Examining the Accuracy of the NASA Standard Break-up Model Using Space Fence Data

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***Abstract*—The United States Space Force (USSF) declared their second-generation space domain awareness (SDA) radar known as "Space Fence" fully operational on March 28th, 2020. Since then, the radar has been collecting a wealth of SDA data for detecting, tracking, and identifying anthropogenic objects in space. This paper presents case studies using the Space Fence data available at MIT Lincoln Laboratories (MIT/LL) to examine the accuracy of the NASA Standard Break-up Model (SBM). NASA developed their model for satellite break-ups in the 1990s with ground test data and limited, low-fidelity SDA data of on-orbit break-ups. The model does not accurately take into account principles of conservation of mass and has already been proven to produce inaccurate debris cloud estimations. Until the advent of Space Fence, very small debris was virtually invisible to SDA observers. Now that Space Fence has been operational for several years and has observed break-up events on-orbit, opportunities have emerged to further investigate and characterize the inaccuracies that exist in the current NASA break-up model. This study involves using the NASA SBM to simulate five known break-up events, identify the debris cloud from the same events captured by Space Fence, and compare the simulated results with the truth data. This paper motivates future areas for research, such as introducing new satellite break-up models using machine learning techniques.**

***Index Terms*—space debris, space sustainability, space traffic management, NASA standard break-up model, Space Fence, machine learning, collision consequence, space domain awareness**

I. Introduction

The USSF's mission to maintain space domain awareness involves monitoring and understanding the space environment to support space operations and ensure the safety and security of military, civil, commercial space assets. The goal of SDA is to provide timely and accurate information on the location, trajectory, and behavior of objects in space, including active satellites, space debris, and any potential adversarial threats [1]. The DoD's SDA program includes a network of ground-based and space-based sensors that detect, track, catalog, and identify objects in space, called the Space Surveillance Network (SSN). This data is used to develop and maintain a comprehensive catalog of space objects, which is used to predict and prevent potential collisions and support space operations [2]. In addition to monitoring and cataloging space objects, the USSF's SDA program also conducts research and development on technologies and techniques to improve SDA capabilities and stay ahead of emerging threats. This includes developing new sensors, algorithms, and data processing techniques, as well as collaborating with international partners to improve global SDA capabilities [1]. The Space Fence system is an example of an advanced technology used for SDA. Space Fence is a ground-based sensor that uses an advanced solid-state S-band phased array radar technology [3]. Space Fence provides the SSN with enhanced SDA in all orbital altitudes, a better revisit rate of objects in low-Earth orbit, and an increased capability to track debris as small as 1-2 cm [4]. The SDA mission is critical for maintaining safe, sustainable, and effective operations in space and protecting national security interests in the increasingly congested and contested space domain.

II. Break-up Events

Space debris is caused by a variety of sources and is made up of items such as rocket bodies, fragments from explosions and accidental collisions, or even paint flakes. Space debris can also be caused by countries conducting weapon tests to destroy their own satellites using anti-satellite (ASAT) missiles. This section explains the five break-up events that are used in this study.

- COSMOS 1408 ASAT Test: On 15 November 2021, Russia conducted a destructive test with a direct-ascent ASAT missile against one of its own satellites, COSMOS 1408. The US openly condemned the action as "reckless," stating that Russia demonstrated "deliberate disregard for the security, safety, stability, and long-term sustainability of the space domain for all nations." Debris from the event caused the International Space Station to conduct emergency procedures following the missile collision [5]. Original estimates for the number of debris pieces caused by the collision vary depending on the source but are roughly on the order of magnitude of 1500 pieces.
- Chang Zheng 6A: On 12 November 2022, an upper-stage rocket body from a Chinese launch vehicle exploded in orbit. In a Twitter post on 13 November, the USSF 18th Space Defense Squadron (SDS) announced that they were tracking over 50 pieces of debris from the rocket explosion [6]. In a later update, the number of debris from the event was estimated as 350 pieces [7].

- H-IIA Launch Vehicle: On 3 July 2022, the 18th SDS confirmed the break-up of a Japanese rocket fairing from the H-IIA launch vehicle, caused by an explosion of leftover fuel vapor in the propulsion tanks. The 18th SDS tracked 23 debris pieces from the explosion [8].
- COSMOS 2499: On 3 January 2023, a Russian satellite known as COSMOS 2499 fragmented into over 85 pieces being tracked by the 18th SDS [9]. The purpose and capabilities of COSMOS 2499 are unknown, and the cause of the fragmentation is also unknown.
- Orbcomm FM36: On 11 March 2023, a US communications satellite from the Orbcomm constellation fragmented into seven pieces being tracked by the 18th SDS [10]. The cause of the fragmentation is unknown.

III. Methodology

A. About the NASA Model

The NASA Standard Break-up Model (SBM) is a model used to predict the fragmentation of an object after an on-orbit collision or explosion. It is based on a set of empirical relationships derived from laboratory experiments and observations of actual in-space impacts (prior to the advent of exquisite sensors such as Space Fence). The NASA SBM predicts that an object breaks up into a certain number of fragments defined by characteristic lengths. For a collision, the model uses the mass of primary (larger) object, mass of secondary (smaller) object, and the relative velocity between the two objects to determine the energy of the collision and either categorize it as "catastrophic" (above 40,000 J/kg) or "non-catastrophic" (under 40,000 J/kg). If the collision is characterized as "catastrophic" then the number of debris pieces per characteristic length is a function of the sum of the masses of the two objects. If the collision is characterized as "non-catastrophic" then the number of debris pieces per characteristic length is a function of only the mass of the secondary object and the relative velocity. For in-space explosions, the model only estimates debris distributions for objects between 600-1000kg and recommends using unitless scaling to estimate debris from explosions outside that range, without providing information on how to scale to estimate [11]. The NASA SBM is based on empirical relationships derived from ground-based tests that may not be applicable to all materials and conditions in space, and it may not accurately predict the behavior of on-orbit collisions and explosions. The model uses a basic power law curve that is only effective at estimating debris between 10 cm and 1m. The only way that the model accounts for conservation of mass is by adding two to eight large pieces of debris after deriving the mass using the area to mass ratio of the 10 cm to 1 m debris. For comparison with Space Fence data in the "USSF Space Fence Results" section, we extended the power law curve lower bound to 2 cm. To account for this extension, the predictions from the NASA SBM are scaled according to the known observation sensitivity of the Space Fence radar, so that a more realistic comparison can be made between what was observed and what was predicted to be observed based on radar accuracy at each debris size.

B. Gathering truth data

To compare the NASA break-up model predictions to the truth data collected by Space Fence, we first must identify which pieces or orbital debris are attributed to each break-up event or collision. Debris may de-orbit shortly after the fragmentation event if it occurred at low altitude, so only tracks formed during the first pass through Space Fence's field of view after the event epoch are included in the analysis. In order to attribute debris to the event during that time window, we use the tracks formed by Space Fence and compare orbital plane inclination, beta-angle, and other orbital elements to form a list of possible debris. Then, we remove any objects that already have associated resident space object (RSO) numbers, indicating that those were known, tracked objects prior to the break-up. Lastly, we can use radar cross-sections to determine the characteristic length of each piece of debris for comparison with the predictions from the NASA model.

IV. NASA Standard Break-up Model Predictions

A. COSMOS 1408 ASAT Test

Figure 1 shows a notional image of the ASAT after launching from a Russian launch site, aligned with the orbit of COSMOS 1408. This break-up event is modeled in the NASA SBM as a catastrophic collision based on publicly available data about the mass of the two objects and their relative velocity. The mass of the primary object (COSMOS 1408) is 1750 kg [12], and the mass of the secondary object (the Russian ASAT) is estimated to be 63.5 kg. The mass of the ASAT was estimated using information from Raytheon missile interceptor kill-vehicle technology [13]. The relative velocity between the two objects, 4.6 km/s, was determined based on information published by COMSPOC Corporation [14]. The results of the analysis are shown in Table I, where the resulting number of debris pieces predicted is broken into two size categories: between 10cm and 1m, and debris larger than 1m.

B. Chang Zheng 6A

For this explosion event, the mass of the rocket body is estimated as 952 kg, with a radius of 3.0 m. This information is based on the US equivalent rocket specifications [15], since the exact Chinese rocket specifications are not publicly available. The results of the NASA SBM analysis for the Chang Zheng 6A fragmentation event is shown in Table II and plots of the debris distribution are shown in Fig. 3.

C. H-IIA Launch Vehicle

For this explosion event, the mass of the rocket body is known to be 1400 kg, with a radius of 8.0 m [16]. The results of the NASA SBM analysis for the H-IIA fragmentation event is shown in Table III and plots of the debris distribution are shown in Fig. 4.

D. COSMOS 2499

The fragmentation of the COSMOS 2499 satellite was due to unknown causes, and could have been either from a low-energy collision (i.e. with a small piece of non-trackable debris) or from an explosion. For this study, both possibilities are considered. For the collision scenario, a secondary object of arbitrarily small mass with high relative velocity is assumed. The mass of the primary object is estimated as 50 kg based on information from Gunter's Space Page [17]. The results of the NASA SBM analysis for the COSMOS 2499 fragmentation event is shown in Table IV and plots of the debris distributions for the two scenarios are shown in Figs. 5-6. Figure 7 shows orbit trajectories for the debris pieces from the COSMOS 2499 break-up event, modeled using the Space Cockpit application.

E. Orbcomm FM36

Similar to the COSMOS 2499 event, the fragmentation of the Orbcomm FM36 satellite was also due to unknown causes, and could have been either from a low-energy collision or from an explosion. For this study, both possibilities are considered. For the collision scenario, a secondary object of arbitrarily small mass with high relative velocity is assumed. The mass of the primary object is known to be 42 kg with a radius 3.5 m based on information from the manufacturer [18]. The results of the NASA SBM analysis for the Orbcomm FM36 fragmentation event is shown in Table V and plots of the debris distributions for the two scenarios are shown in Figs. 8-9.

V. USSF Space Fence Results

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VI. Discussion

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VII. Conclusions and Future Work

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Appendix: Figures and Tables

A. COSMOS 1408 ASAT Test

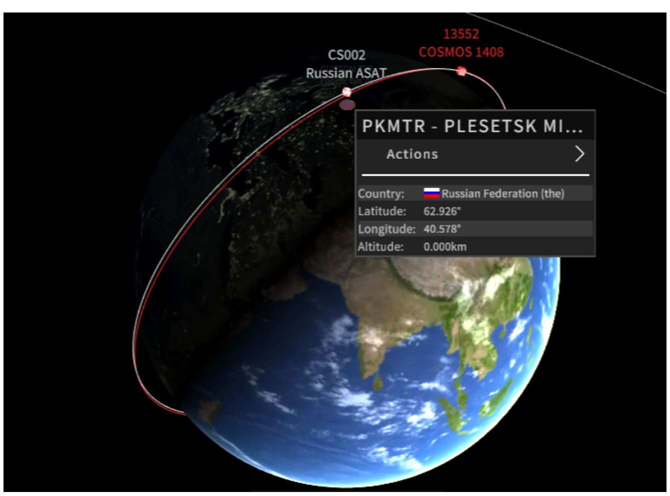

Fig. 1. COSMOS 1408 orbit and Russian ASAT launching to intercept, modeled using Space Cockpit application.

TABLE I
NASA SBM Predictions: COSMOS 1408 ASAT Test

Model Inputs		
Primary Object Mass	1750	kg
Secondary Object Mass	63.5	kg
Relative Velocity	4.6	km/s
Model Outputs		
Classification: Catastrophic Collision		
Num. debris pieces	1403	10 cm - 1 m
Num. debris pieces	2	above 1 m

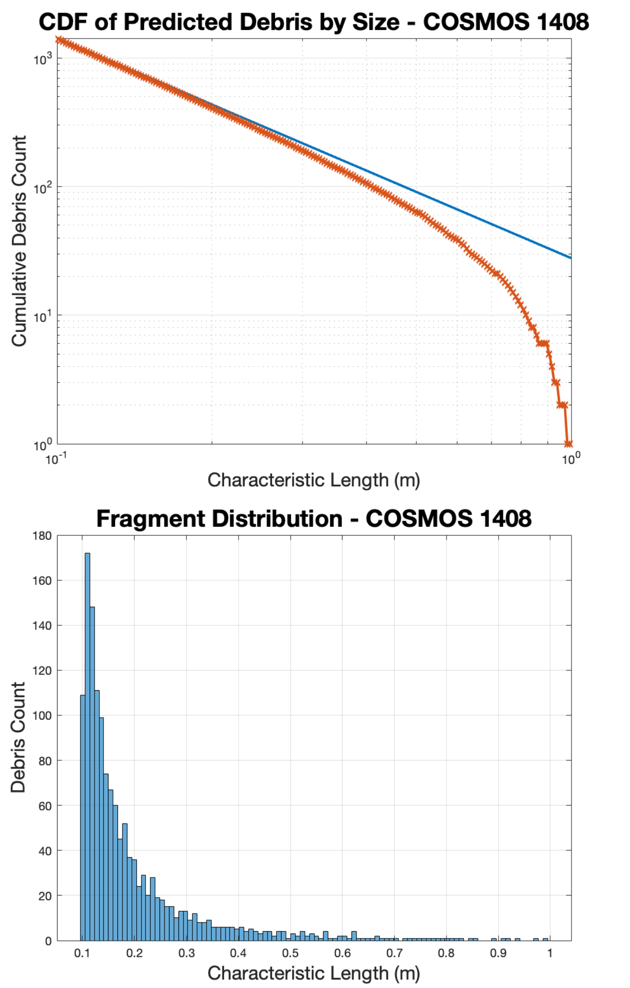

Fig. 2. Debris distribution by characteristic length for COSMOS 1408 collision.

B. Chang Zheng 6A

TABLE II
NASA SBM PREDICTIONS: CHANG ZHENG 6A

Model Inputs		
Primary Object Mass	952	kg
Primary Object Radius	3.0	m
Model Outputs		
Classification: Explosion		
Num. debris pieces	239	10 cm - 1 m
Num. debris pieces	6	above 1 m

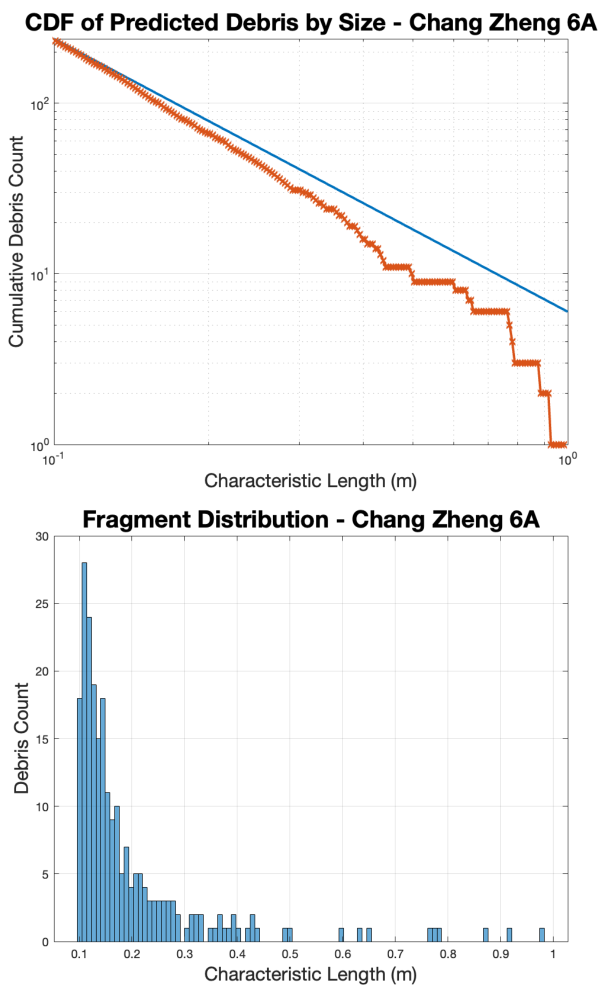

Fig. 3. Debris distribution by characteristic length for Chang Zheng 6A explosion.

C. H-IIA Launch Vehicle

TABLE III
NASA SBM PREDICTIONS: H-IIA LAUNCH VEHICLE

Model Inputs		
Primary Object Mass	1400	kg
Primary Object Radius	8.0	m
Model Outputs		
Classification: Explosion		
Num. debris pieces	242	10 cm - 1 m
Num. debris pieces	8	above 1 m

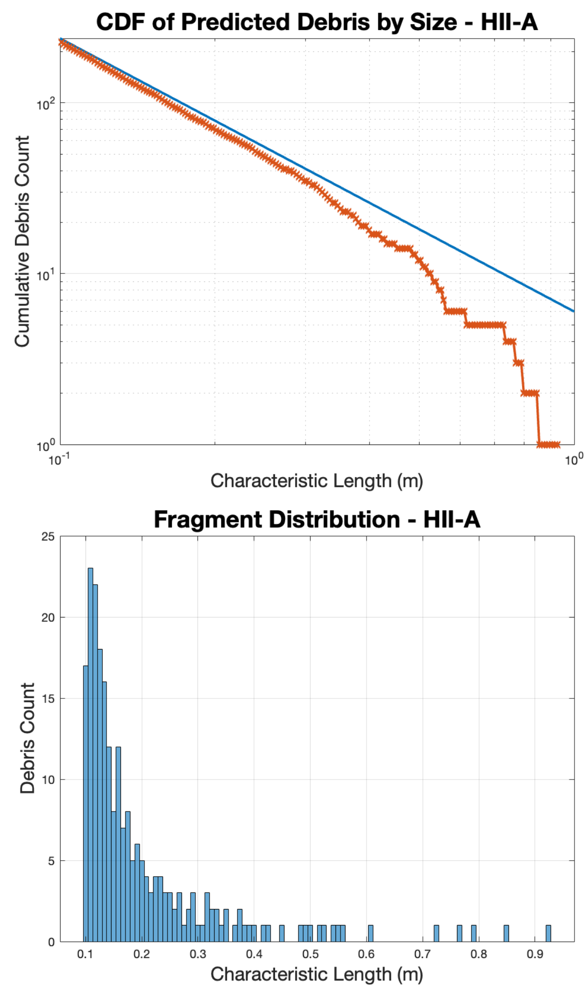

Fig. 4. Debris distribution by characteristic length for H-IIA explosion.

D. COSMOS 2499

TABLE IV
NASA SBM PREDICTIONS: COSMOS 2499

Model Inputs		
Primary Object Mass	50	kg
Primary Object Radius	3.5	m
Secondary Object Mass	1.0	kg
Relative Velocity	5.0	km/s
Model Outputs		
Classification: Non-Catastrophic Collision		
Num. debris pieces	99	10 cm - 1 m
Num. debris pieces	3	above 1 m
Classification: Explosion		
Num. debris pieces	222	10 cm - 1 m
Num. debris pieces	1	above 1 m

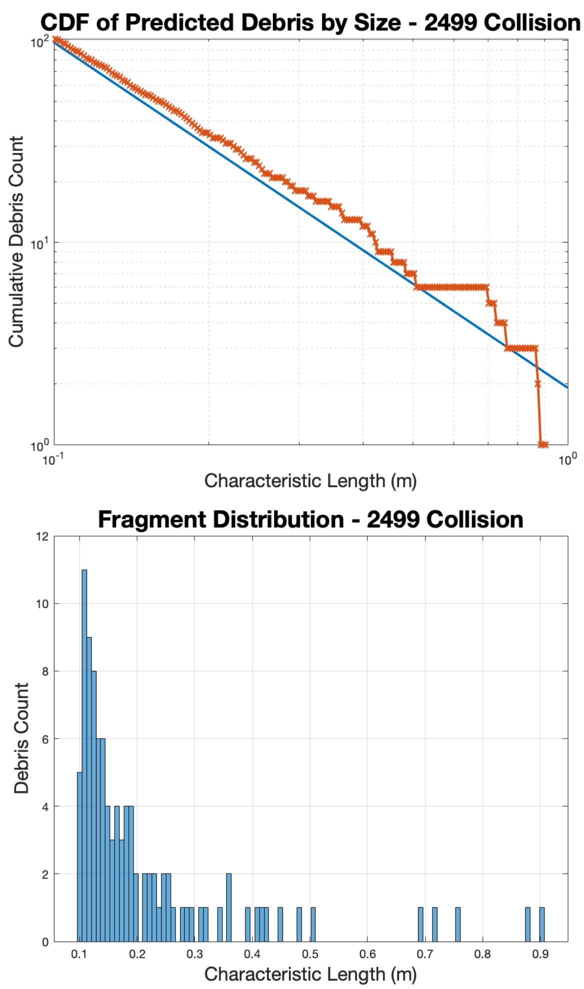

Fig. 5. Debris distribution by characteristic length for COSMOS 2499, modeled as a low-energy collision.

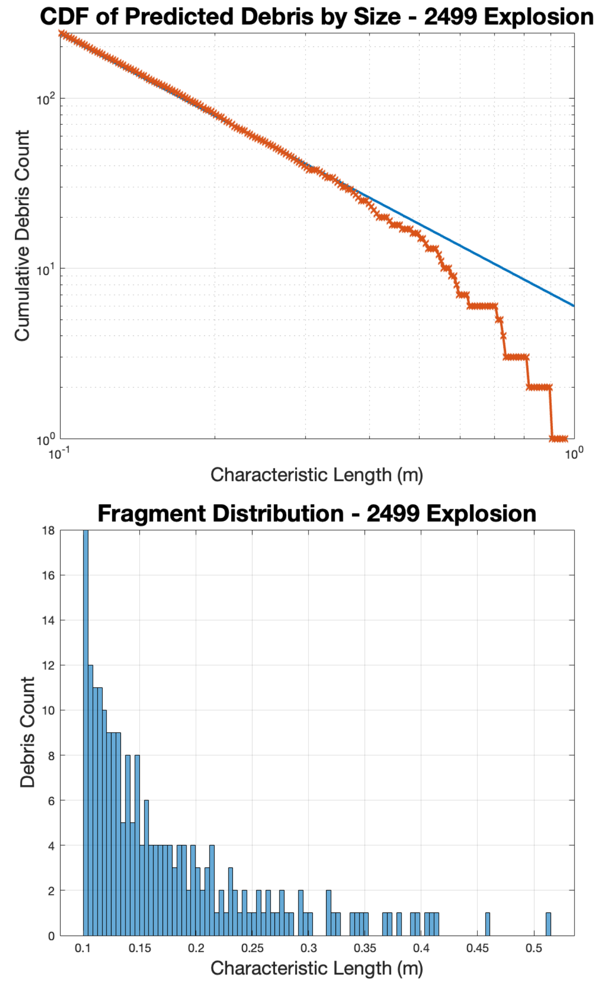

Fig. 6. Debris distribution by characteristic length for COSMOS 2499, modeled as an explosion.

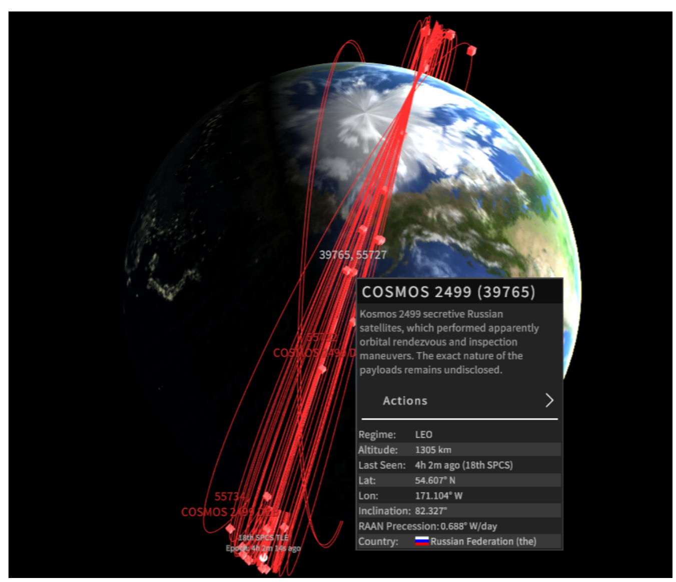

Fig. 7. COSMOS 2499 debris orbits, modeled using Space Cockpit application.

E. Orbcomm FM36

TABLE V
NASA SBM Predictions: Orbcomm FM36

Model Inputs		
Primary Object Mass	42	kg
Primary Object Radius	3.5	m
Secondary Object Mass	0.10	kg
Relative Velocity	5.0	km/s
Model Outputs		
Classification: Non-Catastrophic Collision		
Num. debris pieces	80	10 cm - 1 m
Num. debris pieces	3	above 1 m
Classification: Explosion		
Num. debris pieces	214	10 cm - 1 m
Num. debris pieces	1	above 1 m

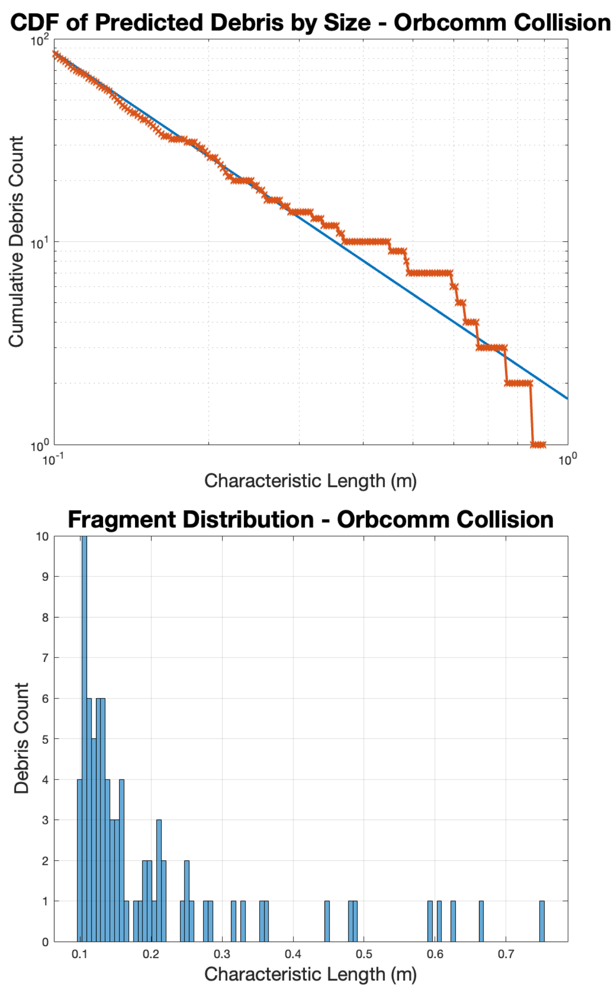

Fig. 8. Debris distribution by characteristic length for Orbcomm FM36, modeled as a low-energy collision.

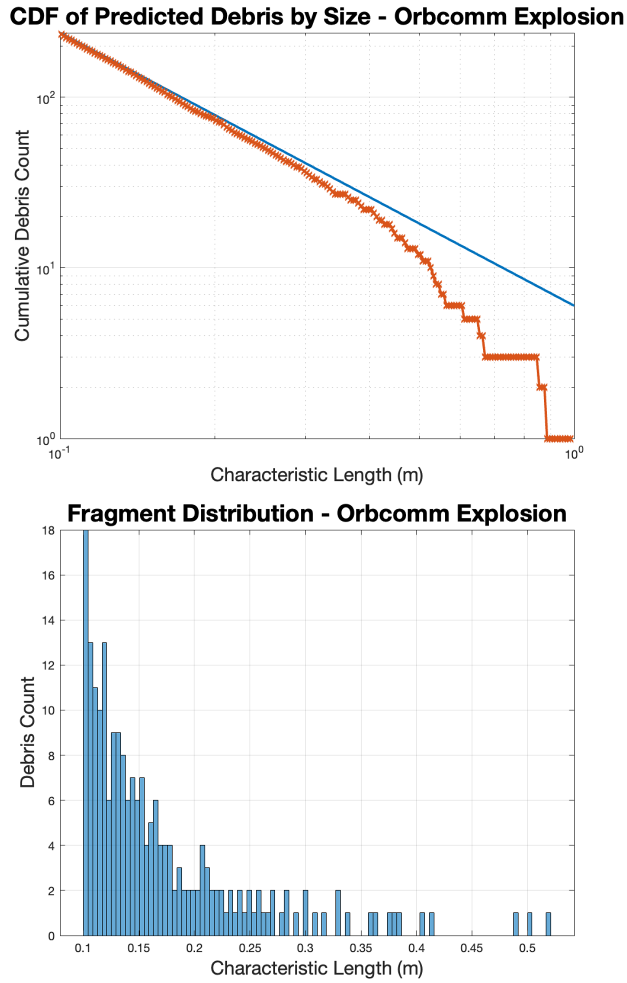

Fig. 9. Debris distribution by characteristic length for Orbcomm FM36, modeled as an explosion.

Appendix: Code Repository

All code used to implement the NASA Standard Break-up Model and to generate the figures for this project is available at this Github code repository: https://github.com/capitalts/Astrodynamics.git. Implementation of the NASA SBM was derived from https://github.mit.edu/arclab/orbitalrisk_MC.

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