debris, such as its shape, mass, material composition, and rotation rate. Characterization also includes understanding population-level statistics, such as the population density for different categories of debris and their evolution over time.

Satellite operators need accurate tracking and characterization of debris to support efficient collision avoidance maneuvers. However, uncertainties associated with debris tracking are substantial and vary by altitude. For example, propagating space debris trajectories one to two days into the future, with modern SSA capabilities, leads to median positional errors of nearly 100 meters for altitudes 600 km and above (Oltrogge and Alfano 2019). At lower altitudes, the uncertainties become too great to be useful for making robust collision avoidance decisions. Further, most debris that poses a risk to active spacecraft is not currently tracked.

Remediation

Remediation of debris is any action to reduce the risks associated with orbital debris by moving, removing, or reusing it. Approaches to remediation include capturing debris in LEO and tugging it to lower orbits for an uncontrolled or controlled reentry; the use of lasers, ion beams, or small satellites to nudge large pieces of debris away from collisions; debris sweepers for cleaning up small debris at scale; reviving defunct spacecraft for use in new missions; or recycling materials from debris to use as propellant or feedstock for in-space manufacturing. Remediation in GEO involves approaches such as raising the orbit of defunct spacecraft into graveyard orbits, or even installing devices on objects to eject them from Earth's orbit completely, such as solar sails.

A Closer Look at Remediation

Most U.S. efforts to address orbital debris focus on mitigation, tracking, and characterization. Indeed, NASA recently convened an Orbital Debris Review Team (ODRT) to identify priority challenges and solutions related to space sustainability. Of the 17 proposed solutions, 7 related to mitigation, 7 to tracking and characterization, 2 to general risk management, and only 1 to remediation. Although remediation is just one method of reducing operational risks in the space environment, it receives relatively little attention within the portfolio of potential actions. In this section, we discuss why that may be and why remediation may now need more attention.

Potential Reasons for a Lack of Remediation Activity

For the last decade, U.S. policy has supported debris remediation efforts. The 2010 National Space Policy called on NASA and the Department of Defense (DoD) to "pursue research and development of technologies and techniques…to mitigate and remove on-orbit debris" (National Space Policy 2010). Updated in 2020, the National Space Policy now calls to "evaluate and pursue, in coordination with allies and partners, active debris removal as a potential long-term approach to ensure the safety of flight in key orbital regimes" (National Space Policy 2020).

However, there is a sense in the space community that debris remediation is less valuable than mitigation or tracking and characterization. For example, while SPD-3 calls for debris remediation "as a necessary long-term approach," it also states that remediation "should not detract from continuing to advance international protocols for debris mitigation associated with current programs" (SPD-3 2018). Some members of the space community have interpreted this passage from SPD-3 in an extreme manner, suggesting that remediation should not be pursued at all until mitigation issues are resolved. Other national-level documents are explicit that "limiting the creation of new debris may be the most cost-effective approach to managing orbital debris risk"

(NSTC 2021). Given the lack of risk-informed work on debris remediation,[3] this value judgement is an assumption, not a fact.

This value judgement, of the relatively low *near-term* value of remediation compared to mitigation and tracking, is also reflected in the two main arguments used to justify debris remediation. The first main argument for remediation relates to a phenomenon known as Kessler Syndrome. Published in the late 1970s by Donald Kessler, the idea is that debris-on-debris collisions create new debris, which then go on to increase the frequency of debris-on-debris collisions (Kessler and Cour-Palais 1978). The cascading creation of debris may eventually render some orbits unusable. Even if all satellite launches ceased permanently, the number of pieces of debris in orbit might continue to grow for many years.

While debris below 650 km naturally de-orbits within 25 years due to atmospheric drag, the only way to stabilize or reduce the number of pieces of debris at higher altitudes is to actively remove them. Figure 4 shows the effect of debris removal on the total number of pieces of debris over a 200-year timespan. We find two important insights here. First, a relatively large number of debris *removals* are required to stabilize the number of pieces of debris in the space environment—approximately five per year. Note that *removal* of debris may not be the most effective method of remediating debris and reducing debris-on-debris collisions. Second, all of the projections assume a post-mission disposal (PMD) compliance rate of 90 percent, somewhat above the current PMD compliance rate.[4] Thus, regardless of the PMD compliance rate, stabilizing the number of debris in space requires some level of remediation.

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[3] A significant amount of work has focused on the value of remediation as measured by the number of pieces of debris in LEO over very long timespans. However, this metric is a poor proxy for risk. Risk is defined as the probability of an event times the consequence of the event. The appropriate consequence by which to measure risk is dollars, not number of pieces of debris.

[4] ESA estimates that payloads in LEO that reached end of life in 2020 were between 85 and 90 percent compliant by count but only about 65 percent compliant by mass (ESA 2022, Figures 6.8 and 6.9). Rocket bodies were about 85 percent compliant by count and about 90 percent compliant by mass. Interestingly, ESA shows that for the decade beginning in 2010, commercial spacecraft had a substantially higher compliance rate than civil and military spacecraft (ESA 2022, Figure 6.2). Further, ESA estimates that commercial systems will widen their lead in the coming decade. Although not the whole story, this information runs contrary to the narrative that commercial operators are irresponsible actors who must be increasingly regulated.

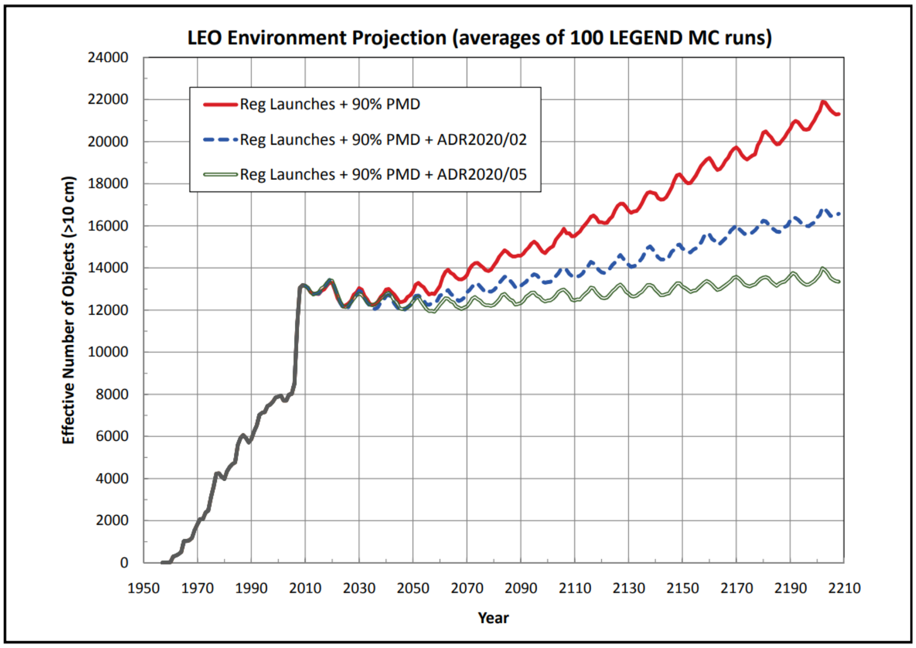

Figure 4. The evolution of trackable debris in LEO over a 200-year timescale. Each line assumes that PMD compliance has risen to 90 percent. The red line assumes that no debris removal occurs. The blue and green lines assume that 2 and 5 large debris objects are removed per year, respectively. Source: (NASA ODPO 2011)

When will important orbits become unusable? Kessler argues that we already experience Kessler Syndrome, but space still supports an increasing amount of activity. The analysis in Figure 4 had to simulate the space environment for the next 200 years to illustrate the point. Even then, debris grows approximately linearly in time, not exponentially. Space might remain usable for hundreds of years. When the timing of the consequences is so far in the future, this argument is challenging to use for justifying action now.

The second main argument for remediation is one of professional and moral responsibility. Space debris is a form of trash. In any other context of human endeavor, we strive to pick up our own trash. In 2021, the White House Office of Science and Technology Policy (OSTP) held a listening session open to the entire space community to discuss debris remediation. One commenter gave the following analogy: if a person's car breaks down on the side of the road, they can't just abandon it; they must pay someone to haul it away. Similar analogies were offered by many other commenters. Likewise, any nation that strives to be a leader in the responsible uses of space may have a hard time justifying the practice of allowing their dead spacecraft to put the spacecraft of other nations at risk. However, the risks associated with active spacecraft interacting with large pieces of debris are poorly characterized and may not be large enough to justify action, especially when no other spacefaring nations have yet committed to remediating their own debris—only doing technology demonstrations.

These two arguments are valid but might be too qualitative and far-future to motivate action now. Therefore, we investigate a rarely pursued third argument: that debris remediation may produce near-term benefits, measured in dollars.

Research into this third argument has been lacking. Most research in this vein is qualitative (Schaub et al. 2015, OECD 2020) or purely theoretical (Adilov et al. 2018); few studies place a dollar value on a piece of debris. Vance and Mense (2013) estimated that small, untracked debris in sun-synchronous orbit (SSO) may be worth \$328 per piece per year in 2009 dollars; however, they incorrectly inflate this value as \$14,500 (for 2009 dollars).[5] Their estimate for the benefits of removing a 2,000 kg piece of debris from SSO is \$306,000 (in 2009 dollars), predicated on their incorrectly inflated value of small debris and possibly compounded by a subsequent inflation error. Macauley (2015) provides a potential framework to place a dollar value on debris; however, the assumptions used to illustrate the framework are somewhat unrealistic. All satellites are assumed to cost \$500 million to design, build, and launch. Dollar values of debris are calculated assuming that they cause a 10 percent or 50 percent loss of productivity in active satellites. Large debris and small debris are treated together; thus, the framework is effectively a calculation of the value of small debris, which significantly outnumbers large debris. Macauley's estimates range from \$0.3 million to \$8.0 million per piece of debris.

Although these studies were commendable efforts, their results do not provide enough clarity for decisions on debris remediation. Nor are they sufficient to contextualize the value of remediation compared to mitigation and tracking. Further, in conversations with satellite operators and potential debris remediators over the last few years, a recurring theme has been that nobody knows how to value a piece of debris or its remediation. The National Orbital Debris R&D Plan highlights this as well, stating that the costs and benefits of debris remediation are not well characterized (NSTC 2021). By better characterizing these costs and benefits, we can better contextualize the value of remediation compared to mitigation and tracking. This study attempts to help close this knowledge gap, by providing information on the *near-term* costs and benefits of debris remediation, measured in dollars.

Why Debris Remediation May Need More Attention

This section discusses some of the recent events that motivated this study. Debris remediation needs more attention now than has historically been provided.[6] Specifically, with more debris and more operational satellites, the risk posed by existing debris is greater. The concepts and associated technologies for remediating large and small debris have made progress in the last

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[5] The authors appear to have divided the annual worth of \$328 per debris by the rate of return of long-term bonds in 2009 at 2.24 percent, for example, \$328/0.0224 = \$14,642. This method is not accepted for calculating present value. An acceptable method is that Present Value = Future Value / (1 + annual rate of return)^years. Using \$328 as the future value and summing the present value for all years that value is compounded, we reach a present value of \$14,500 in about 200 years.

[6] The statement that debris remediation needs increased attention is not meant to suggest that remediation is more important that mitigation or tracking. However, debris remediation has historically been de-emphasized in the trade space of risk-reduction activities for reasons that may be less valid now than before.

decade, which may improve the technical and financial feasibility of remediation. There is also mounting public pressure for governments of the world to take action on debris remediation.

As discussed previously and illustrated in Figure 4, the number of tracked and untracked debris in LEO is projected to grow. The number of debris grows even if no new satellites are launched into space, yet launch traffic is likely to increase in the coming decade compared to recent history. Rather than cover this complicated discussion in depth, we mention a few considerations. On the one hand, some proposed satellite constellations, sometimes called "megaconstellations," may each contain thousands to tens-of-thousands of satellites. Table 1 provides potential sizes for a few of the proposed constellations. If only one or two of these constellations materialize, they represent a substantial increase in the number of operational satellites in space and therefore an increase in the number of pieces of debris that can result from satellite failures or poor post-mission disposal procedures. These satellites themselves may also experience risks due to orbital debris; thus, their launch increases the enterprise-wide risks associated with orbital debris.

Table 1. Summary of potentially emerging large satellite constellations.

Constellation Owner	Number of Satellites	Above 650km
Amazon	4,538	No
Astra	13,620	Split
Boeing	5,670	Yes
China SatNet	12,992	Split
Hughes	1,440	Yes
Inmarsat	198	Yes
OneWeb	6,372	Yes
SpaceX	29,988	No
Telesat	1,788	Yes
Grand Total	76,606	

Source: (Tibor et al. 2022)

On the other hand, we do not wish to overstate the significance of these large constellations or rely too heavily on them for motivation. Attempts in the 1990s to establish large constellations for communication services saw every constellation operator go bankrupt; only one operator (Motorola / Iridium) launched their constellation prior to bankruptcy. We cannot say if the currently proposed constellations will fare better than their predecessors. Regardless, the potential for a large increase in space traffic is a motivating factor for many in the space community.

Debris remediation technologies have made substantial progress in the last decade. These are propelled by U.S. government investments in adjacent in-space servicing, assembly, and manufacturing (ISAM) capabilities, direct support for debris remediation from non-U.S.

governments, reduced cost of space hardware, falling launch costs, and increasing interest from private companies. Commercial active debris remediation is in the early stages of development and demonstration. Firms with some level of development activities for debris removal include Airbus Defense and Space (Multinational in Europe), Altius Space Machines (USA), Astroscale (Japan), Clearspace (Switzerland), Exodus Space Systems (Australia), KMI (USA), Orbit Guardians (USA), Orbit Recycling (Germany), Origin Space (China), Ortum Stellar EO (USA), Scout Aerospace, Shanghai ASES Spaceflight Technology (China), Share My Space (France), Starfish Space (USA), Start Rocket (Russia), and Tethers Unlimited (USA). Some companies have already performed flight demonstrations of subsystem technologies, such as Airbus Defense, Tethers Unlimited, Astroscale, and Origin Space.

The potential size of the market for debris remediation is highly uncertain. The landscape is broadly international, and U.S. companies might be able to access foreign customers. Firms capable of gaining early mover advantages may enhance national competitiveness, provided that certain policy hurdles can be addressed. The size of this market is unknown, though market survey studies suggest estimates of $100M or more per year (Zisk 2022)[7] if regulations supporting active debris removal (ADR) and space sustainability are enacted.

Currently, one example of a market customer is European Space Agency (ESA) for Clearspace-1 mission, which will de-orbit a 100-kilogram piece of European-owned debris. This mission may signal the intent of European countries to purchase further debris remediation services. Japan supports technology demonstration and operational debris remediation missions developed by Astroscale, called the ELSA-d and CRD2 missions, which may signal Japan's intent to pay for commercial remediation of debris. Astroscale is reported to have identified other potential customers, including a $3.5 million contract with OneWeb. While the terms of this contract are unknown, the value proposition of debris remediation services for a proliferated LEO constellation may be to clear out any of its spacecraft that fail in the constellation's operational orbit.

Related to debris remediation, Intelsat recently paid Northrup Grumman for the MEV-1 mission to extend the life of a defunct satellite. This mission involved tugging the Intelsat satellite from a graveyard orbit to an operational orbit. Eventually, MEV-1 will place the Intelsat vehicle back into its graveyard orbit. This mission illustrates another potential value proposition for debris remediation services: a spacecraft may wish to use debris remediation services as a form of life-extension. Rather than terminate its mission early and use its remaining propellant for post-mission disposal, the satellite may extend its lifetime by depleting its onboard propellant, then pay for debris remediation services to dispose of the system.

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[7] This source is reporting on an analysis from Euroconsult that estimates the active debris removal market will generate $980M in revenue by 2031. We roughly annualize this revenue as $100M per year.

Due to the certain increase in orbital debris, the potential increase in space traffic, increased interest from U.S. and international companies to develop remediation capabilities, and nascent commitments from non-U.S. governments to develop capabilities to remediate some portion of their space debris, there is growing pressure on the United States to act. The U.S. DoD has taken the first step, beginning a robust effort to develop certain debris remediation capabilities. However, there is pressure for civil leadership in this area. For example, a bill recently passed by the U.S. Senate, the ORBITS Act, would require NASA to establish a program that matures technologies capable of remediating orbital debris (Foust 2022).

Whether NASA wants to be engaged in debris remediation or not, the Agency may be called upon to take a role. What should that role be? Many uncertainties make it challenging to answer this question. These uncertainties include what types of remediation technique(s) are most promising, which types of debris should be prioritized, what level of effort is justified, and to what degree the costs of performing remediation should be borne by government or private operators. To provide information to answer such questions, the National Orbital Debris Implementation Plan called for “an economic and strategic risk assessment [that] would describe the near-term harm—quantified in dollars and probabilities—to provide an expected value for costs imposed by orbital debris and, by extension, the potential size of the market for active debris removal (ADR) services” (NSTC 2022-OD). This study aims to implement such an economic risk assessment. We do not definitively answer any of the questions regarding NASA’s role, but we do provide a tentative quantitative framework that NASA can use to support the answers to such questions. The study’s insights can also be useful to other government agencies and companies, both foreign and domestic.

Methodology

To estimate the costs and benefits of debris remediation, we followed these three overarching steps:

1. We developed a model for the costs imposed on satellite operators due to interactions with debris, such as collision avoidance maneuvers with large debris and damage done by strikes of small debris. This model provides the baseline costs associated with orbital debris.
2. We posited perturbations to the debris environment—such as removing a large piece of debris or cleaning small debris out of an orbit—and used the model to estimate the resulting change in costs to spacecraft operators, compared to the baseline. A reduction in existing costs or expected avoidance of new costs are the "benefits" in the cost-benefit analysis. Each of the debris perturbations can be created by one or more of the remediation approaches, allowing us to associate equal benefits to each of the remediation approaches.
3. We estimated the cost of creating the debris perturbations, using the relevant remediation approaches. These are the "costs" in the cost-benefit analysis.

By taking the ratio of the costs and benefits, we arrived at a relative comparison of the effectiveness of each type of remediation approach.

The goal of this study is not to produce accurate or precise estimates of costs and benefits, but rather to estimate the relative worth of remediation approaches. Therefore, we used an analytical framework that is high-level, is transparent, and enforces consistent assumptions across all remediation approaches. Our results for costs and benefits are order-of-magnitude estimates. For example, most of the input parameters are rounded to one significant figure (e.g., $976 thousand is rounded to $1 million). However, we expect that the relative ranking of costs and benefits for remediation approaches will be somewhat robust.

In this section, we detail each of the three methodological steps to clarify for analysts and other subject matter experts how we arrived at estimates of relative worth and the decisions underlying the analysis.

Estimate the Risks Imposed by Orbital Debris

To estimate the risks associated with orbital debris, we developed a satellite population model, a debris encounter model, and an operator cost model. Our satellite population model is based on data from the Union of Concerned Scientists and provides the location of all U.S.-operated satellites in orbit, parametrized by altitude, and category of the type of operation. We restricted our attention to U.S. assets only to reduce the scope of work; however, the methodology can be extended to include non-U.S. assets as well. We used a model developed by COMSPOC to estimate the expected number of warnings, maneuvers, and collisions that each satellite will have with pieces of debris per year (COMSPOC n.d.). Finally, we estimated the monetary cost of the per-event costs of warnings, maneuvers, and collisions with a cost model we developed through a combination of discussions with subject matter experts, literature reviews, cost modeling software, and informed judgement where necessary. Using these three sub-models, we can compute the total number of debris encounters that each U.S. spacecraft will have and the resulting annual cost of those encounters.

Satellite Population

The satellite population model is derived from the Union of Concerned Scientists (UCS) Satellite Database (UCS n.d.), which is freely available for download. We made three modifications to the database:

- Binned satellites by average altitude, with bin sizes of 25 km, for altitudes ranging from 125 km to 38,000 km. To calculate the average altitude of each satellite, we added the perigee to the apogee and divided by two.
- Filtered the column “Country of Owner/Operator” to show only spacecraft associated with “USA.”
- Assigned a category to each of the resulting satellites, grouping together satellites that we anticipate have roughly similar costs associated with their debris interactions.

We exported the resulting database, which allows us to count how many satellites of each category are present at each altitude from low LEO up to just above GEO. Note that the International Space Station (ISS) is not associated with “USA” in the UCS database, which categorizes the ISS as “Multinational.” We inserted the ISS by hand into our own population model.

We chose to limit our satellite database to only U.S. operated assets as a matter of scope. For each spacecraft in our analysis, we needed to determine whether it could maneuver to avoid debris; if the spacecraft cannot maneuver, then it incurs no cost associated with collision avoidance maneuvers. Investigating non-U.S. spacecraft to estimate their maneuver capabilities would have taken more time and not changed the relative efficacy of remediation approaches. By omitting non-U.S. spacecraft, we have reduced the potential benefits of remediating debris because there are fewer spacecraft at risk. Had these benefits been included, each remediation approach would reach net benefit sooner than we have estimated; however, the efficacy of all remediation methods would be improved by the same amount, leaving their relative rankings unchanged. In other words, the remediation approach that reaches net benefit the fastest will be the same whether looking only at U.S.-operated spacecraft or all spacecraft. Similar logic applies to the remediation approach that reaches net benefit second-fastest, etc. Our framework is general and can easily incorporate internationally operated assets, which we anticipate doing in future work.

We will discuss the specific categories of satellite operators and the heuristics for assigning spacecraft to each category in Appendix A. We categorized spacecraft by factors such as ownership (civil, defense, or commercial), the ability of the assets to maneuver, and their mass. We had to complete the categorization before we developed the operator cost model and made our first quantitative cost estimates. In subsequent work, we hope to use the insights gained from developing this model to improve the categories, better grouping spacecraft with similar cost characteristics.

Debris Encounter Model

To estimate the number of encounters—warnings, maneuvers, and collisions—that each satellite will have with a piece of debris in a year, we used the Number of Encounters Assessment Tool (NEAT) developed by COMSPOC. Per the website for the tool, “NEAT uses a fast, probability-based algorithm to assess the long-term encounter rate between any and all pairs of satellites” (COMSPOC n.d.). The publicly available tool allows the user to place a test object into a circular orbit; specify characteristic distances for warning, maneuver, and collision events; and then compute the average number of each event that the test object experiences with active satellites and trackable debris. The COMSPOC team graciously offered to assist our study by running their tool for the use cases we specified.

Before running the tool, we first defined the relevant thresholds. We defined a warning as a close approach that comes within 3 km of another object. We assumed that a conjunction data message indicating a miss distance at this threshold will prompt the spacecraft operator to perform some form of risk analysis that likely requires some amount of labor time. We assumed that a close approach within 1 km will prompt the spacecraft operator to perform an avoidance maneuver. Finally, we assumed that a close approach within 5 m will produce a collision. These are the default distances used by the NEAT tool and appear to be reasonable approximations.

The encounter rates vary as a function of inclination; however, our simplified satellite model is parameterized by average altitude only. We asked COMSPOC to provide the minimum and maximum encounter rates at each altitude. While the publicly available version of NEAT estimates encounter rates using a combined satellite-and-debris catalog, we asked COMSPOC to provide separate estimates of encounter rates with active satellites and with trackable debris (greater than 10 cm in diameter). This analysis uses only the encounter rates with trackable debris, which allows for estimation of active-on-debris and debris-on-debris encounters. Costs associated with active-on-active encounters do not involve orbital debris and are thus out of scope, though they could be part of subsequent analysis. COMSPOC also provided the number of debris and satellite objects in each average-altitude bin—information we used later to estimate the effects of perturbing the debris population.

We roughly accounted for differences between large and small debris. As of August 2022, the European Space Agency (ESA) estimated that there were 36,500 pieces of debris above 10cm in diameter and 1 million pieces of debris between 1 and 10cm (ESA n.d.). Thus, the ratio of small to large debris was about a factor of 27. We assumed that small debris has approximately the same distribution across altitudes as large debris; thus, we created a small-debris catalog by multiplying the large debris profile by a factor of about 27. Being untracked, small debris does not generate warnings or encounters but can still generate collisions, which we approximated as occurring 27 times more frequently than the encounter model for trackable debris.

In general, a collision of two debris objects or of an active satellite with untracked debris will result in the generation of new debris. We account for first-order increases in the debris population, but we do not model second-order collisions with our framework, as described in the subsequent sections on debris perturbations and the calculation of benefits.

Operator Cost Model

For spacecraft in each category, we provided estimates of various costs associated with interacting with debris. This section mentions the breadth of possible imposed costs. Although we could not provide estimates for all costs, we summarize our approach for the costs we could estimate. We assign the standard labor rate for an engineer to be about $80 per hour; this is calculated by assuming a median annual salary of $80,000, then applying an overhead factor of 2. Specific estimates for each cost vary by operator and are described quantitatively in Appendix A.

Design and Shielding. To mitigate damage from small pieces of debris, spacecraft are generally designed so that critical components are less likely to be struck. For example, placing critical components on the inside of the satellite means that less critical components are struck first. Also, shielding may be added to protect critical components. Generally, spacecraft are sufficiently robust that they are protected against strikes of debris less than 4mm in diameter. In our discussions with satellite owners, the costs of shielding against human-made debris are not explicitly accounted for because they are commingled with the costs of shielding against naturally occurring micrometeoroids. We asked how much the cost of design and shielding would increase if the debris in their operational orbit were expected to double, but no expert was able to provide an estimate. Likewise, if debris suddenly disappeared, many of the design and shielding decisions would not change due to the presence of naturally occurring micrometeoroids. For this analysis, we do not account for the costs of design and shielding related to orbital debris because we lack an ability to estimate how they would change as the debris population is perturbed.

Insurance. Some spacecraft operators pay for insurance to mitigate the risk that their system might fail. As the potential risks increase, the premiums offered by insurance companies also increase. Thus, an increase in the population of orbital debris may also increase the premiums paid by spacecraft operators. However, our initial assessment suggested that orbital debris appears to have a limited influence on why insurance policies are purchased and how premiums are set (Tibor et al. 2022). Thus, we did not prioritize insurance premiums for analysis in this report. As with design and shielding, we do not account for the costs associated with insurance related to orbital debris because we have no heuristic for estimating how these costs would change with increasing or decreasing debris populations.

Launch Collision Avoidance (COLA). For certain space operations, especially human spaceflight, the spacecraft cannot launch if the trajectory would take it too close to a piece of known debris. In this case, the launch may have to be delayed, which incurs a cost. We do not account for the costs associated with launch COLAs because we do not have an ability to estimate their frequency of occurrence or average severity.

Analysis of Conjunction Data Messages (CDM). Operators receive a large number of CDMs during the course of their operations. CDMs are messages sent by conjunction assessors, such as the 18th Space Control Squadron, that warn satellite operators of predicted conjunctions. A message includes data such as probability of collision, miss distance, and time of closest approach (TCA). However, most CDMs carry information about conjunctions with miss distances that are too great to pose a risk; such messages do not require a human's attention to analyze. Operators with whom we've spoken have generally automated the processing of CDMs. This automation has a cost; however, it is a sunk cost for operators at this point. Further, an increase in debris would only increase the amount of computational time the company purchases to run its algorithms, which is a negligible cost. For these reasons, we estimate that the cost associated with analyzing the majority of debris-related CDMs is effectively zero.

Labor for Risk Analysis Per Warning. While most CDMs may not impose a meaningful cost, some will. A CDM may predict a close approach with trackable debris that is sufficiently risky to warrant human intervention. For the purposes of this analysis, we define such a CDM as a "warning," though this is not a standardized term in the industry. As discussed previously, we use the NEAT tool to identify warnings when a close approach is within 3 km. Upon receipt of a warning, the satellite operator may request additional observations of the debris object from the 18th SDS to reduce uncertainties in its predicted trajectory, do a higher fidelity risk analysis of the potential conjunction (or review the results of an automated risk analysis), and consider potential maneuvers that could be executed to reduce the risks. The variable cost associated with these risk analyses are the labor of the human analysts, which can vary from zero minutes to a few hours per warning, depending on the level of automation used by the spacecraft operator and the value of the vehicle itself. For each category of spacecraft, we provide the estimated value of this labor per warning.

Propellant per Maneuver. If the probability of a collision with trackable debris is sufficiently high, generally above 0.01 percent, the spacecraft operator will maneuver to reduce the risk of collision. For vehicles with propulsion systems, the maneuver will expend propellant. In theory, the loss of propellant may lead to an associated loss of satellite lifetime, because operators must reserve sufficient propellant to lower or raise the vehicle's orbit as part of their post-mission disposal procedures. For each operator category, we assess whether these expenditures of propellant do in fact affect the vehicle's lifetime or otherwise impose a cost. If there is a cost, we estimate the mass of propellant expended and the value of that propellant. For refuellable vehicles, the value of the propellant is the cost of its resupply. For non-refuellable vehicles, the value is the associated loss of revenue or science value due to premature decommissioning of the vehicle.

Lost Operations per Maneuver. During the execution of a maneuver to avoid trackable debris, the spacecraft might not be able to perform its mission. For example, a satellite providing Earth observational data might not be able to take high-quality overhead imagery while the thrusters are firing or if the avoidance maneuver has placed the satellite outside the orbital or attitudinal parameters for which the vehicle is optimized. As with the cost of propellant, we first assess whether each satellite operator does have reduced operations during a maneuver. If there is a loss of operations, we estimate the amount of time the maneuver affects operations and the lost revenue or science value due to this loss.

Labor for Planning per Maneuver. Most satellite operators use humans in the loop for the planning and approval of a maneuver to avoid trackable debris. Operators often plan maneuvers but then decide that maneuvering is not necessary and do not execute the plan. We did not uncover a general heuristic for the proportion of warnings that lead to planning a maneuver, but rather for the maneuver that was not executed—the rate of false positives. Thus, we calculate only the costs associated with labor for planning maneuvers that are then performed—the true positives.

Hardware Damage per Collision. Being struck by a piece of debris may disable the spacecraft. The options for post-collision response include replacing the vehicle, repairing the vehicle, or accepting the loss and doing nothing. For each class of vehicle, we assess which of the three options are likely to be pursued and estimate a cost of lost hardware that accounts for the value of the lost asset. There are many possible methods for estimating these losses, which makes it challenging to provide a summary here. See the subsequent chapter for a discussion tailored to the unique circumstances of each operator category. We assume that spacecraft will maneuver to avoid trackable debris; thus, costs related to collisions come exclusively from small, non-trackable debris.

Lost Operations per Collision. In addition to the cost of the lost hardware, a collision with non-trackable debris will also lead to an immediate loss of operations. For a commercial operator, this may mean a loss of revenue until the satellite can be replaced. For a government operator, this may mean a loss of science data or degradation of an operational capability upon which our society relies, such as extreme weather forecasting or missile warning. As with the cost of damaged hardware, the methods for estimating these costs depend on a wide variety of factors and cannot be summarized here. See the subsequent chapter for a discussion tailored to the unique circumstances of each operator category.

Disposal. A satellite operator might pay for post-mission disposal, using the remaining propellant on their own satellite to operate past its design lifetime. However, operators with whom we've spoken did not seem receptive to this idea. Commercial operators must currently demonstrate, prior to launch, that they can reliably dispose of their satellites.[8] Relying on a third-party service to fulfill the operator's regulatory responsibility seems unlikely until there are multiple reliable providers of debris remediation services and a pathway for allowing them to satisfy regulatory requirements. Until then, satellite operators may pay for life extension services, but they will likely reserve their own propellant for the PMD disposal.

Another cost related to disposal is that if a spacecraft operator fails to perform its PMD, perhaps because the spacecraft suddenly failed in its operational orbit, that defunct spacecraft may inflict risk on others. For this analysis, we do not account for the cost of PMD disposal because subject matter experts indicated that satellite operators are unlikely to rely on a third party to satisfy their PMD requirements. Further, operators currently do not face a financial penalty for unsuccessful PMD.

Uncontrolled Reentry. As a matter of scope, we do not account for the costs associated with damage to life or property on the ground due to uncontrolled reentry. This topic may be the subject of future work.

Estimate the Near-Term Benefits of Perturbing the Debris Environment

To estimate the benefits of performing debris remediation, we perturbed the profile of debris—i.e., the amount and location of debris—compared to the profile in the baseline cost model and used the resulting change in simulated operator costs as the basis for calculating benefits. This

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[8] Since 2004, the FCC's regulatory process requires applicants to disclose information related to their post-mission disposal plans. One of the requirements is to assess and limit the probability that a PMD plan does not succeed. The FCC recently tightened the rules by putting numerical thresholds on PMD success, but these have not yet taken effect. Under the new regulations, a satellite operator's application "must include a demonstration that the probability of success of the chosen disposal method will be 0.9 or greater for any individual space station" (47 CFR § 25.114).

section discusses the debris catalog we used, the perturbations we created, how we calculated the value of those perturbations, and how we calculated the benefits of each perturbation.

Debris Catalog

Although the NEAT tool has a debris catalog to produce estimates of warnings, maneuvers, and collisions, we created our own debris catalog from publicly available data. Our debris catalog enables us to identify specific pieces of debris for removal by their NORAD catalog IDs.

To create this debris catalog, we first downloaded data on objects in space from SpaceTrack.Org as of September 2022. The data contains a column named OBJECT_TYPE, which labels each object with one of the following categories: debris, payload, rocket body, TBA, and unknown. These categories describe the object's status when first entered in the database, not necessarily its current status. For example, objects marked as debris have always been debris, such as satellite deployment devices or debris caused by the fragmentation of a spacecraft. Likewise, objects labeled as payloads were active satellites when first added to the database. Many payloads have since reentered, as indicated by the column DECAY_DATE, which records the historical date of reentry. Objects that lack a decay date are still in space. Some payloads may have ceased to function, becoming debris; however, they are labeled as payloads with no decay date, not as debris. We used the UCS database to identify such objects.

To begin, we identified all objects in the SpaceTrack.Org data that *did not* appear in the UCS database, by filtering by NORAD IDs. The objects identified in this sub-list are thus either some form of debris or currently active satellites launched after the UCS database's last update (December 31, 2021). Using this sub-list, we performed two separate filters to identify debris. First, we filtered these objects to identify only those labeled as a "PAYLOAD" that launched in 2021 or earlier and that did not have a decay date. These objects were active satellites in 2021 but are now debris. We placed them into our debris catalog. Second, we filtered the original sub-list for all objects that *were not* payloads—they have always been debris—and have no decay date. We placed those objects into our debris catalog. These pieces of debris were in space in 2021, though the orbital elements we used are from September 2022.

The SpaceTrack.Org data shows that approximately 1,600 pieces of debris reentered in 2022. We did not add these pieces of debris to our debris catalog because the orbital elements listed were the last-known elements prior to reentry. As such, they are skewed toward very low orbits. Rather than potentially overestimate the amount of debris at such low altitudes, we removed them from consideration.

Perturbations

We chose two main perturbation scenarios to illustrate the costs and benefits associated with removing the largest debris and the smallest debris. The main risk associated with the largest debris (5,000 kg and above) is that it may strike another piece of debris and cause the creation of many new pieces of trackable and non-trackable debris. As a rough approximation for the debris created during a collision, we model the collision on debris generated by the 2007 Chinese ASAT test. Thus, we discuss the 2007 ASAT test prior to discussing large debris removal.

2007 Chinese ASAT. We constructed a perturbation based on the 2007 Chinese ASAT test. We used this scenario to estimate the costs associated with such a test happening again and as a basis for estimating the costs of other collisions at high altitudes in LEO. The total mass involved in the collision was approximately 1,350 kg.[9] Within the debris catalog we created from SpaceTrack.Org data, we find 2,814 pieces of debris from this event. This number is reasonably close to the 3,000 pieces of debris reported by other authors (Weeden 2010). Figure 5 shows the distribution of debris altitudes in this analysis. Despite the breakup occurring 15 years ago, the collision was high enough that the orbits for most of the debris have hardly decayed; the greatest number of debris is in the 850 km altitude bin.

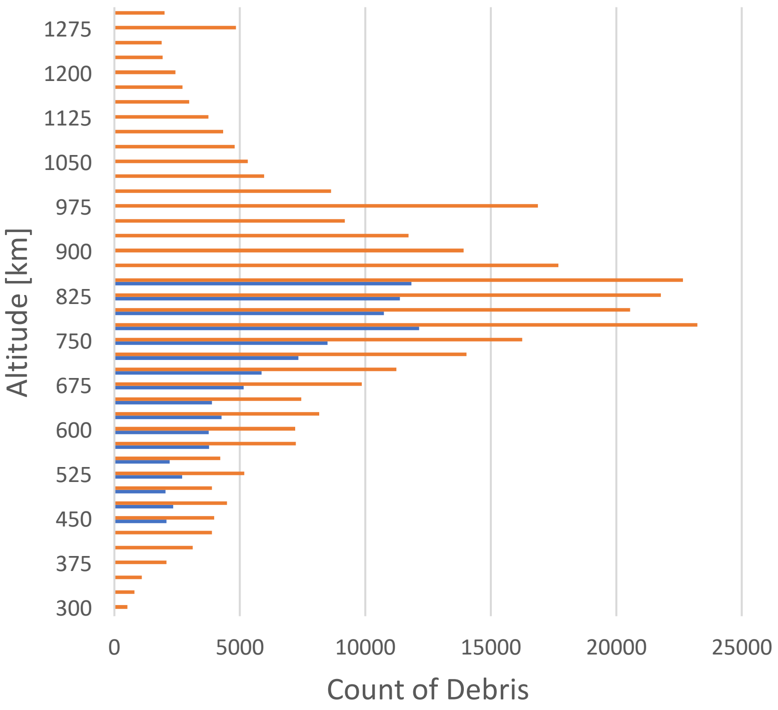

Figure 5. Profile of altitudes for the trackable debris produced by the 2007 Chinese ASAT Test.

The ASAT test would have also created a substantial amount of small, untracked debris. Per our previous discussion, we use a rough heuristic that 27 pieces of debris in the 1-10cm range are

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[9] The mass of the kill vehicle was estimated as 600 kg (Weeden 2010). For simplicity, we assumed that entire mass is dry mass that may contribute to debris. The target of the ASAT, FengYun-1C, had a mass of about 750 kg and was at an altitude of about 865 km. The satellite likely did not have a propulsion system; thus, we assumed the full mass of the satellite is dry mass contributing to debris.

created for every piece of trackable debris created. Thus, we created a profile of orbits for small debris that is about 27 times the profile shown in Figure 5. To use this perturbation to estimate a collision, the debris profile is scaled to have more or less debris, translated up or down to match the altitude of the collision, and the resulting debris considered in addition to the baseline debris.

McKnight Top 50 Remediation. Modeling the remediation of large debris requires at least two perturbations. The first perturbation is simply the removal of the objects. Further perturbations are required to describe the collisions that might have happened if the objects were not removed. To construct the removal perturbation, we scraped the composite top 50 statistically most concerning debris objects identified by McKnight et al (2021).[10] We then calculated the average altitude of each object, binned the altitudes for every 25 km, and generated a histogram of number of objects per altitude bin. To simulate the remediation of this debris, we perturbed the expected number of warnings and maneuvers by calculating the resulting fraction of trackable debris at each altitude range after remediation.[11] Remediation of the Top 50 objects does not create an associated reduction in *pre-existing* small debris, though it reduces the potential for creation of new small debris.

For this and other perturbations, we simplify the remediation process by removing the temporal aspect. Specifically, if the debris is being de-orbited, we assume that all the debris has been simultaneously and instantaneously removed. If the debris is to be nudged so that collisions no longer occur, all relevant debris is no longer able to collide with any other piece of debris. There is no scheduling of which debris to remove first, next, or last. The process is not drawn out over a decade, with benefits accruing at different rates that depend on the order and timing of the remediation process. This simplification allows us to clearly probe the value of the perturbation without other confounding factors.

To simulate the effects of collisions that might happen if debris is not remediated, we constructed three perturbations involving debris objects from the McKnight Top 50: collisions with one of the objects at the highest altitude, with one of the objects at the lowest altitude, and with one of the objects in the most crowded altitude. The parameters for the collision scenarios are given in Table 2. In each case, we assumed that the other object in the collision has a mass of 2,000 kilograms.[12] We calculated the probability of each collision based on the number of pieces of McKnight debris at that altitude and the potential collisions they may have with each other and with other pieces of debris at that altitude level. The resulting debris cloud is derived from the

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[10] Table 4 of the reference lists these 50 objects.

[11] For example, our debris catalog contains 593 pieces of debris at approximately 750 km, 2 of which are in the McKnight top 50. By removing those 2, the number of debris is perturbed by a factor of (593-2)/593 = 0.996627.

[12] Our debris catalog does not give us the masses of each piece of debris, so we use a *representative* mass of trackable debris at these high-LEO altitudes. However, we cannot say how close this mass is to the *average* mass of trackable debris in those altitudes. We have assumed that non-trackable debris is small enough that it won't cause a massive fragmentation event in a collision with another defunct spacecraft, so such collisions are out of scope for this analysis.

profile of debris from the 2007 Chinese ASAT test. We translated the 2007 ASAT debris profile up or down in altitude, such that the altitude bin with the greatest debris became centered on the altitude of the collision with the McKnight Top 50 debris.[13] Next, we scaled the amount of debris from the 2007 ASAT test by the ratio of the mass of McKnight Top 50 debris to the mass of the ASAT debris.

Table 2. Parameters of Estimated Collisions with Objects from the McKnight Top 50

Collision Scenario	High Altitude	Low Altitude	Crowded Altitude
Type of Debris	H-2 R/B	SL-16 R/B	SL-16 R/B
NORAD Number	24279	25861	22566
Altitude Bin [km]	1,075	625	825
Mass of Debris [kg]	2,700	9,000	9,000
Mass of Other Object [kg]	2,000	2,000	2,000
Mass Ratio Compared to 2007 ASAT a	3.5	8.1	8.1
Probability of Collision b	0.02%	0.03%	1.9%

a. The amount of debris from the 2007 ASAT test is scaled up by this factor to roughly account for the increased mass associated with McKnight Top 50 collisions compared to the ASAT collision. The combined mass of the objects involved in the 2007 ASAT is about 1,350 kg. For example, the factor for the high-altitude collision scenario is calculated as (2700+2000)/1350 = 3.5.

b. Calculated for a McKnight object at the collision altitude for a one-year period of time.

The resulting field of trackable debris associated with the low altitude scenario is shown in Figure 6. For comparison, the debris profile has been overlaid with the 2007 ASAT debris profile from Figure 5. This comparison illustrates how the amount of 2007 ASAT debris has been scaled up and the altitudes of the debris shifted lower, so the peak of the debris profile is now in the 625 km altitude bin. For each scenario, we also created associated profiles of non-trackable debris in the 1-10cm range, by multiplying the trackable profiles by a factor of 27.

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[13] In general, the shape of the resulting debris distribution is a function of many factors, such as the total energy involved in the collision, the velocity vectors of both objects in the collision, and the altitude at which the collision occurs. For this high-level analysis, we have not incorporated these effects.

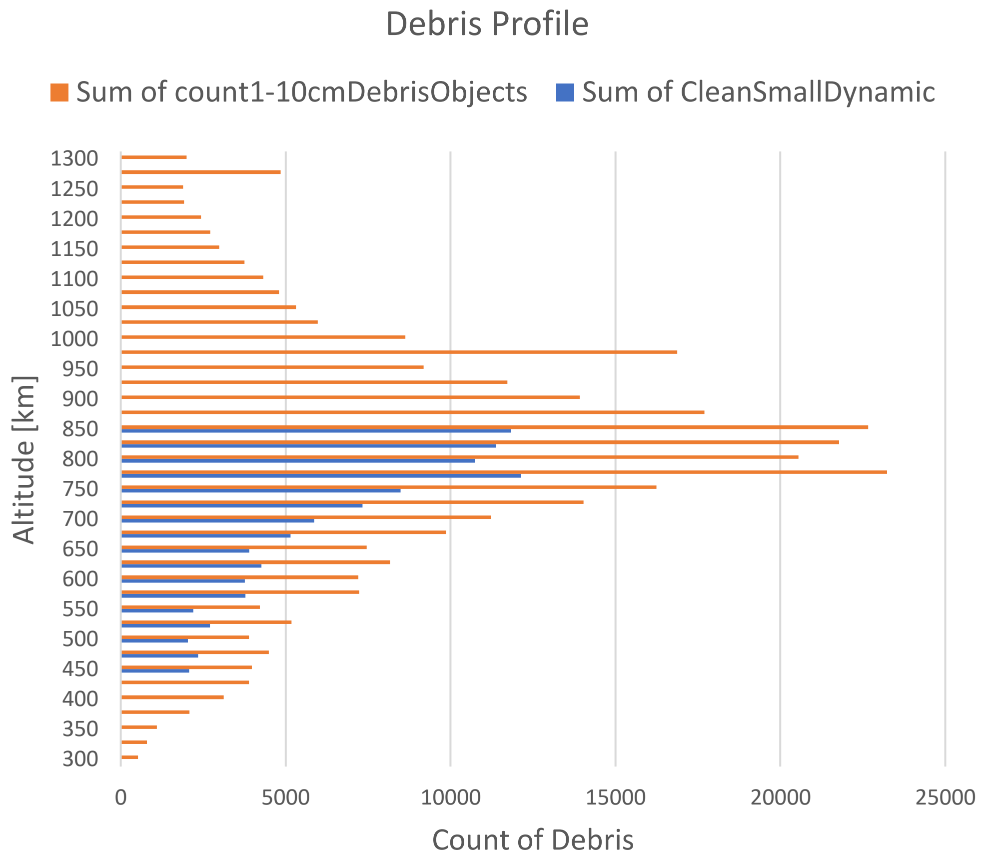

Figure 6. Comparison of trackable debris estimated for a collision involving a low altitude SL-16 R/B from the McKnight Top 50 (orange) and the debris generated from the 2007 Chinese ASAT test (blue).

Remediate 100,000 Pieces of Small (1-10 cm) Debris. To construct this perturbation, we make use of knowledge gained from the analyses of debris removal via space- and ground-based lasers, presented in a subsequent chapter. Specifically, the space-based laser system we investigate may be able to remove 100,000 pieces of small debris in the span of a few months, using favorable assumptions about the material composition of the debris. Alternatively, we provide a more conservative estimate that indicates the laser system may remediate 100,000 pieces of small debris during its entire operational lifetime. Because the costs we have estimated take 100,000 pieces as a natural point of reference, we also construct a perturbation for the removal of the same number of pieces. As discussed previously, perturbations are simulated as being instantaneous; all 100,000 pieces of debris disappear at once.

The space-based laser system indicates an ability to remediate debris within a 400 km altitude band of the laser system. We chose to remove these pieces of debris from the altitude range of 450-850 km because our cost model indicates that this range provides the greatest potential benefit, compared to other 400 km ranges in LEO. Our simplified debris model estimates about

191,000 pieces of 1-10 cm debris in this altitude range. Thus, we remove 48 percent[14] of the debris from each altitude bin to reach a total of 100,000 pieces of debris removed. Figure 7 illustrates the debris removed, overlaid with the total population of 1-10cm debris in low LEO.

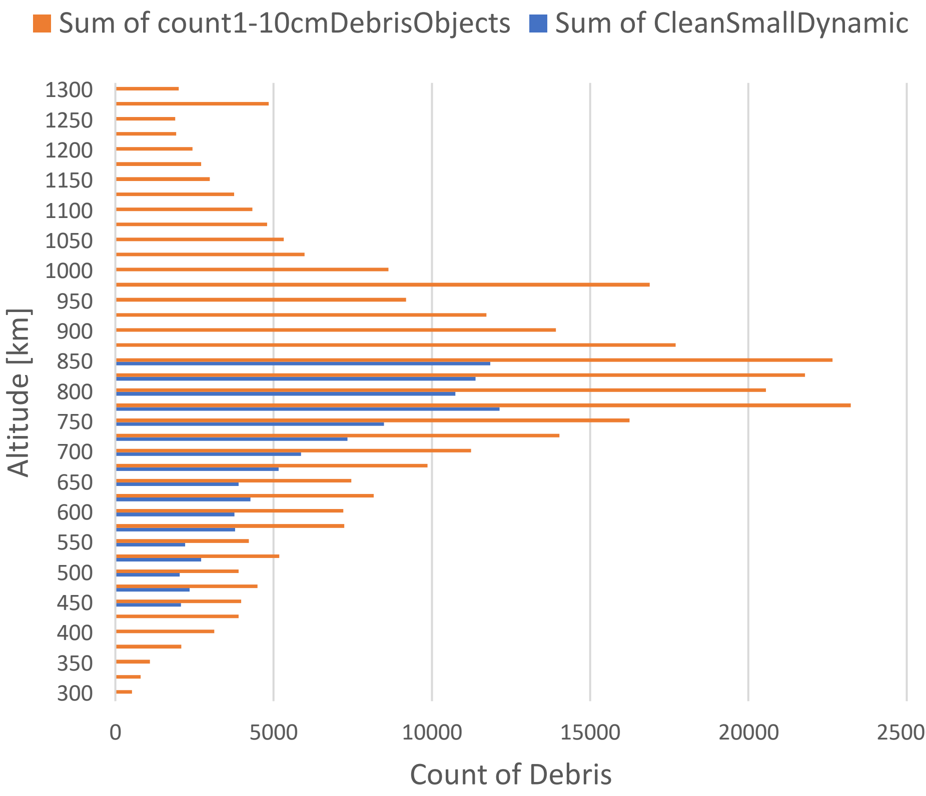

Figure 7. Summary of the small (1-10 cm) debris removed in blue. The orange histogram is the total population of small debris in our simplified debris model.

The debris is removed in uniform proportion from each altitude range because the remediation systems, whether space-based or ground-based, will detect debris probabilistically. As the number of debris in an orbit decreases, the chances to encounter debris in that orbit progressively decrease, which may lead to wasted time in between removing one piece of debris and waiting to detect another. Removing 100,000 pieces of debris from a broad swath of orbits is likely faster and easier than completely cleaning out a few orbital ranges until 100,000 pieces of debris are removed.

Further, by removing some debris from a broad swath of altitude ranges, we can investigate the effect of debris removal on a broader population of spacecraft. If instead we removed all debris from a narrow altitude band, the value of the perturbation would be less robust.

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[14] 1-191,000/100,000.

Calculate the Value of Baseline and Perturbations

In general, the total value of a perturbation or the baseline is the sum of all the costs imposed on all spacecraft at all altitudes.[15] To construct the general formula, we define the following variables:

- **$N_{a,s:}$** The number of spacecraft at altitude *a* from spacecraft category *s.* The categories are discussed in the chapter Spacecraft Operators and Costs They May Incur.
- **$WARN_a^{(trackable)}$:** The daily number of warnings a spacecraft at altitude *a* will experience due to trackable debris. Spacecraft cannot receive warnings for non-trackable debris. This value comes from our debris encounter model.
- **$COSTWARN_s$:** The cost per warning for a spacecraft from category *s*. This value is the "Labor for Risk Analysis Per Warning" from our operator cost model.
- **$MNVR_a^{(trackable)}$:** The daily number of maneuvers a spacecraft at altitude *a* will experience. Spacecraft cannot maneuver to avoid non-trackable debris. This value comes from our debris encounter model.
- **$COSTMNVR_s$:** The cost per maneuver for a spacecraft from category *s*. This value comes from our spacecraft encounter model. It is the sum of the cost of Labor for Planning per Maneuver, Propellant per Maneuver, and Lost Operations per Maneuver.
- **$CLZN_a^{(1\text{-}10cm)}$:** The daily number of collisions a spacecraft at altitude *a* will experience. Collisions occur with non-trackable debris only, because the satellite will maneuver to avoid trackable debris. Our model of non-trackable debris includes only debris in the 1-10cm range. This value comes from our debris encounter model.
- **$COSTCLZN_s$:** The cost per collision for a spacecraft from category *s*. This value comes from our spacecraft encounter model. It is the sum of the cost of Hardware Damage per Collision and Lost Operations per Collision.
- **FRACLETHAL:** The fraction of small debris strikes that are lethal. This is necessary because small debris may strike anywhere on the spacecraft. The strike must do damage to a vital subsystem. Strikes are most likely to impact the solar panels, which generally only causes a degradation of available power and does not disable the spacecraft. We set this value at 10 percent (Tibor et al 2022, page 19). Note that our simplified debris model does not account for any new debris that may be caused by a collision with a piece of non-trackable debris.
- **$PTURB_a^{(trackable)}$:** A scaling factor that accounts for the addition or removal of trackable debris at altitude *a*. If the perturbation is a collision that generates debris, then PTURB is greater than 1. For example, if there are 10 pieces of debris at a certain altitude and a perturbation adds one more piece of debris into that altitude, the factor is 1.1 because

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[15] In this report, we calculate the value to active U.S. spacecraft only.

the amount of debris has increased by 10 percent. If the perturbation is a removal of debris, then PTURB is less than 1. The baseline scenario corresponds to PTURB of 1.

- **$PTURB_a^{(1\text{-}10cm)}$**: A scaling factor that accounts for the addition or removal of 1-10cm debris at altitude *a*.

The annual value of a perturbation for spacecraft in category *s* at altitude *a* is $V_{a,s}$ and given by

$$V_{a,s} = 365\, N_{a,s} \left[(WARN_a * COSTWARN_s + MNVR_a * COSTMNVR_s) * PTURB^{trackable} + CLNZ_a * FRACLETHAL * COSTCLZN_s * PTURB^{\{1-10cm\}}\right].$$

The full annual value is the sum over all altitudes and spacecraft categories:

$$V_p = \sum_a \sum_s V_{a,s}\,. \qquad (1)$$

Calculate Benefits

To calculate the benefits, we first calculate benefits for a single year, then assume that subsequent years will provide the same annual benefit. In other words, the values for the baseline and each relevant debris perturbation are calculated over the duration of a single year that approximately represents the space environment in 2021. The annual benefit of a perturbation is the difference between the values of the baseline and the perturbation.

The distribution of spacecraft, debris populations, and operator costs in this report approximately represent the space environment in 2021. Our methodology does not progressively update these distributions, other than to provide one-time perturbations. Thus, the results become less defensible the further into the future one tries to apply them.

There are two qualitatively different types of benefits. One benefit is the reduction of costs currently being paid by space operators. For example, consider the situation where a space operator pays money to avoid debris X in the baseline scenario and debris X is removed from the perturbation. In this case, the value of the perturbation is less than the value of the baseline; the benefit is a savings of money.

The other benefit is risk avoided by spacecraft operators. Risk is defined as the probability of a bad event times the consequence of the event. For this analysis, the consequences are costs imposed on spacecraft operators, measured in U.S. dollars. For example, consider the situation where the perturbation contains a debris-on-debris collision that is not in the baseline. In the perturbation, trackable debris is generated that spacecraft must then avoid and non-trackable debris is generated that may then disable spacecraft. The value of the costs imposed on operators in the perturbation (V_p) is greater than the value of the operator costs from the baseline (V_0); that difference is the cost of the perturbation (C_p),

$$C_p = V_p - V_0.$$

However, the perturbation is not certain to occur; it occurs with some probability. Multiplying the cost of the perturbation by its probability (P_p) gives the associated risk,

$$Risk = P_p * C_p.$$

If debris remediation allows the perturbation to be avoided, the risk to satellite operators decreases. Decreasing risk does not reduce the costs spacecraft operators currently pay in the baseline but does reduce the costs they may have to pay in the future.

The annual benefit is the sum of the costs saved and the risks avoided. We then use this annual benefit to calculate the benefits on longer timescales. We make the simplifying assumption that the probability of a perturbation (P_p) for the first year is the same for all subsequent years.[16] We account for P_p as a constant to simplify the analysis, because its time dynamics do not affect our ultimate result, which is to find the remediation approaches with the most favorable cost-benefit ratios.[17] Likewise, the cost that a perturbation imposes (C_p) is the same regardless of the year it occurs. Further, we impose this cost not just on the year it occurs, but all subsequent years for which it is applicable. For example, consider a perturbation with a collision that creates an annual cost C_p if it occurs. On a 5-year timeframe (T), a collision that occurs in the first year creates five years of subsequent damage ($5C_p$) as spacecraft maneuver to avoid the new debris and get struck by the newly created non-trackable debris. A collision in the second year creates 4 years of damage ($4C_p$), and so on, until the final year when a collision creates only 1 year of damage ($1C_p$). The total risk experienced over this timeframe is the sum of the risks times their probabilities from each year, expressed mathematically as

$$\begin{aligned} Risk(T) &= \sum_{t=1}^{T} P_p C_p (T - t + 1) \\ &= \tfrac{1}{2} P_p C_p (T^2 + T). \end{aligned} \tag{2}$$

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[16] Assuming the probability is constant is reasonable because it grows so slowly that on short timescales (e.g., 5 years) it will not grow enough to make a difference to our results. For example, the probability that the McKnight Top 50 debris will be involved in a collision (Pc) with other debris is about 3% at time t=0. Assume that if a collision happens at time t, the new probability of collision at t+1 will be twice the probability it was at time t. At that rate, it will take 15 years for the expected value of Pc to reach 5%.

[17] If P_p increases over time, then the benefits associated with a perturbation will increase. However, this same increase in benefit will be applied equally to all remediation approaches that can perform the perturbation. Thus, all remediation approaches will see their cost-benefit ratio increase, but the relative ranking of the remediation approaches remains the same. Specifically, assume that P_p held constant and Approach A has a higher cost-benefit ratio than Approach B; if P_p is allowed to increase over time, both approaches A and B will see their cost-benefit ratios increase, but Approach A will still have a higher cost-benefit ratio than Approach B.

The benefit over the timeframe T is the risk avoided, per the equation, plus the costs saved, which follows a similar relationship.

Table 3 provides a concrete representation of the calculation. In the table, the timeframe (T) is five years, the annual cost imposed by the perturbation (C_p) is $111M, and the annual probability of the perturbation (P_p) is 3.13 percent. A collision that occurs in the first year generates $556M (5*$111M) of damage over the five-year period. Considering that the damage has only a 3.13 percent chance of occurring, the risk for the first year is $17M ($556M * 0.0313). Repeating this process for every year, the total risk over this time horizon is the sum of the annual risks, which equates to about $52M in this example.

Table 3. Example of risks compounding as the timeframe into the future increases nonlinearly.

Years into the Future	Probability of Collision	Value of Collision [$M]	Expected Risk [$M]
1	0.0313	$556	$17
2	0.0313	$445	$14
3	0.0313	$334	$10
4	0.0313	$222	$7
5	0.0313	$111	$3
Total			$52

Estimate Costs and Efficacy of Various Remediation Approaches

To estimate the costs associated with various remediation approaches, we first prioritized the approaches to analyze. These approaches were chosen to ensure that we addressed the remediation of both large and small debris, including non-trackable debris. Most published analysis on the topic of debris remediation has focused on approaches that physically capture debris and tug it to lower altitudes for a controlled or uncontrolled reentry. Thus, we include such approaches in our analysis. Beyond debris removal, lesser studied options for remediating large debris may involve recycling or simply moving debris to avoid collisions. We chose the following approaches for analysis, based on their contribution to a broad portfolio of remediation options:

- Remove small (1-10cm) debris
    - Ground-Based Laser
    - Space-Based Laser
    - Physical Sweeper in Orbit
- Remove large debris
    - Tug to Controlled Reentry
    - Tug to Uncontrolled Reentry
- Move large debris

  - Sounding Rocket for Just-in-time Collision Avoidance (JCA)
  - Lasers for JCA or Large Debris Traffic Management (LDTM)
- Recycling
  - Convert Debris Into ΔV

This list does not cover all possible remediation approaches, but it covers a broad amount of the trade space. Each approach is explained in detail in Chapters Remediation of Small Debris and Remediation of Large Debris.

Our estimates of cost and efficacy were informed by conversations with subject matter experts, but nearly all details in these calculations come from published literature. For each remediation approach, we provide a brief review of the concept, but ultimately we chose one or two papers with sufficient depth to inform our estimates. In some instances, we needed to alter assumptions in the source literature and make our own independent calculations with the updated assumptions. The output of each remediation analysis is a cost per use or a cost per kilogram, depending on the remediation approach. We use these costs in the estimation of costs and benefits for each debris perturbation.

Data Sources

We used space industry news sources and published literature to develop our estimates of the costs that spacecraft incur due to debris interactions and the performance of the various remediation approaches. Wherever possible, we used information that was either publicly available or able to be publicly shared, such as the UCS satellite database, debris data from SpaceTrack.Org, and the results of COMSPOC's NEAT tool. However, our estimates also use information from non-attributional discussions we held with representatives from 35 organizations, illustrated in Figure 8. Of these, 10 organizations were satellite operators who could speak to the cost considerations of the assets they operate and discuss their perspectives on debris remediation. The bulk of our discussions were with potential debris remediators, seven of whom focused on debris removal, five on nudging debris to avoid collisions, and three on recycling debris. Finally, we engaged with 10 subject matter experts for their insights related to the technological feasibility of various remediation approaches and insights into the dynamics and risks associated with orbital debris.

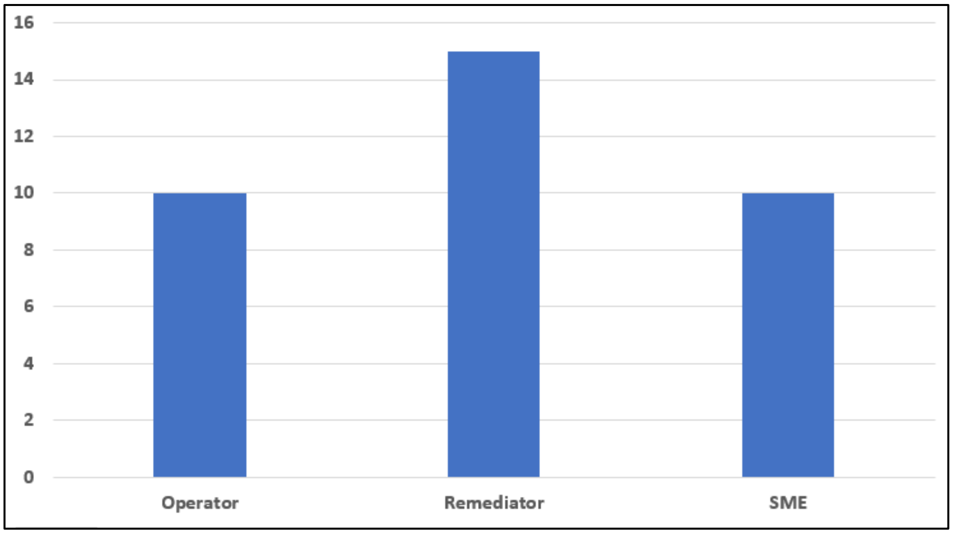

Figure 8. Summary of the Organizations with whom we held informal discussions.

Limitations

This study is a first step toward some ambitious goals not yet seen in the literature. We have taken a landscape view of the risks to spacecraft operators and measured them in dollars. We have explored the trade space of remediation approaches, measured in dollars, and made apples-to-apples comparisons among them. To achieve these broad goals, we had to make many simplifications and scoping decisions to make the problem tractable. We believe that these limitations are unlikely to fundamentally change the final conclusions regarding which debris remediation approaches have the greatest cost-benefit ratios. However, the following limitations must be considered before taking any of our intermediate results out of the context of this study and the final cost-benefit ratio.

- **Does not address the balance between remediation and other aspects of the debris lifecycle.** Remediating debris is one class of methods for reducing the risk to spacecraft operators. This study does not attempt to quantify or compare the risk reductions associated with other methods, such as improved debris mitigation techniques or enhanced SSA and STM capabilities for avoiding collisions.
- **Does not attempt to estimate commercial viability of ADR services.** We have merely assessed the conditions under which the benefits may outweigh costs. We provide no estimates related to potential profits, volume or timing of potential demand, effect of government commitments to procure ADR services, legal and liability issues, etc.
- **Did not investigate the liability to a spacecraft operator caused by the debris they have generated.** While we have estimated the reduced risk to all satellite operators associated with taking away pieces of debris, we did not quantify the risk that one operator's newly defunct satellite may pose to all other satellite operators as its orbit decays. The

significance of this omission is that this liability is likely the basis of the value proposition for a private company to purchase debris remediation services, absent new regulatory incentives. We could simulate this effect with some adjustments to our model; however, due to time constraints, this effort was placed outside our scope. Future work may incorporate the dynamic effect of orbital decay into the model, which would easily allow for this liability simulation to be included.

- **Does not use a discount factor for calculating the value of future benefits.** On the one hand, a lack of discounting may tend to overestimate the benefits as time progresses. On the other hand, this effect is applied consistently across all scenarios and thus does not affect the final ranking of cost-benefit ratios. Further, the focus of our study is on short timeframes, so the missing effects of discounting would not have many years over which to compound.
- **The orbits of satellites and debris are highly simplified**. In both cases, we accounted for all orbits as if they were circular, using their average altitude to define the orbit. However, the numbers provided by COMSPOC were calculated using the realistic, elliptical orbits of the satellites and debris as they transit through the circular orbit of the test object. We use their numbers *as if* the orbits of the debris and satellite population were also circular. For example, this leads to instances in the model where there are no pieces of debris at that average altitude, but there is a non-zero probability of collision with a piece of debris. In truth, debris is transiting through that altitude level, even though there are no debris in circular orbits at that level. On the one hand, our simplification allows the calculations of debris perturbations to be performed in an Excel spreadsheet that can be shared and easily edited by other interested analysts. On the other hand, in our model, removing a piece of debris from an altitude level only reduces the encounters with other satellites in that same altitude level. This simplification therefore overestimates the effect of removal at that altitude and underestimates the effect of a debris removal on adjacent altitude levels. Future work could incorporate a more realistic debris model.
- **Separate debris catalogs**. The debris catalog we created from SpaceTrack.Org for generating perturbations is not the same one as used in the NEAT tool for calculating warnings and collisions. This separation between catalogs should not have much effect on our final results because we use our debris catalog only to calculate perturbations, such as identifying the altitudes where the McKnight Top 50 debris are located.
- **Does not consider debris smaller than 1 cm in diameter.** For small debris, we currently look at 1-10cm debris only. A strike from debris as small as 4mm has the potential to disable a spacecraft. However, debris this size needs to be more like a solid metal sphere than a thin, flat flake of paint to cause fatal damage. Likewise, the debris needs to strike the spacecraft at a critical location but is most likely to strike a spacecraft’s solar panels, which may degrade their performance but is unlikely to compromise the mission.

However, due to the high number of such debris, they may be a leading cause of compromised missions. While our current work indicates the importance of small debris in the 1-10 cm range, future work should incorporate mm-sized debris.

- **We did not account for the unique dynamics of non-trackable debris**. Our assumption that the small debris is collocated with the trackable debris is unlikely to be true beyond a few years after the small debris is generated. As debris gets smaller, its ballistic coefficient decreases and it de-orbits more rapidly. For example, an object with a ballistic coefficient of about 5 kg/m2 will decay from 900 km orbit in about 25 years. This corresponds to a 3 mm aluminum sphere (density of 2,700 kg/m3 and drag coefficient 2.2) and is much faster than a large satellite that will decay from only 650 km in the same amount of time.
- **Probabilities of collision for non-trackable debris have not been validated**. We have spot checked the probabilities associated with a few potential collisions involving small debris to see that they are reasonable compared to the literature. However, our estimates of the probability for active-on-debris collisions with non-trackable is speculative and calculated indirectly. As this appears to represent the largest source of risk in our calculations, refinement of this interaction is a priority for future analysis.
- **Benefits associated with remediation of the McKnight Top 50 are representative, but possibly not average.** We assumed 2,000 kg for representative mass of the second object in the McKnight Top 50 collision scenario. We chose this mass for illustrative purposes because it reflects the mass of other large objects in these orbits; however, our current debris model does not allow us to calculate the average mass of trackable debris by altitude. Thus, we cannot comment on how close 2,000 kg is to the average mass that might be party to a debris-on-debris collision with a McKnight Top 50 object.
- **We have underestimated the mass associated of the FY-1C**. We assumed that it was 750 kg, but some references state that it was 880 kg. This assumption leads to us underestimating the total mass involved in the 2007 ASAT by about 10 percent. As debris from that ASAT event is translated and scaled to create our other debris-generating scenarios, our underestimation propagates through to some of our perturbation scenarios. We did not fix this error because it is unlikely to alter the qualitative conclusions of the report. Further, use of a single event is an oversimplification of the dynamics of debris generation; how much this oversimplification may affect our results compared to use of a higher fidelity breakup model is unknown. Future work should improve the breakup model to be more representative of average collisions.
- **Does not account for second-order collisions with debris in our perturbations**. A collision between two large objects may generate a substantial amount of new debris, both trackable and non-trackable. We account for this in the McKnight Top 50 debris perturbation scenario. In reality, these pieces of new debris may go on to collide with

other debris objects, thereby creating even more debris; however, we did not account for this second-order effect. This is reasonable on short timescales because the probabilities of collision are small.

- **Does not account for debris-on-debris collisions involving non-trackable debris**. If a non-trackable object hits a large piece of debris, it may generate new debris; however, the study team lacks a heuristic for estimating the amount of new debris. We assume that the debris created is much less than what would be created in a collision between two large objects; thus, we have not accounted for debris-on-debris collisions with non-trackable debris because they do not appear to be the driving cause of new debris.
- **Our calculated values of the baseline and of the perturbations have incomplete meaning in isolation.** Our calculations include only the satellite-on-debris and debris-on-debris interactions related to the specific remediation scenarios we investigated. Therefore, the calculated baseline and perturbation values can be properly interpreted only by taking their difference, as we have done to calculate the benefits of each perturbation. Thus, we cannot make claims such as "orbital debris is currently causing $X of risk for spacecraft operators." However, we can make claims such as "removing 100,000 pieces of small debris will reduce the risk to spacecraft operators by $X."
- **Non-recurring engineering (NRE) costs are inconsistently accounted for across debris remediation approaches.** In general, we rely on cost estimates from the literature. The various studies we drew from were independently conducted and did not account for NRE in a consistent manner. Further, we have not taken steps to validate or substantially alter their assumptions about NRE, so the values we use are likely to be optimistic.

Remediation of Small Debris

In this chapter, we outline the remediation approaches considered for nontrackable debris, focusing on 1-10cm debris. We analyzed the possibility of using ground-based lasers, space-based lasers, and physical sweepers that intercept small debris. For each approach, we briefly describe its concept of operations (CONOPS), discuss its potential efficacy, and, most importantly, provide a rough estimate of its cost.

We note two limitations in our analysis of small debris remediation approaches. First, we acknowledge that physical sweepers likely perform better for mm-sized debris than cm-sized debris. However, we investigate them for cm-sized debris as a non-laser point of comparison. Second, due to time constraints, we did not analyze the only other small debris remediation approach of which we were aware. This approach releases a cloud of micron-sized dust particles to create enhanced drag on small debris while leaving active satellites and large debris essentially untouched (Ganguli et al. 2014).

Remove: Ground-Based Laser

Lasers or other forms of directed energy can impart force on an object without making physical contact. This report focuses on two potential mechanisms for creating force-at-a-distance: photon pressure and ablation. Figure 9 provides a general illustration of such a facility.

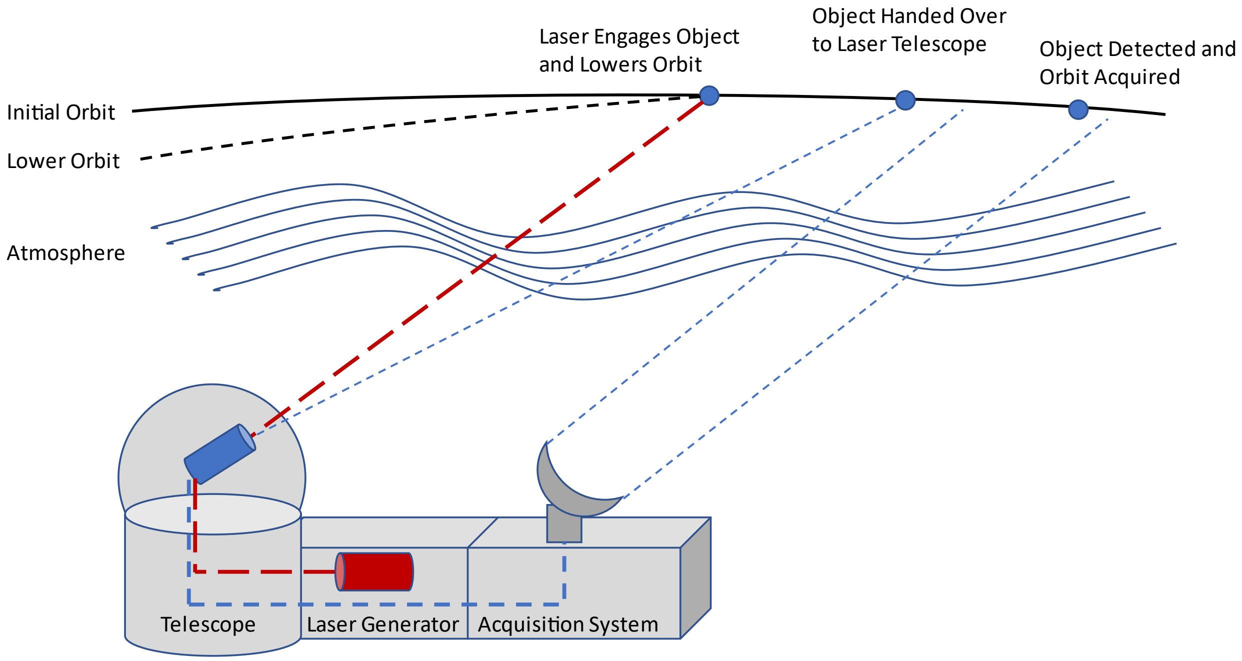

Figure 9. Notional concept of a ground-based laser facility for imparting impulses to orbital debris. The telescope that focuses the laser may require advanced adaptive optics to correct for atmospheric distortions to the beam.

With photon pressure, a laser nudges debris to avoid collisions. Though photons have no mass, they carry a small amount of momentum. When a photon bounces off an object, it transfers some momentum from the photon to the object. This is the same principle that generates thrust on a solar sail. Similarly, using directed energy to irradiate a piece of debris generates thrust on the debris. The thrust is too little to de-orbit debris but enough to potentially nudge debris from the path of a collision. Therefore, we do not consider photon pressure for remediating small debris, but we do consider this mechanism in the chapter on remediating large debris.

With ablation, a laser beam strikes a surface with enough intensity to ablate material, which is ejected approximately perpendicular to the surface and generates thrust in the opposite direction. In general, the ejected material is a combination of hot gas and plasma and therefore does not contribute new debris to the environment. Applied to debris, ablation can generate far greater levels of thrust than photon pressure but requires more powerful laser beams and greater optical precision. Ground-based experimental data and simulations of laser ablation on space debris indicate that this mechanism can de-orbit both non-trackable and trackable debris.

The idea for using lasers to remediate debris is generally credited to Phipps (Campbell 1996); however, the genesis of the idea seems to stretch back to the early 1980s. One subject matter expert noted that as new lasers were developed with progressively shorter wavelengths, engineers noticed that the beam coupled better with materials—to the point where the laser "could blow a hole in a satellite." After President Reagan began the Strategic Defense Initiative in 1984, this idea was developed to detect ICBMs. During this period, many technical aspects of the concept were proven, such as through the tests of the Mid-Infrared Advanced Chemical Laser (MIRACL) and Project Excalibur. These programs were eventually canceled.

Note that programs using directed energy for missile defense and anti-satellite weapons have two major differences with lasers for debris remediation. First, the weaponized lasers were generally "continuous wave," meaning that they generate a high level of power for many seconds to minutes at a time. In contrast, lasers for debris remediation are "pulsed," which means they generate pulses of power in very small amounts of time: each pulse typically lasts for only nanoseconds or picoseconds. The difference in effect is that a continuous wave laser dumps as much destructive energy into its target as possible, while a pulsed laser seeks to ablate very small amounts of material—the top few nanometers of the surface—with minimal heat transfer to the target. For a given wavelength and material to ablate, there is an optimal energy density for maximizing energy coupling to the material. Increasing the incident power on the material beyond this optimum value decreases the efficiency of energy transferred to the material. This property makes it difficult to use pulsed lasers for missile defense or ASAT capabilities.

The second difference between lasers for weaponization and lasers for debris remediation is the power levels needed. When pulsed, lasers for weapons require approximately 100MJ per pulse (Bloembergen et al. 1987). The energy density on the target would need to be at least 1 kJ/cm2, but more likely 100kJ/cm2 for a hardened target (Bloembergen et al. 1987). In contrast, the concepts for debris remediation generally use 10s of kJ per pulse and create energy densities of 5 J/cm2 or less on the surface of the debris. In general, lasers for debris remediation are about 1,000 times less powerful than those for destroying a spacecraft. Whether ground- or space-based, it would be difficult to conceal a laser system powerful enough for a weapon.

Lasers in the power range appropriate for debris remediation have limited potential use as weapons. Critics may note that these lasers could still be used for dazzling or damaging satellite sensors, but doing so requires lower power lasers that are already commonly available. Specifically, ground-based lasers as weak as 10 W can dazzle a satellite, while a 40 W laser guide star commonly used by astronomy observatories can permanently damage satellite sensors (Boháček 2022). Thus, lasers for debris remediation pose approximately as much weaponization risk as ground-based optical astronomy observatories.

Concept of Operations

The bulk of work on lasers for debris remediation has focused on either ground-based lasers for nudging trackable debris or space-based lasers for nudging or removing debris. The most comprehensive work on ground-based lasers for removing non-trackable debris is a study sponsored by NASA and the U.S. Air Force called Project Orion (Campbell et al. 1996). We base our CONOPS and performance estimates on that architecture, supplemented by theoretical and experimental updates since the study's release.

The laser removal system has four main hardware components: a laser generator, a telescope through which the laser beam is focused and fired, a laser guide star and adaptive optics system to correct for atmospheric distortions of the beam, and a method for getting an accurate orbital determination of the debris to guide the telescope. Debris in the 1-10cm range is not trackable in the same sense as larger debris; the orbit of the large debris is determined with sufficient precision that the same object can be reacquired later. However, small debris may be *sufficiently* trackable for removal, by using a radar or passive optical capability to track the debris immediately upon its detection. There is no need to reacquire the debris on subsequent orbital passes—only to track it across the sky long enough for a laser to engage it.

The CONOPS for remediating small debris with a ground-based laser proceeds as follows:

- **Detection**. A radar or passive optical method operates in stare-and-chase mode, waiting to detect a target object at altitudes up to 1,500 km. If using a passive optical method of acquisition, a 1 cm piece of debris at 1,500 km altitude, seen as it passes 30 degrees above the horizon, would have a visual magnitude as low as 19 (Campbell 1996, p133).
- **Acquisition**. Once the object has been detected, the radar or optical method transitions from "stare" to "chase" mode. During this time, the precision of the object's orbit is refined sufficiently to track it. This process is substantially different from conventional SSA

methods, which use radar in stare mode only and must wait for multiple overpasses of the object to determine its orbit. For small debris removal, the radar or optical method needs only to be able to track one object at a time and just long enough to engage it with a laser.

- **Discrimination**. The object is confirmed to be a piece of debris with physical and orbital properties that make it amenable to removal with the laser system. Further, the remediation system calculates the planned path that the laser beam will sweep across the sky and guarantees that no other space objects or aircraft will be illuminated by the beam.
- **Handover**. Tracking of the debris transitions from the radar or passive optical system to the laser system in preparation for the irradiation of the target. Handover is complete when the debris is reliably boresighted by the telescope.
- **Irradiation and Assessment**. The laser irradiates the debris. After every pulse, a flash of plasma should be detectable, indicating successful ablation. Once the engagement is finished, the updated orbit is determined by the laser system.
- **Book-keeping**. The results of the operation are recorded to ensure the risks to operational spacecraft are reduced and the throughput of the laser system is as expected.

Summary of Efficacy and Cost

The estimates provided for the original Project Orion study indicated a worst-case scenario that would cost about $168M to build an operational facility that would remove 30,000 objects over 3 years of operation. This yields an average of $6,000 per piece of debris removed. In a subsequent update to the Project Orion study (Phipps 2010), the system was redesigned to have greater power and reduced times of engagement per debris, resulting in a cost of about $300 per debris removed. It is unclear how many pieces of debris this updated system would remediate. Based on the original Project Orion work, we assume the system removes 150,000 pieces of debris over three years. We cannot vouch for whether these are truly best and worst cases, but they are the bounds of the scenarios we investigated and we used them for our analysis. See Appendix B for more details.

Remove: Space-Based Laser

Compared to a ground-based laser, a space-based laser generates much less power because it must produce all of its power in orbit. An advantage to space-based lasers is that the beam does not pass through the atmosphere, avoiding the associated transmission losses or deformation of the beam. Also, the beam has a more favorable engagement with the target, providing more opportunities to pulse the object in the direction tangential to its orbit. Doing so transfers more energy directly into lowering perigee than pulses from “below,” which may lower perigee but also somewhat raise apogee.

There are multiple concepts for space-based lasers to perform debris remediation. One concept, L'ADROIT (Laser Ablative Space Debris Removal by Orbital Impulse) (Phipps 2014 and 2016), uses a crystal-based laser (Nd:YAG) in an elliptical, polar orbit to de-orbit about 100,000 pieces of small debris (1-10cm) from 560 to 960 km.[18] Another concept for removing small debris from LEO, the International Coherent Amplifier Network (ICAN), uses an emerging laser technology with flexible fibers instead of traditional, large laser crystals. Among the benefits are increased efficiency for pumping the laser and removing heat, ultimately increasing the energy output per kilogram by a factor of about 100 (Phipps 2018). Developers of the concept state that a 100-fiber laser could perform a technology demonstration mission on the ISS using the Extreme Universe Space Observatory telescope on the Japanese Experiment Module, before scaling up to a 10,000-fiber free-flying system designed to remove most cm-sized debris below 1,000 km altitude in four years (Ebisuzaki et al. 2015). Likewise, researchers from China have been analyzing concepts for putting a laser on a crewed space station to de-orbit debris and protect the station from debris strikes (Shen 2014, Fang et al. 2019).

Japanese researchers at the company SKY Perfect JSAT and RIKEN research institute have been investigating the use of space-based lasers for de-tumbling satellites. They have shown that a satellite carrying a 50 W laser could rendezvous with debris and arrest its rotation from a range of about 200 meters. For example, stopping pieces of debris with masses of 150 kg and 8,200 kg from rotating at 1rpm would take 0.4 days or three months, respectively (Fukushima et al. 2021). They also estimated that their laser system could shepherd pieces of debris down to de-orbiting altitudes over the course of a few years,[19] but they recommend using a different vehicle to capture and tug the debris to lower orbits. Thus, a space-based laser system may be enabling for tugging concepts that grapple with tumbling debris.

However, other researchers in Japan have suggested that small lasers for de-orbiting large debris could be put on small satellites. Specifically, they estimated that a 100 W laser with optic diameter of 10cm could chase a 150 kg piece of debris and reduce its altitude from 1,200 km to 500 km in about 1 year (Tsuno et al 2020). Tsuno et al. did not fully develop a satellite concept to host the laser; however, we note that a small satellite, with electric propulsion and a few hundred Watts of power, may be a low-cost, multi-target method of debris removal. The power of the laser could be increased for larger pieces of debris. If costs are low enough, it would not matter that the de-orbit time may take years per object; the satellite simply needs to remove one or two pieces of debris during its operational lifetime.

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[18] For remediation objects in GEO, the designers estimate that a single L'ADROIT satellite could raise the altitude of 10 GEO satellites by 300 km over the course of 3 months to a year.

[19] The laser they used is about 1,000 times less powerful than the lasers used for L'ADROIT and ICAN.

Concept of Operations

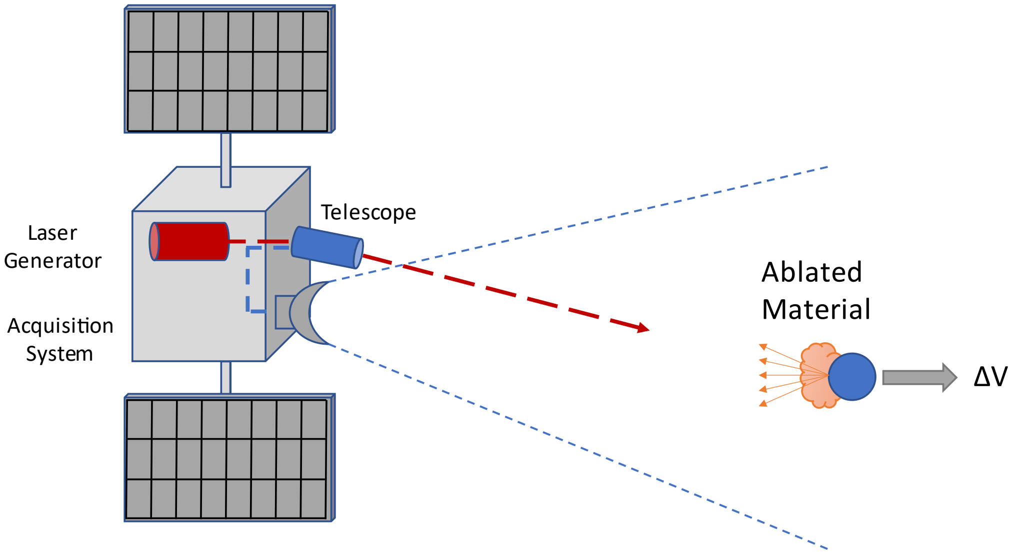

Figure 10. A space-based laser functions similarly to a ground-based laser; however, it requires much less powerful lasers and does not need adaptive optics to correct for atmospheric distortions to the beam.

The L'ADROIT concept forms the basis for our space-based laser calculations due to the detail available in public literature. Such a laser can be used to de-orbit small debris (1-10cm), which we discuss here, or engage with large debris, which we discuss with JCA and LDTM in the next chapter. Roughly speaking, any laser removal system has three components: a wide-field-of-view optical sensor, a laser generator, and a telescope through which the laser beam is focused and fired (Figure 10). The CONOPS for L'ADROIT is as follows:

- **Detection**. A target is passively detected by the onboard optical sensor, which finds debris illuminated by sunlight. The maximum distance from debris at time of detection is 900 km for large debris (analyzed in the next chapter) and 500 km for cm-scale debris.
- **Acquisition**. The telescope is steered onto the target and the tracking is stabilized. With the telescope boresighted on the target debris, the laser begins to fire low-energy pulses.
- **High-Power Mode**. The laser ramps up the energy per pulse, reduces its spot size on the target, and optimizes the pointing of the telescope until a flash of plasma is generated on the target, indicating successful ablation. The laser pulses hold steady near this energy level.
- **Assessment**. With every high-energy pulse, the debris can be localized to within a few millimeters along the direction of the beam and a new trajectory for the debris is estimated. The laser ceases firing once the debris is on a reentry course or if the trajectory of the debris changes counterproductively.

- **Cool Off.** The laser must cool off for 1 to 2 minutes before reentering high-power mode.

Summary of Efficacy and Cost

The 2014 version of the L'ADROIT concept is estimated to cost about $600M in 2020 dollars and to remediate 100,000 pieces of debris, while simultaneously nudging or de-orbiting large debris. Phipps states that such a system yields a cost of $300 per debris removed by amortizing the cost over the portion of the laser system's time spent removing small debris. We found this overall cost of the spacecraft potentially reasonable, though we had some concerns about the assumed efficiency of the system at remediating debris. Specifically, Phipps seems to have assumed that all debris is made of aluminum, which produces a very efficient coupling with the laser but is not generally the case. We instead made a pessimistic assumption that all debris is made of materials to which a laser couples most inefficiently, such as Kevlar epoxy, graphite epoxy, and carbon phenolic. This updated assumption yields a cost of about $3,000 per object removed. See Appendix B for more details.

Remove: Sweeper in Orbit

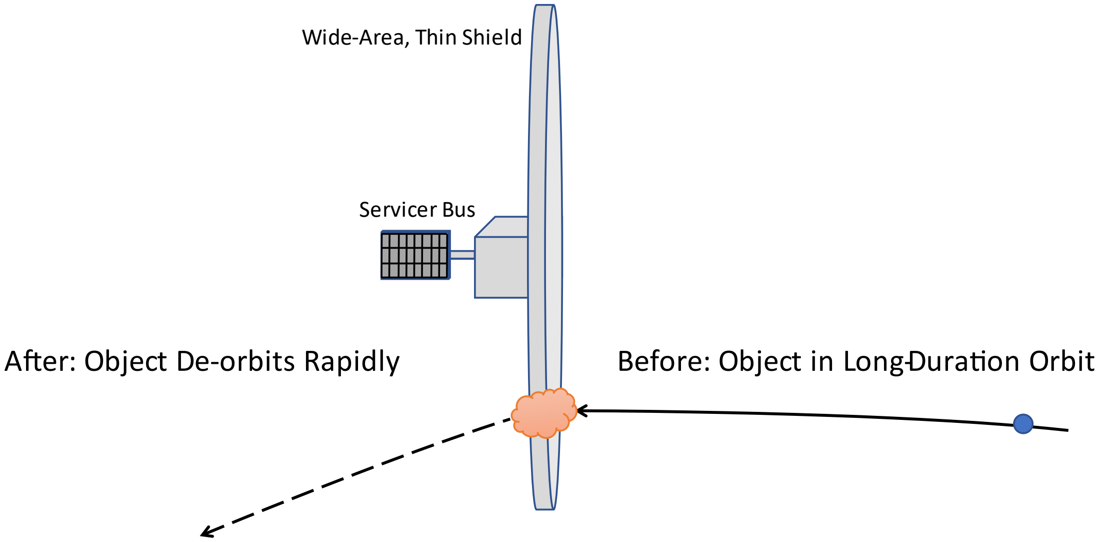

Figure 11. Sweeper concepts generally use a large pad of material to collide with small debris, thereby reducing the velocity of the debris such that it deorbits rapidly.

The goal of large shields, also called sweepers, in orbit is to reduce the populations of non-trackable debris through direct contact, by capturing, retarding, or breaking up the debris. Absorbent structures vary in size, mass, and shape with designs including pads, tethered plates, spheres, and ring trusses. Possible materials for sweepers include aerogels, foams, clothes, and fabrics (especially Beta Cloth, Kevlar, Nextel), often arranged in multilayered, and sometimes stuffed, Whipple shield configurations. The sweeper may capture the debris directly within the material structure, sufficiently slow down the debris as it passes through the material structure expediting orbital decay and reentry, or further break up or shatter the debris as it passes through the material structure (Figure 11). Sweeper concepts have been analyzed by many authors over the last 30 years (Petro and Talent 1989, Werner 2010-ATK, Pulliam 2011, Kaplan 2017, Takeichi and Tachibana 2021, and Foster 2022).

Sweepers can be passive or active, depending on their ability to maneuver out of the path of tracked large debris and into the path of tracked medium and small debris. Tracking, characterizing, calculating an intercept trajectory, and executing an appropriate maneuver could be extremely time-constrained (on the order of less than two minutes) for an object at a range of 1,000 km (Pulliam 2011). Alternatively, more time (and less ΔV) could be afforded by a CONOPS that detects and maneuvers to debris over several consecutive revolutions.

Concept of Operations

We analyzed a CONOPS similar to the approach proposed by Kaplan (2017), because its features appear more attractive than historical shield concepts. In this CONOPS, one or more sweepers are placed in equatorial orbits of 600 km to 1,200 km, where they can maneuver to regions where clusters of non-trackable debris cross the equatorial plane. The sweepers can also maneuver or otherwise reorient to dodge trackable debris through strategic reorientation. The sweepers may include sensing capabilities on the absorbent pads to better characterize and follow clusters of non-trackable debris.

Summary of Efficacy and Cost

Although we struggled to estimate the cost and efficacy of this concept, we roughly estimated a lower bound cost by ignoring the cost of the space hardware and amortizing the launch cost over the number of debris remediated. Optimistically assuming that SpaceX Starship could deliver a 100,000 kg sweeper to the operational orbit for $500 per kg, we assumed the entire mass was used to create the shield. We then estimated how many pieces of non-trackable debris the shield would encounter in its lifetime, assumed to be 5 years. Amortizing the launch costs over only 1-10cm debris leads to minimum costs in the range of $90,000 to $900,000 per piece of debris for an actively maneuverable sweeper and a passive sweeper, respectively. If instead we assumed that this shield was sized to only remove debris smaller than 1 cm, the minimum cost per piece removed drops to $70 and $700 for active and passive sweepers, respectively. However, due to a limitation in our methodology where we did not account for mm-sized debris, we were unable to incorporate the mm-sized cost estimates in the cost-benefit analysis, which is likely the optimal size regime for this concept. See Appendix B for more details.

Remediation of Large Debris

In this chapter, we outline the remediation approaches considered for trackable debris. Given time constraints on the study, we provided reasonably holistic coverage of remediation options but did not include every potential remediation approach in our analysis. For each approach, we briefly describe its CONOPS, discuss its potential efficacy, and, most importantly, provide a rough estimate of its cost.

Remove: Tug to Controlled Reentry

One direct remediation approach is to send a spacecraft to rendezvous with an object, capture it, and then de-orbit it onto a controlled reentry trajectory designed to limit risk to people or property on the surface. Since a debris object may be tumbling, the removal spacecraft would approach the debris object after rendezvous and perform some combination of actions to capture the target object and bring it under control. Many technological options have been considered for these steps, including robotic arms, nets, and magnetic effectors, along with remote options for imparting momentum such as ablating an object's surface with a laser or impinging thrusters on it. After the removal spacecraft has the target object under control, it would conduct a sequence of maneuvers to de-orbit the debris object and direct its reentry to a sparsely populated region of ocean.

After the debris has been captured, a controlled reentry typically occurs in four stages, as described by Bacon (2017). **Step 1**: A target reentry zone is chosen, generally about 6,000 km long, and a very low ΔV burn initiates the descent toward the target. **Step 2**: A phasing burn of about 0.5 m/s, which may take up to 24 weeks to perform, occurs to lock in the ground tracks that the debris will follow during its final days. For quicker de-orbits, the phasing can occur within 6 weeks but requires 2 m/s of ΔV. **Step 3**: During the final days, incremental adjustments to the orbit adjust the perigee so that the object will be in the right position, just uprange of the target zone, on the day of reentry. **Step 4**: The orbit is induced to be Earth-intercepting such that, as the reentering object begins to break up, debris that the object sheds falls into the most uprange portion of the target zone. For low ΔV propulsion capabilities, this step is where the largest dispersions in the reentry zones accumulate, moving either up- or downrange of the target zone.

In general, electric propulsion appears to be an unsuitable technology for performing the final maneuvers necessary for controlled reentry. The force generated by the thruster is so small that it is dominated by the force of atmospheric drag several days prior to the final orbit of the debris (Bacon 2017). That said, a high-power satellite that uses electric propulsion may have large solar panels, and thus a large amount of controllable surface area, that could be used to manipulate the drag forces; in this case, a satellite with electric propulsion may be able to perform a controlled de-orbit, so long as the drag configurations of the satellite are stable (Bacon 2017).

However, for the purposes of this analysis, we assume that bolt-on modules using electric propulsion are insufficient for this use case.

Major contributors to the cost of debris removal through controlled reentry include the need for a high-thrust burn and the difficulty of reusing the removal spacecraft. A few options could reduce the cost. One option is to separate the functionality for rendezvousing, capturing, and detumbling the target from the de-orbit propulsion system. This option allows the reuse of some systems for remediating multiple debris objects even though each removal expends a de-orbit propulsion module. Another option is to use solar electric propulsion to perform some of the orbit lowering. This option lowers cost by reducing the size of the chemical de-orbit system.

Concept of Operations

In surveying the literature, we found the lowest cost estimate for performing controlled reentries in a recent paper by Orbit Fab (O'Leary et al. 2022). This paper provides performance and cost estimates for a chemical-electric propulsion hybrid system and a purely chemical system, both using in-space refueling. Due to the level of detail provided and the extremely low cost, we based our estimates on the high-level architectures they designed. The CONOPS for the architecture is as follows:

- **Transfer to Debris**. The remediation satellite leaves its refueling station and travels to a nearby piece of debris to remove.
- **Capture**. The remediation satellite captures the debris. The method must be reversible so that the removal satellite can eventually release the debris.
- **De-orbit Burn**. The remediation satellite uses chemical propulsion to set the perigee of the debris-and-satellite system to 0 km altitude. Because the remediation satellite is refuellable, it does not need to conserve its propellant usage. As such, steps 2 to 4 of the previously described reentry process can be accomplished quickly, possibly in a single high-thrust burn that de-orbits the debris within a single orbit.
- **Release Debris**. When the remediation satellite and the debris have descended far enough into the atmosphere that their point of reentry is assured, the remediation satellite can release the debris to continue on that trajectory.
- **Re-boost to Refueling Station**. After releasing the debris, the remediation satellite burns to raise its orbit and return to space. It then travels to a refueling station and prepares for another remediation. In general, multiple refueling stations may be positioned within clusters of debris. The choice of location for refueling stations would enable reach to many different debris targets for similar ΔV. The cycle repeats.

Summary of Efficacy and Cost

For our analysis, we base a range of costs for controlled-entry remediation on the studies of removing the largest objects. Our high-cost estimate is $60,000 per kilogram removed, taken from an estimate by Aerospace Corporation (Tibor et al. 2022). Our low-cost estimate is $4,000 per kilogram removed, corresponding to the most optimistic estimate from Orbit Fab's report (O'Leary et al. 2022). See Appendix C for more details on cost and performance.

Remove: Tug to Uncontrolled Reentry

While atmospheric entry of the largest debris objects must be controlled to limit risk to those on the surface, the challenges associated with controlled reentries lead to high costs per removal. For smaller debris objects that pose less entry risk, an alternative is to just lower an object from its original orbit to one in which the object will reenter due to drag within a desired timescale (5 years, for example). The reentry would be uncontrolled—the debris would reenter at a location determined by its orbit and the uncertain timing of its eventual reentry. Relocating an object into an orbit in which it will eventually reenter uncontrolled is typically easier than immediately reentering using a trajectory targeted at an area of ocean.

The early stages of an uncontrolled reentry mission are similar to a controlled mission: the removal spacecraft must rendezvous with the target object and conduct proximity operations to bring the object under control. While controlled reentry requires a high-impulse trajectory change, uncontrolled reentry can use a high-efficiency, low-thrust spacecraft to relocate an object into a disposal orbit that ensures reentry within several years. Employing uncontrolled reentries also eases reuse of vehicles, since a low-thrust solar electric vehicle can climb back to another piece of debris after releasing an object in a disposal orbit. Additionally, reaching orbits for uncontrolled disposal requires less propulsive capacity, since orbits at altitudes of 300 to 400 km are sufficient for uncontrolled reentry while controlled entries require lowering perigee to about 50 km. Depending on the altitude of the debris, propulsive thrust might not be necessary at all to achieve a de-orbit. Specifically, disposable devices such as drag sails, passive tethers, and electrodynamic tethers can attach to the debris to increase drag on the object, causing it to de-orbit rapidly. Likewise, since only gentle forces are necessary to perform a removal by uncontrolled reentry, direct connection between the removal spacecraft and the debris object might not be necessary even during the orbit transfer—remote manipulation via impinging thrusters, laser ablation, or the like may be sufficient. For all of these reasons, allowing debris to reenter uncontrolled is an attractive option.

Concept of Operations

To create a low-cost estimate for tugging debris to uncontrolled reentry, we adapted our low-cost estimate for controlled reentry. Thus, the CONOPS for the uncontrolled reentry is the same as for controlled reentry, except the remediation servicer places the debris into an orbit with perigee of 350 km, rather than 0 km. We chose 350 km so the debris would remain positively controlled until it was below any current or future crewed space stations.

An objection to using a fully chemical system for this mission may be that, without the need for a controlled reentry, electric propulsion would be the most efficient method. On the one hand, this would improve the fuel efficiency of the servicer. However, the Orbit Fab analysis suggests that electric propulsion systems can de-orbit far fewer pieces of debris than an all-chemical system before the servicer's avionics reaches its end of life. We did not have time to explore this tradeoff, but Table 33 indicates that an all-chemical system could remove 80 pieces of debris per servicer, with an average mass of about 1,688 kg, compared to only about 8 pieces of debris for the servicer that relied on electric propulsion for most of the in-space transportation. For the purposes of this analysis, we assume the increased number of debris removed that is associated with a chemical-only propulsion system outweighs the potential fuel efficiencies of an electric propulsion system that removes a smaller number of debris.

We did not have time to assess the potential for small, disposable propulsion modules that might be able to permanently attach to a piece of debris and de-orbit it over a long period time. Single-use spacecraft or disposable modules deployed from a mothership may provide the lowest cost option for uncontrolled reentry. As the cost of space hardware and the cost of launch come down, the value proposition for reusability may be weakened.

Summary of Efficacy and Cost

We estimated that a high-end cost estimate is reasonably around $40,000 per kilogram for any piece of debris in LEO above 100 kg. We based this estimate on two independent architectures. We derived one architecture from publicly available statements about the cost and performance of the Astroscale ELSA-m mission for remediating multiple 800 kg objects. The other architecture is a solar electric spacecraft that removes multiple 1,500 kg pieces of debris (Duchek et al. 2015). We do not claim these estimates are the specific costs of these architectures, but they are reasonable high-end estimates for their costs. We did not attempt a low-end estimate for these two architectures. Our low-end estimate of $3,000 per kilogram removed is based on the CONOPS described in the previous section. See Appendix C for more details.

Move: Lasers for JCA and Large Debris Traffic Management

Just-in-time collision avoidance (JCA) is a method to prevent predicted collisions between large pieces of orbital debris, such as old satellites or spent rocket stages, and active satellites or other debris. To prevent these impending collisions, JCA methods slightly alter the orbit of a satellite or debris object so that it will miss the other object by a safe margin. However, it may not be necessary to wait until a collision is predicted. Large Debris Traffic Management (LDTM) is a related concept where the orbits of an entire population of debris objects are proactively tended, by nudging them with lasers, to reduce the likelihood of potential conjunctions.

Bonnal et al. (2020) provide an excellent review of the major JCA and LDTM approaches, which involve attaching small nanotugs to large pieces of debris, lasers for remotely nudging debris, and rapid-response launches of small rockets. We note that NASA funded research ground-based lasers using photon pressure for JCA and LDTM until about 2016 (Stupl et al. 2014 and Yang Yang et al. 2016) through the LightForce project, while researchers in Europe continue to pursue the concept (Scharring et al. 2021).

For expediency, we chose to analyze concepts that use ground- and space-based lasers because they simplify the cost calculations (Figure 12*)*. There is a tradeoff between lasers and nanotugs; while a laser can be directed at debris from hundreds of kilometers away or more, a nanotug must be delivered to each piece of debris to be placed under active control. A nanotug therefore requires some kind of capture mechanism and the ability to RPO and dock with each spacecraft. This technique may become difficult to scale to any debris except the largest masses. On the other hand, if the tugs have a sufficiently long lifetime, such as 30 years, they could become a lower cost option than lasers; a laser system incurs a cost every time it is pulsed, and 30 years of laser pulses on a single piece of large debris could add up.

Concept of Operations

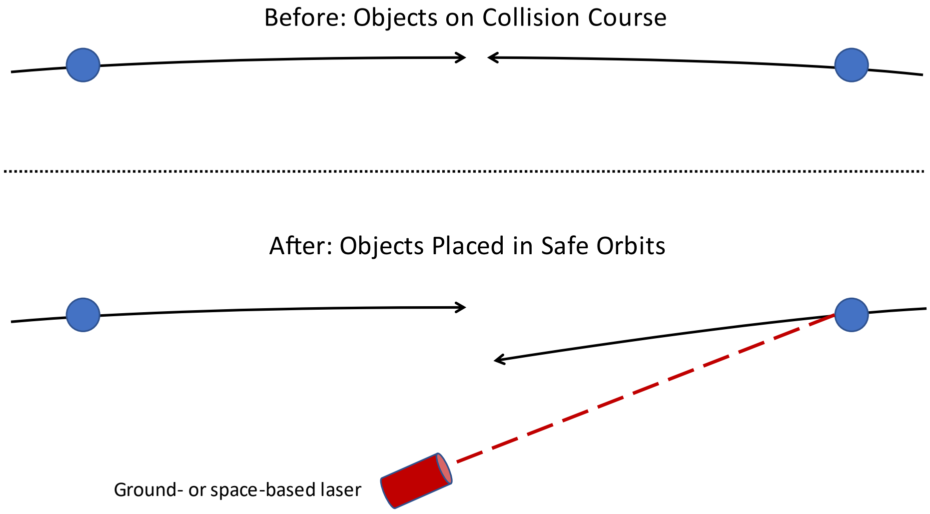

Figure 12. For JCA, a laser nudges the debris when a collision is predicted with high confidence. LDTM is more proactive and makes very small nudges that prevent conjunctions from occurring in the first place.

The physics of the interaction between the debris and the laser is essentially the same as the previously discussed approaches for removing small debris (Figure 9 and Figure 10). The difference is that the impulse delivered by the laser is not sufficient to impart a large ΔV on large debris. However, the ΔV can still be enough to meaningfully change the trajectory of the debris, especially if applied 24 hours in advance. The CONOPS is the same whether using a ground- or space-based laser:

- **Identification of Potential Targets**. While the debris removals we discussed previously were opportunistic, debris nudging targets specific debris objects to reduce the probability of collision with other objects. There are two broad ways to identify targets for nudging. The targets could be involved in a predicted conjunction, most likely a debris-on-debris conjunction where neither object can maneuver to avoid a collision. Alternatively, a prioritized subset of debris may have its orbits actively tended so that risky conjunctions rarely occur. In other words, a subset of debris becomes like a satellite constellation under active control.
- **Orbital Determination of Targets.** The accuracy of the orbits used to generate the conjunction warning may be insufficient for use with JCA; however, the lasers that provide the nudging can also measure the orbit of the debris to extreme precision, allowing the predicted miss distance at the time of closest approach to be calculated with uncertainties in the 1s to low 10s of meters (Scharring 2021).
- **Reassess the Risk.** With most of the uncertainty removed from the orbits of the target objects, the risks of the conjunction can be recalculated. Discussions with satellite operators robustly indicated that most collision avoidance maneuvers they performed would likely not have been needed if the accuracy of the TLEs used to calculate the conjunctions had been better. Thus, only a small percentage of targets initially identified are likely to remain high risk and warrant further engagement with the laser.
- **Nudge Debris**. For those targets that do remain a risk, the laser system engages. The CONOPS for using a space-based laser to nudge large debris is essentially the same CONOPS previously described for removing small debris. Refer to those discussions for more detail.

Whether using photon pressure or ablation, the CONOPS for a ground-based laser to nudge large debris is like the CONOPS previously described for removing small debris. However, there are a few substantial differences in the case where photon pressure is used. Specifically, a single laser facility might not provide a robust capability for nudging debris due to low ΔV applied per engagement and a need for many engagements to avoid a collision. Thus, a network of geographically dispersed laser facilities may be required. In addition to nudging the debris, such a network of laser facilities could maintain custody of the debris to an accuracy of single-digit meters in the along-track direction of the orbit.

Employing such a network changes the CONOPS in two ways. First, we no longer need radar to detect or acquire the debris; passive optical methods of detection are sufficient. After an initial optical detection of the debris, its TLEs can be maintained such that the debris can be ranged or nudged any time it passes overhead. Second, the network of lasers may engage targets that are not being nudged, as part of other SSA services. For example, when presented with a potential conjunction, the laser network may measure both objects to nearly eliminate the uncertainty in their time and distance at close approach. A satellite operator or SSA provider might pay the debris remediator to perform this non-remediation service.

Summary of Efficacy and Cost

We estimated the cost and efficacy of a space-based laser for performing JCA and LDTM based on the performance of the L'ADROIT system discussed previously. A summary of our estimates is shown in Table 4. Our low-cost estimates assume an optimistic efficiency for the ability of the beam's energy to couple with debris materials, while our high-cost estimate uses a pessimistic efficiency. A typical collision avoidance maneuver performed by an active satellite to avoid a piece of trackable debris is about 1 cm/s. Our low-cost estimate assumes that the laser produces this much ΔV on debris objects of varying mass. Our high-cost estimate assumes that 10 cm/s of ΔV is necessary to nudge the debris object safely away from a conjunction. See Appendix C for more details.

Table 4. Costs associated with using L'ADROIT for JCA and LDTM.

Element	100 kg Object	1,000 kg Object	9,000 kg Object
Low Cost Per Maneuver ($) [b]	$6	$60	$500
High Cost Per Maneuver ($) [c]	$700	$7,000	$60,000

a. Calculated in Table 36 and written in bold font.

b. Best case cost scenario is associated with 100 uN/W coupling coefficient and 1 cm/s per maneuver to avoid a potential collision. Cost is rounded to one significant figure.

c. Worst case cost scenario is associated with 10 uN/W coupling coefficient and 10 cm/s per maneuver to avoid a potential collision. Cost is rounded to one significant figure.

Move: Rapid Response Rockets for JCA

Another remediation approach with JCA uses a rapid-response launch vehicle to send a separate spacecraft, equipped with its own propulsion system, to rendezvous with an object and then alter the object's orbit to avoid a collision. This concept has been developed by ESA's Space Debris Office and funded by CNES, with the support and co-funding of CT France. Their concept, SpaceBlower, is shown in Figure 13. In this concept, an air-launched rocket intercepts the debris and then ejects a cloud of particles into the debris object's orbit sufficient to impart a ΔV of 10 cm/s (CNES 2020). If launched 12 hours in advance, a collision could be avoided.

All methods of JCA require precise tracking and prediction of the orbits of both objects that may be involved in the conjunction. Currently, this information is provided by ground-based tracking systems and used to calculate the necessary orbit adjustments in real time. However, such methods are inappropriate for use with a JCA approach that uses a rocket. For every 1 actual collision that occurs, approximately 10,000 CDMs may indicate that a collision is likely enough to justify a maneuver. Therefore, if currently available SSA capabilities are used to trigger the rocket JCA, over 10,000 rockets will launch to stop 1 collision, which is clearly not a tenable approach.

Figure 13. The SpaceBlower concept developed by CNES. Image Credit: CNES (2020)

However, we have already analyzed laser systems that might provide the necessary level of precision for orbital determination. We did not make an accounting of the costs for a laser ranging station designed primarily for the purpose of supporting a rocket JCA approach. Instead, we assumed that a system capable of nudging debris is more than capable of providing laser ranging services to a JCA provider. Thus, we combine the rocket JCA approach with the SSA capabilities of the previously discussed laser JCA system for this analysis.

Concept of Operations

We analyzed a scenario that is slightly different from the SpaceBlower concept. Specifically, we rely on an analysis performed by Aerospace Corporation, which uses a ground-based rocket system installed at six locations around the globe (Tibor et al. 2022). The CONOPS proceeds as follows:

- **Maneuver CDM Received.** The JCA provider receives a CDM, based on traditional SSA capabilities, indicating that a close approach between two debris objects is predicted. The CDM predicts a close approach of 1 km or less, which is the threshold used in the NEAT tool to trigger an active satellite to execute a maneuver.
- **Conjunction is Interrogated with Advanced Techniques.** The objects involved in the predicted conjunction are engaged by a low-power laser to accurately determine their orbits. Having reduced the uncertainty in the conjunction to the point where the probability of collision is accurately known, most conjunctions will be deemed to no longer pose an appreciable collision risk and the CONOPS stops here. In the unlikely event that the collision seems high probability, proceed to the next step.
- **Ready the Rocket.** This step involves calculating the trajectory of the rocket and optimizing the details of its engagement with the debris. The rocket and its payload must necessarily be kept in a state of readiness that enables the rocket to launch on short notice with only minor adjustments pre-launch. All such pre-launch preparations are handled in this step, such as uploading the flight solution to the system and integrating the rocket into the ground- or air-launch infrastructure.
- **Launch the Rocket.** If launched from the ground, this step is achieved quickly. An air-launch may take somewhat longer for the aircraft to take off and fly to its launch location.
- **Engage the Debris.** The rocket travels along its desired trajectory, eventually placing it in a position to eject dust that will intersect with the trajectory of the debris to be nudged.

Summary of Efficacy and Cost

We report on the estimates made by Tibor et al. (2022), who provided a range of values that varied based on the frequency with which the rocket JCA system is launched to create nudges. Based on empirical evidence that large debris-on-debris collisions are rare, we take the cost estimates associated with the most infrequent use of this capability—six nudges per year. In this case, the low-cost estimate is $30 million per nudge and the high-cost estimate is $60 million per nudge. Note that these estimates do not include NRE for developing the responsive launch capabilities. We use the low-cost estimate for nudging a piece of 100 kg debris as a proxy for the cost for interrogating the conjunctions to see if they are sufficiently likely to cause a collision. See Appendix C for more details.

Recycle: Debris Into ΔV

A debris remediation satellite could visit debris, transform a portion of the debris into propellant or reaction mass to increase the ΔV capacity of the remediation satellite, and then de-orbit the remainder of the debris using the harvested ΔV. One concept for this approach is the TAMU

Slingshot. Cislunar industries has also spoken publicly about this concept (Calnan 2022). This concept relies on a metal plasma thruster. In theory, this approach could also scale to small pieces of debris if the material properties of the debris were known before attempting to rendezvous with them. For example, a paint chip would not be useful as propellant for an MPT, but a metal screw might. For this analysis, we investigate the application of this concept only to larger debris objects that can be partially processed into propellant for an MPT.

During an uncontrolled reentry, large objects that may reach the ground partially intact pose a risk to people and property. It may be possible to reduce or eliminate this risk by cutting up an object in the disposal orbit prior to release. Each of the pieces will reenter quickly, and they may pose a lower risk to those on the ground than a single large object. Breaking debris into smaller pieces can also speed reentry, since the ratio of atmospheric drag to mass is larger for smaller pieces. This requires further study but could be valuable on its own for easing reuse of removal vehicles or as part of a reuse or recycling chain.

Concept of Operations

The remediation satellite would need the following capabilities: a capture mechanism that is reversible and reusable, a metal plasma thruster, a method for extracting aluminum from the captured debris, the ability to form the extracted aluminum into one or more fuel rods, and the ability to transfer the rods into the metal plasma thruster for use as propellant. The remediation satellite would be launched with enough propellant to perform its first remediation mission. After launch, we imagine the optimal CONOPS proceeds as follows:

- Remediation satellite captures the debris and uses its onboard fuel to tug the debris down to the disposal altitude.
- The satellite processes a small portion of the debris into propellant and—if possible—purposefully fragments the debris to ensure that it completely burns up during reentry.
- Using the newly created propellant, the satellite travels to another piece of debris to repeat the cycle.

We assume that the best place for processing the debris object into propellant would be in the disposal orbit, a circularized orbit below the altitude of any human-tended spacecraft, where any small pieces of debris created during processing would rapidly decay into the atmosphere.

Summary of Efficacy and Cost

Although a few companies are pursuing this idea, we were unable to find any detailed analyses of this concept upon which we could base our cost and performance estimates. Thus, we adapted the same tug architecture from our two previous options for removing large debris. In this adapted architecture, we assume a fully electric propulsion system and omit the in-space refueling depot, because each piece of debris to de-orbit provides the necessary material for refueling.

Of all the approaches explored in this analysis, this one is the most complicated and least mature. To account for the nascency of most of the subsystems and capabilities mentioned in the CONOPS, we assume an NRE of $2 billion dollars. We have no firm basis for this amount of NRE, which is meant to reflect the perceived difficulty of maturing these various capabilities.

With these assumptions, the remediation satellite can remove large debris for approximately $10,000 per kilogram. Advocates for this technology note that the remediation satellite could produce excess fuel rods from the debris to sell for revenue to other users of MPTs. Incorporating operators' estimates for this potential revenue offsets the NRE costs we assumed and leads to a low cost of $4,000 per kilogram of debris removed. See Appendix C for more details.

Comparison of Costs and Benefits

In this chapter, we bring together all the previously discussed elements to estimate the costs and benefits of various debris remediation approaches. First, we estimated the value associated with each of the perturbations to the debris environment. These perturbations were created and discussed in the methodology section. As a reminder, compared to the baseline level of expected costs associated with debris, a reduction in existing costs or avoidance of new costs caused by a perturbation are considered the "benefits" in the cost-benefit analysis. Next, we estimated the cost of causing the debris perturbations, using the relevant remediation approaches. Finally, we rank the ratio of costs and benefits to illustrate the most promising remediation capabilities.

Value of Debris Perturbations

Table 5. Summary of the Operator Costs Used to Calculate the Value of the Baseline and Perturbations

	Cost Per Warning	Cost Per Maneuver			Cost Per Collision	
Operator Class		Propellant	Labor	Lost Ops	Lost Vehicle	Lost Ops
Civil Operational	$154	-	$769	-	$820,000,000	-
Civil Science Long	$77	-	$769	$533	$270,000,000	$140,000,000
Civil Science Short	-	-	-	-	-	$21,000,000
Commercial Bespoke	$3	-	$462	$234	$500,000,000	$615,000,000
Commercial Large Constellation	-	-	-	-	$1,000,000	-
Commercial Medium Constellation	-	-	-	-	$20,000,000	-
Commercial Small Constellation	-	-	-	-	$3,000,000	-
CubeSat / SmallSat	-	-	-	-	$300,000	-
Human Spaceflight	$200	$1,000,000	$8,000	-	$200,000,000	$300,000,000
Military	$154	-	$769	-	$820,000,000	-
Technology Development	-	-	-	-	-	-

In this section we calculate the value of each perturbation. The operator costs used for the calculations were discussed previously and are summarized here in Table 5. When interpreting the value of the perturbations, some general reminders about operator costs may be useful:

- The cost per warning for an operator is quite low, though warnings happen often.
- Only human spaceflight operators are assumed to have a propellant cost to maneuver.
- There are almost no lost operational costs associated with the maneuvers.
- The large costs are in the collisions, though collisions are very rare.

Baseline (No Perturbation)

To calculate the potential costs reduced or avoided, we first generate a baseline estimate. Table 6 summarizes the costs imposed on each category of satellite operator over a one-year period. The costs are broken out by those due to trackable debris and those due to 1-10cm debris. Nearly all the baseline costs over this time period are due to small debris.

Table 6. Summary of Baseline Costs Imposed by Orbital Debris Over One-Year Period.

Operator Category	Total Cost [$]	Contribution Due To 1-10cm Debris
Civil Operational [GEO]	1,933	96%
Civil Operational [LEO]	12,090,591	96%
Civil Science Long	3,465,646	93%
Civil Science Short	575,561	100%
Commercial Bespoke	4,249,440	99%
Commercial GEO	1,236	0%
Commercial Large Constellation	880,759	100%
Commercial Medium Constellation	1,439,194	100%
Commercial Small Constellation	102,288	100%
CubeSat / SmallSat	107,083	100%
Human Spaceflight	4,100,336	3%
Military [GEO]	12,181	96%
Military [LEO]	31,209,590	96%
TechDev	-	0%
Total	58,235,839	90%

Remember that this estimate uses the assumption that the level of debris in space is constant from year to year. For example, if a piece of small debris strikes and kills a satellite in year 1, that dead satellite does not become a piece of debris that in turn increases the probability of collision at that altitude. We consider this a reasonable assumption because these values are calculated over the period of a single year and collisions that generate substantial new debris are quite rare. Note that we account for potential increases in orbital debris, and the negative effects to active satellites, within the debris perturbations. Likewise, the baseline does not incorporate general increases in debris due to debris-on-debris collisions over the baseline period because, as discussed in the methodology, the baseline scenario estimates only the risks to satellite operators that might be affected by one of the remediation scenarios.

The omission of debris-generating events from the baseline has no effect on the calculated benefits of debris remediation. Any satellite-on-debris or debris-on-debris interaction that might have occurred in the baseline *and* the perturbation will be canceled out when taking the difference between their respective values. For example, imagine that Debris A hits Satellite B in the baseline and goes on to create debris that hazards other satellites. Unless a perturbation scenario is to remove Debris A from orbit, the A-on-B collision and all its related debris will be present in all perturbation scenarios as well. When the value of the perturbation is subtracted from the value of the baseline, the costs associated with the A-on-B collision are present in both and therefore cancel out. We attended to this point closely in the coming discussions of the calculated benefits.

Finally, we note that while the costs are predominantly due to small debris, on longer time scales, large debris generates small debris. In this manner, some of the costs attributed to small debris are actually due to previously fragmented large debris. Attribution of costs to large and small debris become clearer in the perturbation scenarios, where removal of a piece of large debris and its potential for generating small debris can be quantified.

Removing The Top 50 Large Debris

To calculate the benefits associated with removal of the McKnight Top 50, we started by considering all possibilities within the baseline and perturbation scenarios (Table 7). We noted that removing the Top 50 does not change the value of satellites interacting with debris that are not in the Top 50 nor the value of debris-on-debris collisions that do not involve the Top 50. In other words, the removal scenario does not provide benefits in these cases. Thus, we needed to estimate only the benefits associated with avoided Satellites Interactions with the Top 50 and avoided Debris-on-Debris Collisions involving Top50 objects.

We estimated the benefits over a one-year period, as shown in Table 8. During this period, satellite interactions with the Top 50 would have produced a cost of only $10k. However, there is a non-zero chance that debris from the Top 50 would have collided, with themselves or with other pieces of debris, and these potential costs are now avoided. We estimated the benefits of avoiding three representative collisions and the probabilities associated with those collisions. We found that the benefit associated with avoiding some of these collisions could be over $180M; however, the probability associated with that collision is very small. We estimated that if a collision happens, it will cause about $111M of damage per year on average. Factoring in the probability of such a collision, the annual risk is about $3.5M.

Table 7. Summary of satellite interactions and debris events that create a benefit when the Top 50 debris are remediated.

Baseline Scenario	Removal Scenario	Delta Creates Benefit
Satellites Interact with Top50	Top50 Removed	Yes
Satellites Interact with non-Top50	Satellites Interact with non-Top50	No
Debris Collisions Involving Top50	Top50 Removed	Yes
Debris Collisions Not Involving Top50	Debris Collisions Not Involving Top50	No

Finally, we used the annual costs and probabilities to estimate the benefits on longer timescales. Figure 14 illustrates that the total benefits, which is mainly risk avoided, rises over a span of 25 years to about $1.1 billion. This estimate assumes that at the beginning of year 1, the Top 50 debris have been remediated. It was generated using Equation (2), in which the timeframe (T) is 1 to 25 years, the annual cost imposed by the perturbation (C_p) is $111M, and the annual probability of the perturbation (P_p) is 3.13 percent. The Figure also overlays the costs associated with achieving these benefits to determine the point at which benefits outweigh costs.

There are two remediation approaches for creating the benefits associated with this perturbation. Most obviously, the debris could be removed from space via controlled reentry. The cost of performing this removal is paid one time upfront, and the benefits accrue over every subsequent year.

Table 8. Estimated Benefits for Removing the McKnight Top 50 Calculated Over a One-Year Period.

Scenario and Perturbation	Value [$M]	Conditional Benefit [$M]	Probability	Expected Benefit [$M]
Satellite Interactions with McKnight				
Value of Perturbations				
Remove Top 50 No Collisions [a]	$58.22	$0.01	100%	$0.01
Total Expected Benefit				**$0.01**
Debris-on-Debris Collisions Avoided [b]				
Value of Perturbations				
No Perturbation [c]	$58	-		
McKnight Low Altitude Collision [e]	$242	$184		
McKnight Crowded Altitude Collision [f]	$182	$124		
McKnight High Altitude Collision [d]	$102	$44		
Conditional Benefit by Altitude [g]				
625 km		$184	1%	$1.95
…		-	0%	-
750 km		$124	3%	$4.10
775 km		$124	6%	$7.47
800 km		$124	7%	$9.29
825 km		$124	60%	$74.65
850 km		$124	5%	$6.19
…		-	0%	-
950 km		$44	7%	$3.26
975 km		$44	8%	$3.66
1000 km		$44	1%	$0.44
…		-	0%	-
1075 km		$44	1%	$0.23
Sum of Conditional Benefits			**100%**	**$111**
Total Expected Benefit		**$111**	**3.13%**	**$3.5**

a. This value is calculated by removing the Top 50 debris and assuming no debris-on-debris collisions occur. Thus, the only difference between this perturbation and the "No Perturbation" case is the value of active satellites interacting with the Top 50. We took the difference between the values of those two perturbations to estimate the benefit of avoiding those interactions.

b. To estimate the value of avoided debris-on-debris collisions involving the Top 50, we posited four perturbations. There is a chance that no collisions would have occurred; this is represented by the "No Perturbation" case. There is a chance that a collision would have occurred, thus perturbing the debris population. We estimated three such collisions between a named piece from the Top 50 and a generic piece of debris with mass of 2,000 kg.

c. There is an 85 percent chance that no collision would have occurred involving the Top 50. In other words, there is a 15 percent chance in 5 years that one of them hits something trackable.

d. This collision is assumed to involve an H-2 R/B, with NORAD ID 24279. Its mass is 2,700 kg and its average altitude is in the 1075 km altitude bin.

e. This collision is assumed to be an SL-16 R/B, with NORAD ID 25861. Its mass is 9,000 kg and its average altitude is in the 625 km altitude bin.

f. This collision is assumed to be an SL-16 R/B, with NORAD ID 22566. Its mass is 9,000 kg and its average altitude is in the 825 km altitude bin.

g. This section calculates the expected value of a debris-on-debris collision involving Top 50 debris, given that the collision occurs. We assigned the values of the three collisions we simulated to relevant altitude bands where Top 50 debris is present. We show only altitude bands where Top 50 debris is present. We calculate an expected value at each altitude by multiplying the value of the collision by the probability of a collision. Finally, the expected values at each altitude are summed to give the total expected value of a debris-on-debris collision, given that one occurs.

h. Rounded to one significant figure.

Alternatively, JCA could be used to ensure that the McKnight debris never collides with other pieces of debris. Accounting for the costs of JCA requires some subtlety. On the one hand, the costs of creating a ground- or space-based laser system for performing JCA must necessarily be paid upfront before it can begin to remediate debris. However, laser JCA services will be used by the Top 50 debris frequently for the coming years; further, many other pieces of debris will be serviced by the laser systems over the same period of time. Thus, we account for the expense of using JCA to remediate the Top 50 by multiplying the required number of annual laser shots by the amortized cost per shot. Thus, the costs of JCA are effectively paid annually from the time the JCA capability comes online and commits to remediating the Top50. From the perspective of the space environment, the removal and the JCA scenarios are effectively indistinguishable. Table 9 provides summary details of the costs to remediate the Top 50 debris.

Table 9. Summary of Costs to Remediate the Top50 Debris

One-Time Cost of Removal	Cost Per Kg [$]	Mass [kg]	Total Cost [$M]
Tug Controlled Reentry [Low]	$4,000	260,880	$1,044
Tug Controlled Reentry [High]	$60,000	260,880	$15,653
Tug Uncontrolled Reentry [Low]	$3,000	260,880	$783
Tug Uncontrolled Reentry [High]	$40,000	260,880	$10,435
Ongoing Cost of JCA	**Cost per Event [$]**	**Annual Events [a]**	**Annual Cost [$M]**
Laser JCA Per Maneuver [Low]	$500	1248	$0.64
Laser JCA Per Maneuver [High]	$60,000	1248	$77
Laser JCA Per Collision [Low] [b]	$500	1	$0.0082
Laser JCA Per Collision [High] [b]	$60,000	1	$0.068
Rocket JCA Per Collision [Low] [b]	$30,000,000	1	$0.95
Rocket JCA Per Collision [High] [b]	$60,000,000	1	$1.91

a. We artificially set the annual number of collisions to 1 for illustrative purposes. If we were to use the more accurate estimate of 0.03182 expected collisions per year, the costs of even Rocket JCA becomes trivial.

b. In the cases where debris is nudged only if a collision is imminent, each potential conjunction must be interrogated to determine its potential for creating a collision. Thus, for calculating the annual cost, we assume that every warning leads to the laser ranging the debris to refine its orbit. We assign this a cost of $6 per interrogation—the same as the low-cost estimate to nudge a 100 kg object. Then, for the conjunctions that are likely to produce a collision, we nudge the debris at the cost per event given in the Table.

For illustrating remediation costs, Table 9 and Figure 14 have annual collisions set to 1, because otherwise the costs of JCA are completely trivial. This illustrates the high cost of performing Rocket JCA. In the low-cost assumption, scrambling a rocket once per year doesn't produce a net benefit until it has been performed for 16 years. Also, the cost of using Rocket JCA likely becomes larger than the low-cost option of Tug Controlled Reentry after about 35 years of use. The window of opportunity for Rocket JCA is small in this case. The value of Laser JCA Per Collision [High] reaches $1.7 million after 25 years, if there is 1 collision annually to avoid.

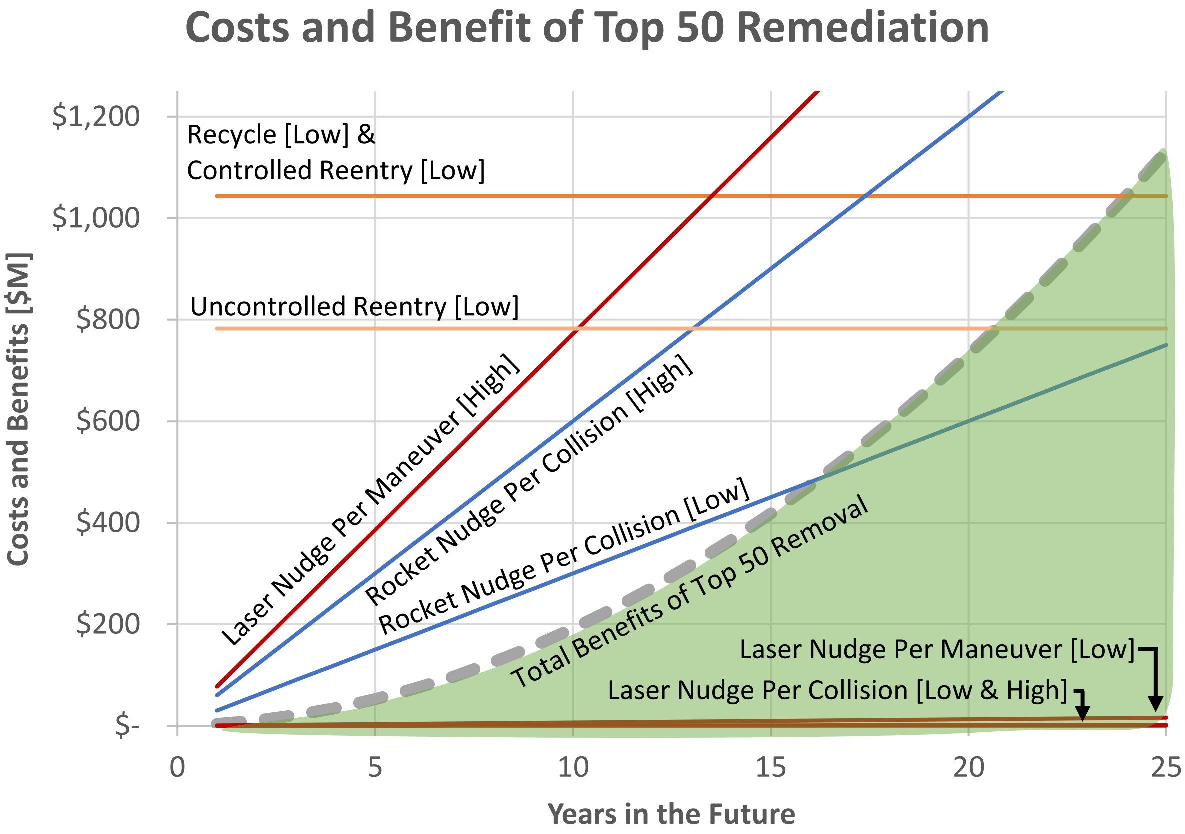

Figure 14. The benefit associated with removing the Top 50 objects identified by McKnight et al. (2021) grows every year after they are remediated, shown by the thick dashed line. The high costs associated with Controlled Reentry, Uncontrolled Reentry, and Recycling are not shown because they are too high to be relevant.

As noted in the Table, the expected number of collisions involving McKnight debris is only 0.03 per year. If the value of collision were reduced from 1 collision annually to 0.03 annually, the costs associated with Rocket JCA would fall to a trivial amount. The extreme unlikelihood that a collision will occur reflects the unlikelihood that the JCA Rocket will ever need to be used. Such uses of a Rocket JCA technique are predicated on high-precision orbital determination of high-risk conjunctions to ensure that false positives are minimized. This precision can likely be provided by a low-power laser ranging system.

For laser systems, both approaches that nudge only in the event of a likely collision are very cost efficient, which also reflects the extreme unlikelihood of a true collision. For systems that nudge a piece of large debris every time it meets the maneuver threshold, the low-cost estimate is still cost efficient, at around $16M over 25 years. The high-cost estimate appears to be undesirable in this case. The benefits never outweigh the costs because the extreme mass of the debris, assumed to be about 9000 kg, requires nearly 100 times more engagements with the laser than a smaller 100kg piece of debris. However, this scenario is unlikely to materialize, because laser systems can do precise orbital determination to reduce the need to maneuver these objects so frequently.

The high-cost estimate for Tug Controlled Reentry is not shown in the Figure. At $60k per kilogram, the total cost to remove the debris would be $15.6 billion. It would take 94 years for that cost to equal its benefits. Even with the lowest cost estimate of $4,000 per kilogram, costs don't equal benefits for at least another 24 years.

Removing 100k Pieces of Small Debris

To calculate the benefits associated with removal of small debris, we started by considering all possibilities within the baseline and perturbation scenarios (Table 10). Small debris can incapacitate a spacecraft, causing a net benefit when that small debris is removed. Collisions involving small debris other than the pieces we removed still occur in the baseline and perturbation scenarios; thus, there is no net benefit associated with those interactions.

Table 10. Summary of satellite interactions and debris events that create a benefit when the 100,000 small debris are remediated.

Baseline Scenario	Removal Scenario	Delta Creates Benefit
Satellites Interact with 100k	100k Removed, No Lost Vehicles	Yes
Satellites Interact with non-100k	Satellites Interact with non-100k	No
Debris Collisions Involving 100k	100k Removed, No Lost Debris	No
Debris Collisions Not Involving 100k	Debris Collisions Not Involving 100k	No

For this analysis, we assumed that a collision involving small (1-10 cm) debris does not create a meaningful amount of new pieces of debris. Thus, we did not need to estimate the value of specific collision events, as we did for the McKnight Top 50. Further, if a piece of small debris strikes and kills an active satellite, we record the cost of the lost spacecraft but do not convert the now-defunct satellite to a piece of debris. In reality, a dead spacecraft would cause an increase in the expected warnings and maneuvers that active spacecraft would experience; however, over short timescales, this effect is marginal and we have ignored it. Because we assumed that pieces of small debris do not meaningfully create new debris upon striking a large, trackable object, there is no net benefit to avoiding large-on-small debris collisions. The annual benefits associated with this perturbation are shown in Table 11.

Table 11. Estimated Benefits for Removing 100,000 Pieces of Small Debris Calculated Over a One-Year Period.

Scenario and Perturbation	Value [$M]	Conditional Benefit [$M]	Probability	Expected Benefit [$M]
Value of Perturbations				
No Perturbation	$58	-		
Remove 100k Small Debris	$35	$23	100%	$23
Total Annual Benefit				$23

On a longer timescale, Figure 15 illustrates that the total benefits, mainly from risk avoided, rises over a span of 10 years to about $1.3 billion. This estimate assumes that at the beginning of year 1, the 100,000 debris have been removed. It was generated using Equation (2), in which the timeframe (T) is 1 to 10 years, the annual cost imposed by the perturbation (Cp) is $23M, and the annual probability of the perturbation (Pp) is 100 percent, because the debris was successfully removed by the beginning of year 1. The Figure also overlays the costs associated with achieving these benefits to determine the point at which benefits outweigh costs.

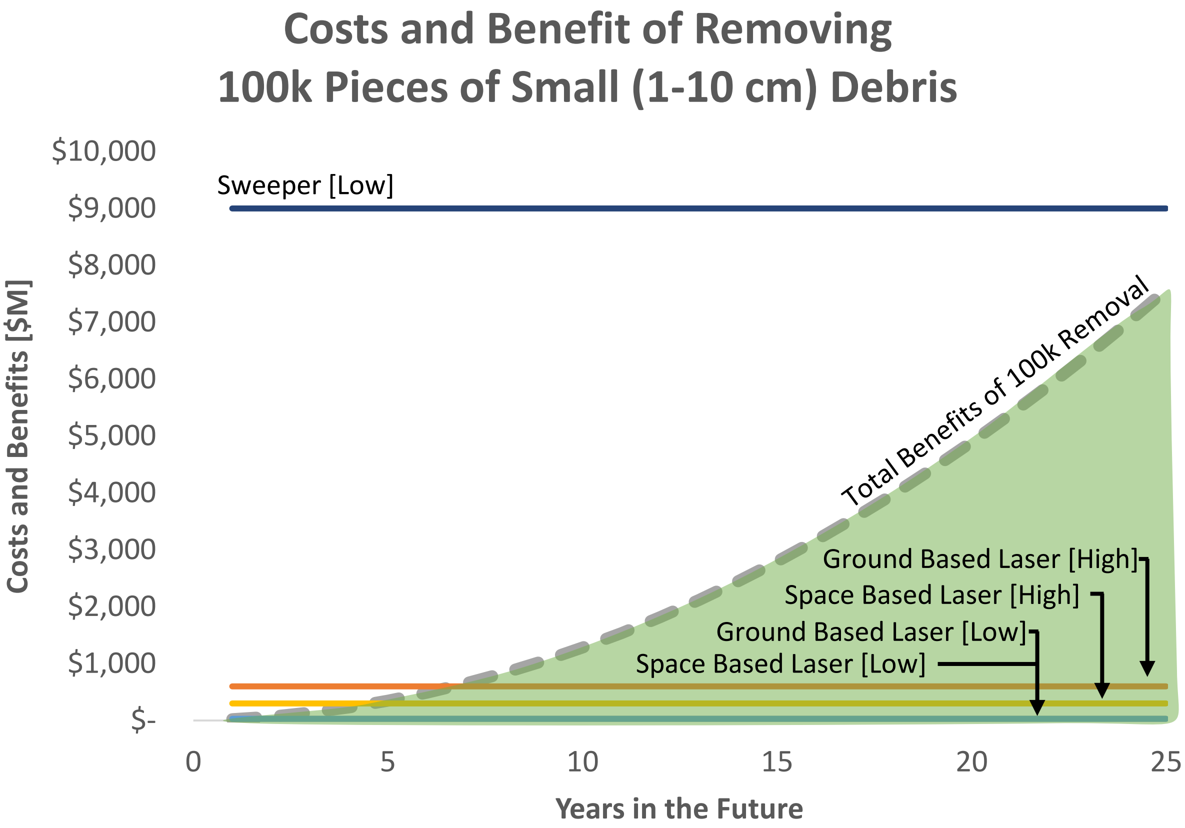

Figure 15. The benefit associated with removing 100,000 pieces of small debris grows every year after they are removed, shown by the thick dashed line. Any remediation method that costs less than this to implement will provide a net benefit in the associated year, shown as the green region below the dashed line. The high cost associated with a Sweeper are not shown because it is too high to be relevant.

For small debris, we caution that the benefits are unlikely to be valid beyond a 10-year timeframe. The orbits of small debris decay more rapidly than those of large debris. Further, the altitudes from which this debris is removed are somewhat lower than the altitudes where collisions involving the Top 50 occur. Thus, over a 10-year timeframe, a substantial portion of the small debris may have de-orbited naturally. This consideration also applies to the Top 50 remediation case, though to a less extent. In general, the shorter the timeframe of interest, the more valid our modeling assumptions are. It is beyond the scope of the current analysis to incorporate the time-varying characteristics of debris populations.

The costs associated with this perturbation are all one-time costs associated with removal and are shown in Table 12. The only approach for removal that is not economically viable, even in the low-cost state, is placing a physical sweeper in orbit. However, due to the limitation in our study of looking only at debris down to 1 cm, we do not incorporate the benefits of removal of 4 mm to 1 cm objects, which also pose a danger to spacecraft. Likewise, because our model of small debris incorporates debris as large as 10 cm, we required that the sweeper be capable of withstanding strikes of debris this large. This requirement adds a large mass penalty to the system and only marginally increases the number of debris to intercept. Thus, due to limitations in our methodology, we have underestimated the benefit and overestimated a portion of the cost, compared to a more rational sweeper design.

On the other hand, our cost estimate accounted only for the launch costs of sending a sweeper of maximal cross-sectional area into orbit; thus, the cost we estimated is an extreme lower bound on the cost of a system for remediating cm-sized debris. Subsequent analysis should incorporate the benefits of removing mm-sized debris and more accurately estimate the cost of the remediation system; we do not have enough information to suggest whether these improvements will increase or decrease the value proposition of the sweeper method.

Table 12. Summary of Costs to Remediate 100,000 Pieces of Small Debris

Method of Removal [Cost Level]	Cost Per Kg [$]	Mass [kg]	Total Cost [$M]
Ground Laser [High]	$6,000	100,000	$600
Ground Laser [Low]	$300	100,000	$30
Space Laser [High]	$3,000	100,000	$300
Space Laser [Low]	$300	100,000	$30
Sweeper [High]	$900,000	100,000	$90,000
Sweeper [Low]	$90,000	100,000	$9,000

The costs associated with laser removal systems are favorable. Low-cost estimates associated with ground- and space-based lasers produce net benefits in under two years. High-cost estimates for these capabilities produce net benefits in five to seven years.

Comparing the Costs and Benefits

The best way to compare the costs and benefits is to calculate the number of years required for the benefits to exceed the costs—that is, to break even. For removal and recycling approaches, we assumed that all costs associated with remediating the debris in the scenarios are paid in year 0. For JCA approaches, the costs are paid annually; thus, the cumulative cost rises over time. Of course, the costs to develop and build the rockets or laser facilities for JCA must be paid prior to year 0; however, once operational in year 0, those same systems will be applied to remediate many more potential collisions than just the ones that involve the McKnight Top 50. Thus, we apportion the share of the costs relevant to the McKnight Top 50 as they are incurred annually. The break-even times, where the cost curves intersect the benefits curves, are shown in Figure 16.

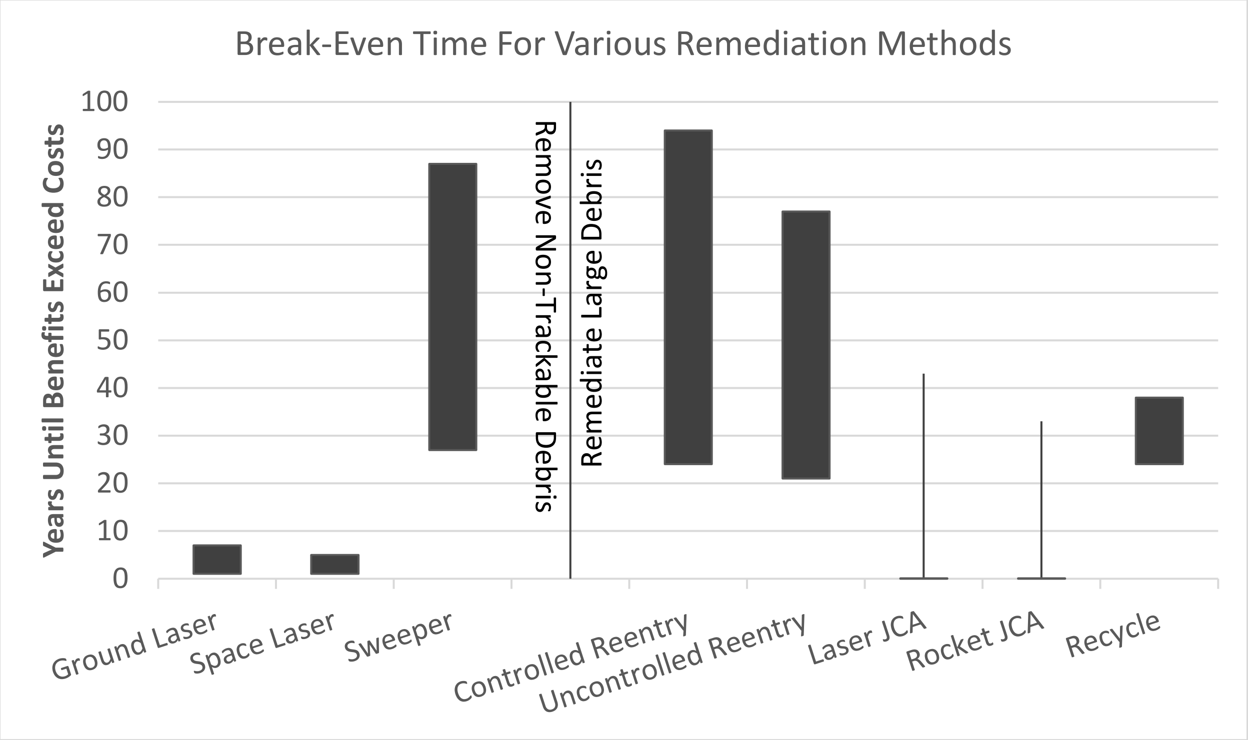

Figure 16. The break-even time for approaches to remove non-trackable debris [left] and remediate large debris [right]. For non-trackable debris, the costs and benefits were calculated for removing 100,000 pieces of debris. For large debris, the costs and benefits were calculated for removing 50 of the largest objects in space. The boxes correspond to the high and low costs associated with optimal use of each remediation approach. For the two JCA approaches, their optimal use causes benefits to exceed costs immediately. However, a more conservative estimate of their usage is represented by the range of the whiskers.

We found that the break-even times are rapid for systems that use lasers, due to two aspects of laser-based systems. First, lasers are the most scalable of any remediation approach we investigated. A single laser, whether ground- or space-based, can affect the orbit of any piece of debris within its field of view for around 10 minutes. All other remediation approaches require close proximity to each piece of debris to remediate. This scalability allows the costs of the laser system to be spread over many more risk-reducing maneuvers than alternative remediation approaches.

Second, lasers provide enhanced SSA capabilities that reduce the need for debris remediation. For example, when a high-threat conjunction with a piece of debris is identified by traditional SSA techniques, a laser can be tasked to remediate the conjunction. The laser system then locks its sights on the piece of debris by determining the orbit of the debris to high precision; however, a high-precision estimate of the orbit may clarify that the conjunction will not result in a collision. In this case, there is no need for the laser system to nudge the debris and the laser can be applied to other ongoing high-threat conjunctions. Given that debris-on-debris collisions are rare—about 0.03 collisions per year involving the McKnight Top 50—a laser system would rarely need to be used to nudge debris, keeping its cost to use low. When a laser system is not nudging debris, it can provide enhanced SSA services.

The break-even times for other systems to remove or recycle debris have wide variation. Their fastest break-even times are over 20 years in the future, which is beyond the applicability of our method for calculating benefits and should therefore be interpreted cautiously. As discussed previously, our methodology may over- or underestimate future benefits; likewise, the true break-even times may be longer or shorter than what we have estimated. Regardless, because we used consistent assumptions to assess the costs and benefits, we can draw some qualitative conclusions. The break-even times may be quite long, especially compared to the worst-case payback times of the JCA systems. However, we see a potential pathway to economic favorability compared to JCA approaches; the lowest cost removal and recycling options we analyzed break even faster than the highest cost JCA systems. Removal and recycling approaches lack the upside potential of JCA approaches but are still competitive.

We were surprised to find that recycling debris into propellant did not yield a substantially cheaper system than remediation systems that use chemical or conventional electric propulsion. On the one hand, turning debris into propellant saves substantial costs by removing the need for in-space refueling assets and launches of propellant. On the other hand, much of the money saved likely goes into the R&D costs needed to mature the capabilities necessary to process debris into raw materials for subsequent use as propellant. Our low-cost estimate for recycling even includes some revenue from selling debris-sourced propellant to other in-space customers. At the level of fidelity of our analysis, there is not a clear advantage to recycling.

Conclusions

This report provided evidence related to a new perspective on debris remediation: that the *near-term* benefits of debris remediation may be significant enough on their own to incentivize immediate action. Such benefits are small for each space operator, but when aggregated across all the operators in the U.S. space enterprise, their sum becomes meaningful. Further, this report provided a holistic view of the landscape for remediation approaches—moving, removing, and reusing debris, both trackable and non-trackable—and assessed representative approaches based on their roughly estimated costs. Prior to this report, most discussions of debris remediation in the United States have focused on the removal of large debris to create long-term benefits. We hope this report provides sufficient evidence to broaden the discussion to include considerations for near-term benefits, moving and reusing large debris, and removal of small debris.

Specifically, this report contributes three new elements to the broader discussion on debris remediation:

- Our estimate of the negative effects that debris imposes on space operators, measured in dollars, is the most rigorous and wide-reaching analysis in the literature. Previous research primarily investigates negative effects to the space environment—an abstract location that cannot suffer harm—via proxies such as total mass or number of debris.
- This study is the first to investigate the landscape of remediation approaches using a framework for comparing the costs and benefits among them on an apples-to-apples basis. Specifically, we posit a perturbation to the debris environment, calculate the benefits associated with the perturbation, and compare the costs of all remediation approaches that can produce the perturbation.
- We are the first to show quantitatively that investments in remediation approaches, specifically those based on laser systems, may achieve net benefits quickly after becoming operational.

The following sections conclude this report with considerations for technology development and policy development as related to debris remediation.

Considerations for Technology Development

Our risk-informed approach to thinking about orbital debris and its remediation is sufficiently novel that there was little heritage from the literature to draw on. Thus, this work breaks new ground and proposes a framework for more principled decision-making related to orbital debris. However, because we attempted to cover a broad swath of risks and remediation approaches, our analysis provides only a high-level view of the landscape. For nearly all aspects of the analysis, we have made simplifying assumptions to enable this landscape view. This analysis could be deepened by including a more physical model of large—and especially small—debris, addressing other remediation approaches that we did not have time to incorporate, enhancing the fidelity of our cost and efficacy estimates for the remediation approaches we analyzed, and broadening the model beyond remediation to assess the relative benefits associated with improved mitigation and enhanced space surveillance capabilities. The results of our analysis should thus be viewed in the context of many limitations. Likewise, the following considerations are preliminary, though principled, recommendations for development of debris remediation approaches.

There are two approaches to remediation that appear most promising. First, lasers offer a compelling approach to remediation. They have the potential to be the lowest cost and most scalable method of reducing the risks posed by orbital debris. They are the only remediation approach that appears capable of remediating trackable and non-trackable debris. For trackable debris, they are capable of nudging debris to avoid collisions and in some circumstances may enable uncontrolled reentry of debris. Further, they can also be used to provide enhanced SSA services when not in use to nudge or remove debris. There is some trepidation in the space community regarding the use of high-power lasers in space, due to concerns about their use as weapons and the process of integrating them with the Laser Clearing House. As described in the report, these concerns appear addressable.

Second, controlled reentry via reusable remediation servicer is also a compelling approach. To our surprise, it is not much more expensive per removal than uncontrolled reentry—indeed, it seems less expensive than many approaches to uncontrolled reentry—and it ensures that no people or assets on the ground are put in danger. The overlaps with other in-space servicing technologies under development by NASA, DoD, and industry also provide an attractive point of leverage, such as in-space refueling and robotic capture mechanisms. The same system for performing controlled reentries can also be used for uncontrolled reentries, making this a versatile development pathway.

This study did not attempt to address the relative costs and benefits between remediation and non-remediation approaches. Thus, we are unable to say whether a dollar invested in remediation will produce a greater risk reduction than if it had been spent on better mitigation methods or improving the capabilities for tracking and characterizing debris. Comparing remediation with non-remediation may be a subject of future work and not require much additional effort. Regardless of the appropriate portfolio balance, we note that the laser-based approaches for remediation are also methods of tracking and characterizing debris. An investment in this area advances both remediation and tracking capabilities. Indeed, the enhanced SSA that a network of laser remediation stations could provide may be a fruitful line of business for the owner of the laser system.

Considerations for Policy Development

This analysis did not address the policy aspects of debris remediation. As such, we cannot make firm recommendations. However, drawing on our professional expertise in this area and feedback from a variety of organizations with whom we held discussions, we can provide the following considerations.

A common opinion held by members of the U.S. government is that companies will develop a business case for the development of debris remediation capabilities and that will be sufficient to incentivize private actors to clean up their debris. Likewise, another common opinion is that private companies contribute the most to generating debris and therefore need to pay for debris remediation. While being careful not to overstate the prevalence of these views or create a strawman argument, we have found these narratives to be weakly supported by our findings.

For both remediation scenarios we investigated, the benefits are almost entirely reductions in risk to satellite operators rather than cost savings. Further, the reductions in risk to any single entity are likely too small to incentivize individual operators to pay for remediation services. In both of our remediation scenarios, governments may be the most appropriate actors to address the collective action problem. As a caveat, we are not saying that business cases based on private demand do not exist; simply that they are unlikely to exist within our two remediation scenarios. Due to time constraints, we did not model remediation scenarios that might form the basis of a business model, such as reducing the liability of a spacecraft operator caused by the debris they generated.

Regarding the balance of responsibility between government and private entities, ESA shows that for the decade beginning in 2010, commercial operators placed their defunct spacecraft into orbits that meet the 25-year rule[20] at a substantially higher rate than civil and military operators. Figure 17 illustrates this trend. Further, they estimate that commercial systems will widen their lead in the coming decade, reaching about 95 percent success with meeting a 25-year rule on average. These figures are globally averaged and may not reflect the rates of U.S. operators. On one hand, while commercial entities may have a higher rate of success, if they are launching more frequently than government operators, their total amount of debris may be greater anyway. On the other hand, this contrasts with the narrative that commercial operators are irresponsible actors that need to be increasingly regulated.

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[20] The “25-year rule” is the name colloquially given to the standard guideline for how soon a spacecraft should deorbit after reaching its end of life. If the spacecraft’s orbit is below about 650 km altitude, it’s orbit will decay naturally and the spacecraft will undergo an uncontrolled reentry within 25 years. If the spacecraft’s operational orbit is higher than 650 km, the operator should lower the orbit of the spacecraft so that it will deorbit within 25 years or sooner.

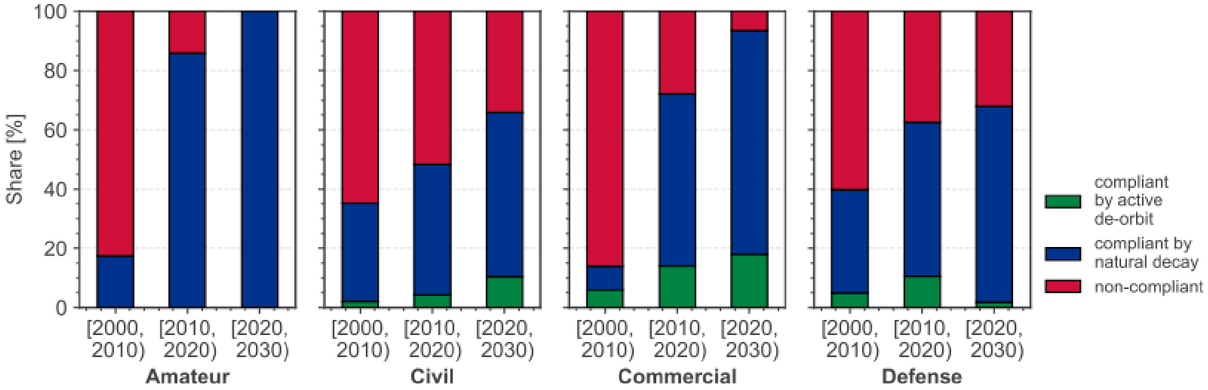

Figure 17. Summary of historical and predicted compliance rates for post-mission disposal, broken out by class of operator. Reproduced from ESA's Annual Space Environment Report (ESA 2022, Figure 6.2).

Finally, we note that removal of small debris appears technically and economically achievable. However, it faces two main policy hurdles. One is the perception that laser systems will not be permitted to operate for fear of their weaponization or potential to cause accidental damage to other satellites. We have discussed the weaponization issue in the report and find such concerns to be addressable in fact, though perceptions may be harder to navigate. Likewise, the United States has a process for safely using laser beams in space called the Laser Clearing House (LCH). The LCH has a reputation for being overly conservative in its risk assessments and the types of laser operations it allows. However, we have spoken with government experts who participated in recent updates to LCH policies and are actively engaged in upgrading the analytic capabilities associated with LCH operations. They indicated that laser tracking of objects can already be performed on rapid timescales through the LCH process, and that new policy and analytical capabilities are likely to smooth the process further. They also indicated that lasers in the power range required for nudging debris might not even be considered in the high-risk category of operations; however, they were skeptical that a ground-based laser could actually nudge a piece of debris. Regardless, we find that laser remediation systems already have a pathway to safe operation, even though the perception remains in the broader space community that lasers do not.

The second main policy hurdle for small debris remediation is that it is unclear under what circumstances a nation has permission to "touch" the debris. In general, debris is the responsibility of the nation that launched it into space. If an entity from one nation wishes to interact with an object it is not responsible for, it must seek permission from the responsible nation. However, it is not possible to determine the responsible nation for any given piece of non-trackable debris. Thus, the process for gaining permission to remediate such debris is unclear. This gap may inhibit the remediation of small debris, which was the source of most risk found in our calculations. It may be time for the U.S. government to provide clarity on policies for small debris remediation.

Potential Next Steps

While rigorous, our analysis provided only a high-level view of the landscape and relied on many simplifying assumptions. We hope to hold a series of discussions with U.S. government, industry, and international experts to gather feedback on how to address, prioritize, and implement efforts to improve the analysis. Based on the feedback from these discussions and subject to the availability of funding, we hope to improve our probabilistic risk model by including mm-sized debris and capturing the dynamic nature of debris populations, reduce cost and performance uncertainties for the most promising debris remediation concepts, and broaden the scope of the current analysis by characterizing the risk reductions and associated costs of improving debris mitigation and tracking capabilities.

Appendix A: Spacecraft Operators and Costs They May Incur

As discussed in the methodology, we partitioned all satellites affiliated with the United States into mutually exclusive categories. The intent was for satellites in each category to have roughly similar costs associated with debris interactions. This chapter describes the heuristics used for assigning spacecraft to each category and provides estimates of various costs associated with interacting with debris. The distribution of satellites across categories is summarized in Table 13.

Table 13. Summary of U.S. Spacecraft Considered in this Analysis.

Category [a]	Number of Spacecraft
Above GEO [b]	4
Civil GEO	18
Civil Operational	15
Civil Science Long	11
Civil Science Short	22
Commercial Bespoke	4
Commercial Bespoke Small	18
Commercial GEO	103
Commercial Large Constellation	2,357
CubeSat / SmallSat	628
Human Spaceflight	1
Military GEO	107
Military LEO	57
Technology Development	10
Total	3,355

a. All satellites in LEO or MEO unless explicitly noted as being in GEO.

b. We have omitted these satellites from the analysis due to their extreme distance from Earth. The four satellites are the Chandra X-Ray Observatory, INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory), the Interstellar Boundary EXplorer (IBEX), and TESS (Transiting Exoplanet Survey Satellite).

Human Spaceflight

Heuristic Used in Satellite Database

The only U.S. spacecraft in the UCS database that falls into this category is the international space station (ISS). It is the only space object analyzed in this paper for which the Country of Operator/Owner is not listed as the United States; its country is listed as ‘multinational’.

Costs Associated with Debris Interactions

For the purposes of analysis, we will also assume that the considerations for a commercial platform are approximately the same as for the ISS and that there will not be a gap between the retirement of the ISS and its commercial successor platform. Our estimates of the costs related to crewed space stations make significant use of public information about the ISS and incorporates input from potential commercial station operators. We do not address costs for crew and cargo transport vehicles. Costs are summarized at the end of this section in Table 14.

Risk Analysis Per Warning. Analysis of conjunction data messages for space stations is expected to be largely automated; however, some human review and analysis is also expected. One expert indicated that roughly two person hours of work would be necessary per high-interest CDM.

Labor Per Maneuver. Subject matter experts indicated that a small fraction (perhaps 2 percent) of high-interest CDMs will warrant planning for a maneuver. That planning is expected to take perhaps 100 person hours of effort charged at the standard labor rate. [21]

Propellant Per Maneuver. Experts state that a burn of about 0.5 m/s would be necessary for each avoidance maneuver. For a chemical propulsion system with a specific impulse of 300 seconds maneuvering a station of similar mass to the ISS, 420,000 kg (NASA 2022-ISS), each burn would require about 70 kg of propellant. Subject matter experts with expertise regarding human spaceflight platforms indicated that most maneuvers to avoid debris would also contribute to routine orbit-raising requirements; thus, propellant expended on debris-avoidance maneuvers would not be wasted.

Retrograde maneuvers that waste propellant represent about 10 percent of historical maneuvers to avoid debris. The total amount of propellant consumed by a retrograde avoidance maneuver should include an additional posigrade maneuver of the same magnitude, to return the spacecraft to its original orbital state. Using the previously calculated 70 kg per burn, a pair of maneuvers to lower and then re-raise the station would use 140 kg of propellant.

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[21] We do not have a heuristic for assessing the false-alarm rate, where a satellite operator spends this labor to prepare for a maneuver but does not execute the maneuver. We do not ascribe any of this labor to the costs per warning; however, this cost is clearly imposed when a maneuver is executed.

With 90 percent of maneuvers wasting zero propellant and 10 percent of maneuvers wasting 140 kg of propellant, implies an *average* of 14 kg of propellant wasted per maneuver.[22] If the cost of cargo is about $70 thousand per kilogram (NASA OIG 2018), the corresponding average cost per maneuver is about $1 million.

We do not have a firm basis for estimating the cost of propellant wasted for a commercial platform. For the purposes of analysis, we naively assume that a commercial platform will have approximately 10 percent of the mass of the ISS. By extension, such a station would have a cost of propellant per maneuver of about $100,000.

Lost Operations Per Maneuver. Subject matter experts indicated that crew do not need to shelter in place for a general maneuver and that maneuvers can be timed for low-activity periods such as when the crew is asleep. Subject matter experts indicated that there may eventually be costs associated with maneuvers, for example if tenant industrial processes require stable microgravity environments that would be interrupted by a burn. Also, there are rare cases when little advance warning is available before a debris conjunction, the ISS crew may shelter in their crew vehicles (NASA 2021). However, subject matter experts indicated that such measures are unlikely to be needed due to improved risk analysis and maneuver capabilities. For this analysis, we assume that there are no lost operations due to maneuvers.

Hardware Cost of Collision. The costs associated with a debris impact on a future commercial station would differ from the costs of an impact on the ISS due to factors like differences in size, design elements such as shielding and redundancy, and types of users that would be affected. However, we use the ISS as a basis for estimating the costs resulting from a collision between debris and a space station, since the design and costs of the ISS are better known and publicly available than those of the commercial space stations.

Since the ISS can maneuver to avoid trackable debris, we assume that any impact would be due to an untracked object. The ISS is shielded to withstand impacts by small debris, generally up to the equivalent of an aluminum sphere with 1 cm diameter (National Research Council 1997), so we assume that a damaging impact would only be caused by a piece of small debris with diameter between 1 cm and 10 cm. Combining this with the fact that the ISS' modules have considerable redundancy, we assume that an impact would have costs on a scale like disabling a single station element. To estimate the hardware costs associated with this event, we assume that i) all station elements contribute equally to the value of continued operations of the ISS, ii) disabling one element does not affect others, and iii) all people onboard can evacuate the affected area and remain safe.

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[22] 0.9 * 0kg + 0.1 * 140kg = 14 kg

The hardware cost would be associated with the launch of repair materials and astronaut labor to make the repairs. We have no firm basis for estimating these costs. For the purpose of analysis, we assume that a full cargo resupply launch will be dedicated to sending up the materials and tools needed to fix the damaged portions of the station. A single cargo resupply mission costs approximately $200 million (NASA OIG 2018).[23] For simplicity, we do not estimate the value of the time spent by the astronauts to perform the repair, the value of the cargo (beyond its transportation cost), or the value of the labor of the engineers on the ground to produce the repair materials and plan the repairs. Thus, this is likely a lower bound on the cost of the repair.

Lost Operations Due to Collision. To estimate the lost operations associated with a single module being disabled, we assume that the average value of a module can be inferred from the operating costs of the ISS. The combined funding allocated to the ISS and commercial-crew and cargo-transportation services for it in NASA's fiscal year 2021 Operating Plan was ~ $3.2 billion (NASA 2022-FY23), and the station has about 20 pressurized and unpressurized major elements contributed by the United States (NASA n.d.-ISS). Together, these indicate a value per element of about $160 million per year. We have no firm basis for estimating how long the struck element would be taken out of operations. For the purposes of analysis, we assume that the ISS would suffer about two years of lost operations of the damaged module, leading to lost operations of about $300 million in total.

Table 14. Summary of Costs for Human Spaceflight.

Cost Element	Value	Timeframe
Risk Analysis	$200	Per Warning
Maneuver Propellant	$1 million [a]	Per Maneuver
Maneuver Labor	$8,000	Per Maneuver
Maneuver Lost Ops	$0	Per Maneuver
Collision Lost Vehicle	$200 million [b]	Per Collision
Collision Lost Ops	$300 million [b]	Per Collision

a. While most maneuvers will not cause a waste of propellant, a small portion will. This is the average cost of waste propellant.
b. A single module is assumed to be damaged, not the entire ISS.

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[23] The reference states the average cost is $191.3 million including "per mission pricing, contract modifications based on requirements changes, and payload integration costs."

Civil Science Short

Heuristic Used in Satellite Database

The 28 satellites in this category are mainly science missions, owned and operated by NASA and NOAA, with design lifetimes that are generally three or fewer years.[24] For many satellites, UCS provides the expected lifetime, which we use where available. We note that while the design lifetimes may be short, a number of satellites in this category have survived to operate for over a decade. The intent for this category is to group together science missions that may have lifecycle costs under $500 million, by using satellite lifetime as a proxy for cost. We spot-checked these costs for a few missions but did not verify that all satellites in this category fall into this cost range. Satellites in this category include AIM (Aeronomy of Ice in Mesosphere), CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation), and OCO 2 (Orbiting Carbon Observatory).

Costs Associated with Debris Interactions

Costs are summarized at the end of this section in Table 16.

Costs Associated with Warnings and Maneuvers. This category contains the 8 satellites in the CYGNSS constellation, which use differential drag to maneuver. CYGNSS satellites would therefore not expend propellant; however, maneuvers take a long time to execute, which may lead to extended periods of lost operations. For the purposes of this analysis, we do not explore these costs. In general, most of the spacecraft in this category lack propulsion; thus, we assigned the costs associated with handling conjunction warnings or maneuvers to be zero. This underestimates the true cost because some spacecraft do have propulsion and satellites with differential drag may also experience costs.

Hardware Cost of Collision. Whether a science spacecraft would be replaced would depend on many factors, including whether it had already achieved its original objectives, the priority the scientific community places on continued observations of the same type, and the cost of replacement. All spacecraft in this category have exceeded their design lifetimes and completed their prime missions. Further, we assumed that NASA would not pay to replace these spacecraft if they were lost; instead, the agency would likely develop and deploy spacecraft that perform other high-priority science missions. Thus, we assigned zero value to the hardware lost in a collision with debris.

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[24] The exceptions to this heuristic are the six COSMIC-2 satellites. We considered these to be operational in nature, not science focused, but their lifecycle costs were more likely similar to short science missions than the other spacecraft in the operational category. In 2019 dollars, the NOAA lifecycle cost of the six COSMIC-2 satellites together was about $75 million (Bartels 2019).

Lost Operations Due to Collision. We were unable to estimate the full value of operational losses, including the societal benefits of the data that is being gathered, due to incapacitation of a scientific satellite. Instead, we roughly approximate the value of the assets by assessing the value that NASA appears to assign them in its budget documents. In other words, the spacecraft are worth whatever NASA is willing to pay for their operations and related program support. Using that perspective, we estimated that NASA values these missions at about $7M per year (Table 15). This is likely an underestimate of the value, since it does not include the broader scientific, technical, educational, political, and social value of these missions beyond NASA.

Table 15. Identified Operations Costs for Various NASA Short Science Missions.

FY22 Budget Requests [a]	Annual Value ($M)
Missions	
AIM	3
Calipso	5
Cloudsat	9
COSMIC [b]	Not Found
CYGNSS [c]	Not Found
ICON	5
IRIS	6
NuSTAR	9
OCO 2	10
Swift	6
TIMED	2
Subtotal Average per Mission	**6**
Other Operational Support per Mission [d]	1
Total Average Value Per Mission	**7**

a. Taken from FY 2022 Budget Estimates (NASA 2022-Budget)
b. Could not find a reference to COSMIC in the budget request
c. The cost for CYGNSS was mixed in with the other Venture-class missions.
d. The Space Sciences Mission Operations requested $11.9 million to support 13 satellite missions, many of which are the missions listed above. We rounded the average per mission up to $1M.

We estimated the remaining lifetime of the Science-short spacecraft based on the findings of SMD's Senior Reviews. After missions complete their finite-duration prime-mission phases, they may later propose further finite-duration extended missions. Proposals for extended missions are assessed by triennial Senior Review panels comprised of scientists and technical experts that make recommendations regarding the value of continuing missions; the panels assess factors including scientific merit, cost, and the health of the spacecraft and instruments. Nine of the ten missions in the Science-short set were subject to a recent Senior Review. (The exception is ICON, which launched in 2019.) The Heliophysics Senior Review considered extensions through fiscal year (FY) 2025 (NASA 2020-Heliophysics), the Earth Science review considered extensions through FY 2026 (NASA 2020-Earth), and the Astrophysics review considered extensions through FY 2027 (NASA 2022-Astrophysics). Of the missions reviewed, all received recommendations to extend for the maximum duration except two: the Earth Science Senior Review only definitively recommended continuing CloudSat through FY 2023 since a new mission was expected to start providing similar data by then, and it stated that CALIPSO was expected to finish at the end of FY 2023 due to insufficient power. Based on this, we estimate that Science-short missions have an average of at least three years of life remaining[25].

As discussed, each satellite may suffer 3 years of lost operations at $7 million per year. Thus, we assign a value of $21 million to the lost operational value of satellites in this category. As previously mentioned, this is likely a significant under-estimate of the value. For example, NASA's Economic impact Report (NASA 2022-EconImpact) shows that every $1 of NASA expenditure generates about $3 of economic output. Other analysts have estimated that Apollo-era expenditures generated an 8-fold increase in economic output per dollar expended by NASA. We recognize that our estimate of the lost operations may be too low by a factor of 3 to 8. However, the underestimate is unlikely to change the relative rankings of the remediation methods; thus, we retain it for conservatism.

Table 16. Summary of Costs for Civil Science Short

Cost Element	Value	Timeframe
Risk Analysis	$0 [a]	Per Warning
Maneuver Propellant	$0 [a]	Per Maneuver
Maneuver Labor	$0 [a]	Per Maneuver
Maneuver Lost Ops	$0 [a]	Per Maneuver
Collision Lost Vehicle	$0 [b]	Per Collision
Collision Lost Ops	$21 million [c]	Per Collision

a. Most satellites in this category lack propulsion. This value may change in the future as new spacecraft are deployed with propulsive capabilities.

b. The currently operational satellites are past their design lifetime and unlikely to be replaced if lost.

c. Each satellite may suffer 3 years of lost operations at $7 million per year.

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[25] However, these missions may last significantly longer. The Senior Review reports state that most of these spacecraft remain scientifically productive and healthy. Although the design lifetimes for these missions were only two or three years, the average age of the 17 spacecraft in this set is ten years.

Civil Science Long

Heuristic Used in Satellite Database

The 11 satellites in this category are science missions, owned and operated by NASA or NOAA, with design lifetimes that are generally three or more years. For many satellites, UCS provides the expected lifetime, which we use where available. The intent for this category is to group together science missions that may have lifecycle costs over $500 million, by using satellite lifetime as a proxy for cost. We spot-checked these costs for a few missions but did not verify that all satellites in this category fall into this cost range. Satellites in this category include Global Precipitation Measurement (GPM) Core Observatory, GRACE Follow-On, Hubble Space Telescope, and ICESat-2. Four of satellites in this category are operated by NASA Earth Science Mission Operations (ESMO) (NASA n.d.-ESMO). Most of the spacecraft in this category have some propulsive capability, with the notable exception of Hubble.

Costs Associated with Debris Interactions

Costs are summarized at the end of this section in Table 18.

Risk Analysis Per Warning: Risk analysis and maneuver processes vary between mission teams—some employ manual risk analysis, while analyses for about half of the Science-long spacecraft are largely automated (Mantziaras 2018). We assumed that the cost per analysis for the highly automated spacecraft is effectively zero. For the rest of the spacecraft, people familiar with conjunction analyses stated that roughly two hours of staff time would be necessary per high-interest conjunction. Averaged over all of the spacecraft in the category (zero cost for the 50 % of spacecraft that are automated and two labor hours for those that are not), about one our per warning is necessary.

Labor Per Maneuver: Subject matter experts with experience planning and executing maneuvers stated that about ten hours of staff time would be necessary per executed maneuver. Sources familiar with avoidance maneuvers also stated that even highly automated conjunction-analysis processes currently involve some human attention for maneuvers, which may also include coordinating with other satellite operators. Thus, we estimated that spacecraft in this category require about ten hours of labor per maneuver.

Propellant Per Maneuver: People familiar with collision-avoidance maneuvers indicated that debris-avoidance maneuvers are almost always posigrade, so the burns contribute to routine orbit-boosting requirements. Therefore, propellant expended for avoidance maneuvers is usually not wasted. Additionally, even for rare cases in which a retrograde maneuver is necessary, the required velocity increments are small (e.g. centimeters per second) and so do not meaningfully affect propellant reserves or spacecraft lifetime. Thus, we estimated zero cost associated with expended propellant.

Lost Operations Per Maneuver: People familiar with science-spacecraft operations stated that avoidance maneuvers typically have little effect on a mission's ability to meet its scientific requirements. Some of the spacecraft in this category may need to slew into a new position, which can cause 20 to 40 minutes of lost science per maneuver. Subject matter experts indicated that maneuvers due to debris are much less common than drag-makeup maneuvers and other forms of conjunction avoidance; thus, debris avoidance is a small fraction of their overall lost operations. We lacked data for all satellites in this category and recognized that some satellites may be able to schedule their maneuvers to avoid having any lost operations. Thus, we assign the average lost operations at about 10 minutes per maneuver.

Hardware Cost of Collision: As for the science-short case, we include hardware costs for missions still in their prime phase. One mission in the Science-long set is still in its prime phase: GRACE Follow-On (GRACE-FO). GRACE-FO is a two-spacecraft mission with a cost to NASA of about $430 million (NASA 2018-GRACE). Losing either spacecraft would end the mission, and we assume that the pair would be replaced rather than just the incapacitated spacecraft, so the hardware-replacement value associated with each is about $430 million. In addition, a person we spoke with who is familiar with Earth-science priorities stated that they expect that the Global Precipitation Measurement (GPM) Core Observatory and ICESat-2 would be particularly likely to be replaced, so we include the development costs for each as well: $1.02 billion[26] for the GPM Core Observatory (NASA and JAXA 2014) and $1.06 billion for ICESat-2 (Krygiel 2019). Although actual replacement choices may differ from ours, and the cost of replacing a mission may be less than its original development cost, this provides a notion of the scale of replacement that might occur. We assigned the lost hardware value per satellite as $270 million.[27]

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[26] Reported as $932.8 million in 2014 and inflated to 2020 dollars by a factor of 1.0964.

[27] This is the approximate average cost of hardware replacement across the whole category. There are 4 satellites that would be replaced if lost and 7 that may not. We summed the value of the 4 that would be replaced: $430 million for each of the two GRACE-FO spacecraft (because loss of one creates an effective loss of the other), plus $1.02 billion for the GPM Core Observatory, and $1.06 billion for ICESat-2. This adds to $2.94 billion. We divided this cost across all eleven spacecraft, for about $270 million per spacecraft.

Lost Operations Due to Collision: We used the same approach described for Science-short. We assigned the annual value of each mission to be $28 million per year (Table 17).

Table 17. Identified Operations Costs for Various NASA Long Science Missions

FY22 Budget Requests [a]	Annual Value ($M)
Missions	
Terra	30
Aura	23
Aqua	32
Fermi Gamma-Ray Space Telescope	14
GCOM-1, Shikuzu [b]	Not Found
GPM	21
GRACE-FO1	11
GRACE-FO2	11
Hubble	98
Icesat-2	22
SMAP	13
Total Average Value Per Mission	**28**

a. Taken from FY 2022 Budget Estimates (NASA 2022-Budget)

b. Could not find because this mission is operated by JAXA. The UCS database lists this as a joint project between the United States and Japan; thus, it is included in this analysis.

For the 7 satellites that are not certain to be replaced, we assumed their remaining lifetimes to be 5 or more years.[28] For the 4 satellites that are likely to be replaced, we assumed that the replacement would take 5 or more years, because there are no spares to launch. Thus, for all satellites in this category, their incapacitation would lead to about five years of lost operations valued at $28 million per year—totaling $140 million in lost operations per spacecraft.

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[28] These missions were intended to have long lifetimes, the average age of the spacecraft is 13 years, and of the nine spacecraft currently operating in an extended mission, the Senior Review panels (NASA 2020-Heliophysics, NASA 2020-Earth, and NASA 2022-Astrophysics) found them to be productive and largely in good health. The Earth Science review states that three spacecraft, Aqua, Aura, and Terra, were expected to maneuver from their normal science orbits toward disposal orbits in 2022 due to low propellant levels, but even so the review recommended continuing scientific operations for all three though at least FY 2026 (i.e., for at least four more years from now).

Table 18. Summary of Costs for Civil Long Science Missions

Cost Element	Value	Timeframe
Risk Analysis	\$77 [a]	Per Warning
Maneuver Propellant	\$0 [b]	Per Maneuver
Maneuver Labor	\$770 [c]	Per Maneuver
Maneuver Lost Ops	\$530 [d]	Per Maneuver
Collision Lost Vehicle	\$270 million [e]	Per Collision
Collision Lost Ops	\$140 million [f]	Per Collision

a. One hour of labor at the standard rate.
b. Maneuvers are generally orbit-raising, so the propellant is not wasted.
c. Ten hours of labor at the standard rate.
d. The annual operational value is estimated at \$28 million per year—or \$53 per minute. There are 10 minutes of lost operations.
e. The value of the satellites that would be replaced if lost, divided by the total number of satellites in this category.
f. Each satellite may suffer 5 years of lost operations at \$28 million per year.

Civil Operational

Heuristic Used in Satellite Database

The satellites we assigned to this category are National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), and NASA Earth-observing spacecraft that provide data, the purpose of which is not primarily research, about weather, agriculture, natural resources, and other aspects of the environment. This category incorporates spacecraft (Table 19) in both LEO and GEO.

Costs Associated with Debris Interactions

Costs are summarized at the end of this section in Table 20.

Risk Analysis Per Warning: Spacecraft in this category generally do not appear to have highly automated procedures for performing and evaluating risk analyses of warnings. As discussed in the Science-long case, it may take about 2 hours of staff time per warning.

Labor Per Maneuver: Like the Science-long spacecraft, we estimated that ten hours of staff time would be necessary per maneuver, regardless of the spacecraft's level of automation.

Propellant Per Maneuver: We expect that avoidance maneuvers will contribute to maintenance of the orbit; thus, the propellant is not wasted.

Lost Operations Per Maneuver: We expect no lost operational cost per maneuver. The operational capabilities provided by these spacecraft in LEO are somewhat redundant—able to be performed by more than one spacecraft. Observational spacecraft in GEO, such as the GOES satellites, hold steady over their areas of interest and do not meaningfully lose viewing opportunities if they have to pause operations momentarily.

Hardware Cost of Collision: We estimate the replacement cost of a Civil-operational spacecraft by estimating the hardware costs of each of the major types of satellites in the category and then averaging across all of the 27 satellites in the category.

The Joint Polar Satellite System (JPSS) spacecraft is not in our satellite database, because it was launched in 2022; however, it may be illustrative of the replacement costs for some satellites in this category. Thus, we estimated its cost. We based our estimate on JPSS contract awards described in a Department of Commerce Office of Inspector General (2016) report. The report describes two sets of contracts. One set of contracts is for development of the JPSS-2 spacecraft though on-orbit commissioning, with options for the JPSS-3 and -4 spacecraft. That set of contracts excludes the costs instruments and launch. The other set of contracts mentioned in the OIG report is for the JPSS-2 instruments. The value of the JPSS-2 spacecraft contract was \$244.8 million, and the JPSS-3 and -4 options were for \$119.9 million and \$74.0 million, respectively. We average these three for a JPSS spacecraft value of about $150 million. The combined value of the four JPSS-2 instrument contracts was $690 million. This provides a total estimate for the spacecraft and instruments in 2016 dollars of $840 million; inflated to October 2022 (25 %), the cost of the spacecraft plus instruments is about $1 billion. The cost of launch services in 2017 dollars was $170.6 million (NASA 2017); inflated to October 2022 (22 %), the launch cost was about $210 million. Combining the launch cost with those of the spacecraft and instruments provides our estimate of a replacement JPSS satellite: about $1.2 billion.

Suomi NPP was a technology pathfinder for JPSS, so we assume that its replacement would be a JPSS satellite. Similarly, JPSS is the successor to the Polar Operational Environmental Satellite (POES) system, so we assume that if any of the remaining POES spacecraft (NOAA-15, -18, and -19) were hit, they would be replaced by a JPSS satellite.

We base our estimate of hardware costs for Geostationary Operational Environmental Satellite (GOES) spacecraft on an audit by the DOC OIG (2013). The current GOES development program, known as GOES-R, will build, launch, and operate four satellites (GOES-R, -S, -T, and -U), three of which are already in orbit. The OIG reported that the GOES-R program office estimated that completion of the full set of four spacecraft plus two of their major instruments would cost $2.147 billion. In October 2022 dollars (28 % inflation), the combined cost of the four spacecraft and those instruments is about $2.4 billion. We divide this equally among the four spacecraft to obtain an estimated cost for each spacecraft plus its instruments of about $690 million. Additionally, the cost of the most recent launch in the series, for GOES-T, now called GOES-18, was $165.7 million in 2019 dollars (NASA 2019-GOES-T). Inflating by 16 % to October 2022 dollars, the launch cost was about $190 million. Combining the spacecraft and launch costs, we estimate the hardware cost of a GOES satellite as $880 million.

For the Tracking and Data Relay System (TDRS) satellites, we base our estimate on the cost of building the most recent spacecraft, TDRS-13, previously known as TDRS-M. (NASA is currently exploring replacing TDRS satellites with commercial services (NASA n.d.-CSP), but the cost of replacement under that model is currently unknown, so we use the TDRS hardware cost as a stand-in.) In 2011, NASA exercised a contract option to build TDRS-13 for $289 million (Leone 2011). In October 2022 dollars (inflation by 32 %), the cost of the spacecraft is approximately $380 million. In 2015, NASA estimated the cost of TDRS-13's launch as $132 million. In October 2022 dollars (inflation by 25 %), the launch cost is approximately $170 million. Combining the spacecraft and launch, our estimate of the hardware cost of a lost TDRS satellite is $550 million.

Our estimate for replacing a Landsat spacecraft is based on a 2021 Government Accountability Office (GAO 2021) report. The report stated that the latest estimate for development of the most recent spacecraft, Landsat 9, through commencement of operations was $838.5 million. Inflated to October 2021 dollars (11 %), the development cost estimate was about $930 million. Additionally, the 2017 expected cost of Landsat 9's launch was $153.8 million (NASA 2017-Landsat); inflated by 21 % the launch cost in today's dollars is about $190 million. Our total estimate of developing and launching a replacement Landsat satellite is then approximately $1.1 billion.

For Jason-3, we use its $177 million NOAA life-cycle cost (LCC) as our estimate of its replacement cost (NOAA n.d.-JASON).

Our estimate for the cost of replacing a Civil-operational spacecraft is the average hardware costs across all 22 spacecraft (Table 19) that we incorporate in the analysis: $820 million per spacecraft.

Table 19: Estimated replacement costs for Civil-operational spacecraft.

Mission	Number	Replacement cost per satellite
GOES	4	$880 million
Jason-3	1	$177 million
JPSS-1, Suomi-NPP, and POES	5	$1.2 billion
Landsat	3	$1.1 billion
TDRS	9	$550 million
Average over all spacecraft		**$820 million**

Lost Operations Due to Collision: The Civil-operational satellite programs mostly incorporate significant redundancy, so we assumed that incapacitating a single satellite would not have an associated cost due to interrupted operations because it would be replaced. This case is qualitatively different from the science long category, where there was no redundancy associated with the satellites; a lost science satellite would create a loss of operations. The assumption that redundancy leads to a continuity of operations may only be true on a somewhat short timescale. For instance, if multiple satellites within a family are lost, then the loss of operations could be total. This could happen if one satellite is hit by debris, while another suffers an anomaly not related to debris. Or a single debris-generating event could cause a shower of debris that subsequently disables multiple other satellites. We believed that it should be possible to assess an economic cost due to reduced redundancy, but we did not attempt to incorporate such a cost.

Table 20. Summary of Costs for Civil Operational Missions

Cost Element	Value	Timeframe
Risk Analysis	\$154 [a]	Per Warning
Maneuver Propellant	\$0 [b]	Per Maneuver
Maneuver Labor	\$770 [c]	Per Maneuver
Maneuver Lost Operations	\$0 [d]	Per Maneuver
Collision Lost Vehicle	\$820 million [e]	Per Collision
Collision Lost Operations	\$0 [d]	Per Collision

a. Two hours of labor at the standard rate.
b. Maneuvers are generally orbit-raising, so the propellant is not wasted.
c. Ten hours of labor at the standard rate.
d. Operational satellites tend to be part of architectures that use redundancies to avoid accidental loss of mission due to an anomaly on a single satellite.
e. Estimated replacement cost.

Military

Heuristic Used in Satellite Database

We assigned satellites to this category if the UCS database listed the users of the satellite as "Military," either in whole or in part. This includes 57 satellites in LEO, 35 GPS satellites in MEO, and 72 satellites in GEO or highly eccentric orbits.

Costs Associated with Debris Interactions

Data on many of these spacecraft are highly sensitive. Due to these sensitivities, we did not attempt to provide estimates for satellites in this category. Instead, we noted that nearly all of the spacecraft appear to serve operational purposes, such as intelligence gathering, communications, and PNT services. Thus, we assign all satellites in this category the same costs as spacecraft from the Civil Operational category.

Commercial Bespoke

Heuristic Used in Satellite Database

Satellites in this category are commercially operated, operating in LEO, have a mass above 200 kilograms, and are not members of a constellation of greater than 10 satellites. The satellites all have maneuver capability.

Costs Associated with Debris Interactions

Costs are summarized at the end of this section in Table 21.

Risk Analysis Per Warning. One subject matter expert said it takes about 20 minutes of analyst time per day to monitor their automated CA system. We estimate the number of warnings per day operators may receive to further estimate the amount of time per warning. The NEAT tool shows warnings for debris may range for less than 1 per day to many hundred per day. We assume that most of these warnings are due to debris.[29] For the purposes of the analysis, we roughly estimate that satellite operators receive 10 warnings per day from all sources. Thus, the labor burden per warning is assumed to be about 2 minutes per warning (20 minutes per day divided by 10 warnings per day). The cost per warning is about 2 minutes of labor at the rate provided in the methodology section.

Labor Per Maneuver. One satellite operator indicated that there are enhanced labor costs associated with planning and performing a maneuver. The operator estimated the labor burden as about 6 hours. We do not have a heuristic for assessing the false-alarm rate, where a satellite operator spends this labor to prepare for a maneuver but does not execute the maneuver. We do not ascribe any of this labor to the costs per warning; however, this cost is clearly imposed when a maneuver is executed. Thus, we estimate that the labor cost per maneuver is 6 hours charged at the standard rate for labor.

Propellant Per Maneuver. For a chemical propulsion system of relatively large satellites, above 1,000 kg in LEO, one satellite operator indicated that they had expended about 0.05 kg of propellant per debris avoidance maneuver. We use this value for all chemical propellant systems on spacecraft above 1,000 kg.

For context, note that a satellite in this mass range may be 10 to 45 percent comprised of propellant, or 100 to 450 kg of propellant. Roughly assume that about 10 percent of the propellant is used for post-mission disposal and that the satellite was placed into its final orbit by the launch vehicle without the satellite expending onboard propellant. Thus, the propellant

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[29] For satellites in 450-600km orbits, there is less debris than active satellites, though in all other orbits, debris outnumbers active satellites by a wide margin.

remaining for operational maneuvers is about 90 to 405 kg. With about 0.05 kg of propellant per maneuver, and operator could perform 1,800 to 8,100 maneuvers over its lifetime. Operators with whom we've spoken, appear to perform station keeping maneuvers approximately once per month. Assuming 30 years of satellite operations at 12 maneuvers per month is only 360 maneuvers over the lifetime of the satellite. Using these very rough order-of-magnitude assumptions, the maneuvers a satellite operator performs would need to increase by at least a factor of 5 before the propellant expended is great enough to threaten the operational lifetime of large satellites.

Current practice for satellite operators is to time their debris collision maneuvers so that they are also supportive of the spacecraft's station keeping goals. Rarely, if ever, do operators appear to make collision maneuvers that are not also productive for station keeping. Thus, we assume that costs associated with expending propellant are effectively zero. There is likely a tipping point, where maneuvers are so frequent that they become a burden. Based on the order-of-magnitude analysis previously show, we assume the tipping point may be around 60 maneuvers per year (a 5-times increase over current traffic). Until debris traffic reaches that level, operators could perform smaller maneuvers more frequently.

Lost Operations Per Maneuver. We estimate the hourly rate of revenue generation for commercial satellites. For the purposes of analysis, we investigate publicly held companies with transparent financial reports. For example, in 2021, Maxar reported $492 million in revenue for its Earth observation line of business (Maxar 2022). This revenue may be spread along multiple platforms, such as GeoEye, WorldView, and Vricon. The latter of these is a joint-venture between Saab and Digital Globe, which mainly produces intelligence products. For this analysis, we will assume that the other lines of business are mainly using data produced by their own satellites; thus, we attribute all of Maxar's revenue for the data analytics as ultimately revenue produced by the satellites. Maxar flies three Digital Globe satellites and one Geo-Eye satellite. Thus, we roughly estimate the revenue of a single satellite as $123 million annually or $234 per minute ($492 million annual revenue divided by 4 satellites, divided by 525,600 minutes per year).

Commercial satellite operators with whom we've spoken indicate that their collision avoidance maneuvers can be scheduled at times that do not negatively affect their revenue. This is because revenue generating opportunities are not uniformly distributed through time and space. For example, satellites that provide optical imagery generally do not create revenue when they are over the ocean or areas of Earth that are in the dark of night. Likewise, some communications satellites may not generate much revenue when passing over areas where there are few-if-any subscribers, such as oceans, low-population areas, or countries where the operator is not licensed to provide services. However, there are scenarios where this may no longer hold true in the future. For instance, as more terrestrial and in-space users adopt space-based communications services, there may be more continuous opportunities for revenue. Likewise, as satellites begin to provide in-space optical SSA, operators providing optical imagery may be able to generate more continuous revenue. In the short term, we note that operators using synthetic aperture radar (SAR) can already generate revenues at night.

Satellite operators uniformly indicated that maneuvers do not take much time, generally giving answers like "maybe a few minutes". Recognizing the caveats previously discussed that most maneuvers do not reduce operator revenue, for the purposes of analysis, we assume that each maneuver takes 1 minute and that the operator does experience a loss of revenue for that amount of time.

Hardware Cost of Collision. To estimate the cost to develop and operate a satellite of this class we use the cost estimation tool QuickCost version 6.1. We assume that a 1,000 kilogram satellite of this class will cost around $500 million to design, manufacture, launch, and operate, over the lifetime of the vehicle.[30] If a satellite were rendered inoperable by debris, this is approximately the cost that would be required to replace the inoperable satellite. In reality, the original satellite would have generated some revenue, thereby covering a portion of its cost. Thus, the full replacement cost is the upper bound on the cost of lost hardware.

Lost Operations Due to Collision. Loss of a satellite in this class will also lead to a loss of revenue until the satellite can be replaced. Subject matter experts with whom we've spoken estimated that it may take around 5 years to replace the lost asset. Thus, we estimate the lost revenue opportunity as 5 years of revenue—about $615 million.

Table 21. Summary of Costs for Commercial Bespoke Spacecraft

Cost Element	Value	Timeframe
Risk Analysis	$3 [a]	Per Warning
Maneuver Propellant	$0 [b]	Per Maneuver
Maneuver Labor	460 [c]	Per Maneuver
Maneuver Lost Ops	$234 [d]	Per Maneuver
Collision Lost Vehicle	$500 million	Per Collision
Collision Lost Ops	$615 million	Per Collision

a. Roughly 2 minutes of labor multiplied by our standard rate for labor
b. Collision avoidance maneuvers are planned to also provide necessary station keeping
c. Estimate as 6 hours charged at the standard rate for labor.
d. One minute of lost revenue at a rate of $234 per minute.

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[30] Result from the QuickCost 6.1 cost estimation tool for a spacecraft bus of 850 kg, a camera mass of 50 kg, a few hundred kg of propellant (quickcost does not estimate wet mass or require the user to specify it), design life of 10 years, and launch cost of $55 million. Quickcost provided a wide range of estimates, from $250 to $750 million. We choose the midpoint of $500 million.

Commercial Small Constellation

Heuristic Used in Satellite Database

These are commercial constellations of roughly identical spacecraft containing less than twenty satellites each.

Table 22. Commercial Small Constellation members.

	Number of Satellites	Cost per Satellite ($M)	Total Cost ($M)
Constellation			
Blacksky Global	12	$6	$42
Capella Space	5	$5	$25
HawkEye 360	9	$5	$45
Orbcomm	12	$13	$156
Planet SkySat	19	$5	$95
PlanetiQ	2	$5	$10
Umbra	1	$3	$3
Total	**60**		**$376**
Average		**$6**	
Average Remaining Value [a]		**$3**	

a. Assuming that if a satellite is struck, it will be halfway through its lifetime.

Costs Associated with Debris Interactions

Costs are summarized at the end of this section in Table 23.

Risk Analysis per Warning. Commercial operators have largely automated their analysis and response to debris interactions. We assigned zero labor costs to this category.

Labor per Maneuver: Commercial operators have largely automated their analysis and response to debris interactions. We assigned zero labor costs to this category.

Propellant per maneuver: These spacecraft, like many others, can use debris avoidance maneuvers to support their orbit-maintenance requirements, so no propellant is wasted. Further, based on input from subject matter experts, we assumed that propellant is not a limiting factor on these satellites' lifetimes. Based on these assumptions, we assigned no meaningful costs of propellant due debris-avoidance maneuvers.

Lost operations per maneuver: We assumed that a combination of redundancy in these constellations and flexibility in timing maneuvers means that the cost of lost operations is negligible.

Hardware cost of collision: We estimated the value of the satellites in each of the six constellations and then average across all of the satellites in the category.

BlackSky Global satellites were designed to cost between $3 to $5 million each, according to the CEO of the company(Farley 2016). BlackSky satellites have launched on a mix of dedicated Rocket Lab Electron flights and SpaceX rideshare missions; two BlackSky satellites fly per Electron launch and each has a mass of about 55 kilograms (Clark 2021). To estimate launch costs, we assumed an even split of dedicated and rideshare launches. Electron flights cost around $7 million (Sheetz 2021), so the cost for each satellite in a pair would be about $3.5 million. However, the cost to launch as a rideshare on a SpaceX Falcon 9 would be less. For this analysis, we assign the cost of building and deploying a BlackSky satellite to be about $6 million.

Representatives from Capella Space stated that its satellites are "hundreds of times less expensive than traditional SAR satellites that can cost upward of $500M" (Capella Space 2018), so we assumed that Capella's satellites cost $5 million each.

HawkEye 360 raised a $145 million investment round in 2021 to deploy 30 additional spacecraft and invest in other capabilities (Mohney 2021). For our estimate of the cost of their spacecraft, we assume that all of that funding round will go to building and deploying the new satellites, for an average cost of about $5 million per spacecraft.

We base our estimate for the value of Orbcomm satellites on a $180 million contract award in 2008 by Orbcomm to Sierra Nevada to build 18 satellites (Werner 2010), which provides a cost per satellite of about $10 million. Additionally, Orbcomm had a $55 million contract with SpaceX to launch up to 18 satellites (de Selding 2012), corresponding to about $3 million per spacecraft. This yields a total cost of spacecraft and launch of $13 million per satellite.

The cost of a PlanetiQ spacecraft is reported to be $5 million (Ball 2012). They are 36 kilogram spacecraft carrying Global Positioning System occultation radio payloads. We assume that their cost is the same as the average of the others in this category.

Planet's SkySats were originally developed by Skybox Imaging, and a press report stated that the SkySats cost about $3 million to $6 million each to build (Temple 2014). Each satellite has a mass of about 110 kilograms (Clark 2020), recent satellites launch as Falcon 9 rideshare payloads, and SpaceX currently advertises that the cost of launching a 110 kilogram payload would be about $660 thousand.[31] Taking the midpoint of the range of launch costs plus the spacecraft costs, we estimate a hardware value for each satellite of about $5 million.

In 2021, Umbra announced raising $41 million (Werner 2021) and is developing a 12-satellite constellation (Starbridge 2018). For lack of more detailed information, we estimate the cost of Umbra's satellites by assume that this investment round will be solely devoted to building and deploying those twelve spacecraft. This provides an estimate of $3 million per spacecraft.

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[31] SpaceX Rideshare Program: https://rideshare.spacex.com/search?orbitClassification=2&launchDate=2023-02-04&payloadMass=100

Averaging across the 60 satellites in the category for which we can assess values, we estimate the hardware cost per Commercial Small Constellation spacecraft as about $6 million each, as shown in Table 22. For the sake of simplicity, we assume that any satellite struck by a piece of debris will be hit about halfway through its operational lifetime, thus the value of lost hardware is about half of the full cost—i.e., $3 million per lost spacecraft.

Table 23. Summary of Costs for Commercial Small Constellations

Cost Element	Value ($M)	Timeframe
Risk Analysis	$0 [a]	Per Warning
Maneuver Propellant	$0 [b]	Per Maneuver
Maneuver Labor	$0 [a]	Per Maneuver
Maneuver Lost Ops	$0 [c]	Per Maneuver
Collision Lost Vehicle	$3 [d]	Per Collision
Collision Lost Ops	$0 [c]	Per Collision

a. Highly automated, such that labor costs are zero.
b. Debris maneuvers also support orbit-raising.
c. While not all constellations are built out yet, a constellation may have sufficient redundancy to avoid a loss of operations
d. Summary of estimate from Table 22.

Commercial Medium Constellation

Heuristic Used in Satellite Database

These are commercial constellations containing 20-100 satellites each.

Table 24. Commercial Small Constellation members.

	Number of Satellites	Cost per Satellite ($M)	Total Cost ($M)
Constellation			
Globalstar	32	$29	$928
Iridium	73	$49	$3,577
Total	105		$4,505
Average		$43	
Average Remaining Value [a]		$20	

a. Assuming that if a satellite is struck, it will be halfway through its lifetime. Rounded to one significant figure.

Costs Associated with Debris Interactions

Costs are summarized at the end of this section in Table 25.

All Costs Except Hardware. We assign all costs to be the same as the commercial small constellation category.

Hardware cost of collision: To generate our estimate, we again generate estimates for each operator and then average across all of the satellites in the category.

In February, Globalstar announced a contract to build 17 new satellites, with options for up to nine more (Foust 2022-MDA). The total cost of the contract, including all options, was $450 million, providing a cost per satellite of about $17 million. Launch of 24 Globalstar satellites was covered by a contract worth $300 million (SpaceNews Editor 2007), so we estimate the cost to launch each was about $12 million. This yields a total value of spacecraft plus launch of about $29 million.

In 2010 Iridium announced a $4 billion contract with Thales Alenia Space to design, manufacture, and launch 72 satellites for the Iridium NEXT constellation (Iridium 2010). The contract also included construction of nine ground spares. Ignoring the launch cost for the spares, this provides an average total hardware cost for each satellite of $49 million.

Averaging across all 105 Globalstar and Iridium satellites in our analysis, we estimate the value of a Commercial Medium Constellation satellite of about $43 million, shown in Table 24. For the sake of simplicity, we assume that any satellite struck by a piece of debris will be hit about halfway through its operational lifetime, thus the value of lost hardware is about half of the full cost—i.e., about $20 million per lost spacecraft.

Table 25. Summary of Costs for Commercial Medium Constellations

Cost Element	Value	Timeframe
Risk Analysis	$0 [a]	Per Warning
Maneuver Propellant	$0 [b]	Per Maneuver
Maneuver Labor	$0 [a]	Per Maneuver
Maneuver Lost Ops	$0 [c]	Per Maneuver
Collision Lost Vehicle	$20 [d]	Per Collision
Collision Lost Ops	$0 [c]	Per Collision

a. Highly automated, such that labor costs are zero.
b. Debris maneuvers also support orbit-raising.
c. The constellations have sufficient redundancy to avoid a loss of operations.
d. Summary of estimate from Table 24.

Commercial Large Constellation

Heuristic Used in Satellite Database

These are emerging communications constellations containing hundreds to thousands of spacecraft.

Table 26. Commercial Large Constellation members.

	Number of Satellites	Cost per Satellite ($M)	Total Cost ($M)
Constellation			
OneWeb	394	$2.4	$946
SpaceX Starlink	1815	$1.6	$2,904
Total	**2209**		**$3,850**
Average		**$1.7**	
Average Remaining Value [a]		**$1**	

[a] Assuming that if a satellite is struck, it will be halfway through its lifetime. Rounded to one significant figure.

Costs Associated with Debris Interactions

Costs are summarized at the end of this section in Table 27.

All Costs Except Hardware. We assign all costs to be the same as the commercial small constellation category.

Hardware cost of collision: We again generate estimates for hardware cost for each operator and then average across all of the satellites in the category.

Press reports indicate that the cost to manufacture a OneWeb satellite is about $1 million (Proud 2020). OneWeb is expected to be able to fit about 48 satellites on a Falcon 9 (Clark 2022-Oneweb), so using the current $67 million price of a Falcon 9, we estimate the launch cost to be about $1.4 million per satellite. Combining the spacecraft and launch costs yields a total hardware cost of about $2.4 million.

Public remarks by SpaceX have indicated that the cost per Starlink satellite is less than $1 million (Ralph 2019). Since SpaceX launches their Starlink satellites themselves, we use an estimate of their internal launch of about $30 million (Najjar 2020). Each launch carries about 50 satellites (Howell 2022), so the launch cost per satellite is about $600 thousand. This provides a combined hardware cost of about $1.6 million.

Averaging across all of the OneWeb and Starlink satellites in our analysis, we estimate the value of a Commercial Large Constellation satellite to be about $1.7 million, shown in Table 26. For the sake of simplicity, we assume that any satellite struck by a piece of debris will be hit about halfway through its operational lifetime, thus the value of lost hardware is about half of the full cost—i.e., about $1 million per lost spacecraft, rounding to one significant figure.

Table 27. Summary of Costs for Commercial Large Constellations

Cost Element	Value	Timeframe
Risk Analysis	$0 [a]	Per Warning
Maneuver Propellant	$0 [b]	Per Maneuver
Maneuver Labor	$0 [a]	Per Maneuver
Maneuver Lost Ops	$0 [c]	Per Maneuver
Collision Lost Vehicle	$1 [d]	Per Collision
Collision Lost Ops	$0 [c]	Per Collision

a. Highly automated, such that labor costs are zero.
b. Debris maneuvers also support orbit-raising.
c. The constellations have sufficient redundancy to avoid a loss of operations.
d. Summary of estimate from Table 26.

CubeSat / SmallSat

Heuristic Used in Satellite Database

This category predominantly contains satellites that have less than 11 kg of dry mass. Such objects do not generally have any propulsion capability to avoid conjunctions. Some cubesats are beginning to incorporate maneuverability, either propulsive or differential drag, and there may be policy pressure for this trend to accelerate. Regardless of maneuver capability, we assume that such small satellites are unlikely to be considered a substantial loss if one is struck by a piece of small debris.

We have also used this as a placeholder for a few larger satellites that do not have maneuver capability and are old or defunct, but still present in the UCS database.

Costs Associated with Debris Interactions

Regarding the cost of a collision, we use the cost of an illustrative CubeSat mission. The cost of a CubeSat is about $50k per U. (Endurosat n.d.). For analysis, we assume the average CubeSat in the database is 6U. That leads to $300k in satellite costs. Launch costs are approximately $50k per U, leading to an extra $30k for launch. Thus, the total cost is about $600k per satellite. As with other satellites, we assume that the cubesat is struck when it is halfway through its intended operational lifetime; thus, the cost of lost hardware is around $300k per satellite.

Loss of a small satellite does not necessarily incur a cost associated with lost operations. In the case of a commercial non-maneuverable SmallSat, there are likely to be many such satellites operating, such that loss of one does not harm the revenue of the company beyond the vehicle's replacement cost. In the case of a university or science-related SmallSat, we are generally unable to estimate the value of the lost science or the detrimental effect it may have on the careers of the researchers; thus, we assign the value as zero. Costs are summarized at the end of this section in Table 28.

Table 28. Summary of CubeSat Costs

Cost Element	Value [$M]
Risk Analysis Per Warning	0 [a]
Maneuver Propellant	0 [a]
Maneuver Labor	0 [a]
Maneuver Lost Ops	0 [a]
Collision Lost Vehicle	$0.3
Collision Lost Ops	0

[a] Lack of propulsion precludes costs associated with maneuvers and disposal.

Commercial GEO Satellites

Due to time constraints and the non-trivial effort required to generalize our simplified debris encounter model to GEO, we were unable to properly address risks in GEO in this study. Thus, we did not estimate the operational costs associated with the 104 satellites tagged as being commercially operated in GEO.

Technology Development Satellites

The database lists 10 satellites that we have categorized as Technology Development and which the UCS have also generally considered Technology Development. While technology development satellites can be expensive, they also tend to be short-lived. For the purposes of this analysis, we assume that the value of these satellites will not contribute meaningfully to the final results and have, for the sake of scope, omitted them from the analysis. This is reasonable because there are so few of these satellites and the probability that they will be disabled by debris is low enough that the satellites are unlikely to have their primary mission interrupted.

Appendix B: Efficacy and Cost of Small Debris Remediation

Remove: Ground-Based Laser

See the main text of the document for the high level CONOPs that corresponds to this remediation option. In summary, we analyzed the use of a ground-based laser to ablate material from 1-10cm debris, thus providing sufficient impulse to de-orbit the debris.

Efficacy

In the original work on Project Orion, the laser would need to be able to provide 4 to 6 J/cm2 on target at 800 km altitude at least and hopefully as high as 1,500 km. Taking the worst case scenario, with a piece of debris in a high orbit and made of a material that does not ablate efficiently, the laser would need to engage the target for approximately 3 minutes to lower perigee to 200 km.[32] The total amount of time needed per removal was in the range of approximately 10 minutes, factoring in the amount of time required for detection, acquisition, discrimination, and handover. Table 29 provides a brief summary of the system properties for a demonstration system and two operational capabilities.

Relatively few researchers have addressed the benefits and challenges of using a ground-based laser for debris remediation since Project Orion. One of the major uncertainties associated with this concept are the linear and nonlinear losses the beam experiences as it transits through the atmosphere. Some losses, such as whole-beam thermal blooming and simulated thermal Rayleigh scattering are both avoided by using short pulses—anything below 10 ns will do (Campbell 1996). Disturbances to the beam from ‘nonlinear refractive index’, also called atmospheric self-focusing, were not well understood at the time of Project Orion, but did not appear to be the active constraint on beam intensity delivered to the target.

At the time of Project Orion, technologies such as adaptive optics for correcting beam distortions from atmospheric interference did not yet exist. Adaptive optics techniques, which are now commonly used in astronomy to probe the atmosphere and adjust the optics of the telescope in real-time to correct for atmospheric disturbances, may allow a laser remediator to get around losses due to turbulence and atmospheric absorption. Subsequent research has shown that if the focal length of the mirror is much greater than the thickness of the atmosphere, that a simple model predicts the beam shape after traveling through the atmosphere; further, adaptive optics can be used to pre-correct the beam, as it leaves the laser, so that its shape is gaussian after exiting the atmosphere (Vaseva 2016). We cannot suggest that adaptive optics are able to solve

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[32] Project Orion estimated that small debris needed between 90 m/s and 190 m/s to de-orbit from apogees as high as 1,500 km. Note that small debris tend to be in highly eccentric orbits, so the ΔV requirements are less than if the debris were in circular orbits.

all the issues related to atmospheric transmission nor are we able to assess whether the current level of adaptive optics are sufficient to perform such corrections; however, we have not been able to identify any evidence that indicates these challenges are not addressable. More research is likely needed on these points.

Table 29. Summary of the performance and cost of Project Orion

	Demo System	System A	System B
Laser			
Pulse (on debris)	0.1 kJ at 1-10 ns	5 kJ at 5 ns	2-4 kJ at 100 ps or 10-20 kJ at 10 ps
Rep Rate		1-5 Hz	1-5 Hz
Beam Mirror Width		3.5 m	6 m
Debris			
Highest Apogee	300 km	800 km	1,500 km
Targets Removed	Demo	30,000	150,000
Daily Hours of Operation	Demo	4	20
Total Years of Operation	1	3	3
Total Cost in 2020 Dollars			
Min [$M]	$20	$89	$218
Max [$M]	$44	$168	$371
Cost Per Debris Removal			
Min [$]/debris	N/A	$3,000	$1,000
Max [$]/debris	N/A	$6,000	$2,000

Cost per removal is rounded to one significant figure.

In 2011, DARPA released a study that addressed a CONOPS for ground-based lasers (Pulliam 2011). We note that the concept of operations—and associated efficiency—we analyzed in this report is substantially different from the one analyzed in the Catcher's Mitt study. For removing small debris, Pulliam analyzed a laser operating permanently in "stare mode"; the laser beam is always on, always pointing in the same direction, waiting for pieces of debris to enter its beam opportunistically. Using this CONOPS, the laser would need a spot-size of 100 meters at an altitude of 850 km to encounter about 10 pieces of debris per year that were larger than 5 mm.[33] Pulliam assumed an energy density of about 28 J/cm2 was required to cause ablation. This was a reasonable assumption for a system that cannot track the debris it is de-orbiting; however, when applied over a spot size 100 m in diameter, the system would require terajoules per pulse. By contrast, the most powerful lasers in the world only deliver about 20 kJ per pulse. Thus, using this stare-mode CONOPS is clearly not feasible. Pulliam chose stare-mode for analysis because, at the time, it was "infeasible to increase the time on target by tracking the debris … objects in the 5mm – 10cm size range are too small to be precision-tracked by ground radars and optical sites since they cannot be reliably detected and correlated" (Pulliam 2011).

Emerging capabilities may make it feasible to track cm-sized debris for the approximately 10 minutes needed to engage and remove the debris. Some of the experts we spoke with indicated that passive optical techniques are likely sufficient to detect and track cm-scale debris for this purpose. We are unable to confirm these claims but, based on our engineering intuition, it seems feasible with a sufficiently large-aperture telescope given the ability of relatively small telescopes to detect objects of the single-digit meter size and above. EOS Space Systems has published that they were able to use their laser ranging system to track objects less than 10cm (Smith 2006), though no other details appear to be publicly available.

While passive optical techniques would likely be lower cost, existing radar systems appear capable of tracking small debris on timescales that enable their removal. For example, Muntoni (2021) provides a review of radar measurements of space debris, which contains a few experiments that demonstrated the ability to track small debris. To detect debris, radar are used in "stare" mode until a piece of debris crosses their field of view. To track the debris, once debris is detected the radar shifts into "chase" mode to follow the piece of debris and determine its orbit. For example, in 1994 the TRADEX radar demonstrated the ability to track objects in the range of 3 – 6cm at ranges of 500 to 1,300 km. In 2004, ALTAIR demonstrated a more sensitive capability, tracking 3cm debris at 1,000 km. Detection experiments using Cobra Dane in 2004 showed the ability to detect 5cm debris at around 2,000 km range; while detection is not tracking, Cobra Dane is a phased array antenna capable of tracking objects, so it could in theory track these small detectable objects as well.

In an update to the Project Orion analysis, Phipps provided a new range of laser parameters, performance characteristics, and associated costs (Phipps 2010). Compared to Project Orion, these options use a larger diameter mirror, higher repetition rates for lower-energy pulses, and

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[33] We suspect that this may be underestimating the total number of debris encounters by a substantial amount. The 10-per-year amount was calculated in the context of a physical sweeper located at an altitude of 850 km; thus, it could only interact with debris at that same altitude. However, a laser with a spot size of 100m at 850 km would also be shining through all altitudes below 850 km, though with a progressively smaller spot size.

posits the use of higher energy pulses. For example, Phipps' suggested parameters for removing small debris included:

- 2.2 kJ pulses with 0.1 ns width and 41 Hz;
- 25 kJ pulses with 10ns width and 3.3 Hz; and
- 140 kJ pulses with 100 ns width and 0.2 Hz.

These changes allow for substantially reduced engagement times of about two minutes on average, significantly less than the 10 minutes of engagement required in Project Orion. We note that lasers above 20 kJ are not currently in operation, though they could be developed. If such high-energy options are not developed, there are lower energy options that also suffice for the task. Phipps states that a system with these parameters would remove 250,000 pieces of debris per year.

Cost

A range of potential costs for the project were provided by Project Orion (Campbell 1996) and were reported in Table 29. The costs vary from about $1,000 to $6,000 per 1-10cm debris removed. In the 2010 update, Phipps (2010) estimated that the cost per debris is $330 for 250,000 pieces of debris per year. Note that this implies operating for 23 hours per day. This is unlikely if debris smaller than 10 cm were the only targets; however, included in the 250,000 are other pieces of currently trackable debris up to about 1.7 kg. We use Phipps' highly optimistic estimate as our low-cost value because, in principle, the laser system may engage larger targets and provide other services than simply removing sub-10-cm debris. Thus, we interpret the cost of $330 per debris as the cost of small debris removal, after accounting for the amortization of the full system costs over all lines of business. For the purposes of this analysis, we use the highest cost offered of $6,000 per piece and the lowest cost offered, rounded to one significant figure of $300 per debris.

Remove: Space-Based Laser

See the main text of the document for the high level CONOPs that corresponds to this remediation option.

Efficacy

For use in LEO to de-orbit small debris, as reported by Phipps (2014), the system has a mass of 10,000 kg. It operates in an eccentric polar orbit with apogee of 960 km and perigee of 560 km, allowing it to cross the orbits of all debris in that altitude range. The laser delivers 100ps pulses at ultraviolet wavelengths (343 to 355 nm). Each pulse contains 380 J of energy and the laser fires at a frequency of 56 Hz. The entire spacecraft would require 67 kW of power, with 48 kW feeding the laser and 15 kW for the heat removal system. With these parameters, Phipps estimates that the laser would interact with debris head-on to produce reentry in 10 seconds. Phipps indicates that such a system could remove about 100,000 targets in the span of 4.6 months, before moving on to other lines of business.

We found that this estimate is predicated on a potentially optimistic assumption about how effectively laser energy will couple to small debris to produce thrust. Thus, we also introduced an assumption that the laser is 10 times less effective than reported on average.[34] All else being equal, this assumption means the laser would need to operate for about 10 times longer, for a period of 46 months, to clean out 100,000 targets. Phipps implicitly indicated that the operational lifetime of the remediation satellite is 48 months. Thus, using our more conservative assumption of laser coupling, the satellite would effectively spend its entire lifetime remediating small debris and would not have spare capacity for other lines of business.[35]

Researchers at the Harbin Institute of Technology and Beijing Institute of Spacecraft Environment Engineering have analyzed the efficacy of de-orbiting small debris from various angles of engagement. They demonstrate that a 50g piece of debris can be de-orbited in 10s of seconds if the debris and laser system are co-planar; however, if the laser is in a plane 15 degrees different from the debris, it takes 1000s of seconds to de-orbit (Yang et al. 2022). The L'ADROIT concept

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[34] The Phipps estimate is predicated on all small debris having a coupling coefficient of 99 uN/W; we are unable to assess the reasonability of this assumption because the coupling coefficient varies by the material being ablated and the material composition of small debris is poorly characterized. On the one hand, aluminum is the most common material used in spacecraft, making it also likely to be the most common material for debris. The coupling coefficient for pure aluminum has been measured at 155uN/W, much higher than the assumed coupling coefficient used in the analysis. On the other hand, aluminum also has the highest coupling coefficient of the materials that are commonly used to produce spacecraft. Other materials may have coupling coefficients that are around 10 uN/W. While aluminum may be the most common debris material, debris from fragmented satellites may contain multiple materials in addition to aluminum. Laser ablation of these other materials may produce much less thrust than the case of pure aluminum. To add a layer of conservatism to the estimate, we roughly assume that all small debris has a coupling coefficient of about 10uN/W; this corresponds to materials such as Kevlar epoxy, graphite epoxy, and is a bit lower than carbon phenolic (Phipps 1988).

[35] If the satellite is only de-orbiting small debris, then the power needs may be approximately cut in half, such a satellite may only need about 35 kW of power.

does not appear to consider the efficacy of the system when the laser and the debris are not co-planar. However, unlike some systems for protecting crewed space stations, the L'ADROIT concept is not trying to protect in-space assets against specific pieces of debris that may cause a collision. Instead, it can choose to target whatever piece of debris has the most favorable engagement geometry at the time, which will likely be a piece that is fairly co-planar.

These concepts for space-based lasers to de-orbit debris would require a much larger amount of power than a typical satellite. These power levels may be achievable in the near future. For example, the Roll Out Solar Array (ROSA) was recently demonstrated on the ISS; it stows a 20 kW array compactly by being rolled into a cylinder, unfurling after launch. As a next step, the OSAM-2 mission will demonstrate the ability to additively manufacture scaffolding in space for use on potentially larger roll-out solar arrays. Through capabilities like these, a satellite could be deployed with nearly 100 kW of power for a substantially lower cost than previously possible. There are also concepts for nuclear-powered spacecraft to perform laser removal of debris. The fission surface power project will demonstrate a 40kWe nuclear reactor around the year 2030, which could be augmented to produce somewhat more power for laser debris removal. There may be overlap with other NASA and DOD efforts to develop nuclear propulsion for missions to Mars and to maneuver in cislunar space.

Cost

We made high- and low-cost estimates, shown in Table 30. Over the lifetime of the satellite, Phipps states that the system can remediate 100,000 pieces of small debris for a cost of $310 per object in 2014 dollars, which we used for our low-cost estimate. For the high-cost estimate, the satellite would spend its entire lifetime remediating small debris, due to a much lower coupling of laser energy to debris than Phipps assumed. Noting that the small debris can only be passively acquired for about half the hours of a day, that leaves the other half of the day available for other lines of business. We assumed that the satellite would find other lines of business over which to spread its costs, such as SSA services or nudging large debris objects. Thus, we amortize half of the cost of the system evenly across all 100,000 pieces of debris.

We find the cost of the spacecraft hardware to be reasonable. This system would represent one of the highest power spacecraft to ever fly and the highest power laser to ever fly. Regarding the cost of providing the power, one source reports that the old ISS arrays were $3,500/W (Beauchamp at al. 2015). This is likely an upper bound on the cost of power. The same source estimates that the cost of the solar panels on the Dawn mission from 2007 were about $900/W; this is less than a quarter of the cost associated with the ISS. Further, the source speculates that future developments could bring costs down to below $250/W. It is unclear in what year the historical costs are measured and in what year the future costs may be realized. To get an up-to-date estimate, we take the recent upgrades to the ISS solar panels as a case study. NASA paid $103M for the installation of six iROSA arrays (Clark 2022-iROSA), each of which generates

20kW in full daylight (NASA 2021-iROSA). Conservatively assuming the entire cost is solely for the iROSA hardware, neglecting launch and installation costs, yields $858/W for the iROSA system. Using a cost $858/W in 2020 dollars to build 67kW of solar arrays leads to a total cost of $58M.

Table 30. Costs associated with the L'ADROIT concept.

Element	Mass [kg]	Number	Cost [$2014]	Cost [$2020]
System Costs [a]				
Satellite	10,000		$410M	$450M
Launch [b]			$145M	
Operations [Five Years]			$5M	
Total [c]			$560M	$614M
Low Performance Cost Estimate [d]				
Small Debris Removed		100,000		
Fraction of Lifetime Remediating Small Debris		0.5		
Price per Debris Removed [$/object] [e]			$3,000	$3,000
High Performance Cost Estimate				
Price per Debris Removed [$/object] [a]			$300	$300

a. From Phipps (2014). System costs are verbatim. Price per debris removed is rounded to one significant figure.
b. Falcon 9 launch prices from 2020 were about $5,000 per kilogram for primary payloads. At this price, the cost of launch would be only $50 million. For conservatism, we use the launch cost given by Phipps, though it is about $100M greater than the market rate.
c. The Bureau of Economic Analysis calculates the inflation factor from 2014 dollars to 2020 dollars as 1.0964.
d. Assuming 10 uN/W coupling between laser and debris.
e. Total cost of satellite, multiplied by the fraction of the satellite's lifetime spent remediating small debris, divided by the number of small debris removed, quantity rounded to one significant figure.

What about the cost of the laser? Our understanding from the literature and discussions with one of our sources is that it is not hard to adapt a terrestrial laser for space applications. The main challenges are thermal management and increasing the reliability of the system so that it does not need periodic maintenance. Thus, the cost of a terrestrial laser is a decent point of reference. The Army is paying $123M for a 50kW laser weapon (Judson 2022), which is the same power as the laser onboard this spacecraft. We can conservatively assume that this cost is for the laser and optics only, neglecting the costs of all other weapon subsystems and hardening the weapon for the battlefield. Subtracting this cost of the laser and the $58M for the cost of the solar array from the $450M [$2020] of the L'ADROIT spacecraft leaves $270M for the remaining spacecraft subsystems and integration, which is reasonable.

Remove: Sweeper in Orbit

See the main text of the document for the high level CONOPs that corresponds to this remediation option.

Efficacy

The most recent estimate of performance we were able to find in the literature for a large sweeper comes from the Catcher's Mitt study, which estimated that such concepts were infeasible. For a passive sweeper, that cannot maneuver to a target, they noted that "a 20m sweeper would not likely encounter any debris object larger than 5 mm" in a year (Pulliam 2011). Worse, they estimated that a passive sweeper large enough to capture a substantial number of 5mm debris objects would also collide with hundreds of large objects, which would destroy the sweeper and create more debris. They noted that an active sweeper—one which can maneuver to intercept a piece of debris when detected at a range of 1,000 km—must be able to intercept debris within an effective diameter of 430 meters to remove 200 pieces of debris per year. This may require about 340 m/s of ΔV for a 100 kg-class satellite.

More recent, qualitative descriptions by others in the literature appear to indicate much more favorable encounter rates. For example, "a constellation of [sweeper] spacecraft, all stationed in equatorial orbits, could eliminate thousands of debris items every hour without targeting any specific object" (Kaplan 2019). This estimate appears to rely on "an estimated 100 trillion objects that could cause at least minor damage" (Kaplan 2019), which consists mainly of debris smaller than 1 mm. The number of satellites and their cross-sectional area are not given. Another example states "preliminary debris capture estimates for a 12 m AstroMesh [orbital debris removal] system deployed over a 1-year period would number in the thousands" (Foster 2022). The AstroMesh concept is targeting 4 mm to 9 cm pieces of debris. Unlike the Catcher's Mitt Study, neither paper provides supporting information for these removal rates. Thus, we have generated our own independent estimate.

We used our model for 1-10cm debris to estimate the flux of debris passing through the equator in a year. The flux is the number of pieces of debris that are flowing through a 1 square-meter area every year. The details of our calculation are contained in our calculation spreadsheet. For now, it is sufficient to report that for altitudes between 400 and 1,000 km, our model estimated that the maximum flux occurs in the 850-875 km altitude band. We estimated the flux in this altitude band to be about 2E-4 particles per meter-squared per year, which is reasonable compared to values in the literature.[36]

The number of pieces of debris encountered per year by the sweeper can be found by multiplying the flux by the area of the sweeper. For a 12 m diameter pad, like the one referenced by Foster (2022), we estimate that 0.02 pieces of debris in the 1-10cm range would be impacted per year by a passive sweeper. Using the flux rate for 1-10mm pieces of debris, we find an annual hit rate of only 3 debris per year.[37] This is nowhere near the “thousands” of debris previously estimated; however, our estimate is well aligned with the results from the Catcher’s Mitt study. To achieve a reasonable level of debris remediation, there must either be a very large constellation of sweepers or perhaps a single large sweeper.

Before attempting a cost estimate, we first estimated the mass of the sweeper pads. Petro and Talent provide an equation for calculating the mass of material needed in the pad. Their own analysis indicates that the pad only needs to change the velocity of the debris by about 1 percent to effectively de-orbit it. Specifically, they say “a change in orbital speed of only 1% at 500 kilometers can reduce the time on orbit by about 98% for a spherical aluminum particle having a diameter of 0.01 meters; at 900 kilometers, for the same ΔV of 1%, the reduction would be 93%” (Petro and Talent 1989). Table 31 shows the area-density of the sweeper pad that we calculated would be required to de-orbit debris of various diameters. The mass of the sweeper pad can be found by multiplying the area-density by the surface area of the pad.

Table 31. Area-Density Needed to Reduce Orbital Velocity by 1 Percent

Diameter [m][a]	Area-Density of Sweeper [kg/m2][b]
0.001	0.018
0.01	0.18
0.05	0.91
0.1	1.8

a. Debris is assumed to be an aluminum sphere with density 2700 kg/m3.

b. According to Equation 7 from Petro and Talent (1989), Area Density = Mass $_{\text{Debris}}$ * (ΔV/V) / [Area $_{\text{Debris}}$*(1-ΔV/V)]. Note that ΔV/V is 0.01, or 1 percent.

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[36] ODPO uses various radar data to validate its ORDEM model, which also estimates debris fluxes. Radar data from 2016 shows the debris flux for debris greater than 1 cm in diameter, passing through orbits between 400-1000 km, was about 1E-4 as measured by the HUSIR radar and as estimated by ORDEM 3.1 (Matney et al 2019). This half the value of the flux we used in our calculation, which we calculated as the maximum flux. Further, our model estimated the average flux over the entire 400 – 1000 km range as 1E-4 for debris 1 cm and larger, which is in line with the HUSIR and ORDEM values reported.

[37] There are approximately 130 pieces of 1-10mm debris for every piece of 1-10cm debris; thus, we multiplied by 130.

Cost

Instead of attempting to estimate the total cost of a sweeper, we made a rough estimate of the *lower bound* of the cost associated with this concept, shown in Table 32. To do this, we made the following assumptions, all of which are clear under-estimates of the true cost. We assume the sweeper will launch on a SpaceX Starship, which is launched from a barge at the equator. This allows the Starship to throw its full payload mass of 100,000 kg into an equatorial orbit. We disregard the performance penalty of reaching higher altitudes and allow the full payload mass to be delivered to any altitude in LEO at the lowest possible launch cost we can justify. To maximize the area of the sweeper, we allow the full payload mass to be used for the pad of the sweeper; in other words, we disregard the mass associated with all subsystems other than the sweeper's pad. Likewise, we disregard all costs *except* the launch cost.

Next, we estimated the number of pieces of debris a sweeper with this much mass could potentially de-orbit. For a fixed mass of 100,000 kg, the greatest pad area is achieved by creating one large circular pad, rather than a constellation of smaller pads. Thus, we divide the payload mass by the required area-density of the pad to arrive at the total area of the pad. The area can then be multiplied by the debris flux and number of years it is in operation to calculate the total debris encountered during its lifetime. We provided estimates for debris de-orbited whether the pad is targeting cm-sized debris or mm-sized debris. Finally, we calculated the cost per debris by dividing the cost by the number of pieces of debris de-orbited. Note that this concept of using just the nominal area of the sweeper implies that it is passive.

How much better would an active sweeper perform? The Catcher's Mitt study estimated that an active sweeper might be able to capture 200 objects per year if it had an effective radius of 215 m. This would require using 1.7 m/s of ΔV to move 150 m in any direction, once the debris is detected at a range of 1,000 km (Pulliam 2011). This implies that the true radius of the sweeper is 75 m and that the use of an active system increases the effective radius of the sweeper by a factor of about 3.[38] For our estimate, we generously assume that the active sweeper is 10 times more efficient than the passive system and we do not enforce any mass or cost penalty for the ΔV required per debris encounter.

We see that even with some unrealistically optimistic assumptions, the cost per 1-10 cm debris is substantially more expensive than doing removal with a space-based laser. One caveat is that a sweeper capable of de-orbiting 10cm debris will also be de-orbiting all debris smaller than 10cm; however, we have omitted the number of 1-10mm pieces removed from this cost-per-debris estimate. The reason is that our debris model does not currently incorporate debris below 1cm, so we have no way to assess the benefits of removing such debris. Another caveat to this

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[38] The true radius is 215 m - 150 m = 75 m. The ratio of the effective radius to the true radius is 215/75 = 2.87, which is about 3.

assessment is that space lasers may not be able to address debris as small as 4 mm, so these remediation solutions occupy slightly different niches. Though if a space laser can address debris that small, it will likely win for same reason it wins here. Finally, as SSA capabilities improve to track cm-scale debris, the economics of an active sweeper may become more favorable than a space-based laser. This would require a level of analysis that we did not have time to address. All we can say for sure in this analysis, is that remediation of debris up to 10cm is likely not cost-effective compared to space-based lasers. Subsequent work should refine the costs associated with mm-scale debris and incorporate a method for estimating benefits of removing mm-scale debris.

Table 32. Estimated Lower Bound Costs of a Large Debris Sweeper

Element	1-10cm Debris	1-10mm Debris	Units
Total Mass of Shield [a]	100,000	100,000	kg
Costs Accounted for Passive System [b]			
Non-Recurring Engineering	-	-	$
Sweeper Hardware	-	-	$
Sensing Capabilities for Debris	-	-	$
Propellant for Maneuvering	-	-	$
Operations	-	-	$
Launch @ $500/kg [c]	$50,000,000	$50,000,000	$
SubTotal	**$50,000,000**	**$50,000,000**	**$**
Area-Density of Shield [d]	1.8	0.18	kg/m2
Shield Area [e]	55,556	555,556	m2
Debris Flux Per Year @ 850 - 875km [f]	2.05E-04	2.67E-02	#/(m2-yr)
Operational Lifetime of Sweeper	5	5	yr
Debris Caught During Lifetime (Passive) [g]	57	74,195	#
Minimum Cost Per Debris (Passive) [h]	**$900,000**	**$700**	**$**
Minimum Cost Per Debris (Active, 10x Passive) [h]	**$90,000**	**$70**	**$**

a. Total mass of Starship payload to LEO. Generally this would be for delivery to 400km altitude, but we use it here for higher orbits to estimate a lower bound on the costs.

b. To generate a lower bound on the cost, only looking at the launch cost. The blank values for the other costs are to emphasize what has been omitted.

c. In a previous analysis performed by the author, we estimated that the lowest realistic cost for Starship is about $500 per kilogram (Colvin et al. 2021). For this analysis, we assumed Starship launches the debris sweeper from a barge at the equator, so that the full 100,000 payload can be delivered to an equatorial orbit in one launch.

d. See Table 31.

e. Total mass launched to orbit divided by the area-density of the sweeper for that size-class of debris.

f. See the Flux Calculation box in the spreadsheet for more details.

g. Debris Caught = Flux * Shield Area * Operational Lifetime

h. Cost SubTotal divided by lifetime debris caught. Rounded to 1 significant figure.

Appendix C: Efficacy and Cost of Large Debris Remediation

Remove: Tug to Controlled Reentry

See the main text of the document for the high level CONOPs that corresponds to this remediation option. In summary, the concept we base our estimate on is a system that captures a piece of debris, uses chemical propulsion to immediately set the trajectory of the debris to be a controlled reentry, releases the debris when sufficiently low in Earth's atmosphere, boosts back up to orbit, refuels, and travels to the next piece of debris.

Efficacy

Table 33 illustrates the high-level performance characteristics of the three architectures described in O'Leary et al. (2022). The table illustrates the tradeoff between the type of propulsion system used for conducting the removal and the number of debris removed per servicer. Specifically, while electric-propulsion systems have a reputation for efficiency due to their high specific impulse, they are much slower than chemical propulsion systems. At the system level and for a fixed spacecraft lifetime, a single remediation servicer using chemical propulsion can capture and de-orbit more pieces of debris before its lifetime expires than an equivalent system using electric propulsion. Further, the CONOPS of the purely chemical system used here does not require the servicer to circularize its orbit during the de-orbit—the debris and servicer enter immediately into a transfer orbit with a perigee of 0 km, de-orbit the debris within half an orbital period of the initial burn—saving time and propellant.

Table 33. Summary of the performance of the concept proposed by Orbit Fab

	Chemical-Electric (Disposable)	Chemical-Electric (with Refueling)	Chemical Only With Refueling
Dry Mass [kg] [a]	1,000	1,000	1,000
Maximum Propellant [kg] [b]	863	542	920
Servicers Built and Launched [#] [a]	258	63	7
Servicers Survived After 10% Fail [#] [c]	232	57	6
Operational Lifetime [y] [d]	5	15	15
Number of Refueling Operations [#] [b]	0	470	470
Debris Removed Per Servicer [#]	**2**	**8.4**	**80**

a. Table 3 from O'Leary et al. (2022)
b. Table 2 from O'Leary et al. (2022)
c. They assume that 10 percent of their servicers will fail.
d. Assumption #13 on page 8 of O'Leary et al. (2022)
c. 480 pieces of debris divided by the number of surviving servicers.

O'Leary at al. did not give a precise accounting of the debris their system is removing. We infer that they are removing 480 pieces of large debris with a total mass of 810,000 kg. The average mass of each piece is 1,688 kg. They do not list the minimum and maximum masses of the debris; however, we assume this system is capable of removing objects as large as 9,000 kg. The debris are grouped into six clusters, such that the ΔV between clusters is less than 300 m/s and the ΔV between objects within a cluster is around 50 m/s. With this topology, refueling depots can be placed in locations that allow for many pieces of debris to be removed per depot. We inferred from the paper that the mass-weighted average altitude of the debris is about 1,000 km.

Cost

In this section, we first address the low-cost estimate of controlled reentries based on the Orbit Fab analysis. Then we provide a brief review of a few other cost estimates from the literature.

Table 34. Summary of the Orbit Fab Controlled Reentry System Using Only Chemical Propulsion.

Elements: Chemical Only with Refueling	Mass [kg]	O'Leary Cost [$]	Our Cost[$]
ADR Servicer			
Hardware [a]	1,000	$115,160,000	
Propellant Needed at Launch [a]	395		
Total Mass	1,395		
Launch Cost @ $15,000/kg		$20,925,000	
Cost per Servicer		$136,085,000	
7 Servicers are Needed [a]			
SubTotal Servicer Costs		**$952,595,000**	**$952,595,000**
SubTotal Removal Operations Costs [a]		**$44,070,000**	**$44,070,000**
Refueling Ops			
Fuel Mass Delivered During Refueling [kg] [a]	183,265		
SubTotal Refuel Launch Cost @ $15,000/kg			**$2,748,975,000**
SubTotal Orbit Fab Architecture Cost [a]		**$2,300,000,000**	**$2,300,000,000**
Orbit Fab Sums			
Orbit Fab Reports [a]		$3,300,000,000	
Servicer, Operations, and Architecture Costs		**$3,296,665,000**	
Cost per Kg Removed		$4,070	
Our Sums			
Servicer, Operations, Architecture, and Refuel Launch Costs			**$6,045,640,000**
Cost per Kg Removed			$7,464

a. Reported by O'leary et al. (2022)

O'leary et al. (2022) estimated that a removal spacecraft using a purely chemical propulsion system would be able to remove 480 pieces of debris over 15 years at a total cost of $3.3 billion. This amounts to $4,100 per kilogram of debris removed. Table 34 shows our attempt to recreate O'leary's cost calculations, based on the parameters reported in the paper. In reproducing their calculation, they appear to have omitted the costs associated with launching the propellant for refueling. Incorporating these costs increases the total cost to nearly $6.1 billion and a cost of $7,400 per kilogram removed. We did not have time to contact O'leary to discuss this discrepancy; it is possible that we have misunderstood some aspect of their architecture. Therefore, for the sake of argument, we use O'leary's lowest reported cost rounded to one significant figure as our low-cost estimate: $4,000 per kilogram of debris removed.

To contextualize the low-cost estimate and to develop a high-cost estimate, we review a few other concepts from the literature. The European Space Agency recently funded a debris removal mission that will employ a controlled entry. In 2020, ESA entered into a contract with ClearSpace SA to remove a 112 kilogram payload adapter from a Vega rocket from a 730 km orbit (Biesbrock et al. 2021). The mission is estimated to cost €100 million, with ESA providing €86 million and ClearSpace SA contributing €14 million plus €10 million in margin. The total cost corresponds to ~ $1 million per kilogram removed, but the cost of this first mission is likely much higher than those that a long-running program of frequent removals would be able to achieve. Therefore, we do not use this demonstration mission as representative of a high-cost debris removal operation.

An ESA concept , e.Deorbit, targeted removing Envisat—a roughly 8000 kg science spacecraft that ceased operation in 2012—from an approximately 800 km sun-synchronous orbit (Biesbrock et al. 2013; Biesbrock et al. 2017; Estable et al. 2017). Based on cost estimates from early design work, in about 2015 ESA established a cost cap for e.Deorbit development and operations of €150 million, excluding launch on a Vega C rocket and margins. Converting to dollars, inflating to 2022, adding $40 million for launch (Sheetz 2020), and adding 20 percent margin, this corresponds to $300 million, or about $40 thousand per kilogram removed.

A recent Aerospace study (Tibor et al. 2022) considered controlled-entry removals of the largest debris objects (up to ~ 9000 kg each). They estimated costs for a program of controlled removals as a function of the rate of removals and the duration of the program. For a five-year program conducting one removal per year, their estimate corresponds to $540 million per removal. For a program sustained for 25 years conducting 12 removals each year, their estimate corresponds to $110 million per removal. For a 9000 kg rocket-stage debris object, these estimates yield costs per unit mass removed of ~ $60 thousand and $10 thousand per kilogram, respectively.

One subject matter expert with whom we spoke had commissioned industry studies of debris removal found that for controlled de-orbiting of similar very large pieces of debris, the costs may be in the $10 to 20 million range when debris remediation becomes frequent. This estimate omits non-recurring development costs, and the lower cost figure assumes the use of nets for capturing debris, while the higher figure assumes robotic arms. For a 9000 kg debris object, this range corresponds to ~ $1,000 to $2,000 per kilogram removed. However, the subject matter expert was unable to share the analysis for proprietary reasons. Without a citation or having more details to support this estimate, we mention it here for completeness, but did not use it in our analysis.

For our analysis, we base a range of costs for controlled-entry remediation on the studies of removing the largest objects. **Our upper limit, $60 thousand per kilogram removed**, taken from the Aerospace low-rate-program estimate. **Our lower limit, $4 thousand per kilogram removed**, corresponding to Orbit Fab’s reported estimate.

Remove: Tug to Uncontrolled Reentry

See the main text of the document for the high level CONOPs that corresponds to this remediation option. In summary, the CONOPS we use for our low-cost estimate is a variation on the CONOPS of the controlled reentry case; instead of setting the perigee of the debris to 0 km, we set it to 350 km.

Efficacy

Uncontrolled reentry may pose a risk to terrestrial assets and people, due to the lack of knowledge about where the debris will reenter. Considerations regarding this risk include:

- A piece of debris in LEO would reenter uncontrolled anyway due to drag. Moving an object to a lower orbit does not introduce a new uncontrolled entry; it only changes the timing of the reentry.
- Moving an object may affect perceived liability for any consequences of the reentry.

To first order, the number of debris removed per lifetime of the servicer spacecraft is the same for uncontrolled reentry and controlled reentry. Both operations would take approximately the same amount of time per removal. However, the uncontrolled reentry scenario is more fuel efficient, which leads to decrease in the cost to perform the removals.

We first replicated the performance numbers associated with O'leary's purely chemical approach for controlled reentry, using the rocket equation and inferring some performance characteristics of the system. This served as our validation that our simulation methodology was reasonably correct. We then changed only the ΔV needed for the reentry burn. Using a Hohmann approximation and assuming the average piece of debris starts at 1000 km, we estimated that the average ΔV to reduce perigee to 0 km is 260 m/s. For an uncontrolled reentry, perigee is reduced only to 350 km, which requires a 170 m/s burn. This leads to a savings of 122 kg of propellant per remediation mission. As there are 480 pieces of debris and 7 servicers, that leads to 473 refueling operations required, and a total propellant savings of about 58,000 kg. From that savings, we reduced the costs associated with launching propellant for refueling and the cost of the supporting infrastructure.

While this approach to tugging debris to an uncontrolled reentry may be cheaper than most passive means for performing an uncontrolled reentry, it may also create a level of risk that is statistically or politically unacceptable. We are not requiring that the remediation servicer circularize the orbit of the debris that is reentering. Thus, the debris will be left in a highly eccentric orbit until it reenters, crossing the orbits of many more spacecraft than prior to its remediation. On the one hand, satellites with maneuver capability will avoid the debris as it decays and our cost model indicates that maneuvering to avoid debris does not impose a significant cost on most spacecraft operators. Further, the debris can be placed into an orbit with a perigee low enough that it decays quickly. On the other hand, it will be a nuisance until the de-orbit is completed. Worse, if the debris does fragment for some reason, it will scatter debris in a highly elliptical orbit. Each resulting fragment will generally have a lower ballistic coefficient than the original piece of debris; thus, the fragments will de-orbit faster than the original debris. Regardless, a highly elliptical cloud of small debris may impose significant risk to spacecraft operators and may be politically infeasible. Further analysis is required to determine whether this CONOPS produces a net reduction in risk compared to leaving the debris unremediated.

Cost

We update the costs of the O'Leary architecture to reflect the reduced propellant usage in Table 35. We assumed that the uncontrolled reentry campaign has the same unit, launch, and operations costs as the controlled case. We reduced only the value of the "Orbit Fab Architecture Cost". For the uncontrolled case, we calculated that only 125,347 kg of propellant is required for all the refueling operations, compared to 183,265 for the controlled reentry case. That is a 68 percent reduction. We apply this reduction factor to the value of "Orbit Fab Architecture Cost from the controlled reentry case. Summing these costs and dividing by the total mass of debris leads to an average cost of about $3,000 per kilogram removed. As before, we believe that the Orbit Fab sum was missing the cost associated with *launching* the propellant for the refueling operations. Incorporating that missing element, we found an average cost of about $5,500 per kilogram removed. For the purposes of this analysis, we use the lower of these estimates as our low-cost value.

Disposal via uncontrolled entry should typically be less expensive than controlled entry; indeed, our low-cost estimate for uncontrolled reentry is lower than our low-cost estimate for controlled reentry. However, the high cost of an uncontrolled reentry approach may be above the low-cost of a controlled reentry. We provide estimates for two demonstration missions, which serve as a high-end estimate of the costs, and we draw a low-end estimate from the Aerospace analysis of end-of-life removal of satellites from large constellations.

Duchek et al. (2015) examined using a solar-electric spacecraft to relocate five debris rocket stages of mass 1400 kg from sun-synchronous orbits with altitudes ranging from 500 to 1000 km down to disposal orbits with 400 km altitude. They estimated that the cost of developing the spacecraft for a demonstration mission would be $200 to $300 million. This corresponds to $40 to $60 million per disposal or $20 to $40 thousand per kilogram disposed.

Table 35. Summary of the Orbit Fab Controlled Reentry System Using Only Chemical Propulsion.

Elements: Chemical Only with Refueling	Mass [kg]	O'Leary Cost [$]	Our Cost[$]
Cost per Servicer [a]		$136,085,000	
7 Servicers are Needed			
SubTotal Servicer Costs		**$952,595,000**	**$952,595,000**
SubTotal Removal Operations Costs [a]		**$44,070,000**	**$44,070,000**
Refueling Operations			
Fuel Mass Delivered During Refueling [kg] [b]	125,347		
SubTotal Refuel Launch Cost @ $15,000/kg			**$1,880,197,883**
SubTotal Orbit Fab Architecture Cost [b]		**$1,573,115,481**	**$1,573,115,481**
Orbit Fab Sums			
Servicer, Operations, and Architecture Costs		**$2,569,780,481**	
Cost per Kg Removed		$3,173	
Our Sums			
Servicer, Operations, Architecture, and Refuel Launch Costs			**$4,449,978,364**
Cost per Kg Removed			$5,494

a. From Table 34.
b. Value from Table 34 reduced by 68 percent—the amount of propellant saved.

One company is already preparing to remove a satellite via uncontrolled reentry. Astroscale is developing a removal vehicle called ELSA-m that will conduct a demonstration mission in 2024 (Astroscale 2022). ELSA-m requires target spacecraft to be equipped with a special docking plate to aid rendezvous and capture. A news report indicates that a recent ESA award of about $16 million for ELSA-m would cover about a third of the cost to design and build the spacecraft and that the mass of ELSA-m would be a few hundred kilograms (Rainbow 2022), so we estimate that it will cost about $50 million to design and build ELSA-m and that it can launch on a roughly $10 million booster, for a total cost per mission of about $60 million. The news report also states that ELSA-m would be able to remove satellites with masses up to 800 kg and be able to conduct additional removals after its first mission. Even if the ELSA-m spacecraft is only used twice on 800 kg spacecraft, the cost would be about $30 million per debris removal or $40,000 per kilogram. We do not know how many pieces of the debris a single ELSA-m may be capable of removing; thus, the real cost per kilogram could be substantially less than this.

The previously described costs are for demonstration missions and do not represent the costs expected for operational missions if this method of remediation becomes routine. The Aerospace report examined providing a backup post-mission-disposal capability to large LEO constellations by having removal spacecraft launch with constellation satellites as rideshare partners. They considered target satellites with masses up to 800 kg, and they estimated costs for programs performing from 10 removals per year over five years up to 100 removals per year for 25 years. Their estimates correspond to $26 million per removal for the former and $6.5 million per removal for the latter, or $32 thousand and $8 thousand per kilogram of satellite removed, respectively.

There are a number of other approaches for uncontrolled reentry that we were unable to address in time for this report. Some of these include the use of SmallSats (sometimes called ‘nanotugs’) for debris removal; remediation servicer that use ion beams, rocket exhaust, or lasers to shepherd debris to lower orbits; or attaching drag devices to spacecraft to accelerate their orbital decay. We hope to incorporate these in future analyses; however, we find that the uncontrolled reentry case we have analyzed may provide a lower cost to de-orbit than these other approaches.

The only method we found that may provide a lower cost per kilogram to de-orbit uses an electrodynamic tether (EDT). However, the information was shared with us at the end of the study and is not publicly available; thus, we did not have the chance to critically engage with the cost estimate. We may address this in a subsequent analysis, but it is out of scope for now.

For the purposes of this analysis, we assume that a high-end cost estimate is reasonably around $40 thousand per kilogram for any piece of debris in LEO above 100 kg. The assumption that costs per kilogram are approximately constant as a function of debris mass and altitude is partially supported by the ELSA-m and the Duchek demonstration missions; both yield similar costs per kilogram, though they remediate debris with substantially different mass (800 kg versus 1400 kg) and different altitude ranges (1,200 km and 500 – 1000 km). For a low-cost estimate, we use our calculated value of $3 thousand per kilogram, derived from the Orbit Fab analysis.

Move: Lasers for JCA and Large Debris Traffic Management

See the main text of the document for the CONOPs that corresponds to this remediation option.

Efficacy

The same system we analyzed for removal of small debris with a space-based laser could also be used to nudge or de-orbit large debris in LEO. Phipps designed the system to move 2000 objects over a period of 4 years, each with a mass of 1000 kg, by 40km altitude. We find the utility of this CONOPS likely to be low; however, we used the parameters of the system to estimate its performance for JCA. Whereas a small piece of debris can be de-orbited with one engagement, a piece of debris with mass of 1,000 kg can only be nudged by about 8.3 cm/s (Phipps 2014). Based on those parameters, we developed high and low performance estimates, shown in Table X.

Table 36. Summary of the L'ADROIT System for Use in JCA.

Element	100 kg Object	1,000 kg Object	9,000 kg Object
High Performance Estimate [a]			
ΔV on Object per Shot [m/s] [b]	0.83	0.083	0.0092
Max Possible dV Over Lifetime [m/s] [c]	1,037,500	103,750	11,484
Max Possible Maneuvers High dV [#] [d]	10,375,000	1,037,500	114,845
Max Possible Maneuvers Low dV [#] [d]	103,750,000	10,375,000	1,148,448
Low Performance Estimate			
ΔV on Object per Shot [m/s] [e]	0.083	0.0083	0.00092
Max Possible dV Over Lifetime [m/s] [c]	86,113	8,611	953
Max Possible Maneuvers High dV [#] [d]	861,125	86,113	9,532
Max Possible Maneuvers Low dV [#] [d]	8,611,250	861,125	95,321

a. For the high-performance scenario, we rely on estimates reported by Phipps (2014) for a 1,000 kg piece of debris. Estimates for the 100 kg and 9,000 kg pieces of debris are derived from the performance associated with the 1,000 kg debris.

b. We use the rocket equation to estimate the ΔV for the 100 kg and 9,000 kg objects. In another paper, Phipps estimated that a UV laser ablating pure aluminum with a coupling coefficient of 100uN/W would produce a specific impulse of 1670 seconds (Phipps 2016). We solved the rocket equation using this specific impulse, a mass of 1000 kg, and ΔV of 8.3 cm/s to find that about 5 grams of material would be ablated. Assuming the same specific impulse and mass of ablated material per pulse, the rocket equation indicates that a 9000 kg object would experience a ΔV of 9.2 mm/s per pulse. Likewise a 100 kg object would experience 83 cm/s of ΔV per pulse. This result is effectively independent of the specific impulse we assumed and holds true so long as the ablated mass is less than 1 kg per pulse.

c. Phipps (2014) estimated that the laser may have 1.25 million shots at debris over a 4-year period. The maximum possible ΔV the laser system can create on each type of object is 1.25 million times the ΔV per shot.

d. The average amount of ΔV for collision avoidance maneuvers is between 1 and 10 cm/s. The maximum number of maneuvers the laser can create is the max ΔV divided by the ΔV per maneuver.

e. For the low performance estimate, we assume the laser is not coupling to pure aluminum but also other materials as well. Like the case for removing small debris, we assume that the coupling coefficient may be as low at 10uN/W. This has the effect of reducing the ΔV per shot by a factor of 10 compared to Phipps (2014).

Cost

To estimate a range of costs per nudge associated with a space-based laser, we divide the total system cost by the maximum number of maneuvers that the system can accomplish in its lifetime. The cost of this system was discussed previously in the context of removing small debris and we retain the same cost for this application. Table 37 summarizes the ranges of costs we estimated.

Table 37. Costs associated with using L'ADROIT for JCA.

Element	100 kg Object	1,000 kg Object	9,000 kg Object
High Performance Estimate			
Max Possible Maneuvers Low dV [#] [a]	103,750,000	10,375,000	1,148,448
Best Case Cost Per Nudge ($) [b]	$6	$60	$500
Low Performance Estimate			
Max Possible Maneuvers High dV [#] [a]	861,125	86,113	9,532
Worst Case Cost Per Nudge ($) [c]	$700	$7,000	$60,000

a. Calculated in Table 36 and written in bold font.

b. Best case cost scenario is associated with 100 uN/W coupling coefficient and 1 cm/s per maneuver to avoid a potential collision. Total system cost is about $600 million, per Table 30. Cost is rounded to one significant figure.

c. Worst case cost scenario is associated with 10 uN/W coupling coefficient and 10 cm/s per maneuver to avoid a potential collision. Total system cost is about $600 million, per Table 30. Cost is rounded to one significant figure.

Recall that our model of the debris risk uses three levels of debris interaction: warning, maneuver, and collision. To calculate a total cost of remediation in the subsequent chapter, the costs per nudge need to be paired with a heuristic for when to nudge based on the three interactions we model. There are a few options for such a heuristic.

If the conjunction is between an active satellite and a piece of debris:

- **Nudge every warning**. A satellite operator may opt to nudge the debris at the warning stage, then avoid paying the risk analysis costs and maneuver costs. Note that the best-case costs to maneuver 100 kg and 1,000 kg objects are below the costs we've estimated that some satellite operators will expend doing risk analyses of warnings. It may make financial sense to engage the laser nudging system for every debris warning instead of worrying about it.
- **Nudge every maneuver.** If the satellite operator would have decided to maneuver, they may have preferred to pay to nudge the debris out of the way instead. This may be preferable depending on the cost of performing the maneuver. Our cost estimates correspond to nudges of 1 cm/s and 10 cm/s of ΔV, which is equivalent to a typical debris avoidance maneuver performed by active satellites.
- **Nudge every collision**. As previously mentioned, warnings and maneuver decisions are based on SSA capabilities that have high uncertainties. This creates

a significant number of false-positive events, where remediation actions are taken to avoid a collision that would not have occurred anyways. Using lasers to triage warnings and maneuvers could reduce uncertainties to the point where false positives become infrequent. In this situation, satellite operators would be able to avoid taking remediation action until a collision was certain. Using this as a heuristic for when to nudge a piece of debris incorporates the effect of improved orbital determination capabilities that are provided by the laser systems.

If the conjunction is between two pieces of debris:

- **Nudge every warning. T**he debris could be nudged every time there is a warning, thus ensuring that collisions are always avoided. This is unlikely to be necessary, given the improved accuracy of orbital determination that the laser system can provide. However, in some cases, the cost associated with ranging the debris to determine that no risk is present may be comparable to the cost of nudging the debris.
- **Nudge every maneuver.** Since lasers provide debris with maneuver capability, the laser could be used to nudge the debris whenever an active satellite would have maneuvered. This is a reasonably conservative approach.
- **Nudge every collision.** The considerations for this heuristic are the same as for when an active satellite is involved. Using the enhanced ability to determine the orbits of the debris, the debris would only need to be nudged if the collision was fairly certain.

Move: Rapid Response Rockets for JCA

See the main text of the document for the high level CONOPs that corresponds to this remediation option. In summary, when a conjunction assessment provider predicts that a collision with debris is likely, a rocket is launched to intercept the orbit of the debris and gently nudge the debris away from the collision.

Efficacy

There are three main aspects of efficacy that need to be address for such a system: accuracy of the conjunction assessments, ability to launch the rocket in a timely manner, and ability of the rocket to nudge the debris after launch. We relied primarily on Tibor et al. (2022) for our analysis of cost and efficiency.

Ideally, a rocket for performing JCA would be launched only when a collision was certain to occur. However, modern capabilities for SSA do not allow for such accuracy. As we previously noted, a satellite operator will maneuver to avoid a conjunction if the probability of collision is 0.01 percent or greater. If this same threshold were applied to the use of a rocket for JCA, we may find that 10,000 rockets are launched to prevent only 1 collision. This false-positive rate for collisions would be unacceptably high, given the cost of launching the rockets.

However, we assume that the cost of a laser system for performing JCA is comparable to or greater than the cost of a basis laser ranging capability. Thus, we use the cost of our laser JCA solution as a proxy for the cost of the enhanced SSA capabilities that would be required for the rocket JCA approach to have a low-enough false-positive rate to be feasible. In our estimates for the remediation of the Top 50 debris, the estimated probability of a debris-on-debris collision involving those debris is about 3 percent; however, for analysis, we assume that the false-positive rate of the laser-SSA capability is such that we launch one rocket per year to remediate those debris.

Regarding the other two aspects of efficiency—responsive launch and ability to nudge—we were unable to make any assessments. We simply note that responsive launch is a goal of many companies, such as Astra, Rocket Lab, and Virgin Orbit. Such capabilities are being actively supported by the Department of Defense. The short-lived hardware needed for the in-space operations is also likely to be fairly cheap and easy to have on-call for a launch. Thus, we assumed that such responsive capabilities are possible, with the caveat that responsive launch capabilities have been under development for at least two decades and no providers have yet emerged with a mature service.

Cost

Aerospace provided a range of costs based on the size of the rocket needed to nudge debris (Table 38). The rockets are assumed to be from six ground missile launch sites, which require development and regular sustainment. While the concept for rocket JCA proposed by CNES uses an air-launched rocket, these ground-based costs are likely sufficient to understand the order of magnitude of costs involved.

Table 38. Summary of hardware costs for a rocket JCA system

		Cost ($M) [$2022]			
Bin	Launch Mass (kg)	Development	Hardware	Site Infrastructure	Monthly Sustainment
Small	500	$250	$5	$65	$10
Medium	1,000	$1,000	$25	$225	$25
Large	2,000	$2,000	$50	$500	$50

Credit: Tibor et al. (2022)

Aerospace then calculated the annual costs associated with using the capability amortized over various timeframes (5 to 25 years) and launch rates (6 to 12 per year). Table 39 shows a range of costs for using the capability. For our analysis, take the high and low range associated with a launch rate of 6 rockets per year, rounding them to one significant figure. Thus, we use a low cost of $30M and a high cost of $60M per use of a rocket JCA system.

Table 39. A range of costs per nudge for a rocket JCA system.

Cost	Timeframe	Nudges Per Year	Total Nudges	Cost Per Nudge
$1,700,000,000	5	6	30	$56,666,667
$2,400,000,000	10	6	60	$40,000,000
$4,600,000,000	25	6	150	$30,666,667
$1,900,000,000	5	12	60	$31,666,667
$2,800,000,000	10	12	120	$23,333,333
$5,700,000,000	25	12	300	$19,000,000

Recycle: Debris Into ΔV

See the main text of the document for the high level CONOPs that corresponds to this remediation option.

Efficacy

It seems likely that the debris throughput for a fully electric satellite will be less than the throughput assumed for a controlled reentry like those posited by O'Leary (2022). In the controlled reentry case, the perigee of the debris is set to zero, thus the debris reenters almost immediately, within half an orbit from the burn. A purely EP system could not achieve such a quick disposal, even for an uncontrolled reentry. We have no basis for estimating the increased amount of time such an operation would take; thus, for the purposes of this analysis, we assume that a pure-EP system can remediate the same number of debris in its lifetime as the chemical-electric hybrid system from O'Leary (2022)—about 7 or 8.

To estimate the efficiency of a debris-to-ΔV system, we first constructed a validation case to simulate architecture #2 from O'Leary et al. (2022), the chemical-electric-hybrid system with refueling. With a reasonable replication of that architecture, we modified it to perform debris remediation using only electric propulsion and tugging debris to 350 km altitude instead of 0 km altitude. The EP system from O'Leary uses krypton as propellant and has a specific impulse of 1,500 seconds. Finally, the debris-to-ΔV case is the same as the electric-only system, except that it does not require any external refueling architecture or operations.

For the validation case, it was not fully clear during which legs of the journey the Orbit Fab analysis architecture 2 was using chemical or electric propellant. We assumed that electric propulsion was used from the depot to the debris, for RPO to capture the debris,[39] and for most of the de-orbit burn. Chemical propulsion was used for the final portion of the de-orbit burn (about 43 m/s imparted to the debris) and then used for the burn that re-raises the servicer's orbit immediately after detaching from the debris near perigee. The servicer is assumed to arrive empty back at the depot. We then tuned the model parameters to replicate Orbit Fab's results. For the Uncontrolled reentry validation case, discussed previously, we had tuned the ΔV from depot to debris to be 65 m/s on average. We retained that tuning parameter for architecture 2. To our surprise, our results matched O'Leary's perfectly if we assumed that the ΔV needed for the de-orbit burn was the same for both chemical and electric propulsion systems. In general, this equivalency should not be true since EP systems require greater ΔV than chemical systems—suggesting a flaw in either our simulation or O'Leary's. Regardless, we shall use it as

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[39] We cannot confirm that electric propulsion can be effectively used for RPO; however, there are companies attempting to develop this capability. For simplicity, we assume that electric propulsion is used for RPO here.

a simplifying assumption for the purposes of this analysis because it places us in exact agreement with our validation case.

Next, we calculated the propellant used assuming a purely electric propulsion system that tugs the debris down to 350 km altitude, holding all other assumptions fixed. We found that this would require 55 kg of Krypton, compared to the validation case which uses 56 kg of Krypton and 178 kg of chemical propellant. As seen in Table 40, the total amount of propellant used for refueling in the validation case was over 97,000 kg, while the pure-EP system requires only around 23,000 kg for refueling. As mentioned previously, the debris-to-ΔV concept would not require any propellant to be launched from earth for refueling, thus it saves about 23,000 kg compared to the pure-EP case.

We provide the same caution for this remediation approach as for the uncontrolled reentry case. The debris is being deposited into a highly elliptical orbit, which may or may not be acceptable. The discussion on the efficiency of remediation by uncontrolled reentry provides more detail on this point. The main unique point here is that recycling is itself a form of fragmentation and may generate debris under nominal operations, making it even more risky to use in this highly elliptical manner. This effect may be balanced by the reduced cost of propellant; once the servicer attaches to the debris, it may be able to remove all the aluminum it needs to circularize the orbit of debris at its new disposal altitude. This would likely increase the time per debris remediation and reduce the number of debris a single remediation servicer could service in its lifetime.

Cost

Using the validation case as a baseline from which to make changes, we: reduced the propellant required at launch and for refueling, reduced the cost of the Orbit Fab Architecture by the ratio the mass of propellant for refueling, and added in $2 billion of non-recurring engineering for the debris-to-ΔV case. We found that the cost associated with the debris-to-ΔV case might cost about the same amount per kilogram remediated as the chem-electric hybrid architecture from the validation case; while the debris-to-ΔV option eliminates the cost of depots and refueling, it may also require that those savings are directed into the NRE to bring the concept to fruition. What if the NRE were effectively zero, perhaps because the same technology were matured for ISAM purposes other than debris remediation? In this case, the debris-to-ΔV scenario costs about the same as the pure-electric propulsion architecture; there is no longer any need for the roughly $300 million in fuel depots and refueling, but on a per-kilogram basis, that cost savings is spread out over about 810,000 kg—a reduction in cost of only about $370 / kg[40] compared to the pure EP case.

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[40] $300 Million divided by 810,000 kg.

Table 40. Summary of the Controlled Reentry System We Used as a Point of Departure, an EP-only Approach to Uncontrolled Reentries, and a Recycling Concept

Elements	Mass [kg]	Cost of Architecture 2 from O'Leary [$]	Mass [kg]	EP-only Uncontrolled Reentry Cost [$]	Mass [kg]	Our Debris to ΔV Cost [$]
Servicer Costs						
Hardware per Servicer [a]	1,000	$76,770,000	1,000	$76,770,000	1,000	$76,770,000
Propellant Needed at Launch	239		55		55	
63 Servicers are Needed						
Launch Cost per Servicer @ $15,000/kg	1,239	$18,585,000	1,055	$15,825,000	1,055	$15,825,000
Subtotal per Servicer		$95,355,000		$92,595,000		$92,595,000
Subtotal Servicer Costs		**$6,007,365,000**		**$5,833,485,000**		**$5,833,485,000**
Subtotal Removal Operations Costs [a]		**$125,400,000**		**$125,400,000**		**$125,400,000**
Refueling Operations						
Fuel Mass Delivered Total [kg]	112,423		26,241		3,465	
Fuel Mass Delivered with Servicer [kg]	239		55		55	
Fuel Mass Delivered During Refueling [kg]	97,366		22,797		-	
Subtotal Refuel Launch Cost @ $15,000/kg		**$1,460,490,000**		**$341,957,716**		**$-**
Subtotal Orbit Fab Architecture Cost [b]		**$1,300,000,000**		**$304,380,743**		**$-**
Non-Recurring Engineering		**$-**		**$-**		**$2,000,000,000**
Orbit Fab Sums						
Servicer, Operations, and Architecture		$7,432,765,000		$6,263,265,743		$7,958,885,000
Cost per Kg Removed		**$9,176**		**$7,732**		**$9,826**
Our Sums						
Orbit Fab Sum Plus Refuel Launch Costs		$8,893,255,000		$6,605,223,459		$7,958,885,000
Cost per Kg Removed		**$10,979**		**$8,155**		**$9,826**

a. From Table 34.

b. The architecture costs for the EP and recycling case are the cost of O'Leary multiplied by the ratio of fuel mass delivered compared to O'Leary.

While the cost of the debris-to-ΔV concept may be about the same as the EP-only architecture we've simulated, it potentially offers a capability that the EP-only architecture cannot provide. The remediation satellite could chop up the debris so objects that would have needed a controlled reentry can now undergo an uncontrolled reentry. It is even more interesting that, even if NRE for this concept were zero, the associated cost per kilogram is *still* higher than our lowest cost for controlled reentry.

These costs are counter-intuitive findings that must be taken lightly for now. While creating our validation cases, it appeared that some important aspects of the operations may not have been included. For example, the validation cases do not appear to incorporate significant drag losses from the remediation satellite dipping so low into the atmosphere, nor do the validation cases seem to account for the higher amount of ΔV required for an EP system to perform a maneuver that is equivalent to a chemical propulsion system. This is not meant as a criticism of the O'Leary work, but simply a caveat to the findings in our own analysis. Likewise, we did not account for how the mass of the remediation satellite may change as the propulsion and remediation methods are changed. We also did not account for the variability in the amount of time required to remediate a single piece of debris that a pure-EP or debris-to-ΔV satellite. Finally, we are relying on a very coarse approximation of the ΔV required to reach and to de-orbit the target debris; O'Leary was bound by the locations of the clusters of debris and the locations of the refueling depots, but the debris-to-ΔV architecture would not have such constraints. Subsequent analyses on the debris-to-ΔV concept should attend to these considerations.

The same satellite that makes fuel rods for removal of debris could also make fuel rods for other in-space MPTs or generate feedstock for ISAM processes by recycling most of the aluminum in the satellites, not just the amount needed for the de-orbit. Cislunar Industries is developing such a capability. Their pitch deck (Calnan 2022) indicates that revenue may be $1.1 to $5.5 billion (Slide 24). In context, we take this to be annual revenue, since the annual revenue from recycling Starlink satellites alone is listed as $200M to $1B per year (Slide 27). We are skeptical that this market will exist in 10 years; however, we will assume that it does for the sake of analysis. We assign the total revenue from this market as $3 billion over 15 years, using the annual revenue from Starlink satellites as a point of reference.[41] To reach as low a cost as possible, we also generously disregard the NRE. These two assumptions lead to a discount of about $5 billion off the total cost, bring the cost of remediation down to about $3.6k/kg. This is effective the same cost as the controlled reentry case, only now the aluminum of the debris are not being wasted and vaporized as debris reenters the atmosphere.

We used $10,000 / kg for the "high cost" estimate. Factoring in the potential revenue from selling fuel rods or ISAM feedstock, we get $4,000 / kg for the low-cost estimate. These numbers are

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[41] $200M per in revenue operating for 15 years while these pieces of debris are removed $200M * 15 = $3 billion.

highly speculative and should be considered only in the context of the numerous, previously stated caveats.

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