The Efficacy of Limiting Catastrophic Fragmentations in Low Earth Orbit by Regulating Probability of Collision with Large Objects

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Abstract

Limiting the growth of the orbital debris population is critical to long-term space sustainability. Ensuring future safety of flight operations for human and robotic spacecraft requires first an improved quantification of collision risk, and then effective management of that risk. A significant contributor to this collision risk is debris that is energetic enough to cause catastrophic fragmentation upon impact, small enough to be difficult to track, and prohibitively expensive to remove due to quantity and orbital distribution.

Currently, the most effective way to reduce the long-term risk of orbital debris is to prevent its creation in the first place. In line with this, the United States Federal Communications Commission (FCC) requires, as part of their license application processes, compliance with regulations designed to limit the likelihood of events which would generate debris.

One such regulation is the limitation of the probability of collision with large objects [1]. In this instance, a "large object" is any object larger than 10 cm in diameter, and the legacy maximum probability of collision is 1.0e-3 per satellite, assessed over its lifetime. To show compliance with this regulation, satellite operators commonly use NASA's Debris Assessment Software (DAS) tool. Historically, DAS has provided adequate means for assessing lifetime collision risk for single-satellite missions operating in low earth orbit (LEO). However, given the rapid increase in the number of spacecraft and large constellations that are being launched into orbit, it is necessary to re-evaluate both the regulation requirement itself, and the method by which compliance is determined.

This paper explores the origin and intent of the requirement and assesses its efficacy through six case studies representing different spacecraft in various orbits. In each case study, the likelihood and impact dimensions of catastrophic fragmentation risk are computed and compared to numbers output by DAS.

Analysis results show that not only does the likelihood of catastrophic fragmentation consistently exceed reported DAS outputs, but the environmental impact may also be underestimated for spacecraft more massive than 50 kg.

1. Background

With the continued growth of the orbital debris population, spacecraft operators are frequently performing collision avoidance. Consequently, many operators already acknowledge the self-benefits of minimizing space debris creation, though international policies and regulations can provide an additional impetus for responsible behaviors in support of protecting the environment and other operators' spacecraft. Many of these regulations exist to limit the negative impact that one operator is allowed to have on another, such as the collision risk that can be introduced by one spacecraft operating near another, absent coordination. Another example of such a regulation is the limitation of the probability that a given satellite will collide with another large object in space [2], which would create a debris cloud that would negatively impact other spacecraft in nearby orbits.

A commonly referenced example of such an occurrence is the Iridium 33 Cosmos 2251 collision, which created debris fragments that spanned hundreds of kilometers of LEO. This is illustrated in the Gabbard diagram in Fig. 1, which charts the current distribution of 10 cm debris objects originating from the event. As it can be seen, catastrophic collisions like this one can negatively impact not only nearby spacecraft, but also spacecraft in very distant orbits by introducing additional collision risk. It is precisely this risk that many regulations aim to limit.

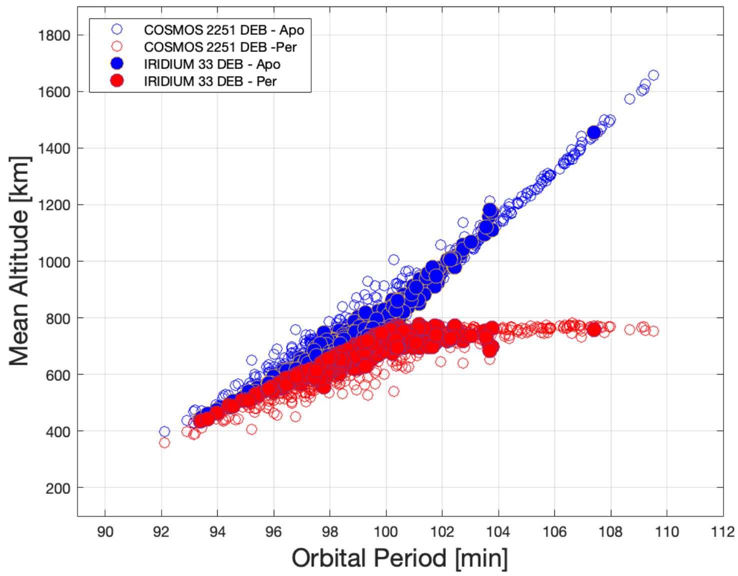

Fig. 1 Gabbard Plot Showing Altitude Spread of Iridium-Cosmos Debris Objects

1.1 Quantifying and Limiting Risk

Several different models, such as ORDEM and MASTER, have been created to estimate the composition and density of orbital debris. While different modeling assumptions often lead to significantly different results for small objects or the overall density of the debris population, the common trend in these models is that smaller objects are much more plentiful than larger ones. This size distribution can be seen in the example ORDEM flux output shown in Fig. 2 below. The trend implies that if an operator has a satellite in orbit which has failed or otherwise cannot maneuver, its collision risk while decaying in orbit would be inversely proportional to secondary debris object diameter.

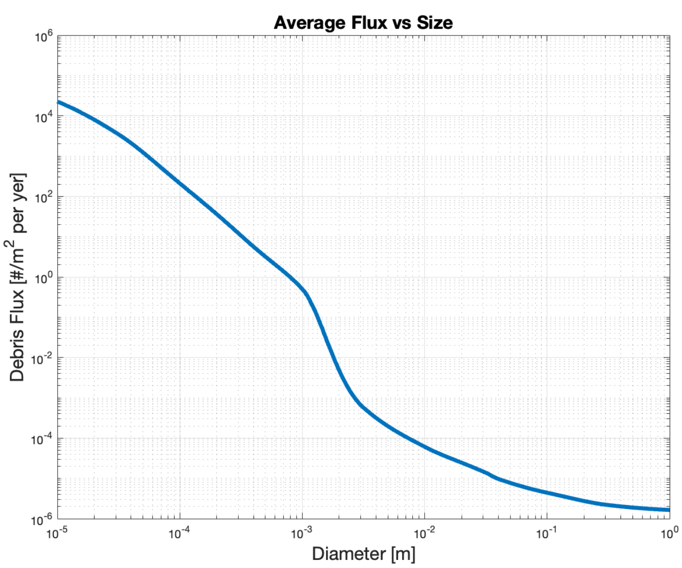

Fig. 2 Example ORDEM Output Showing Debris Flux vs. Object Size

This is perhaps a favorable relation, though, because while collision risk will greatly increase as smaller debris objects are considered, there exists a threshold size for which collisions no longer involve sufficient momentum for catastrophic fragmentation. This threshold is a critical metric in monitoring and managing the space environment, if regulators wish to limit the number of catastrophic fragmentations in LEO.

In NASA-STD-8719.14B, which is the NASA technical standard process for limiting orbital debris, NASA attempts to accomplish the limitation described above. In section 4.5.3.1 of this document, NASA states that by keeping the probability that a primary spacecraft collides with a large object below 1.0e-3 (as per requirement 4.5-1), the probability that a 1 mm piece of debris from a catastrophic fragmentation would impact another spacecraft should be below 1.0e-6 [3]. NASA then states this has been verified by simulating the catastrophic fragmentation of a 50 kg spacecraft and then measuring the impact to "average" spacecraft operating within the resulting debris cloud.

The secondary object threshold size of 10 cm and the associated 1.0e-3 probabilistic limit are also referenced by regulators such as the FCC, which is currently enforcing this limit to ensure the safety of large constellations. One critical, and oft unchecked question, however, is whether 10 cm is an appropriate threshold diameter for determining risk of catastrophic fragmentation. Another unchecked question is whether the fragmentation of a spacecraft with more than 50 kg of mass would comply with the intended limits on environmental impact. These issues are discussed in the sections below.

2. Analysis

While some regulators limit the allowable probability of collision between a licensed spacecraft and objects greater than 10 cm in diameter, this probability may differ from the probability of catastrophic fragmentation, which depends on the momentum involved in the collision, and not necessarily the size of the secondary object alone. Typically, a collision entailing more than 40,000 J/kg, as calculated below in (1), is predicted to completely fragment both of the involved objects [4].

$$\frac{M_{secondary} * V_{relative}^2}{2 * M_{primary}} > 40{,}000\ \frac{J}{kg} \tag{1}$$

This relationship demonstrates that for any given relative collision velocity, the threshold secondary object mass required for catastrophic fragmentation is proportional to the mass of the primary satellite. For example, 50 kg primary may be completely fragmented by a secondary object of 17.8 g, whereas a 500 kg primary may only be fragmented by objects greater than 178 g (assuming a 15 km/s, head-on collision in circular LEO). If the secondary objects are approximated as solid aluminum spheres, these masses would translate to object diameters of 2.3 cm and 5.0 cm: well below the 10 cm threshold commonly used in regulations. Reference [5] also notes similar concerns for the OneWeb satellites currently in orbit, which could be catastrophically fragmented by objects as small as 3 cm in diameter.

While the example above demonstrates that with worst-case geometries, catastrophic fragmentation is possible with debris objects much smaller than 10 cm, the distributions of both secondary object mass density and relative collision velocity must first be characterized before a meaningful probabilistic comparison can be made between current regulatory metrics validated by DAS, and more holistic considerations of risk.

2.1 ATREIDES Introduction

To enable a meaningful comparison of risk metrics, we have created the Astroscale Tool for Risk Evaluation of Impacting DEbriS (ATREIDES). The tool reads in mission-specific debris flux data (e.g., debris sizes and relative velocities) from an external source such as ORDEM, combines this with a debris object mass density model, and runs a Monte-Carlo simulation to generate the probability of catastrophic collision (PoCC) over a specified mission time frame. The tool was validated with ORDEM data to match the probability of collision (PoC) results of DAS, which also processes the same ORDEM data [6]. By running each satellite mission profile through both DAS and ATREIDES, a meaningful comparison can be made between the two.

2.2 ATREIDES Process and Assumptions

The flowchart in Fig. 3 outlines the ATREIDES process. First, the mission and spacecraft properties are defined and entered into both DAS and ORDEM. DAS will then output a PoC with objects greater than 10 cm, which matches a

PoC based on mean flux values from ORDEM, but without considering variance. For the ATREIDES process, additional ORDEM output data is analyzed to create a distribution of energies for the secondary objects which, when processed with the mass of the primary, allows for a momentum-based calculation of PoCC. This is accomplished by performing several million random draws on both secondary object size and relative velocity, based on the output distributions from ORDEM.

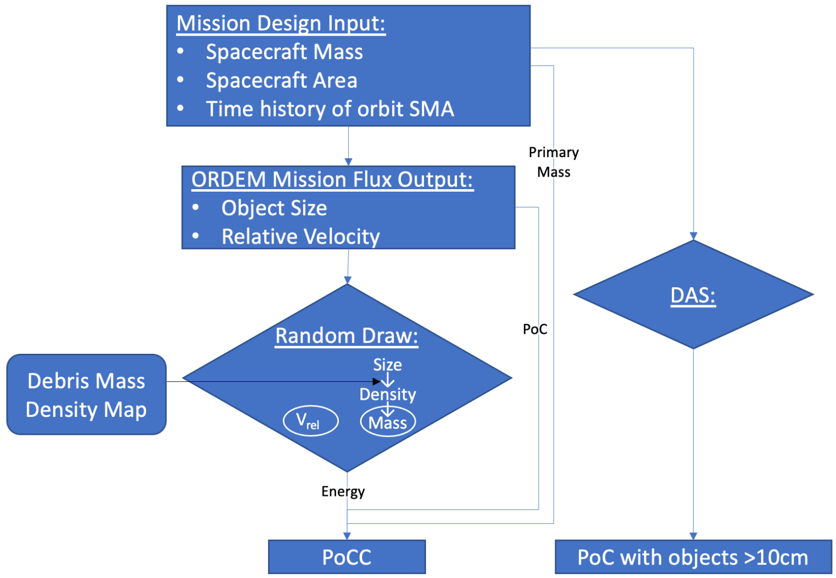

Fig. 3. The ATREIDES Process

While ORDEM does include a debris object mass density model, its assumption that most debris objects have mass densities of solid aluminum may be over-conservative. Such high mass densities may be reasonable for smaller debris objects, but many larger objects are expected to be deformed or crumpled with imperfect packing, and thus may have lower effective mass densities. As such, a more representative mass density model is desirable. While [4] develops a mass estimation model using satellite ballistic coefficients, this can only be validated with larger tracked objects such as NanoSats. To develop a model for smaller, untracked objects, ATREIDES builds on empirical data in [7], which presents measured characteristics of debris from a small satellite that was catastrophically fragmented in a vacuum chamber on Earth. With the understanding that the debris environment is dominated by anthropogenic objects, the fragments from the DebriSat experiment are assumed to be a useful reference for modelling the debris population currently in orbit.

An interesting characteristic of the DebriSat data is that for objects larger than about 2 cm, metal becomes the dominant material, and at 6 cm, metal becomes the sole material [7]. Similar results are seen in SOCIT data analysis presented in [8] where medium density (2.8 g/cm^3) material dominates for objects larger than about 1.5 cm. While these trends align with more conservative models of material distribution, the packing efficiency of the fragments must also be modeled before mass can be inferred from object size. In [9], the mass density ratio (material density divided by object density) of several DebriSat fragments are assessed and quantified by material type. The analysis found that most of the smaller metallic objects had a mass density ratio of around 1, which implies near-perfect packing and little-to-no folding. Results are unspecified for larger objects, however.

For ATRIEDES, the mass density map was simplified into two groups. The first group is medium density material at 2.8 g/cm^3, representing either solid aluminum or denser metals such as steel, copper, and titanium with mass density ratios greater than one. The second group is low density material at 1.4 g/cm^3, representing carbon-fiber reinforced polymers (CFRP), epoxy, and metals with even higher mass density ratios. For larger objects, this low-density material group can also represent intact, mixed-material components and systems similar to CubeSats [10]. The respective proportions of each material group are estimated based on DebriSat data analysis and are presented as the ATREIDES mass density map in Fig. 4.

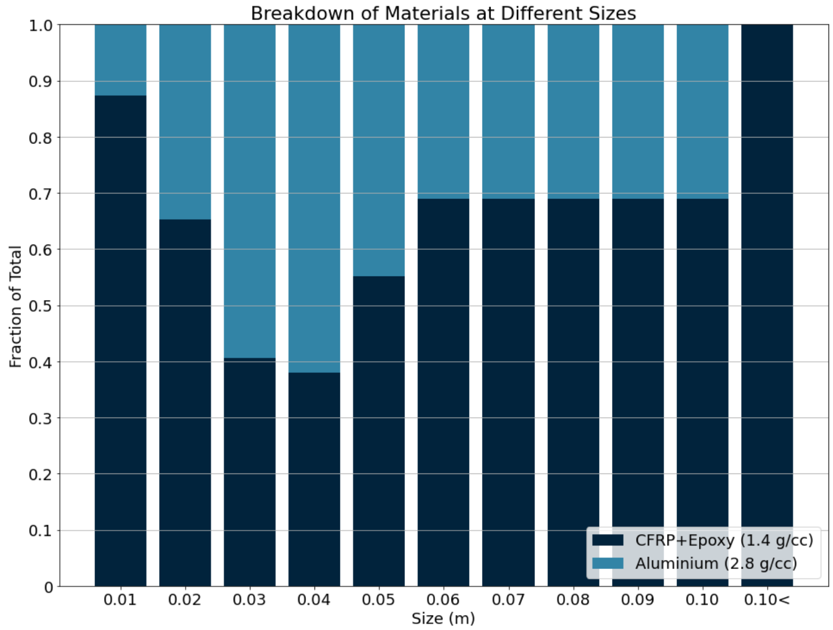

Fig. 4. The ATREIDES Debris Mass Density Map

After ATREIDES randomly draws the relative velocity and size for a colliding object, it assigns a mass based on this map. This allows the tool to compute and compare the collision momentum to the threshold value of 40,000 J/kg in order to determine whether the collision is catastrophic, given that it occurs. This probability is assessed across the millions of draws and is then scaled by the mission PoC (for objects >1 cm) to compute the final PoCC value.

2.3 ATREIDES Test Cases and Inputs

The ATREIDES process was run for six cases, listed in Table 1 below, to analyze the difference between 10 cm PoC values and PoCC values that consider the momentum of any collision with an object larger than 1 cm. Each case is analyzed for a single year in operational orbit, which was chosen to reduce the overall runtime of DAS. This mission period is shorter than the full lifetime that is usually considered for DAS, and may affect the results when comparing to a fully propagated profile of a failed satellite decaying from its operational orbit through to atmospheric reentry.

Table 1: ATREIDES Test Case Definitions

Test Case	Mass (kg)	Area (m^2)	Orbit Altitude (km)	Inclination (deg)
1	50	0.25	600	55
2	500	10	600	55
3	500	10	600	98
4	150	1.69	1200	87.9
5	260	10	550	53
6	700	35	1015	98.98

2.4 ATREIDES Outputs

The outputs of ATREIDES for Cases 1 and 3 are shown below in Fig. 5. The red line shows the 10 cm PoC from DAS, with red error bars added from ORDEM flux sigma values. The dark blue bar shows the PoCC arising from collisions with objects greater than 10 cm. For Case 1, the absence of a gap between the dark blue bar and the red line indicates that nearly all collisions with 10 cm objects would result in catastrophic fragmentation. The lighter blue bar represents the portion of PoCC arising from collisions with objects between 1 and 10 cm in diameter. For both cases, the results indicate that a significant portion of the catastrophic fragmentation risk would be unaccounted for in a DAS-only assessment.

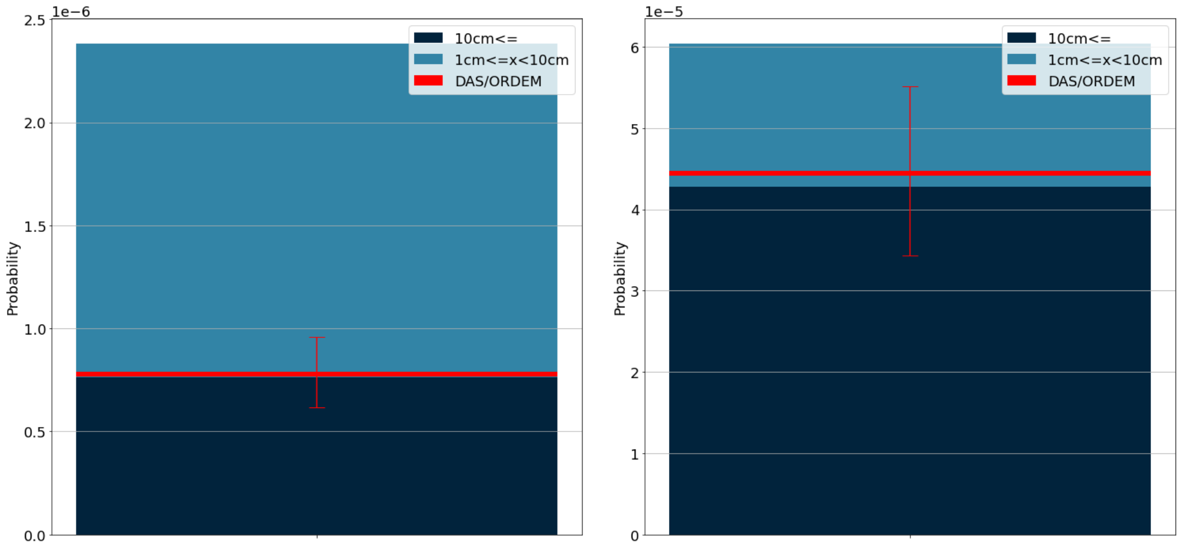

Fig. 5. 10 cm PoC vs. PoCC by Debris Size for Case 1 (left) and Case 3 (right)

Interim results of the ATREIDES Monte-Carlo runs, before PoC is applied, are shown for Case 1 in Fig. 6 below. The plot shows that for a 10 cm secondary object, a given collision would have nearly a 100% probability of catastrophic fragmentation. At half this diameter, however, the probability that a given collision would be catastrophic is still around 90%. This relation helps to explain why ignoring the flux of smaller objects could substantially underestimate the PoCC of a spacecraft.

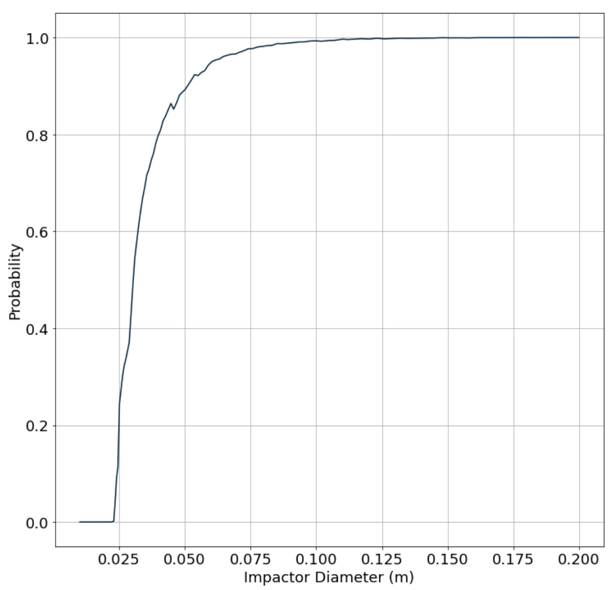

Fig. 6. Probability that a Given Collision is Catastrophic vs. Debris Size for Case 1

While Case 1 considers a smaller 50 kg primary spacecraft, the 500 kg spacecraft results in Case 3 still indicate that a DAS-only approach to calculating risk results in underestimation. As Fig. 7 shows, a collision with a 5 cm object has about a 20% chance of causing catastrophic fragmentation, whereas DAS would assume 0%.

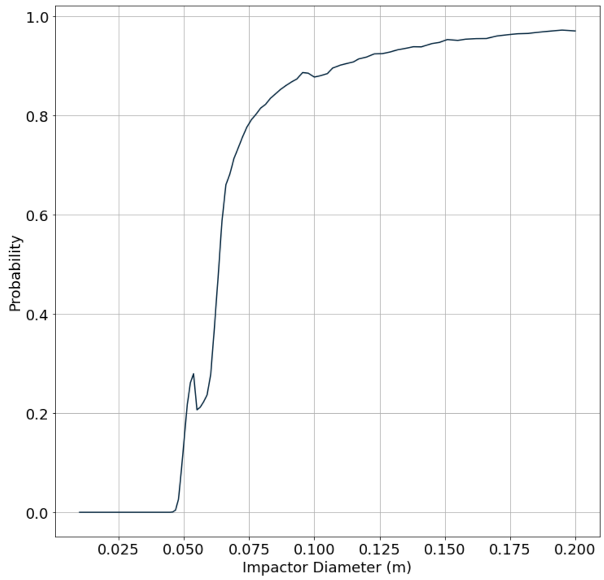

Fig. 7. Probability that a Given Collision is Catastrophic vs. Debris Size for Case 3
(The discontinuity in this plot likely arises from the mass density map transition between five and six centimeters.)

While the probability that a 10 cm object would cause fragmentation is below 100% for Case 3, indicating a slight overestimation of risk by DAS, the higher flux of small objects more than compensates for this gap, ultimately resulting in a higher overall PoCC than DAS would suggest. The ATREIDES outputs for all six test cases are presented in Fig. 8 below. Absolute value results are on the left, while the right side presents the relative proportions of risk created by objects of different sizes. The results show that a spacecraft's PoCC may be between 25-210% higher than what is reported by DAS, depending on its mass and orbit.

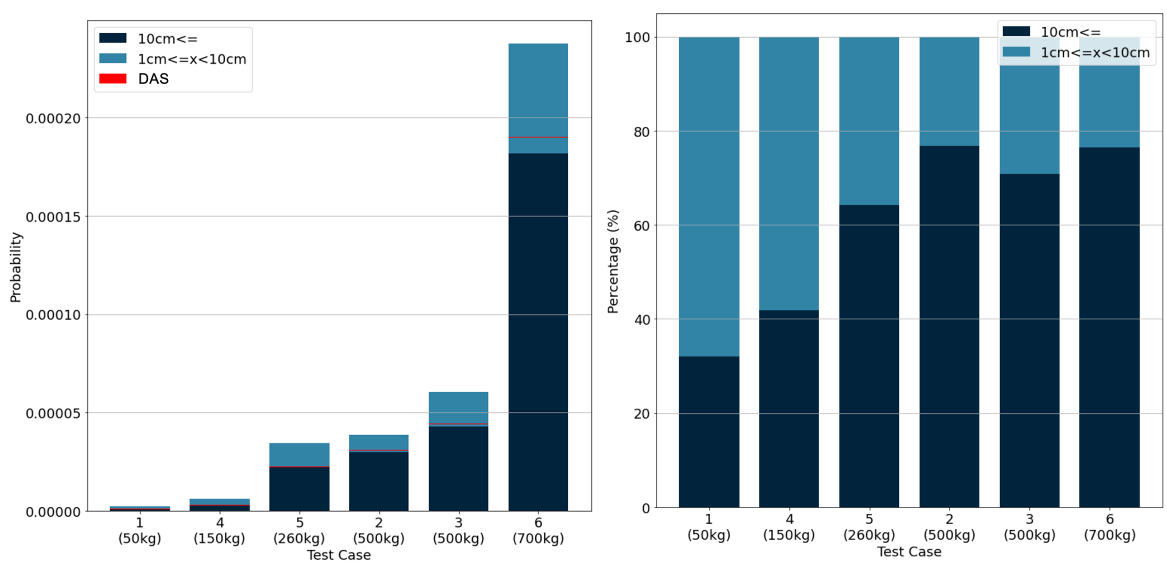

Fig. 8. Comparison of Catastrophic Collision Probability Grouped by Debris Size

2.5 Impact Scales with Mass

For many of the cases analyzed, the ATREIDES results indicates a substantial underestimation of the likelihood of catastrophic fragmentation when only collisions with large objects are considered. In addition to this, the outcome of a fragmentation event may also be underestimated if the primary spacecraft is more than 50 kg in mass. The original goal of the NASA standard is to limit the impact that one fragmentation event has on other satellites in nearby orbits, specifically focusing on the subsequent risk created by fragments larger than 1 mm. While the negative impact of a fragmentation event depends on several factors, the number of debris objects created can be approximated to scale with the ratio of the primary spacecraft mass to the 50 kg baseline, as per equation (2) below [11].

$$scale = \left(\frac{M_{primary}}{50\,kg}\right)^{0.75} \tag{2}$$

As NASA validated the goal of NASA-STD-8719.14B requirement 4.5-1 by simulating a primary spacecraft mass of 50 kg, it can be estimated that the catastrophic fragmentation of a 500 kg primary spacecraft would have an environmental impact about 5.6 times as severe.

3. Regulatory Implications

The potential underestimations of both risk likelihood and risk impact come into play when a regulator must evaluate the environmental footprint of a spacecraft operator's license. Typically, an operator will present the PoC of 10 cm objects for each one of its satellites, evaluated via DAS. Because an operational and maneuverable satellite has the capability to avoid these large, tracked objects, this PoC output from DAS commonly considers only the passive decay phase of the mission, during which the primary cannot maneuver. As this study has shown, however, even if DAS demonstrates compliance with the 1.0e-3 PoC regulation, the actual probability of catastrophic fragmentation may exceed this value.

For systems of multiple spacecraft, some regulators will aggregate the risk from all potential failed satellites in the proposed constellation, as was done in the recent grant by the FCC of SpaceX's third modification of its Starlink constellation [12]. In this grant, the aggregate PoC, as computed by DAS, was limited to 5.0e-3 for the license period: five times the original per-satellite value in NASA-STD-8719.14b. If this relaxed aggregate metric were to be applied to all systems in the same manner, the environmental risk product of likelihood (as scaled by ATREIDES) and impact (as scaled relative to the NASA validation example of 50 kg) would be as shown in the penultimate column of Table 2 below.

Table 2. Regulated Risk and Total Environmental Risk, Compared to Goal of NASA Standard

Test Case	Mass (kg)	Example Limit of Aggregate PoC (DAS)	Likelihood Scale Factor (ATREIDES PoCC vs. DAS)	Impact Scale Factor $(mass/50\ kg)^{0.75}$	Aggregate 1 mm PoC risk caused to other satellites (NASA goal < 1e-6)	Effective Aggregate PoC (DAS) required to meet NASA goal
1	50	5.0e-3	3.12x	1x	1.56e-5	3.21e-4
2	500	5.0e-3	1.26x	5.6x	3.53e-5	1.42e-4
3	500	5.0e-3	1.37x	5.6x	3.84e-5	1.30e-4
4	150	5.0e-3	2.36x	2.3x	2.71e-5	1.84e-4
5	260	5.0e-3	1.54x	3.4x	2.62e-5	1.91e-4
6	700	5.0e-3	1.25x	7.2x	4.50e-5	1.11e-4

These results imply that a constellation comprising spacecraft from any of these test cases, limited to a system aggregate 10 cm PoC of 5.0e-3 as validated by DAS, could have an actual environmental risk that is more than one order of magnitude more severe than the NASA standard had originally intended. The effective aggregate PoC limits that would ensure the NASA goal is met for each case are shown in the final column of the table.

4. Conclusions and Future Work

Before risk can be effectively managed and limited, it must first be accurately quantified. This study and its results suggest that the space debris environmental risk, as described by NASA-STD-8719.14b, is possibly being underestimated by an order of magnitude by regulators using DAS or similar tools to process license applications. This underestimation arises from ignoring both the population of debris objects smaller than 10 cm and the mass of spacecraft, and should be addressed by operators and regulators alike.

Without proper limitation of the risk arising from non-maneuverable spacecraft, the LEO environment will continue to see increasing amounts of small debris generation, which is significantly more difficult to remediate than larger objects. While this study is an initial assessment into the underestimation of this risk, future work should entail a more detailed debris object mass density map, a rigorous statistical error analysis on the results of ATREIDES, and additional cases analyzed to allow for the characterization of any potential trends.

5. References

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