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A Cost and Benefit Analysis of Orbital Debris Remediation, Mitigation, Tracking, and Characterization

Thomas J. Colvin*, Jericho Locke

Office of Technology, Policy, and Strategy, NASA Headquarters, 300 E St SW, Washington, DC 20546
* Corresponding Author: thomas.j.colvin@nasa.gov

Abstract

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 (Colvin, Karcz, and Wusk. 2023), referred to here as Phase 1, assessed the costs and benefits of performing debris remediation on operationally relevant timescales. The current paper summarizes the work of Locke and Colvin (2024), which 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.

Keywords: space debris, orbital debris, debris remediation, risk, cost-benefit analysis

Acronyms/Abbreviations

AD2:	Advancement Degree of Difficulty
GEO:	Geostationary Earth Orbit
JCA:	Just-in-time Collision Avoidance
LEO:	Low Earth Orbit
MASTER:	Meteoroid and Space Debris Terrestrial Environment Reference
MEC:	Mission-Ending Collision
NESC:	NASA Engineering and Safety Center
ORDEM:	Orbital Debris Engineering Model
OTPS:	Office of Technology, Policy, and Strategy
SSA:	Space Situational Awareness
TRL:	Technology Readiness Level

1. Introduction

1.1 Background

Orbital debris is defined as "any human-made space object orbiting Earth that no longer serves any useful purpose" (Space Policy Directive-3). 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* 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

* 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.

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.

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.

1.2 Purpose and Scope of Current Work

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.

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

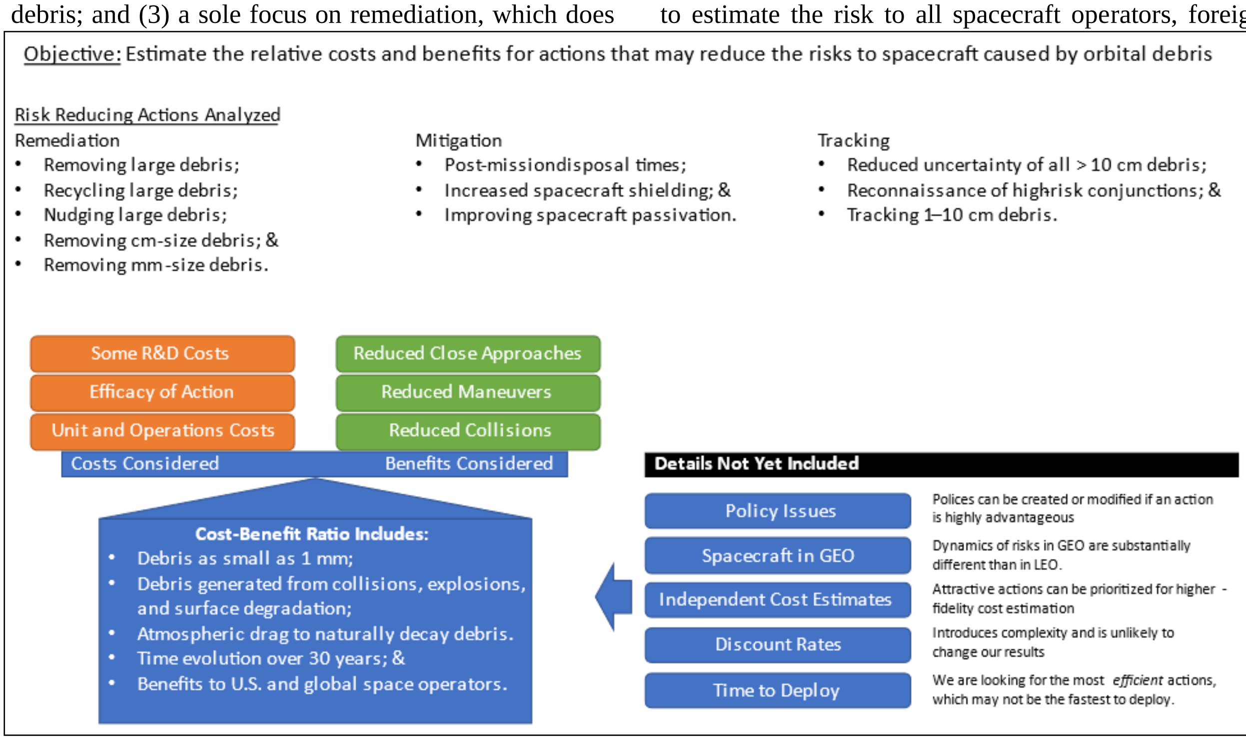

Figure 1. Cost-benefit considerations included in the current study.

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.

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2. Material and methods

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 Locke and Colvin (2024); 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.[†] As of December 2022, 42% of tracked debris were derelict

[†] 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).

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.[‡] 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 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 Meteoroid and Space Debris Terrestrial Environment Reference (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.

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.

Table 1. Overview of 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

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 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.

[‡] 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).

Table 2. Risks from Orbital Debris in First Year of Simulation, Measured in Millions of U.S. Dollars

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

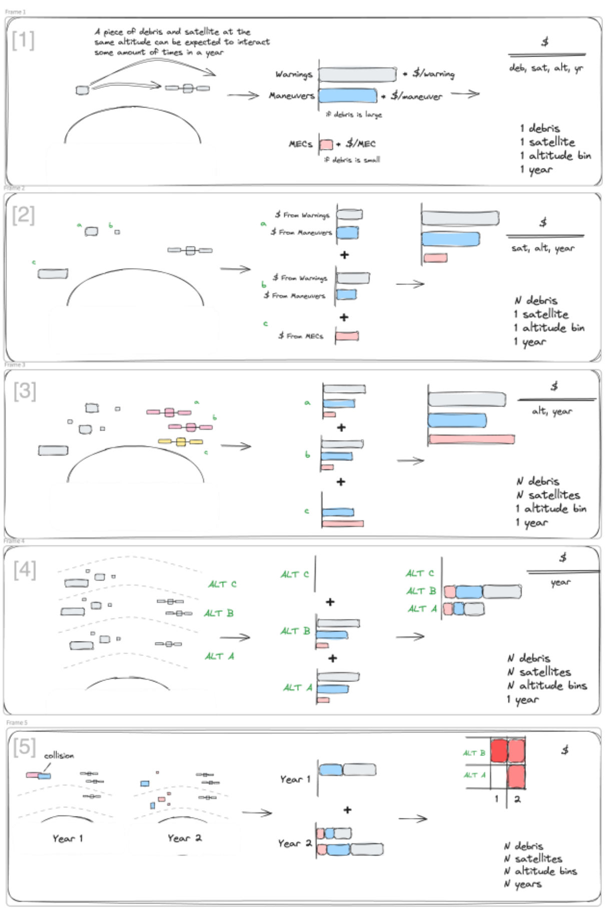

Figure 2. Illustration of the method for estimating debris risk to all spacecraft. Generated using Excalidraw.

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.

To aid comprehension, 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.

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. 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.

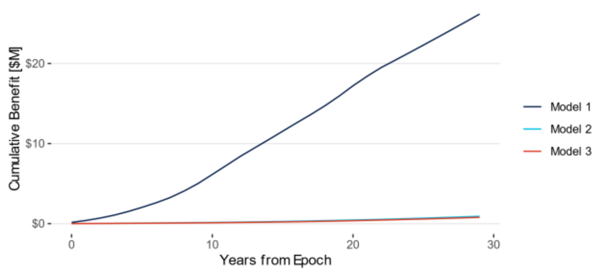

Figure 3. Cumulative benefit of not adding a medium derelict at 650 kilometers.

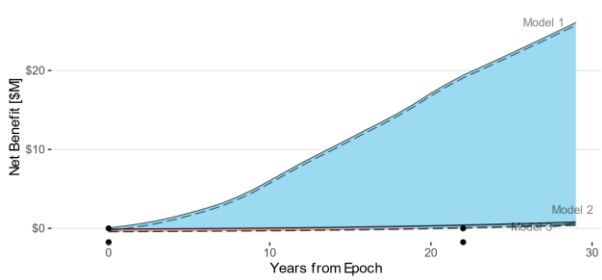

Figure 4. Net benefit of not adding a medium derelict spacecraft at 650 kilometers.

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; and (3) 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 Locke and Colvin (2024).

4. Results

In the preceding sections, 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 5 shows the estimated ratios of benefits divided by costs after 30 years for most of the actions considered in this report.

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.

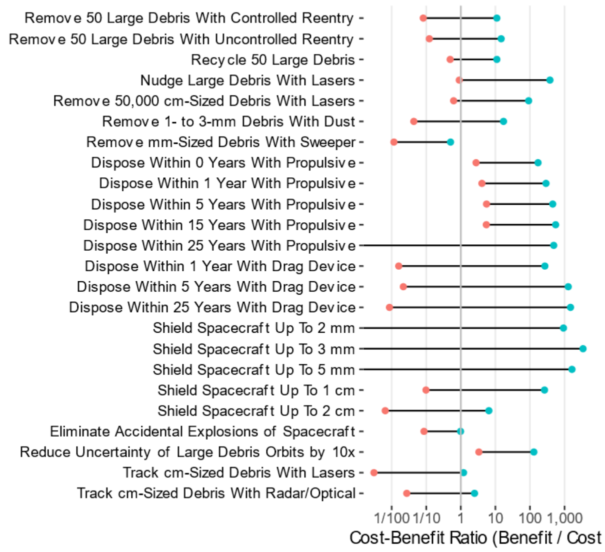

Figure 5. Benefit-cost ratios of the actions analyzed in this report. Note: The x axis uses a log scale. For each action, the figure presents a ratio range, with the left-most ratio representing the low-benefit, high-cost estimate and the right-most ratio representing the high-benefit, low-cost estimate. 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.

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.[§] 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.

5. Discussion

5.1 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 6 shows the net benefit and cost-benefit ratios associated with changing from a 25-year rule to a lower-year rule. 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.

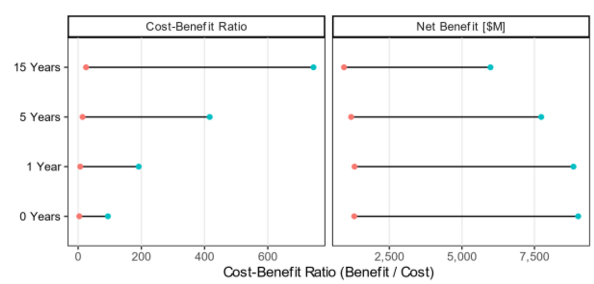

Figure 6. Conditional cost-benefit ratios and net benefits, after 30 years, for moving from a 25-year rule to faster deorbit times for defunct spacecraft.

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

[§] 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.

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.

5.2 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 7. 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.

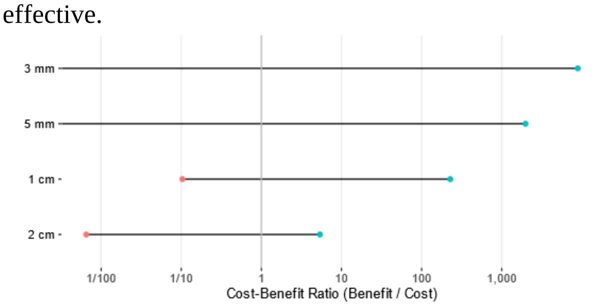

Figure 7. Conditional cost-benefit ratios, after 30 years, for increasing shielding of spacecraft.

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.

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.

5.3 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.

5.4 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.

5.5 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 8. 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.

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.

6. 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. 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

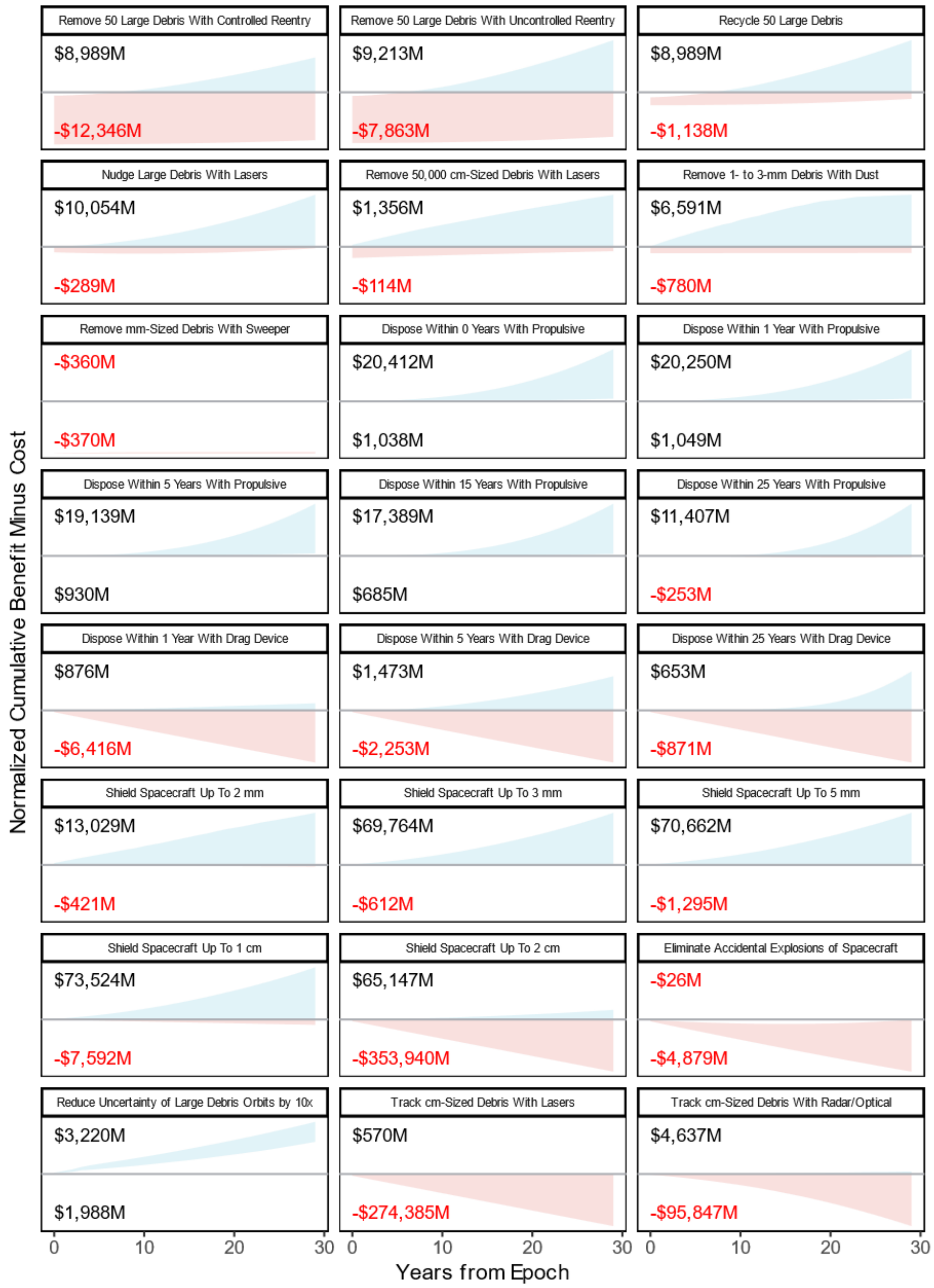

Figure 8. Comparison of the cumulative net benefits of all actions. Note: The numbers are the maximum and minimum benefits (at year 30); these numbers provide a sense of the nonnormalized differences.

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.

List of references

Colvin, Thomas J., John Karcz, and Grace Wusk. 2023. "Cost and Benefit Analysis of Orbital Debris Remediation." NASA. https://www.nasa.gov/wp-content/uploads/2023/03/otps_-_cost_and_benefit_analysis_of_orbital_debris_remediation_-_final.pdf.

Horstmann, Andre, Alyssa Manis, Vitali Braun, Mark Matney, Andrew Vavrin, Drake Gates, John Seago, Phillip Anz-meador, Carsten Wiedemann, and Stijn Lemmens. 2021. "Flux Comparison of MASTER-8 and ORDEM 3.1 Modelled Space Debris Population." https://ntrs.nasa.gov/citations/20210011563.

Locke, Jericho, Thomas J. Colvin, Laura Ratliff, Asaad Abdul-Hamid, and Colin Samples. 2024. Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris. NASA. https://www.nasa.gov/wp-content/uploads/2024/05/2024-otps-cba-of-orbital-debris-phase-2-plus-svgs-v3-tjc-tagged.pdf

NASA Orbital Debris Program Office (ODPO). 2022. "History of On-orbit Satellite Fragmentations, 16th Edition." Available at: https://orbitaldebris.jsc.nasa.gov/library/HOOSF_16e.pdf.

Space Policy Directive-3. 2018. "National Space Traffic Management Policy." Executive Office of the President. https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/

Squire, Michael D., William J. Cooke, Joel Williamsen, Donald Kessler, William E. Vesely, Scott H. Hull, William Schonberg, Glenn E. Peterson, Alan B. Jenkin, and Steven L. Cornford. 2015. "Joint Polar Satellite System (JPSS) Micrometeoroid and Orbital Debris (MMOD) Assessment." NASA. https://ntrs.nasa.gov/citations/20150017054.

Squire, Michael D. 2017. Evaluating Micrometeoroid and Orbital Debris Risk Assessments Using Anomaly Data. NASA. https://ntrs.nasa.gov/api/citations/20170010258/downloads/20170010258.pdf