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Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris

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Executive Summary

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Purpose

Orbital debris may collide with crewed and robotic spacecraft, placing them at risk. The wide range of debris, from 9,000-kilogram rocket bodies to millions of millimeter-size debris, has led to a similarly wide range of proposed actions for addressing the risks posed by debris. However, the costs and benefits of these actions have historically been unknown. This is a challenge for decision makers who are choosing which actions to support through technology development or policy changes. NASA's Office of Technology, Policy, and Strategy is addressing these technical and economic uncertainties by building a capability to (1) complete rigorous calculations of the net present value of each action, (2) identify an optimal portfolio of actions to reduce risk, and (3) quantitatively analyze policies related to space sustainability. This report describes our progress toward that capability and to solicit feedback from the space and economic communities.

Our previous work,[1] referred to here as Phase 1, assessed the costs and benefits of performing debris remediation on operationally relevant timescales. The current analysis contains major updates to the risk model used in Phase 1 and expands the breadth of actions considered to include mitigating the creation of debris, improving the ability to track debris, and more methods for cleaning up existing debris. We demonstrate that our approach of measuring risks in dollars allows for the effectiveness of seemingly incommensurate actions to be compared and generates insights that other approaches to measuring risk have missed.

Background

Orbital debris is defined as all human-made objects, including fragments and other elements, that are in Earth's orbit or are reentering the atmosphere and that are nonfunctional. Debris hinder 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 increase the costs of space operations by requiring efforts to shield against or maneuver around debris, threatens the safety of astronauts and satellites, limits the ability to launch spacecraft, and may eventually make entire orbits unusable.

[1] Colvin, Karcz, and Wusk. 2023. Cost and Benefit Analysis of Orbital Debris Remediation. https://ntrs.nasa.gov/citations/20230002817

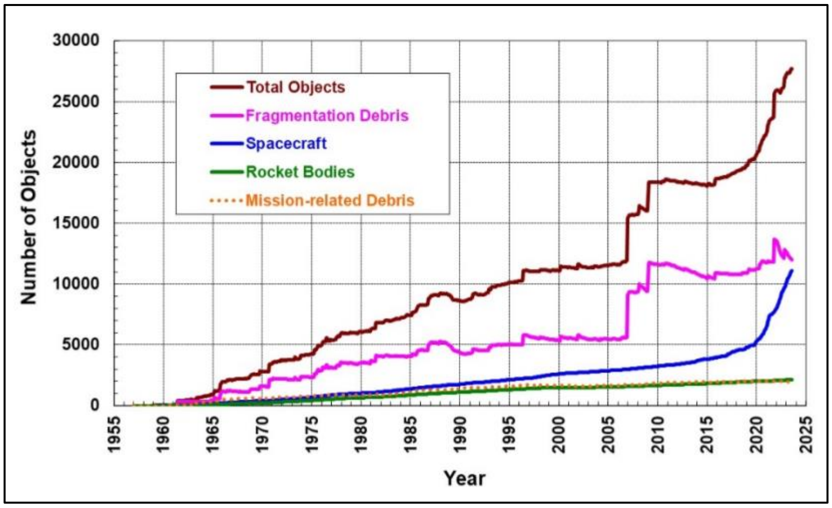


Figure ES-1. Growth in the number of tracked space objects.

About 25% of tracked objects are debris from nominal space operations (Figure ES-1); these objects include defunct spacecraft, rocket bodies, and items intentionally released during missions. About 50% of tracked objects were created during fragmentation events, such as anti-satellite tests, explosions of propulsion systems and batteries, and accidental collisions. The first-known satellite fragmentation occurred in 1961, when the Ablestar upper stage exploded and produced nearly 300 trackable pieces of debris. In total, about 75% of tracked objects are debris.

Using space situational awareness capabilities, satellite operators can maneuver to avoid large, tracked debris. However, most debris are not tracked. Specifically, NASA's Orbital Debris Program Office estimates that over 100 million pieces of small debris are not currently tracked or avoidable by spacecraft. Nevertheless, the debris are large enough to degrade or destroy spacecraft. These small, untracked debris are generated through the fragmentation or surface degradation of large debris. The risks these debris pose may increase, as the volume of debris, tracked and untracked, is projected to increase. It is unclear what the most cost-effective means are to reduce the risks associated with orbital debris.

Improvements Compared to the Phase 1 Risk Model and Analysis

The Phase 1 study was the first step toward an economically rigorous assessment of the costs and benefits of addressing orbital debris. It contained several major limitations, including: (1) rough fidelity on the estimated costs to develop the systems and not accounting for the development timelines; (2) omission of key parts of the risk landscape, such as debris smaller than 1 centimeter and the orbital decay of debris; and (3) a sole focus on remediation, which does not inform effectiveness relative to mitigating, tracking, and characterizing debris. This study addresses the second and third limitations. The scope of the study is illustrated in Figure ES-2.

We simulate the evolution of space debris over a period of 30 years. We also model the financial consequences that spacecraft operators incur as they assess their risks to close approaches, maneuver to reduce risks, and experience mission-ending collisions with debris that are not currently tracked. We combine the models of the evolving debris environment with the financial consequences of operating in the environment to estimate the risk to all spacecraft operators, foreign and domestic, measured in dollars. Further, we model how taking specific actions to alter (1) the debris environment or (2) spacecraft operators' interactions with the environment change the risks to all space operators. The risk reduced by an action is the benefit of that action.

Compared to Phase 1, we have added debris as small as 1 millimeter to the risk model. We have improved our modeling of debris generating events to include not only collisions, but also accidental explosions and the shedding of millimeter-size debris from the surface degradation of large debris. This risk model now includes the effects of atmospheric drag, which cause the orbits of debris to lower naturally over time.

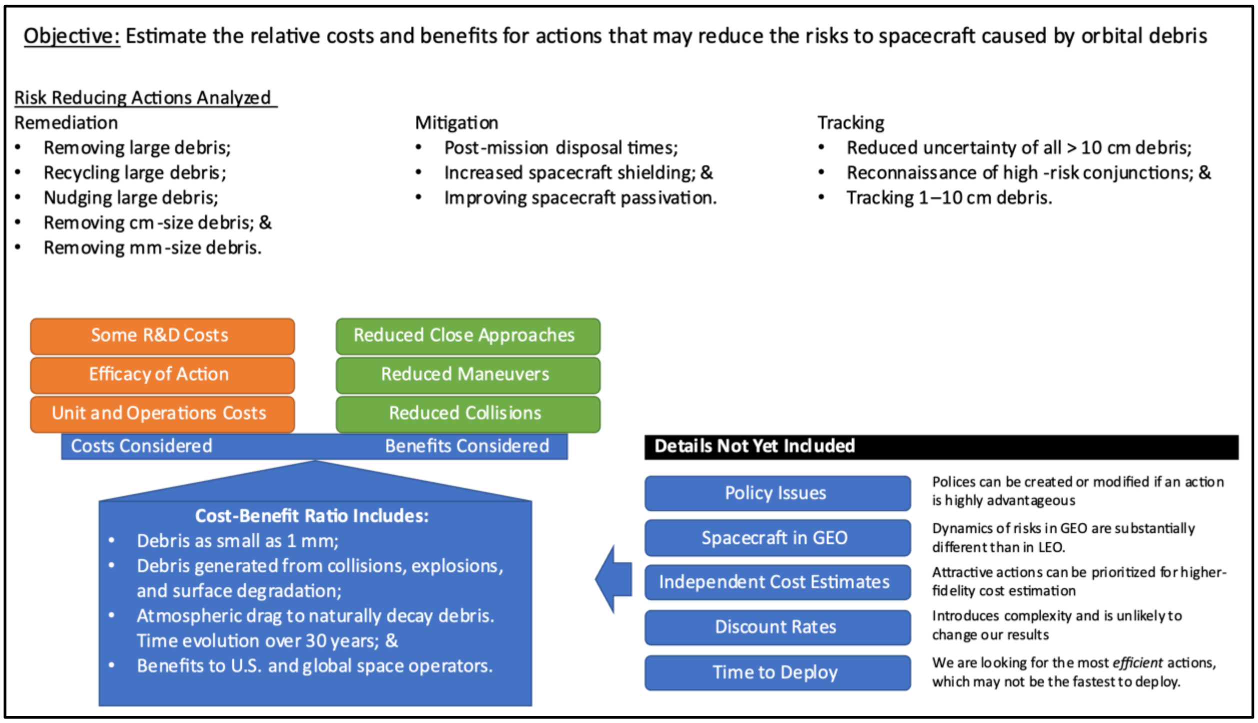
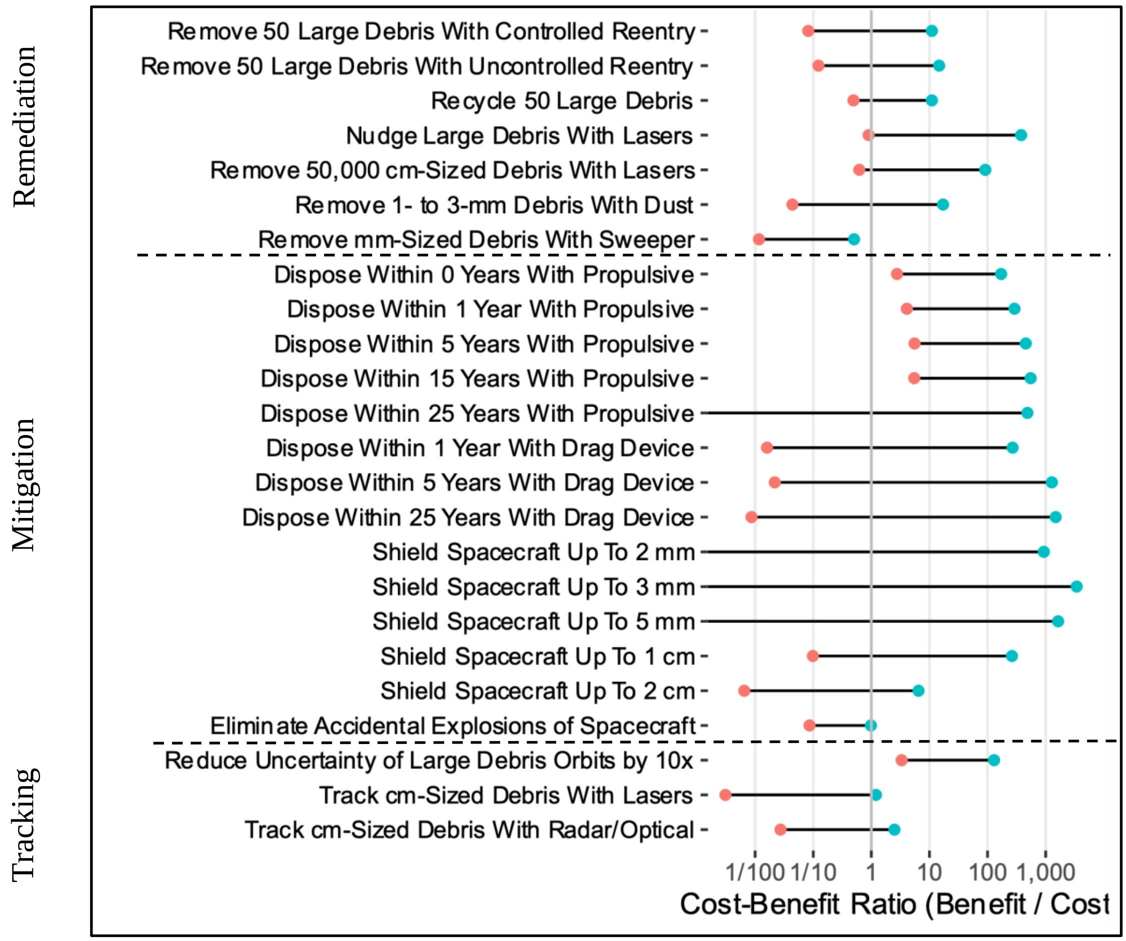


Figure ES-2. Cost-benefit considerations included in the current study.

The risk-reducing actions in Phase 1 were limited to debris remediation. The current work expands the scope of actions considered to include actions related to debris mitigation and tracking. Mitigation actions include reducing the number of years a defunct spacecraft can remain in orbit as part of its postmission disposal, increasing the shielding on a spacecraft to protect it from greater numbers of debris, and passivating the spacecraft to eliminate its chances of accidentally exploding. Tracking actions include beginning to track centimeter-size debris and reducing the uncertainty of the orbits of debris that are already tracked. Remediation actions include removing and recycling very large debris, nudging large debris to eliminate the risk that they will collide with other debris, and removing centimeter- and millimeter-size debris.

Measuring Debris Risk in Dollars Enables the Effectiveness of Mitigation, Tracking, and Remediation to Be Compared

We have demonstrated that measuring costs and benefits in dollars enables comparisons of the effectiveness for seemingly incommensurable actions. The costs and benefits of each action vary widely; thus, we calculated benefit-cost ratios for each action to enable fairer comparisons between actions. Figure ES-3 shows the estimated ratios for most of the actions considered in this report. For example, the figure shows that eliminating accidental explosions of spacecraft through passivation may be less cost-effective than improved tracking of large debris or just-in-time nudging of large debris away from predicted collisions. We are unaware of another analytical approach that allows for such broad comparisons or that indicates where to spend a marginal dollar to most effectively reduce the risks of operating in space.



For each action, the figure presents a ratio range, with the left-most ratio representing the low-benefit, high-cost estimate and the right-most ratio representing the high-benefit, low-cost estimate. A ratio greater than 1 indicates that the action produces more benefits than it costs to implement after 30 years. For example, removing 50 large pieces of debris has a minimum ratio of approximately 1/10 and a maximum ratio of approximately 10; therefore, a dollar spent removing some of these large debris may produce a risk reduction of 10 cents to $10, depending on the costs to perform the removal and assumptions about the effect of those debris on the operating environment.

Figure ES-3. The estimated range of cost-benefit ratios associated with each action after 30 years.

We also demonstrated that measuring space sustainability in terms of monetary risk to spacecraft operators provides insights not captured by measuring proxies for risk, such as the number of debris in space or the number of conjunctions with debris. For example, if the number of large debris in space is the metric of concern, then any approaches that do not directly reduce the number of large debris—such as improving debris tracking, nudging large debris away from collisions, and removing small debris—will have a low value and likely not be considered. However, these types of actions are precisely the types our study found to be highly valuable. Rather than discuss all of the implications of our findings, we focus the remainder of the discussion on two of our biggest insights.

Debris Remediation Can Be as Cost-Effective as Tracking and Mitigation

Our results in Figure ES-3 show that debris remediation capabilities can provide just as much risk reduction per dollar spent as tracking and mitigation can. The most effective form of remediation is just-in-time collision avoidance, which nudges large debris away from possible collisions, as needed; this approach eliminates the risk that a piece of large debris will collide with another object, which would create vast showers of untracked debris that increase mission-ending collisions for all spacecraft at altitudes below the collision. The nudges can be provided by a variety of technologies, including ground-based lasers, space-based lasers, and sounding rockets that release dust to increase drag on the debris, among others. The next-most-effective remediation action is to remove centimeter-size debris with a laser system. In the best cases, just-in-time collision avoidance and removal of centimeter-size debris may return benefits that are 300 and 100 times their costs, respectively.

These ratios compare favorably to the best ratios in mitigation and tracking. Our ratios for each action have wide ranges, and we make no claims about what costs and benefits are most likely within those ranges. Therefore, if the true costs of mitigation are higher than our optimistic estimates or the benefits are lower than our optimistic estimates, the actual effectiveness of mitigation options could fall below the effectiveness of remediation options. In other words, remediation may be better than mitigation in some circumstances. We encourage the space community to realize that the effectiveness of remediation can be comparable to—and perhaps better than—mitigation and tracking.

Rapidly Deorbiting Defunct Spacecraft Is Highly Cost-Effective

Our analysis indicates that as spacecraft are deorbited more rapidly, the net benefits to spacecraft operators increase. This trend holds all the way down to immediate reentry of spacecraft at their end of mission. A spacecraft in low Earth orbit should be deorbited within 25 years after its mission ends, according to the U.S. Government Orbital Debris Mitigation Standard Practices. However, some U.S. regulatory agencies and the European Space Agency are moving toward a 5-year rule for deorbiting defunct spacecraft. Our analysis indicates that these reduced deorbit timelines cost-effectively reduce risk to space operators and that more net benefits could be gained by reducing the deorbit timeline further.

Figure ES-4 shows the net benefit and cost-benefit ratios associated with changing from a 25-year rule to a lower-year rule.[2] We estimated that the benefits of moving to a 15-year rule are 20–750 times the costs and may produce up to $6 billion in net benefits during our timeframe of interest. There are diminishing returns associated with deorbiting spacecraft more rapidly; however, the ratios are still favorable and net benefits continue to increase. Moving all the way to a 0-year rule can result in nearly $9B in net benefits.

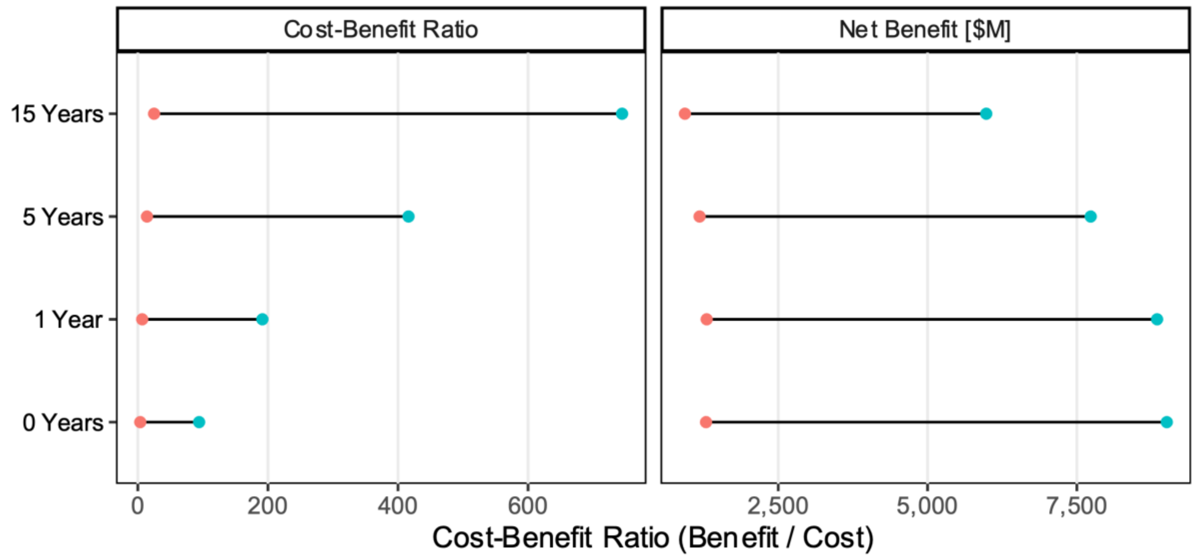


Figure ES-4. Conditional cost-benefit ratios and net benefits, after 30 years, for moving from a 25-year rule to faster deorbit times for defunct spacecraft.

Other analyses of deorbit timelines have found that deorbiting defunct spacecraft faster than 25 years has a small change on the number of long-lasting debris—those that persist in space for hundreds of years. Our results do not conflict with that finding; rather, our analysis had added to that finding by accounting for the risks to operators posed by debris that are not as long-lasting. For example, a defunct spacecraft complying with a 25-year rule will be left at an altitude no higher than 650 kilometers. From this altitude, any debris it generates will not be long-lasting debris. However, such debris may cause millions of dollars in expected risk to spacecraft operators as the debris spends the next 25 years passing through the orbits of all active spacecraft below it. By accounting for the risks of all debris, not just the number of long-lived debris, we find that rapidly deorbiting spacecraft is highly cost-effective for reducing risk.

[2] This is different than the results shown in Figure ES-3, which show the benefit ratios of post-mission disposal compared to allowing defunct spacecraft to be left in their operational orbit.

Next Steps

This report provides insight into our ongoing analysis as we work toward creating a rigorous methodology for assessing the economic costs and benefits of space sustainability. We welcome feedback to help guide our approach and to improve the assumptions and underlying data used in our analysis. To that end, we are beginning the process of publicly releasing our research code, written in Python, and underlying data. Simultaneously, we intend to begin discounting the cash flows associated with the development and operational timelines of each action. Doing so will allow us to calculate the net present value of each action and make economically rigorous comparisons. A further goal is to identify an optimal combination of actions for reducing risk, as we have defined it. Achieving this goal presents a complex problem because taking any one action changes the benefits (and possibly costs) of all other possible actions. These interdependencies must be taken into account when creating an optimal portfolio of risk-reducing actions. Finally, analyses of proposed policies for space sustainability have been hampered by a lack of insight into the costs and benefits that those policies may generate. Our research is laying the technoeconomic foundation upon which policy proposals can soon be rigorously and quantitatively analyzed.

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Introduction

Background

Orbital debris is defined as "any human-made space object orbiting Earth that no longer serves any useful purpose" (Executive Office of the President 2018). Debris ranges from 9,000-kilogram upper stages to 1-millimeter flecks of paint and metal. Debris are generated through the normal course of space activities, such as when materials are discarded during the launch process and spacecraft are left behind at the end of a mission, as well as in more exceptional ways, such as through the explosive fragmentation of a spacecraft or an anti-satellite test. Additionally, the number of debris increases over time through collisions, surface weathering, and other means.

This growing population of orbital debris poses a risk for spacecraft operations: debris may collide with active spacecraft, leading to degradation or even mission-ending damage. Larger debris[3] can be tracked through existing space situational awareness (SSA) capabilities, so spacecraft operators monitor close approaches with these debris and maneuver to minimize the collision risk; therefore, large debris mainly require monitoring and maneuvering to avoid risks. Smaller debris, which are not currently tracked, pose a direct risk to active spacecrafts.

There are many ways to address the risks of orbital debris; however, it is unclear what the most effective means are to reduce the risk. U.S. policy has organized potential actions to reduce risks into three categories: (1) mitigate the creation of new debris, (2) track and characterize existing debris to better address risk, and (3) remediate debris in the environment. Together, these categories of actions constitute the means to sustainably manage orbital debris. The relative value of these actions has not yet been fully explored, making it difficult to assess trade-offs and to design a balanced portfolio that uses them. Rigorously assessing the benefits and costs of mitigating, tracking and characterizing, and remediating debris requires a holistic consideration of the orbital debris environment.

In March 2023, the NASA Office of Technology, Policy, and Strategy (OTPS) took a step toward quantifying the relative values by releasing *Cost and Benefit Analysis of Orbital Debris Remediation* (Colvin, Karcz, and Wusk 2023). This analysis measured, in dollars, the negative effects that debris imposes on space operators. Additionally, the analysis was the first to assess the relative value of a wide range of debris remediation methods and demonstrates that some remediation methods may achieve net benefits in under a decade. Further, the analysis found that framing the discussion in terms of real risk, measured in dollars, led to different answers than focusing on proxies for risk, such as total mass of debris, total number of pieces of debris, and total number of conjunctions with debris.

[3] The rule of thumb is that debris with a characteristic length (i.e., an average length) greater than or equal to 10 centimeters can be tracked. This heuristic misses complexity that results in smaller debris being tracked and larger debris being overlooked but will be used as the rough dividing line in this report.

The analysis from 2023, referred to here as Phase 1, was intended to be a first step and contained a number of limitations—some known at the time of its publication and others uncovered in subsequent conversations with the space community. The major limitations can be sorted into three groups: (1) rough fidelity on the estimated costs to develop the systems and not accounting for the development timelines; (2) omission of key parts of the risk landscape, such as debris smaller than 1 centimeter and the orbital decay of debris; and (3) a sole focus on remediation, which does not inform effectiveness relative to mitigating, tracking, and characterizing debris.

Purpose and Scope

This report is an update to NASA's previous work to estimate the costs and benefits of actions that reduce the risks that orbital debris pose to satellite operators. The current analysis contains updates to the risk model used in Colvin et al. (2023) and expands the breadth of actions considered to include reducing the creation of debris, improving the ability to track debris, and more methods for cleaning up existing debris. This report is a snapshot of our analysis as we build toward the capability to (1) complete rigorous calculations of the net present value of each action, (2) identify an optimal portfolio of actions to reduce risk, and (3) quantitatively analyze policies related to space sustainability. Figure 1 provides an overview of what is and is not included in the analysis.

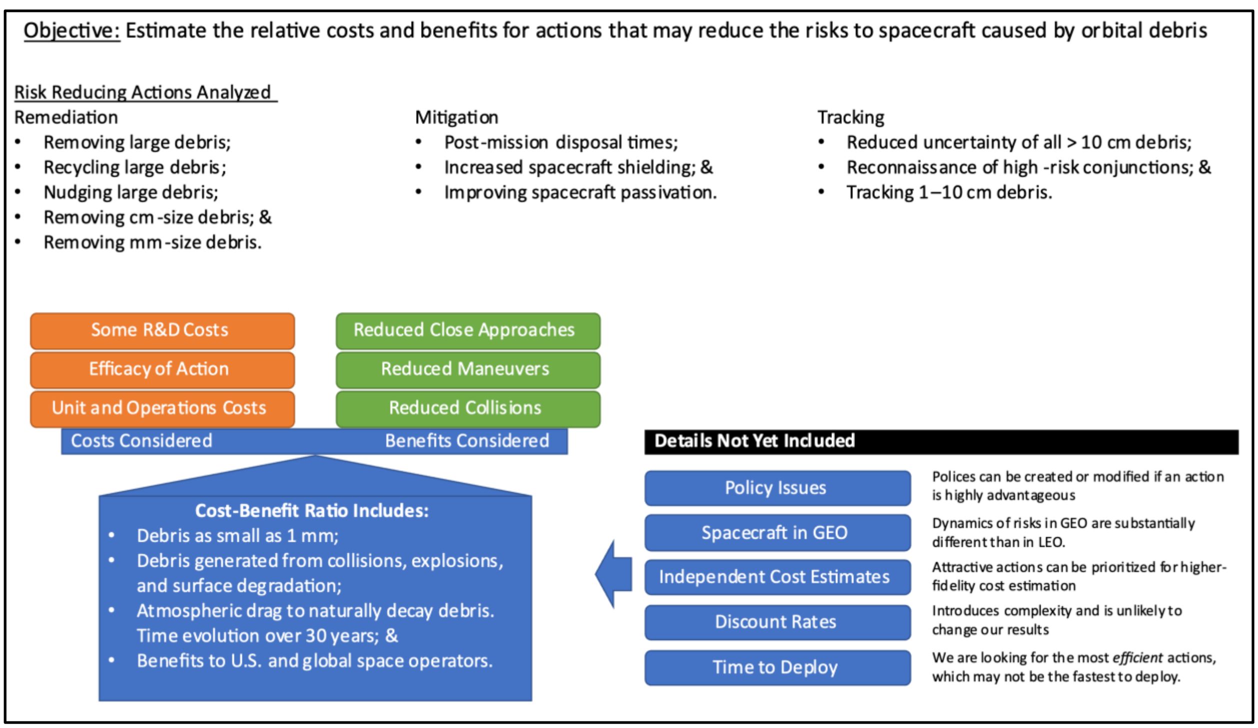

Figure 1. Cost-benefit considerations included in the current study.

This study simulated the evolution of space debris 1 millimeter and larger, including the effects of atmospheric drag that will deorbit debris, over a period of 30 years. This evolution included the generation of debris through collisions, accidental explosions, and shedding of millimeter-size debris from the surface degradation of large debris. We also modeled the financial consequences that spacecraft operators incur as they assess their risks to close approaches, maneuver to reduce risks, and experience mission-ending collisions with debris that are not currently tracked. We combined the models of the evolving debris environment with the financial consequences of operating in the environment to estimate the risk to all spacecraft operators, foreign and domestic, measured in dollars. Further, we modeled how taking specific actions to alter (1) the debris environment or (2) spacecraft operators' interactions with the environment change the risks to all space operators. The risk reduced by an action is the benefit of that action.

In our previous work (Colvin et al. 2023), we estimated the costs to develop and operate a variety of risk-reducing actions, all of which were related to debris remediation. The current work expands the scope of actions considered to include actions related to debris mitigation and tracking. Mitigation actions include reducing the number of years a defunct spacecraft can remain in orbit as part of its postmission disposal, increasing the shielding on a spacecraft to protect it from greater numbers of debris, and passivating the spacecraft to eliminate its chances of accidentally exploding. Tracking actions include beginning to track centimeter-size debris and reducing the uncertainty of the orbits of debris that are already tracked. Remediation actions include removing and recycling very large debris, nudging large debris to eliminate the risk that they will collide with other debris, and removing centimeter- and millimeter-size debris.

This study can be considered the next step, not the final one, in the work started by Colvin, Karcz, and Wusk (2023). Notably, this study has limitations that deserve attention. The first limitation is that it considers spacecraft in low Earth orbit (LEO) only. Space sustainability in geostationary Earth orbit (GEO) is a serious and understudied issue. The incentives for sustainability may be greater because nearly all assets in GEO are extremely valuable and there is a lack of any atmospheric drag to naturally remove debris from GEO. However, the orbital dynamics of debris and spacecraft in GEO are substantially different from those in LEO, and we have not been able to attend to these differences properly.

The second limitation is that we continue to omit policy concerns regarding risk-reducing actions. This study attempts to lay the foundation for future policy analyses by providing estimates of costs and benefits for a wide range of potential actions. Therefore, if a low-cost, high-benefit action is not pursued because of policy concerns, the space community will have an estimate of the opportunity cost of that decision.

A third limitation is that the costs associated with the development of mitigation, tracking, and remediation actions are rough estimates. We did not address Phase 1's first limitation (simplifications in estimates of development time and cost) and indeed relied on similar simplifications for the new risk-reducing actions introduced in this report. Estimating the development and deployment timelines for each action would allow a more rigorous comparison between the actions for space sustainability. However, the scope of this study did not allow for assessing the technology readiness level (TRL) and the advancement degree of difficulty (AD2) of the each of the systems. To mitigate the optimism or pessimism associated with the cost estimates found in the literature, we attempted to provide ranges of costs and efficacies based on our assessments or analogous capabilities. For some concepts, this study may contain the first-ever attempts to estimate the costs of the proposed systems, and relatively little information was available to draw on when creating the estimates. Overall, this study does not attempt to provide high-fidelity or definitive costs and benefits, because increasing the depth of analysis regarding any one action would necessitate increased depth of analysis in all topics so that fair comparisons can be made. This study is a strategic analysis to identify actions of potentially high promise.

This study updates and expands the findings of Colvin, Karcz, and Wusk (2023) and represents a snapshot as we build toward the capability to (1) complete rigorous calculations of the net present value of each action, (2) identify an optimal portfolio of actions to reduce risk, and (3) quantitatively analyze policies related to space sustainability.

The Orbital Debris Risk Landscape and the Methodology of This Study

This study relies on models of the orbital debris environment and how that environment affects spacecraft; both the models and the effects come with substantial uncertainties. A detailed description of the modeling process can be found in Appendix A; in this section, we provide an overview.

Earth's orbit contains a great number of human-made space objects that no longer serve any useful purpose; these objects are considered orbital debris.[4] As of December 2022, 42% of tracked debris were derelict spacecraft or rocket bodies and 47% were fragments from breakup events (NASA Orbital Debris Program Office 2022). These debris are often described in terms of their characteristic length—that is, the average of their length, width, and depth. Estimates of the total debris in LEO with a characteristic length of 1 millimeter or greater ranges from 30 million to 1.8 billion.[5] The Phase 1 study included debris only 1 centimeter and bigger, whereas the current study includes debris as small as 1 millimeter.

Debris can strike active satellites, degrading or even ending their missions. The space community currently tracks debris larger than 10 centimeters so that space operators can maneuver to reduce their probability of colliding with these debris. These interactions with orbital debris create negative financial consequences for spacecraft operators, which pay to assess close approaches (i.e., warnings) and, if necessary, to maneuver away from the debris. Debris smaller than 10 centimeters are not tracked and may collide with spacecraft, potentially resulting in a

[4] This definition comes from Space Policy Directive-3 (2018). This definition is similar to other definitions, such as the definition in *IADC Space Debris Mitigation Guidelines*: "Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional" (p. 6).

[5] The estimate of 30 million comes from the European Space Agency's MASTER risk assessment tool; the estimate of 1.8 billion comes from NASA's Orbital Debris Engineering Model. The difference in estimates is mainly from counts of 1- to 3-millimeter debris, as has been documented elsewhere (e.g., Horstmann et al. 2021).

mission-ending collision (MEC) if the debris strikes a vulnerable and critical component. This study considered risk to be the sum of the expected encounters—warnings, maneuvers, and MECs—multiplied by their respective consequences.

We relied on three submodels to estimate the current number of debris and the number of warnings, maneuvers, and collisions these debris cause. The three models, summarized in Table 1, represent a diversity of opinions on the risk of orbital debris. For example, Model 1, based on NASA's Orbital Debris Engineering Model (ORDEM), estimates far more 1-millimeter debris than do the other two models, which are based on the European Space Agency's MASTER risk assessment tool. Model 3 does not include 1- to 5-millimeter debris as hazards; LeoLabs chose this approach because they have assessed that there are a lack of observed spacecraft failures that would be expected from a population of mission-ending debris in the 1- to 5-millimeter size range. We are not in a position to assess the correctness of the models; rather, we used them as an ensemble to explore the range of reasonable assumptions about the space environment.

Table 1. Overview of the Ensembled Encounter Models

Encounter Model	Description	Model Source
Model 1	Developed by the study team and calculates the number of encounters using fluxes from ORDEM	ORDEM
Model 2	The COMSPOC Volumetric Encounter Model (VEM), from which the Number of Encounters Assessment Tool (NEAT) is derived	MASTER
Model 3	The LeoLabs risk model and data based on the kinetic gas theory	MASTER

Colvin et al. (2023) modeled the financial consequences that spacecraft operators incur as they assess their risks to close approaches, maneuver to reduce risks, and experience mission-ending collisions with debris that are not currently tracked. The financial consequences vary depending on the size and mission of the spacecraft; thus, all spacecraft in LEO have been assigned a category of operations, where spacecraft in each category are assumed to have similar costs for close approaches, maneuvers, and collisions. Compared to Phase 1, this study expanded the spacecraft included in the financial calculations from just U.S. spacecraft to all spacecraft in the global population. Combining these financial consequences with our ensemble of encounter models, we calculated the total debris risk in dollars to spacecraft operators. Table 2 shows the estimated risk that current orbital debris pose to current spacecraft.

The current study refined Colvin, Karcz, and Wusk's (2023) methodology, resulting in different values for the baseline risk, as shown in Table 2. These differences can mainly be attributed to (1) expanding the active satellite population to include non-U.S. spacecraft; (2)

including MECs resulting from debris with a characteristic length of 1-10 millimeters; (3) refining the encounter model in Colvin, Karcz, and Wusk's study, including by using more accurate, less conservative collision assumptions; and (4) omitting spacecraft in GEO from the study.

Table 2. Risks from Orbital Debris in First Year of Simulation

	Encounter Model	MECs	Maneuvers	Warnings	Total
Total	Model 1	$666 M	$13 M	$13 M	**$692 M**
	Model 2	$136 M	$ 15 M	$14 M	**$164 M**
	Model 3	$91 M	$ 13 M	$12 M	**$115 M**
U.S. Only	Phase 1				**$58 M**
	Model 1	$162 M	$6 M	$2 M	**$171 M**
	Model 2	$33 M	$8 M	$2 M	**$43 M**
	Model 3	$21 M	$7 M	$2 M	**$30 M**

Table 2 estimates of the risk apply to the current environment, but the environment will change over time. Debris can beget new debris through collisions, explosions, and surface degradation, and active spacecraft become debris through fragmentations and failed post-mission disposal. Launches can place more spacecraft and debris in orbit. Debris may eventually exit orbit as it decays into Earth's atmosphere. This report considers a range of sources and sinks, allowing us to consider actions, such as mitigation, that affect future debris generation.

Figure 2 illustrates the process we used to estimate the risk in a given environment. First, large debris can be expected to cause a certain number of warnings and collision avoidance maneuvers, while untracked debris cause a certain number of small MECs; the risk is the sum of the expected events multiplied by the consequences for the spacecraft operator. Second, each piece of debris creates risks to a spacecraft, and the total risk to the spacecraft is the sum of the risks contributed by all debris. Third, debris pose risks to each nearby spacecraft, so the total risk in a location (i.e., altitude band) is the sum of the effects of all debris on each spacecraft. Fourth, multiple altitudes can be treated separately—as "particles in a box"—and the total risk is the sum of the risk in each altitude bin. Fifth, the environment changes with time—for example, a collision might introduce new debris in year two—and we sum the increased risk posed by the new debris over a 30 year time horizon to estimate the cumulative risk overall. Therefore, we can estimate the risk in any LEO environment over time.

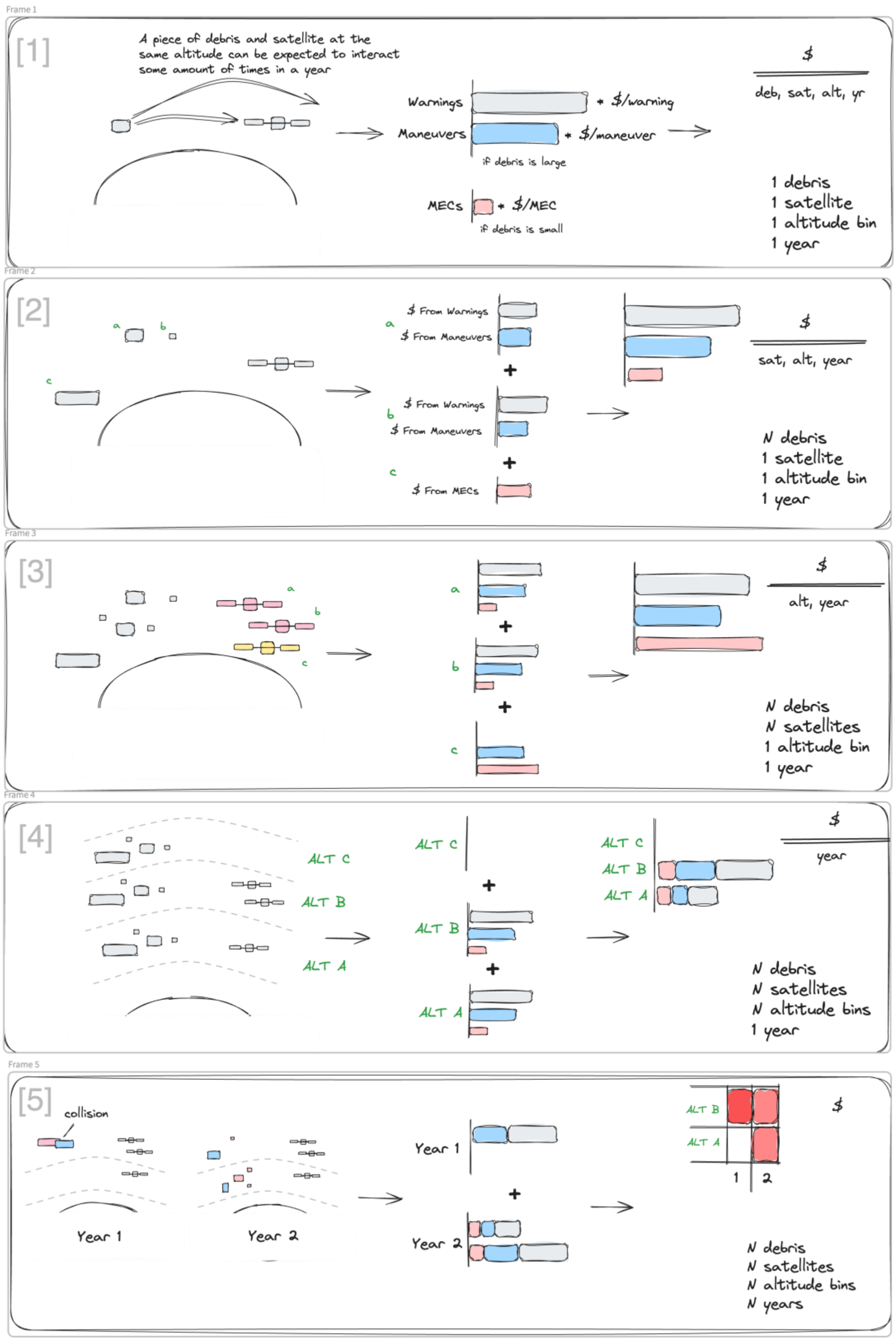

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Figure 2. Illustration of the method for estimating debris risk to all spacecraft.

To aid comprehension of the graphs and results in this report, we now walk through an example calculation. The effect of a risk-reducing action is estimated by taking the difference between two versions of the environment: in one version, the action took place; in the other version, the action did not take place. Consider the following scenario: a space operator has a medium-size spacecraft at 800 kilometers and can spend a certain amount of money to be able to deorbit the spacecraft at its end of life or do nothing and leave the derelict object at the operating altitude. The benefit of the deorbiting action is the difference in the risk between these two options. This calculation captures the risk caused by the derelict and any debris it would have generated. Figure 3 shows the total cumulative benefit from removing the spacecraft. As we will see throughout the study, Model 1 far exceeds the other two models due to its orders of magnitude higher surface degradation rate.

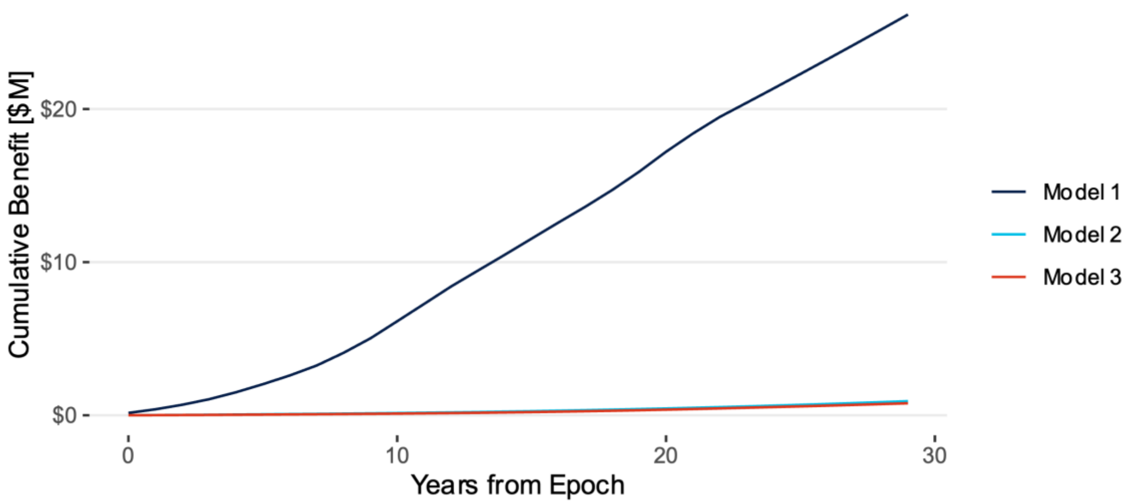

Figure 3. Cumulative benefit of not adding a medium derelict at 650 kilometers.

The figure shows that if the spacecraft is removed at year 0, then the total benefit (i.e., risk removed) after 30 years is between $800,000 and $26,000,000, spread across all spacecraft operators globally. This benefit comes from two sources. First, about $25,000–50,000 comes from the warnings and maneuvers the derelict spacecraft would have caused, mostly to military and civil operational satellites. Second, the majority of the benefits come from the risks that could have been caused by the derelict generating new debris through surface degradation, collisions with other debris, or explosions. Each year, the derelict spacecraft would be expected to participate in 0.0002 to 0.0004 large collisions. Small debris generated by these three events, factoring in the probability that they occur, would soon rain down through the orbits of spacecraft operating at lower altitudes, because small debris deorbits relatively quickly.

The additional cost of launching a medium satellite with extra propellant to immediately deorbit from 800 km ranges between $85,000 and $425,000 (see Appendix C). By subtracting these costs from the benefits, we calculate the net benefit of removing the spacecraft. Figure 4 shows the bounds of the cumulative net benefit over time. The upper, or optimistic, bound on the plot shows the best possible net benefit case, or the highest benefit (Model 1) minus the lowest cost. The bottom, or pessimistic, bound shows the lowest benefit (Model 3) minus the highest cost. The other lines show the other combinations of cost and benefit, with the dotted lines representing the high-cost cases. Blue regions indicate the net benefits are positive and pink regions indicate negative net benefits. The dots at years 1 and 22 show where the upper and lower bounds cross from negative to positive net benefits.

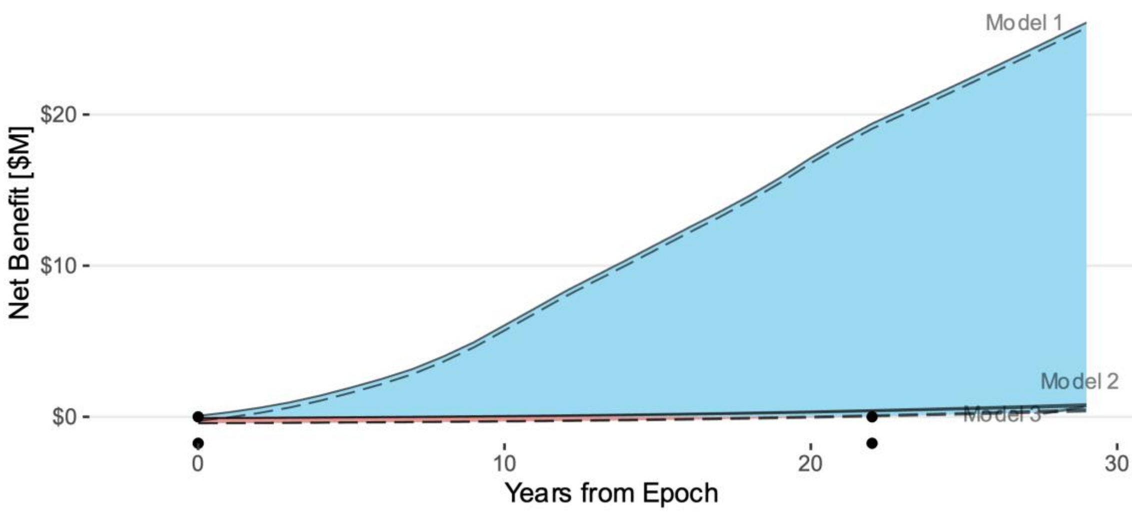

Figure 4. Net benefit of not adding a medium derelict spacecraft at 650 kilometers.

This study calculates the benefits of actions for three decades after the action is taken. This approach contrasts with much of the space sustainability literature, which considers the increase in debris over hundreds of years. We chose a shorter timeline for a few key reasons, including the following: (1) Calculating risk to spacecraft operators requires being able to estimate with some certainty the consequences those operators will face because of debris; confidently estimating the consequences of potential actors 100 years in the future is nearly impossible. (2) We can only speak with confidence about options to reduce the risks resulting from orbital debris that are imaginable in the near term; longer-term technological growth might obviate these methods. (3). Most importantly, we prioritize the near-term timelines most relevant to today's decision makers. For example, if the effectiveness of space sustainability solutions is measured by the total number of debris in space 200 years from now, then activities that reduce debris generated below 700 kilometers altitude are effectively irrelevant; all debris generated below 700 kilometers will naturally deorbit within 200 years, and most spacecraft in LEO operate below 700 kilometers. We chose 30 years as the minimum timeline because it exceeds the longest-term option in this study (the 25-year postmission disposal rule) and provides useful information on the trends of benefits.

With any near-term horizon, there exists the possibility of recommending actions that perform poorly over a longer time frame. In this report, we attempt to point out areas in which a longer-term perspective could lead to different findings. In general, we expect the relative value to be relatively robust with time, as we are measuring the cumulative value rather than the value at a single point in time. Near-term benefit tends to compound into greater long-term benefit. We believe directly quantifying risk to satellite operators during a shorter period is of more significance than is estimating proxies for risk, like the number of debris in space or conjunctions with debris, over long periods. More details on the methodology are described in Appendix A.

Organization of the Remainder of This Report

The following chapters of this report focus on the major categories of actions that enhance space sustainability: remediation, tracking, and mitigation. In each section, we analyze multiple risk-reducing actions related to the topic of the chapter. For each action, we present a brief concept of operations (CONOPS) that illustrates how the action would work and we also provide a brief summary of the costs and efficacy of the action. The benefits of the actions, which are reduced risks to global space operators measured in dollars, are compared with the costs of performing the actions. The report concludes with a summary, presenting the benefit-cost ratios together, and potential insights. The conclusion is followed by appendices that provide greater details on the costs and performance of the actions.

Remediation

Debris remediation is any action that reduces the risks associated with orbital debris already in the environment. Approaches to remediation include removing large debris in LEO by tugging the debris to lower orbits for an uncontrolled or controlled reentry; nudging large pieces of debris away from a collision; removing small debris at scale; reviving defunct spacecraft to use in new missions; and recycling materials from debris to use as propellant or feedstock for in-space manufacturing. Remediation in GEO (not in this report's scope) involves moving the debris into graveyard orbits and even installing devices, such as solar sails, on objects to eject them from Earth's orbit completely (so they are not on a return trajectory).

This chapter analyzes the costs and benefits of removing large debris, nudging large debris away from impending collisions, removing centimeter-sized debris, and removing millimeter-sized debris. All remediation actions are analyzed for LEO only.

Remove Large Debris

Large debris have long been considered the obvious candidates for remediation because they have the potential to generate thousands or even millions of smaller debris (see Appendix A). Large debris to be removed include tracked fragments, but most often the focus is on rocket bodies and large derelict spacecraft. This section considers the costs and benefits of methods that remove large debris from the orbital environment.

CONOPS and Costs

In LEO, the main remediation concepts involve deorbiting debris so that it quickly reenters Earth's atmosphere. Many grab-and-deorbit methods have been proposed, including sophisticated architectures targeting clusters of debris. We group the methods into three categories: tug to controlled reentry, tug to uncontrolled reentry, and tug to recycling. In this study, the CONOPS we used for each category were prepared by Colvin, Karcz, and Wusk (2023). Approaches that were not evaluated include attaching drag devices in order to more quickly deorbit the derelicts and reviving defunct spacecraft to use in new missions.

The CONOPS in Colvin et al. (2023) for the low-cost method of performing a controlled reentry is the following:

- **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 so that the debris reenters within a single orbit.

- **Release Debris**. When the remediation satellite and the debris have descended far enough into the atmosphere that the debris' point of reentry is assured, the remediation releases 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. The cycle repeats.

This method of controlled reentry was sufficiently low-cost that it appeared more economical than other methods of uncontrolled reentry that we examined. Thus, we used the same CONOPS for our low-cost estimate of uncontrolled reentries, with the exception that perigee for the debris is set to 350 km, thereby saving propellant.

For the analysis of recycling (Colvin et al. 2023), we assumed that the remediation satellite would extract aluminum from the debris to use as propellant. Further, in our low-cost estimate, we optimistically assumed that customers exist who would purchase aluminum as propellant, thereby providing revenues to the remediation provider. Such a spacecraft would need the following capabilities: a capture mechanism that is reversible and reusable, a metal plasma thruster that uses aluminum as propellant, 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:

- **Capture and Re-position**. The remediation satellite captures the debris and uses its onboard fuel to tug the debris down to the disposal altitude.
- **Extract Metal Propellant**. 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.
- **Travel to Next Target**. Using the newly created propellant, the satellite travels to another piece of debris to repeat the cycle.

We modeled the cost of removing debris as dollars per kilogram; doing so allowed us to bound the removal costs for any object in LEO. Table 3 summarizes the rates carried over from Colvin, Karcz, and Wusk (2023). Controlled reentry represents the highest cost, as it requires more propellant to ensure a reentry trajectory that limits the risk to people and property on the ground. Recycling represents a more-speculative approach, in which a remediation satellite harvests material from the derelict spacecraft into propellant for metal plasma thrusters; the revenue from selling this propellant lowers the potential cost.

Table 3. Summary of Cost Range for Remediating Large Objects

Method	Low Cost [$/Kg]	High Cost [$/Kg]
Tug to Controlled Reentry	$4,000	$60,000
Tug to Uncontrolled Reentry	$3,000	$40,000
Tug to Recycling	$4,000	$10,000

Note: See Appendix C of Colvin, Karcz, and Wusk (2023) for the details on these estimates.

For continuity with the Phase 1 report, we applied these three removal methods to the high-risk objects published in McKnight et al. (2021a). McKnight et al.'s list contains 50 large satellites and rocket bodies, with a total mass of about 260,000 kilograms, in orbits between 600 and 1,100 kilometers.[6] Using the rates per kilogram shown in Table 3 allowed us to estimate the total cost of using each method to remove the objects. We modeled the debris as being removed at the beginning of the simulation and assumed that the remediation added no additional risk to the environment.

Benefits and Comparisons with the Costs

Large debris pose two types of risk: (1) they directly threaten spacecraft, causing warnings and requiring maneuvers, and (2) they generate smaller debris through surface degradation, catastrophic collisions, and explosions, thereby increasing the threats to spacecraft. The latter risk makes up more than 99% of the risk that large debris pose (see Figure 5). The benefits for remediating these large objects, then, come mostly from removing their debris-generating potential. Because the large debris would have continued to generate debris year after year and the new debris would have threatened spacecraft for years, the benefit of removing large debris grows exponentially with time. Figure 6 shows how the benefit accumulates during the 30 years after removing the 50 large objects. (From here on, the identified benefits are to the global spacecraft population. Any nation-specific benefits will be identified as such.)

[6] Section 3 of Appendix A shows how our model represents all rocket bodies through two paradigmatic objects, with a mean mass and size based on either small or heavy upper stages in LEO. The total mass in our representation of McKnight's 50 objects is 224,150 kilograms, slightly less than the actual objects. We used this mass to calculate the cost of removal, and we address the potential underestimates at the end of this section.

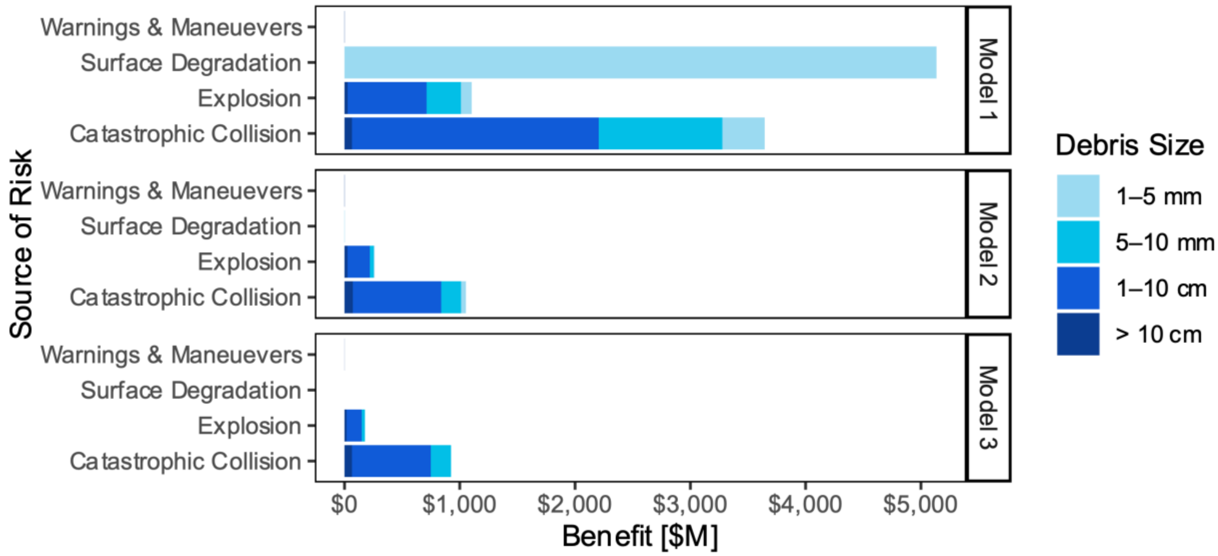

Figure 5. Benefit from removing 50 large objects, categorized by the source of the avoided risk.

The large differences between the models can mostly be explained by two major factors. First, as explained in Appendix A, Model 1 generally assigns a risk that is 2–4 times higher for all small debris. Model 1 (based on NASA's ORDEM) also give significant weight to surface degradation: Model 1 has a surface degradation rate that is three orders of magnitude higher than the rate in the other two models (which are based on the European Space Agency's MASTER). Figure 5 shows that surface degradation makes up 54% of the risk for Model 1 but only about 0.2% for Model 2. More information on the models and their differences can be found in Appendix A.

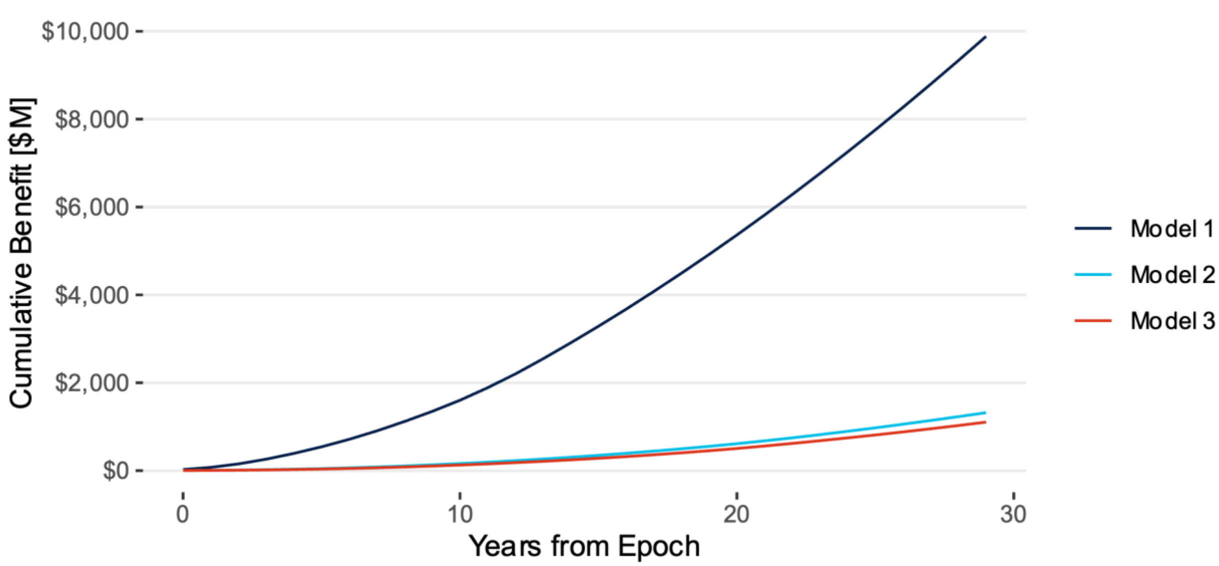

Figure 6. Accumulation of benefits over 30 years by removing McKnight et al.'s (2021a) 50 Large Debris. Note: The model indexes from year 0, so the 30th year of the model is year 29.

Looking across the models, the average benefit for removing a single large object ranges from $22 million to $200 million over 30 years.[7] The value of removing a specific piece of debris depends on its size and location.[8] Figure 7 shows that the value of removing large objects peaks between 700 and 1,000 kilometers. At those congested altitudes, the debris generated by the large objects will generate the most risk over 30 years. This area of LEO is where the objects on McKnight et al.'s (2021a) list, represented by the blue points, congregate in the figure. Additionally, 60% of those objects are rocket bodies (represented as triangles), whose greater size leads to more debris being generated through surface degradation and greater mass leads to more debris in the event of a collision. The value of removing each of the 50 objects exceeds the low cost ($3,000 per kilogram) using Model 1, but for Models 2 and 3 the values of only 33% and 19% of the objects exceed the lowest cost.

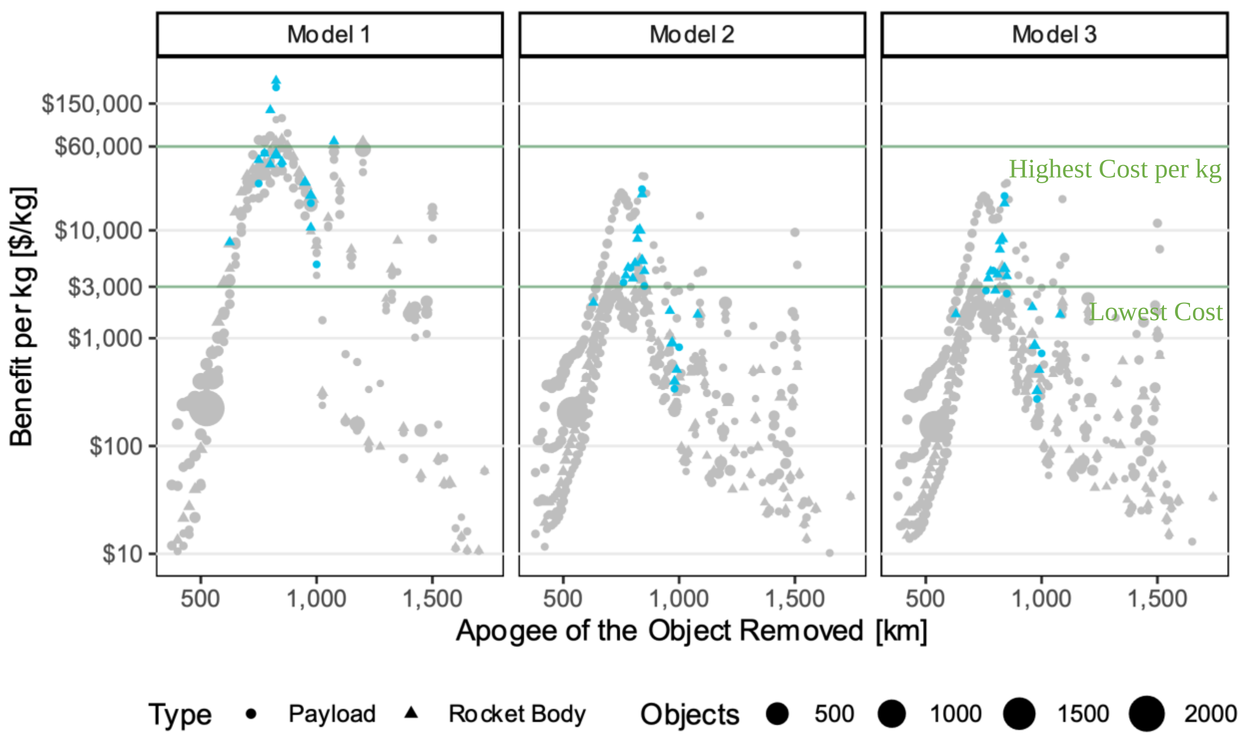

Figure 7. Benefit per kilogram after 30 years by removing large objects.

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[7] Setting aside surface degradation, the estimated benefits are lower than estimated in the Phase 1 report, despite the inclusion of international satellites. The difference is mainly because the Phase 1 report assumed a more conservative collision area (5 meters Hard Body Radius [HBR]), while the current instantiation attempts to use a more realistic size (see Appendix A for more details). Other improvements, such as regarding decay, contribute much less to the lower level of estimated benefits.

[8] Surface area affects the amount of surface degradation, collision area affects the probability of collision, and mass affects the number of debris generated in a collision or explosion. The orbit affects the probability of collision, the amount of time the large object and the debris it generates will be in LEO, and which spacecraft are threatened.

With the benefits and costs identified, we can calculate the net benefit for remediating the 50 large objects. Figure 8 shows how the costs and benefits evolve over time. Specifically, the figure shows the high level of benefits associated with Model 1 minus the low- and high-cost options for remediation. Over a 30-year time frame, the most optimistic estimates (highest benefits and lowest costs) cross into a positive net benefit, with uncontrolled entry becoming positive first. The pessimistic estimates, however, "lose" billions of dollars and have only a slight upward slope.

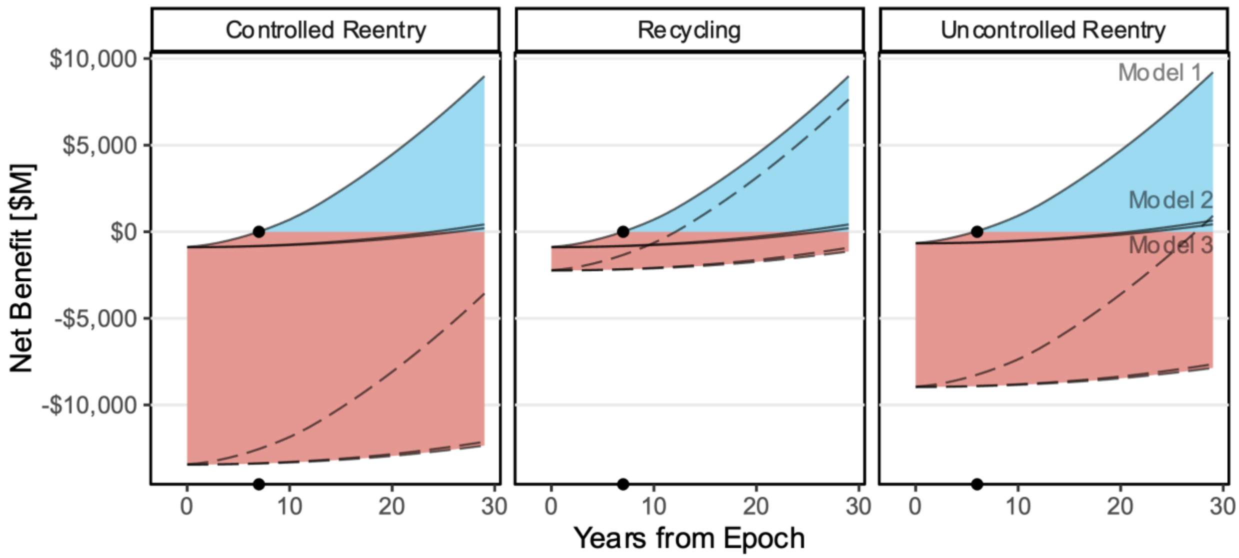

Figure 8. Benefit minus cost of removing McKnight et al.'s 50 large objects.

These net benefits have a few considerations. First, the total benefit will exceed our estimate as the time horizon increases. It would take hundreds of years for the majority of the large objects to decay, and during that time the benefits of having removed the objects would continue to accumulate exponentially; for example, we expect that the optimistic net benefit would triple after 50 years. In other words, a one-time payment can be expected to result in long-term dividends. Second, about 95% of the risks that these large objects pose are to military or civil operational spacecraft; adding constellations of commercial satellites does not significantly increase the benefits.

Nudge Large Debris

Rather than remove debris from orbit, the orbits of debris can be manipulated through just-in-time collision avoidance (JCA). JCA methods slightly nudge the orbit of a satellite or tracked orbital debris to impart sufficient delta V for the objects to avoid a potential collision. This effectively gives large debris the capability to perform collision avoidance maneuvers. The just-in-time action differentiates this approach from large debris traffic management, a related concept in which the orbits of an entire population of debris are proactively nudged to reduce the likelihood of conjunctions (before they are even predicted). We will focus on JCA methods, which include the use of lasers, dust, and nano-tugs—small propulsive modules that are attached to debris (Bonnal 2020).

CONOPS and Costs

We used the two JCA concepts from Colvin, Karcz, and Wusk (2023): (1) a ground- or space-based laser that transfers momentum to the objects or (2) a sounding rocket that releases dust, which increases the momentum of the object as it passes through the dust. The sounding rocket approach ended up being several orders of magnitude more expensive, so we focused on the laser-based approach.

The CONOPS is illustrated in Figure 9 and is the same for ground- and space-based lasers:

- **Identification of Potential Targets**. The targets are predicted to be in debris-on-debris conjunction where neither object can maneuver to avoid a collision.
- **Orbital Determination of Targets.** The accuracy of the orbits used to generate the conjunction warning may be insufficient for use with JCA; thus, a laser ranging capability is used to measure the orbits of the objects and allow their miss-distance 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. 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 laser is powerful enough that it causes ablations on the skin of the debris, imparting a ΔV of 1-10 centimeters per second—the size of a typical collision avoidance maneuver performed by active spacecraft.

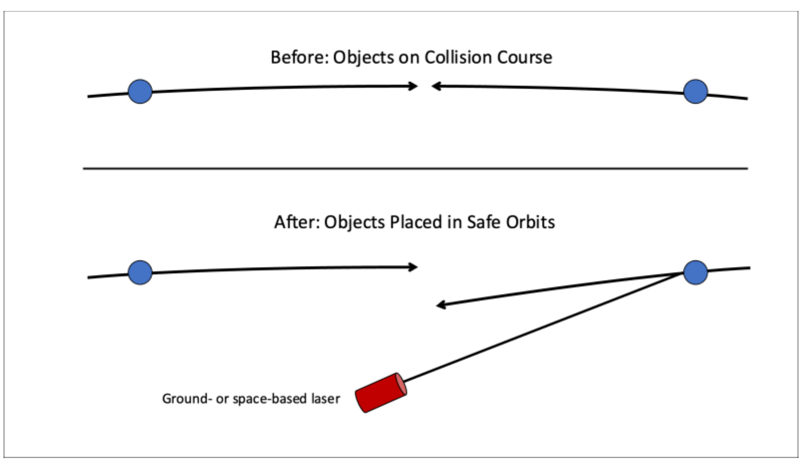

Figure 9. Example of a CONOPS for a laser JCA system.

Unlike in Phase 1, we sized the systems to be able to nudge all intact derelict spacecraft (as opposed to just the 50 large objects) to enable a more realistic comparison with other methods. We slightly modified the cost estimates used in Colvin, Karcz, and Wusk (2023) by increasing the upper-bound start-up costs. Additionally, instead of modeling the costs as dollars per debris, we modeled the costs as building a system that can serve the needed range of nudges per day. Appendix B includes the details of the updated calculations, and the total costs are summarized in Table 4.

Table 4. Costs for Nudging All Intact Debris

Bound	Start-Up Costs	Annual Costs
Low	$360 M	$15 M
High	$1,120 M	$50 M

Benefits and Comparisons with the Costs

The benefits of JCA come from reducing the number of expected collisions in LEO and removing the effects of the debris the collisions would have generated. For the purposes of comparison, we used a scenario in which the nudging keeps all debris in the current environment from colliding for the next 30 years. Figure 10 shows the value of nudging debris based on their orbits and types. As with removing debris, the benefits of nudging debris peak around 800 kilometers, but in the current scenario, rocket bodies clearly are the best choices for nudging because of their higher collision risk.

Figure 11 shows the cumulative benefit of nudging all intact derelict objects for 30 years, avoiding about 0.15 collisions per year. The benefit includes only the reduced collision risk because the debris remain in space and can generate new debris through accidental explosions and surface degradation.[9] Nevertheless, the benefit increases exponentially because the avoided collisions continue to have benefits for years after the fact. As with the models for removing debris, Model 1 for nudging debris predicts higher collision probabilities; the higher number account for the majority of the differences between the models.

[9] This reduced relative benefit is an update to the Phase 1 study, which did not consider debris that resulted from accidental explosions or surface degradation.

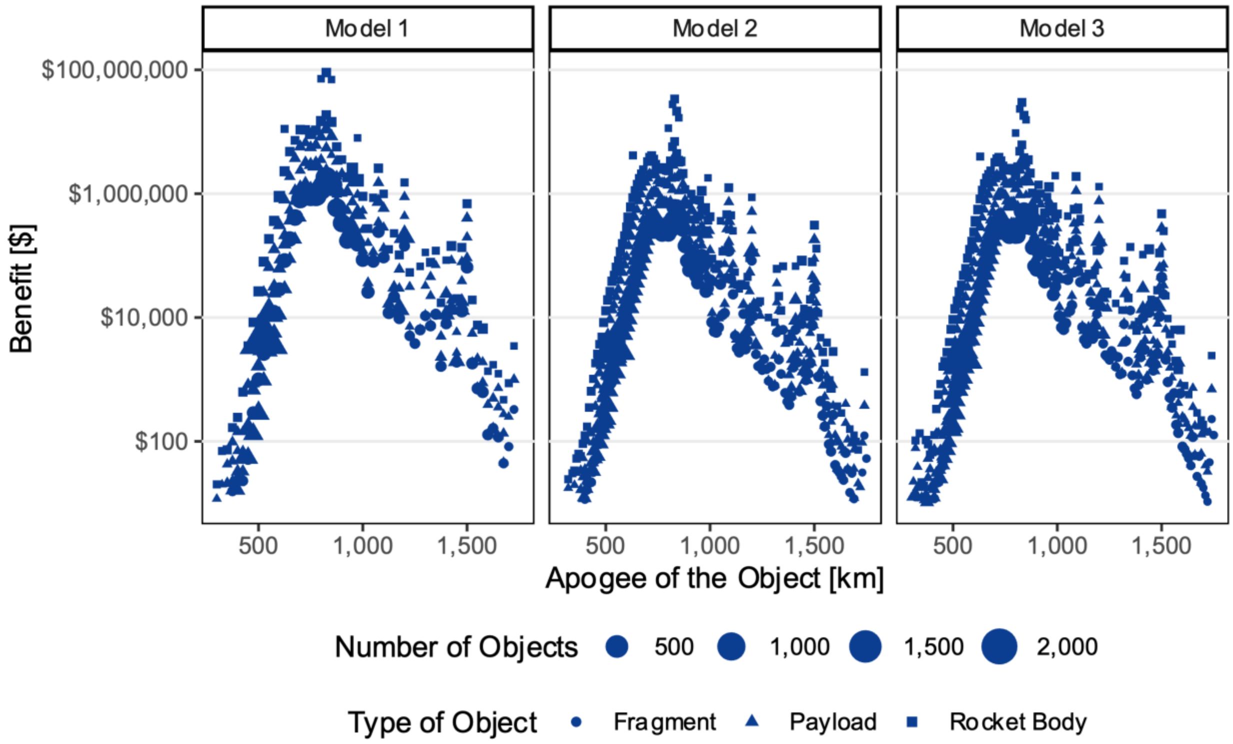

Figure 10. Benefit per debris after 30 years of nudging objects away from potential collisions.

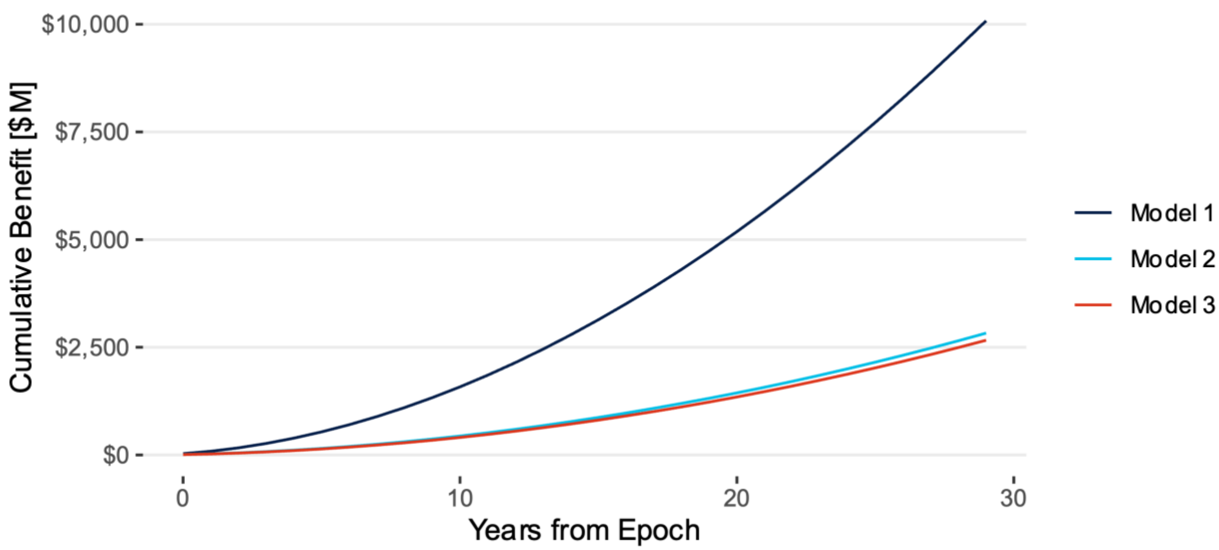

Figure 11. Cumulative benefits over 30 years from nudging all tracked objects in LEO to avoid collisions with other debris.

Figure 12 shows the net benefits over time. The total costs of nudging grow at an approximately constant rate over time, and the benefits exceed the costs within a few years. For the low-cost estimate, all three models reach positive benefits by year 30, with an upper bound of about $3.5 billion. In the most pessimistic estimates, the $1 billion start-up costs are not recouped and only toward the end of the time frame does more benefit than the annual operations costs begin to accumulate.

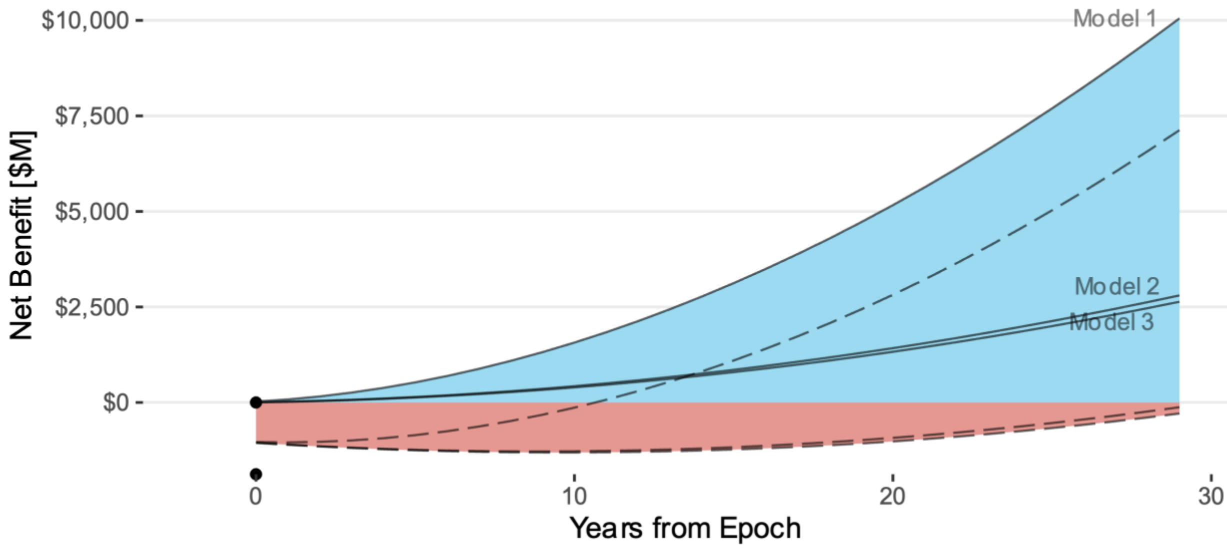

Figure 12. Net benefits of nudging all tracked objects in LEO.

Unlike removing debris, nudging debris requires an ongoing effort and investment. The benefits grow exponentially, whereas the costs grow linearly. Perhaps more importantly, with time the infrastructure will require replacements or even expansion if more debris are added to the environment. It should be noted that this nudging laser system can contribute to a number of the other methods in this study, such as on-demand tracking and remediating of smaller debris. Other potential benefits we did not consider here include the opportunity to use any extra bandwidth in the system to nudge derelict objects away from active-on-debris conjunctions, thereby saving propellant. In a similar vein, the sounding rocket approach may be more a more expensive method of nudging derelict objects, but the approach could by highly effective in very-high-value situations, such as when responding to fragmentation events.

Remove Centimeter-Size Debris

Because small debris present the majority of risk to spacecraft, their direct removal may be valuable. We are unaware of methods to nudge or recycle small debris, so we focused on removal. Phase 1 investigated the use of lasers and wide-area sweepers to remove 1- to 10-centimeter debris; in this study, we applied sweepers to remove 1- to 10-millimeter debris; thus, we focus solely on laser removal for the current study.

CONOPS and Costs

As in Colvin et al. (2023), we considered two systems that use the latter approach and have the potential to detect and engage 1- to 10-centimeter debris: a ground-based laser system and a space-based laser system. For the purposes of illustration, we describe the ground-based CONOPS below. See Colvin et al. (2023) for the description of the space-based concept.

The ground-based laser removal system has four main hardware components: a pulsed 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 is illustrated in Figure 13 and 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.
- **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 while it passes overhead.
- **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. Each pulse imparts momentum to the debris in the retrograde direction, lowering its perigee and accelerating its reentry into the atmosphere. 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.

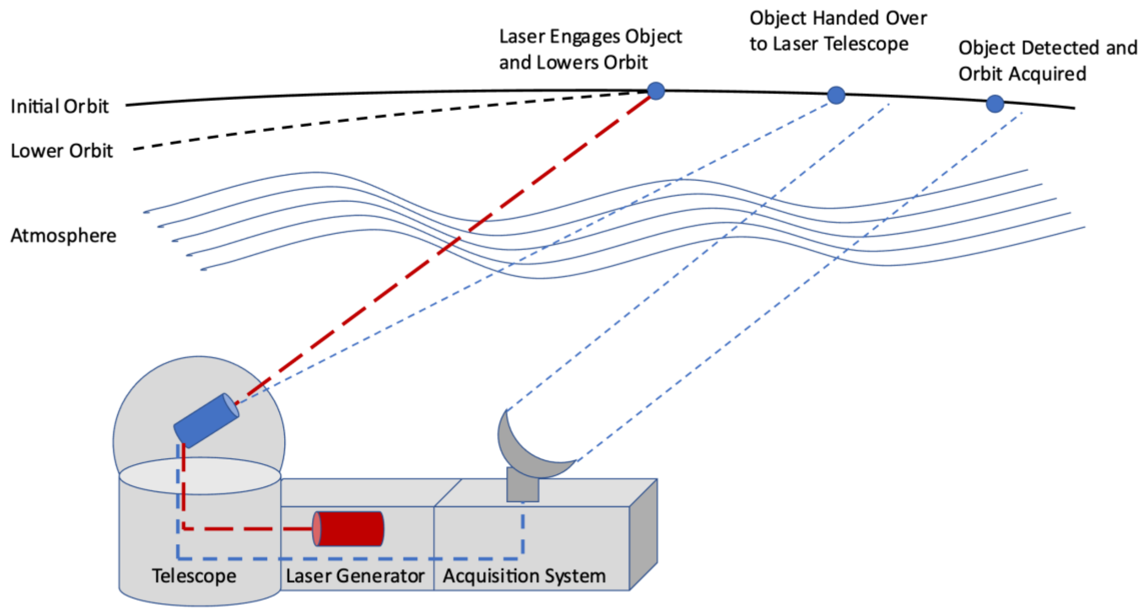

Figure 13. Notional concept for removing small debris with a laser ground station.

Colvin, Karcz, and Wusk (2023) estimated the costs for both ground- and space-based systems. The systems must include the ability to detect, acquire, discriminate/associate, and irradiate the debris. Those requirements bound the costs of both systems as dollars per debris, as summarized in Table 5.

Table 5. Cost to Remove 50,000 Centimeter-Size Debris

Method	Cost per Debris	Number of Debris	Total Cost
Ground Laser	\$300–\$6,000	50,000	\$15 M–\$300 M
Space Laser	\$300–\$3,000		\$15 M–\$150 M

Note: See Colvin, Karcz, and Wusk (2023) for the sources of these estimates.

As Appendix A shows, there are between 145,000 (Model 1) and 425,000 (Models 2 and 3) pieces of 1- to 10-centimeter debris in LEO. We modeled removing a subset of these debris at the beginning of the simulation, with benefit accumulating over 30 years. For continuity with Colvin, Karcz, and Wusk (2023), we considered debris at 450–850 kilometers, thereby targeting debris in some of the more valuable regions, but also in low orbits to be more readily reachable from the ground. For comparability with removing large debris, we calculated the benefits and costs of removing Figure 14 shows the distribution of these debris compared with the entire current population. This scenario removed 34% of the 1-centimeter debris predicted by ORDEM (Model 1) and 12% of the centimeter-size debris predicted by MASTER (Models 2 and 3).

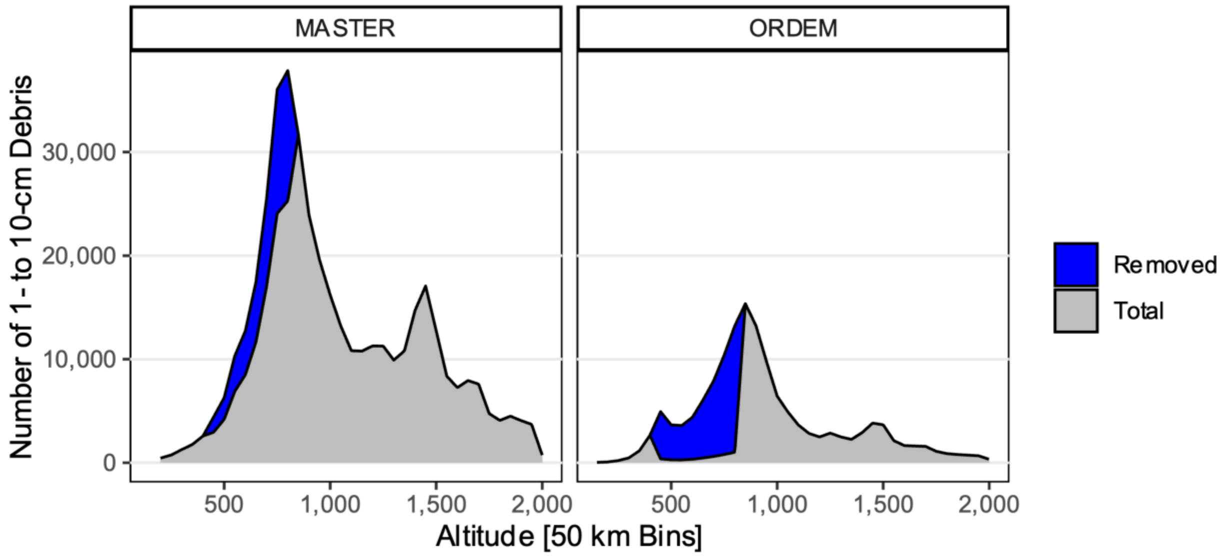

Figure 14. The 50,000 debris removed (blue) and the total debris population (grey)

Benefits and Comparisons with the Costs

All of the benefits from removing 1- to 10-centimeter debris come from reducing the number of mission-ending collisions the debris may have otherwise had with active spacecraft. In reality, 1-centimeter debris may also generate new debris during collisions with other satellites or could reduce the performance of spacecraft in nonlethal strikes; we did not include these considerations in the model. The value of the risk for a piece of debris depends on its size (larger debris are more dangerous and will likely stay on-orbit longer) and its location (some orbits are closer to valuable assets, and higher orbits keep debris in-orbit longer). Figure 15 shows the value (over 30 years) for all centimeter-size debris in LEO.

As might be expected, the models differ in their evaluations of benefit, with Model 1 assigning slightly more benefit per piece of debris. Unique to this case, Model 1 provides a more fine-grained discretization of debris (1–2 centimeters, 2–3 centimeters, etc.) while Model 3 groups all centimeter-size debris into a single category (1–10 centimeters). As a result, in Model 3 the debris are assigned the weighted average size (~2 centimeters).

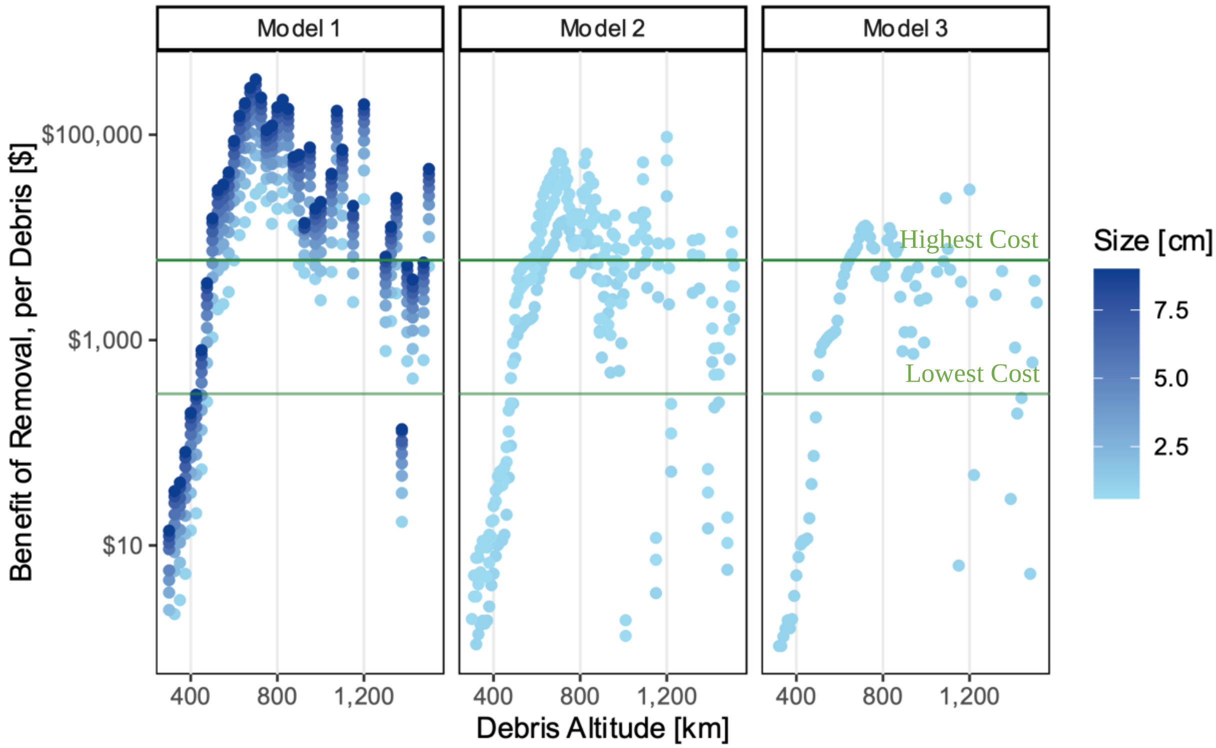

Figure 15. The 30-year value of removing 1- to 10-centimeter debris, by location and size.

The cumulative benefits of removing the 50,000 debris between 450 and 850 kilometers is shown in Figure 16. The benefits decrease over time because 1- to 10-centimeter debris do not generate new debris and as time goes on the debris naturally deorbit.[10]

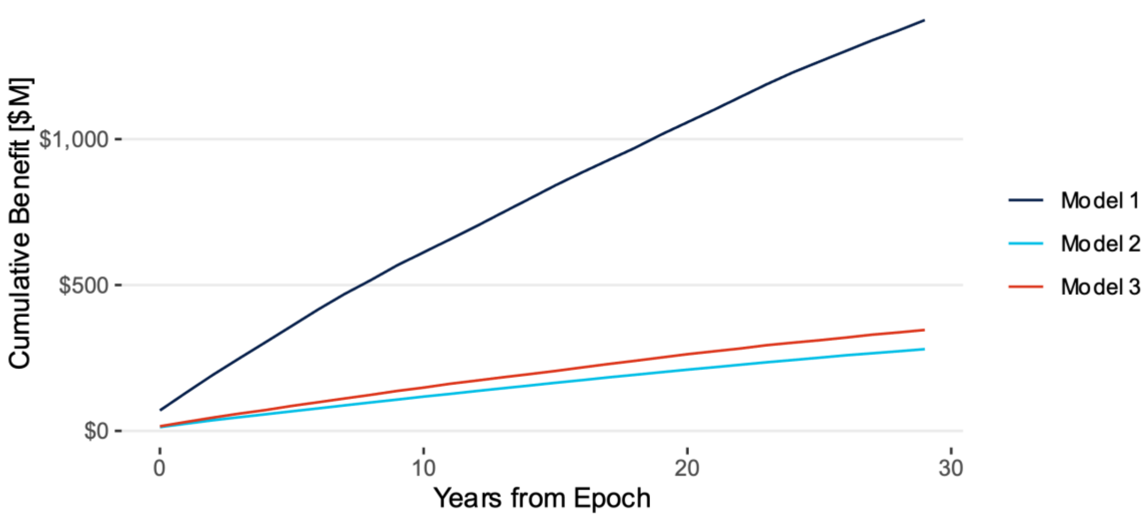

Figure 16. Cumulative benefits from removing 50,000 centimeter-size debris.

[10] This emergent behavior of the model is an update to the Phase 1 results, which found a quadratic increase in benefits over time.

We used the costs we summarized in the previous section to calculate the net benefits, as shown in Figure 17. According to Model 1, removing a 1- to 10-centimeter piece of debris could provide a net benefit of up to $25,000 per the average piece of debris; Models 2 and 3 estimate a net benefit of less than $5,000 per the average piece of debris. The pessimistic bound for a ground laser, which has higher costs, does not become positive, resulting in a "loss" of up to $2,500 per piece of debris. As with the benefit, the slope of the net benefit decreases with time because the objects would naturally decay.

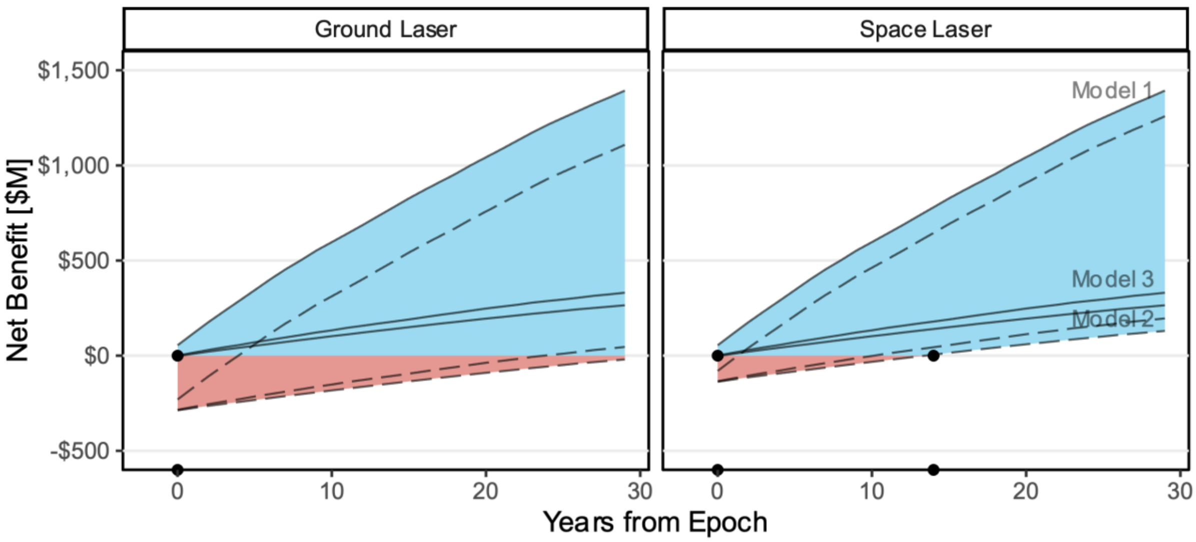

Figure 17. Net benefit of removing centimeter-size debris.

By focusing on the mission-ending risk of 1-10-centimeter debris, we may have underestimated the long-term benefit of removing centimeter-size debris. The debris could generate new debris with time, including by disabling spacecraft.

Remove Millimeter-Size Debris

As a substantial update to the Phase 1 analysis, we added the costs and benefits associated with removing millimeter-size debris. As with 1- to 10-centimeter debris, 1- to 10-millimeter debris pose a threat to spacecraft; therefore, directly removing this small debris may be valuable.

CONOPS and Costs

We consider two methods for removing millimeter-size debris: sweepers and dust. These systems make physical contact with the millimeter-size debris to either capture them or accelerate their orbital demise. Appendix B provides details on the methods, their CONOPS, and their costs; we briefly summarize the information here.

A number of sweeper concepts have been proposed, including the concepts considered in Colvin, Karcz, and Wusk (2023). We define a sweeper as a wide-area spacecraft that makes direct contact with small debris to remediate them. We examined two types of sweepers: one type fully captures the debris upon contact, using a modified Whipple shield;[11] the other type contains a thin sheet of material that absorbs energy from small debris as they puncture the sheet. We call these two systems Whipple sweepers and sheet sweepers, respectively. The sweepers we consider here are passive, meaning they wait to be struck rather than seek out debris.

Another concept for removing millimeter-size debris involves injecting a cloud of tungsten dust into LEO. According to the models in Ganguli et al. (2012) and Crabtree et al. (2013), a cloud of dust dispersed as a ring at 1,100 kilometers will deorbit small debris through hypervelocity collisions between the dust and debris. The dust de-orbits at a similar rate as the millimeter-size debris, creating a "'sweeping' or 'snowplow' effect that can remove large quantities of debris spread over a very large volume" (Crabtree et al. 2013). The cloud of 30–60 micron-size dust will also interact with active spacecraft in orbit. The dust is similar in characteristic size and energy to micrometeoroids, from which spacecraft are already shielded; thus, the dust is not expected to harm spacecraft.

Appendix B contains estimates of the costs of Whipple sweepers, sheet sweepers, and dust. Unlike in the previous sections, which fixed the effects to the environment (e.g. removing 50,000 debris), in this section we start with the removal methods and then calculate the number of debris they might remove. For the sweepers, we fixed their cost and varied the surface area of the sweeper this investment could purchase. Placing the sweeper in an orbit between 800 and 850 kilometers, we used the models to calculate the number of debris the sweepers would be expected to collide with and remove.

We estimated that the cost of deploying 20–40 tons of tungsten dust at 1,100 kilometers would be $408 million–$816 million. Ganguli et al. (2012) found that debris with a mass-over–area-ratio of 5 kilograms per square meter or less can be deorbited by the dust; using NASA's model for fragment sizes, this ratio equates to objects of 3 millimeters and lower (see Appendix B). Following this analysis, we assumed that the dust would remove *all* 1- to 3- millimeter debris below 1,100 kilometers. According to Model 1 (based on ORDEM), the costs would be distributed across 1.2 billion debris removed. In Model 3, which excludes 1- to 5-millimeter debris, the costs do not remove any debris. The costs for both all three methods are summarized in Table 6.

Table 6. Summary of Costs to Remove 1- to 10-Millimeter Debris

Concept	Model 1 [$/debris]	Model 2 [$/debris]	Model 3 [$/debris]
Whipple Sweeper	$16K–$90K	$2 M–$13 M	$74 M–$370 M
Sheet Sweeper	$0.3K–$2K	$50K–$260K	$2 M–$9 M
Dust	$0.34K–$0.70K	$27K–$54K	N/A

[11] A Whipple shield is a type of shielding often found on spacecraft, with spaced plates of material used to protect against hypervelocity impacts.

Benefits and Comparisons with the Costs

As with centimeter-size debris, the benefit of removing a piece of millimeter-size debris is a function of its location and size as shown in Figure 18. Specifically, the larger the object, the more lethal we modeled it to be, such that a piece of 9-millimeter debris is 1,000 times more valuable than a 1-millimeter piece.

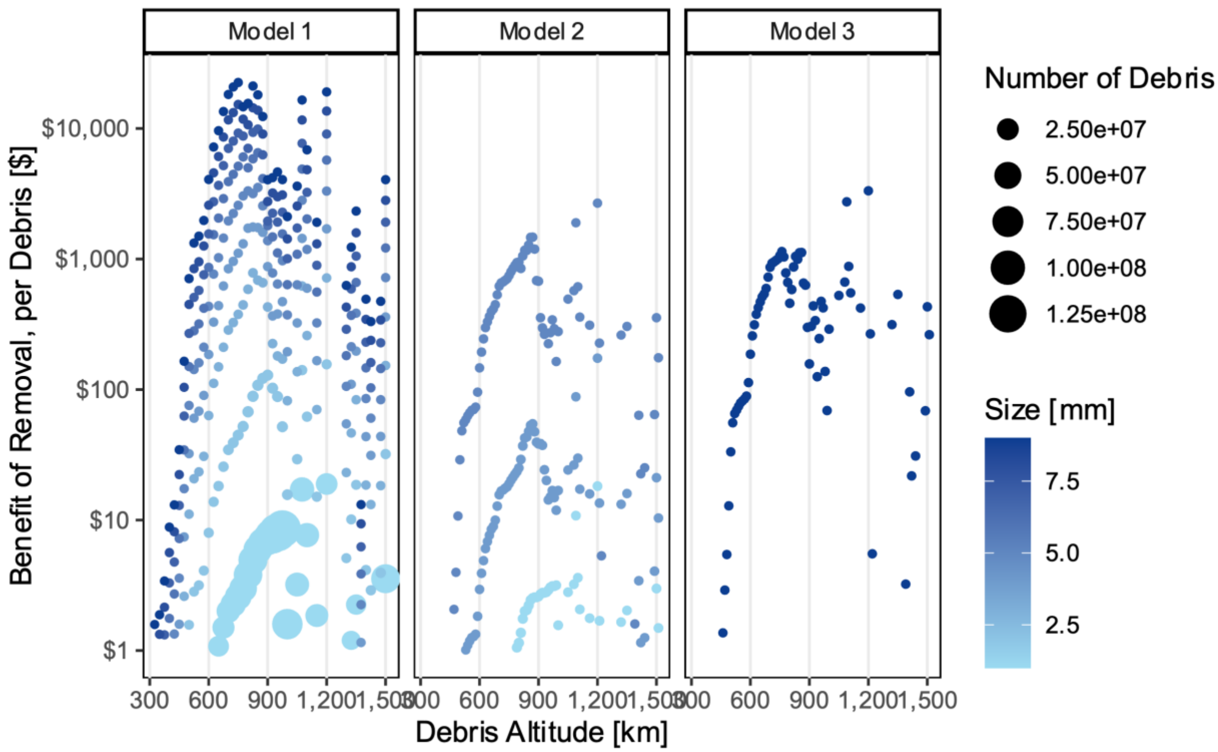

Figure 18. Distribution of benefit from removing 1- to 10-millimeter Debris.

A sweeper's benefit depends on the number of debris it is expected to run into and, thus, on its cross-sectional area. As Figure 19 shows, a sheet sweeper can be expected to reach a far larger area for the same price as a Whipple Sweeper and thus has a much higher potential benefit. In general, the cost will be sublinear as millimeter-size debris would have otherwise deorbited naturally. Given the low ballistic coefficient of very small (1–3 millimeters), most of these debris will decay in the first seven or eight years, resulting in the knee of the curve in the figure.

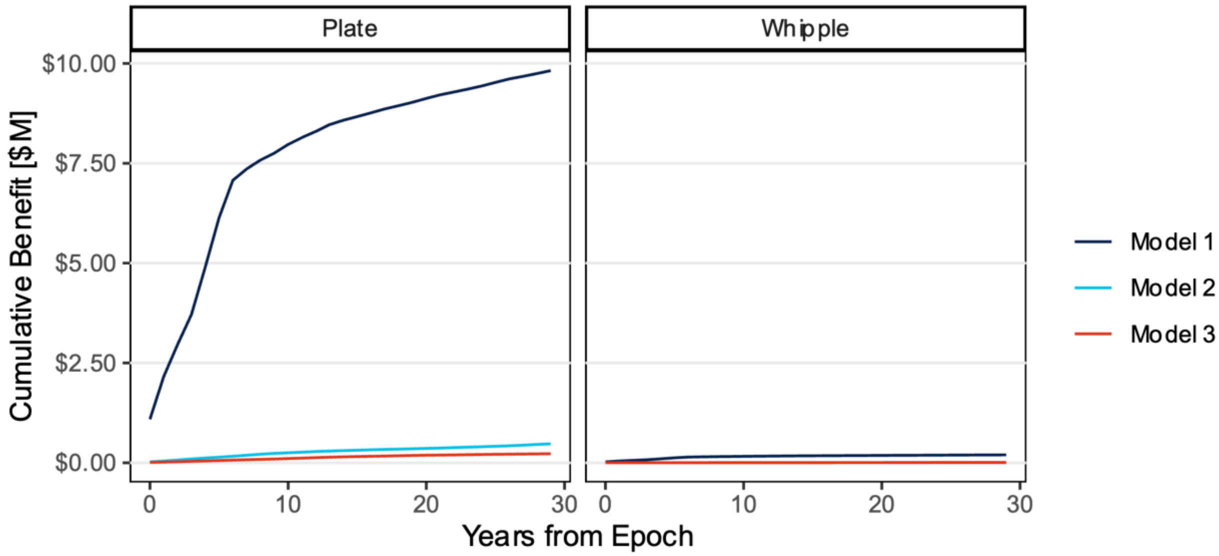

Figure 19. Cumulative benefits of sweepers. Note: The knee at about seven years corresponds with the time it takes 1- to 3-millimeter debris to deorbit from 800–850 kilometers.

Whereas a sweeper removes a relatively small proportion of the total millimeter-size debris, the dust concept purports to remove all debris below a certain altitude and with a characteristic length of approximately 3 millimeters or less. The cumulative benefits in this scenario are shown in Figure 20. Because of the high population of 1- to 3-millimeter debris in ORDEM, Model 1 estimates nearly 200 times more benefits than Model 2 does. Model 3 estimates zero benefits, as it does not include any risk from debris this small.

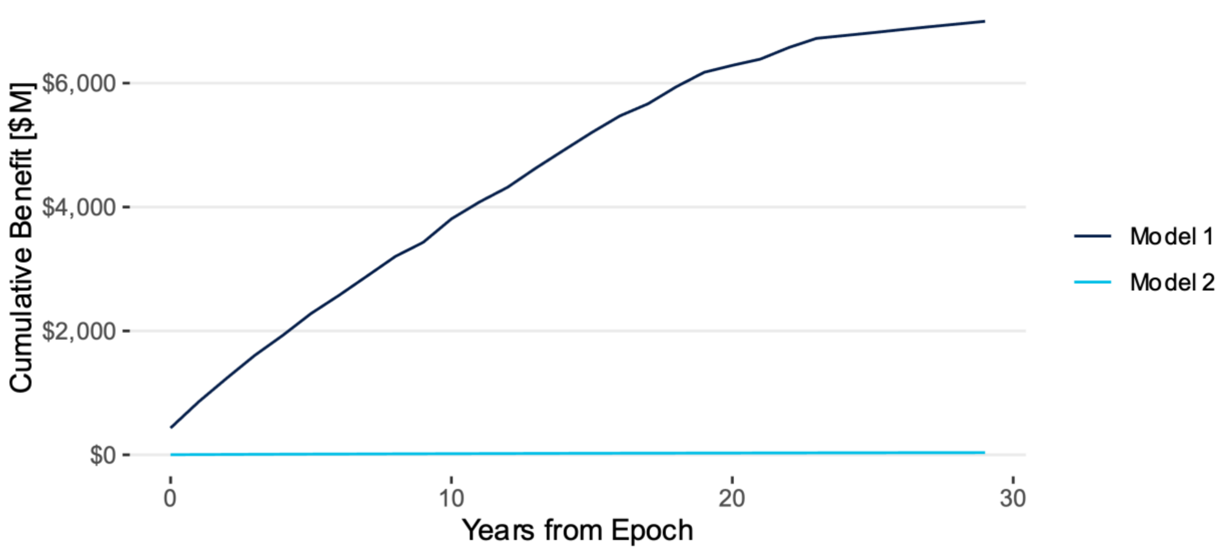

Figure 20. Cumulative benefits of using tungsten dust.

The potential benefits of the dust exceed the benefits of a sweeper by several orders of magnitude, while the potential costs are similar. Thus, as shown in Figure 21, the net benefits for the dust far exceed those of a sweeper. As with other approaches, the rate of increase in dust's benefits slow over time because more objects would naturally deorbit. The pessimistic estimate of the dust method is lower than that of the sweeper because both concepts have the potential to be ineffective, but dust is likely more expensive than a single sweeper.

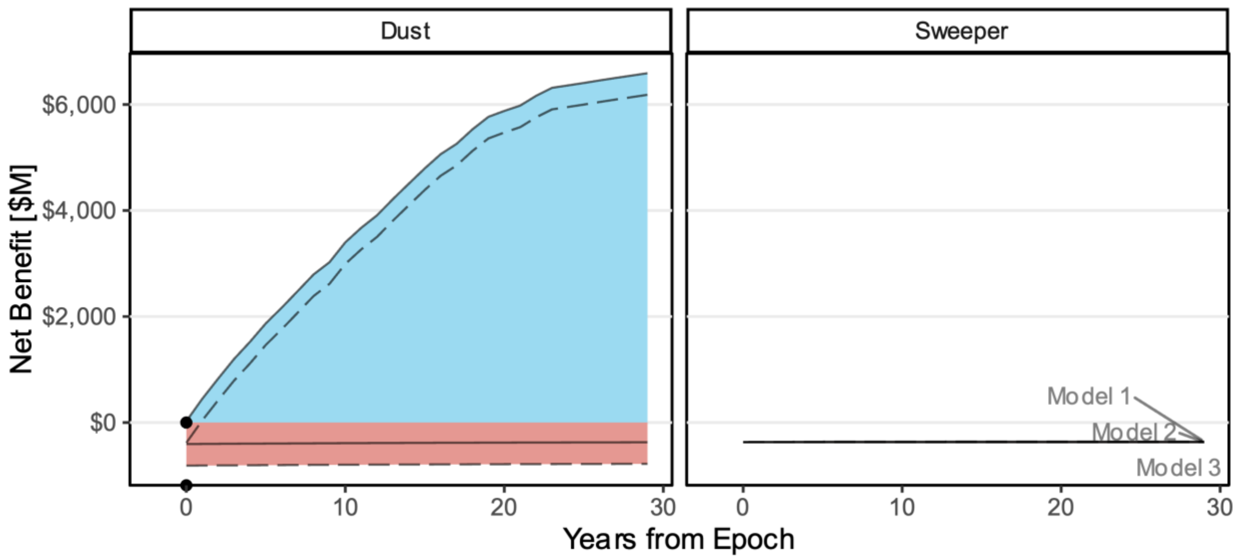

Figure 21. Net benefit of remediation efforts targeting millimeter-size debris

Some literature has concluded that sweepers, especially passive sweepers, might not effectively remediate debris (e.g., Pulliam 2011). It may be possible for sweepers to perform better by using them as active seekers of debris, with their effective radius increased at the expense of propellant, or by having them target uniquely dense orbits, such as the orbits of fragmentation events. Alternatively, if more debris are on-orbit or small debris (e.g., < 1 millimeter) are dangerous, then sweepers will perform better. To reach a positive net benefit, however, the number of valuable debris captured by a sweeper needs to increase by about 40 times our calculations, even using ORDEM. In comparison, dust represents a potentially high net benefit but is a more speculative mechanism. More work would need to be done to validate the concept and its level of impact on active spacecraft before the concept would be ready to implement.

Mitigation

Satellites and satellite operators can mitigate the generation of new, long-lived debris. According to the U.S. Orbital Debris Mitigation Standard Practices (ODMSP), mitigation limits "the generation of new, long-lived debris by the control of debris released during normal operations, minimizing the debris generated by accidental explosions, the selection of safe flight profile and operational configuration to minimize accidental collisions, and the disposal of space structures" (U.S. Government 2019, 1).

This study investigated three classes of action that designers, planners, and operators take to limit the creation of debris from spacecraft: spacecraft shielding, explosion passivation, and postmission disposal (PMD). We focused on the three leading contenders, saving for future analysis several other actions that could be considered mitigation strategies, such as designing more-reliable spacecraft, selecting less-dangerous orbits, and space traffic coordination to avoid collisions with other tracked objects.

PMD

Satellites and upper stages at the end of their lives become debris until they are removed from the space environment. They may pose a collision threat to active spacecraft, generate debris as they collide with non-maneuverable space objects, explode accidentally, and shed debris through surface degradation. Before spacecraft become debris, the risks that spacecraft pose can be reduced by moving the spacecraft to a safer orbit or reentering them in the Earth's atmosphere. In this study, we considered spacecraft respecting an "*N*-year rule," in which the defunct spacecraft must deorbit within *N* years.[12] Currently, NASA requires spacecraft to reenter within 25 years, and the FCC requires commercial spacecraft to reenter within 5 years.

CONOPS and Costs

There are two classes of technologies that can be used to accelerate the deorbiting of a defunct spacecraft: propulsive technologies and drag devices. With propulsive technologies, the spacecraft uses its own propulsion system, whether chemical or electric, to maneuver to a lower orbit and will then decay naturally. With drag devices, the spacecraft uses a drag sail or tether to generate a large increase in drag forces, causing the spacecraft to deorbit faster than it otherwise would.

When using propulsive disposal, a spacecraft (with maneuver capability) will maneuver (1) into a circular orbit that will cause the spacecraft to deorbit within N years or (2) to a perigee that is low enough to cause nearly immediate deorbiting. The cost of deorbiting a satellite depends on its operational altitude, mass, and propulsion system. We do not know the type of propulsion system of each spacecraft, so we used electric and monopropellant systems as the low- and high-

[12] All spacecraft in our population are at 1,5000 kilometers or below, so we assume their disposal pathway is to lower themselves to decrease the time to deorbit.

cost bounds. The costs were calculated as the launch costs of the additional fuel needed to perform the disposal maneuver. The results are presented in Appendix C and summarized in Table 7.

Table 7. Estimated costs to dispose of a spacecraft operating at 1,000 km

	Micro	Small	Medium	Large
25 Year	\$1,738 - \$8,424	\$19,554 - \$94,770	\$56,489 - \$273,780	\$130,359 - \$631,800
15 Year	\$2,000 - \$9,737	\$22,495 - \$109,544	\$64,984 - \$316,460	\$149,964 - \$730,291
5 Year	\$2,264 - \$11,080	\$25,474 - \$124,655	\$73,592 - \$360,115	\$169,829 - \$831,034
1 Year	\$2,805 - \$13,861	\$31,554 - \$155,934	\$91,156 - \$450,475	\$210,359 - \$1,039,558
0 Year	\$3,643 - \$18,281	\$40,986 - \$205,663	\$118,404 - \$594,139	\$273,239 - \$1,371,090

Note: The altitude values calculated for the three *N*-year rules are 650 km, 600 km, 550 km, 450 km, and and 300 km.

When using drag device disposal, a drag sail or tether is deployed at the end of the spacecraft's life, decreasing the ballistic coefficient and thus the time to deorbit. The drag device does not impulsively maneuver the derelict spacecraft to the disposal orbit but applies a constant additional force on the debris due to enhance drag that causes the spacecraft to deorbit in N years. The cost of the drag devices can be calculated as the hardware costs and launch costs, both bounded by the areas summarized in Table 8.[13] We considered the drag sail and tether together when calculating the low- and high-cost bounds.

Table 8. Costs of Drag Devices

Device	Areal Mass (kg/m^2)	Hardware Cost per Area (m^2)	Total Cost per Area (m^2)
Drag Sail	1/12–1/14	\$40–\$80,000	\$400–\$80,400
Tether	1/10–1/12	\$500–\$8,000	\$915–\$8,500

Note: Appendix C details the calculations for these costs and compares them with flown hardware.

Benefits and Comparisons with the Costs

We modeled the benefits of PMD as the difference in risk between leaving the defunct spacecraft in its operational orbit and disposing the spacecraft to deorbit within *N* years. We varied *N* from 25 years to 0 years and examined the full benefits and costs for the propulsive option before proceeding to the drag devices.

Figure 22 shows the range of benefits calculated for a 90% compliance rate.[14] Model 1 predicts a benefit that is one order of magnitude higher, primarily because of surface degradation.

[13] In applying drag devices, we modeled scenarios with a prescribed maximum added drag area so that the drag devices would only be used in cases in which they could meet the *N*-year rule.

[14] We assumed that all operators attempt to meet the prescribed PMD rule, though in reality it is not reasonable to expect that all operators will comply with the rule. We assumed that 90% of attempts at PMD are successful (the

For example, for the 5-year rule, Model 1 estimates $16 billion in avoided damage from surface degradation—83% of the total benefits. In Models 2 and 3, the greatest value comes from avoiding collisions, followed closely by avoiding explosions. These results illustrate the joint nature of risk-reducing actions; for example, a lower-year PMD rule can serve as a potential alternative to passivation measures.

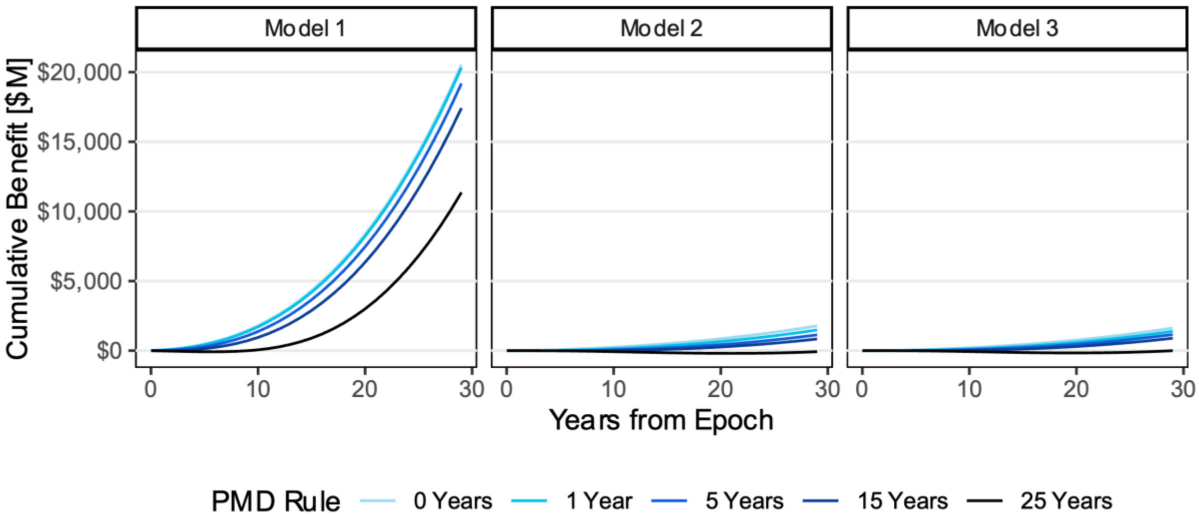

Figure 22. Benefits of propulsive PMD over 30 years.

As expected, the benefits associated with lower-year rules exceed the benefits associated with higher-year rules. The benefits come from disposing of defunct spacecraft in orbits below other active satellites, thereby avoiding any added mission-ending risk to those satellites. When a defunct spacecraft is placed in its disposal orbit, it will generate untracked debris through surface degradation and has the potential to generate large quantities of small and large debris through collisions and explosions. This untracked debris will rain down on active spacecraft below the disposal orbit, increasing the risk of mission-ending collisions.

Perhaps surprisingly, the benefit associated with the 25-year rule is negative in Models 2 and 3. In other words, the 25-year rule results in the disposal of spacecraft in crowded orbits, causing greater risk than if the derelict spacecraft are left at the operational orbit. Eventually, the benefits would become positive for all models; Model 1 became positive the quickest because of the influence of surface degradation.

Figure 23 shows the altitudes of the added or reduced risk in Model 2. The 25-year rule causes more near-term risk because of the large population of spacecraft around or below the 650-kilometer disposal altitude. Research shows that operators tend to congregate at the maximum altitude they will naturally be compliant at (Rao and Letizia 2021), so we might expect an *N*-year

NASA standard for PMD reliability) and that for 10% of spacecraft will fail to reach the designated disposal orbit even though the operators paid for the extra fuel required. These assumptions result in a much higher rate of adherence than the current rate of 40%–70%.

rule to pose higher risk when imposed on all operators (the 25-year year will have this effect in the extreme). Alternatively, one of the reasons the 1- and 0-year rules have such a high benefit is that they apply to more satellites than do longer *N*-year rules; all else being equal, with more spacecraft taking risk-reducing actions, the benefits of shorter *N*-year rules are greater. These insights suggest that benefits could be improved by requiring some level of personalization in deorbiting rules. For example, if lower-altitude spacecraft cleared out more quickly, perhaps higher-altitude spacecraft would not need to deorbit as aggressively; in this way, the costs of space sustainability could be shared more evenly among operators.

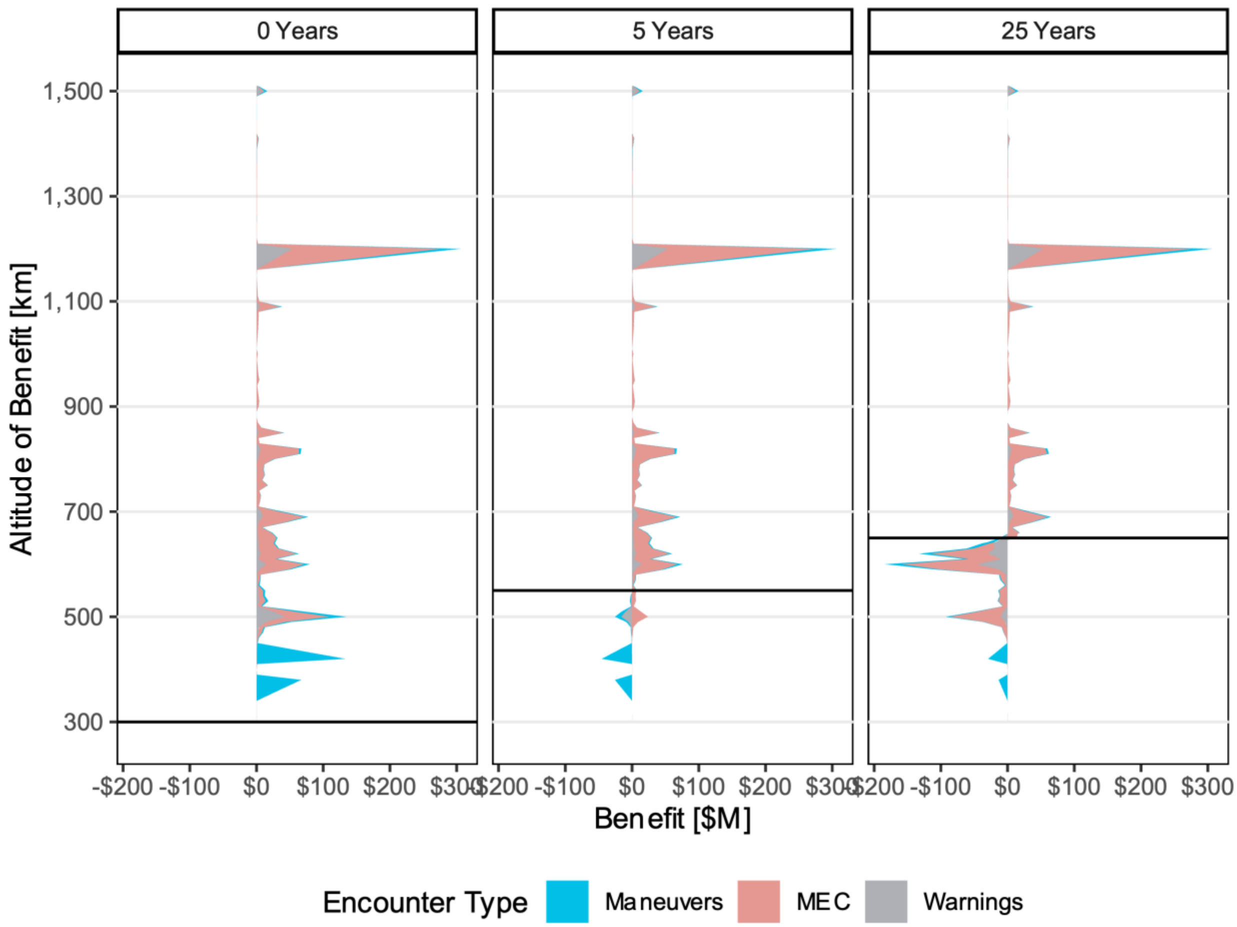

Figure 23. Location of added and removed risk in Model 2 for propulsive PMD.

Figure 24 shows how the expected benefits minus the costs evolve over time. Although the difference between the highest and lowest cost benefits is substantial, even the pessimistic estimates have positive outcomes for the 1-, 5-, and 15-year rules. In contrast, the pessimistic estimates for the 25-year rule do not become positive over 30 years.

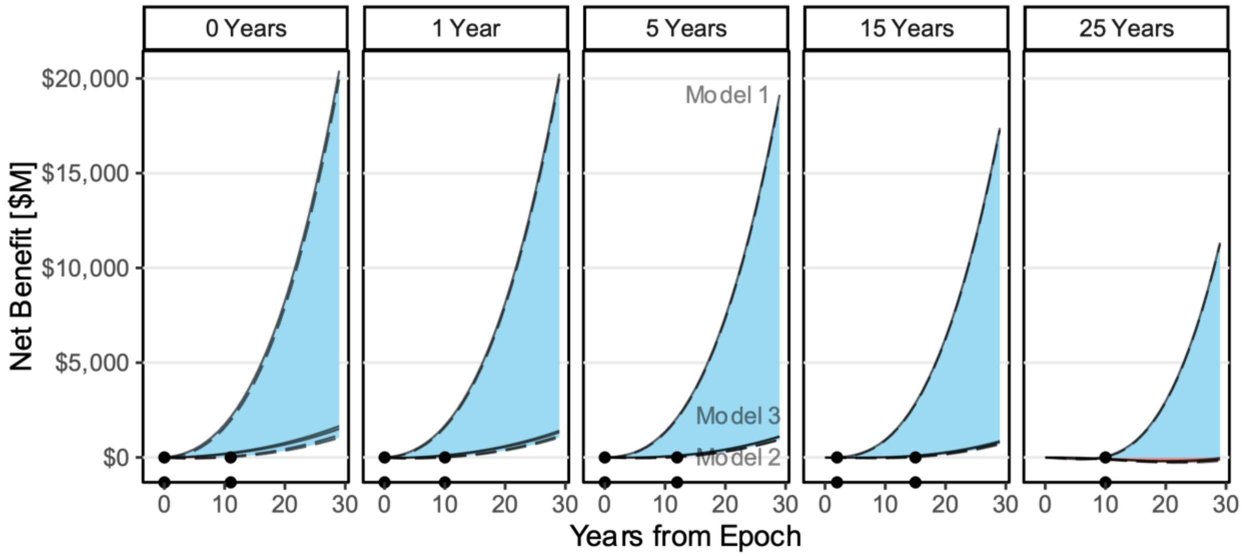

Figure 24. Net benefits for propulsive PMD.

The benefits and costs resulting from PMD with a drag device must be modeled completely differently. Satellites with a deployed drag device deorbit more quickly but must pass through all altitudes below their operating position with a larger collision area because of the sail or tether. The benefit, or consequence, of adding the drag device is the combination of removing the derelict spacecraft faster while considering the additional collision risk. At some point of increasing drag area, we expect the additional risk to overwhelm any benefit.

To explore the potential benefits of a drag device, we modeled 16 combinations, varying the *N*-year rules and maximum drag device areas as shown in Figure 25. As an example, for a 5-year rule and a 50-square-meter area, drag devices were attached to all satellites when the devices could lower the lifetimes to 5 years without needing more than 50 square meters of additional area. As the maximum area increases, so does the number of applicable satellites and the potential for added risk (which scales with the area added). We do not know the consequence of a collision involving a drag device; thus, we attempted to bound the problem by assuming that if a large piece of debris with a drag device collides with another object, the collision will be catastrophic collision or have no effect (e.g., the debris just punches through). The bounded risk is shown in Figure 25. We also combined the tethers and drag sails into a single option to bound the possible benefits and costs.

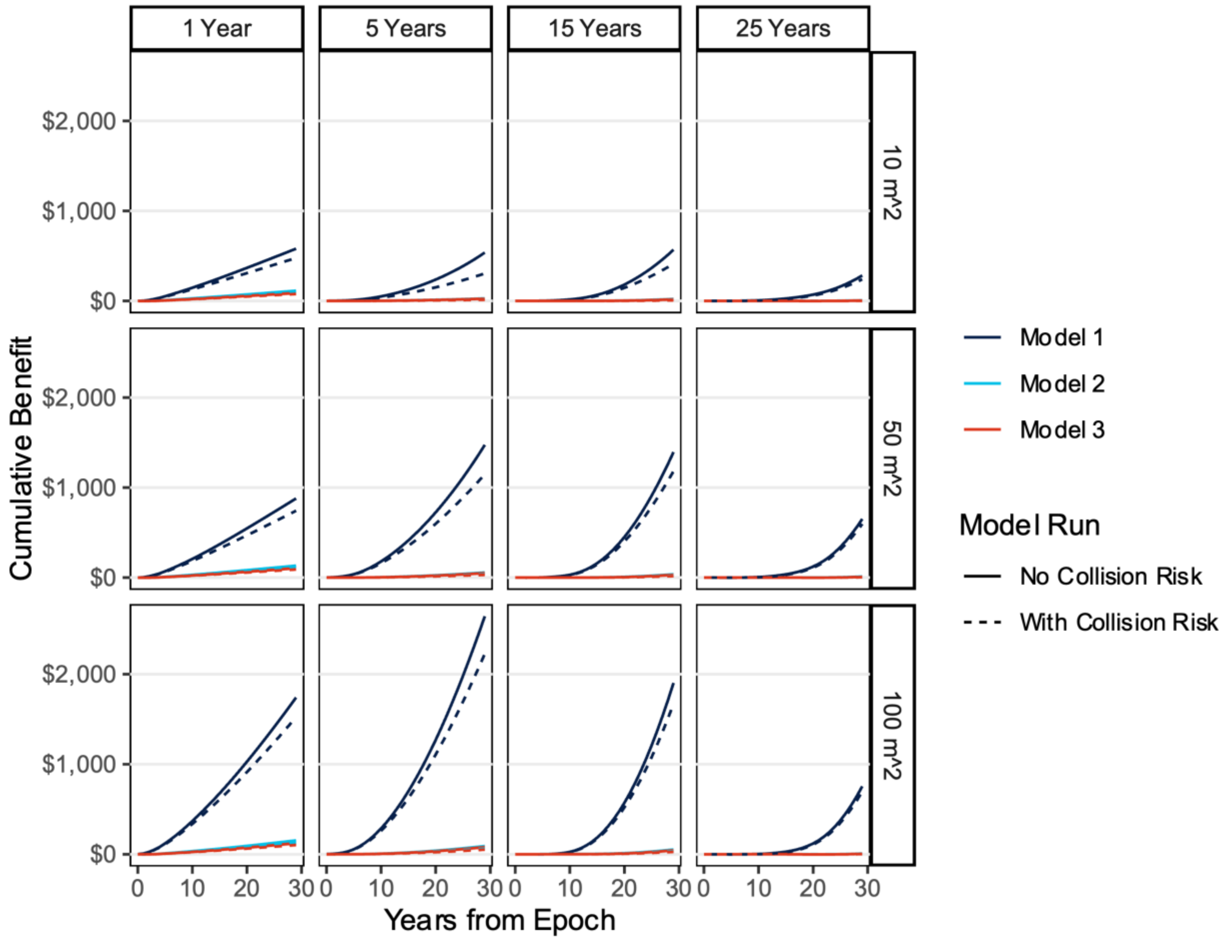

Figure 25. Cumulative benefits of PMD attachments.

These benefits show that low *N*-year rules appear to offer greater benefit than high *N*-year rules because derelict spacecraft are removed faster and the large drag surface is exposed to the environment for a shorter time. Second, the collision assumption are only decisively bad for the largest drag areas in the highest *N*-year rules. Assuming that the drag device poses the same collision risk as hitting the spacecraft bus, only small devices result in a positive benefit. These smaller devices are the type that have been tested before, such as in DRAGRACER, PROX-1, and NPSat-1. Even with more conservative collision parameters, implementing a controllable concept could alleviate risk by maneuvering a decaying satellite around potential collisions, albeit there will be additional costs to operate the spacecraft throughout its disposal.

The two methods we considered—drag sails and tethers—can both provide the drag area needed to achieve the benefits described above. To determine the net benefit, we considered them together to identify the high- and low-cost bound, as shown in Figure 26. The net benefit shows just the 50 m^2 scenario, chosen to maximize the benefit ratio.

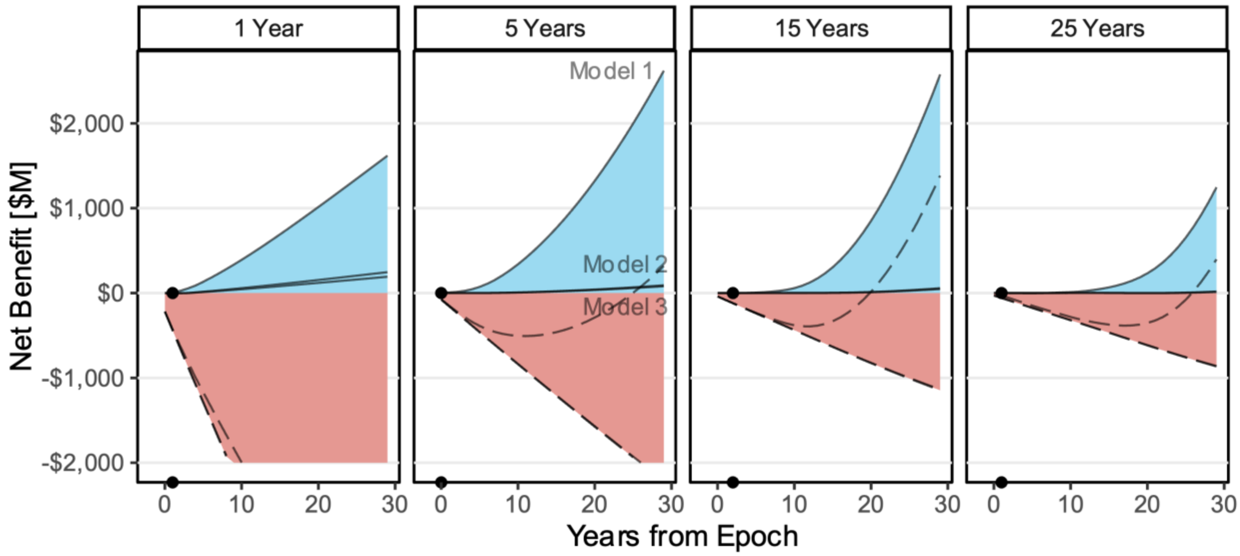

Figure 26. Net benefits of PMD drag sails and tethers. Note: Plot cut off at -$2,000.

Considered together, the drag sails and tethers show some potential in deorbiting satellites at their end of life. Looking solely at tethers offers a more positive bound, including completely positive benefits for all 5-year implementations. Therefore, using PMD attachments is a promising method, especially if the added collision risk can be accounted for and better modeled than what was possible in this study.

Shielding

Spacecraft are shielded for two reasons: (1) protection, which reduces the probability that a mission will end because of a small-debris strike, and (2) mitigation, which increases the chance that the spacecraft will successfully perform its PMD. For the purposes of this analysis, we assumed that if a critical area of a spacecraft is penetrated by a piece of small debris, the mission is lost *and* no PMD actions can be taken. We did not account for situations in which the mission is lost but PMD actions can still be completed or in which the mission was not lost but PMD actions were not taken.

CONOPS and Costs

Spacecraft use many types of shielding; for example, critical components are placed behind the natural structure of the bus, protective layers (e.g., Kevlar) are added, and bulky Whipple shields are incorporated. Most shielding consists of layers of mass with empty volume between the layers. For the purposes of this analysis, we parametrized all shielding by the amount of added mass required to shield critical areas from penetration of debris up to a chosen characteristic length.

For the CONOPS of shielding, we assumed that all spacecraft are naturally shielded against debris 1 millimeter and smaller.[15] Designers identify the amount of critical area that remains insufficiently shielded and then add material with sufficient stopping power for the size threshold specified. As described in Appendix C, we bounded the amount of shielding potentially needed by the spacecraft to reach a given level of protection. Finally, we converted the added mass to a cost by using a launch rate of $5,000 per kilogram. Additionally, we added an installation time value of $100,000 per kilogram to the upper bound. The lower bound is shown in Figure 27; the upper bound is about an order of magnitude greater, with a similarly shaped curve.

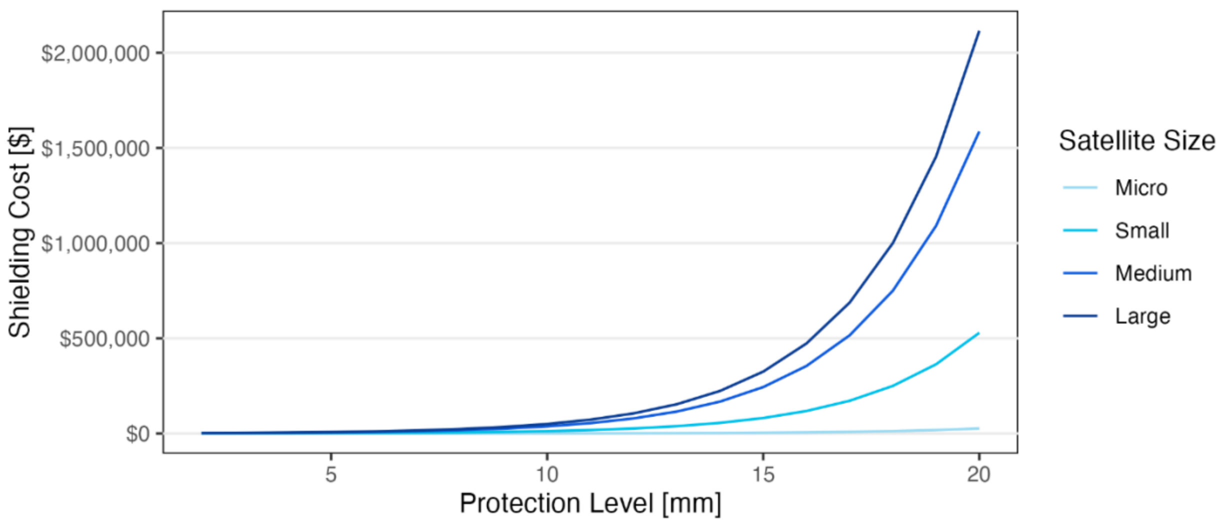

Figure 27. Low-bound cost estimates of shielding for classes of spacecraft.

Benefits and Comparisons with the Costs

The benefits of shielding spacecraft can easily reach tens of billions of dollars, as shown in Figure 28. In our methodology, any shielding for debris larger than 1 millimeter continuously reduces the direct risk that untracked particles pose to spacecraft and also avoids generating debris as a result of a mission-ending strike. The benefits of added shielding are calculated assuming that the spacecraft have not already added any shielding to meet the ODMSP standards (< 1% risk of PMD failure), so the benefits of adding shielding beyond the current requirements would be less than our estimates. Model 3 does not include 1- to 5-millimeter debris because of the uncertainty

[15] Spacecraft may be susceptible to smaller, high-density debris (Squire et al. 2015), but we did not account for high-density debris for the purposes of this analysis (see Appendix A). The baseline spacecraft can be roughly thought of as unshielded spacecraft, though it depends on the particulars of the environment and the spacecraft. In other words, no additional shielding mass has been added. Whether this assumption is accurate depends on the true penetration risk of the spacecraft and the existence of high-density particles in the orbit. For example, the NESC MMOD assessment for JPSS found that medium-density particles become potentially damaging when at least 1.2 millimeters, while high-density impactors are a threat when at least 0.6 millimeters (Squire et al. 2015).

about the danger of these debris; therefore, Model 3 represents a counterpoint to the high 1- to 3-millimeter population in Model 1.

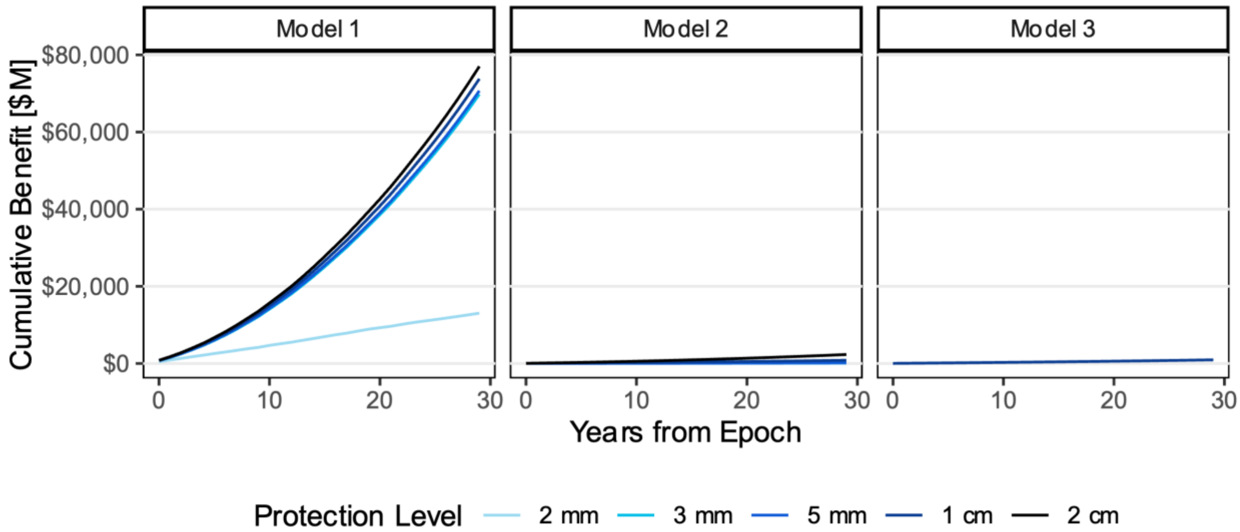

Figure 28. Cumulative benefits of adding shielding to unshielded spacecraft.

Most of the benefits are associated with protecting the spacecraft's mission; the higher probability of reaching PMD accounts for less than 1% of the total benefits. The proportion of benefits due to successful PMD compliance tends to increase as the time horizon of the benefits is extended or the *N*-year rule is decreased. Regardless, in the first few decades, the potential benefits of shielding mainly come from mitigating the damage done to operational spacecraft rather than enhancing PMD compliance.

To calculate the benefits, we assumed that all spacecraft take on added shielding.[16] However, a small minority of the population is most at risk from small debris and stands to gain the most benefit. In fact, over 90% of the benefits come from shielding just 10% of the spacecraft in orbit.

The benefits of increased shielding are shown in Figure 29. This initial analysis shows high potential benefits for all shielding strategies, although the low estimate of net benefit worsens when debris are larger than 1 centimeter. The lower bound remains below zero for shieling that protects again debris that are 5 millimeters and smaller because Model 3 does not estimate a benefit. If there is indeed a risk from such small debris, protecting spacecraft from those debris may be the most effective way to reduce the risk of mission-ending collisions.

[16] This assumption includes newly launched spacecraft. It was assumed that all spacecraft immediately took on this level of shielding at the beginning of the simulation.

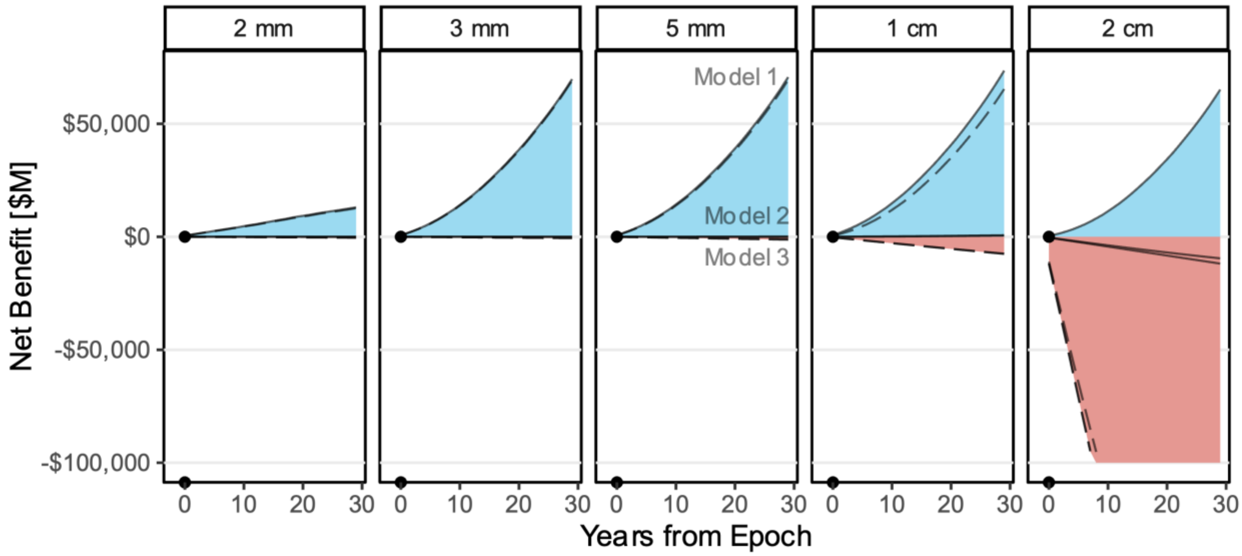

Figure 29. Net benefit of spacecraft shielding. Note: Limited the lower bound of the plot to -$100B.

Fragmentation Mitigation (Passivation)

Spacecraft store energy onboard in batteries and propellant tanks. Under certain conditions, this energy can be released dramatically, essentially causing the spacecraft to break up. Such explosions are responsible for a large portion of the current debris population (NASA 2022a). Spacecraft can be designed to reduce the probability of these explosions, both during spacecrafts' active lives and after their demise.

CONOPS and Costs

Spacecraft are at risk of exploding both during operations and after the end of their operational lifetime. Both time frames have historically required mitigating actions: during life, under safe operations; after life, under PMD. We focused on PMD, or passivation, but considered benefits to operations if applicable. Further, we focused on mitigating the risk from payloads—active and derelict satellites—since our limited model does not yet include adding new rocket bodies to the environment.

Both electrical and propulsion explosions can be mitigated in a number of ways, ranging from completely disconnecting the batteries to running the propulsion system longer to use up most of the propellant. Many of the mitigation methods impose a level of risk that is difficult to quantify; specifically, these methods add to mission risk by increasing complexity or a single point of failure. Further, many only partially reduce the explosion risk. We attempted to find a CONOPS with small added mission risk and virtually complete explosion prevention so we could more simply estimate the cost and benefit. Thus, the CONOPS used here will be one of the approaches used by spacecraft designers and likely not the most commonly used approach.

For mitigation of electrical explosions, we estimated the cost of mitigation based on replacing conventional satellite batteries with batteries robust to thermal runaway. This replacement would approximately double the battery mass of the spacecraft. The electrical system would still need to be protected from overcharging, but the addition of redundant switches could, in theory, reduce the probability of an electrical explosion to nearly zero during and after operations.

For mitigation of propulsion system explosions, we considered adding pyrotechnic valves to the system, either as a flow orifice that vents the pressurized propellant. This solution would only lessen the risk of postmission propulsion explosions. As an added single point of failure, this solution would also likely add some measure of mission risk, which we omitted for this analysis.

The cost of the combined mitigation approach (i.e., to mitigate electrical explosions and propulsion explosions) depends primarily on the size of the spacecraft because of battery mass. That cost is summarized in Table 9.

Table 9. Explosion Mitigation Cost per Satellite

Satellite Size	Electrical Mitigation Cost	Propulsive Mitigation Cost
Micro	\$3,000–\$5,000	\$10,000–\$150,000
Small	\$63,000–\$125,000	
Medium	\$163,000–\$325,000	
Large	\$375,000–\$750,000	

Benefits and Comparisons with the Costs

The benefits of the methods to mitigate explosions depend on the reduction of the probability of all electrical explosions and propulsion explosions regarding payloads (see Appendix C for the calculations). Our calculation indicates the benefit is the elimination of, on average, 1.1 fragmentation events per year. Figure 30 shows the benefits estimated over 30 years.

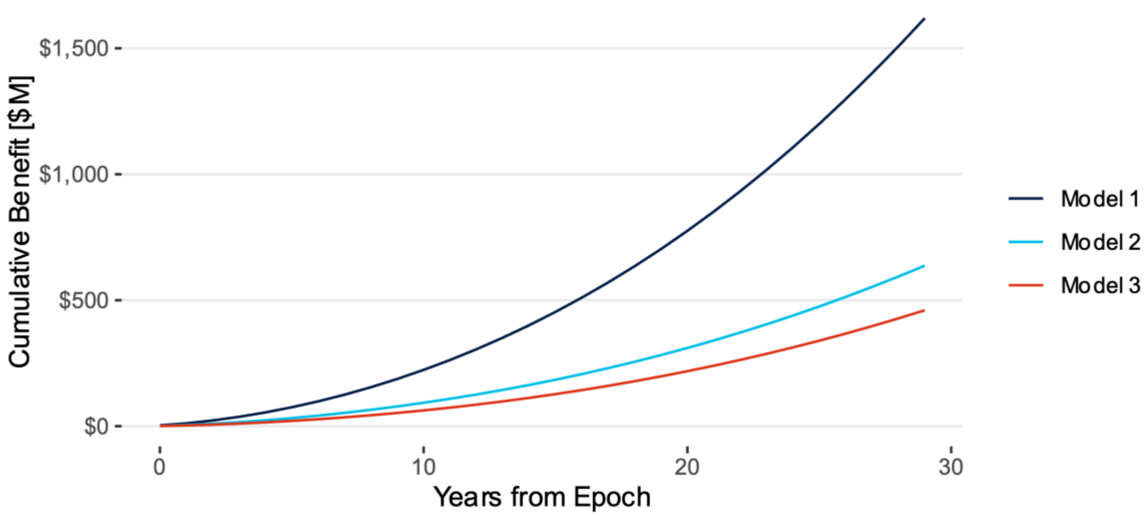

Figure 30. Cumulative benefits of mitigating accidental explosions.

About 90% of these benefits come from electrical passivation, which is the most common (attributed) historical cause of explosions in payloads. In our exemplar mitigation methods, adding resilient batteries creates a much higher cost, especially for large satellites, in which the cost is an order of magnitude greater. The benefit is also much higher for larger satellites and for satellites at higher altitudes, since the consequences of their fragmentation are much greater.

When combining electrical and propulsion risk mitigation, the net benefits do not reach a positive value within 30 years, as shown in Figure 31. Eventually, as the benefits continued to accumulate with time and across generations of spacecraft, the benefits would presumably reach a positive value. However, in the near term, the results indicate that investing more resources into the explosion mitigation methods we outlined will not likely be cost-effective. To reach a net benefit for the pessimistic bound, the costs would need to be about 10 times lower than estimated here.

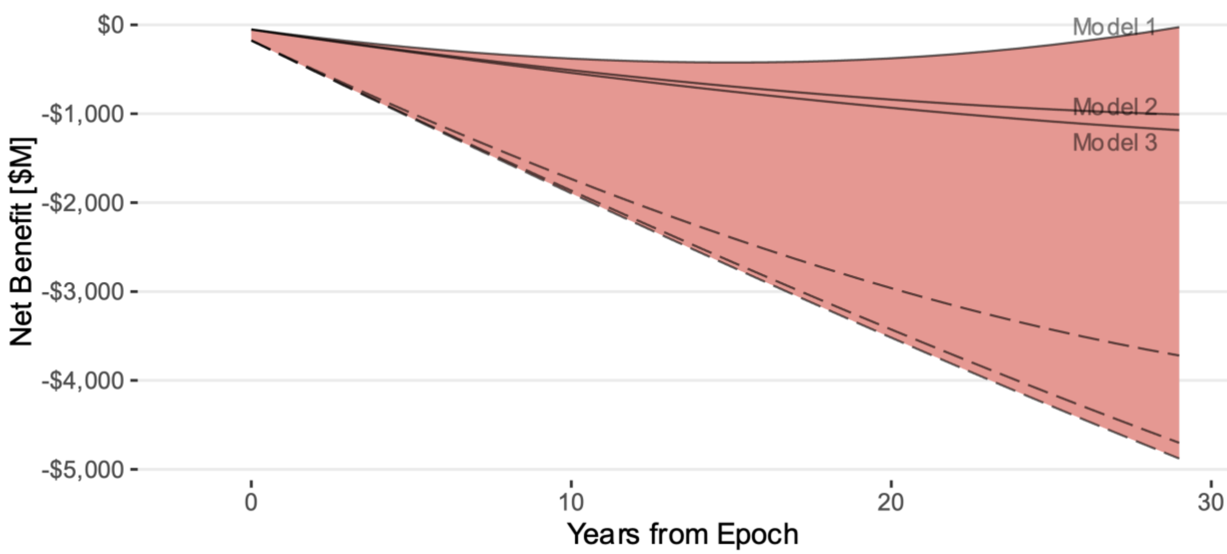

Figure 31. Net benefit of mitigating accidental explosions.

We present three caveats to our findings here. First, unlike in other parts of our analysis, we based the fragmentation rate on empirical data and thus current actions. So, the benefit we considered here is not the benefit of doing any explosion mitigation but for doing more than is already done. Second, we considered only two of the many mitigation approaches, which may not be the most cost-effective.[17] The results are not yet comprehensive enough to speak to all explosion mitigation. Finally, it is worth repeating that this analysis was conducted on a very broad level across all spacecraft. It is likely that targeted applications of even the approaches we mentioned here could yield high benefit-cost ratios.

[17] Of particular note are "soft passivation" options; with these options, hardware changes are not necessarily made but changes in CONOPS reduce or even effectively eliminate explosion risk.

Tracking

Compared to estimates produced using unimproved tracking capabilities, improved tracking capabilities can decrease errors in the estimated probability of collision (PC) between two objects. Decreasing the errors creates two main benefits for satellite operators: reduced maneuvers to avoid already-tracked debris and the ability to avoid previously untracked debris.

Specifically, improved tracking capabilities may decrease the estimated PC associated with conjunctions that were previously estimated to be high risk, thereby reducing the number of warnings and maneuvers that spacecraft operators experience. Alternatively, the estimated PC of conjunctions may increase. If the conjunction was previously assessed to be low risk, the improved tracking may reveal that the risk of collision is higher than previously thought. Further, debris smaller than 10 centimeters is not currently tracked in LEO, and PC is not able to be calculated. Improved tracking capabilities may allow for meaningful PC estimates regarding small debris; the improved estimates can be used to inform collision avoidance maneuvers that would not have otherwise been made.

For the purposes of analysis, we made the simplifying assumption that all tracked debris (currently objects 10 centimeters and larger in LEO) are always avoided by maneuverable spacecraft. In reality, there is some probability that a maneuver will fail to avoid a collision or that a conjunction will have an estimated PC of less than 1 in 10,000 and will still result in a collision. We did not account for these edge cases. Further, actions that track large or small debris might have a large overlap; however, for simplicity we considered them independently.

Track 1- to 10-Millimeter Debris

We were unable to analyze concepts capable of tracking millimeter-size debris to support conjunction analysis and collision avoidance maneuvers. This area of research is emerging and remains theoretical. In particular, we highlight the work of Hartzell et al. (2019), whose lab focuses on simulating and detecting ionospheric disturbances caused by millimeter-size debris. Her coauthor and former PhD student Alexis Truitt is currently the program manager for the SINTRA program at IARPA. SINTRA’s goal is “to identify and track space debris as small as 1 mm” (IARPA 2023), and the program has recently given awards to four teams of performers (Seffers 2023). When the four-year SINTRA program concludes, concepts for tracking millimeter-size debris may be at the point that their cost and efficacy can be roughly analyzed.

Track 1- to 10-Centimeter Debris

Current SSA systems are generally reliable in tracking LEO space objects with a characteristic length as small as 10 centimeters. For debris below that size, operators are not able to take mitigating actions, and spacecraft are thus vulnerable to unknown collisions that may degrade or end the missions. It may be possible to maintain custody of small debris, enabling satellites to maneuver to avoid them.

We analyzed four theoretical methods of tracking 1- to 10-centimeter debris; all of these methods have a similar CONOPS. The following steps are common to all methods:

1. **Detect new debris**. A radar or passive optical system stares at the sky until the system detects a new object.
2. **Add debris to centimeter-size debris catalog**. The detection system tips a sensor to "chase" the object. The chasing sensor may be the same radar or passive optical system that detected the debris or could be a laser-ranging sensor. The chasing sensor provides accurate position and velocity measurements of the debris so the orbit can be determined. Once the orbit is determined, the information is added to the catalog or associated with a previously cataloged object.
3. **Maintain catalog**. Network sensors periodically revisit the debris in the catalog to determine the current orbit of a piece of debris. This action must be completed frequently enough that the sensor can find the debris quickly with only a modest search. If the uncertainty about the orbit of the debris grows large enough, the search times may become unacceptably long, meaning that custody has been lost. Creating a catalog of all 600,000 debris objects will take some time; for simplicity, we did not account for this effect.
4. **Remove deorbited objects from the catalog**. If the objects are low enough that they eventually deorbit, they are removed from the catalog. If an object unexplainably disappears, it may have been involved in a collision and is removed from the catalog.

CONOPS for Ground-Based Lasers

Laser ranging is commonly used to gather information on the position and orbital velocity of active satellites.[18] We analyzed a global network of ground-based laser stations to track centimeter-size debris. The network is called LARAMOTIONS and is based on a similar concept for tracking large debris that DLR researchers proposed (Scharring et al. 2021). We adapted their analysis to estimate the performance of a global network of laser stations that could range centimeter-size debris frequently enough to maintain custody of them. Ranging debris smaller than 10 centimeters has been demonstrated by the Space Environment Research Center in Australia; however, the details of the demonstration are not publicly available. We estimated the costs of this CONOPS to be $6,000–$40,000 per piece of debris per year; see the Appendix D for more details.

CONOPS for Ground-Based Radars

A global network of ground-based radars can collect the data needed to detect, determine the orbit of, and maintain custody of debris in LEO. The CONOPS we analyzed is based on a two-site implementation of Space Fence, with minor modifications such that the radar stations are tuned to

[18] For example, active NASA spacecraft such as GRACE, GOCE, GEOS1-3, CHAMP, and TOPEX have all used laser retroreflectors to enable high-precision ranging. Likewise, the European Space Agency's Sentinel-3 is still in operation and has laser retroreflectors.

track all centimeter-size debris in LEO. Unlike Space Fence, this system would be dedicated solely to tracking debris and would not participate in defense missions. A two-site implementation of Space Fence has been publicly estimated to be capable of maintaining custody of 200,000 objects, which we would assign to centimeter-size debris. Approximately six total fences would be required to maintain custody of all 600,000 pieces of centimeter-size debris in LEO. We estimated the costs of this CONOPS to be $275–$1,350 per piece of debris per year; see Appendix D for more details.

CONOPS for Ground-Based Optical Telescopes

Optical telescopes are able to accurately measure the orbits of space objects. These telescopes excel at measuring the position and velocity of objects in-track and cross-track but struggle to generate estimates of range or range rate. Unlike radars, telescopes on the ground are limited by weather and illumination conditions. Consequently, an optical network requires far more observing sites than a radar network requires; however, the costs of the telescopes may be sufficiently low that a network can be produced for an overall lower cost.

One such system, proposed by Carroll (2019), uses one hundred 0.5-meter telescopes spread across fifty locations to track debris in the 0.5- to 2-centimeter range. For the purposes of our analysis, we used Carroll's system to analyze the tracking of 1- to 10-centimeter objects. This decision was reasonable because a system than can track objects smaller than 1 centimeter can also track 1- to 10-centimeter objects. Further, based on our rough assessment of the revisit rates needed, we increased the number of telescopes to 320.

Carroll (2019) also proposed several software tasks to improve orbit and conjunction prediction and object discovery. He noted that improvements in modeling the drag and spin axis could extend the amount of time required before revisiting an object. Increasing the minimum revisit rate could allow the catalog to be filled faster or to be maintained with fewer stations. Such changes are out of scope for this analysis, but because revisit rate is a major driver of cost (particularly in laser systems), improvements in that area may influence which tracking approach is most cost-effective. We estimated the costs of this CONOPS to be $3–$8 per piece of debris per year; see Appendix D for more details.

CONOPS for Space-Based Optical Network

Phipps and Bonnal (2019) proposed a constellation of satellites that could be used to build a catalog of 1- to 10-centimeter debris objects. Ground-based laser ranging stations would periodically range the satellites to establish highly accurate measurements of their positions, allowing the satellites to be used as reference points to make accurate measurements of debris. Each satellite would carry a passive optical system to detect debris and a series of low-power lasers to range a piece of debris to provide a highly accurate determination of its orbit. We estimated the costs of this CONOPS to be $1,000–$4,000 per piece of debris per year; see Appendix D for more details.

Benefits and Comparisons

We modeled the tracking of all 1- to 10-centimeter debris between 400 and 1,000 kilometers—the altitude range for most spacecraft. Tracking these small debris will reduce the number of expected lethalities. If the orbital uncertainties are comparable to the uncertainties associated with current methods for tracking large debris, adding the centimeter-size objects to the catalog would create a large increase in warnings and maneuvers. As Figure 32 shows, the benefits of avoided collisions are overwhelmed by the added costs of warnings and maneuvers. Thus, if a free system magically appeared to track all centimeter-size debris at the same fidelity as large debris, the information would not be valuable.

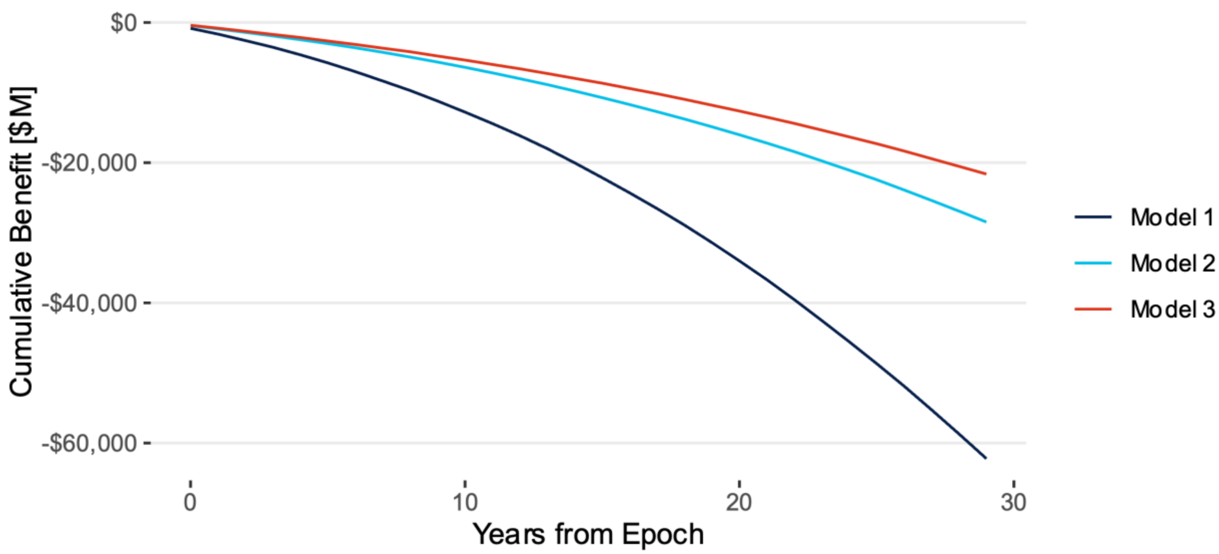

Figure 32. Benefits of tracking 1- to 10-centimeter debris between 400 and 1,000 kilometers, with the same miss-distance assumptions as for large debris (3 km and 1 km for warnings and maneuvers, respectively).

How then might improved tracking lead to positive benefits? The high cost-per-encounter of a subset of government satellites causes the cumulative benefits to be negative. By omitting these spacecraft, we found that operators with very low costs per warning or maneuver have an expected positive benefit.[19] These operators' spacecraft include those in commercial constellations and short civil science missions. The positive benefit is based on the assumption that these operators will continue to have negligible costs even with an increased number of encounters. Of note, our calculations did not include casualties to crew aboard crewed platforms. The value of avoiding centimeter-size debris to prevent human causalities in orbit may be favorable; however, we do not assign a monetary value to human life and thus do not estimate the benefits of preventing human causalities.

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[19] Operator costs per warning, maneuver, and collision were assessed in Colvin et al.'s (2023) appendices and summarized in Table tabSummaryCostsPerEncounter of this report.

A way to achieve positive benefits for all robotic spacecraft operators is to reduce the positional uncertainty of centimeter-size debris and thereby reduce the inflation of PC for the conjunctions in which these debris are involved. So far, the analysis has used the same miss-distance for closest-approach thresholds for warnings and maneuvers, but perhaps smaller debris necessitate better tracking.

Reduced PC inflation can be created in two ways; the benefits of each are shown in Figure 33. The top two charts show the benefits of improving by factors of 10 and 100 the tracking fidelity of all debris below 1,000 kilometers. This improvement could be achieved by using ground-based radars, ground-based passive opticals, and space-based optical systems; however, at the level of our analysis, we cannot assess how likely the improvement is. The number of warnings and maneuvers for all operators are reduced by the factors specified in the column name. The bottom charts show the benefits of deploying the previous systems, with the assumption that they produce conjunctions with fidelity comparable to nominal SSA capabilities for large debris; the SSA capabilities need to be augmented by a ground-based laser ranging capability. In this case, every time an operator receives a warning or makes a maneuver, the operator pays for a laser ranging capability to assess the encounter instead of paying the costs associated with warnings and maneuvers. For the purposes of analysis, we assumed that the laser ranging capability would assess that all warnings are harmless and that the number of maneuvers would decrease by the factor specified in the column.

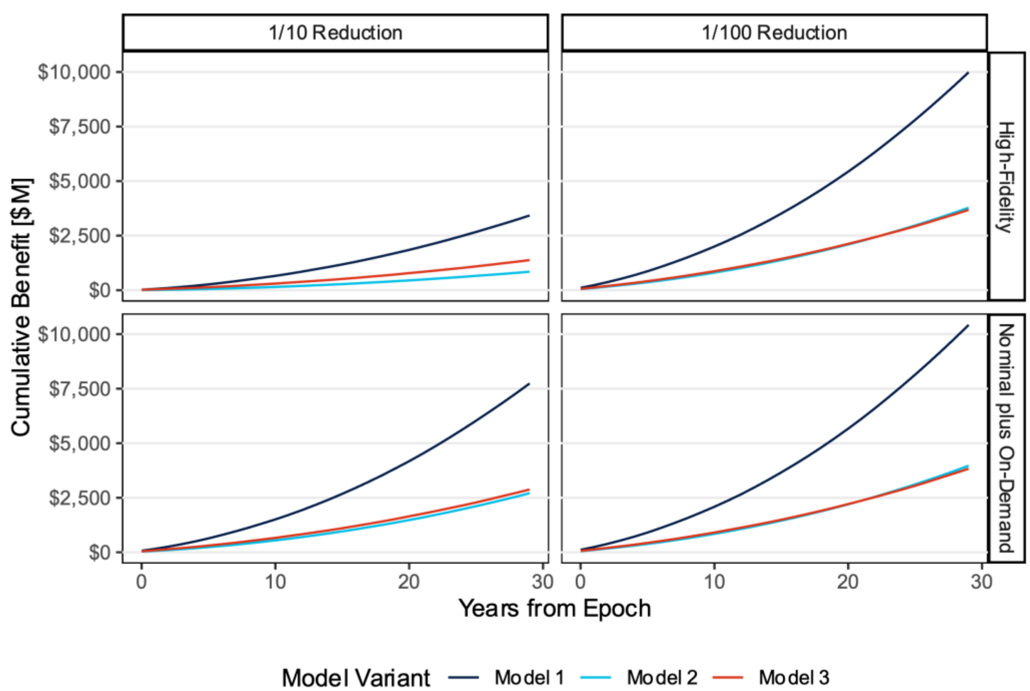


Figure 33. Benefits of tracking 1- 10-centimeter debris (400–1,000 kilometers) with reduced inflation of PC for conjunctions.

We factored in the costs associated with the tracking concepts to determine the net benefit of each, shown in Figure 34. The benefits minus costs span a very large range because of the large range of costs and varying assumptions about the benefits, which include the nominal tracking fidelity and factor of 10-100 improvements over nominal. The most optimistic assumptions result in net benefits of single-digit billions over 30 years, whereas the pessimistic net benefits continue to decrease into the negative.

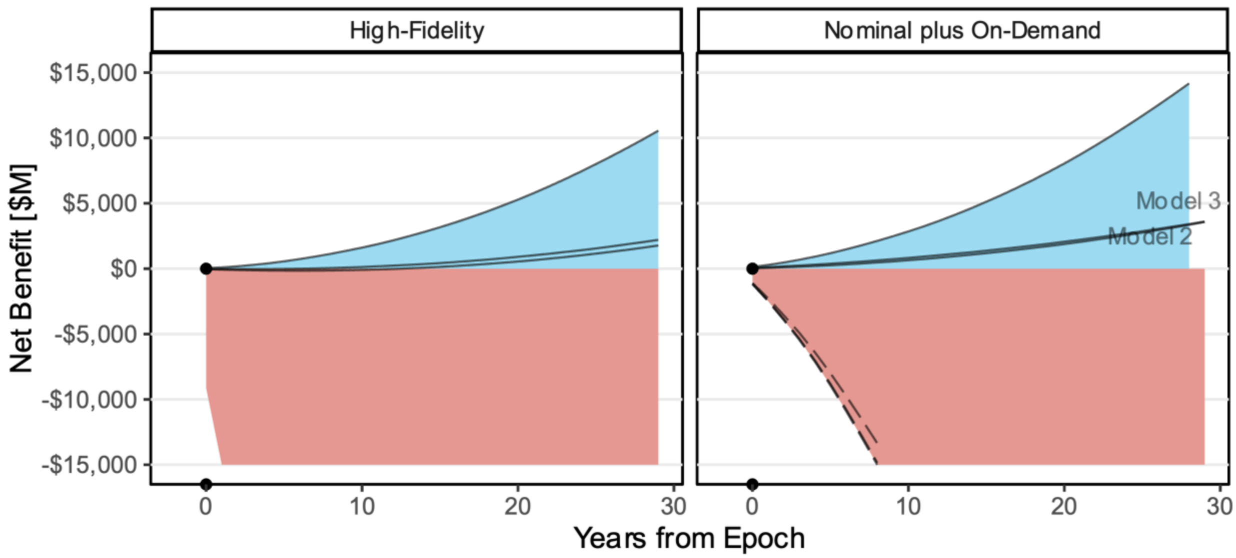


Figure 34. Net benefit of tracking 1- to 10-centimeter debris (400–1,000 kilometers). Note: Values below -$10,000 million were removed.

Tracking small debris does not necessarily promise to reduce the risk to operators and increase the benefit to the ecosystem. The large numbers of debris can overwhelm current operating norms unless the inclusion of debris is coupled with increases in positional certainty and/or innovative practices. This insight is not new; however, our risk-based approach has illustrated some of the conditions under which tracking small debris may have net benefits to the full space ecosystem and to specific operators.

Track All > 10 Centimeter Debris Better

Reducing the positional uncertainty of debris and the satellites that debris might collide with can reduce the incidence of inflated PC values, both in the warnings the operators receive and in the maneuvers the operators make. On average, operators consider maneuvering their satellites when their assessment of the PC exceeds one in ten thousand. Reducing the positional uncertainty of objects can improve the accuracy of PC calculations, thereby decreasing the number of conjunctions that cross this PC threshold.

The primary source of inflated PC for objects involved in a close approach is the uncertainty in predictions of the atmosphere and determinations of objects' orbits when they are measured. Lower positional uncertainties lead to better estimations of the actual PC. For this analysis, we investigated the benefits of lowering the effect of inflated PC at the time of closest approach by improving the accuracy of determining the orbits of debris. The accuracy can be achieved through a variety of approaches, such as conducting more accurate observations, completing more frequent observations, improving the modeling of the future orbit position (propagation and associated modeling), and making observations at the predicted time of closet approach. Many architectures could contribute to improvements in each approach.

We were not able to develop a cost estimate for improving the tracking of all objects in the catalog, partially because of limited literature on system designs that can reduce inflated PC by 10–100 times. For example, we did not have the ability to assess how much inflated PC values could be reduced by adding new radar or optical observing stations to the existing ecosystem of SSA sensors. Alternatively, some experts in the community believe that existing sensor data is sufficient and that improvements in computational and analytic assumptions can reduce inflated PC values relatively cheaply. We have no way to assess the costs of such improvements; however, one expert suggested an essentially free method to reduce uncertainties by over a factor of 10.[20] In the time available, we were unable to assess these options.

Benefits

We modeled the benefit of higher-fidelity tracking with a corresponding reduction in warnings and maneuvers of one and two orders of magnitude. The cumulative benefits are shown in Figure 35. If the population of > 10 centimeter objects was constant over time, the cumulative-benefits curve would linearly increase. However, some debris are regularly added to this population because of debris-on-debris collisions, accidental explosions, and the entry of spacecraft into the PMD phase. Consequently, the cumulative benefits increase slightly faster than linearly. Further, most of the benefits are realized by improving the fidelity of tracking by a factor of 10. Therefore, if accuracy can be improved by a factor of 10 through making a low-cost change in how existing data are processed, then there may not be an incentive to build new sensors, which may be costly.

[20] The expert indicated that conjunction data messages published by the 18th Space Defense Squadron assume that debris fragments have a hard-body radius of 1 meter, while radar measurements suggest that 75% of such objects have a hard body radius of 0.1 meters or less. Improving the accuracy of the hard body radii used when calculating conjunctions could lead to large reductions in estimated PC.

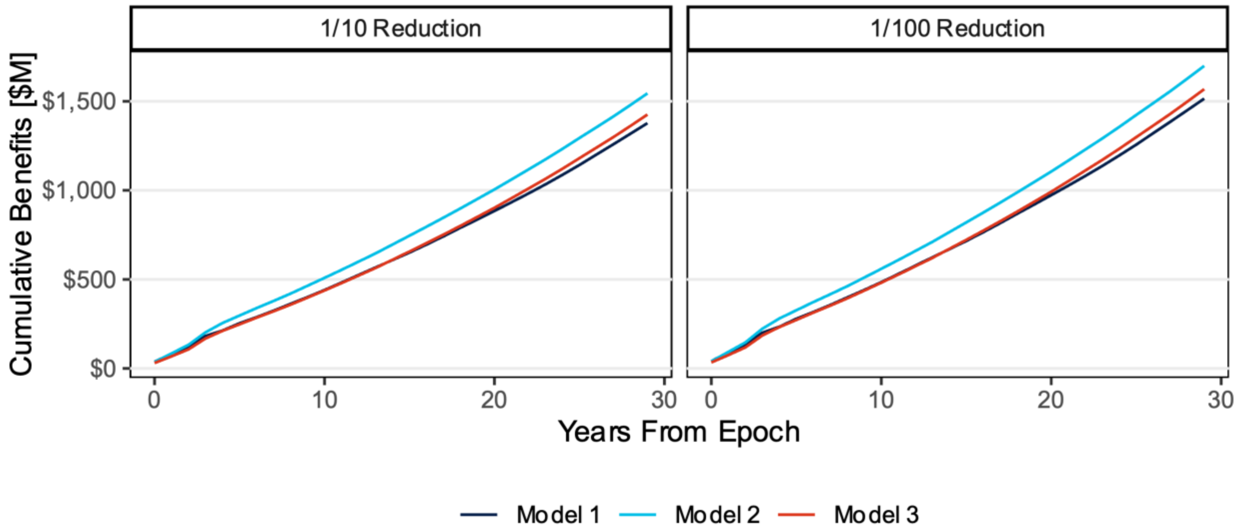


Figure 35. 30-year accumulated benefit of reduction in inflated PC for conjunctions.

On-Demand Tracking of > 10-Centimeter Debris

Instead of maintaining a higher fidelity across the entire catalog, it is possible to improve the tracking of selected objects on demand. When the Space Surveillance Network (SSN) identifies a high-risk conjunction involving a maneuverable spacecraft and a piece of debris, additional sensors may be tasked with gathering high-precision measurements of the debris and spacecraft to reduce the uncertainty in the PC values associated with the conjunction.

CONOPS for Laser Ground Station

We based our analysis on DLR's LARAMOTIONS concept (Scharring et al. 2021), which uses a global network of ground-based laser ranging stations. This network of ground stations is the same one on which we based our analysis for ground-based laser tracking of 1- to 10-centimeter debris. Here, the lasers are used only to range debris that are about to be involved in a high-probability conjunction. The following is the CONOPS:

1. **Identify a high-risk conjunction**. The SSN identifies a close approach that will occur within 48 hours and that may induce the spacecraft operator to maneuver to reduce the risk to the spacecraft.
2. **Assign laser stations to range objects**. The latest orbital elements available are used to predict the trajectories of both objects, and available laser ground stations are assigned to range the objects.
3. **Laser stations gains temporary custody of the objects**. The beam director executes a search of the sky, in the predicted location of the debris, to gain custody of the debris. The beam director is likely to need the help of a wider field-of-view sensor, such as a passive optical telescope or radar, to reduce search time.

4. **Range the objects**. Once the laser system has the object in custody, the laser ranging measurement is taken.
5. **Refine the uncertainty of the conjunction**. The measurements are used to calculate a more accurate orbit propagation, which will reduce the uncertainty in the PC at the time of closest approach.

We estimated the costs of this CONOPS to be \$10–\$300 per conjunction; see Appendix D for more details. This method is far less costly than using lasers to maintain custody of debris.

CONOPS for Radar Ground Station

As mentioned in the discussion on tracking all > 10-centimeter debris, we were unable to estimate the costs and efficacy of adding radar sites. This omission is important and should be addressed in future work.

Benefits and Comparisons

The benefits of reducing maneuvers by ranging debris that are about to be involved in a high-probability conjunction are shown in Figure 36. The benefits are identical to those of better tracking all > 10-centimeter debris, because the end effects are the same; a single system assesses all nominal warnings and maneuvers automatically and reports only the conjunctions that require operator attention. Similar to our analysis for tracking all debris, we estimated the benefits and net benefits associated with reducing warnings and maneuvers by factors of 10 and 100. As before, a one-order-of-magnitude reduction provides the vast majority of the expected benefits.

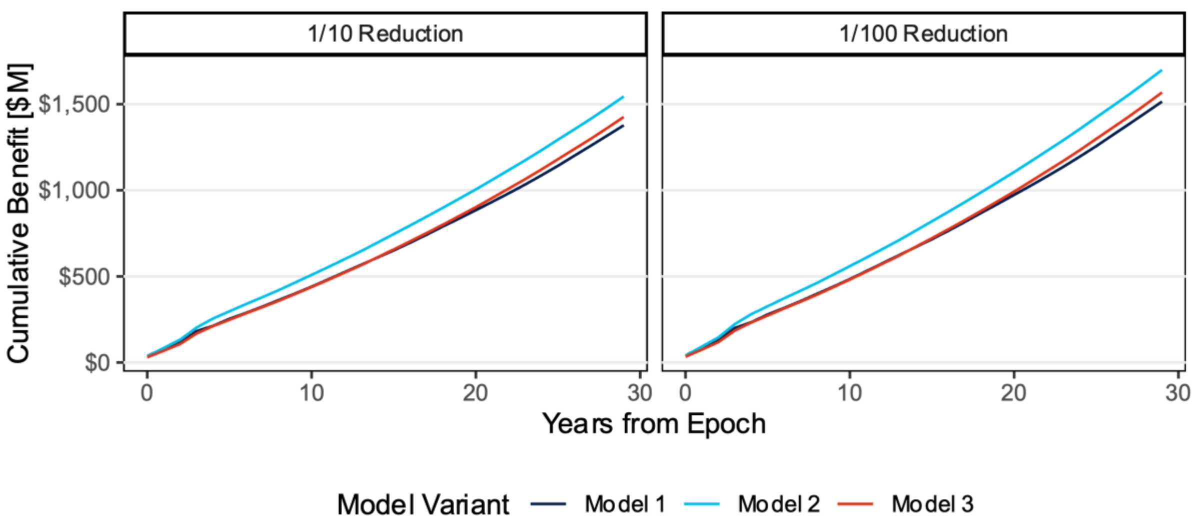


Figure 36. Benefits for on-demand tracking of debris that would otherwise cause warnings and maneuvers.

The net benefits of this approach are shown in Figure 37. The results are highly favorable because the benefits of tracking all large debris are generated at a fraction of the cost. Further, the cost to assess each conjunction in this CONOPS is less than the costs that operators currently incur because of warnings; thus, it makes sense to outsource the analysis of these conjunctions to an SSA provider with the ability to assign a laser or radar to reduce the uncertainty of the conjunction.

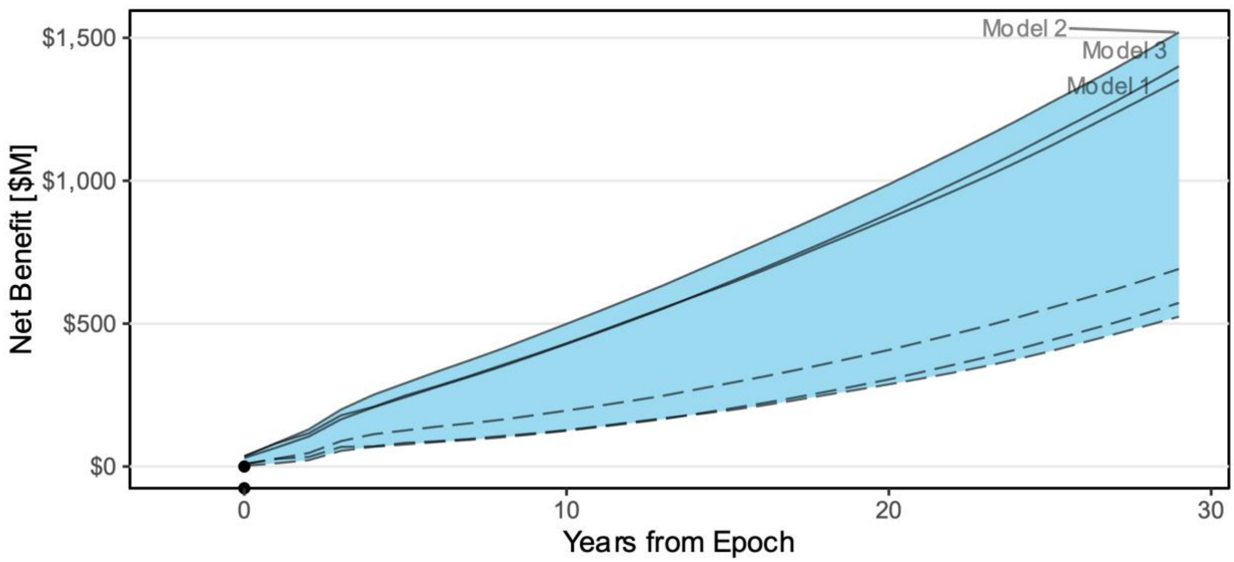
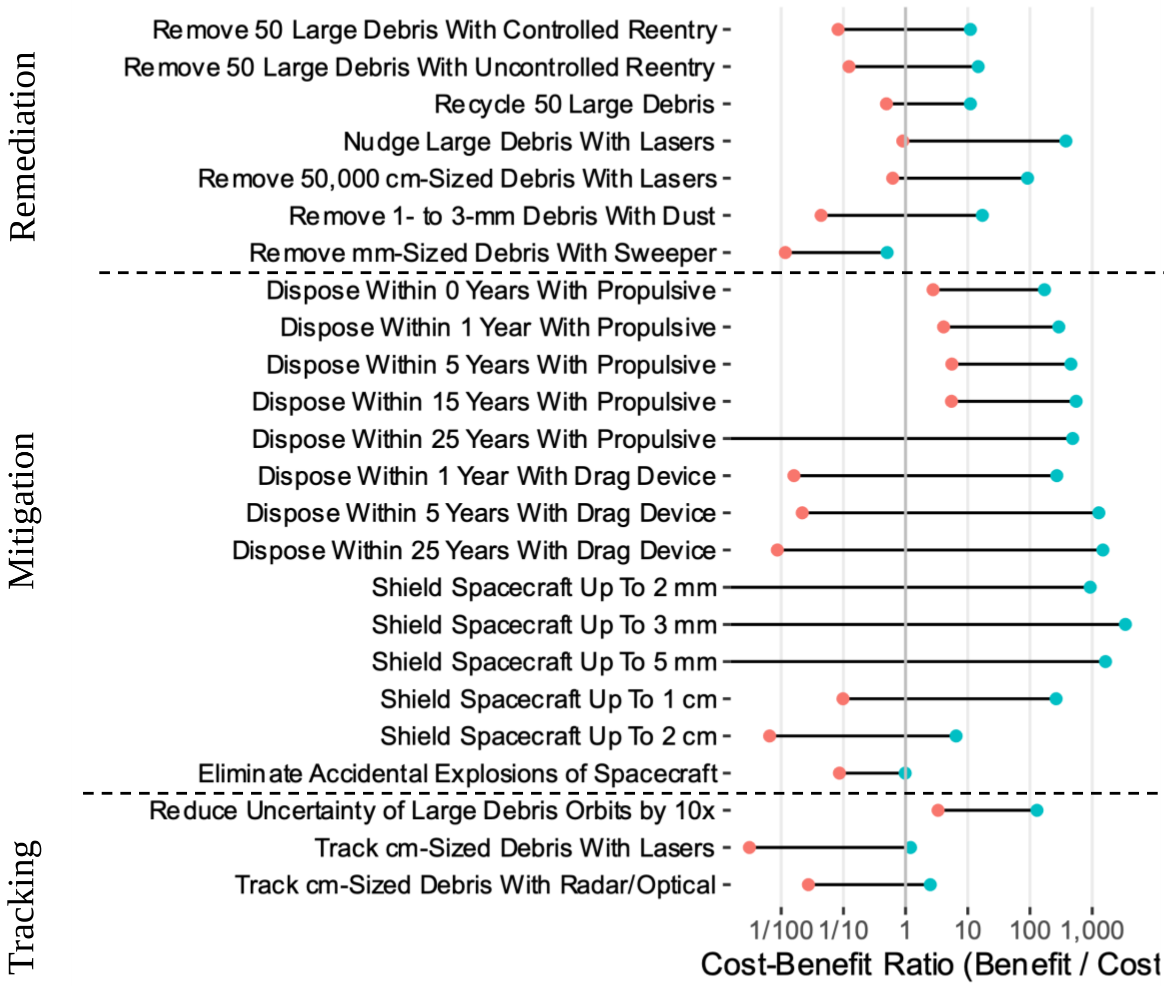


Figure 37. Net benefits for on-demand tracking of debris that would otherwise cause warnings and maneuvers.

Summary and Conclusions

Summary of Benefit-to-Cost Ratios

In the preceding chapters, the costs and benefits of each action have varied widely; thus, we calculated benefit-cost ratios for each action to enable fairer comparisons between actions. Figure 38 shows the estimated ratios of benefits divided by costs after 30 years for most of the actions considered in this report.



For each action, the figure presents a ratio range, with the left-most ratio representing the low-benefit, high-cost estimate and the right-most ratio representing the high-benefit, low-cost estimate. A ratio greater than 1 indicates that the action produces more benefits than it costs to implement after 30 years. For example, removing 50 large pieces of debris has a minimum ratio of approximately 1/10 and a maximum ratio of approximately 10; therefore, a dollar spent removing some of these large debris may produce a risk reduction of 10 cents to $10, depending on the costs to perform the removal and assumptions about the effect of those debris on the operating environment.

Figure 38. Benefit-cost ratios of the actions analyzed in this report. Note: The x axis uses a log scale.

The width of the ratio ranges is primarily due to differences in the numerator—the estimated benefits of the action from the three models. Model 1, based on ORDEM, estimates that the risks are very high; thus, actions taken to mitigate or remediate debris produce benefits that are tens of billions of dollars greater than the benefits calculated by the other two models. Extreme cases of this phenomenon are seen in the ratios for the 25-year rule and shielding spacecraft from debris up to 5 millimeters in size. For these actions, model 2 or 3 estimated that the benefits may be zero or even negative, pushing the ratio off the chart to the left. The costs of the actions—the denominator—vary widely as well. These variations are mainly due to the ability of the actions to mitigate, track, or remediate debris at scale.

Presenting the benefit-cost ratios is the fairest way to compare the various actions, because the ratios normalize the benefits by the costs and remove the need to refer to the specifics of each action's implementation.[21] For example, of all the shielding actions we investigated, shielding to 1 centimeter has the highest net benefit (benefits minus costs); however, the high net benefit does not mean that this action is an efficient step to take. Shielding to 1 centimeter provides an extreme level of protection and comes at a relatively steep cost. Shielding to only 2 or 3 millimeters is far more efficient at reducing risk because the benefit generated per dollar spent is higher. These cases are mismatched in the scale of costs required to achieve them, and the benefits must be normalized by their costs. Further, the ratios allow for decision makers to approximately see where to spend their marginal dollar to reduce the most risk.

Findings

Deorbiting Defunct Spacecraft in Less Than 25 Years Is Highly Cost-Effective

The Orbital Debris Mitigation Standard Practices codify the U.S. Government's policy that a spacecraft should be deorbited within 25 years of its mission ending. U.S. regulatory agencies, such as the Federal Communications Commission and Federal Aviation Administration, are moving toward a 5-year rule for deorbiting defunct commercial spacecraft. Likewise, the European Space Agency recently approved a 5-year rule for its spacecraft. Our analysis indicates that these reduced deorbit timelines cost-effectively reduce risk to space operators. Further, the net benefits increase at favorable rates as the number of years is decreased, all the way to a 0-year rule.

Figure 39 shows the net benefit and cost-benefit ratios associated with changing from a 25-year rule to a lower-year rule.[22] We estimated that the benefits of moving to a 15-year rule are 20–750 times the costs and may produce up to $6 billion in net benefits during our timeframe of interest. There are diminishing returns associated with deorbiting spacecraft more rapidly;

[21] Ideally, net present values could be compared; however, we did not fix the budget available to spend on risk-reducing actions, so the actions vary widely in their costs and scope, making comparisons of net present values or net benefits misleading. We leave the calculation of net present values to future work.

[22] This is different than the results shown in Figure ES-XXX, which show the benefit ratios of post-mission disposal compared to allowing defunct spacecraft to be left in their operational orbit.

however, the ratios are still favorable and net benefits continue to increase. Moving all the way to a 0-year rule can result in nearly $9B in net benefits.

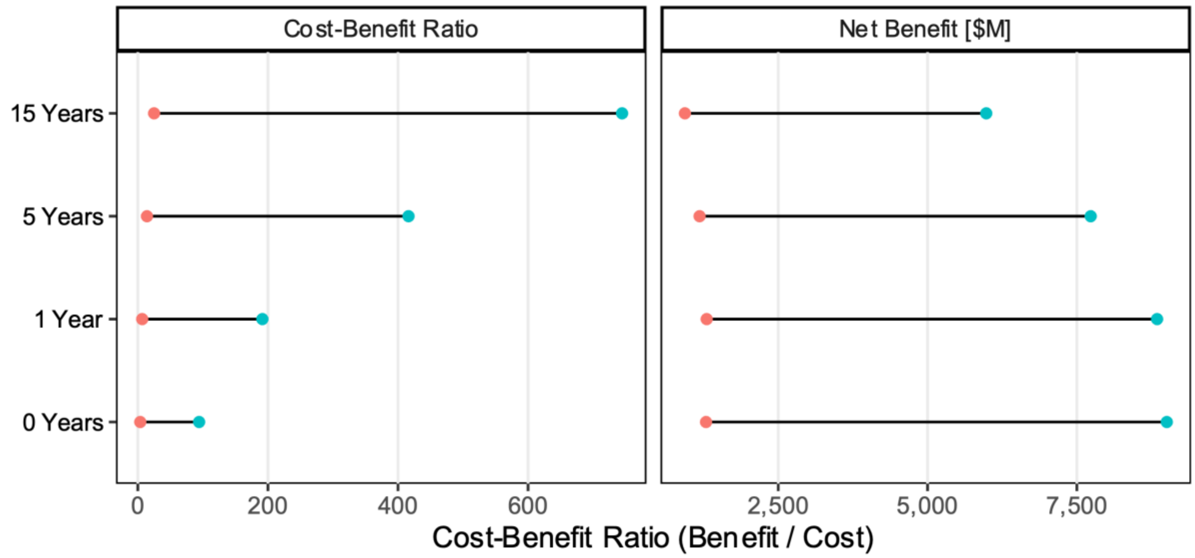


Figure 39. Conditional cost-benefit ratios and net benefits, after 30 years, for moving from a 25-year rule to faster deorbit times for defunct spacecraft.

Other analyses of deorbit timelines have found that deorbiting defunct spacecraft faster than 25 years has a small change on the number of long-lasting debris—those that persist in space for hundreds of years. Our results do not conflict with that finding; rather, our analysis had added to that finding by accounting for the risks to operators posed by debris that are not as long-lasting. For example, a defunct spacecraft complying with a 25-year rule will be left at an altitude no higher than 650 kilometers. From this altitude, any debris it generates will not be long-lasting debris. However, such debris may cause millions of dollars in expected risk to spacecraft operators as the debris spends the next 25 years passing through the orbits of all active spacecraft below it. By accounting for the risks of all debris, not just the number of long-lived debris, we find that rapidly deorbiting spacecraft is highly cost-effective for reducing risk.

The benefits come from disposing of defunct spacecraft in orbits below other active satellites, thereby avoiding any added mission-ending risk to those satellites. When a defunct spacecraft is placed in its disposal orbit, it will generate untracked debris through surface degradation and has the potential to generate large quantities of small and large debris through collisions and explosions. This untracked debris will fall through the orbits of active spacecraft below the disposal orbit, increasing the risk of mission-ending collisions. Our estimates indicate that the costs of performing a deorbit in 5 or fewer years are outweighed by the benefits to the space operating environment by several hundred times.

Performing these same deorbits with drag devices, whether drag sails or tethers, may be even more efficient. Indeed, drag devices have the highest ratios of any action we investigated. A five-year rule achieved with drag devices could produce benefits that are 1,000 times greater than the costs. This potential upside is caveated with a greater potential downside than propulsive maneuvers. The downside comes from the increased probability of collision with these wide-area drag devices. More attention is needed to the effects of collisions with such lightweight materials and the possibility to add maneuverability to these devices before they are adopted. Regardless, our analysis indicates they may be a highly efficient way to reduce risk.

Reducing from a 5-year rule to a 1- or 0-year rule still produces greater benefits than costs, though with a much smaller ratio. However, there may be other benefits to these rapid deorbits that were not accounted for our in the analysis. First, compliance with a rapid-deorbit rule may be easier to enforce and assess, because compliance is immediately apparent. These rules reduce the uncertainties in deorbit time associated with fluctuations in atmospheric density. Additionally, rapid deorbiting effectively removes the need to passivate the spacecraft; if all spacecraft deorbited rapidly, money would not need to be spent on improving passivation and could instead be used for higher-efficiency actions or given back to missions to offset the costs of implementing the rapid deorbiting.

Importantly, rapid deorbits will generally reduce the risks that deorbiting debris pose to people and property on Earth. Some people in the space community believe that accelerating the reentry of debris, either through active debris removal or deorbit-year rules, merely shifts the timing of risks and does not change the magnitude of risks. This perspective may be true in some cases but generally appears to be false. For a given piece of reentering debris, the risks to people and property will be driven by the number of people and value of property on Earth, both of which are projected to increase in the future. For example, the United Nations (n.d.) estimates that the global population will increase by about 2.4 billion people in the next 60 years. Unless debris are kept in space for so long that global populations have peaked and subsequently declined, uncontrolled reentries pose less risk if they occur sooner than later, while the Earth is less populated. A 0-year rule, implemented through controlled reentries, could nearly eliminate the risk to the uninvolved public. Alternatively, large debris with long deorbit time frames could be left in place to wait for reuse or recycling capabilities to emerge so that the material is gainfully used in space and not deorbited at all.

Shielding Spacecraft From 3-Millimeter Debris is Highly Cost-Effective

Another highly cost-effective action appears to be increasing the shielding of spacecraft. Our most favorable estimates for these actions show that benefits of shielding to 3-millimeter debris can produce benefits 1,000 times greater than the costs over 30 years. However, the estimates for the benefits and costs are measured from a baseline of no shielding, which may not reflect the baseline from which most spacecraft are designed. The marginal benefits of moving to more robust shielding are shown in Figure 40. If many high-value spacecraft are already shielded to 2- or 3-millimeters, then the marginal benefits of adding more shielding are relatively modest compared to other risk-reducing actions. However, if spacecraft are mostly unshielded to debris above 1 millimeter, adding shielding up to 3 millimeters may be highly cost-effective.

The benefit ratios for shielding may also indicate zero benefit for every dollar spent. The range results from the uncertainty in the number of 1- to 3-millimeter debris as well as their potential to cause mission-ending collisions. The upper bound estimates of the benefits are based on NASA's ORDEM model, reflecting the underlying research that these debris are numerous and pose a compelling risk to spacecraft (e.g., Squire 2015). Other models, including Model 2 based on ESA's MASTER, estimate far less millimeter debris in LEO, especially high-density particles (Horstmann 2021). Alternatively, the lethality of these debris is highly uncertain. For example, collision models may have overestimated the risk if the millimeter debris population lacks high-density particles or has particles that are shaped more like flakes than spheres. In both cases, a strike involving millimeter-size debris may not be energetic enough to cause a mission-ending failure. Further, such debris would have even lower ballistic coefficients, causing it to deorbit more rapidly than if it were spherical or high-density.

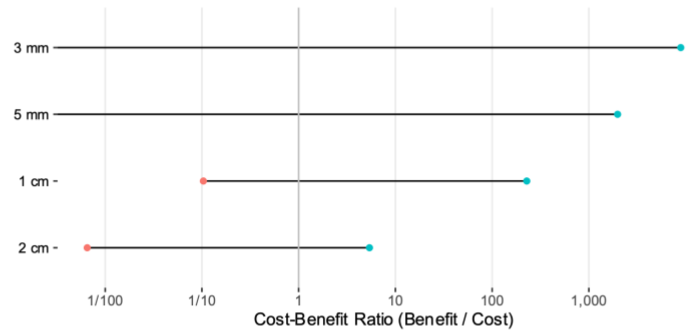


Figure 40. Conditional cost-benefit ratios, after 30 years, for increasing shielding of spacecraft.

Along these lines Model 3 from LeoLabs does not include debris in the 1- to 5-millimeter range, because they assess that such debris do not pose a significant danger. The LeoLabs team chose this approach because their own modeling found that observed spacecraft anomalies, thought to be caused by small debris collisions, are well predicted by MASTER's debris population for 5 millimeter to 10 centimeter debris. In other words, there is a lack of observed spacecraft failures that would be expected from a population of mission-ending debris in the 1- to 5-millimeter size range. Similarly, an analysis from the NASA Engineering and Safety Center (NESC) showed that ORDEM 3.0 overpredicted mission-ending risk to robotic spacecraft by a factor of 5 and momentum transfer to spacecraft from collisions with small debris by a factor of 10 (Squire 2017). ORDEM has since been updated and we are unaware of an updated study from NESC to demonstrate whether ORDEM's current predictions of mission-ending failures are aligned with the empirical rate of spacecraft failure. As stated previously, we are not in a position to adjudicate which models is "correct". Instead, we have used the various models to represent the diversity of expert opinion on the matter. The takeaway from this discussion is that only the risk model based on ORDEM leads to high net benefits for added shielding of spacecraft. If this prediction is accurate, then shielding spacecraft from very small debris could be an especially cost-effective approach.

Debris Remediation Can Be as Cost-Effective as Tracking and Mitigation

Some members of the space community have said that debris remediation is important in the long term, but that near-term efforts should focus on mitigation and tracking. Our results show that, even during timeframes that are operationally relevant, debris remediation capabilities can provide just as much risk reduction per dollar spent as tracking and mitigation can. The most effective form of remediation is just-in-time collision avoidance, which nudges large debris away from possible collisions, as needed; this approach eliminates the risk that a piece of large debris will collide with another object, which would create vast showers of untracked debris that increase mission-ending collisions for all spacecraft at altitudes below the collision. The nudges can be provided by a variety of technologies, including ground-based lasers, space-based lasers, and sounding rockets that release dust to increase drag on the debris, among others. The next-most-effective remediation action is to remove centimeter-size debris with a laser system. In the best cases, just-in-time collision avoidance and removal of centimeter-size debris may return benefits that are 300 and 100 times their costs, respectively.

These ratios compare favorably to the best ratios in mitigation and tracking. Our ratios for each action have wide ranges, and we make no claims about what costs and benefits are most likely within those ranges. Therefore, if the true costs of mitigation are higher than our optimistic estimates or the benefits are lower than our optimistic estimates, the actual effectiveness of mitigation options could fall below the effectiveness of remediation options. In other words, remediation may be better than mitigation in some circumstances. We encourage the space community to realize that the effectiveness of remediation is comparable to—and perhaps better than—mitigation and tracking. More analysis is needed to clarify the robustness of this finding.

Tracking Estimates Are Incomplete, but 10x Reductions in Uncertainty for High-Risk Conjunctions are Clearly Valuable

Reducing uncertainty of high-risk conjunctions on demand is another action that has estimated benefits that are robustly positive. In the optimistic case, the benefits are over 100 times the costs. Even the pessimistic estimate not only delivers positive net benefits but has the second-highest benefit-to-cost ratio of all the pessimistic estimates. Surprisingly, this action appears far more efficient than tracking centimeter-size debris. The greater efficiency is likely the result of (1) the on-demand nature of the action and (2) sunk costs we did not account for. Tracking large debris on-demand is very efficient because it directs resources toward largely reducing specific risky conjunctions. Tracking centimeter-size debris reduces risk associated with a vast number of debris, most of which will never hit a spacecraft. Also, the costs associated with tracking centimeter-size debris are massive because no infrastructure for this task is currently in operation; thus, our analysis of centimeter-size debris tracking included building the entire capability from scratch. Tracking large debris on-demand assumes that existing SSA capabilities can identify risky conjunctions and that such capabilities are essentially free to access. If the full cost of modern SSA capabilities had been accounted for, tracking large debris on-demand may not look so attractive. Regardless, given the current state of capabilities, this action is a very efficient way to reduce risk.

In the optimistic cases, tracking centimeter-size debris provides positive net benefits, but as previously discussed, requires large expenditures to avoid a relatively small number of collisions. A challenge is that the uncertainties in the predicted conjunctions involving centimeter-size debris must be much better than the uncertainties associated with currently tracked debris. Otherwise, operators will be inundated with so many warnings and maneuvers that the net benefits will be deeply negative. Given the high potential for lethality from centimeter-size debris, methods that reduce the cost of providing this service could be extremely valuable for the space community.

This study was limited in its ability to find and assess methods for better tracking of all debris larger than 10 centimeters. We noted that there may be a simple, software-based solution to improve the probabilities of predicted conjunctions but could not assess its cost. Thus, we can only state that the benefits of reducing uncertainty about high-risk conjunctions by a factor of 10 may be worth about $1.5 billion over thirty years and that a solution would need to cost less than that to produce net benefits. Reducing uncertainty by another factor of 10 does not provide meaningfully more benefits.

Short-Term Net Benefits Turn into Long-Term Net Benefits

Estimating the evolution of the costs and benefits over 30 years allowed us to identify trends that can be reasonably extrapolated into the future. To illustrate this point, the benefits minus the costs for all actions analyzed in this report are summarized in Figure 41. For each action, the top curve is the low-cost, high-performance estimate, and the bottom curve is the high-cost, low-performance estimate. The area between the curves represents the net benefits possible between the most and least efficient scenarios analyzed in this report. To enable easy visualization of the qualitative trends, all curves are normalized so that their maximum absolute value is 1. The high and low values at the 30-year mark are given so that magnitudes of the net benefits can be compared.

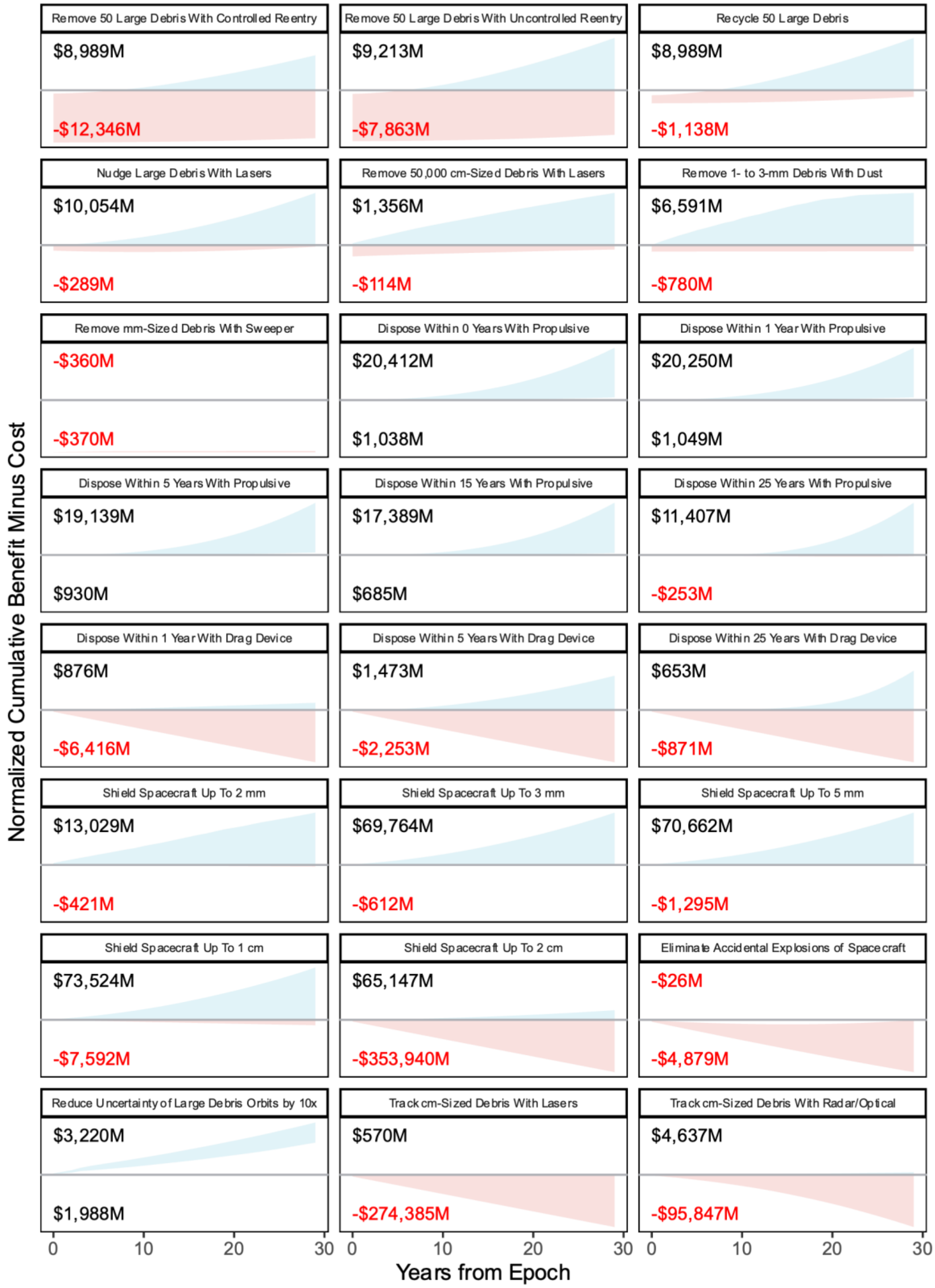


Figure 41. Comparison of the cumulative net benefits of all actions. Note: The numbers are the maximum and minimum benefits (at year 30); these numbers provide a sense of the nonnormalized differences.

Solutions that remove large debris tend to have net benefits that grow approximately quadratically over time, the same behavior as analytically estimated in the Phase 1 report. This trend applies to actively removing debris and reducing the PMD timeline. Surprisingly, this trend also applies to JCA. The Phase 1 analysis found JCA to be very efficient because it *in effect* removes large debris from space by stopping them from colliding with other objects. However, the large pieces of debris remain in space, where they will certainly shed millimeter-size debris because of surface degradation and may generate debris, both large and small, because of accidental explosions. We assumed that including these debris-generating events in our analysis would substantially reduce the effectiveness of JCA. However, that assumption appears to be incorrect. The probabilities of explosion and the number of millimeter-debris generated are low enough that they do not have a decisive effect on the trend of the net benefits curve. Thus, JCA not only has a much higher benefit-cost ratio than removal of large debris but also shows no evidence of producing undesirable long-term effects. This finding contrasts with the common belief in the space community that removing or recycling debris are the only long-term or sustainable remediation options.

Removing small debris produces a roughly linear increase in net benefits over time. This finding contrasts with the Phase 1 report's estimate that the benefits increase quadratically. The reason for the discrepancy is that collisions with small debris do not generally create large numbers of lethal debris, so these small debris do not compound the debris problem in the way that collisions with large debris do. Although the trend is only linear, or possibly just sublinear, the trend does not suggest any undesirable long-term effects. Indeed, the action removes the debris that directly threaten spacecraft and that compose the bulk of the operational risk. There may be some concerns with using micron-size dust to remove millimeter-size debris. Our initial discussion with subject matter experts suggests that the dust is unlikely to have a negative effect on operational spacecraft and should be safe to use; this effect should be investigated more deeply before deploying such a solution.

The linear growth in the benefit of removing small debris does not necessarily make it a less efficient long-term option than removing large debris. For a given amount of money spent on debris remediation, removing small debris will produce benefits more quickly. Eventually, the net benefits of removing large debris will likely overtake the net benefits of removing small debris. However, that shift may take a very long time—perhaps hundreds of years. Further, this study did not incorporate a discount rate; therefore, the implicit rate is 0%. All else being equal, the further into the future a benefit is generated, the less it is worth when making decisions today. We leave it to the reader to consider whether such a long horizon is reasonable for making decisions and how the incorporation of discount rates may affect decisions.

Next Steps

This report provides insight into our ongoing analysis as we work toward creating a rigorous methodology for assessing the economic costs and benefits of space sustainability. We welcome feedback to help guide our approach and to improve the assumptions and underlying data used in our analysis. To that end, we are beginning the pro9cess of publicly releasing our research code, written in Python, and underlying data. Simultaneously, we intend to begin discounting the cash flows associated with the development and operational timelines of each action. Doing so will allow us to calculate the net present value of each action and make economically rigorous comparisons.

A further goal is to identify an optimal combination of actions for reducing risk. Achieving this goal presents a complex problem because taking any one action changes the benefits (and possibly costs) of all other possible actions. These interdependencies must be taken into account when creating an optimal portfolio of risk-reducing actions. Interdependencies of interest include:

- Faster deorbit timelines for PMD rules should reduce the benefits for passivation;
- JCA should decrease the difference between PMD rules;
- Increased shielding should reduce the value of remediation and mitigation; and
- Improved characterization of the small debris population may change our understanding of the most effective risk-reducing actions.

Finally, analyses of proposed policies for space sustainability have been hindered by a lack of insight into the financial costs and benefits that those policies may generate. Our research is laying the technoeconomic foundation upon which policy proposals can be rigorously and quantitatively analyzed.

Appendix A: Risk Methodology

This study's methodology quantifies in monetary terms how changes in the orbital debris environment affect satellite operators. Other appendixes detail how we calculated the costs of these changes, and this appendix sets up the methodology for forecasting the impact of the changes.

As an early attempt at an ecosystem-wide risk assessment, the methodology is unique to this study. We prioritized comparing risk-reduction measures over making precise calculations of the risk. We did not attempt to make concrete near-term recommendations for actions to pursue but, rather, explored the relative value of—and trade-offs between—potential actions. We used the current environment as a starting point but focused on general trends and averages, not decade-specific predictions. Because of time constraints, we kept the approach relatively simple, balancing accuracy, explanatory power, and transparency. Our models have not been validated, but when possible we attempted to incorporate validated or industry-standard models. In general, we view this iteration as a waypoint in an evolving research methodology and model.

This appendix walks through our modeling methodology, beginning with the consequences that debris can cause for spacecraft and their operators: warnings, maneuvers, and collisions. To estimate risk, we combined these consequences with probability. We first explored what models estimate about the current environment and then we extended the estimates to arbitrary populations. Next, we combined these encounter models with methods for predicting the growth of debris populations. Altogether, this model estimates risks over time.

I. Consequences and Risks

A piece of debris can strike and damage an active satellite. All orbital debris risk is derived from this potential consequence. If we assume that operators will choose to preempt potential collisions, then the consequence can be extended to include those preventative measures (e.g., parsing warnings or maneuvering out of the way). The strike or preemptive action imposes some cost, or consequence, on the operator.

In this model, a piece of debris can affect an active satellite in one of three ways. First, the debris can trigger a *warning* to the operator if the debris is heading toward the satellite. Satellite operators are sent conjunction data messages (CDMs) by conjunction assessors, such as the 18th Space Control Squadron. Many CDMs can be readily discarded, but some warrant further risk analysis. To the latter type of CDMs, which require expending labor, we apply the term *warnings*. In reality, whether a warning occurs is a function of an operator's risk tolerance and the operator's information some number of days and hours before the time of closest approach (TCA). In the model, we needed to predict warnings based on trends regarding the end-result: the actual distance between objects at TCA. To make this prediction, we estimated that all operators would treat a CDM as a warning for conjunctions with debris that ultimately pass within a certain distance of spacecraft—3 kilometers for current space situational awareness (SSA) technology.[23] Further, to trigger a warning, the debris must be tracked (and thus be large enough to be tracked) and the spacecraft must be maneuverable (for the operator to pay for risk analysis).

Second, the warning could prompt the operator to *maneuver* the satellite to reduce the probability of collision (PC). The operator may expend labor to plan the maneuver, use propellant to execute the maneuver, and lose operational capacity while undertaking the maneuver. Therefore, the PC must be sufficiently high to warrant maneuvering the satellite. Again, in reality the decision to maneuver is made by the operator at some time before TCA, most often based on a PC threshold, such as 1 in 10,000; in this model, we predicted whether the operator would maneuver given the range at TCA. We used a distance threshold as a simple heuristic—namely, that given current SSA technology, an operator will maneuver when the debris would have missed by 1 kilometer or less.[24] Again, the debris must be trackable and tracked, and the satellite must have maneuver capability. Using these simple thresholds, we thus assumed that operators will always maneuver to avoid tracked debris; further, we assumed that they always successfully maneuver, including by not causing a different collision that would have otherwise not occurred.

Third, the debris could strike and damage the satellite. A *mission-ending collision* (MEC) will occur when a piece of debris disables some crucial element of the satellite or even catastrophically breaks it, ending the mission. Given an MEC, the operator will immediately lose operations and may need to pay to replace or repair the vehicle. Since we assumed operators will always maneuver to avoid tracked debris, a lethality can occur only if the debris is not tracked or the satellite does not have maneuver capability. The expected number of MECs is a product of the expected number of collisions and the probability a collision (to the satellite bus) will be lethal. To our knowledge, no model of a probability of MECs for an average satellite has been developed; for this study, we estimated that probability as a discontinuous univariate function of debris characteristic length, as shown in Figure A-1, decreasing from 100% at 10 centimeters to 10% at 1 centimeter and finally to 0.01% at 1 millimeter.[25]

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[23] The distance of 3 kilometers was a standard assumption for the model on which the Phase 1 study was based, and we used that value in this iteration.

[24] The distance of 1 kilometer was a standard assumption for the model on which the Phase 1 study was based, and we used that value in this iteration.

[25] This parameter is very important in the model, and we have very limited data to make this assumption. We used Phase 1 assumption that 10% of small (~1 centimeter) debris will be lethal, assuming that 100% of centimeter-size strikes will penetrate the bus and centimeter-strikes will be energetic enough to be lethal for 10% of the surface area of the spacecraft. For 1 millimeter-debris, we estimated the probability of penetration for a nominal spacecraft based on a 2015 NASA study on the orbital debris risk for JPSS (Squire et al. 2015). In that study, the researchers modeled the penetration of a generalize cube covered in MLI to act as a small bumper shield. Given the orbit, our analysis of their findings shows that about 2% of strikes resulted in penetration when we ignore high-density debris (flux of ~3, damage fluence of ~0.4, and lifetime of 7 years). The next step in the estimate, requiring estimating what percent of the surface area of the spacecraft (really, just the RAM direction) harbors areas for which a penetrating millimeter-size strike would be lethal. We estimated that 10% of the area is susceptible and 10% of the penetrations would be lethal, leaving us with a total probability of 1 in 10,000. There are a wide range of defensible alternatives; these values best aligned the ORDEM estimates with orders of magnitude for available anomaly data.

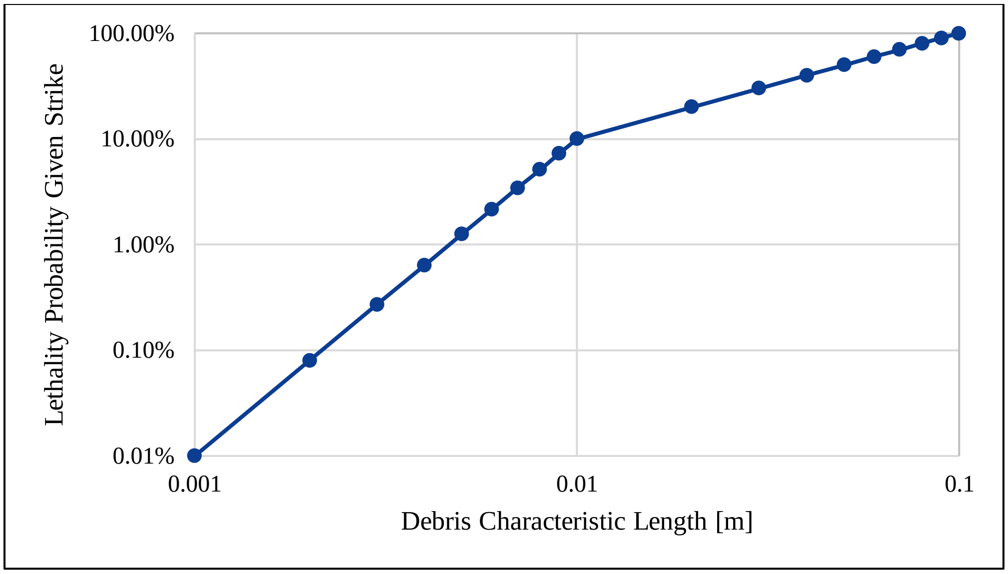


Figure A-1. Simple model of probability of a mission-ending strike given a certain characteristic length of debris.

Several other sources of consequence could be included beyond these three, such as losing performance in a nonlethal collision, purchasing more insurance, or launching collision avoidance. Each of these were considered and excluded in Colvin, Karcz, and Wusk's (2023) report.

That report also investigated the costs associated with each of the encounter events: warning, maneuver, and MEC. The report identified per-event costs ($/event) for different classes of operators. In general, the cost per warning is often 0—operators automate the analysis processes. Further, costs per maneuver are low—almost all operators use collision avoidance maneuvers for their station-keeping requirements. Table A-1 summarizes the costs for each encounter type and operator cost.

Table A-1. Summary of the Operator Costs per Encounter ($/Event)

	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	—	—	—	—	—	—

Note: For more information on these estimates, see Appendix A of Colvin, Karcz, and Wusk (2023).

As an example, if a civil operational satellite such as the Joint Polar Satellite System (JPSS) experiences 10 warnings and 1 maneuver in a year, this model predicts costs to the National Oceanic and Atmospheric Administration (NOAA) of about $2,300 in additional consequences because of orbital debris. Similarly, if we expect JPSS to experience 10 warnings, 1.5 maneuvers, and 0.01 MEC strikes next year, we expect a total consequence of $8,201,924. This risk comes from the product of consequence and probability expressed, as an expected value, as shown in the following formula:

$$RISK = E[warn] * COST(warn) + E[mnvr] * COST(mnvr) + E[MEC] * COST(MEC)$$

The sources of the expected warnings, maneuvers, and lethalities were described above. Ultimately, we can derive all of them from some distribution of close approaches to the spacecraft, parameterized by the miss distance or range (R) and size of the debris (S). Using the logic described above, for example, we can transfer from these close approaches to the expected number of maneuvers $E[warn] = M(E[encs]_{S,R}, S_t, R_t)$, where M is a Boolean threshold function applied to the distribution of expected close encounters.

Assumptions and Limitations

- We used the final-miss distance to estimate whether an operator would have been warned or would have maneuvered. The transfer function must encapsulate the SSA system as well as the operator's preferences; the best such function would include altitude, size of the objects, solar cycle information, and the operator's risk preferences. As a simple first attempt, we only utilized the miss distances of 3 kilometers and 1 kilometer. This model will not accurately predict individual warnings or maneuvers, and the large distances may lead to overestimates on the average. The univariate nature also means that all operators in our model act when the distance threshold is broken, potentially leading to nonsensical conclusions, such as that tracking all debris will raise the total risk.
- We assumed that all maneuvers are successful and safe, meaning that if an operator chooses to maneuver, it will not collide with any debris as a result of the maneuver. This assumption led us to slightly underestimate the risk associated with a maneuver.
- We did not include any encounters with active satellites, as they are out of the scope of this analysis.
- The mission-terminating probability model we developed for this study is unvalidated and should be considered a large source of uncertainty. We had little data from which to extrapolate. Developing a generic estimator is a fraught exercise, as the vulnerability of spacecraft varies dramatically and the danger of small debris is debated. A generalized model is very important to future cost-benefit research for debris and should be an area of future research.
- The costs per encounter represent our rough estimates for the average spacecraft in the category. The costs per encounter are not accurate for any one operator.
- We omitted some other potential sources of risk to operators—namely, the negative effects of collisions that do not end the mission of a spacecraft. For example, surface degradation to the solar arrays could reduce the power and thus value of the spacecraft by some amount, or a strike could disrupt a specific payload but not the entire spacecraft. As a result, we likely underestimated the total risk posed by debris.
- We omitted the consequences of orbital debris for humans in orbit and on the ground.

II. Current Population

Several models specialize in estimating the expected number of close approaches between spacecraft and debris. We term these models *encounter models*, which use a population of debris to predict encounters for one or more spacecraft. In this section, we introduce those tools and models using the current debris environment.

The encounter model should provide encounter—i.e., close approach—rates for the orbit of a specified spacecraft. We looked only at low Earth orbit (LEO), and we assumed that all satellites are in circular orbits (e.g., a satellite with an apogee of 550 kilometers and perigee of 500 kilometers will be placed in a circular orbit at 525 kilometers). We also separated orbits into altitude and inclination bins (e.g., 5 kilometers and 10°), assuming random right ascension of the ascending node (RAAN) and argument of perigee. We expected the encounter models to predict the expected rate of encounters for such orbits.

In this study, we formed an ensemble from three encounter models. As summarized in Table A-2, one model was assembled in-house at the NASA Office of Technology, Policy, and Strategy (OTPS) and is based on the Orbital Debris Engineering Model (ORDEM).[26] The other two were provided by COMSPOC and LeoLabs, respectively, and are based on the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER). We make no assessments regarding the relative values of the models; each makes reasonable assumptions about the space debris environment. Their inclusion together is meant to illustrate the range of risks and how those risks may vary based on assumptions about the debris environment.

Table A-2. Overview of the Ensembled Encounter Models

Encounter Model	Description	Model Source
Model 1	The reference model, extrapolating the number of encounters from the flux provided by ORDEM.	ORDEM
Model 2	The COMSPOC Volumetric Encounter Model (VEM), from which their Number of Encounters Assessment Tool (NEAT) is derived.	MASTER
Model 3	LeoLabs risk model and data based on the kinetic gas theory.	MASTER

Model 1 (OTPS Reference, Using ORDEM)

ORDEM has the capability to estimate the expected flux for a specific spacecraft in time, factoring in parameters such as year, apogee, perigee, inclination, RAAN, and argument of perigee. The model provides the expected flux in units of debris per square meter per year, including distributions by particle size (characteristic length),[27] density, and velocity, among other measurements. This flux represents the average encounter rate across the satellite's entire orbit.

To predict encounters (warnings, maneuvers, and collisions) using ORDEM, we applied the flux to spheres of varying sizes. ORDEM returned the flux, $\Phi\ (\frac{\#}{m^2\,yr})$ for a sphere with a surface area (SA) of 1 m^2 (radius of 0.282 m) that proceeded through its orbit for a year. Thus, to estimate the number of collisions, we expanded the 1 m^2 sphere to a sphere representing the bus, specifically with the hard body radius (HBR) of the satellite. Thus, the number of collisions are $\Phi * \frac{4\pi\,\mathrm{HBR}^2}{1} \rightarrow \left(\frac{\#}{yr}\right)$, when ignoring the HBR of the colliding object, such as for very small debris.

NASA's Orbital Debris Program Office (ODPO), the organization that maintains ORDEM, indicated that ODPO does not typically use the model for collisions with larger objects; rather, it typically uses other tools based on the current debris catalogue. Accordingly, we did not use

[26] More details on the model, including its process and validation, can be found at ODPO's website: https://orbitaldebris.jsc.nasa.gov/modeling/ordem.html. We used the latest version, 3.2.

[27] Characteristic length is the average of the length, width, and height dimensions.

ORDEM for these large debris and the warnings or maneuvers they cause. Instead, for large debris we used the average returned by Models 2 and 3, both of which use the debris catalogue for larger debris. Therefore, information for objects below 10 centimeters came from ORDEM, and information for larger objects came from an aggregation of the other models.

In essence, ORDEM works by estimating the spatial density of pockets of space (bins of eccentricity, inclination, and altitude); for each, the kinetic theory of gases (physical analogy) provides a frequency of collisions: $E[collisions] = AC * VR * SPD$, where VR is the relative velocity (m/s) and AC is the collision area. This frequency is computed for each of the bins in which a spacecraft spends time and for different debris categories.

We should mention a few other important features of ORDEM and how we used them. We ran flux calculations for spacecraft at circular orbits every 25 kilometers and 5° (with a random RAAN and argument of perigee). We kept flux for only debris with a characteristic length of 1 millimeter and larger, divided into 1 millimeter, 1 centimeter, and 1 decimeter bins (e.g., 1–2 millimeters, 2–3 millimeters, etc., 1–2 centimeters, 2–3 centimeters, etc., 10–20 centimeters, etc., >1 meter). Further, because of memory limitations and for comparability with the other models, we discarded density information, essentially assuming all debris are aluminum.[28] The latter assumption is especially impactful for ORDEM, as its high-density small debris differ dramatically from those in other models and have large implications for spacecraft risk.[29]

Model 2 (COMSPOC, Using MASTER)

A team from COMSPOC participated in this study to provide analytic assistance and run their own tools to be included in the analysis. The encounter model provided by COMSPOC is based on its Volumetric Encounter Model (VEM), from which the online Number of Encounters Assessment Tool (NEAT) is derived. VEM works by propagating a ring torus of elliptical cross-section around a satellite's orbit and assessing whether a second satellite penetrates that torus. VEM can then do the same for all debris in the current public catalogue as well as representative space catalogs derived from the MASTER model. VEM then estimates the total number of encounters within that torus radius (e.g., a circular cross-section is typically employed when a HBR for collisions or 3 kilometers for warnings is used for screening). This approach utilizes a physical orbit model rather than the kinetic-theory-of-gases analogy.[30]

The baseline VEM and NEAT tools use two-line elements (TLEs) from the tracked debris catalogue to generate colliding objects. For this study, the team generated representative TLEs for untracked objects, drawing from the European Space Agency's MASTER; the details of the

[28] This assumption is effectively included in our assumed lethal probabilities, such as 1% for 1-to 10-millimeter debris. This assumption will come up again in the methodology when we discuss the decay of debris.
[29] We point interested readers to the 2015 JPSS report at https://ntrs.nasa.gov/citations/20150017054, which illustrates the significance of these high-density populations, and to a more recent comparison of ORDEM and ESA's MASTER, available at https://ntrs.nasa.gov/citations/20210011563.
[30] More information on NEAT and other models can be found on COMSPOC's website and in its publications, such as the one at https://doi.org/10.1016/j.actaastro.2018.09.030.

method were presented in Oltrogge (2016). The hybrid catalogue of tracked TLEs and represented untracked TLEs were used as the input for NEAT.

The COMSPOC team provided encounter rates for spacecraft in circular orbits at 10 kilometers altitude and 5° inclination bins. The rates were separated by characteristic length (1–2 millimeters, 2–5 millimeters, 5–10 millimeters, 1–2 centimeters, 2–5 centimeters, 5–10 centimeters, and >10 centimeters).

Model 3 (LeoLabs, Using MASTER)

A team from LeoLabs participated in this study to provide analytic assistance and run the lab's own tools to be included in the analysis. To meet the unique needs of the encounter model, LeoLabs combined aspects of its LeoRisk and LeoMap tools.

LeoLabs estimated encounters using a kinetic-theory-of-gas approach. The team estimated the spatial density of bins using LeoLabs' own catalogue combined with spatial density predictions from the MASTER model. The team also used its own estimates of the average relative velocity in each bin. With these estimates, OTPS could apply a scaled collision area representing, for example, either the combined HBR, a 1-kilometer maneuver threshold, or a 3-kilometer warning threshold.

The LeoLabs team provided encounter rates for spacecraft in circular orbits at 10 kilometers altitude and 15° inclination bins. The rates were separated by characteristic length of debris (5 millimeters–1 centimeter, 1 centimeter–10 centimeters, and >10 centimeters). LeoLabs intentionally does not model debris below 5 millimeters, so these debris effectively do not pose any risk in this model.

Combination of Models 1–3

Together, the three models provide three different estimates of the expected number of encounters a satellite will experience in the current orbital debris environment. The estimates represent two physical-modeling approaches and two small-debris models. Figure A-2 shows the encounter rates for a satellite with a 2-meter HBR. In general, the OTPS model shows a drastically higher rate of millimeter-size MECs, as expected based on ORDEM's characteristics.

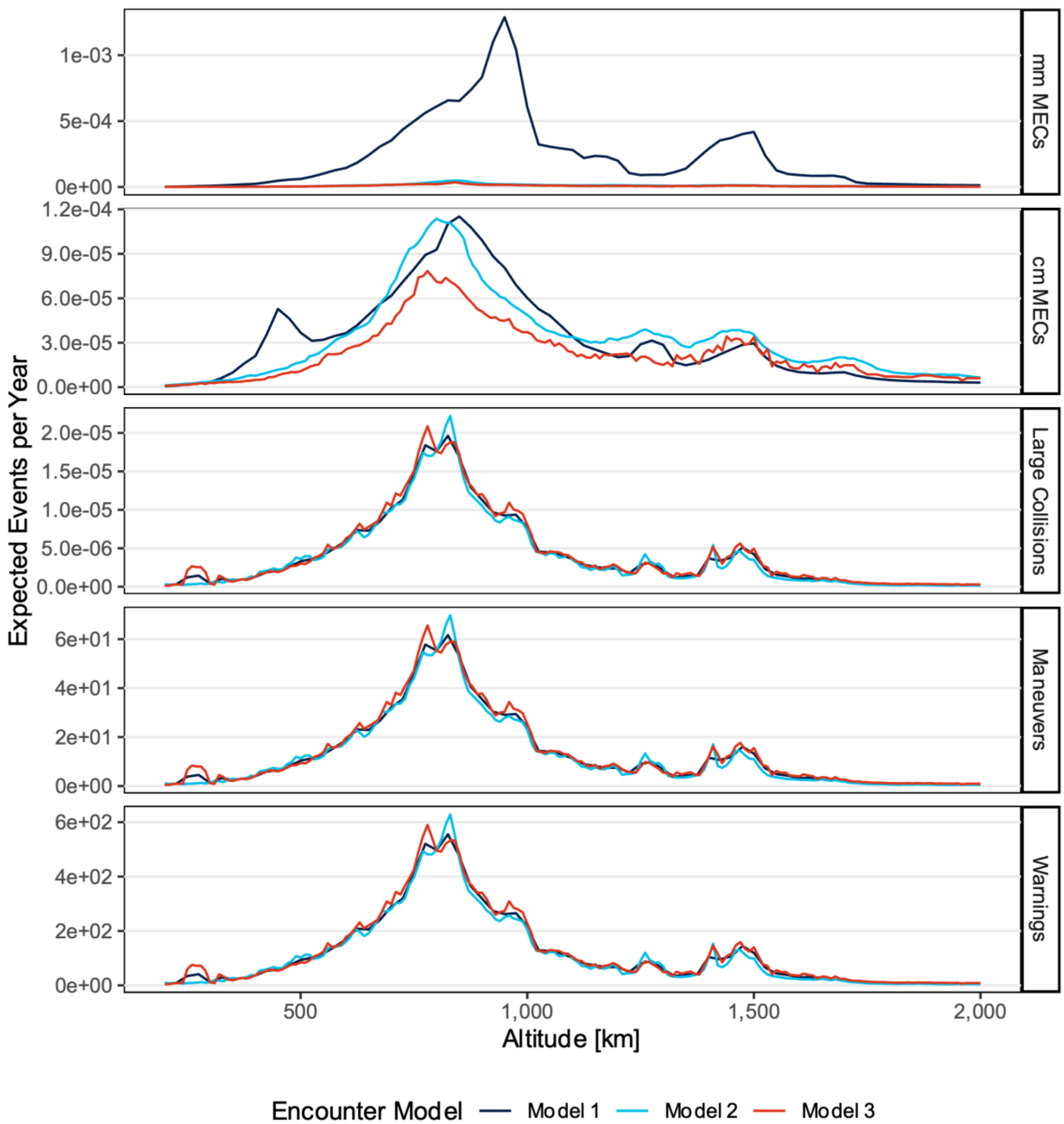


Figure A-2. Encounter rates for a nominal satellite (1 square meter Collision Area at 90° inclination).[31]

[31] Note: The "Large Collisions" category does not account for the combined HBR of the nominal satellite and the debris with which the satellite may collide. When implementing the model, we used the average cross-sectional area of large debris (>10 centimeters or >1 meter) of 4.1 square meters from the Database and Information System Characterising Objects in Space (DISCOS), and thus the combined HBR is 4.1 plus the CA of the satellite. We derived 4.1 from the mean cross-sectional area of all large debris documented in the DISCOS.

These models provide distributions of the expected close encounters, from collisions to 1-kilometer misses, between debris and any spacecraft in LEO with a circular orbit. The close encounters can then be translated to events using the methods described in the previous section. For example, say we want to estimate the number of lethalities posed by 1- to 10-centimeter debris cause to a medium satellite in a circular orbit at an altitude of 805 kilometers and inclination of 63°. First, we bin the orbital parameters for the model to 800 kilometers and 60°. For this bin, the models predict the expected number of collisions to a test particle (sphere with a 1 m radius). We adjust the size of the spacecraft from the test particle to a medium satellite with a HBR of 1.5 m—E[collisions] $* \frac{1.5^2}{1^2}$—and convert the collisions to MECs using the lethal probability transfer function presented earlier. We ignore the HBR of these small debris, but debris larger than >10cm we add 4.1 square meters to the numerator as the average cross-sectional area of tracked debris from the European Space Agency's Database and Information System Characterising Objects in Space (DISCOS). Table A-3 shows the expected annual events from these models for the baseline spacecraft population described in the next section.

Table A-3. Total Expected Events per Year for the Baseline Environment [#/Year]

Event Type	Model 1	Model 2	Model 3
mm-Size Debris MECs	1.05	0.07	0.03
cm-Size Debris MECs	0.22	0.21	0.15
Maneuvers	10,174	10,531	9,287
Warnings	91,559	94,776	83,574

Limitations

- We used only three encounter models of the many available options, including variants of the underlying methodologies or submodels represented in the three encounter models. For example, ORDEM has uncertainty bounds that we did not take advantage of, in order to simplify the analysis and results.
- We pushed the kinetic-theory-of-gas models even further beyond its intended analogy by passing through a large volume instead of colliding with another particle. This use is unvalidated and borderline dubious but appears sufficient to provide a very rough estimate of the encounters.
- We kept only the characteristic length of debris and discarded other information, such as the density of debris, that could be used to better refine probability of lethality or decay predictions.

- We binned all of LEO into 10- or 25-kilometer altitude bins and 5° or 15° inclination bins. Further we separated debris into different bins of characteristic length. Doing so appears reasonable, although we acknowledge that the granularity could have unexpected on specific results.
- We assumed all spacecraft are in circular orbits, and we calculated the encounter rates for only spacecraft in circular orbits. This decision led to inaccuracies on a per-satellite basis and potentially overall. The models themselves do not internally assume circular orbits; in fact, each considers elliptical debris interacting with our circular orbits, although we never explicitly programmed anything elliptical.
- The values produced by the models depend, in some part, on the discretizations used. For example, Model 1 tracks 1- to 10-centimeter debris in 10 bins (1–2 centimeters, 2–3 centimeters, etc.), whereas Model 3 tracks only 1- to 10-centimeter debris as a whole. How then should the lethality model be applied? We chose to apply it to the weighted mean characteristic length, assuming an empirically derived power law, but this choice can have significant ramifications for the absolute (not necessarily relative) results. This issue repeats in several areas, and the best we can do for now is call out its known effects.
- We used the estimates of the encounters with large debris from Models 2 and 3 for Model 1, to better match ODPO's processes. This choice appears reasonable but blurs the lines between the models and may more poorly explore the decision space.
- Throughout the model, we used expected values instead of probabilities, such as using expected collisions from the models instead of converting to a PC. Doing so allowed for potential cases in which a single spacecraft could be expected to have multiple lethalities in a year (i.e., with millimeter-size debris), but this case did not occur for zeroth-year populations.

III. Extension of the Models to Other Populations

The previous section estimated encounters for a single spacecraft in the current debris environment, but what if we want to estimate encounters for a different population of debris and spacecraft? For example, we might want to estimate the risk resulting from a newly derelict satellite at 650 kilometers or the reduced risk (i.e., benefit) from preventing a collision at 1,000 kilometers. In this section, we extend the encounter models to predict encounters for an arbitrary population of debris and satellites.

To predict encounter rates, each model assumes a population of debris, captured either as spatial density or TLEs. The model then calculates the total encounters as a sum of the contribution of each of these pieces of debris. Moving in reverse, we can combine the total encounters with the number of debris to calculate the average contribution per piece of debris: $\frac{E[encounters]}{|DEBRIS|}$. This calculation can be repeated for subsets of debris—for example, all the lethalities from centimeter-size debris divided by the number of 1- to 10-centimeter debris. In this way, we can estimate the expected number of encounters for different numbers of debris: $E[encounters]_{new} = E[encounters]_{baseline} * \frac{|DEBRIS_{new}|}{|DEBRIS_{baseline}|}$.

We parameterized the average contribution of a piece of debris by altitude, specifically by the altitude bins of each encounter model (10 or 25 kilometers). For example, Model 2 predicted that a satellite will experience about 500 warnings per year from 340 tracked >10-centimeter debris at 800–810 kilometers and that, on average, each tracked debris will cause 1.5 warnings per year. If the number of tracked debris at 800–825 kilometers decreases to 300, then the satellite's expected warnings decrease to $\frac{300}{340} * 500 \rightarrow 440$. With smaller populations, the numbers become less meaningful; with very large populations, the numbers are meaningless, but (by definition) we expect the average to hold.

We should offer a few clarifications regarding the calculations. First, the 340 debris at 800–825 kilometers need not all be in circular orbits between the apogee bounds. The number of debris in each bin is the effective count, or the number of debris that could be expected to be in the bin at any point in time. For example, the 340 debris could represent 680 debris, each of which spends 50% of its time between 800 and 810 kilometers. Second, the models predict different numbers of encounters depending on the inclination of a spacecraft, but the number of debris in a bin is not a function of inclination. The average contribution of a piece of debris to a spacecraft is parameterized by the inclination of the spacecraft. For example, the average piece of debris may be expected to cause 1.8 warnings per year for a spacecraft at 60° but only 1 warning per year for a spacecraft at 20°. The models are therefore responsible for assigning how the debris in an altitude bin interact with different inclinations.

To implement this methodology, LeoLabs provided counts from MASTER and the catalogue that we used for Models 2 and 3, as well as for the large debris in Model 1.[32] ODPO provided a simplified spatial density of the populations underlying ORDEM 3.2. The debris counts for the three are shown in Figure A-3.

[32] Ideally, we would have used unique debris counts from each of the encounter model sources, so being forced to rely on a single source is a limitation of this version of the model.

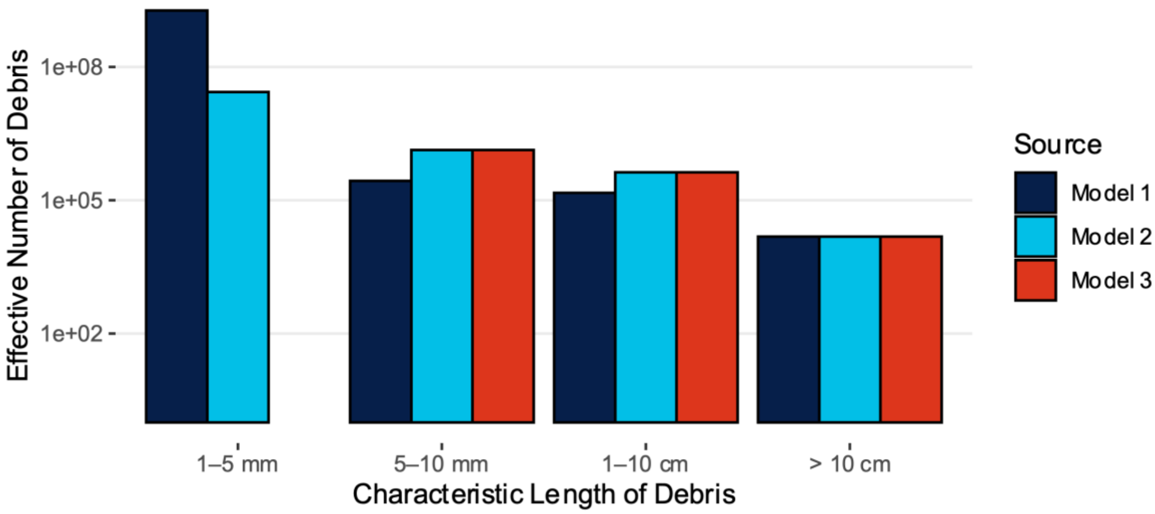


Figure A-3. Comparison of debris counts in LEO.

In total, the number of debris vary dramatically across the models. For example, MASTER estimated only 9 million 1- to 10-millimeter debris, but ORDEM estimated more than 1.8 billion 1- to 10-millimeter debris. This latter estimate matches previously published analyses, such as by Horstmann et al. (2021).[33] As a reminder, the LeoLabs/Model 3 model does not include any debris below 5 millimeters. The uncertainty regarding the number of debris has an important impact on the risk added by different debris and thus the value of their effects.

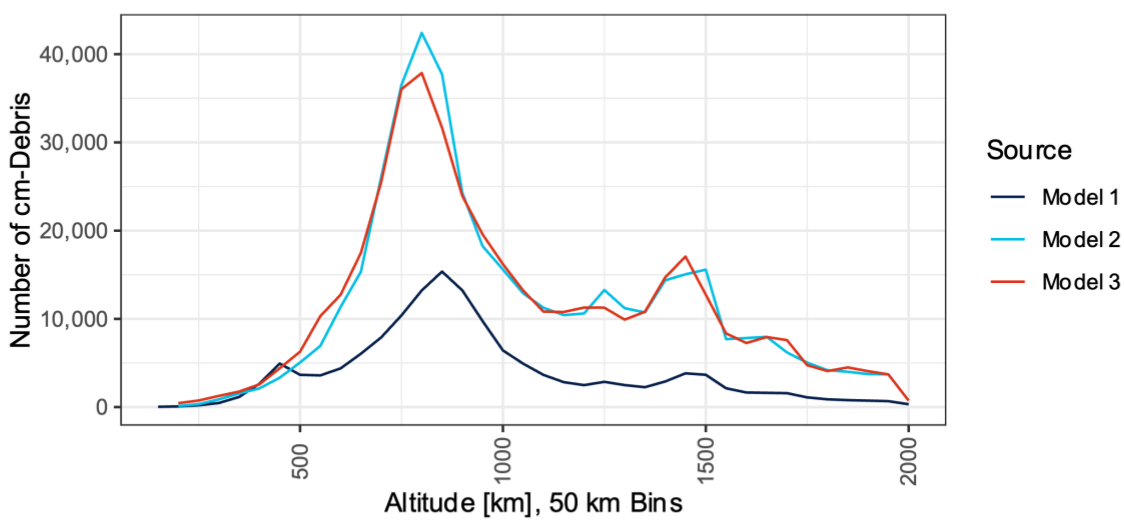


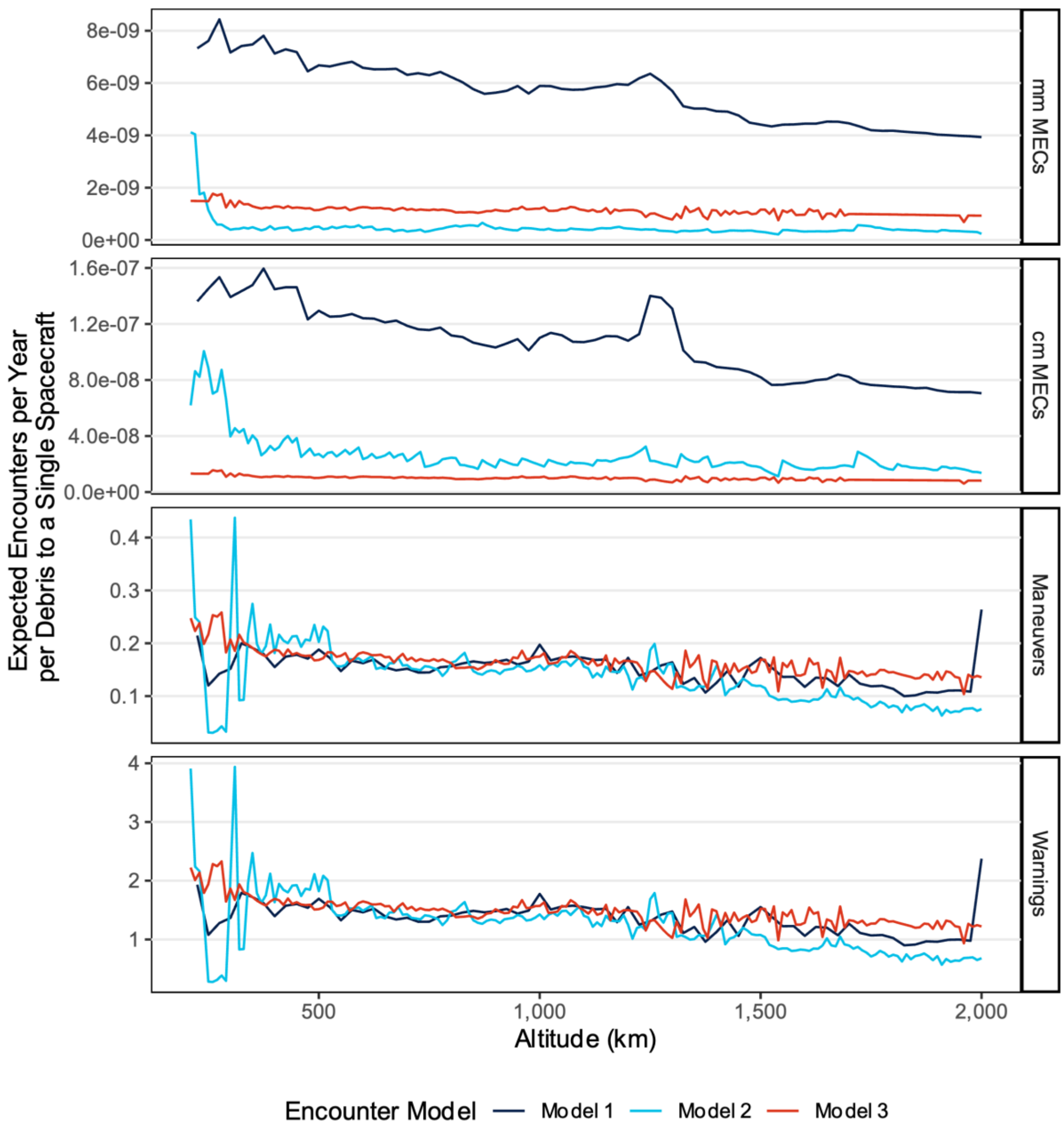
Figure A-4. Counts of 1- to 10-centimeter debris by altitude.

With the debris populations and baseline encounter estimates, we derived the average contribution per piece of debris for each attitude bin. Figure A-5 shows those averages, which

[33] Our very rough decoding of Figure 6 in Horstmann et al. (2021) is that there are about 1.5 billion debris bigger than 1 millimeter. The 1.8 billion number used in this report came from spatial density data generously provided directly from ODPO.

represent the contribution of a single debris to our representative satellite. For example, at around 800 kilometers, a >10-centimeter piece of debris is expected by Model 1 to cause 1.83 warnings and 0.2 maneuvers for a single satellite operating at the same altitude in a 60° inclination. At a 90° inclination, that piece of debris would be expected to cause 2.41 warnings.[34] As shown in Figure A-5, Model 1 (based on ORDEM) in general predicts that each piece of debris will be cause more events than the other models do. In fact, Figure A-5 underestimates the difference by about 2.5 times, as the 25-kilometer bins for Model 1 (versus the 10-kilometer bins for Models 2 and 3), cause the same number of events to be spread over more debris.

[34] This calculation is not based on an intrinsic quality of a satellite operating in different inclinations. We hold the inclination of the debris uncertain. The model then implicitly assigns some expected inclination information the model gleaned from the baseline population, which the model used to understand different encounter rates by inclination.



Note: The marginal contribution varies for each encounter, so for maneuvers and warnings, it is >10 centimeters, while for MECs it is smaller. So, the marginal contribution of a small piece of debris to maneuvers would be 0, while a large piece of debris would contribute 0 MECs. The statistic shown here is the mean across all debris lengths applicable to that event, so warnings are the average across all size bins greater than 10 centimeters (e.g., 10–11 centimeters, 11–12 centimeters, etc.).

Figure A-5. Average contribution of a single piece of debris to a single test satellite (encounters per year per debris) at 60° inclination.

We now can estimate the encounters generated by an arbitrary population of debris and can thus estimate the risk they pose to a single satellite. To complete the calculation, we need to be able to apply the encounters to any population of satellites. This proposition, fortunately, is straightforward. If we assume independence—in other words, that no interactions between a satellite and debris affect interactions between another satellite and that debris—we can simply estimate encounters for each of the satellites separately. For example, say we have four satellites, two at 800 kilometers and 60°, one at 800 kilometers and 90°, and one at 1,000 kilometers and 90°. We simply run the encounter model for each satellite (e.g., 601 × 2, 794, and 749 warnings) and sum all the encounters (2,745 warnings all together). As long as we assume independence, we can trivially calculate the encounters for an arbitrary number of spacecraft.

We derived these spacecraft from the Union of Concerned Scientists (UCS) Satellite Database at the end of 2021. This database was also used in the Phase 1 study; for the current analysis, we extended the data examined to include all global spacecraft. We also enhanced the characteristics of certain satellites by using information obtained from DISCOS, which allowed us to refine mass and size estimates for the satellites.

As in Phase 1, we assigned 1 of 11 operator categories to each spacecraft in order to group satellites that we expected to have approximately similar costs associated with their interactions with debris. The methodology for assigning the spacecraft was described in that report; we followed the same methodology, except that we did not assign spacecraft to the CubeSat category solely because they were nonmaneuverable. Table A-4 summarizes the categories and their assigned number of spacecraft.

Table A-4. Summary of Operator Profiles

Operator Profile	Description	Assumed Lifetime	# of Satellites (USA Only)
Civil Operational	Civil government satellites, the purpose of which is not primarily research.	6	144 (9)
Civil Science Long	Owned and operated by science agencies with design lifetimes generally of 3 or more years.	6	12 (4)
Civil Science Short	Owned and operated by science agencies with design lifetimes generally lower than 3 years.	3	118 (16)
Commercial Bespoke	Commercially operated, operate in LEO, have a mass above 200 kilograms, and are not members of a constellation of more than 10 satellites.	6	17 (4)
Commercial Large Constellation	Emerging communications constellations containing hundreds to thousands of spacecraft.	3	2,239 (1,815)
Commercial Medium Constellation	Commercial constellations containing 20–100 satellites each.	3	134 (107)
Commercial Small Constellation	Commercial constellations of roughly identical spacecraft containing fewer than 20 satellites each.	3	119 (60)
CubeSat/SmallSat	Satellites that have fewer than 11 kilograms of dry mass.	2	892 (611)
Human Spaceflight	LEO space stations.	30	2 (1)

Military	Satellites for which the UCS database listed the users as "Military," either in whole or in part.	6	261 (48)
Technology Development	Listed in the UCS database as technology development.	3	149 (14)

In addition to this profile categorization, we assigned each spacecraft a category representing its physical characteristics, such as mass, bus size, and expected lifetime. Table A-5 summarizes the four size categories for satellites, along with one for derelict rocket bodies. Spacecraft were assigned to these categories by using launch mass in the UCS database as a proxy. Satellites were assigned categories based on their cross-sectional area in DISCOS, and then we assumed their remaining parameters. The names of satellites do not necessarily refer to the common industry terms *smallsats* and *microsats*; the names just happen to represent the categories used in this model.

Table A-5. Physical Parameters Assigned to Satellites

	Micro	**Small**	**Medium**	**Large**	**Rocket Body**[a]	**Heavy Rocket Body**[a]
Exemplar[b]	CuSP (6U CubeSat)	SCISAT	DSCOVR, Iridium	Radarsat-2, NOAA 20	SL-14	SL-16
Launch Mass Proxy	<100 kg	100-500 kg	500 to 10,000 kg	>1,000 kg	N/A	N/A
Count	1,119	2,502	241	224	0	0
Dry Mass[c]	20 kg	250 kg	650 kg	1,500 kg	1,500 kg	9,000 kg
Bus Collision Area[d]	0.1 m^2	1 m^2	5 m^2	10 m^2	N/A	N/A
Bus Surface Area[d]	0.25 m^2	5 m^2	15 m^2	20 m^2	40 m^2	110 m^2
Cross-Section Area[e]	0.8 m^2	4 m^2	14 m^2	16 m^2	20 m^2	40 m^2
BC[f]	10	30	20	35	60	60

[a] Rocket bodies are listed here for future reference in generating debris. We did not consider any "active" rocket bodies in the study.
[b] The characteristics from DISCOS for exemplar satellites were used along with other sources to help generate the assumptions for the category.
[c] The dry mass of these categories is a synthesis of the average dry mass from UCS for these launch mass proxy categories and the representative designs in McKnight et al. (2021) The dry mass of rocket bodies is more difficult to nail down. Without an immediately better methodology, we used the mean launch mass of the rocket bodies in DISCOS of about 1,5000 kilograms. This number is obviously an overestimate but helped to compensate for the much more massive outliers.
[d] The collision area and surface area of the spacecraft bus was extrapolated from the bus dimensions of the exemplars in DISCOS. Thus, we ignored solar arrays since we were mainly concerned with small debris strikes.
[e] The cross-sectional area was used to calculate the ballistic coefficient and was derived from the mean cross-section areas listed in the table, applied to dry mass from DISCOS.
[f] The ballistic coefficient was estimated using the dry mass and cross-sectional area listed in the table. The coefficient assumes a coefficient of drag of 2.2, although we acknowledge that this number is likely a large underestimate of actual drag coefficients. For example, see Mehta et al. (2022).

We now have a baseline of spacecraft to which we can apply the encounter rates and for which we can estimate risk. In total, the baseline laydown contains 4,087, of which 2,688 are registered under the United States.

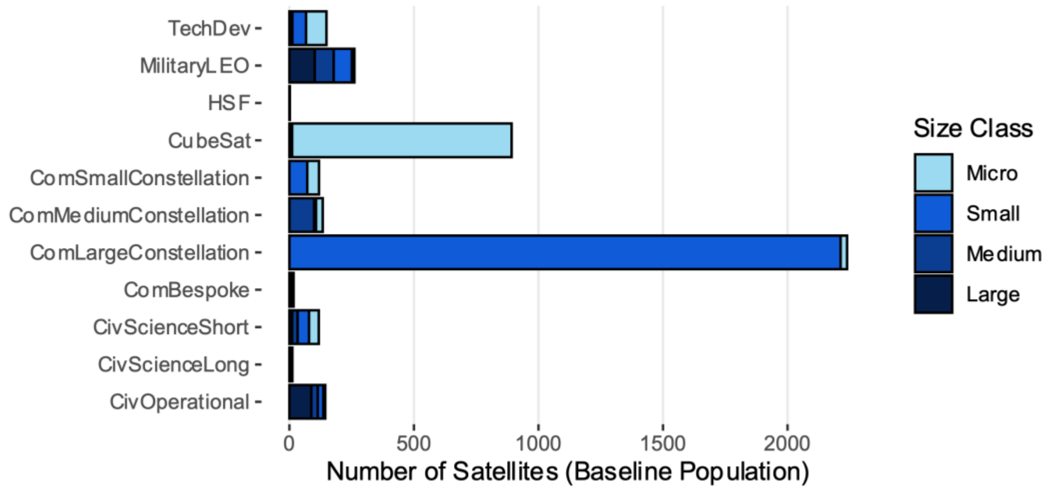


Figure A-6. Baseline spacecraft population composition.

We call the above population the baseline population, because at times we augmented it with predicted future space traffic. Specifically, we added the three new large constellations representing the planned Starlink expansion, as well as the planned GuoWong, Kuiper, and OneWeb constellations. Figure A-7 shows the increase in populations, given the new constellations. For the most part, we used the baseline population unless otherwise stated. Other than the contingent addition of constellations, the baseline population stayed constant throughout the simulations.

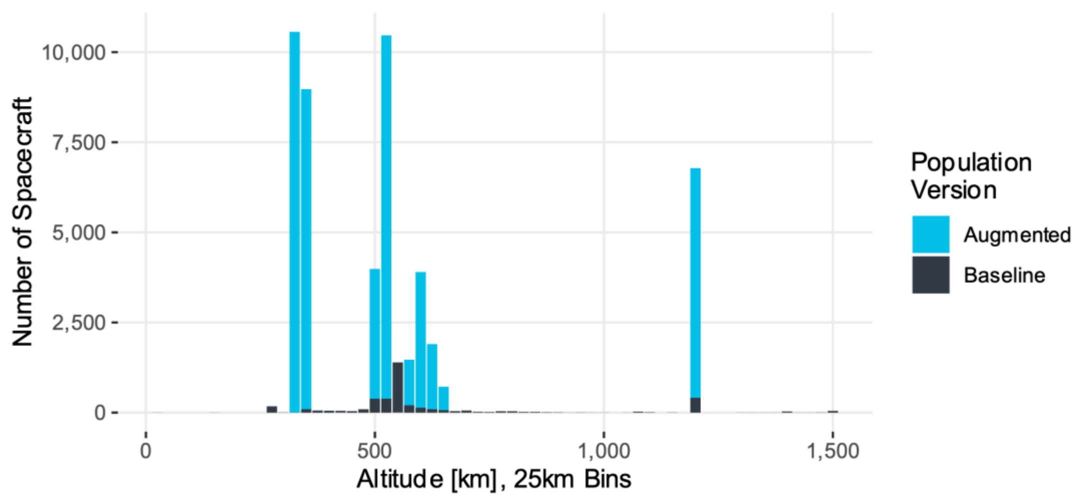


Figure A-7. Comparison of the augmented constellations and the baseline population.

With this information, we can represent virtually any population of debris and operational spacecraft and estimate the risk that the former poses to the latter. Further, we have an approximation of the current orbital environment, for which we can estimate the current risk. Table A-6 shows the estimated risk in the current environment; the risk ranges from $66 million to $1.4 billion in the first year of our simulation. Perhaps counterintuitively, adding the hundreds of thousands of constellation satellites (the "Augmented" section in the table) only slightly increases the total risk; the constellation spacecraft are in the Commercial Large Constellation category and, as shown in Table A-6, have no maneuver or warning costs and have a lethality consequence of only $1 million.

Table A-6. Baseline Environment Risk Rates [$/Year]

	Encounter Model	MECs	Maneuvers	Warnings	Total
Total	Model 1	$666M	$13M	$13M	$692M
	Model 2	$136M	$15M	$13M	$164M
	Model 3	$91M	$13M	$14M	$115M
U.S. Only	Model 1	$162M	$20M	$4M	$171M
	Model 2	$33M	$8M	$2M	$43M
	Model 3	$21M	$7M	$2M	$30M
Augmented	Model 1	$688M	$6M	$2M	$714M
	Model 2	$141M	$8M	$2M	$170M
	Model 3	$95M	$7M	$2M	$120M

We did not conduct a formal sensitivity analysis of these results and the encounter model but knew enough to predict the most sensitive values. By far the most sensitive, especially considering Model 1, is the probability that a collision will end a mission. A 1-in-100 chance of MEC from a strike to the bus would be defensible on a physical level but result in nearly 100 mission-terminating events per year. In general, MECs present most of the risk and are thus the source of greatest sensitivity, with the centimeter-size lethality rate and collision areas also playing a large role.

The warning and maneuver thresholds (3 kilometers and 1 kilometer) represent another area of high uncertainty. NASA's collision avoidance handbook notes that "the lack of any strong correlation between Pc [probability of collision] and miss distance is clear: the span of miss distances for critical events (less than 100 m to more than 10 kilometers) is extremely broad and overlaps significantly with the results for the non-critical events." (NASA 2023, 82). Although the distances we chose are recognized as standard rules of thumb, distances as low as 50 meters for a maneuver threshold would be defensible based on our analysis of conjunction data. Adopting this threshold would, for example, decrease the maneuver costs shown in Table A-6 by three to four orders of magnitude. Further research is needed to improve the models of operator behavior and SSA uncertainty.

In conclusion, a final way to look at the current risk is by the amount of risk that the average piece of debris can be expected to cause. This calculation is simply the total risk shown in Table A-5 divided by the total number of debris. Figure A-7 shows the average value parameterized by altitude and characteristic length. If we look at 800 kilometers, for example, a 1- to 5-millimeter piece of debris is expected to cause \$1–20 of risk per year, whereas a >10-centimeter piece is expected to cause \$1,300–\$1,900 of risk per year. Even if we don't consider debris generation, tracked debris cause more risk via warnings and maneuvers, whereas larger untracked debris generate more risk than smaller debris because larger debris have a higher probability of lethality. Finally, we can see that the risk estimates in Model 1 (the reference model derived from ORDEM) exceed the risk estimates in the other models, in this case by nearly an order of magnitude for <10-centimeter debris.

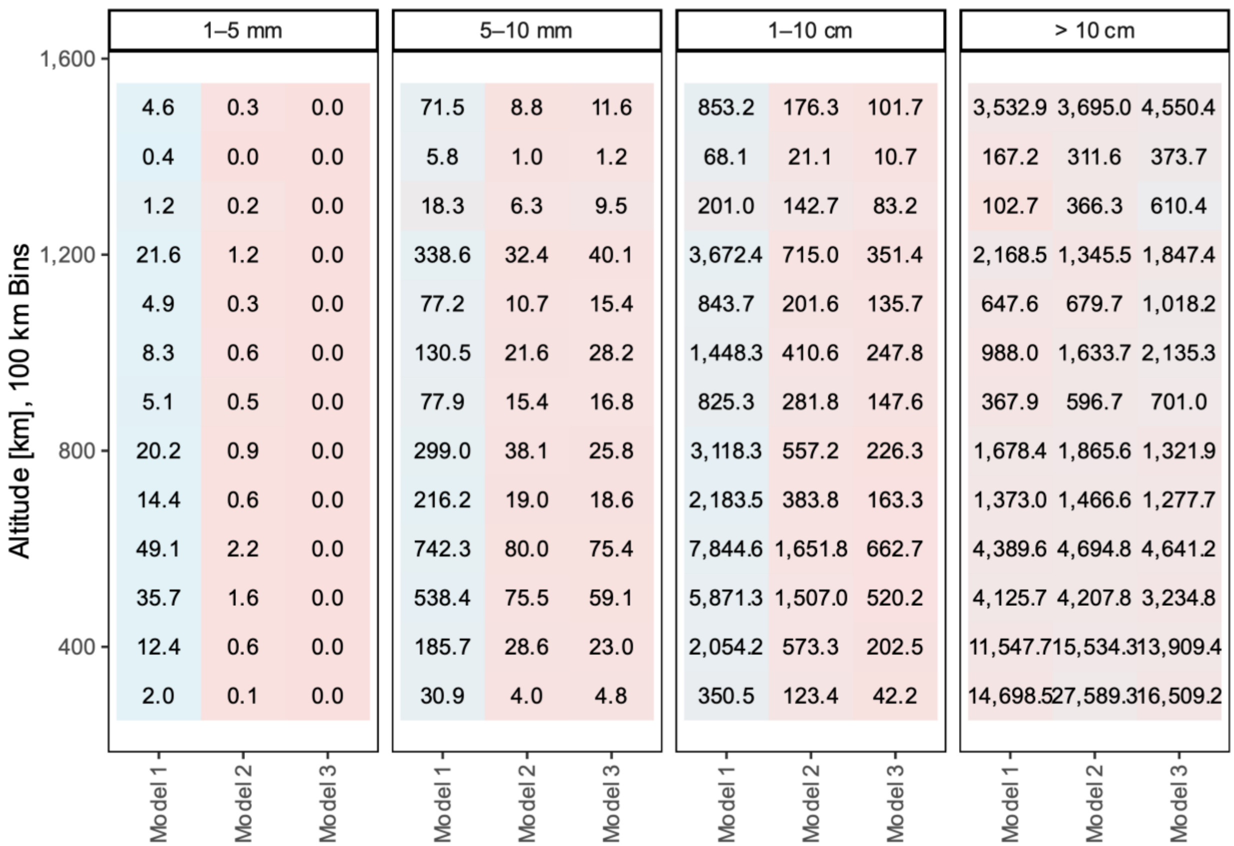


Figure A-7. Total risk rate [\$/Year] generated by average piece of debris for all baseline satellites.

So far, we have chosen to express the risk in dollars per year, but a different denominator, such as dollars per second, would have been equally valid. Up to this point, we have used the model to predict the risk that a population of orbital debris pose to a population of spacecraft—the longer the spacecraft are exposed to the debris, the more the risk (i.e., expected consequence) accumulates. That model, as it is currently expressed, is independent of time. For a given population, the model returns the same rate of risk whether the year is 2024 or 2060 or whether the populations will be static for a decade or will change the next second. To measure risk over time, we needed to change the populations, adding and removing debris and spacecraft. In the next section, we summarize how we added time dynamics—sources and sinks—to the model.

Assumptions and Limitations for Extending the Models to Other Populations

- We relied on the average contribution of a piece of debris by characteristic length to estimate the risk from different populations of debris. We assumed the new debris populations to be similar in latent characteristics, such as inclination. Because of this decision, we missed effects on the tails of the distribution, such as a cloud of debris all at the same inclination.
- We calculated the average contribution across all debris in an altitude bin, although only the circular debris at the same altitude interact with a satellite. Again, on average this decision was considered acceptable but limited our ability to model localized effects.
- As we did with encounter numbers, we relied on the population numbers provided by LeoLabs and by ODPO. The final results are sensitive to the number of debris (denominator), so this reliance reduced the parts of the decision space we explored.
- To project the encounters to multiple spacecraft, we assumed independence between all spacecraft. We assumed that encounters between one piece of debris and a satellite do not affect encounters between that debris and another satellite (e.g., we allowed a piece of debris to potentially collide with multiple satellites in our model). This assumption is not ideal but makes the model much simpler, and the joint probabilities are sufficiently low to be discarded without an expected large loss in accuracy. We also assumed that interactions between spacecraft have no effect on the model (e.g., an avoidance maneuver between two satellites will not affect either of their expected number of collisions).
- The methodology for assigning spacecraft to operator profiles was applied manually and somewhat inconsistently. Additionally, the assignment methodology was not designed for this case, in which we could track the maneuverability and size of the spacecraft separately. For the fidelity of this report, however, we expected the current groupings to be sufficient.
- We used an old version of the UCS database (2022) and thus an old satellite laydown. We at times augmented this database with speculative representations of future constellations, which are illustrative if not accurate.

- We very roughly discretized all intact satellites (payloads and rocket bodies) into categories with a representative object. Doing so was necessary for assigning physical parameters not in the databases (dry mass and bus size) simply and limiting computation for the full model. Doing so also came at a large cost in accuracy and richness, especially for rocket bodies in which the long tail of size may provide much of the risk.
- The full results relied heavily on parameters we had to set ourselves—for example, the probability of lethality. We must emphasize the exploratory nature of our analysis and hope that our analysis motivates others to validate better estimates for these key parameters. Any absolute magnitudes presented in this study should be considered carefully.

IV. Extension Over Time

Evaluating the risk posed by debris requires understanding the potential of debris and spacecraft to beget new debris—that is, to indirectly create risk to future spacecraft. Further, an evolutionary model is necessary to evaluate the effectiveness of actions that mitigate the creation of new debris.

The three encounter models operate by estimating a rate for a picture of an environment. To estimate the risk over time, we provided a series of environments and estimated the encounter rates for each environment. We then assumed that the rate is representative for a length of time—for example, 1 year. We calculated the risk to spacecraft from the debris environment in the first year, evolved the debris environment to a new state in year 2, and calculated the risks to spacecraft in the new environment. The total risk is the sum of the annual risks. In general, we calculated risks for a 30-year period.

The challenge we faced was how to evolve the space environment from one year to the next in a way that is flexible yet credibly reflects the average annual risks. To tackle this issue, we devised a very simple evolutionary debris model. We did not use an established evolutionary model, such as NASA's LEGEND (LEO-to-GEO Environment Debris model), because we needed the flexibility to control parameters related to debris creation so that we could simulate our risk-reduction actions. Additionally, we needed a deterministic model with a fast-run time in so that we could run multiple combinations quickly. In the future, we hope open-source models will enable researchers to do this type of analysis without needing to stitch together their own models. Because of the current situation, we stitched together our model using, whenever possible, the standard statistical models behind tools such as LEGEND. In the following sections, we explain each debris source and sink and then consolidate them to determine the total expected growth of debris in space.

Source: Collisions

Table A-7. Source of Debris: Collisions

Description	**A catastrophic collision between two objects in which both break up and generate new debris.**
Source Objects	Any satellite (active or debris) 10 centimeters or larger without maneuver capability.
Baseline Probability	Estimated from the encounter model as the expected number of strikes from a >10-centimeter piece of debris.
Consequence	Estimated using a simplified version of NASA's Standard Breakup Model.

A catastrophic collision occurs when two objects collide (1) at an impact velocity above 6 km/s and (2) with enough energy for both to break apart (i.e., 35–45 J/g). Noncatastrophic collisions also occur and might result in debris generation but are considered within the surface degradation discussion. For the remainder of this analysis, we refer to catastrophic collisions simply as *collisions*.

Currently, any debris or derelict spacecraft with a characteristic greater than 10 centimeters are allowed in the model to generate new debris via a collision.[35] Further, only satellites without maneuver capability, such as fragments, derelicts, and active spacecraft without propulsion systems, are assumed to produce debris via collision. The expected collisions (~PC) for one of these nonmaneuverable satellites is calculated using the encounter model as described above (except that we did not have inclination information for debris, so we instead used the mean across all inclinations). For example, for a medium derelict spacecraft at an altitude of 650 kilometers, Model 1 predicts an average collision rate of 5.6e-6 per year per square meters collision area.[36] To calculate the expected collisions for the medium derelict spacecraft, we scaled the model for the derelict's collision area (5 square meters, as shown in Table A-5) plus the average collision area of >10-centimeter debris—4.1 square meters, according to DISCOS. As a result, in this example, the estimate is ~5.1e-5 collisions per year. We always used the baseline environment in the encounter models to estimate the expected collisions per spacecraft because we, as a general rule, did not model *N*-order effects. Using the baseline environment led us to underestimate the growth in the environment and in collision risk with time.

To estimate the number of debris generated, we used NASA's Standard Breakup Model (Johnson et al. 2001), which describes a single power law distribution for the characteristic length of debris, generated dependent upon the total mass involved in the collision: $N_{cum} = 0.1 * M_{tot}^{0.75} * L_c^{-1.71}$. To estimate the mass of the impactor, we simulated the collisions with all the large objects

[35] NASA's Standard Breakup Model states that a catastrophic collision occurs when the ratio of the impactor energy to mass of the target exceeds 40 Joules per gram. Assuming a collision speed of 10 km/s, a 10-centimeter impactor (using NASA's mass assumptions) will impart about 1.3 MJ of energy, or about 9 J/g to our representative large satellite, or 59 J/g to the small satellite. We assumed this bound is the lower bound of a particle causing a catastrophic collision and thus used the encounter model as described in section I.B.3. to estimate the probability.

[36] We chose the maximum because most debris, by definition, will be around the highest flux inclinations and because we needed to compensate for our underrepresentation of the target collision area, which resulted from using only a bus.

in the orbits (e.g., rocket bodies, derelict spacecraft, and fragments); we then weighted the contribution of each collision event by the percent of the total collision area each object represented. The standard breakup model can provide a (lognormal) distribution of resulting velocity vectors; we spread the debris directly into effective counts using a Pareto distribution.[37] The model assumes that the collision happened at the beginning of the year, and the decay model (described later) spreads those debris throughout the year.

To illustrate the model, let's assume we're focusing on a medium satellite orbiting at 650 kilometers. At that altitude, the PC is 2.31e-4 per year. The model generates a probability-weighted cloud of debris that follows the distributions of the standard breakup model. In other words, a collision involving a medium satellite might create 2 million debris, but we only expect there to be $2\ million\ x\ 2.31e-4 \cong 370\ debris$. The 370 debris then interact with and pose risks (including collision risks) to active spacecraft.[38] Table A-8 summarizes the statistics for other sizes of spacecraft.

Table A-8. Model 1: Example Collision Generation at 650 Kilometers

Generating Object	Simulated Debris	Expected Collisions	Expected Debris	Expected Consequence[a]
Micro Derelict	2.94e6	2.4e-5	70	$3,100
Small Derelict	3.30e6	2.9e-5	95	$4,300
Medium Derelict	3.99e6	5.1e-5	205	$9,300
Large Derelict	5.24e6	8.0e-5	417	$19,000
Rocket Body	5.24e6	1.4e-4	715	$32,000

[a] The consequence is calculated over one year using the OTPS encounter model with baseline assumptions.

Assumptions and Limitations for Collisions

- We modeled only first-order collision effects—that is, the first potential collision of a baseline object—not collisions of newly generated objects. We always used the baseline environment to estimate the expected number of collisions, since we did not allow newly created debris (nonbaseline debris) to collide with anything. Consequently, the total risk was underestimated (and the tails were missed), but the effects should be limited by the small joint probability of more than one collision.
- We only use one collision model, NASA's Standard Breakup Model, while other collision models exist and might provide a different range of answers.

[37] We chose this altitude range by looking at the altitude at which more realistic collision models (e.g., those provided by LeoLabs and COMSPOC) estimate that about 90% of the total debris will end up. The truncated normal means that we placed 100% of the generated debris in this range.
[38] We did not choose 370 of the generated debris to go on to exist in the model. All of the debris continued to "exist" and were weighted by their probability of existing. Consequently, we could continue to represent the full range of altitudes and sizes generated.

- Model 1 relies on the original formulation of NASA's Standard Breakup Model, which does not conserve mass. We did not implement any additional algorithmic checks or helps to conserve mass (i.e., we did not conserve mass).
- To conserve computation time, the OTPS model assumed a truncated distribution around the collision (± 250 kilometers). This assumption did not fully account for elliptical effects of the created debris or the debris and risk that can travel multiple hundreds of kilometers. To compensate, we generated the same number of debris and drew the 250-kilometer bound to represent over 90% of typical spreads.
- We assumed a collision occurs at the beginning of the year; this assumption slightly overestimated the risk since it should be expected to occur, on average, halfway through the year and pose only 6 months of risk in that year. This simplification was useful four our purposes.

Source: Explosions

Table A-9. Source of Debris: Explosions

Description	**A catastrophic release of energy from the spacecraft or rocket body.**
Source Objects	Active or derelict intact spacecraft.
Baseline Probability	Estimated from recent history.
Consequence	Estimated using a simplified version of NASA's Standard Breakup Model.

Spacecraft store chemical and electrical energy that can be released suddenly, resulting in what is referred to as an explosion. Explosions might be triggered by external stimuli, even the strike of a small piece of debris, but the energy causing the fragmentation comes from the stored energy. Both active and derelict spacecraft (payloads and rocket bodies) have exploded and can in the future.

Models for the probability of explosion have been used in other models. For example, an old ODPO model estimates the probability of explosion for Soviet and Chinese rocket bodies as 1.4e-4 per year (until year 11, when the probability becomes 0). For other spacecraft, the probability of explosion ranges from 6e-3 to 7.5e-4 per year. We included these numbers as reference marks, but these models did not suffice for our purposes because we needed to separate the probability of explosion during operations from the probability after operations. We also needed to delineate electrical and propulsive causes. Thus, we decided to create a very simple reference model.

In this analysis, we focused on electrical and propulsive explosions. The European Space Agency's fragmentation database contains information on 487 nondeliberate explosions. Of these, 157 were attributed to propulsive explosions, and 27 were attributed to electrical explosions (the cause of 100 is unknown). Payloads (i.e., active satellites) were responsible for 100% of the electrical explosions but only 3% of the propulsive explosions. (The rest were caused by rocket bodies or mission-related debris.) According to the database, no satellites launched in 2010 or later have exploded (yet).

From this empirical record, we estimated the probability of a satellite exploding in a given year. The DISCOS contains 22,964 payloads and rocket bodies in LEO, with over 200,000 years of on-orbit data for each. These data were used to calculate the explosion rates shown in Table A-10. Note that the rates would be much lower if we did not include unknown events.

Table A-10. Explosion Rates and Probabilities

Object Type	Event Type	Probability per Year	Total per Year	Percent During Operation	Active Total	Derelict Total
	Electrical	0.009%		41%		
Payload	Propulsion	0.002%	0.03%	40%	0.013%	0.017%
	Unknown	0.02%		65%		
	Electrical	0%		100%		
Rocket Body	Propulsion	0.04%	0.06%	0%	N/A	0.06%
	Unknown	0.02%		0%		

In our model, we used the active and derelict estimates as the expected number of explosions for the spacecraft. We expected that the model would slightly overestimate current and future rates, as the model includes all the history in the fragmentation database. We assumed that only intact objects (i.e., not fragments) still have stored energy and the potential for a fragmentation event.

The number of debris generated in an explosion is described in NASA's Standard Breakup Model (Johnson et al. 2001), this time only parameterized by the length of the resulting fragments: $N_{cum} = sf * 6 * L_c^{-1.6}$. In the equation, sf is a scaling factor that can better represent certain events, but all explosions in this model used the default scaling factor of 1, following suggested best practice. This model, even more than the collision model, does not conserve mass. We took liberties to conserve mass, scaling the debris generated by the exploding object's mass over the average mass of the inputs in the model (800 kilograms). Otherwise, we used the same methodology for debris generation as we did for collisions. All models used this same explosion model.

Table A-11. Example Explosion Generations at 650 Kilometers

Generating Object	Simulated Debris	Expected Explosions per Year	Expected Debris	Expected Consequence[a]
Micro Derelict	9.5e3	1.7e-4	1.6	$90
Small Derelict	1.1e5		18.1	$1,030
Medium Derelict	3.1e5		52.3	$3,000
Large Derelict	7.1e5		120.7	$6,900
Rocket Body	7.1e5	6e-4	425.9	$24,000

[a] The consequence was calculated over one year using the ORDEM flux model with baseline assumptions.

Assumptions and Limitations for Explosions

- We created our simple explosion probability model based on past fragmentation events. We assumed that past probabilities, specifically those DISCOS, will apply in the future. We did not find a way to easily validate the probabilities we identified in this exercise. DISCOS tends to have more events than NASA's History of On-Orbit Satellite Fragmentations (HOOSF) and therefore represents a more conservative bound. HOOSF would have been an appropriate alternative source of information.
- As for collisions, we relied on NASA's Standard Breakup Model. We attempted to better represent mass by scaling the number of generated debris by the mass of the spacecraft, although doing so did not necessarily conserve mass.
- We applied the truncated normal distribution and beginning-of-the-year assumptions to explosions.

Source: Surface Degradation

Table A-12. Source of Debris: Surface Degradation

Description	**Surface weathering or shedding from small strikes of intact spacecraft.**
Source Objects	Active or derelict intact spacecraft.
Baseline Probability	Assumed all intact spacecraft (including rocket bodies) have surface degradation.
Consequence	Estimated using the same rate from ORDEM (0.1 pieces/m^2 of surface area/month)

A satellite may shed pieces as it is exposed to the space environment (e.g. UV degradation, thermal flexing, atomic oxygen erosion, manufactured and natural particulate impact, etc.). Following NASA's ORDEM model (section 3.2.1 of ODPO 2022b), we combined all degradation, ejecta, and paint flakes into a single surface degradation source generating debris with a characteristic length between 1 and 3 millimeters (since we filtered out everything below 1 millimeter). ODPO stated that the number used in ORDEM 3.2 is 1,000 pieces generated per square meter of surface area per month. We chose to use 150 pieces per square meter per month because we had more sources of surface degradation than used in ORDEM (because we used the debris from LeoLabs). Therefore, we tuned the value to keep the millimeter-size debris population in ORDEM's baseline. For Model 2, we used a coefficient of only 0.2 pieces per square meter per month since MASTER has a much smaller 1- to 3-millimeter population and this rate maintains the starting population. We did not specify the shape of the new debris but, rather, let the decay model assume a shape from the characteristic length (essentially, a modified sphere, as discussed in the next section).

Table A-13. One Year of Surface Degradation at 650 Kilometers

	Model 1		Model 2	
Generating Object	Expected Debris	Expected Consequence	Expected Debris	Expected Consequence[a]
Micro Derelict	420	$3,000	0.5	$1.5
Small Derelict	8,400	$60,000	10	$25
Medium Derelict	25,000	$180,000	30	$71
Large Derelict	34,000	$240,000	45	$95
Rocket Body	67,000	$480,000	85	$190

[a] The expected consequence was calculated over the first year of generation.

Assumptions and Limitations for Surface Degradation

- We relied on ORDEM's formulation of surface degradation without investigating or validating any alternatives. Following ORDEM's lead, we also assumed only intacts (i.e., rocket bodies and derelict payloads) can generate debris from surface degradation. Because we has a different source population in our models, we had to "tune" our rate based on the current populations in the models, relying on the assumption that they must exist because a similar rate is used in the models. We also had to use a similar process to apply the surface degradation concept to Model 2.
- Using the spacecraft physical dimensions categories likely resulted in misestimating the total surface degradation production.

Source: Spacecraft

Table A-14. Source of Debris: Spacecraft

Description	S**atellites** at the end of life, either **premature**ly because of **a lethal debris strike or** at the **expected** time**.**
Source Objects	Active satellites.
Baseline Probability	Estimated the same way as described in the previous section. As a baseline, we assumed no satellites dispose of themselves.
Consequence	A new intact that is then used to generate new debris.

Spacecraft, or active satellites, play multiple roles in the evolution of the space environment: more spacecraft will be launched and added to LEO; spacecraft can generate debris while they are active, such as through surface degradation and even a fragmentation event; and at the end of their active life, spacecraft turn into derelict objects.

For future spacecraft (the launch model), we chose to keep the spacecraft population constant. In other words, the satellite population will look exactly the same in year 0 and year 30, with all lost satellites immediately replaced. Keeping the spacecraft population constant is overly simplistic and not particularly realistic, but we did not have the capability to predict future launch traffic, and keeping the number of spacecraft constant vastly simplified the model while allowing us to make effective comparisons among risk-reducing items. To explore the potential effects of future traffic, at times we added the future constellations detailed in section III of this appendix.

The previous sections addressed the generation of debris during the active life of spacecraft. We expected an active medium spacecraft to degrade at the same rate as a derelict spacecraft, and the explosion probabilities for active spacecraft was presented in Table A-10.

The main discussion of debris generation for spacecraft regards their end of life. The lifetime may end because of the nominal ending of the mission or because of a debris strike that prematurely ends the mission. The cause of the mission's end affects the altitude at which the derelict spacecraft is placed (Figure A-8).

For PMD, we calculated the probability that a satellite would end its mission in a given year. As discussed previously, we assumed that when a spacecraft is removed from operation, it is replaced by a new similar spacecraft. Thus, in this steady state, we assumed that the probability a spacecraft will undergoes PMD is constant in time and given by one divided its planned lifetime A spacecraft with maneuver capability will attempt to reduce its altitude, if necessary, to meet the deorbit policy being analyzed, becoming a derelict at that final altitude. This maneuver succeeds with probability $p_{pmd\ success}$. If the maneuver fails, if the spacecraft lacks maneuver capability, or the spacecraft is noncompliant, the spacecraft becomes a derelict in place. Finally, we assumed that a spacecraft that is naturally compliant with the deorbit policy will be left in place.

If the spacecraft does not undergo PMD, which happens with the probability of 1-(1/planned-lifetime), we assessed the probability that its will mission end because of a collision with untracked debris. The calculation of a lethality follows the same logic outlined in the previous sections on the encounter models. A lethality results in a new derelict of the same size at the altitude the satellite was operating at.

The expected risks in the first year are shown in Figure A-8. The figure shows four "versions" of the satellite. One is the active satellite, which continues on because of our replacement assumptions. The second is a derelict created at the operating altitude because of a potential lethality strike. The last two are derelicts from PMD, one of which is at the operating altitude because the PMD was unsuccessful and the other of which is at PMD altitude because the PMD was successful.

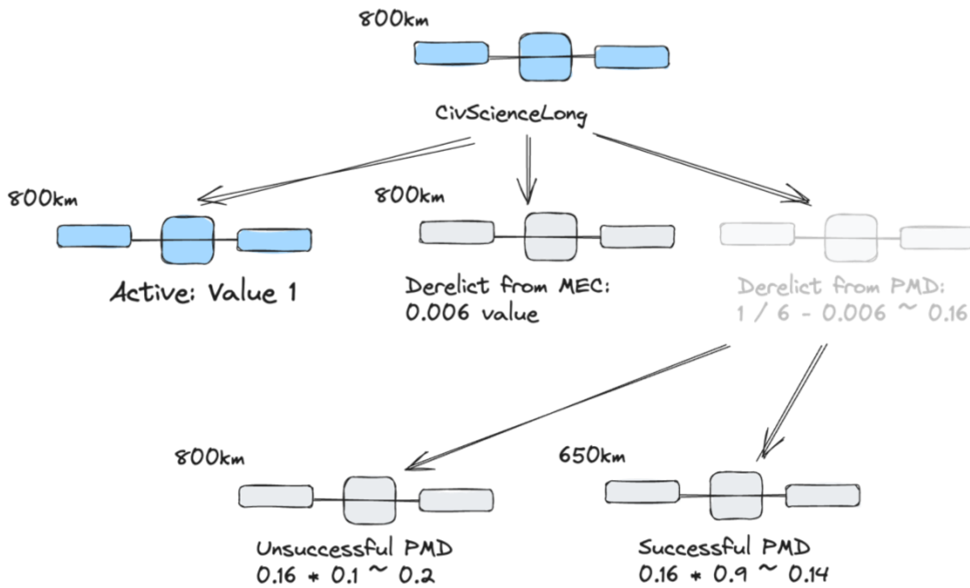


Figure A-8. Example of debris generated in a single year from one active satellite. Note: The active satellite has a value of 1 because all spacecraft are replaced immediately. Image generated using Excalidraw software.

This study estimated the risks of debris created from collisions, explosions, surface degradation, and satellite deaths. We continued to omit *N*-order effects in the model; therefore, debris created from explosions, collisions, and surface degradation could collide with operational spacecraft. However, we made the simplifying assumption that such collisions do not generate more debris. This assumption is relatively reasonable because second-order collisions have a low probability of debris generation—they are conditioned on the already-low probability of the first-order collision—over the timespan of a few decades. Incorporating these second-order effects would be unlikely to significantly change our results but would significantly increase the run-time of our models. The one exception is satellite derelicts, those resulting from PMD and lethalities, which were used as new sources from the year they originated and onward. These newly created debris may have higher starting probabilities, which can make the joint probabilities significant.

Assumptions and Limitations for Active Spacecraft Generation

- The launch traffic model is overly simplistic, assuming the same population for the next *N* years. This assumption led us to rank more highly the actions that are better adapted to the current environment than the actual future spacecraft environment. Many predictions forecast an increased number of spacecraft in the future, in which case we consistently underestimated future risk. Finally, this launch model is not responsive to changes in the environment, so measuring only first-order effects.
- We ignored the rocket bodies that would have been added in the implicit launch model. Consequently, we underestimated debris growth.

- We did not properly account for the probability that a spacecraft would be able to attempt a PMD maneuver. By simply subtracting the lethality probability from the end-of-life probability, we effectively did a Taylor expansion around the lethality probability at 0, for which our simplification will only be accurate if the lethality probability is sufficiently low.
- As in the other generation methods, we assumed that any satellite-generated debris are generated at the beginning of the year. We also assumed that these derelicts would be immediately available to generate new debris.

Sink: Decay

Atmospheric drag will reduce the altitude of orbital debris over time—a process referred to as *orbital decay* or often simply *decay*. Eventually, nearly all orbital debris in LEO will be removed from orbit because of orbital decay (among other factors). We modeled this effect by assuming all fragments are spheres, applying a simple atmospheric density not modulated by solar activity, and ignoring solar radiation pressure. For large derelict spacecraft, we used the ballistic coefficients shown in Table A-5.

The ballistic coefficient of an object affects how much drag the object experiences as it passes through the atmosphere. Following the approach taken in NASA's orbital debris modeling, including NASA's Standard Breakup Model (Johnson et al. 2001; Schuhmacher 2021), we modeled fragments as spheres with density parameterized by it's the characteristic length.

$$\rho(L_c) = \begin{cases} \rho_{AL} = 2698.9 & if\ L_c < 0.01m \\ 92.937\ x\ L_c^{-0.74} & otherwise \end{cases}$$

$$M(L_c) = \frac{4}{3}\pi * \left(\frac{L_C}{2}\right)^3 * \rho(L_c)$$

$$A_x(L_c) = \begin{cases} 0.540424 * L_C^2 & where\ L_C < 0.00167\ m \\ 0.556945 * L_c^2 & otherwise \end{cases}$$

Using these equations, we specified the characteristic length of a piece of debris and calculated its mass $M(L_c)$ and cross-sectional area $A_x(L_c)$. To calculate the ballistic coefficient, the mass is divided by the cross-sectional area and the coefficient of drag, which is a unitless number that depends on the shape of the object and the properties of the atmosphere flowing around it. The standard assumption for small debris is that the coefficient of drag equals 2.2.[39] For intact satellites, the ballistic coefficients we used are shown in Table A-5. Figure A-9 summarizes

[39] This assumption is common practice in atmospheric drag modeling (e.g., see Prieto, Graziano, and Roberts 2014). We acknowledge that this assumption is likely a large underestimate of actual drag coefficients (e.g., see Mehta et al. 2022).

the ballistic coefficients used in this analysis.

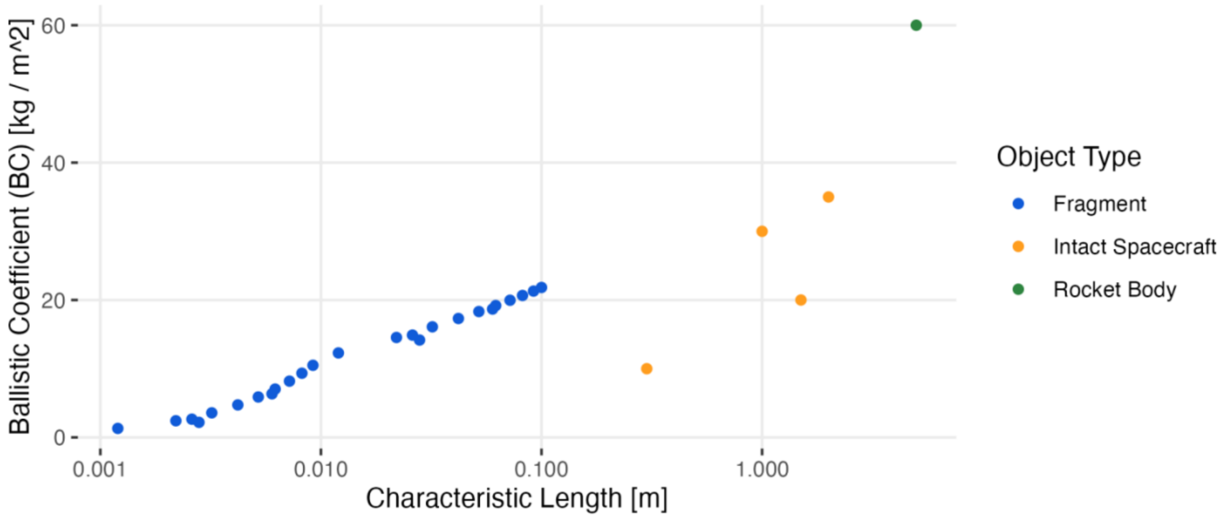


Figure A-9. Assumed ballistic coefficients of small debris.

The atmospheric drag is calculated using a numeric integration that employs the U.S. Standard Atmospheric Density Model (NOAA 1976). That model does not include any atmosphere above 1,000 kilometers, so all objects above that altitude are left in place. Figure A-10 illustrates our estimates of the deorbit times for debris, assuming they are hollow spheres, per NASA's Standard Breakup Model. Note that the large objects deorbit in 25 years from altitudes between 600 kilometers and 650 kilometers; this finding agrees with common knowledge of the deorbit times for spacecraft. Small debris deorbit much faster. We estimated that a 1-millimeter fragment will deorbit from 900 kilometers in about 25 years. In general, small debris are unlikely to be spherical; incorporating more realistic shapes would decrease the ballistic coefficient of small debris and cause them to reenter faster than we calculated here.

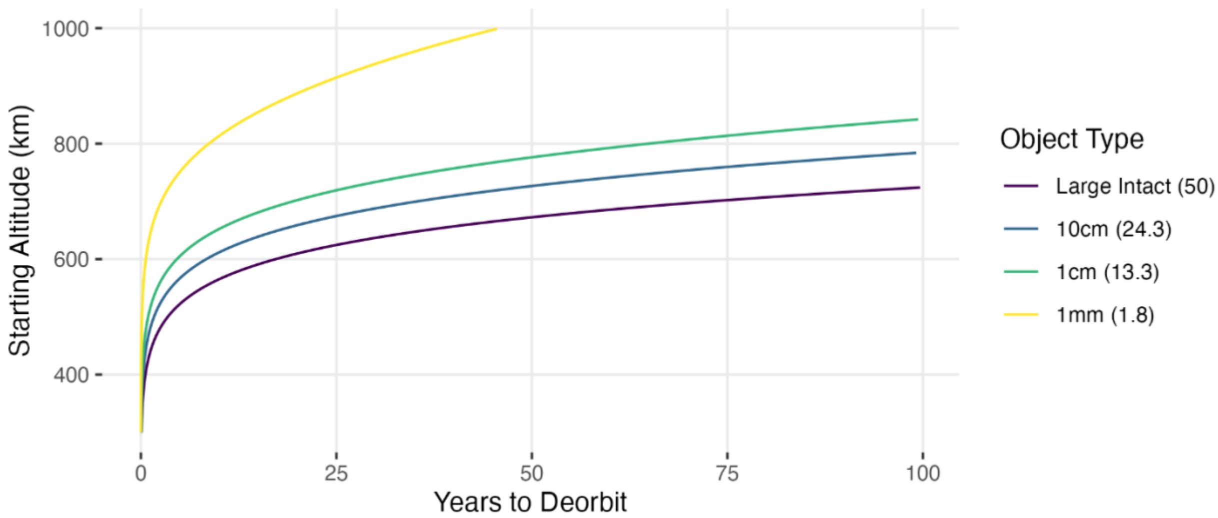


Figure A-10. Deorbit times for the standard atmospheric decay model.

As debris deorbits, it may transit through multiple altitude bands in a single year. Thus, we calculated the amount of time each object spends at each altitude bin throughout the year, and we used this information to weight the probability that the object is in each altitude bin for the given year. In Figure A-11, a 1-centimeter piece of debris starts at 600 kilometers and then deorbits naturally, spending a fraction of its time in different bins. This modeling allowed us to incorporate sub-one-year elements of time, essentially smearing the debris across their expected locations in any given year.

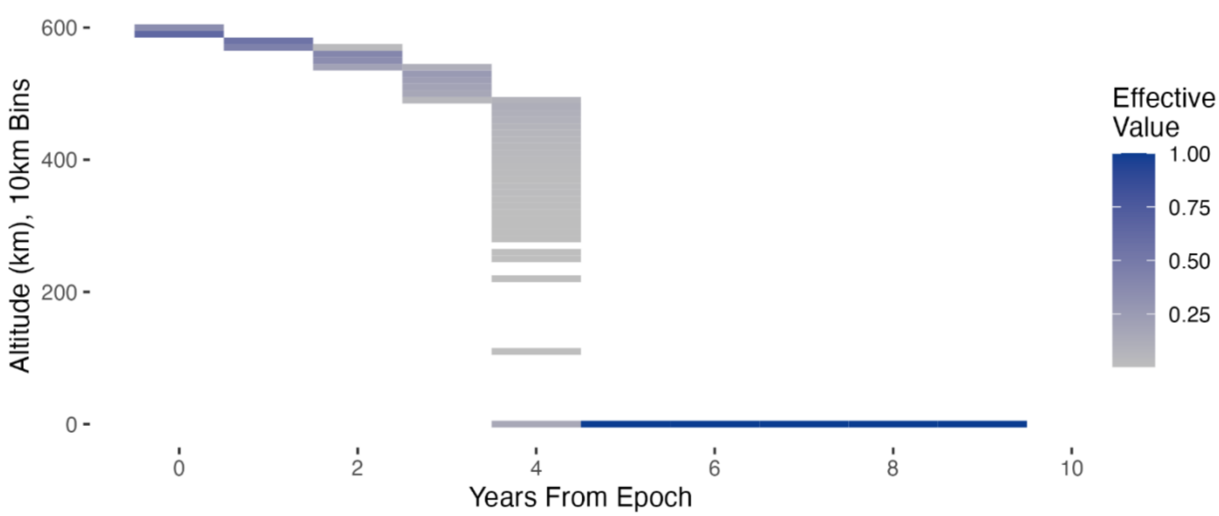


Figure A-11. Decay spread of a 1-centimeter fragment starting at 600 kilometers. Note: The decay becomes discontinuous at year 4 as the semianalytic model is run at 0.1-day intervals, skipping over some bins as the object quickly deorbits at the lower altitudes.

Assumptions and Limitations for Active Decay

- We assumed all fragments are spherical and made of aluminum; we compensated for their density by using statistical approximation from ODPO. In reality, debris, especially small debris, better approximate oblong rectangles or flakes; therefore, we likely overestimate the ballistic coefficient and consequently the persistence and risk from all fragments.
- The exponential atmospheric density model is simple, including no space weather effects and no decay above 1,000 kilometers. The latter is especially important for very small debris, which might still decay from that height within 30 years. This aspect is a critical limitation of our current evolutionary model.

Summary: Total Growth

With the four sources of debris and single sink, we have a complete evolutionary model that can simulate the evolution of the debris and spacecraft environment over a number of years. Figure A-12 shows the growth of >10 centimeter debris over 30 years from the model epoch. Although the model is very simple, it falls within the European Space Agency's predictions of that the number of large debris will approximately double in the next 30 years; the estimate exceeds NASA's current LEGEND predictions.[40] Figure A-12 shows the generation from debris and satellites with no PMD.

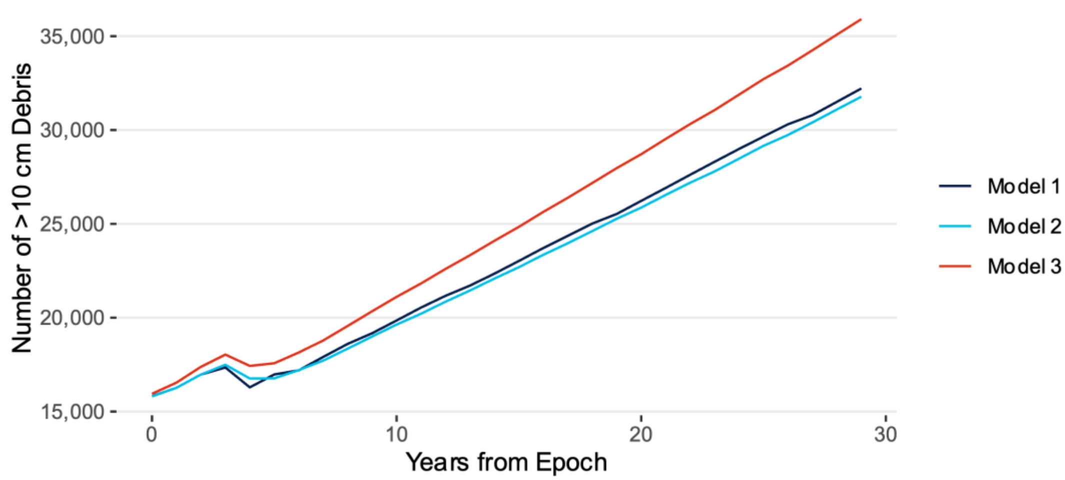


Figure A-12. Simulations of the growth of >10-centimeter debris populations. Note: The COMSPOC collision model predicts a greater representation of large debris from collisions, which explains the higher growth rate of these debris.

[40] See NASA's predictions on its website for LEGEND: https://orbitaldebris.jsc.nasa.gov/modeling/legend.html. For the European Space Agency's predictions, see p. 120 of *ESA's Space Environment Report*, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf.

The total-growth multiples over 30 years for Models 1, 2, and 3 are 1.51, 2.51, and 2.26, respectively. Figure A-13 shows the sources of the debris in year 30, including the debris present in the original baseline environment.

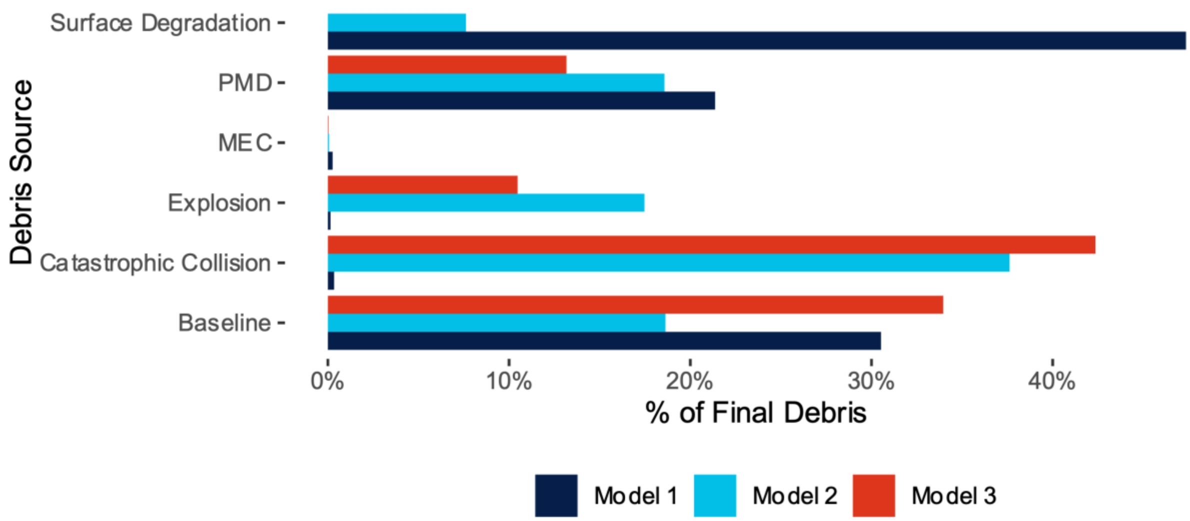


Figure A-13. Debris sources as a percentage of the final population.

Assumptions and Limitations for the Full Model

We listed some of the assumptions and limitations in previous sections. Here, we attempt to summarize some of the overall implications.

- The model is fundamentally a source–sink model that estimates the expected growth, or the expected value. Further, since we assumed independence and only first-ish-order effects, the expected value does not include any of the tails. Since orbital debris growth likely has a fat-tailed distribution, we likely underestimated overall growth.
- Our satellite replacement model is naïve and not intended to be predictive. It does make the math simpler but does not include time growth of the satellite population. Assuming that the satellite population will grow, we likely underestimated the long-term risk. More interestingly, since we continued to put satellites in the same places, our estimates are fragile to new placements of satellites or constellations; thus, our model should not be used to tune location-specific information.

IV. Summary and Further Research

This appendix has introduced the models used in this study: the risk model estimating risk from close encounters, the encounter models estimating close encounters in the orbital environment, and evolutionary models predicting future environments by examining past ones. Table A-15 summarizes the key parameters for these models.

Table A-15. Key Parameters for the Models in This Study

Parameter	Value(s)
Actual Miss Distance to Warnings	$Range < 3\ km$
Actual Miss Distance to Maneuvers	$Range < 1\ km$
Probability of MEC Given Hit to Bus	$\begin{cases} 1\ where\ L_c \geq 0.1 \\ 10 * L_c\ where\ L_c \geq 0.01 \\ 10 * (3 * Log10(L_c) + 5)\ otherwise \end{cases}$
Consequence per Event	Empirically assigned values. See Table A-1 or Appendix A of Colvin, Karcz, and Wusk (2023).
Encounter Models	Related an environment of debris to expected close encounters at different orbits. • Model 1: OTPS reference model based on ORDEM. • Model 2: COMSPOC volumetric encounter model based on MASTER. • Model 3: LeoLabs kinetic-theory-of-gas model based on MASTER.
Baseline Debris Population	Counts from either MASTER (via LeoLabs) or from ORDEM via ODPO.
Baseline Satellite Population	UCS Satellite Database at the end of 2021. All active spacecraft included.
Satellite Sizes	Physical details were prescribed for five types of intact satellites (see Table A-5). For fragments, NASA's Standard Breakup Model (Johnson et al. 2001; Schuhmacher 2021) was used; the model estimates physical characteristics based on characteristic length. Each model discretized characteristic length differently.
Satellite Orbits	All orbits were effectively circularized, creating a simple particle-in-a-box model. Depending on the model, 10- or 25-kilometer altitude bins were used.
Launch Model	The spacecraft population was held constant, so the launch model immediately replenished any lost spacecraft. The rocket bodies used in the launches were ignored.
Collision Model	Collision probabilities were assigned from the encounter model, and the collision was simulated using NASA's Standard Breakup Model (Johnson et al. 2001).
Explosion Model	NASA's Standard Breakup Model was used to model the consequence of all explosions (Johnson et al. 2001). OTPS created its own probability-of-explosion model based on historical explosion rates.
Surface Degradation	OTPS assigned production rates to maintain or slightly increase the 1- to 3-millimeter populations for Models 1 and 2, or 150 and 0.2 pieces per m^2 per month, respectively.
Decay	Used the U.S. Standard Atmospheric Density Model. Ballistic coefficients were prescribed to intact objects and estimated for fragments using NASA's standard approach.

The modeling meets our goals for this study, enabling us to compare the risk-reducing actions in a simply and clearly manner and with sufficient confidence. The model does leave much to be desired in terms of being fully comprehensive, descriptive, and accurate. We identified areas in which we hope to see the modeling progress, both in our specific implementation and in the community writ large. The areas of fertile research for fundamental debris modeling include the following:

- Models to better predict the occurrence of a warning or maneuver given a simulation of the environment, particularly using a particle-in-a-box model.
- Models that better predict the probability of a mission-terminating event given a strike on a spacecraft. Current models that make this prediction work only for a specific spacecraft design, whereas effective modeling needs to better understand the distribution across representative spacecraft design. Improvement here will be important for better understanding the nature of orbital debris risk.
- Evolutionary and risk models that do not rely on an assumption of spherical debris. ODPO is working on expanding the geometries used to model debris. Improvements on accurately modeling the ballistic coefficients will be useful.
- We had to develop an evolutionary model to be able to predict the effects of mitigation actions. Ideally, researchers in the future will not need to develop their own models but can will be able to rely on open-source standards and variants for their needs. The published NASA standard models support these efforts, but an end-to-end model will help make high-level research easier and more consistent.
- Our traffic model is overly simplistic, but we also lacked principled alternatives beyond extrapolating the past launches. Further, several of the mitigation actions will likely have secondary effects in terms of where operators choose to launch, so progress in responsive launch models will be valuable to this research (e.g., see Rao and Letizia 2022).

We have also identified several relevant extensions of our work:

- **More accurate and precise cost.** This study did not make any improvements on the fidelity of the cost estimates from Phase 1 and continued to use the same coarseness for the new methods. Doing so was sufficient to make some initial findings, but further research is needed to confirm the current estimates and narrow the bounds to provide more actionable insights.
- **Action and actor combinations.** This study viewed effects at only the monolithic, ecosystem-level but hinted at potentially valuable combinations in risk-reducing methods and in applying actions to a subset of actors or debris. Further research that explores these dynamics may identify very valuable combinations or new rankings in the value of methods.
- **Time dynamics.** This study considered the growth of benefits over time but largely ignored many potential time dynamics, including the technology readiness level and advancement degree of difficulty for technologies, the phasing or application of one or more of the methods together, and different on-demand methods that react to events in the environment.
- **Exploration of the distribution.** This study and its model focused solely on the expected value of risk and risk-reducing actions. The findings can be informative but leave out a

wealth of potential futures and implications. The approach we took can and should be expanded beyond the deterministic, expected-value approach. This expansion could include stochastic methods and the implementation of defined contingencies.

Appendix B: Remediation of Debris

Debris remediation is any action that reduces the risks associated with orbital debris already in the environment. Approaches to remediation include removing large pieces of debris in LEO by tugging them to lower orbits for an uncontrolled or controlled reentry, nudging large pieces of debris away from a collision, removing small debris at scale, reviving defunct spacecraft for use in new missions, and recycling materials from debris to use as propellant or feedstock for in-space manufacturing. Remediation in geostationary orbit (GEO) (out of scope for this report) involves moving the debris into graveyard orbits or even installing devices such as solar sails on objects to completely eject them from Earth's orbit (so that they are not on a return trajectory).

In this study, we categorized remediation concepts according to the size of debris they target: >10 centimeters (tracked), 1–10 centimeters, and 1–10 millimeters. For the first two categories, we used the eight concepts analyzed in the Phase 1 study. We also added two methods that target 1- to 10-millimeter debris.

Summary of Phase 1 Findings

The prior study assessed eight concepts to remediate debris ≥ 1 centimeter. The current study included all of those concepts, as summarized in Table B-1. Colvin, Karcz, and Wusk (2023) includes detailed descriptions of the concept of operations (CONOPS) and the cost estimates for each of those concepts. In this appendix, we note where we made changes and refer interested readers back to Colvin, Karcz, and Wusk

Table B-1. Remediation Concepts From the Phase 1 Study

Debris Size	Type	Concept	Notes
1–10 cm	Remove	Ground-based laser	Debris ablation using ground-based lasers
1–10 cm	Remove	Space-based laser	Debris ablation using orbital lasers
1–10 cm	Remove	Sweeper in orbit	Orbiter plates that collide with small debris
≥ 10 cm	Remove	Tug to controlled reentry	Rendezvous, capture, and deorbit of debris
≥ 10 cm	Remove	Tug to uncontrolled reentry	
≥ 10 cm	Move	Lasers for just-in-time collision avoidance	Ground- or space-based laser nudging of debris
≥ 10 cm	Move	Rapid-response rockets for just-in-time collision avoidance	Rendezvous using rapid-launch capability
≥ 10 cm	Recycle	Debris into ΔV	Use of debris as propellant to alter ΔV

Sweeper

CONOPS

A number of sweeper concepts have been proposed, as discussed in the Phase 1 study. We define a sweeper as a wide-area spacecraft that makes direct contact with small debris to remediate it. In this study, we examined two types of sweepers. One type fully captures the debris upon contact, using a modified Whipple shield. For a discussion of Whipple shields, see Appendix C. The second type uses a thin sheet of material that absorbs energy from small debris as they puncture the sheet. The energy lost to the collision reduces the perigee of the debris, causing them to experience greater drag forces, which accelerate the deorbit of the debris. We call the two types of sweepers *Whipple sweepers* and *sheet sweepers*, respectively.

The CONOPS for each type of sweeper is essentially the same and very simple. A sweeper is placed in an orbit where it will cross paths with the millimeter-size debris that are to be removed. For this analysis, we assumed the sweeper would be placed in an equatorial orbit because the orbits of all debris pass through the equator twice per orbit. The sweeper loiters in that orbit while the millimeter-size debris strike the spacecraft. Once the orbit is cleaned, as evidenced by a large reduction in debris strikes, the sweeper moves to target debris in new orbits or simply deorbits itself. The DARPA Catcher's Mitt study roughly estimated that a sweeper might be able to catch 10 times more debris if it were able to actively sense and maneuver toward nearby debris, rather than just passively waiting to be struck. A maneuver capability may also be required because the wide area of the sweeper is likely to be struck and damaged by larger pieces of debris if it does not have some collision avoidance capability. Debris strikes on the sweeper could potentially form new small debris through ejecta, but in keeping with the rest of the study we omitted the debris-generating potential of the removal concepts.

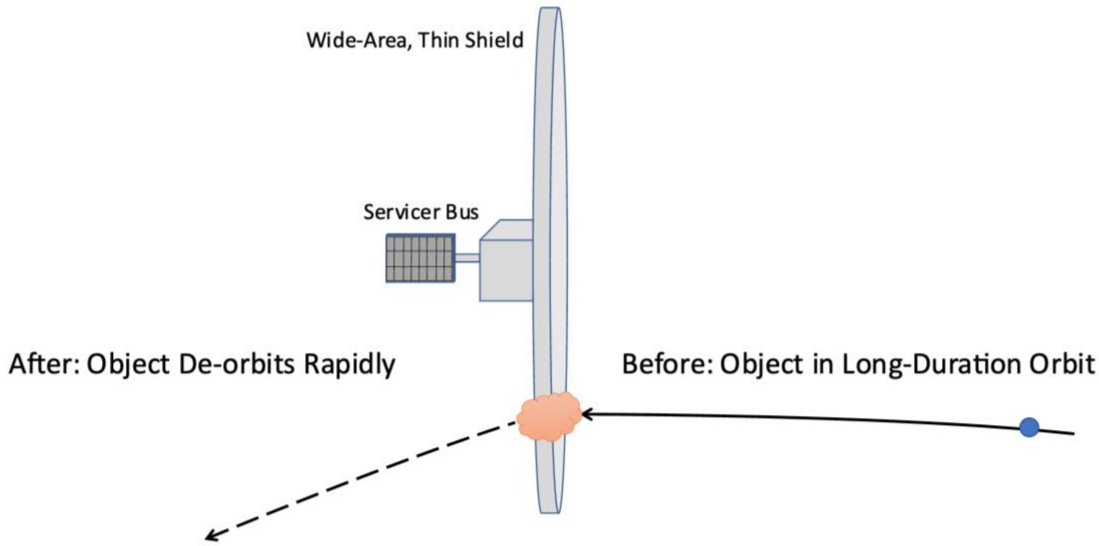


Figure B-42. Sweeper concepts. These concepts generally use a large pad of material to collide with small debris, thereby reducing the velocity of the debris so that it deorbits rapidly. Note: The figure and caption are from the Phase 1 report.

Efficacy

The Phase 1 study estimated that sweepers do not have a favorable cost-benefit ratio compared to other remediation methods; however, the analysis was severely limited. Specifically, the analysis investigated sweeping up to only centimeter-size debris, which is not the use case for which a sweeper is designed. By targeting centimeter-size debris, the mass of the sweeper was oversized because it had to survive impacts with debris as large as 10 centimeters (e.g., a 1U CubeSat). Likewise, there are orders of magnitude more debris in the millimeter-size range than in the centimeter-size range; consequently, Phase 1 underestimated the number of debris remediated. The current analysis attempts to remedy these shortcomings.

The efficacy of each sweeper concept depends primarily on two factors: the cross-sectional area of the sweeper and the flux of debris the sweeper will encounter at its operational altitude. To estimate the area of the sweeper, we assumed that a Falcon 9 vehicle will be dedicated to launching the sweeper. We then worked backward through the mass budget to estimate the maximum area of the sweeper. For the purposes of this analysis, the Falcon 9 is assumed to be able to carry roughly 20,000 kilograms to an equatorial orbit. We assigned the SSL 1300 as the bus to carry the sweeper. This bus is designed for use in GEO and is very large; however, we assumed that a wide-area shield will require a large bus to maintain attitude control and maneuver capability to avoid debris that may destroy the sweeper. The difference between the launch capacity of the Falcon 9 and the mass of the bus was assumed to be available for the shield. Table B-2 shows the masses and costs assumed in this analysis.

With the mass of the shield, we could estimate its area under various assumptions. For the Whipple shield sweeper, we used a representative area density of a Whipple shield, taken from the analysis in Appendix A. For the sheet sweeper, Petro and Talent (1989) provided an equation for calculating the mass of material needed in the pad. Their analysis indicates that the shield needs to change the velocity of the debris by only about 1% to effectively deorbit the debris. Specifically, the researchers reported that "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 delta-*v* of 1%, the reduction would be 93%" (Petro and Talent 1989). Table B-3 shows the area densities used for this study.

The maximum area of the sweeper shield is thus the mass of the shield divided by the area density. In reality, there must also be support mass to deploy the shield and hold it in place after deployment. To account for this mass, we assumed a mass packing factor (X): for every 1 kilogram of shield material, the system will need X kilograms of extra mass to support it. We had no point of reference for choosing this factor, so we allowed it to vary from 1 to 10. For a packing factor of 1, there is no support material and the entire mass budget of the shield can be divided by the area density to get the area of the shield. For a packing factor of 10, only 1/11 of the mass budget for the shield is converted into useable area, with the remaining 10/11 of the mass going to support and deployment structures. The resulting areas are shown in Table B-3.

Next, we estimated the number of debris that may be remediated. We did so by multiplying the area of the sweeper by the flux of debris at a representative altitude, here taken to be 800–850 kilometers. Estimates for the flux of debris at this altitude vary widely depending on the debris model used. ORDEM estimated an expected value of 5.4 pieces of millimeter-size debris per year per square meter at this altitude. Alternatively, LeoLabs assessed that debris below 5 millimeters are not meaningful threats to spacecraft; thus, LeoLabs' estimate for debris that are meaningful to clean up are those from 5 to 10 millimeters, the flux of which is about 1,000 times less than the ORDEM flux. The flux multiplied by the area gives the annual number of debris remediated. Multiplying by the lifetime of the sweeper gives the total amount of debris remediated, as shown in Table B-3.

Costs

The costs associated with the spacecraft are shown in Table B-2. The recurring costs for the bus and launch are anchored to actual market prices. However, the recurring cost of the shield is an optimistic guess, with an assumed cost of $10,000 per kilogram of mass. For context, the hardware cost of the bus is about $25,000 per kilogram. CubeSats cost about $50,000 per kilogram. However, these cost ratios are for full spacecraft. We optimistically assumed that the shields will cost less per kilogram than the bus because the shield is just one or more layers of material with some additional support structures. However, we did not have a point of reference for our estimate. The annual cost of operations for a civil science short spacecraft is about $7 million. We generously assumed that the operation costs for this—much larger—spacecraft will be somewhat less, perhaps $5 million per year.

Significantly, we were unsure what to assign for nonrecurring engineering (NRE) costs. Nothing of this size has been demonstrated in space or on the ground. The largest solar sail deployment in a ground test was recently completed by Redwire as part of its development of NASA's Solar Cruiser project, which is slated to launch in 2025. Redwire unfurled one quarter of a sail, which has an area of about 400 square meters. For symmetry, the total area of the Solar Cruiser will be 1,600 square meters in space. Alternatively, the iROSA photovoltaic arrays recently deployed on the International Space Station are each 110 square meters. With six already deployed and another two on the way, there will be 880 square meters of deployed wide-area technology on a single platform. The thickness of the sheet sweeper will be greater than the solar sail but likely less than the iROSA, so it seems likely that the sheet sweeper can be deployed via similar methods. We note that the sheet sweeper is a few orders of magnitude greater in total area than the current state of the art. Alternatively, the sweeper platform could be disaggregated into multiple smaller sweepers with much smaller buses and smaller areas per sweeper to reach a similar total area swept. For these reasons and the lack of a reasonable estimate for the cost, we set the NRE to zero with a caution that this effectively makes the low-cost to be a lower bound on the potential cost of the full system.

Table B-2. Cost of a Sweeper Spacecraft

Element	Mass	Cost
Hardware		
SSL 1300 Bus	4,700 kg	$125M
Shield	15,300 kg	$153M
Launch		$67M
Subtotal	**20,000 kg**	**$345M**
Operations ($5M/Yr for 5 years)		$25M
NRE		$0
Subtotal		**$25M**
Total		**$370M**

Finally, we divided the total system cost by the number of debris remediated to calculate the average cost per debris. Table B-3 contains our estimates for a range of assumptions about the total area of the sweeper and the number of debris remediated.

Table B-3. Efficacy of a Sweeper Spacecraft

Element	Sheet Low Cost	Sheet High Cost	Whipple Low Cost	Whipple High Cost
Area Density of Shield [kg/m^2][a]	0.18	0.18	9.0	9.0
Mass Packing Factor[b]	1	10	1	10
Shield Area [m^2]	42,075	7,650	850	154
Debris Flux @ 800–850 km [Collisions/Yr/m^2]	5.4	0.0013	5.4	0.0013
Debris Remediated per Year	228,863	10	4623	0.2
Debris Remediated Over Lifetime	1,144,313	50	23,117	1.0
Cost per Debris Remediated	$323	$7,390,800	$16,005	$365,844,615

[a] The area density of the Whipple shield is taken from Appendix C. The value for the sheet sweeper is calculated according to equation 7 in Petro and Talent (1989): Area Density = Mass $_{\text{Debris}}$ * ($\Delta V/V$) / [Area $_{\text{Debris}}$*(1-$\Delta V/V$)]. Note that $\Delta V/V$ is 0.01, or 1&. Also, the area of the debris is calculated assuming it is a 10-millimeter sphere.
[b] The packing factor accounts for the extra mass that is required to deploy and support the sweeper. For every 1 kilogram of shield material, the sweeper needs X kilograms of extra mass.

The costs provided are based on the assumption that the sweeper is mostly passive and unable to maneuver toward the debris it will remediate. Using the same logic as in the Phase 1 study, we optimistically assumed that an active sweeper can capture up to 10 times more debris; for context, the DARPA Catcher's Mitt study assumed that an active sweeper will get a three-times improvement. Further, the costs associated with the added delta-*v* and systems to track millimeter-size debris are unknown and possibly large. Optimistically setting these costs to $0 and allowing a 100-times improvement in debris capture suggests the cost of remediating millimeter-size debris cannot fall below about $30 per piece of debris.

Dust

CONOPS

The CONOPS and performance estimate for dust is based on the model described by Crabtree et al. (2013). They described a ring of micron-sized tungsten dust that is injected into LEO. This dust encounters small debris (<10 centimeters), decreasing the altitude of the debris. The order of magnitude of total mass of tungsten dust required is a function of revolutions before deorbit, revolution period, desired rate of debris descent, ballistic coefficient (mass-to-area ratio), dust drag magnification factor, and radial extent of the ring. The total lifetime of the dust ring is relative to the average size of each dust particle, with smaller particles resulting in a shorter lifetime.

- **Dust dispersal.** A spacecraft in a circularly polar orbit at 1100 kilometers disperses space dust into orbit in 4-hour intervals.
- **Dust ring formation.** In roughly 36 days, the dust ring is complete. The resulting ring has a thickness of approximately 30 kilometers.

- **Dust ring contact with debris.** The hypervelocity collisions with debris generate high-pressure shock waves, resulting in a large ΔV, which lowers the orbit of the debris.
- **Dust ring descent.** Over the course of the dust ring's lifetime, it decreases in altitude, ultimately creating a snowplow or sweeper affect that reduces the altitude of small debris that the ring encounters. For this mission scenario, we considered dust particles of 60 microns in diameter, resulting in a lifetime of 26 years, according to Crabtree et al.
- **Dust ring and debris reentry.** Ultimately, the dust ring and the small debris burn up upon reentering Earth's atmosphere.

Crabtree et al. concluded that the risk of penetration from these debris, and thus the risk of an MEC as defined in the study, should be very small but that the dust could lead to an unknown amount of surface degradation. In keeping with the methodology of the current study to model only the risk caused by MECs (i.e., not mission-degrading collisions) and the general approach of not assessing the potential negative impacts of other actions, we noted the potential for damage but did not carry it forward in the analysis. Spacecraft could also maneuver around the cloud.

Efficacy

Research on dust as a method of remediation is thin and driven by a single research group at the Naval Research Laboratory. Their results suggest that 20–40 tons of dust, in the size ranges of 30–60 microns, would be sufficient to deorbit most debris with a mass-to-area ratio[41] less than 5 kilograms per square meter from orbits of 1,100 kilometers and lower (Ganguli et al. 2012). We are unaware of a higher-fidelity analysis that estimates the proportion of such debris that could be removed; thus, for the purposes of this analysis, we generously assumed that all debris with mass-to-area ratios of 5 or less will be removed. To estimate how much debris is remediated, we first estimated the characteristic lengths of debris associated with a mass-to-area ratio of 5. The characteristic lengths can be combined with the estimated amount of such debris by altitude.

For a given mass-to-area ratio, the associated characteristic length may vary widely based on the assumed shape of the debris. For this analysis, we calculated lengths for debris that are rectangular prisms and solid spheres. For a solid sphere, the mass to area ratio can be written as

$$B = \frac{(4/3)\pi R^3 \rho}{\pi R^2},$$

where rho is the density of the debris and *R* is the characteristic length (L_C) divided by 2. Assuming the debris is made of aluminum and has a density of 2,700 kilograms per cubic meter, then L_C=3 millimeters.

Alternatively, if the debris is a rectangular prism with an aspect ratio α, we can solve for its dimensions by assuming x=y, and z=αx. With these assumptions, $x=3*L_C/(2+\alpha)$. For the area,

[41] Ganguli et al. (2012) referred to the mass-to-area ratio as the "ballistic coefficient"; however, this ratio is simply the mass divided by the area. A proper ballistic coefficient is the mass divided by the area and by the coefficient of drag.

there will be two faces with an area $x*x$ and four faces with an area of $x*z$. These equations can be used to find the average cross-sectional area. The mass-to-area ratio is thus

$$B = \frac{xyz\rho}{(2x^2 + 4xz)\ /\ 6}.$$

Substituting in L_C and α and assuming an aspect ratio of 10 yields a characteristic length of L_C = 5 millimeters.

NASA's ORDEM model estimates about 1.8 billion pieces of 1- to 2-millimeter debris at altitudes below 1,100 kilometers. The total amount of debris in the 2- to 5-millimeter range is 100 times less. In comparison, the MASTER model estimates around 21 million pieces of 1- to 2-millimeter debris and 6.7 million debris in the 2- to 5-millimeter range at altitudes below 1,100 kilometers. For the high-efficiency estimate, we used the ORDEM values; thus, 8.7 billion pieces of debris are effectively removed via injecting 20–40 metric tons of dust. For the low-efficiency estimate, we used the LeoLab assumption that debris below 5 millimeters do not pose a significant risk to spacecraft compared to the environment writ large; thus, on the low bound, no benefits are accumulated.

Cost

The costs associated with the spacecraft are shown in Table B-4. Our rough estimate of the cost was based on a paper with design considerations for such a spacecraft (Zedd 2014). Zedd stated that a single spacecraft is capable of deploying 10,000 kilograms of 30-micron dust. He further states that "the entire spacecraft might have a mass of 13,500 kg or more." We used an SSL 1300 bus to deploy the dust. The combined mass of the dust and the bus exceed Zedd's estimate of 13,500 kilograms. To allow for the packing inefficiencies of the dust, we assumed that the Falcon 9 will not have volume for further payloads, necessitating a dedicated launch for the spacecraft. Further, Zedd estimated that the spacecraft would remain in the orbit of the dust for a year "to estimate particle density and perhaps witness myriad collisions between tungsten particles and debris." Factoring in time for the launch and deployment of the dust, which we assumed will take about one year, the total system lifetime is assumed to be two years.

The current market price for tungsten powder does not appear to vary based on the size of the particles. For example, Atlantic Equipment Engineers sells 1- to 5-micron tungsten particles for $75 per pound ($165 per kilogram).[42] Tungsten Parts Wyoming sells tungsten powder for $70 per pound ($155 per kilogram), for both 45-micron and 150-micron tungsten powders.[43] Inframat Advanced Materials offers many sizes of tungsten powder between 1 micron and 20 microns for $92 per kilogram;[44] this is the lowest price we found during a cursory search on the internet. In

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[42] Atlantic Equipment Engineers, "Tungsten Powder," accessed March 13, 2024, https://micronmetals.com/product/tungsten-metal-powder-4/.

[43] Tungsten Parts Wyoming, "Tungsten Powders," accessed March 13, 2024, https://tungstenparts.com/product/tungsten-powder/.

[44] Inframat Advanced Materials, "Tungsten Powder, 99.95+%, APS 10-20 µm,"accessed March 13, 2024, http://www.advancedmaterials.us/74MR-0006.htm.

these cases, the price quotes are for only 10 kilograms of material, the largest quantity for which suppliers publicly quoted a price. For debris remediation, a bulk purchase of 20–40 metric tons will be required, presumably leading to a substantially lower average price per kilogram.

The prices quoted are also for bare metal powder, which is unlikely to be suitable for use in space. When two pieces of clean bare metal make contact in the vacuum of space, they bond permanently, which would cause the dust to clump into large particles or jam inside the deployment device. To avoid these issues, the dust will likely need some form of protective coating that presents bare metal-on-metal contact between particles. We have no basis for estimating the cost of this coating. Thus, for the purposes of our analysis, we used the current market price for 10 kilograms of pure dust ($155 per kilogram) to estimate the cost of the remediation dust. In effect, we assumed that the cost reductions from making a bulk purchase 1,000 times greater than used for the current market prices will offset the added costs associated with coating the dust.

Finally, we had no estimate for the NRE associated with this concept. As with the sweepers, we set the NRE to zero and again caution readers that setting the NRE to zero pushes our low-cost estimate toward a lower bound.

Table B-4. Cost for a Dust-Releasing Spacecraft

Element	Mass	Cost
Hardware		
SSL 1300 Bus	4,700 kg	$125M
Shield	10,000 kg	$2M
Launch		$67M
Subtotal	**14,700 kg**	**$194M**
Operations ($5M/Yr for 2 years)		$10M
NRE		$0
Subtotal		**$10M**
Total		**$204M**

Finally, we calculated the approximate cost per debris removed (see Table B-5). In our low-cost estimate, we assumed that only 20 tons of dust is needed to clean up the number of debris estimated by ORDEM at altitudes below 1,100 kilometers. For the high-cost estimate, we used the LeoLabs assumption that debris smaller than 5 millimeters are insignificant; thus, the cost per debris remediated is effectively infinite because no debris greater than 5 millimeters are meaningfully remediated. These per-debris estimates are provided as potential reference points; however, they were not used explicitly in the analysis. Instead, for each encounter model we removed all 1- to 5-millimeter debris from altitudes below 1,100 kilometers in the first year of the simulation. In subsequent years, the 1- to 5-millimeter debris population are gradually replenished as explosions, collisions, and surface degradation occur.

Table B-5. Total Cost of the Dust Concept

Element	Dust Low Cost	Dust High Cost
Total Dust Dispensed	20 tons	40 tons
Number of Spacecraft Needed	2	4
Cost per Remediation Spacecraft	$204M	$204M
Total Cost	**$408M**	**$816M**
Number of Debris Remediated	**8.7B**	**0**
Cost per Debris	**$0.05**	**N/A**

Appendix C: Mitigation of Debris

For this report, we define *debris mitigation* as actions that designers, planners, and operators take to limit the creation of debris from a spacecraft during and after its operations. This definition matches the definition of the U.S. Orbital Debris Mitigation Standard Practices (ODMSP) for activities limiting "the generation of new, long-lived debris by the control of debris released during normal operations, minimizing the debris generated by accidental explosions, the selection of safe flight profile and operational configuration to minimize accidental collisions, and the disposal of space structures" (U.S. Government 2019, 1).

A spacecraft can generate new debris in several ways:

- **Fragmentation.** The spacecraft collides with a piece of debris or explodes, generating or even turning into a cloud of smaller debris.
- **Space weathering.** Exposure to the space environment, such as strikes from micrometeoroids or irradiation, cause the shedding small debris.
- **Mission-related debris**. The planned course of the mission might include releasing part of a spacecraft, generating new debris.
- **End of life**. Once a spacecraft is no longer active, it will become a derelict—a large piece of debris. The spacecraft's end of life will occur through planned obsolescence or via a malfunction or failure, such as a lethal strike from small debris.

Therefore, a spacecraft can generate debris while active and after its end of life. Actions to reduce this generation potential either reduce the probability of one of the generation events (e.g., design a mission to not intentionally release any debris) or lessen the consequences (e.g., move the spacecraft to a different location at its end of life). Spacecraft designs can include numerous mitigation strategies, including avoiding collisions with large debris and other spacecraft, selecting less risky orbits, designing missions to not intentionally release debris, and designing spacecraft to be less susceptible to space weathering. Three additional methods stand out as leading contenders:

- **PMD.** At the end of life, the satellite is moved to a safe orbit or one in which the spacecraft will deorbit quickly; we split this strategy into two subcategories: (1) using the onboard propulsion system and (2) using onboard drag-enhancing devices.
- **Spacecraft shielding**. A clever design is employed or extra shielding is added to reduce the probability of a premature death from small debris.
- **Explosion mitigation.** Steps are taken to lower the probability that a spacecraft will explode during and after operations.

This section explores and estimates the costs of accomplishing these three mitigation methods.

PMD: Propulsion

Once a satellite reaches its end of life, it continues to generate debris as a derelict object. The primary way to address the potential for debris generation is to place the defunct satellite in a disposal orbit that either causes the spacecraft to deorbit sooner or moves it away from operational spacecraft. Disposal-orbit options include directly deorbiting the satellite, placing it in an orbit that will decay more quickly, or placing it in a graveyard orbit (the last is out of scope in this study, which focuses on LEO).

The concept of PMD often includes other actions done to the spacecraft at the end of life to decrease generation risk, such as passivating stored energy sources to reduce the risk of explosion. However, this section considers only the action of moving the satellite to a disposal orbit. Several methods can be used to accomplish this end-of-life disposal, but this section considers only when the satellite uses its own propulsion system to move itself. A following section will extend the analysis to other disposal methods.

CONOPS

In a propulsive disposal, a satellite uses its onboard propulsion system to move itself to a disposal orbit that, in theory, reduces the risk of generating new debris or the consequences of the newly generated debris. Thus, this concept applies only to spacecraft with maneuver capability.

Spacecraft in LEO can dispose of themselves by maneuvering to a storage zone between LEO and GEO or by lowering themselves into an orbit which enables them to deorbit more quickly. Because the spacecraft in this study are in LEO altitudes below 1,500 kilometers, we dealt exclusively with the latter. In this domain, spacecraft usually place themselves in an orbit named by the number of years it should take the spacecraft to deorbit. So, a 25-year rule moves spacecraft into an orbit from which it will take around 25 years to deorbit. This new orbit is often circularized (e.g., 650 kilometers for a 25-year rule) but could be highly elliptical with an equivalent lifetime. Staying with our circular assumptions, we focused on moving into a new circular orbit. Table C-1 illustrates the disposal altitudes we used for various deorbit timelines.

Table C-1. PMD Altitudes Used in the Analysis

PMD *N*-Year	Assumed Disposal Altitude
25	650 km
20	625 km
15	600 km
5	550 km
1	450 km
0	300 km

The spacecraft needs to move itself from its operating orbit into a new disposal orbit representing its PMD policy. Doing so requires a propulsive maneuver including propellant to burn. We assumed that the spacecraft will execute two Hohmann transfers with an instantaneous burn. For example, to move from 1,500 kilometers to 550 kilometers requires meters per second of delta-*v*. The required delta-*v* is computed between all satellites and their intended destinations. If a satellite is not maneuverable or is already operating below the disposal altitude, it is left in place (i.e., delta-*v* of 0).

In calculating the fuel required to execute this maneuver, we leaned heavily on the analysis conducted by McKnight, Cassidy, and Hoskins (2021). In determining a lower bound, we assumed that all spacecraft are equipped with an electric propulsion system with a specific impulse of 1,500 seconds.[45] For the upper bound, we assumed a monopropellant system with a specific impulse of 230 seconds. The dry mass of each satellite is prescribed in section III of Appendix A. Finally, we assumed that each spacecraft requires 21 meters per second of delta-*v* for applications other than PMD. The total fuel added by the PMD requirement, then, is the fuel for the PMD maneuver plus the additional fuel to perform the other functions required by that new weight. Examples of the fuel requirement are shown in Table C-2.

Table C-2. Examples of Estimated Fuel Requirements for Disposal

Satellite	25 Years, 650 km	5 Years, 450 km	0 Years, 100 km
Large @ 800 km	11.4–54.0 kg	27.2–132.0 kg	57.1–287.5 kg
Medium @ 800 km	4.9–23.4 kg	11.8–57.2 kg	24.7–124.6 kg
Small @ 800 km	1.7–8.1 kg	4.1–19.8 kg	8.6–43.1 kg
Micro @ 800 km	0.15–0.72 kg	0.4–1.8 kg	0.8–3.8 kg

Not all spacecraft will dispose of themselves. Spacecraft already at or below the disposal altitude will be left in place. Even those that are maneuverable and above the disposal altitude may not dispose of themselves because of unsuccessful disposal maneuvers or noncompliance. We assumed a 90% PMD rate implies and that all spacecraft attempt to comply and thus pay to attempt to comply but that the noncompliant portion is simply unsuccessful.

Cost

We assumed that the entire PMD cost comes from launching the additional propellant needed to conduct the maneuver. This assumption, of course, is naïve. It ignores potential costs such as a larger tank and procuring the actual propellant, as well as certain alternatives, such as switching to

[45] To calculate the delta-*v* required for the Hohmann transfer, we assumed an efficient instantaneous burn, which is not close to realistic for electric propulsion. To compensate for the slower electric propulsion maneuver and thus the extra thrust required, we multiplied the required delta-*v* by 1.4.

electric propulsion from chemical propulsion. It was our hope to bound the true cost between all spacecraft using electric or monopropellant propulsion.

The cost per spacecraft is the mass of the required fuel multiplied by the assumed launch cost ($5,000 per kilogram). As previously discussed, the mass of fuel is weighted by the probability of compliance. Figure C-1 illustrates the range of costs.

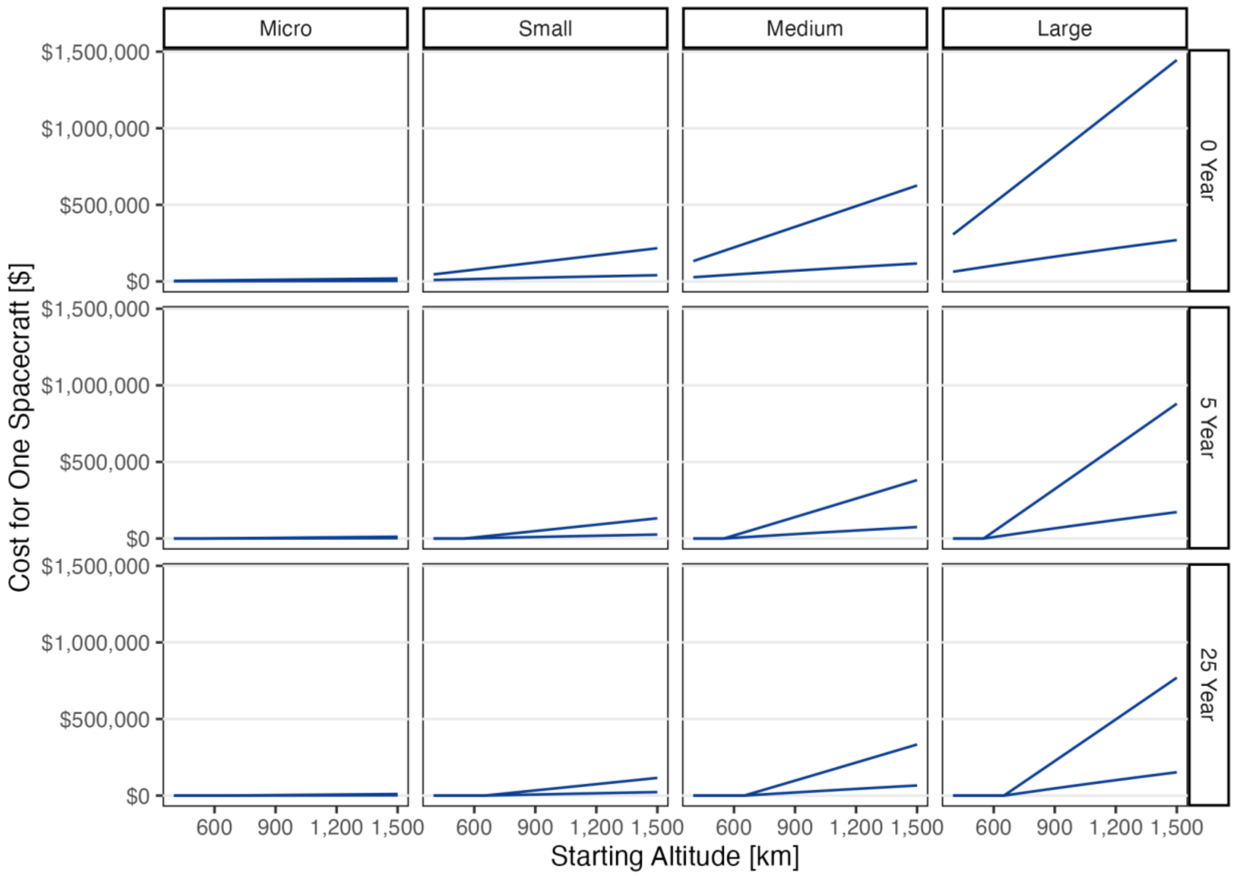

Figure C-1. Estimated cost per spacecraft to maneuver to disposal.

Because the spacecraft in our model are replaced at the end of their lives, this PMD cost is reoccurring. To account for this reoccurrence, we amortized the cost per spacecraft over its lifetime; on average, it will cost $TOTAL / LIFETIME per year.

PMD: Attached Tether or Drag-Augmentation Device

As an alternative to a satellite disposing of itself using its propulsion system, a satellite could decrease its deorbit time by increasing its drag. Specifically, a satellite might carry a tether or drag sail, which it could deploy at the end of life.

CONOPS

In this attachment concept, a satellite carries a stored tether or drag sail throughout operations. Once operations are complete, the satellite deploys the device, thereby increasing its cross-sectional area and ballistic coefficient. Doing so causes the satellite to deorbit more quickly—for example, meeting one of the deorbit rules explored in the previous section.

This concept has several major differences from the propulsive options. First, the satellite still has to transit all the altitudes below it to dispose of itself, albeit at a faster rate. The risk it incurs and causes at these intermediate altitudes is increased by the greater size of the spacecraft; the larger size is expected to cause more collisions and potentially more warnings and maneuvers.

Second, this concept relies more on drag (and our model of it) than the propulsive option does. Specifically, the size that is chosen for the tether or drag sail must work within the environment. A smaller device can be more effective by using a tether that can benefit from electrodynamic forces, especially if active electrodynamic drag can be induced. For this study, we considered only the passive drag induced by the devices.

The appropriate size of the tether or drag sail is determined by calculating the additional cross-sectional area needed to meet a ballistic coefficient that will deorbit the satellite within the desired timeframe.[46] The calculations are presented in Table C-3.

Table C-3. Example Estimates of Drag Device Requirements

			25-Year Rule		**5-Year Rule**	
Satellite	Original BC [kg/m^2]	Altitude	BC Required [kg/m^2]	Drag Area [m^2]	BC Required [kg/m^2]	Drag Area [m^2]
Micro	10	600	62	N/A	14	N/A
		700	15	N/A	3	2
		800	4	1.4	1	8
Large	50	600	62	N/A	14	29
		700	15	26	3	208
		800	4	151	1	662

Note: *BC = ballistic coefficient*.

Cost

The cost depends on the hardware cost of the drag device and additional launch mass. For the drag sail, we assumed that the mass and hardware costs increase proportionally with area. The closest launched analog here is solar sails, of which JAXA's IKAROS solar sail appears to be the largest. Each 14 square meters of the sail was about 1 kilogram (196 square meters for 14 kilograms), although a ratio of 12:1 might be a more conservative assumption (Fuller, 2021). The total cost to develop the project was reportedly $15 million (Phys.org 2010), which is on a similar

[46] $BC_{required} = \frac{M}{c_d(A_{og}+A_{supp})}$, so $A_{supp} = \frac{M}{BC_{required}*c_d} - A_{og}$. In theory, the c_d should change, but in lieu of a way to estimate that new coefficient, we used the original the c_d: 2.2.

order of magnitude with previous NASA estimates ($25 million) for a solar sail propulsion flight system (Johnson n.d.). It likely that a simple drag sail, without propulsion or instruments, would be less expensive. At the extreme low end, a student team out of Brown University attached a drag sail to a satellite for $30 (we used $50); the size was about 0.25 square meters.

For the tether, we similarly assumed that the mass and cost scale with the length (i.e., area) of tape. A 70-meter tape (×0.15 meter for 10 square meters) used in the DRAGRACER, PROX-1, and NPSat-1 experiments weighed about 1 kilogram, although longer tapes would likely show a better ratio, given the fixed attachment hardware. We assumed a ratio of 10:1 is the low point and a ratio of 12:1 is a more optimistic guess. Terminator tape reportedly retails for $50,000–$75,000 (we used $80,000) (Aerospace America 2020), although the material costs are sufficiently low to potentially enable 70-meter unit costs as low as $5,000.

Table C-4. Costs of Drag Devices

Device	Areal Mass [kg/m^2]	Hardware Costs per Area [$/m^2]	Total Cost per Area [$ / m$^{2]}$
Drag Sail	1/12–1/14	$40–80,000	$400–$80,400
Tether	1/10–1/12	$500–$8,000	$915–$8,500

Spacecraft Shielding

The majority of debris are too small to be tracked and avoided. These debris pose some probability of striking and damaging the spacecraft. A small debris strike might do the following:

- Hit but not damage some part of the spacecraft. In theory, debris of a particle size, energy, and momentum could cause damage to all components of a spacecraft. A sufficiently large strike might be required to break a structure apart, while a small impact might break a sensitive component.
- Cause damage that affects but doesn't end the performance of a spacecraft. Strikes to solar arrays might lower the power draw, and dents in a telescope mirror might lower performance but will not cause lethal damage.
- Be lethal to the spacecraft or cause a loss of mission. Debris that energetically strikes a propulsion tank might take out the entire spacecraft, and debris that hits a sensor might eliminate the main scientific impact.

Only the last item poses a direct risk of generating new debris by disabling the spacecraft (since we are considering surface degradation separately). Thus, in shielding the spacecraft, we focused on protecting components critical to the life and maneuverability of the spacecraft (but not necessarily its mission). These components include the propulsion tank, batteries, flight computer, cable bundles, and communications equipment, among others.

Increasing the shielding has two potential implications for our analysis: (1) a better shielded satellite will suffer less harm from debris, thus affecting the expected consequence of the orbital debris environment writ large, and (2) a better shielded spacecraft has a better chance of making it to PMD and avoiding accidental explosions during the postmission phase, thus mitigating the creation of new debris. These consequences are not independent.

In this study, we defined *shielding* as additional material that serves the sole purpose of protecting the spacecraft from micrometeoroid and orbital debris. Clever designs can use existing hardware to protect sensitive components, but sometimes more layers of protection need to be added. The additional material can defend against relatively large projectiles; the U.S. modules on the international space station are shielded from debris up to 1 centimeter. The mass of the shielding increases—typically exponentially—with the level of protection. So, in practice, level-of-protection requirements involve a tradeoff between risk and mass.

CONOPS

In this study, spacecraft were shielded by adding layers of additional mass that absorbs the energy of the impact and prevents the debris from penetrating into the spacecraft. The added mass contributes to increased launch costs and is generally seen as more burdensome than using the bus as a natural shield. The amount of added shielding mass varies depending on the expected debris fluxes at the chosen orbit, the largest size of debris that are prevented from penetrating, the architecture and materials of the shielding, and the cross-sectional area of the vulnerable subsystems being protected. The mass (and cost) of dedicated shielding depends on the area that requires shielding and the protection level that shielding needs.

Regarding the area of the spacecraft requiring dedicated shielding, some critical components may not be able to be protected using the bus, and others might require additional shielding. Since each spacecraft is each unique, we were unable to find a consensus on the percent of a spacecraft's surface area that typically requires shielding, nor were we able to find analyses that included a range of vulnerability for multiple spacecraft. To cover a conservative range of options, we used past designs—namely, JPSS (Squire et al., 2015) and Landsat-9 (Ryan 2022)—to inform a wide range of vulnerability estimates. These spacecraft plus, frankly, a basic guess resulted in us deciding that a vulnerability of 5%–25% of the surface area requires additional shielding. Note that we are referring to surface area, not the percent of the ram-facing direction of the collision area.

Regarding the protection level required, in general the shield mass increases exponentially as the protection level required increases (NASA 2009). The protection level is often characterized by the thickness (i.e., areal mass in kilograms per square meter) required to stop a sphere of material traveling at average relative velocities (e.g., 10 to 12 kilometers per second). Different shielding types have more or less areal mass to stop the same projectile, for example some of the more advanced shielding taking up much more volume in exchange for mass efficiency.

The actual effectiveness of shielding and the protection level required can vary. For the former, a spacecraft designer may opt to use more or less mass-efficient shielding because of availability or volume constraints. The protection level varies by the kinetic energy and momentum of the particles, so higher-velocity or higher-density particles have greater penetrating power. As such, a given protection level is usually designed to stop a certain percentage of projectiles. In our case, we assumed that a certain shielding level stops all projectiles below a certain characteristic length. To account for the varying thickness that may be required, we bounded the areal mass using medium- and high-density particles. Figure C-2 shows our assumed relationships.

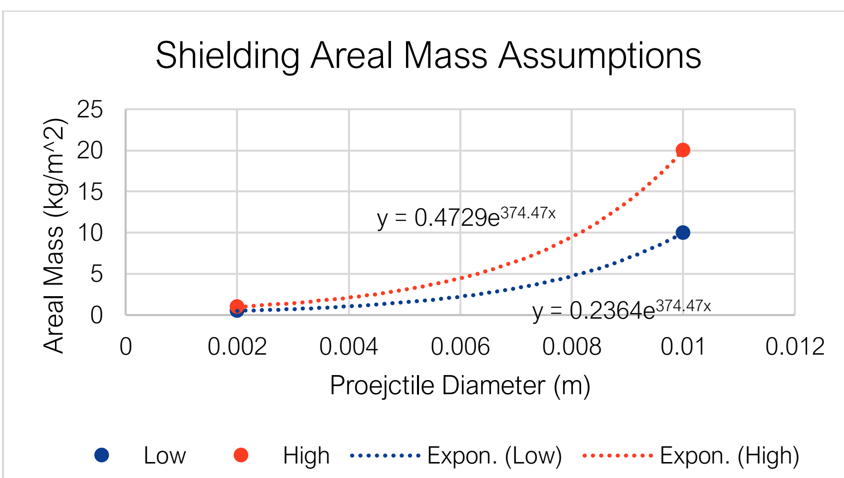

Figure C-2. Areal mass assumptions based on protection level.

Based on past analysis and conversations with experts, we assumed that shielding with an areal mass of 0.5 kilograms per square meter can stop a 2-millimeter-diameter aluminum sphere and that 1 kilogram per square meter can stop a 2 millimeter-diameter steel sphere. We used the medium- and high-density assumptions as high and low bounds for the shielding requirements. The centimeter range contains far fewer high-density particles, so we created bounds based on the range of shielding options. Using estimates generated in creating shielding for the International Space Station, we determined that stopping a 1-centimeter projectile requires shielding between 10 and 20 kilograms per square meter (multishock vs. stuffed Whipple (NASA 2009). We interpolated between these two points by using a natural exponential; the resulting shielding masses are shown in Table C-5.

Table C-5. Required Shielding Mass

Debris Size	Areal Mass [kg/m^2]	Micro Satellite Mass [kg]	Large Satellite Mass [kg]
2mm	0.5–1	0.006–0.06	0.5–5
3mm	0.7–1.5	0.009–0.09	0.7–7.5
5mm	1.5–3.1	0.02–0.2	1.5–15
1cm	10–20	0.13–1.3	10–100
2cm	42–85	0.5–5	42–420

Note: The surface area of the micro and large satellites in this example come from the standard satellite sizes as described in Appendix A (e.g., 0.25 square meters for micro satellites and 20 square meters for large satellites).

Cost

An uncertain contributor to the cost of shielding is the time needed on the spacecraft to add the material to the spacecraft. In the past, adding tens of kilograms of shielding has cost millions of dollars. Ideally, if shielding is considered early in the process, the “touch-time” cost will be negligible. To include the potential cost of applying the shielding, we added $100,000 per kilogram to the upper bound (based on past NASA missions) and left the lower bound at $0.

We also assigned a cost from the marginal launch cost of getting the added shielding to orbit. Again, our decision was hugely naïve: Often, shielding may fit within the existing mass budget and represent no real added cost. Further, the decision ignores the time, effort, and materials spent in designing the shielding solution (nonnegligible but very difficult to price). The launch cost was simply the best way for us to assign a cost. As we did elsewhere in the report, we assumed the launch cost is $5,000 per kilogram. Likewise, we repeated the cost for each new satellite launch. Thus, we amortized the cost over the lifetime of each satellite and made the cost a recurring expense.

Explosion Mitigation

Spacecraft store energy onboard in batteries and propellant tanks. Under certain stimuli, this energy can be released dramatically, essentially causing the spacecraft to explode. Such explosions are responsible for a large portion of the current debris population.

Fragmentations can be caused by a number of events. DISCOS contains the following causes:

- **Accidental.** Subsystems with design flaws that ultimately resulted in breakups.
- **Aerodynamics**. A breakup most often caused by an overpressure resulting from atmospheric drag.
- **Deliberate.** All intentional events, including ASAT tests and planned detonation.
- **Electrical**. An electrical-related explosion, often the overcharging and subsequent explosion of batteries.
- **Propulsion.** Explosions caused by the stored energy in propulsion-related systems.
- **Anomalous**. The unplanned separation of one or more detachable objects each of which remain essentially intact.
- **Unconfirmed/unknown.** Cause not yet known, including because information is lacking.

In this analysis, we focused on electrical and propulsive explosions. Appendix A contains an analysis of how often these explosion events occur and the probability of explosion for any given satellite. The final probabilities are shown in Table C-6. Over 10 years, these estimates sum to 1.2 explosions per year. This benefit will increase with time as explosions continue to be avoided for every year the satellite is active.

Table C-6. Explosion Rates and Probabilities

Object Type	Event Type	Probability per Year	Total per Year	Percent During Operation	Active Total	Derelict Total
Payload	Electrical	0.009%	0.03%	41%	0.013%	0.017%
	Propulsion	0.002%		40%		
	Unknown	0.02%		65%		
Rocket Body	Electrical	0%	0.06%	100%	N/A	0.06%
	Propulsion	0.04%		0%		
	Unknown	0.02%		0%		

Since our analysis did not include the addition of new rocket bodies to the environment, we focused on mitigating the risk from the explosions of payloads (i.e., active and derelict satellites).

CONOPS

The risk of explosion must be managed and considered in two distinct stages for two subsystems. During operations, the electrical and propulsion systems will be used and it will be virtually impossible to eliminate the risk of explosion. The ODMSP standard for explosions during mission operations calls for an explosion probability of less than 1 in 1,000 for each spacecraft and upper stage (excluding any explosions caused by a small strike). Although the risk can never be eliminated, it can be reduced through cautious designing the spacecraft and operating it within its designed limits (particularly thermal).

When the spacecraft is no longer operational, any energy remaining on the spacecraft poses the risk of explosion. Dealing with this energy is termed *passivation* and is a crucial part of PMD. This process can involve *hard passivation*, in which all energy is depleted and cannot be regenerated, or it can be *soft passivation*, in which any extent energy or regeneration potential is made safe.

During spacecraft operation and after disposal, a battery may explode if it is overcharged or experiences an event (e.g., a debris strike) that causes thermal runaway. Mitigation concepts during operation typically require (1) power management systems that avoid overcharging and (2) shielding that protects against debris strikes. After a spacecraft is no longer operating, its electrical system should be hard passivated by disconnecting the electrical power source from the power distribution system or should be soft passivated by using methods such as disconnecting the batteries. The ability to disconnect the power source adds a single point of failure to the system, increasing mission risk. This mission risk can be partially mitigated through techniques such as disconnecting relays and not uploading the disconnect commands until passivation, but zeroing out the risk of postdisposal electrical explosions appears to require taking on some level of failure risk.

An alternative to these options is to use segmented batteries, making the batteries robust to thermal runaway (e.g., MMOD strike or arcing). The electrical system would still need to be protected from overcharging, but the addition of redundant switches could, in theory, reduce the probability of electrical explosion to zero. According to conversations with experts, it is safe to assume that the implications of a segmented battery would be double the battery mass. Most satellite designers will be unlikely to opt for this heavy of an option, but it gives us a robust CONOPS to virtually eliminate electrical-explosion risk during and after operations. The estimated range of added mass for spacecraft is summarized in Table C-7.

Table C-7. Battery Mass for Eliminating Electrical Propulsion Risk

Spacecraft Size	Additional Battery Mass [kg]
Micro	0.5–1
Small	12.5–25
Medium	33–65
Large	75–150

Note: We estimated that 5%–10% of the dry mass is the battery mass, relying on the power percentage in McKnight, Cassidy, and Hoskins (2021) and the battery portion of that subsystem in Kenny (1990). The dry mass is presented in Appendix A.

The propulsion system poses less of the total explosion risk for payloads (see Table C-6). The propulsion system may explode during operation because of a component failure, an MMOD strike, or thermal cycling. It is currently unclear what additional steps could be taken or what technology could be added to reduce the risk of explosions during operations. At the end of life, a spacecraft's propulsion system can be passivated by depleting the system of all propellant (hard passivation) or most propellant (soft passivation). A current rule of thumb for soft passivation is to reduce the existing tank pressure to lower than 15% of the burst pressure. The propellant can be released by using it all (either in PMD burn or in a fuel-wasting maneuver), somehow opening the system to allow the propellant to leave, or adding pyrotechnic valves specifically for releasing propellant.

Conversations with experts led to the CONOPS of adding pyrotechnic valves to the system, either as a flow orifice to vent the pressurant or as a valve linking both sides of a bipropellant system. Two experts estimated the costs of the hardware (valves and latches) as $10,000–$150,000. This solution would remove only the risk of a postmission propulsion explosion. The solution would also likely add some measure of mission risk, which we omitted in this analysis.[47]

In sum, our example CONOPS includes implementing a segmented battery system and adding passivation valves to the propulsion system. We assumed that doing so completely eliminates the explosion risk for electrical systems and the postmission explosion risk for propulsion systems. This CONOPS is only one of many potential CONOPS but should serve as a good starting place for a follow-on study.

Costs

We attempted to quantify the cost of mitigating electrical system explosions by estimating the launch cost ($5,000 per kilogram) associated with the additional battery mass. For the propulsion system mitigation, we took the expert estimates as the full costs of adding the hardware, including materials, testing, and launch. The total costs are summarized in Table C-8.

Table C-8. Explosion Mitigation Cost per Satellite

<table>
<tr><th>Satellite Size</th><th>Electrical Mitigation Cost</th><th>Propulsive Mitigation Cost</th></tr>
<tr><td>Micro</td><td>$3K–$5K</td><td rowspan="4">$10K–$150K</td></tr>
<tr><td>Small</td><td>$63K–$125K</td></tr>
<tr><td>Medium</td><td>$163K–$325K</td></tr>
<tr><td>Large</td><td>$375K–$750K</td></tr>
</table>

As with the other mitigation options, the costs must be repeated for each new satellite launch. Thus, we amortized the cost over the lifetime of each satellite and made the cost a repeating expense.

[47] An alternative upper bound could involve increasing the thickness of the propellant tanks. For example, the thickness might be great enough that the operating pressure is still less than 15% of the burst pressure. This action could conceivably eliminate any propulsion-burst risk when coupled with normal propulsion-system best practices. However, given the incredibly high cost of such a solution, we chose to leave the risk of an operating explosion unmitigated and to use the valves for the postmission passivation.

Appendix D: Tracking of Debris

Tracking 1- to 10-Centimeter Debris

Existing radars in the Space Surveillance Network (SSN) have the capability to detect debris within the 1- to 10-centimeter range, but it is unclear how many can track debris of this size. Detection is useful for understanding the debris environment from a statistical perspective; tracking enables orbit determination, conjunction assessment, debris remediation activities, and active satellite avoidance maneuvers. Although the benefits are clear, maintaining an accurate catalog of 1- to 10-centimeter debris would be challenging because of the number of debris. Current estimates suggest approximately 1 million pieces of centimeter-size debris are in orbit, more than 27 times the >10-centimeter population of approximately 36,000 objects (ESA Space Debris Office 2023). The large number of 1- to 10-centimeter debris combined with the frequency of passes needed to maintain custody of the objects requires a much larger capacity for data collection, processing, and storage than the current catalog requires. In addition, the smaller size drives greater instrument sensitivity and results in reduced detection ranges.

Building and maintaining a catalog of centimeter-size debris involves initially detecting objects, predicting objects' future locations via orbit determination, and completing follow-up measurements based on the objects' expected paths. Detection data must be converted from a radar return or a streak on an image to position and velocity information using a variety of signal processing tools. In predicting the orbit and future location, influences such as drag and solar radiation pressure must be estimated, introducing potentially large uncertainty. This prediction capability is necessary to determine whether the measure represents a newly seen object or is associated with an object that has already been catalogued. The uncertainties that accrue in the time after detection and the uncertainty in the detection itself drive revisit times. Thus, the characteristics of the debris, the detection system, and the detection-processing capabilities all contribute to the efficacy of the tracking system, the number of required detection elements, and the overall system cost. In turn, improvements in detection, signal analysis, and environmental modeling can contribute separately or together to the construction of a centimeter-debris catalog.

New algorithms can improve the interpretation of raw data into tracks and the correlation of tracks of uncatalogued debris. There is considerable literature on the topic, and AI/ML may continue to offer advances beyond physics-based calculations. Over the next four years, effort will be focused on improving data processing for tracking centimeter- and millimeter-size debris as part of the Space Debris Identification and Tracking (SINTRA) program being conducted by IARPA. SINTRA has set a goal for its participants to track debris down to 1 millimeter (IARPA 2023).

Inputs into prediction algorithms, such as the fluctuation in drag and the effects of solar radiation pressure, increase orbit prediction uncertainty. Drag is a function of atmospheric mass density and the ballistic coefficient of the debris, and drag is particularly impactful on debris trajectories in lower LEO (Emmert 2017). Small pieces of debris are particularly susceptible to orbit changes via drag because of the high surface-area-to-mass ratios of these debris. Atmospheric density models are commonly quoted as having around 10%–15% error rates, but this estimate is derived from a 2008 study and may have improved in the years since (Vallado 2008). Mass-density models can be improved via collecting data from accelerometers and neutral mass spectrometers onboard satellites and by examining trajectories (Emmert 2015; Sang et al. 2012). Solar radiation pressure also is particularly influential on small debris, again because of the high surface-area-to-mass ratio of these debris. Improving the capability to predict the extent to which these effects influence debris could lower the frequency with which debris must be revisited to maintain object custody.

The optimal system to initially find small debris is not necessarily the same as the optimal system to revisit (or maintain custody of) small debris and update cataloged orbits. Initial detection benefits from a large field of view so that more new objects will cross the sensor. Because the direction of the objects is not known in advance, passive collectors (those that do not move with a specific piece of debris), work to collect a streak of data. Active sensors that follow the piece of debris are able to capture more precise data than passive systems and are therefore preferred once a piece of debris has been catalogued. Some systems, such as Space Fence, may contain both capabilities, whereas others are optimized for one approach. Because of the differing system requirements, tracking may be best completed with a heterogenous mix of sensors, some optimized for initially detecting debris and some for updating the catalog.

Even within one function (catalog production or maintenance), uniform systems of sensors probably do not provide the best capability. This analysis may be conservative in its costs for a centimeter tracking network because the analysis does not explore options to combine sensor types into complementary suites. For example, radar is best for detection of debris in LEO, whereas space-based lasers and optical systems tend to focus on and improve the precision of orbit estimates. The SSN takes advantage of these strengths by employing radar to monitor LEO activities and optical sensors to monitor GEO activities.

Orbit determination may be achievable with optical, laser, or radar measurements taken from the ground or from space. There is not one clearly preferred operational sphere for this activity. Ground systems are cheaper and more modifiable but are hindered by atmospheric effects. Space systems may have better illumination but are repair- and mass-limited and require much more responsive optics for varying ranges. For this study, we considered the following four architectures, which vary in their use of the ground and space systems: a ground-based laser network, a ground-based radar network, a space-based optical stare / laser chase satellite system, and a ground-based optical network.

Ground-Based Laser Network

CONOPS

Laser ranging is commonly used to gather information on the position and velocity of active satellites. This concept proposes building a global network of laser stations that can range centimeter-size debris frequently enough to maintain custody of them. The CONOPS is as follows:

- **Detect new debris**. A radar or passive optical system detects new debris.
- **Add debris to centimeter-size catalog**. A laser measures and ranges the debris, providing accurate position and velocity measurements to do orbit determination. Once orbit is determined, it is added to the catalog or associated with a previously catalogued object.
- **Maintain catalog**. Lasers from the network periodically range the debris in the catalog. The debris are ranged frequently enough that the uncertainty in the orbit of the debris allows the laser to dead reckon it's the predicted position of the debris and find the debris through executing a modest search. If the uncertainty in the orbit of the debris grows large enough, the laser search times may become unacceptably long.
- **Remove deorbited objects from the catalog**. If the objects are low enough that they deorbit, they are removed from the catalog. Likewise, if an object unexplainably disappears from the catalog, it may have been involved in a collision and is removed from the catalog.

Efficacy

We based our analysis on DLR's LARAMOTIONS concept (Scharring et al. 2021), which uses a global network of ground-based laser stations. These stations would use lasers with nanosecond pulses and pulse energy ranging from tens of millijoules to 2 Joules. As described in the CONOPS, the debris will be revisited frequently enough that the laser system can effectively dead reckon to find the debris at any time of day or night. The revisit rate for a laser system is a function of altitude, with debris in lower altitudes requiring more-frequent revisits. Our approach to estimating the efficacy of this tracking method assumed that each laser ground station in the network contributes to maintaining custody of approximately the same number of debris. We estimated the number of pieces of debris that a single ground station can maintain custody of. A network can be built by adding as many ground stations as necessary to reach the desired number of debris tracked. Our calculations are shown in Table C-9. At the lower end, each station can track only about 36 objects because of the high revisit rates. At best, one station can track about 228 objects.

Table C-9. Performance of Ground-Based Laser Tracking of Centimeter-Size Debris

Measure	Orbit of Debris [km]							
	400	**500**	**600**	**700**	**800**	**900**	**1,000**	**1,100**
Minutes Between Observations [m][a]	3	3	3	3	3	3	3	3
Duty Cycle of Station[b]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Annual Observations per Station[c]	87,600	87,600	87,600	87,600	87,600	87,600	87,600	87,600
Time Between Laser Ranges for Custody [hours][d]	3.6	5.2	7.2	9.5	12.3	15.4	18.9	22.8
Annual Observations Required for Custody of Single Debris[e]	2,447	1,687	1,220	918	713	569	463	385
Debris in Custody per Station[f]	36	52	72	95	123	154	189	228
ORDEM: Estimated Debris ± 50 km	3,800	8,600	8,000	14,000	23,700	28,600	16,200	8,600
Stations Needed for Total Custody[g]	**106**	**166**	**111**	**147**	**193**	**186**	**86**	**38**
MASTER: Estimated Debris ± 50 km	2,600	5,500	10,500	20,700	33,800	23,200	13,300	7,400
Stations Needed for Total Custody[g]	**73**	**106**	**146**	**217**	**275**	**151**	**70**	**32**

[a] Our back-calculation of the time between the laser observations implied in Table 2 of Scharring et al. (2021).
[b] Realistically, continuous operation is unlikely; current laser ranging networks experience cloud cover more than 50% of the time at some sites (Scharring et al 2021).
[c] Calculated as the number of hours in a year divided by hours between laser ranges.
[d] The time (T) in hours needed between measurements for maintaining custody of the debris with a laser is given as a function of altitude (X) in kilometers by Scharring et al. (2021) as $T = (54 - 0.05*X + 0.00113*X\char`^2)/60$.
[e] Calculated as the total number of minutes in a year multiplied by the duty cycle and divided by the number of minutes between observations.
[f] Calculated as the number of debris at this altitude divided by the number of debris in custody per station.
[g] Calculated as the number of annual observations possible per station divided by the number of observations required to maintain custody of a single debris.

Compared to the radar system simulated in Scharring et al. (2021), the researchers estimated their laser ranging network can reduce the number of "false alerts" by 10–100 times. We interpreted this estimate to mean that the PC inflation of conjunctions is reduced such that operators experience 10–100 times fewer warnings and maneuvers compared to present-day operations. In our encounter model, we used a 1-kilometer miss distance at TCA as a proxy for a predicted 1E-4 PC based on current SSA capabilities. If laser ranging were able to improve the accuracy in the predicted PC, then a 1E-4 collision probability would correspond to a smaller than 1 kilometer miss distances at TCA. For this analysis, 10- and 100-times reduction in PC inflation corresponds to new miss distances of 316 meters and 100 meters,[48] respectively.

Cost

Existing laser ranging stations can provide estimates of cost per station. Some experimental debris-specific satellite laser ranging stations are already being deployed, such as the Izaña-1 laser ranging station in Tenerife, Spain, and the Tsukuba Satellite Laser Ranging Station in Japan. However, the costs of the Tenerife and Tsukuba stations are not available. NASA awarded a contract with a maximum value of $48 million for the construction, deployment, and commissioning of up to six Space Geodesy Satellite Laser Ranging stations (NASA 2018). This amount implies a cost of $8 million per station, and we used that amount as the cost of each station in the network in our analysis. The geodesy stations will use lower-power lasers than will the network of laser stations used for this CONOPS, but subject matter experts we spoke with indicated that the added costs are likely negligible.

Laser-based ranging to find satellites is a mature technology that has been used since the 1960s to provide precise information on the locations of space objects. Traditionally, satellites being ranged have had retroreflectors, but recent technological advances have enabled ranging of objects without retroreflectors, such as space debris. Thus, we did not include NRE because this technology is proven.

A subject matter expert indicated that a modern laser station requires about $500,000 annually to operate; however, this amount may not include maintenance costs, so we inflated the annual operations cost to $1 million. Operation costs could be much lower. These stations will be largely autonomous and will operate without significant personnel presence, particularly because there are so many stations. Table C-10 shows our cost estimates, which range from $6,000 to $40,000 per debris per year.

Table C-10. Costs of a Single Ground-Based Laser Station for Tracking Centimeter-Size Debris Within a Scalable Network of Laser Ranging Stations

Element	Units	Unit Cost	Total Cost
Hardware			
Laser Ranging Station	1	$8M	$8M
O&M			
Lifetime of Station [years]	20		
Annual O&M		$1M	$20M

[48] The collision rate depends on the cross-sectional area of the encounter sphere. Thus a 10-times reduction in maneuvers means a new sphere with 10 times less cross-sectional area. Thus, r_new = sqrt(1/10)*r_old.

Total Lifetime Cost			**$28M**

Element	Units	Low Cost	High Cost
Number of Ground Stations	1		
Debris in Custody per Station at 400 km	35.8		
Estimated Cost Per Debris Per Year			$39,106
Debris in Custody per Station at 1100 km	228		
Estimated Cost Per Debris Per Year		$6,148	
Summary of Estimated Cost Per Debris Per Year		**$6,000**	**$40,000**

Note: *O&M = operations and management*. If minutes per observation were reduced to 1 minute and operating costs were reduced to $500,000 per year, the estimated low and high costs would be $1,000 and $8,000, respectively.

Ground-Based Radars

CONOPS

A global network of two ground-based radars can collect the data needed for detecting, determining orbit of, and maintaining custody of debris in a specified altitude band in LEO. The network of radar stations will be tuned to track all centimeter-size debris in specific altitude bands rather than to track all debris in LEO. However, the number of radar stations could be increased to track more debris at different orbits. Specifically, our concept is based on a two-site implementation of Space Fence, with minor modifications. The main difference is that the sole mission of the radar system is to maintain custody of centimeter-size debris and to support conjunction assessments involving the debris, whereas Space Fence performs many defense-related missions in addition to maintaining custody of space objects.

Efficacy

Space Fence uses an S-band radar to detect and then track debris, with capabilities to track debris down to approximately 5 centimeters (Gruss 2014). Initial contract information for Space Fence states that, together, two stations could track 200,000 pieces of debris, with one station having approximately 80% of the capability of the pair (Gruss 2014). For this analysis, we assumed that the performance of a radar network scales linearly; therefore, adding two radar stations increases the number of debris tracked by 200,000 pieces. In reality, the addition of more stations may nonlinearly enhance the performance of the network because individual pieces of debris should cross more fences per day. This fact could reduce the uncertainty of predicted orbits once items are catalogued and could prevent loss of custody. Nevertheless, we did not account for any nonlinear benefits in this analysis.

We generously assumed that a two-site fence system will produce CA products of quality equivalent to those currently produced for 10-centimeter and larger objects. In our model, this capability is implemented as warnings and maneuvers triggered at miss distances of 3 kilometers and 1 kilometer, respectively. Likewise, we assumed that the wavelength of the phased-array radar used in the fence will be reduced to maximize returns from centimeter-size objects, allowing tracking of objects down to 1 centimeter. We did not have the ability to calculate the desired wavelength, which would require balancing the ability to resolve the debris by using smaller wavelengths with the increased power requirements for broadcasting at these higher frequencies.

The benefits of tracking and doing conjunction assessment of small debris may have a net imposition of costs if the quality of the data and analyses are simply on par with those for large debris. It may be necessary to supplement the high-risk conjunctions identified by the radar with laser ranging to reduce unnecessary maneuvers.

Cost

When Space Fence was declared operational in 2020, it reportedly cost $1.5 billion (Erwin 2020). This amount accords with a December 2019 budget document that indicates Space Fence expenditures from 2005 to 2019 totaled $1.446 billion in 2019 dollars (Department of Defense 2019). We used this value for our high-cost estimate. However, all of these funds are considered to be for research, development, testing, and engineering, and none of the categories are considered procurement. Thus, when trying to estimate the cost of a subsequent unit, even with slight modifications, the full program cost would be an overestimate, since the entire program budget was essentially NRE to get to the first unit.

Instead, for our low-cost estimate, we assumed that the cost to manufacture the first unit is approximately the cost of the program after it passed its critical design review. A Government Accountability Office (2015) report two months prior to the critical design review estimated that the program still needed $705 million in 2015 dollars to reach completion. Thus, we used this amount as the cost of the first unit; this amount includes some NRE and likely some operating costs but excludes the more foundational NRE. Although we cannot confidently speculate about the cost of the next unit, we can make an informed guess. Previous work has used a factor-of-two heuristic to relate the cost of a first unit to subsequent units and found a few examples of this heuristic in space vehicles (Colvin, Karcz, and Wusk 2021). We applied it here to roughly estimate that the cost of subsequent Space Fence units may be $350 million.

As noted in the CONOPS, our postulated radar systems will be modified to optimally detect centimeter-size debris. We assumed that this modification to smaller wavelengths and possibly higher transmitting power will not substantially increase the cost of the system beyond the estimates made in the previous paragraphs. This assumption is reasonable because the cost of phased array antennae have fallen rapidly in the last few years. Since Space Fence was built, phased array technology has become important to 5G wireless infrastructure, spurring reductions in cost (Carlson 2018). For example, SpaceX Starlink uses Ka-band phased array antennae for user terminals, and it is unlikely the radar would need to use smaller wavelengths.

The operation costs of the Space Fence are about $60 million annually in 2019 dollars (Department of Defense 2019). We used this value for our high-cost estimate. The cost associated with using such a system for a purely civil mission is likely to be less because the system need only watch for debris and correlated tracks. Department of Defense systems spend much of their time doing in-depth analyses of actively maneuvering spacecraft and other defense-related missions, none of which are germane to simply building a debris catalog. Thus, we assigned a low-cost estimate of $10 million per radar station, in line with the average cost of the former Air Force Space Surveillance System (Department of Defense 2019).

If laser ranging is required to improve the accuracy of prioritized conjunction assessments, we would apply the cost calculated in the section of this appendix on laser ranging trackable debris. Doing so is fair because centimeter-size debris are now trackable with the postulated radar system. The cost per conjunction will almost surely be near the lower estimate because there will be very many high-risk conjunctions to assess.

Table C-11. Costs for a Radar to Track Small Debris

Element	Units	Low Cost	High Cost
Hardware			
NRE	0	$0	$0
Radar Station	2	$350M	$1,500M
Subtotal		**$700M**	**$3,000M**
Operations & Maintenance			
Lifetime of Stations [Years]	20		
Annual Operations & Maintenance	2	$10M	$60M
Subtotal		**$400M**	**$2,400M**
Total Lifetime Cost		$1,100M	$5,400M
Annualized Cost		**$55M**	**$270M**
	Units	**Low Cost**	**High Cost**
Number of Debris Tracked	200,000		
Annualized Cost per Debris		**$275**	**$1,350**
Laser Ranging per Conjunction [a]		**$10**	**$300**

[a] Summarized from Table C-16. We used the costs associated with on-demand tracking of large debris because it is analogous to the on-demand nature used here.

Ground-Based Optical Network

CONOPS

Optical telescopes are able to provide more accurate two-directional data than historically provided by radars.[49] Unlike radars, telescopes on the ground are limited by weather and illumination conditions. This fact suggests that space-based optical networks might be more useful, with longer duty cycles, but satellites may struggle to reposition their optics quickly. Ground-based systems benefit from fast slew rates, which allow them to follow the path of a piece of debris and collect clusters of pixels rather than a streak of data, thereby improving accuracy.

One ground-based system, proposed by Carroll (2019), utilizes 100 0.5-meter telescopes spread across 50 locations to track debris in the 0.5- to 2-centimeter range. For the purposes of our analysis, we used Carroll's system to analyze the tracking of 1- to 10-centimeter objects. Doing so is reasonable because a system than can track subcentimeter objects can also track 1- to 10-centimeter objects. Tracking these objects requires fast, direct-drive mounts that can follow individual pieces of debris along their paths. Data are collected by taking two exposures, each about 1.2 seconds. The first is used to determine the best signal-to-noise ratio for the second exposure, which then lasts for slightly longer than the first. Using two separate exposures allows for the signal to noise adjustment and contributes to understanding the direction of motion of the object. These images are also processed to find "fellow travelers": other debris that cross the image frame and thus can be added to the catalog with additional imaging.

In addition to proposing the telescope network, Carroll (2019) proposed several software tasks to improve orbit and conjunction prediction and object discovery. He noted that improvements in modeling drag and spin axis could extend the amount of time required before an object is revisited. Increasing the minimum revisit rate could allow the catalog to be filled faster or to be maintained with fewer stations. Such changes are out of scope for this analysis, but because revisit rate is a major driver of cost (in laser systems particularly), improvements in that area may influence which tracking approach is most cost-effective.

Efficacy

Carroll (2019) envisioned that this system will track 1 million pieces of debris in the 5-millimeter to 2-centimeter range with altitude-azimuth errors of a few meters. We note that a 5-millimeter sphere at 778 kilometers altitude with 10% diffuse reflectance has a magnitude of 19.6, and it seems unlikely that similarly small objects will be visible to these telescopes at higher altitudes. To improve the chances that this system will be able to track the full altitude range considered for the other concepts and to align the object size and count with the other concepts, the system will be scaled to track the centimeter debris considered for the other concepts. Doing

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[49] Some modern radars can use interferometric approaches to estimate angles in addition to range/doppler pairs.

so loses some of the potential benefit this system has to offer by targeting a smaller class of objects, which the other concepts may not excel at observing. The scaling of this concept relies on the relationship between the number of stations required and the revisit rate for each debris item. Carroll stated that with approximately 3-second tracks, each station may make approximately 5,000 catalog updates per night and may do so for 280 clear nights out of the year. For a million-item catalog, the following equation shows the relationship between the catalog count, number of stations, and revisit rate:

$$\frac{(1.4E6 \frac{observations}{station * year} * 100\ stations)}{1E6\ items * 365\ days} = 0.38 \frac{obs}{item * day}$$

To obtain the days between observations, the inverse is taken, resulting in 2.6 days between observations. Carroll confirmed this outcome and stated that 2.6 days may be frequent enough if models of drag are improved, thereby decreasing the error on orbital predictions.

Without improvements in drag modeling, a more conservative revisit rate of every 12 hours may be preferred. For our estimates, we used a 12-hour revisit rate applied to the ~600,000 centimeter-size objects that are estimated to exist in LEO. Consequently, a global network of 320 telescope stations would be needed. Though we assumed that two observations per day are adequate to maintain the catalog, but they may not be enough for building out the catalog. Carroll recommended adding three 0.7-meter telescopes with approximately 28 times more area in their field of view to construct the catalog. The additional telescopes are estimated to reduce the time to build the catalog from approximately 14 years to approximately 4 years. Carroll suggested that three observations across one pass (potentially at three aligned sites) would be enough to get the initial orbit determination needed to catalog an item. For the purposes of this analysis, we did not account for the time required to build the catalog.

Cost

Because Carroll (2019) provided information on the specific telescopes considered for the concept and the costs for installation, the main areas of cost uncertainty regard the number of stations needed and whether the recommended telescopes are added. We based our low cost estimate on 100 stations and our high cost estimate on 320 stations and 3 larger telescopes. The costs for this concept are significantly lower than those for other concepts, as detailed in Table C-13. The lower cost is probably in part because the hardware cost does not include building a facility to house each telescope. The cost of $200,000 per scope includes about $75,000 for the scope and camera and the remaining $125,000 presumably for installation and other setup costs. The estimated $200,000 is not enough to buy property for 50 stations and to construct facilities on those sites (beyond, possibly, a small shed for each scope). Their small size will allow them to be easily colocated with other observatories or academic, government, and/or research facilities, but those placements may incur costs that are not captured here.

Table C-13. Ground-Based Passive Optical System to Make a Small-Debris Catalog from 350 to 11,500 Kilometers

	Low-Cost Estimate			High-Cost Estimate		
Element	**Units**	**Unit Cost**	**Total Cost**	**Units**	**Unit Cost**	**Cost**
Hardware						
0.5-m Station	100	$200,000	$20,000,000	320	$200,000	$64,000,000
0.7-m Station	0	$600,000	0	3	$600,000	$1,800,000
Subtotal			**$20,000,000**			**$65,800,000**
	Years	**Annual Cost**	**Cost**	**Years**	**Annual Cost**	**Cost**
O&M[a]	30	$1,000,000	**$30,000,000**	30	$3,290,000	**$98,700,000**
Lifetime Cost			**$50,000,000**			**$164,500,000**
Cost per Debris per Year[b]			**$3**			**$8**

[a] *O&M = operations and maintenance* and is 5% of the total hardware cost.
[b] Calculated as lifetime cost divided by years in operation and 630,000 debris, rounded to the nearest significant figure.

Space-Based Optical Constellation

CONOPS

Phipps and Bonnal (2019) proposed a constellation of satellites that could be used to build a catalog of 1- to 10-centimeter debris. Each satellite would carry a passive optical system to detect debris and a series of low-power lasers to range the debris for a highly accurate determination of their orbits. The CONOPS is effectively the same as for the ground-based laser ranging approach, discussed previously, with an added step to ensure accurate orbit determination of the spacecraft. The CONOPS for a single satellite within the constellation is as follows:

- **Localize the satellite**. Ground-based laser ranging stations periodically range the satellite to establish a highly accurate measurement of its position. The satellite carries a GPS receiver to assist. With an accurate determination of the spacecraft's position and orbit, it can be used as a reference point to make accurate measurements of debris.
- **Detect debris**. A passive optical system operates in staring mode to detect debris via reflected sunlight. The diameter of the optic is 50 centimeters.
- **Add debris to centimeter-size catalog**. The onboard laser is tipped to range the debris. Doing so gives accurate position and velocity measurements, which are relayed to the ground for orbit determination. Once the orbit is determined, it is added to the catalog or associated with a previously catalogued object.

- **Maintain catalog**. Lasers from the network periodically range the debris in the catalog. The debris are ranged frequently enough that the uncertainty in the orbit of the debris allows the laser to dead reckon it's the predicted position of the debris and find the debris through executing a modest search. If the uncertainty in the orbit of the debris grows large enough, the laser search times may become unacceptably long.
- **Remove deorbited objects from the catalog.** If the objects are low enough that they deorbit, they are removed from the catalog. Likewise, if an object unexplainably disappears from the catalog, it may have been involved in a collision and is removed from the catalog.

Efficacy

The optical/laser constellation is estimated to bring range precision down to 10 centimeters for all objects it ranges (Phipps 2022). The size of detectable objects is dependent on their distance; the passive optical sensor can detect a 1-centimeter object 200 kilometers away and a 10-centimeter object 1,000 kilometers away. At the farthest distance, the debris crosses the one-degree field of view in 2 seconds. During this time, the sensor must reduce the uncertainty of the track to the order of meters so that the laser, with its 2.3-meter spot size, is able to find the object. The laser is capable of ranging with 4-centimeter precision for objects in the centimeter-size range (Phipps 2022). Thus, the optical portion is able to detect objects that the laser is unable to track, giving a rougher track estimate for smaller debris while the laser refines objects in the upper-centimeter range.

With a 2-second optical track, tasking of the laser, and then laser ranging, the total process of detecting and tracking is assumed to take approximately 30 seconds per piece of debris. With an 80% duty cycle, each station could conduct approximately 840,000 tracks per year. This information and the calculations used for the laser network concept were applied to find the number of stations required. For custody of a piece of debris to be retained, it must be tracked with a minimum revisit rate dependent on its altitude. We used an equation for the revisit rate from Scharring et al. (2021) to calculate the number of observations needed per debris per year (see footnote e in Table C-9).

Table C-14 shows how we calculated the number of spacecraft needed to maintain custody of the debris. At each altitude, we used the estimated number of centimeter-size debris, according to COMSPOC. Estimating that each observation takes 30 seconds to complete implies that each spacecraft can theoretically make over 1 million observations in a year. Finally, using Scharring et al.'s estimated revisit rates to maintain custody of an object, we estimated the number of spacecraft in that altitude band that could achieve that revisit rate. Spacecraft at the highest altitude band could track six times as many debris pieces as spacecraft at the lowest band because of the high revisit rates for debris in low LEO. To cover most of LEO would require about 530 spacecraft.

Table C-14. Number of Spacecraft Needed to Track Centimeter-Size Debris

Element	Values							
Altitude [km]	400	500	600	700	800	900	1000	1,100
Count cm-Size Debris	20,000	50,000	70,000	100,000	200,000	100,000	60,000	20,000
Minutes per Observation				0.5				
Annual Observations per Satellite				1,051,200				
Revisit Rate[a] [h]	3.6	5.2	7.2	9.5	12.3	15.4	18.9	22.8
Annual Revisits[a]	2447	1687	1220	918	713	569	463	385
Satellites Needed	55	76	80	91	142	52	27	7

[a] To maintain custody of a single piece of debris

Cost

To estimate the costs of performing this service, we assigned each spacecraft a Blue Canyon X-Sat bus. The Venus-Class and the Saturn-Class have sufficient payload dimensions to handle an optic with a 50-centimeter diameter. The DARPA Blackjack program purchased these busses at $5 million each (Colvin, Karcz, and Wusk 2021). We assigned $1 million for the cost of the payload; however, this number is a guess. Our only point of reference was that Phipps (2019) stated the laser system costs $135,000. We assumed the spacecraft will operate for 5 years, consistent with the lifetime of the bus in LEO. We estimated the costs associated with deploying spacecraft to track debris near 400 kilometers and 1,110 altitudes; the resulting numbers form our high- and low-cost estimates. Each altitude layer has approximately the same number of debris; however, far more spacecraft are required to maintain custody of debris at 400 kilometers than at 1,100 kilometers because of the enhanced revisit rate required at lower altitudes.

Table C-15. Costs for Satellites That Track Centimeter-Size Debris

	Low-Cost Estimate			High-Cost Estimate		
Element	**Units**	**Unit Cost**	**Total Cost**	**Units**	**Unit Cost**	**Total Cost**
Hardware						
Payload	7	$1M	$5.25M	55	$1M	$41.25M
Bus	7	$5M	$35M	55	$5M	$275M
Subtotal			**$42M**			**$330M**
Launch	Mass			Mass		
Spacecraft	150 kg			150 kg		
Subtotal	1,050 kg	$5K	**$5.25M**	8,250 kg	$5K	**$41.25M**
	Years	**Cost/Year**	**Total Cost**	**Years**	**Cost/Year**	**Total Cost**
O&M[a]	5	$10M	**$50M**	5	$10M	**$50M**
Lifetime Cost			**$96M**			**$408M**
	Per-Debris Calculations @ 1,100 km			Per-Debris Calculations @ 400 km		
	Units	**Annual Cost**	**Cost**	**Units**	**Annual Cost**	**Cost**
System Cost[b]		$19,450,000			$84,250,000	
Debris	20,000			20,000		
Cost per Debris per Year[c]			**$1,000**			**$4,000**

[a] *O&M = operations and management* We made the simplifying assumption that the operation costs are approximately independent of the number of spacecraft, because of automation. Annual operation costs for comparably sized spacecraft missions at NASA are approximately $10 million per year (Colvin, Karcz, and Wusk 2023).
[b] Calculated as the lifetime cost divided by the number of years.
[c] Calculated as the annual system cost divided by debris at this altitude, rounded to the nearest significant figure.

Tracking Debris 10 cm and Larger

Tracking objects larger than 10 centimeters is unique in that this capability is already operational. In this section, we explore an approach to improving this capability. Due to limitations in the literature and our relatively unfamiliarity with radar systems, we were only able to provide an estimate of performance and cost for one approach: ground-based laser ranging. Future work should consider the additional possibilities discussed in the main text of this report.

Background

The U.S. Space Force operates the SSN to maintain SSA for the United States. This system is the most comprehensive SSA system, and in July 2023, the Space Force reported that the SSN tracks approximately 44,600 objects, including 8,400 active satellites, 19,200 debris, and 17,300 additional objects not meeting quality standards.

There are two concepts for tracking large debris for which we provide estimates of efficiency and cost. These on-demand concepts reduce the uncertainties associated with conjunctions identified by the SSN; the concepts are completed using laser ranging from ground-based or space-based platforms. We briefly discussed other approaches but were unable to assess their performance or costs. These approaches include improved data processing, improved modeling of the neutral density atmosphere, and use of more radars.

On-Demand Ground-Based Laser Ranging

CONOPS

We based our analysis on DLR's LARAMOTIONS concept (Scharring et al. 2021), which uses a global network of ground-based laser stations. The CONOPS is as follows:

1. **Identify a high-risk conjunction**. The SSN identifies a close approach that will occur within 48 hours and that may induce the spacecraft operator to maneuver to reduce the risk to the spacecraft. Relevant close approaches are active-on-active and active-on-debris interactions. For debris-on-debris collisions, there is generally no possibility of maneuver and, thus, no reason to assess the PC to a higher fidelity. However, if laser ranging is used with JCA, interrogating debris-on-debris collisions becomes valuable.
2. **Assign laser stations to range objects**. The latest orbital elements available are used to predict the trajectories of objects. The objects are tasked to available laser ground stations for ranging. The tasking is based on relevant factors, such as weather downtime, time and geometry of overflight, and workload of the sensor.
3. **Gain custody of the objects**. Each station has a method of gaining custody of objects so they can be ranged. The method could involve using a passive optical camera or a small radar that can perform a reasonably wide field-of-view search to locate an object and refine the location of its orbit to the point that custody can be transferred to the beam director of the laser. Alternatively, if there are few conjunctions to assess, the laser beam director could search the sky until the object is found.
4. **Range the objects**. Once the laser system has gained custody of the object, the laser ranging measurement is taken. The lasers will be of sufficient power that objects do not need retroreflectors or any special preparation. Both objects that are party to the conjunction are ranged to reduce the uncertainty of the conjunction. The measurements of both objects do not need to occur simultaneously; however, the measurements should likely be taken within a few hours of each other.
5. **Refine the uncertainty of the conjunction**. The measurements are used to recompute a more accurate orbit propagation, which will then reduce the uncertainty in the PC at TCA.

Based on this reduced uncertainty, the operator(s) can make a more informed decision about whether to perform an avoidance maneuver.

Efficacy

To examine the potential efficacy, Scharring et al. (2021) performed simulations of the ground-station network under different duty-cycle assumptions (to help account for atmospheric variations). We inferred from the researchers' analysis that each ground station will make approximately 230 measurements per day, with about 3 minutes between measurements. These numbers account for local weather conditions, which will cause each ground station to be inoperable for an average of 12 hours a day. Assessing a potential conjunction would require two measurements: one for each object in the conjunction. Thus, a network of five stations could make about 1,150 measurements per day, which corresponds to 575 conjunctions interrogated daily.

We retained the same assumptions about the reduced collision uncertainties as in the analysis for centimeter-size debris. Specifically, the laser network of five ground stations may reduce the uncertainties by a factor of 10–100. For context, using a 1-kilometer miss distance, the three models estimate about 30 maneuvers per day. The network of five laser stations has the capacity to handle many more conjunctions than 70 per day.

Cost

Table C-16 shows the costs we estimated, including the low and high costs per conjunction assessed. Our costs for each laser station are the same as previously described for tracking centimeter-size debris with ground-based lasers. The low-cost estimate assumes that the laser system operates at maximum capacity and is able to find customers to pay for every laser shot; in general, these customers will pay for services other than assessing active-on-debris conjunctions; examples include active-on-active conjunctions and geodesy. For the high-cost estimate, we assumed that the laser system is engaged for only active-on-debris conjunctions that would otherwise require a maneuver.

Table C-16. Costs for Ground-Based Laser Ranging System

Element	Units	Unit Cost	Total Cost
Hardware			
Laser Ranging Station	5	$8M	$40M
O&M			
Lifetime of Station [Years]	20		
Annual Operations and Maintenance		$1M	$20M
Total Lifetime Cost			**$60M**

Element	Units	Low Cost	High Cost
Laser Operates at Full Capacity			
Number of Ground Stations	5		
Daily Measurements per Ground Station	230		
Measurements Possible over Lifetime	8,395,000		
Estimated Cost per Measurement		$7	
Measurements per Conjunction	2		
Estimated Cost per Conjunction		**$14**	
Laser Ranges of Potential Maneuvers			
Daily Maneuvers in Baseline	30		
Maneuvers Made in Lifetime	219,000		
Estimated Cost per Conjunction			**$274**
Estimated Cost per Conjunction [a]		**$10**	**$300**

[a] Calculated using the values above, with the value rounded to one significant figure.

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