A METHOD TO REFINE FRAGMENTS DISTRIBUTIONS WITH IMPACT GEOMETRY ANALYSIS

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ABSTRACT

In recent decades, near-Earth orbit usage has led to numerous fragmentation events, increasing the amount of potentially hazardous space debris. Understanding the mechanics of satellite collisions and identifying key factors that influence fragment formation have therefore become essential.

In this work, numerical simulations with the Collision Simulation Tool Solver are applied to analyze a broader set of collision scenarios, assessing the influence of different impact parameters; results are expressed in terms of fragment distributions. Furthermore, for each impact geometry a statistical weight is assigned, calculated on the satellite's visibility to the impactor. The model thus produces a weighted average fragment distribution that, unlike the NASA SBM, incorporates the effect of different impact geometries and may offer a more accurate prediction of debris dispersal.

This approach marks a significant improvement in estimating space debris, enhancing the reliability of predictions with a defined confidence interval.

Keywords: NASA SBM, hypervelocity impact, impact geometry, COSMO-SkyMed.

1. INTRODUCTION

In recent decades, the use of near-Earth orbits has led to numerous fragmentation events, increasing the amount of potentially hazardous space debris [1, 2]. Understanding the mechanics of satellite collisions and identifying key factors that influence fragment formation have therefore become essential [3]. Currently, the NASA Standard Breakup Model (SBM) is the main analytical tool for predicting fragment distributions resulting from collisions, using the Energy-to-Mass Ratio (EMR) as a key parameter based on the mass or momentum of the bodies involved [4]. However, due to its simplicity, the NASA SBM does not take into account the object's detailed design, and cannot distinguish between events with similar specific energy but different impact geometries [5, 6]. Furthermore, this latter information is often unavailable, as it has not been possible to directly observe when collision events occur, only their consequences [7]. New analytical models are being developed to address the current limits of the NASA SBM, showing that different impact conditions can strongly influence the breakup phenomena and the generated fragments distributions [8, 9].

To overcome these limitations, numerical simulations can be applied to analyze a broader set of collision scenarios, assessing the influence of different impact parameters. In this context, the Space Debris Group at the University of Padova, through collaborations in the framework of different contracts with the European Space Agency (ESA) and the Italian Space Agency (ASI), has developed the Collision Simulation Tool Solver (CSTS), a semi-empirical model that simulates satellite collisions and provides statistically accurate characteristic length, mass, area-to-mass and delta-velocity distributions of fragments [10, 11]. The CSTS approach models colliding objects using a mesh of Macroscopic Elements that represent major satellite components, such as panels and plates. These elements are connected by structural links. The fragmentation process is treated with a hybrid modelling method, where semi-empirical breakup models are applied to individual Macroscopic Elements, specifically targeting those spacecraft parts directly involved in the collision. Breakage, structural distortion, and separation of the satellite's broken parts are addressed through a discrete-element approach, taking into account energy dissipation both within elements and across links. The required inputs include the impactor's velocity direction, the location of the impact, and a high-level understanding of the bodies' structure and mass distribution. Although it is difficult to obtain this information from literature or observations, the predictive power of the model can be leveraged by providing a statistical average result, aggregating the distributions of fragments obtained from different impact geometries, as will be demonstrated in this work. This approach represents a significant advancement in the analysis of fragmentation events in space. Unlike previous methods that provided only a single expected distribution of fragments, this new technique offers a more comprehensive understanding of potential

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outcomes. By incorporating statistical analysis, it not only generates the most probable fragment distribution but also provides upper and lower bounds for these distributions. This additional information, including confidence intervals and statistical significance, allows researchers and space debris analysts to better assess the range of possible scenarios following a fragmentation event. This enhanced predictive capability is crucial for improving space situational awareness, refining risk assessments for operational satellites, and developing more effective debris mitigation strategies.
This study specifically focuses on the simulation results of a potential hypervelocity impact on a representative medium-class LEO orbit satellite, such as those within the Italian COSMO-SkyMed constellation, developed by ASI in collaboration with the Ministry of Defence. The study could, in principle, be applied to any spacecraft, provided the necessary data are available; the selection of this particular satellite is based on the availability of its geometrical and mass distribution data.
The remainder of this work is organised as follows. Next section focuses on the method employed to model the spacecraft and the different distributions, as well as on the definition of the weight factor for each obtained curve. Section 3 discusses the results and their representation in terms of average distributions with confidence intervals. Finally, a few conclusions are presented.

2. METHODS

The satellite model under study is created using available online data [12] and replicates certain specifications of satellites from the Sentinel family [13], which are very shared among them. The model consists of a central body measuring $1.4 \times 1.4 \times 3.6$ m, to which a Synthetic Aperture Radar (SAR) with an area of approximately $8\,\mathrm{m}^2$ is attached below. Two solar panels, with a total area of approximately $18\,\mathrm{m}^2$, are connected laterally via trusses. Additional components are incorporated to recreate typical features, such as the tank, antennas, trusses, internal walls, reaction wheels, and electronics grouped in boxes. Each object is assigned a thickness and material to ensure compliance with the total mass constraint of around 1700 kg. Primarily, materials such as Aluminium, CFRP, steel, and honeycomb structures are used. The impactor, on the other hand, is an Aluminium sphere with a diameter of 1 cm and a mass of 1.5 g, impacting the satellite at a velocity of 10 km/s (EMR = $3.7 \cdot 10^{-2}$ J/g).
The impact of the sphere on several faces of the spacecraft is simulated using CSTS, specifically on the SAR ("bottom"), the solar panels ("appendage"), the upper face of the main body ("top"), and the face of the main body parallel to the solar panels, distinguishing between the areas with and without the propellant tank (referred to as "tank" and "central", respectively). The SAR antenna area is divided into two parts: one adjacent to the main body ("int. bottom") and the other not attached ("ext. bottom"). For each of these six impact points, four simulations are performed, considering four different directions of velocity for the impacting sphere. The angles with respect to the normal of the face considered are 22.5°, 45°, 67.5° and 90°. The velocity of the impactor lies within a plane defined by the x-axis and the normal to the face. In total, 24 distributions of fragment-related quantities are obtained, including in particular the characteristic length (L_C) and the area-to-mass ratio (A/m).
To aggregate these distributions into a mean distribution, the Monte Carlo method is used to calculate the statistical weight of each, as follows: it is assumed that the impactor could come from any direction in space (or, in other words, considering any orientation of the spacecraft as equally probable). Impact points belonging to the same face are grouped under the same category (e.g., "top", "central", etc.), with a 10° tolerance applied to the velocity direction of the sphere along all axes. In addition, a 5° tolerance on the velocity vector is considered for sensitivity analysis.
In Fig. 1, the simplified COSMO-SkyMed model used for this Monte Carlo simulation is shown, with the different impact faces highlighted in different colours and the impactor represented in black. The convergence of the results is reached after 10^8 iterations in a relatively short time.

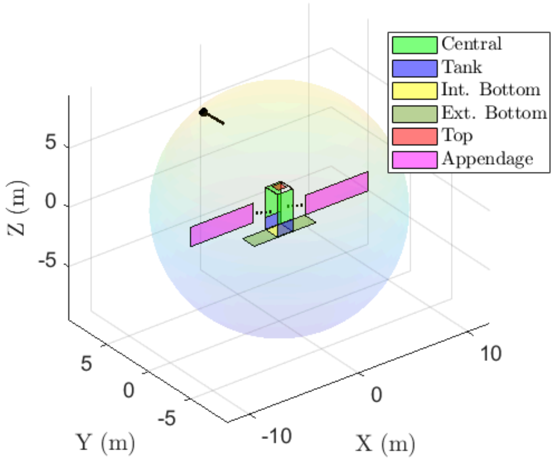

Figure 1: Representation of COSMO-SkyMed simplified model used for calculation of view factor weights by Monte Carlo method. The impactor and its velocity vector are depicted in black.

The statistical weights obtained correspond to the probability that a given impact configuration occurs, given the set of cases studied. In other words, the probability of a particular geometry is given by the ratio of the number of impacts on that geometry to the total number of simulated impacts.
With the statistical weight now available for each configuration, the 24 distributions are aggregated into a single mean distribution. For each mean value X_i, a 95% confidence interval is calculated as $CI_i = X_i \pm t_{0.95} \cdot \sigma_i$, where σ_i is the standard deviation and $t_{0.95}$ is the value of the Student's t-distribution.
Finally, for the L_C distribution, the results are presented in the usual form of a cumulative distribution.

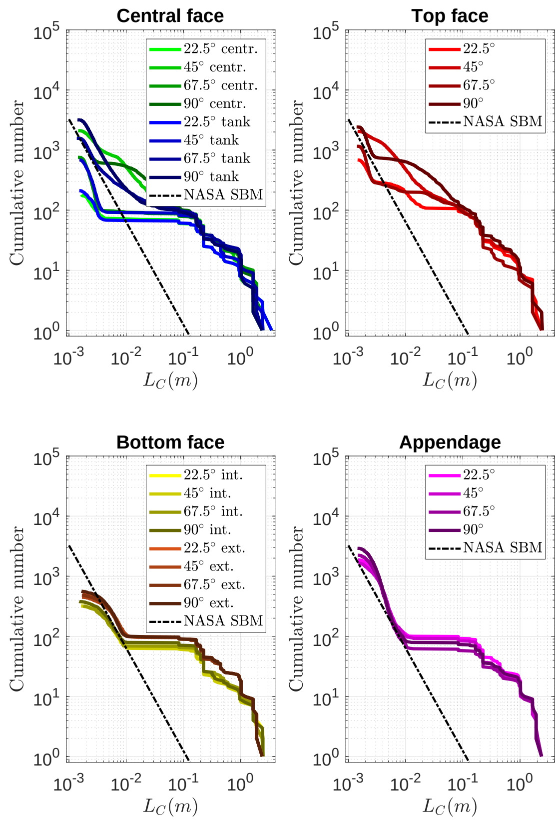

Figure 2: Characteristic length (L_C) distributions of fragments derived from CSTS simulations of a hypervelocity impact of an aluminium sphere on COSMO-SkyMed, with varying impact geometries. Note that, for each graph, darker colors indicate higher impact angles. The NASA SBM prediction is represented by the dark dashed line.

3. RESULTS AND DISCUSSION

The results of the simulations using CSTS and the Monte Carlo method are presented first. This is followed by the presentation of the weighted average distributions, and finally, the initial results of a sensitivity analysis of the method employed are presented.

3.1. Simulation results

The statistical view factor weights are presented in Tab. 1 in terms of probability percentages. As can be observed, there is no common trend concerning the angles for each impacted face. However, it can be noted that the most probable configurations are "central" and "bottom" (combining, for the latter, the "internal" and "external" cases). It should be noted that the SAR can be reached by the impactor not only from the bottom upwards, but also in the opposite direction, without encountering most of the spacecraft components (see Fig. 1 for the orientation).

Table 1: View factor weights calculated by Monte Carlo simulation with a $10°$ angle tolerance on impactor velocity direction. They are expressed in terms of probability percentage.

Impact point	α				$\sum \alpha$
	$22.5°$	$45°$	$67.5°$	$90°$	
central	4.0	8.2	8.0	3.8	24.0
tank	0.6	1.0	0.9	0.4	2.9
top	0.1	0.5	3.0	11.0	14.6
int. bottom	0.4	1.4	9.6	6.1	17.5
ext. bottom	1.8	9.1	10.4	9.9	31.2
appendage	4.2	2.4	2.2	1.0	9.8

The cumulative distributions of the characteristic fragment length, derived from simulations using CSTS, are shown in Fig. 2. The following observations can be made: the order of magnitude of the number of fragments generated at the centimetre threshold ranges between 10^2 and 10^3, depending on the considered geometry, with the NASA SBM prediction aligning with the lower estimate. The curves exhibiting greater dispersion relative to the angle of the velocity vector of the impacting sphere, below the 10 cm threshold, correspond to configurations on the central face ("central" and "tank") and the "top" case. For the SAR and solar panel configurations, the impact angle has virtually no significant influence.
Regarding the trends in the area-to-mass ratio distributions of the fragments, Fig. 3 shows the same dispersion as previously discussed. Notable in the "tank" configuration is the presence of well-defined peaks around values of approximately $1\ \mathrm{m^2/kg}$, in contrast to the "appendage" case, which produces a series of fragments with an area-to-mass ratio of around $5 \cdot 10^{-2}\ \mathrm{m^2/kg}$. This difference, which cannot be captured by the NASA SBM model, is attributed not only to the geometry of the impact but also to the materials and geometries of the spacecraft components directly affected by collision.

3.2. Average Weighted Distribution

By aggregating the data shown in Fig. 2 and Fig. 3 with the statistical weights presented in Tab. 1, the weighted average distribution curves are obtained, as shown in Fig. 4 and Fig. 5 (red line). It is remarkable that the average of the L_C distributions exceeds the NASA SBM prediction up to the 3 mm threshold; this behaviour is also observed for the lower bound of the confidence interval, up to values below 5 mm. This highlights the importance of developing new distribution models that account for this behaviour. It can also be observed that the distribution is not a straight line but consists of several segments, a feature attributable to the complex mass distribution and composition of the spacecraft. This factor also influences the A/m distribution, as seen in Fig. 5, where the two main peaks are located at $6 \cdot 10^{-1}\ \mathrm{m^2/kg}$

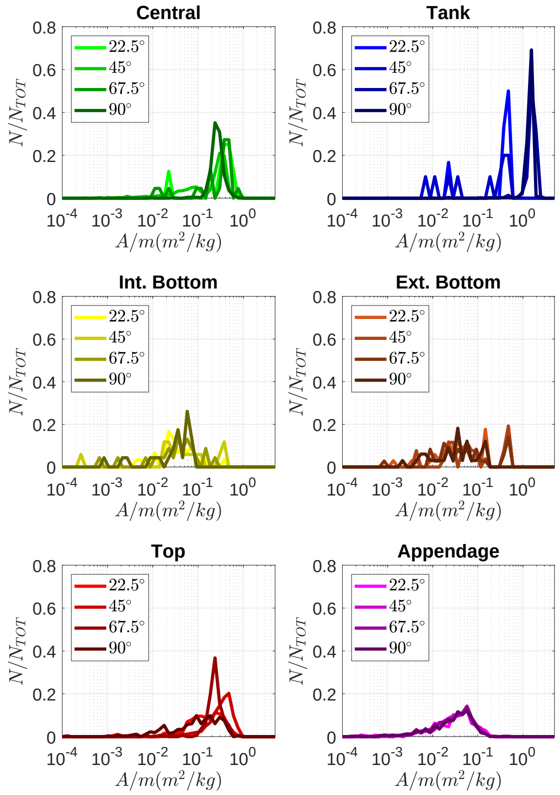

Figure 3: Area-to-mass ratio (A/m) distributions of fragments derived from CSTS simulations of a hypervelocity impact of an aluminium sphere on COSMO-SkyMed, with varying impact geometries. Note that, for each graph, darker colors indicate higher impact angles.

and $2 \cdot 10^{-3}\,\mathrm{m^2/kg}$. In this case, the upper confidence interval is very large: a possible reason for this is the coarse estimation of the fragments' area. Further investigation is currently underway to reduce the uncertainty of the model and improve the confidence level.

3.3. Sensitivity Analysis

The method proposed so far is tested by varying the parameter of angular tolerance in the direction of the impactor velocity, used in the Monte Carlo simulation to calculate the statistical view factor weights. The angle being referred to is reduced by a factor of 2, from 10° to 5°. The probability results are reported in Tab. 2. When comparing them with the previous case (Tab. 1), it can be observed that, for most of the geometries studied, no significant variations are observed, except for the "top" configuration. Comparing the weighted average distributions calculated with the weights for the two different angular tolerances, the difference is negligible (Fig. 6 and Fig. 7).

These initial results already suggest the robustness of the adopted method; however, it is necessary to test

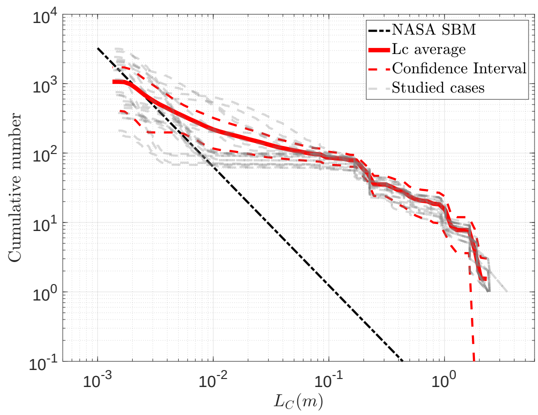

Figure 4: Characteristic length (L_C) weighted average distribution of fragments is shown by the red line, with the confidence interval indicated by the dashed red line. The NASA SBM prediction is represented by the dark dashed line, while all L_C distributions shown in Fig. 2 are depicted in grey.

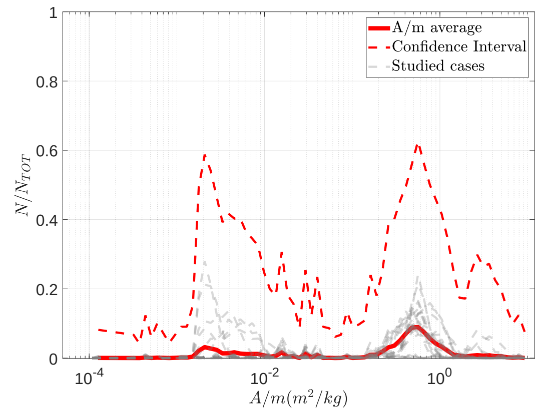

Figure 5: Area-to-mass ratio (A/m) weighted average distribution of fragments is shown by the red line, with the upper confidence interval indicated by the dashed green line. All A/m distributions shown in Fig. 3 are depicted in grey.

Table 2: View factor weights calculated by Monte Carlo simulation with a 5° angle tolerance on impactor velocity direction. They are expressed in terms of probability percentage.

Impact point	α 22.5°	45°	67.5°	90°	$\sum\alpha$
central	3.3	7.3	6.8	3.1	20.5
tank	0.6	0.9	0.8	0.3	2.6
top	0.1	0.4	2.2	19.9	22.6
int. bottom	0.4	1.2	8.3	8.4	18.3
ext. bottom	1.5	8.1	9.0	8.8	27.4
appendage	3.7	2.1	1.9	0.9	8.6

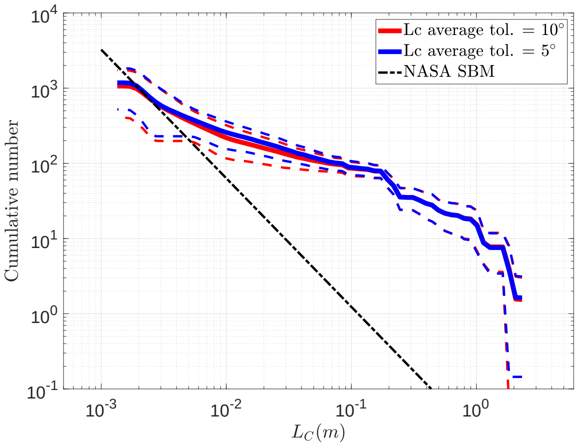

Figure 6: Characteristic length (L_C) weighted average distribution of fragments, with the confidence interval indicated by the red color for a 10° angle tolerance on impactor velocity. The same distribution and confidence interval are shown in blue for a 5° angle tolerance. The NASA SBM prediction is represented by the dark dashed line.

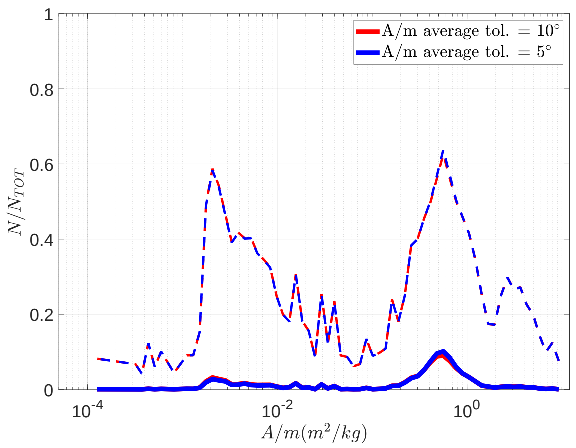

Figure 7: Area-to-mass ratio (A/m) weighted average distribution of fragments, with upper confidence interval indicated by the red color for a 10° angle tolerance on impactor velocity. The same distribution and upper confidence interval are shown in blue for a 5° angle tolerance.

the other hypothesis considered, namely that all points belonging to the same face result in an equivalent fragment distribution when simulated with CSTS. An initial result concerns the "appendage" configuration, where normal impact is tested at a central point, a point closer to the central body, and a point farther from it. The corresponding L_C distributions, shown in Fig. 8, are very similar.

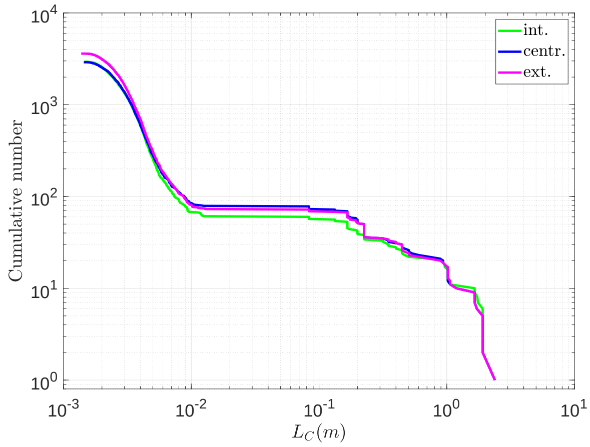

Figure 8: Characteristic length (L_C) distributions of fragments in the case of "appendage" face in three different impact points: closer to the central body (green), central (blue) and farther from the central body (magenta).

4. CONCLUSIONS

In recent decades, the increasing frequency and severity of fragmentation events in near-Earth orbits have led to a substantial increase in space debris number, highlighting the need for a deeper understanding of satellite collision mechanics and the factors influencing fragments formation. This study demonstrates the application of a novel simulation-based approach to overcome the limitations of the NASA Standard Breakup Model (SBM). While the NASA SBM is widely used, it fails to account for the detailed design of objects or variations in impact geometries. By incorporating the Collision Simulation Tool Solver (CSTS) and statistical analysis using the Monte Carlo method, this study provides more accurate and comprehensive predictions of fragment distributions.

Simulations conducted on the COSMO-SkyMed satellite under various impact scenarios confirmed that the impact geometry and the detailed structure of the satellite play essential roles in determining fragmentation patterns. The results, including distributions of characteristic length (L_C) and area-to-mass ratio (A/m), revealed that fragmentation behaviour is not uniform across different geometries and impact angles. Notably, the weighted average L_C distribution, with weights calculated based on the satellite's visibility to the impactor and assuming a uniform distribution of impactor velocity directions, exceeded the NASA SBM prediction, up to lower thresholds, underscoring the importance of considering detailed structural and geometrical factors when predicting debris generation.

Furthermore, the weighted average distributions indicate that the complexity of the results, especially regarding the A/m ratio, cannot be captured by the NASA SBM. This highlights the need for new models that incorporate these complexities, particularly with respect to material properties and energy dissipation during impacts.

An additional sensitivity analysis, which examined the effect of angular tolerance on the direction of the impactor velocity, also showed that variations in tolerance did not significantly affect the fragmentation results for the majority of the investigated geometries.
These findings underscore the robustness of the adopted simulation method and demonstrate its potential for predicting space debris generation. Ongoing studies aim to refine the model, particularly in terms of calculating fragment areas and testing alternative hypotheses regarding uniform fragment distributions across different spacecraft surfaces, or considering the explosion of the satellite's tank. In conclusion, the CSTS approach, when coupled with statistical analysis, represents a significant advancement in predicting satellite breakup and fragment distribution. It provides a more detailed and statistically robust framework for assessing fragmentation events and offers a powerful tool for improving space debris management.

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