Forensic analysis of recent debris-generating events

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ABSTRACT

Every on-orbit collision or explosion can pose a threat, not only to the existing satellite population but also to the long-term usability of Earth orbit. This threat exists even if satellites can actively maneuver to avoid trackable debris fragments, since an estimated 96 percent of potentially mission-ending (>1cm) debris is untrackable [1]. Prevention of every on-orbit breakup may not be possible. However, armed with an understanding of the likely causes of fragmentation events, satellite developers and operators can take actions to mitigate such events in the future. Astrodynamics forensic analyses, the sleuthing techniques used to gather an event's known details and estimate its unknown parameters, can be used to develop theories about the causes of a breakup and to predict its consequences.

In the past five years, several on-orbit collisions and explosions have occurred, involving a variety of orbiting objects with varying amounts of available observational data. Techniques and tools developed at The Aerospace Corporation are used to characterize key parameters of these events, including spread velocity of the debris pieces, energy involved in the breakup events, and mass and area estimates of the individual debris fragments. Representative models of events are developed using the IMPACT fragmentation tool, and predictions of the lifetimes of the subtrackable orbital debris are included. Where event sources are unknown, breakup parameters and trends are used to suggest possible causes. This paper will show solutions for a variety of event types including collisions, such as the Cosmos 1408 ASAT test and SL-14 rocket body breakup, rocket body fragmentations such as the 2022 Long March 6A breakup, and satellite fragmentations such as the Resuro-01 breakup. The challenges of analyzing an orbital breakup mystery with few observational clues are also discussed.

1 INTRODUCTION

Notable debris-generating fragmentation events have been occurring on orbit since 1961, with the first serious on-orbit satellite fragmentation [2]. These events have generally been the result of material degradation, such as shedding, or sudden energy releases such as explosions. Another, less frequent but potentially more impactful to the orbital environment, cause of fragmentations is the collision between two objects. The first intentional collision involving Cosmos 248 was in 1968, and the first confirmed accidental collision involving the Cerise satellite was in 1996. Debris mitigation best practices and collision avoidance (COLA) have helped to prevent some events. However, some of the most significant events have occurred in the last 20 years. The first accidental collision of two intact spacecraft, Iridium 33 and Cosmos 2251 in 2009, and the intentional fragmentations of the FY-1C payload in 2007 and the Cosmos 1408 payload in 2021 are the three largest contributors of on-orbit debris.

Complete prevention of on-orbit fragmentation events may not be possible. However, techniques can be developed to minimize their frequency [3]. Forensic analyses can reveal details about fragmentation events that may shed light on the likely causes of these events and provide valuable models of the resultant debris that can be used for near-term characterization of the risk to other on-orbit assets by
tools such as Aerospace’s Debris Analysis Response Tool (DART) and for long-term predictions of the debris environment by tools such as the Aerospace Debris Environment Projection Tool (ADEPT) [4].

1.1 Background

For over 35 years, The Aerospace Corporation has analyzed and modeled over 50 on-orbit energetic fragmentation events (i.e., explosions and collisions) and several ground tests. Analysis is focused on obtaining key parameters of a breakup, including the time of the event, spread (relative) velocity of the debris fragments, the energy involved in the breakup event, and mass and area estimates of individual debris fragments. The breakup information can be used to develop a model of the event for near-term active satellite risk assessments and for long-term orbital environment predictions. Breakup parameters reveal event characteristics that can be compared to past analyses to develop theories about the causes of the breakup and to propose actions to mitigate future events. Numerous tools have been developed through this research to model and aid in the assessment of these energetic on-orbit events [5]. These tools rely on radar tracking information from the 18th Space Control Squadron (18 SPCS) of the U.S. Space Force Space Surveillance Network (SSN) to characterize the debris from a breakup event.

The software package Collision Vision (CV) [6] was developed to support operational launch collision avoidance and can estimate the time of fragmentation using cataloged data shortly after the event occurs. Fragments are propagated backwards to find the most likely common position with the pre-event object and to estimate relative velocities of the fragments. An additional approach is used to evaluate debris objects that may not be added to the catalog until weeks or months after the event. The slowly varying orbit elements of debris objects are compared with the original pre-event object to estimate the relative (spread) speeds of the debris fragments immediately following the event [7]. Spread speeds provide valuable insight into the mechanism of the fragmentation. Equations were derived to relate the average spreading speed of observed (trackable) fragments, the mass of the object(s), and the total energy of an explosion or collision event [8]. Estimates of the event energy provide insight into the root cause of the breakup and the characteristics of the resultant fragments.

A fragment’s orbital lifetime is influenced by its area-to-mass ratio (AMR). ADOBE [9] estimates the AMR over an interval of time, using the two-line element (TLE) sets for all trackable debris.

The Aerospace Corporation’s IMPACT [10] collision and explosion tool combines empirical relationships derived from ground test and on-orbit event data with conservation laws and boundary conditions to generate fragment number, mass, spreading velocity, and AMR distributions. An extensive evaluation of over 11,000 pieces of debris from more than three-dozen historical on-orbit events [11] showed good agreement between the IMPACT model and trackable fragments from observed on-orbit events. Results also provided insight into “standard” inputs to the tool that provide a good baseline for evaluation of events within certain categories. Inclusion of the data from the 2014 DebriSat ground test [12] in IMPACT 8.0 [13] has increased confidence in the model’s validity for prediction of sub-trackable objects.

1.2 Assumptions

Lifetime analysis via long-term orbit propagation is performed by an efficient long-term mean element propagator using the Draper Semi-analytic Satellite Theory [14].

“Trackable” refers to objects that are detected and cataloged using the SSN. In general, cataloged debris is 10cm in diameter or larger, though some smaller objects are detectable at lower altitudes. IMPACT analysis includes fragments as small as 1cm, which are small enough to be undetectable but large enough to cause damage and most likely be mission-ending if they collide with an orbiting vehicle.
2 COLLISION ANALYSIS: Cosmos 1408

The Cosmos 1408 (1982-092A, SSN #13552) derelict Soviet electronic and signals intelligence Tselina-D-class spacecraft was launched in 1982 and was the target of a direct-ascent anti-satellite test on November 15, 2021. At the time of the event, the spacecraft was in an orbit of 490 x 465km altitude at an inclination of 82.6 degrees. More than 1600 trackable fragments were associated with the event [15].

Aerospace analysis assumed a mass of 2000kg for Cosmos 1408. From analysis of the trackable fragments, the most likely time of the event is 2:45:23.6 on November 15, 2021. Plots of the spread velocity vector components of the trackable fragments are shown in Figure 1. The velocity components are evaluated in the RTN frame, where R (radial) is defined by the position vector from the Earth to the orbiting object, N (normal) is the vector normal to the plane of motion in the direction of the orbit angular momentum vector, and T (tangential) completes a right-handed coordinate frame. The fragments have spread velocities roughly perpendicular to the radial vector with an average spread speed of 183 m/s. At this average speed, the estimated collision energy is 1900MJ, corresponding to an estimated relative collision velocity of 6.3 km/s based on an assumed interceptor mass. Because the estimated collision energy for the FY-1C ASAT event was comparable, at 1300MJ, fragment distributions are expected to be similar, and comparison can provide confidence in the Cosmos 1408 reconstruction.

![Figure 1: Cosmos 1408 Spread Velocity Component Plots in RTN Frame](image1.png)

The IMPACT model of this collision produces an estimated 1320 trackable (10cm) fragments and 1940 fragments larger than 5cm. Figure 2 compares the Gabbard diagram created from the on-orbit data to the diagram created from IMPACT model data for trackable-sized fragments. The Gabbard diagram is a plot of the apogee altitudes, in red, and the perigee altitudes, in blue, versus the orbital periods of the fragments. The majority of the fragments that remained in orbit after the event were ejected into eccentric orbits with higher apogees than the original Cosmos 1408 orbit and will thus remain on orbit for some time, as will be discussed below.

![Figure 2: Cosmos 1408 Gabbard Diagrams from Data (left) and IMPACT (right)](image2.png)
The cumulative mass distribution from the IMPACT model is shown in Figure 3. The slope of this curve is an indicator of the energy involved in the event and is consistent with analysis of the FY-1C collision fragments.

Figure 3: Cumulative Mass Distributions from IMPACT model of Cosmos 1408 FY-1C Data

Comparisons of the IMPACT and Adobe Area-to-Mass ratios (AMR) are shown in Figure 4(a), and IMPACT and TLE data spread velocity distributions are shown in Figure 4(b). The IMPACT model includes a spherically symmetric spread velocity distribution relative to a post-collision center-of-mass velocity, which will bias the spreading velocities directions dependent on the intercept geometry. Small errors in the intercept geometry may result in a direction bias that differs with Figure 1, so velocity components are not compared. However, the velocity magnitudes align, providing confidence in the reconstruction.

Figure 4: (a) Cosmos 1408 Spread Velocity Distributions from IMPACT and Data, and (b) Cosmos 1408 Cumulative Area-to-Mass Ratio Distribution from IMPACT and Adobe

One of the larger concerns about an event of this magnitude is its effect on the long-term orbital environment. The IMPACT model estimates that this event produced over 200,000 fragments with diameters of 1cm or larger. Figure 5 is a plot of the number of all 1cm or larger fragments remaining in orbit versus time. This plot was produced by propagation of all predicted fragments, and it shows that a considerable number of potentially mission-ending fragments will remain on orbit for over 1 year. A handful will still be on orbit over 10 years.
Numerous significant analyses of this event have been published [16] [17] [18] [19]. The Aerospace Corporation analysis of this event is consistent with their findings.

3 EXPLOSION EVENT ANALYSIS: CZ-6A R/B

On November 12, 2022, a Long March 6A upper stage (2022-151B, SSN#54236) experienced a major breakup. The dry mass of this upper stage is approximately 5800kg, and at the time of the breakup the object was in an 847 x 813 km altitude orbit at an inclination of 98.8 degrees. Over 500 fragments were identified and cataloged [20]. The spread velocity distribution of the fragments, as seen in Figure 6, shows some directionality in the ejection of the fragments.

The on-orbit fragments have an average spread velocity of 92 m/s. This is consistent with an explosion energy of 18 MJ. The IMPACT model spread velocity distribution (Figure 7) compares well to the data.
The resulting IMPACT model produced 734 trackable fragments. Due to the energy associated with this event and the altitude of the upper stage, fragments from this event are expected to remain in orbit for decades. While there were only 734 trackable fragments predicted from the IMPACT model, roughly 20,000 fragments greater than 1cm were expected to be produced. As shown in the plot of orbital lifetimes in Figure 8, thousands of fragments will remain on orbit for decades, and nearly a thousand will remain in orbit beyond 100 years.

![Figure 8: Lifetimes of CZ-6A Fragments > 1cm](image)

4 EVENTs WITH UNKNOWN CAUSES

4.1 SL-14 Upper Stage

On February 12, 2020, at 10:46 GMT, the breakup of a SL-14/Tsyklon 3 upper stage (1991-056B, SSN#21656) was observed. The 1400kg dry mass stage had been on orbit 28 years and was in a 1206 x 1186km altitude orbit at 82.56 degrees inclination at the time of the event. The stage uses storable hypergolic fuel, and five other Tsyklon stages have previously fragmented and were attributed to residual propellant [21]. By July, 93 pieces of debris were associated with the event [22].

Plots of the spread velocities of the tracked fragments in Figure 9 show directionality perpendicular to the radial vector. The average spread velocity is 53 m/s.

![Figure 9: SL-14 Spread Velocity Component Plots in RTN Frame](image)

The spread velocity distribution is consistent with a 1.4 MJ explosion of a booster. The IMPACT explosion model produced 327 trackable fragments. The IMPACT spread velocity distribution and AMR distribution are consistent with available on-orbit data (Figure 10), although the higher AMRs of the trackable fragments indicate the possibility of some lower-density materials in the debris than the materials included in the IMPACT model. The high altitude of this event also affects the accuracy of AMR estimates.
While approximately one hundred trackable fragments were observed, and a few hundred trackable fragments were predicted from IMPACT, the model predicts several thousand subtrackable fragments capable of inflicting damage during a collision with orbital assets. Due to the higher altitude of this breakup event, many of these fragments are expected to remain on orbit for well over 100 years, as shown in Figure 11.

The past explosions of Tskyon stages and the characteristics of this event did strongly suggest that the SL-14 exploded. However, forensic analysis also explored the possibility of a collision with a subtrackable object. A spread velocity of 53 m/s would be consistent with a relative collision velocity of over 20 km/s with a subtrackable (.05kg) object. The collision model was discarded in favor of an explosion model.

### 4.2 Resur-O1 Satellite

Resur-O1 (1994-07A, SSN#23342) is a retired 1900kg Russian Earth observation satellite originally launched in 1994. The fragmentation of this vehicle was observed on August 27, 2020. At the time, it was in a 660 x 633km altitude orbit at 97.92 degrees inclination [23]. Over 100 fragments were associated with the event. Debris shedding events have been associated with the same spacecraft bus but spread velocities of the fragments from this event suggest the possibility of a higher-energy event.

The spread velocity component plots for this event are shown in Figure 12. Forensic analysis of this event explored the possibility of a collision with a subtrackable object as well as an explosion. The average spread velocity from the observed fragments, 5.7m/s, is consistent with a relative collision velocity of over 17 km/s with a subtrackable object, which is unlikely. Additionally, the IMPACT model for this collision results in an incomplete fragmentation. The majority of the Resur-O1 mass remains
intact, and only subtrackable fragments are produced. Because of the number of larger trackable fragments observed from this event, the possibility of a collision was ruled out.

Figure 12: Resur-O1 Spread Velocity Component Plots in RTN Frame

The observed average spread velocity suggests an associated explosion energy of a satellite of 0.24MJ. The resulting IMPACT explosion model produced 147 trackable fragments. The model compares reasonably well to the spread velocities and AMRs from a subset of the fragments in Figure 13. The relatively low explosion energy is comparable to the estimated 0.3MJ breakup of NOAA-16 in 2015. The NOAA-16 fragments had much higher AMRs (Figure 14), suggesting debris with less density than the Resur-O1 debris. With breakups like these the physical characteristics of the fragments will be highly dependent on where on the satellite the breakup event took place, determining the types of materials and structures that would generate debris.

Figure 13: (a) Resur-O1 Spread Velocity Distributions from IMPACT and Data, and (b) Cumulative Area-to-Mass Ratio Distribution from IMPACT and Adobe

Figure 14: (a) NOAA16 Spread Velocity Distributions from IMPACT and Data, and (b) Cumulative Area-to-Mass Ratio Distribution from IMPACT and Adobe
The IMPACT model predicts nearly 1600 fragments > 1cm, and long-term propagation (Figure 15) suggests that most will deorbit within 5 years. A few fragments are expected orbit as long as 30 years.

![Figure 15: Lifetimes of Resur-O1 Fragments > 1cm](image)

### 5 CONCLUSION

Regardless of efforts to eliminate explosions and avoid intentional collisions, breakup events continue to occur. Characteristics of debris from these fragmentation events can be insightful in understanding the events, determining possible causes, and suggesting possible mitigation techniques for the future. Additionally, evaluation of these events provides meaningful insight about the effectiveness of fragmentation models, and, as demonstrated by evaluation of the similarities between the NOAA16 and Resur-O1 events, maintenance of repositories of previous events provides insight into modeling techniques for future events.

### 6 References


