Forensic Analysis of Debris-Generating Events: Orbcomm FM 16

Glenn E. Peterson(1), Marlon E. Sorge(2), John P. McVey(1)

(1)The Aerospace Corporation, 2310 E. El Segundo Blvd, Los Angeles, CA, 90009-2957, USA
Email: glenn.e.peterson@aero.org, john.p.mcvey@aero.org
(2)The Aerospace Corporation, 2155 Louisiana Blvd, Suite 5000, NE Albuquerque, NM, 87110, USA
Email: marlon.e.sorge@aero.org

ABSTRACT

On December 22, 2018, the Orbcomm FM 16 satellite experienced a debris generating event. Numerous pieces of debris were cataloged, and this paper documents a forensic analysis of the observed debris. The Aerospace Corporation has developed various techniques to evaluate debris-generating events and determine various characteristics of those events such as spread velocity of the debris pieces, energy of the event, and area/mass estimates of the individual objects. These techniques were applied to the Orbcomm FM 16 event. Analysis indicates the event occurred at ~05:16:55 UT on December 22, 2018, when the satellite was over the Pacific Ocean headed southwards. It was found that the average velocity imparted to the debris was ~91.2 m/sec. Nearly all of the resulting orbits had higher apogees than the main satellite, although a few pieces of debris experienced only a small orbit change in the main orbit when compared to all of the others. What made this event highly unusual is the strong linear correlation in the radial/along-track plane of the delta-V distribution. Coupled with the dominance of the normal component in a single direction (except for one extraneous object), the distribution indicates that the debris pieces were given off in a distinct fan-shape. This fan-shape of debris does not fall into the normal behavior observed in previous explosions or collisions. The source of the event is currently unknown, with explosions typically showing more spherical distributions of debris while collisions are typically conical in distribution. Estimates of the collision energy and area-to-mass ratio of the individual pieces are made in an attempt to identify possible causes.

1 INTRODUCTION

Debris-generating events have been occurring on orbit from early in the space age and have continued until the present [1]. Fragmentation debris is distinguished from other forms of debris, such as abandoned satellites and rocket stages or intentionally released debris such as lens caps, in that it is generated from the dissociation of an on-orbit object due to sudden energy releases like explosions, collisions with other objects, or material degradation through shedding. By examining the debris from an event, it is possible to determine certain event characteristics, and these characteristics can be used to better understand the event for several purposes: identifying the source of the event, anomaly resolution, modelling the amount of debris produced by the event too small to detect but which may be large enough to cause damage to satellites, and to determine the long-term effect on the orbit environment.

Over the course of the last several years The Aerospace Corporation (Aerospace) has examined over ten thousand pieces of debris from over forty energetic fragmentation events (i.e., explosions and collisions) involving both satellites and upper stages [2]. Several different techniques have been developed in the course of these examinations to use Resident Space Object catalog data to calculate debris fragment characteristics. The characteristics that are routinely determined include the spreading velocities (the velocities imparted to the fragments by the debris-producing event), the fragment area-to-mass ratios, the fragment masses, and the energy of the event.

There are two parts to the spread velocity analysis method: determining the time of the event and determining the spread velocity distribution [3]. To estimate the event time, debris objects that have been identified shortly after an event are propagated backwards to find the most likely common point with the pre-event original object and with each other. Comparing the objects to each other as well as to the originating body assists when there are not many pieces to analyze or when the original object does not have pre-event information. This latter case often occurs with newly launched upper stages that explode shortly after launch. The software package Collision Vision (CV) is used to support operational launch collision avoidance and is used here to find the points of closest approach [4]. While this process works well when many debris objects are identified soon after an event. However, its accuracy deteriorates as the propagation time grows or if there are few debris objects available close to the events which is often the case with older historical events. Various efforts have been made to address this issue [5], but the CV approach was used here.

Approved for public release. OTR 2020-00077.

However, many debris objects are not added to the catalog until days or weeks, or even months to years after the event. The second part of the methodology was developed to address this challenge and is based on a comparison of the slowly varying orbit elements (hereafter referred to as OE) of the debris pieces and the original pre-event object. The slowly-varying elements are defined by the semi-major axis, eccentricity vector (combination of the eccentricity and argument of perigee), inclination, and right ascension of ascending node. The short period terms (mean, true, or eccentric anomaly) are not included as along-track errors build up quickly. Given the differences in the slowly-varying orbit elements between the pre-event primary object and the post-event debris pieces, the three spread velocity components that were imparted onto each debris piece can be estimated. The advantage of using only the slowly-varying elements is that debris requiring long back propagation times to establish a connection to the breakup event can be included. This method allows for additional debris objects to be added to the base data set, hopefully yielding a more accurate final spread velocity estimate. The two processes (CV and OE) are used in tandem when analyzing actual breakups: CV is used to determine the approximate time of the event while OE is used to develop the spread velocity distribution.

To determine the area-to-mass ratios of the debris, an orbit determination process is used to estimate the area-to-mass ratio over an interval of time. As the most abundant source of orbital data for debris are two-line element (TLE) sets, the TLE data are treated as observables in the estimation process over the fit span for a given epoch. The process is repeated for each piece of debris over all available TLE sets, providing a collection of area-to-mass ratios [6]. Examination of the area-to-mass ratio estimates leads to a wealth of information about each debris piece, such as mass given radar cross-section (RCS) measurements, material density approximation, long-term attitude trends, and shape approximation [7]. This technique can yield valuable insight into the characteristics of the individual debris objects, collision and explosion events and their associated parent objects. Mass, for example, is an important parameter in determining the amount of energy involved in the fragmentation event, particularly in an explosion where there is not necessarily any kinematic information to assist in the energy determination process.

In order to extract an estimate of the fragment mass from the area-to-mass ratio, an estimate of the fragment's cross-sectional area is needed. For tracked debris, this estimate can be recovered from the average radar cross-section (RCS) measurements in the space object catalog. Generally, the longer the time period over which the RCS measurements are taken the better the estimate. The extended time period produces more measurements with potentially different geometric perspectives on the debris to average out orientation and rotational axis-induced biases as well as to include multiple radar sites. Consideration also needs to be taken for the potential differences due to radar site wavelength particularly for debris that are sufficiently small to be on the order of the wavelength of the radar.

The use of RCS for deriving an approximate area has a number of potential problems that can affect the area estimates. RCS can be affected by the shape of an object as well as its material composition. Because both of these are likely unknown for debris fragments there can be significant uncertainties in the resulting mass estimates as compared to the determination of area-to-mass ratio and spreading velocity. In order to make an estimate of the potential variability caused by the indirect relationship between physical area and RCS, the debris from a number of historical fragmentation events were analyzed and an estimate made of the total mass of the observed fragments [8]. Since the original mass of the object is known, a comparison was then made between the known mass and the estimated total mass of the fragments. It was found that the errors for typical complete fragmentations, where "typical" means objects composed primarily of metals, were generally 40% or less with about half being less than 20%. The errors tended to be equally likely to be positive or negative. Some cases with more difficult materials, such as one with a composite over-wrapped tank, had higher errors. In that case the errors were closer to 60% which is to be expected given the complications that the composite material may cause in terms of its RCS to physical size relationship.

One of the most common sources of error in the total mass estimates was found to be attributable to certain fragments that consistently showed a much higher RCS value than was likely possible. These fragments, based on their typically small area-to-mass ratios, would then produce very large mass estimates. The objects could frequently be identified by comparing the mass estimate and the spreading speed estimates. These objects tended to show up as significant outliers with unrealistic imparted kinetic energies.

The general accuracy levels, although not as high as would be preferred, are sufficient to discern important information about fragmentation events including whether the event was a complete or partial fragmentation. They are also sufficient to generate distributions of cumulative number versus mass since the debris pieces are being examined in aggregate. For events with a large number of fragments the trend of the distribution can be established.

Another important parameter in understanding a fragmentation event is the amount of energy that was contributed to the fragmentation. This energy, particularly for explosions and other single initial object events, is needed not only to help determine or substantiate a proposed cause, but also to model the event in order to determine the risk of its debris to operational satellites. An approach has been developed to estimate the fragmentation event energy based on the average spreading speed of observed fragments along with the total mass of fragments [9].

To estimate the event energy, a relationship was derived between the average spreading speed of the observed fragments, the mass of the object, and its physical type (satellite or upper stage) and the total energy of the fragmentation event. For sub-catastrophic events, where the majority of the parent objects remains in a single piece, it is also necessary to determine the mass of the fragments, excluding the main body, which must be used in place of the object mass. When attempting to estimate energy before there is sufficient time and tracking information to determine debris object area-to-mass ratios and therefore mass, estimates of the fragment mass must be used based on similar historical events. These early energy estimates can be updated as sufficient data become available.

2 DELTA-V RECONSTRUCTION

On December 22, 2018, the Orbcomm FM 16 satellite (NORAD id 25417) experienced a debris generating event. Even though only twelve pieces of debris eventually made it into the public catalog, over forty pieces were initially identified and used in this analysis. When using the CV methodology, the best estimate of the time of the event was determined to be December 22, 2018 at 05:16:55 UT. The minimum distance between the pre-event and post-event satellite TLEs was less than 1 km at this time while seven other debris pieces had minimum miss distances with the pre-event satellite at this time as well. Figure 1 shows the orbital geometry of the satellite and debris. The vehicle was traveling over the Pacific towards the Southern Hemisphere when the debris event occurred. The picture on the right shows the planar view of the initial debris. In this view, it is apparent that many of the debris pieces, when back-propagated to the time of the event, do not coincide with the main satellite and so cannot be used directly to compute a delta-V. This shows the benefit of the OE method of reconstruction; the OE solution is not dependent upon the debris matching the satellite’s exact position.

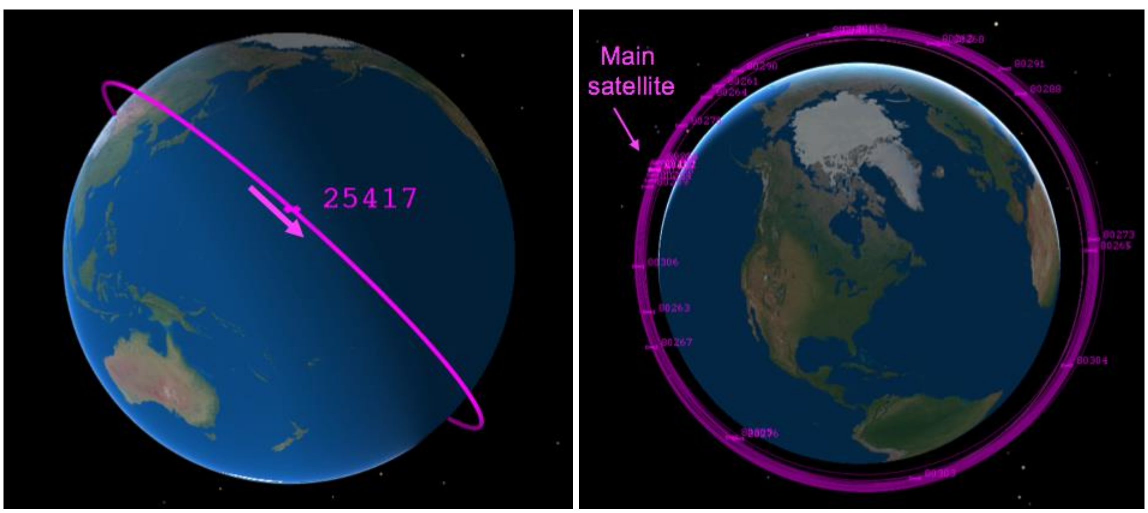

Figure 1: Location of Orbcomm FM 16 at the time of the event

Figure 2 shows the initial orbit elements of the tracked debris based on their first appearance in the catalog (debris piece 0 in these plots denotes the post-event main satellite). While the majority of debris was pushed into an orbit with a higher apogee, it is noticeable that many (~16) of the debris pieces had perigee altitudes that stayed relatively unchanged. As a consequence of the high perigees, the decay for these pieces will be slow and they will stay in orbit for decades. In addition, along with the object being tagged as the main satellite (piece 0), there were four other pieces that showed little change in elements. With one exception, the inclinations of the debris were pushed into one direction indicating the event was directional (i.e., not explosive in the spherical manner exhibited by some upper stage breakup events due to residual fuel).

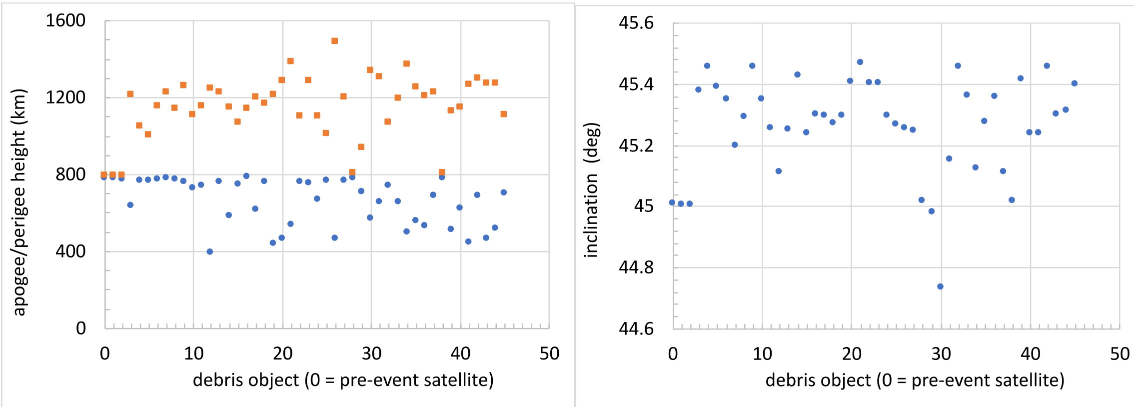

Figure 2: Initial orbit elements of tracked debris

Figure 3 shows the change in the orbit elements of the main satellite at the time of the event. Consider how small the y-axis scales are in Figure 3 in comparison to the axis for the debris field in Figure 2. While inclination and perigee altitude change, apogee altitude does not at this scale. The main satellite (debris piece 0 in Figure 2) overall showed small change in the elements implying that the debris pieces had small mass in relation to the main satellite. When considering that the pre-event satellite had a mass of approximately 41 kg, the debris was likely in the sub-kg mass range.

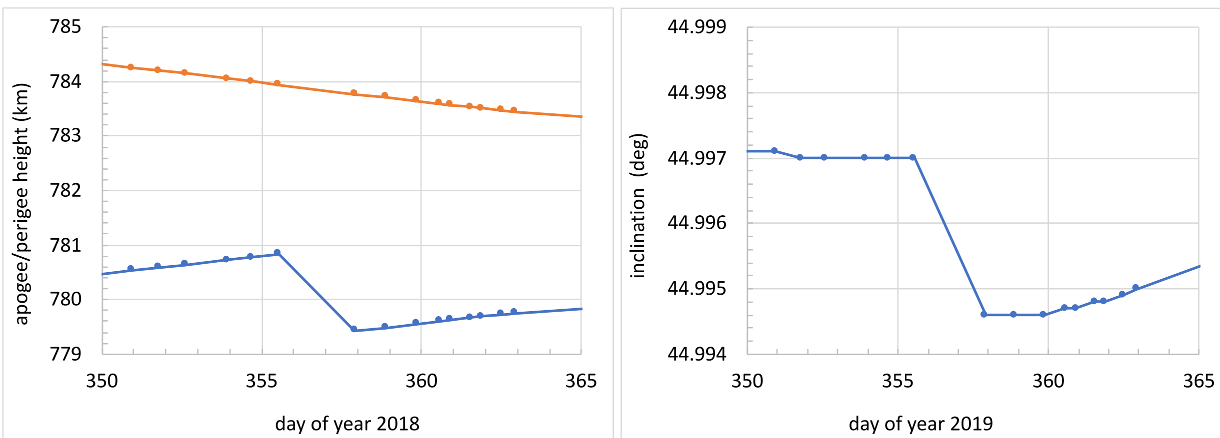

Figure 3: Change in orbit elements of main satellite at time of event

Figure 4 shows the time history of the perigee altitude, apogee altitude, and the inclination for the observed debris. Several pieces have re-entered at the current time, but most of the debris is still in orbit and will likely be for a long period of time. It is also useful to note that the perigee/apogee altitudes of much of the debris are going through a long period oscillation due to Sun/Moon perturbations pulling on the eccentricity. These oscillations will continue and will, in some cases, cause the perigee to dip lower into the atmosphere thereby enhancing the eventual decay of that particular piece. The inclinations have stayed fairly constant since the time of the event with the exception of one of the pieces that re-entered around day 120. This piece is not related to the high-apogee object as it was not close to re-entering at the time and so likely represents a debris at the edge of trackability that subsequently has been lost.

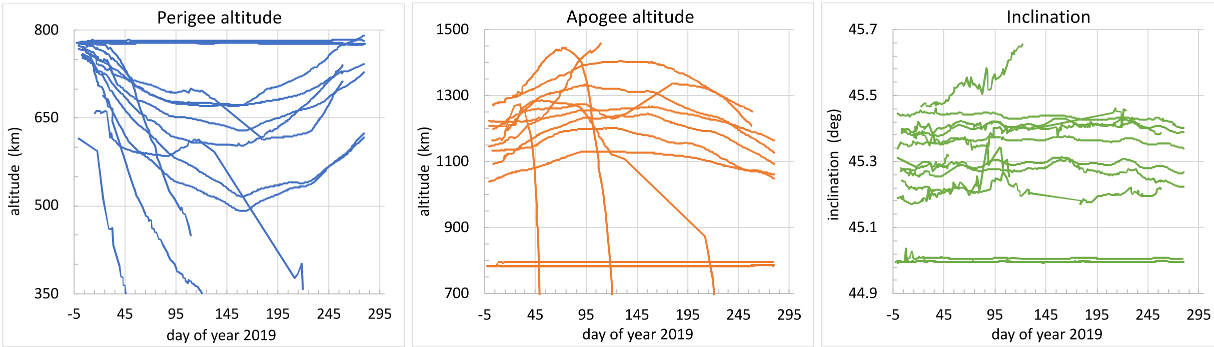

Figure 4: Time history of orbit elements of debris

The delta-V distribution computed from the OE method is shown in Figure 5 and did not conform to the usual types of explosions or collisions that have been observed in other events [2]. In explosions, the distribution typically has a much more spherical shape while in collisions, the distribution tends to be lop-sided but ill-defined. In this case, there was a very high degree of correlation between the radial and along-track components (plot on the left) while the normal-to-the-orbit component of the delta-Vs was almost uniformly pushed in one direction. The plot on the right shows the normal-to-the-orbit component when looking down on the radial: along-track line in the left plot (denoted by the eye symbol and the solid arrow; i.e., the “fan plane” is the plane perpendicular to the black arrow). Taken in a three-dimension sense, this indicates the debris was given off in a distinct fan-shape. Given the actual shape of the Orbcomm satellites (solid disc of approximately 1-meter diameter and 15 cm thick with two solar panels and a 3.3 m boom antenna), the resulting delta-V distribution can be potentially understood as the disc fragmenting due to an internal explosion with the solar panels and the boom separating from the disc with little impulsive force but remaining largely intact.

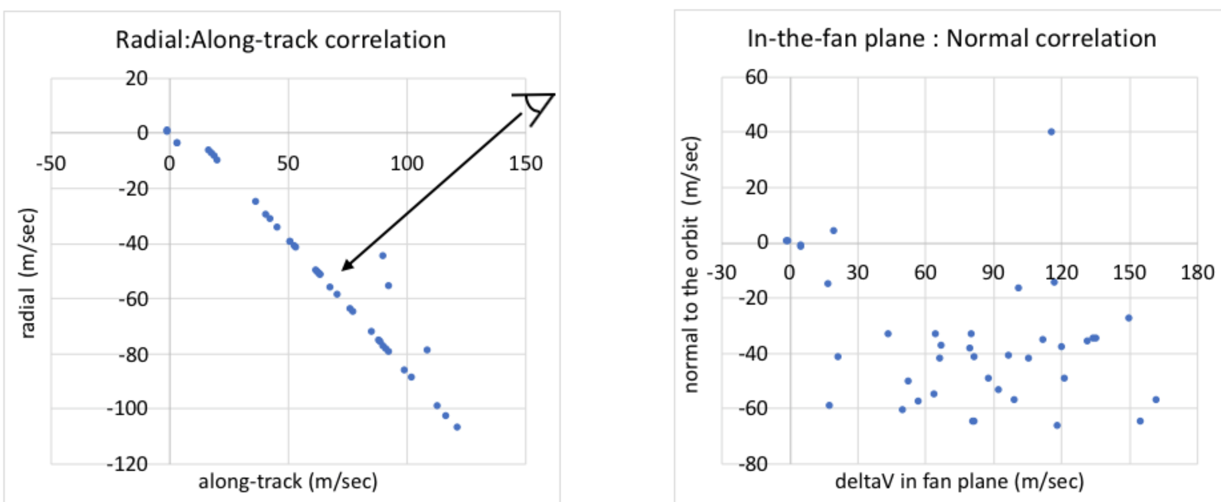

Figure 5: Delta-V of debris from Orbcomm FM 16 event

3 AREA-TO-MASS RATIO ESTIMATE

Debris fragment area-to-mass (A/m) ratios provide insight into material properties of the debris including rough density information. The A/m estimation process also provides insights into the quality of the estimations. The parent objects consist of many different materials, which are dispersed amongst the debris during a breakup. The debris event will consist of a subset of these materials but could contain multiple materials in one object. Therefore, the density of the debris is difficult to determine uniquely, but will generally fall into three categories: high, medium, and low-density material. Evaluating the weighted average of all the estimated area-to-mass ratios for a given piece of debris is key to approximating their material density individually. The weighting formulation assigns higher weights to the area-to-mass ratio with lower residual values from their orbit estimations and visa-versa.

The TLEs of the debris from the Orbcomm FM16, the satellite itself, and several other Orbcomm satellites (in order to provide points of comparison) were analyzed, and the area-to-mass ratios estimated. Figure 6 depicts the time series of these estimates for each of the Orbcomm satellites FM13 through FM20. These satellites all have the same block design and were launched at the same time including Orbcomm FM16, so the estimates should be in family with respect to each other. Each satellite's estimate has a corresponding 1 sigma root sum square residual value for each fit of approximately 1 km. In general, A/m estimates typically oscillate within a range due to non-sphericity of the object, noise and errors within the data and the estimation process itself. The A/m estimation range of oscillation between satellites are similar and remain relatively stable over ~10-month time period demonstrating the expected consistency. The larger spike from FM16 is due to estimation over the debris-generating event and is not a reflection of significant change in A/m. In fact, the FM16 A/m estimates remain in the same relative oscillatory range both before and after the event on December 22nd. The FM16 estimate does indicate that something anomalous did occur over that time interval.

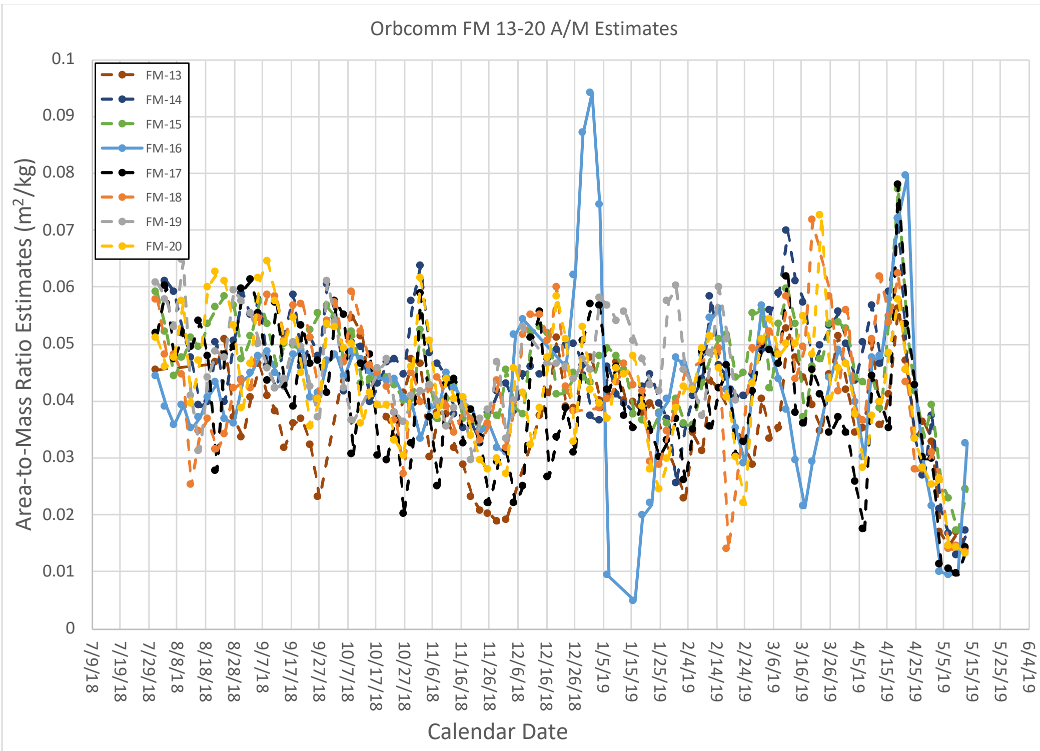

Figure 6: Orbcomm Satellite FM 13-20 A/M Estimates Versus Calendar Date

Through the experience of analyzing many vehicle breakups [6,7], there exists a range of A/m estimate values that correspond to material densities for fragmentation events. Low values of A/m estimates (0.001 – 0.1 m^2/kg) tend to be higher density materials like steel and titanium, with some aluminum alloys also showing toward the higher end of this range. High values of area-to-mass ratio estimates (1 - 10 m^2/kg) tend to be lower density materials like multi-layer insulation (MLI), carbon composites, and solar panel fragments. Estimated values in the middle range of estimated values (0.1 - 1 m^2/kg) are more difficult to determine due to the approximate nature of this technique, but typically, these debris fragments could consist of many aluminum alloys, and electronic components like circuit board material. The following breakup demonstrates how to use the A/m estimates to infer what materials comprised the released debris. Knowledge of the materials provides more context about the breakup event.

Figure 7 shows the weighted average area-to-mass ratio estimates for the publicly cataloged debris released from the Orbcomm FM16 event (total of 12 pieces). The estimated values for ten of the debris pieces fall into a range between 1 - 11 m^2/kg, which suggests lighter materials like MLI, or solar panel fragments. The other two pieces of debris are in the high-density range (~0.03-0.05) and suggest materials like an aluminum support material, a metal bracket, or possibly battery material. It should be noted that the two high-density pieces had delta-Vs of less than 6 m/s while the 10 other low-density objects had delta-Vs of over 100 m/s. The delta-V analysis and A/m analysis are therefore consistent with each other to the extent that data are available.

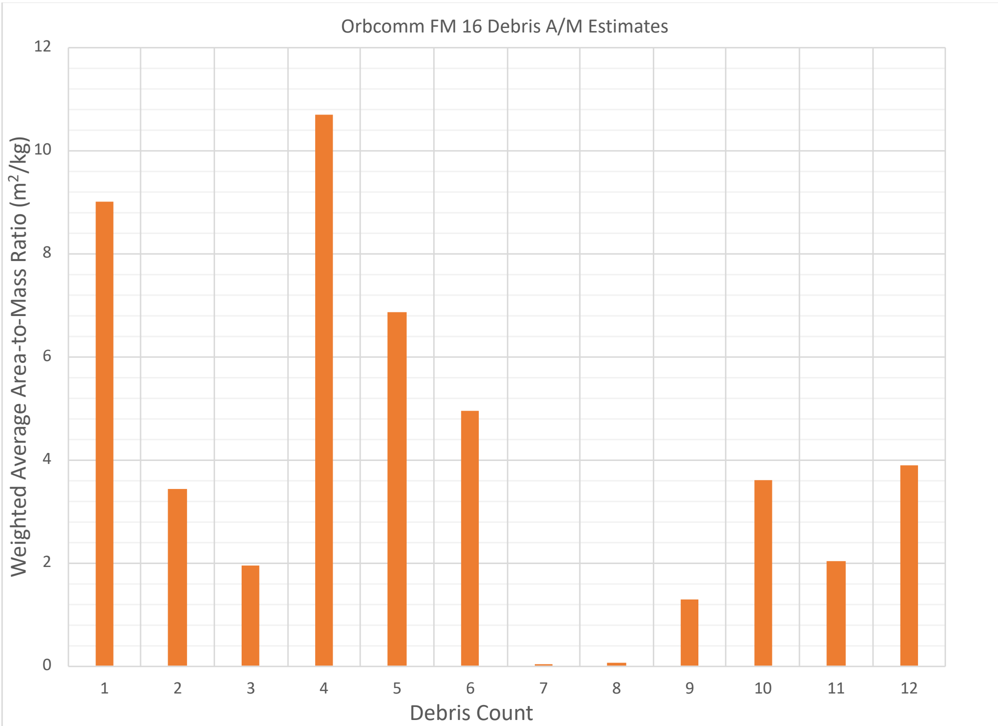

Figure 7: Orbcomm Debris Weighted Average A/M Estimates

4 EVENT ENERGY

A technique was developed using fragmentation modeling and data from on-orbit events to estimate the overall energy that drove a collision or explosion event [9]. This technique uses the average spreading speed of the SSN-observed fragments along with the type of object (satellite or upper stage) and either the total mass of the object or the mass of the debris generated if the fragmentation event was not catastrophic. In this case "not catastrophic" means that a majority of the main object remained intact after the fragmentation event. The estimation of the total energy of the event is approximate but has shown reasonable success at reproducing actual events.

From the analysis above, the average spreading speed of the observed fragments was found to be 91 m/s. The area-to-mass estimation for the fragments placed all but two of the fragments analyzed above 1 m^2/kg and many were far above 1 m^2/kg. These high A/m values, especially coupled with the high spreading speeds of Figure 5, would suggest that the fragments had quite low mass. This has been fairly consistently the case in other fragmentation events.

The Orbcomm FM16 breakup is unusual in terms of its characteristics in that, based on the A/m of the fragments as analyzed above, the total debris mass is small but the spreading speeds are large. In most of the small sub-catastrophic events observed, the spreading speeds of low mass events have been low. As an example, consider the Iridium-91 debris-generating event. Four fragments were observed. Three of these fragments had spreading speeds below 40 m/s while only the fourth, the smallest fragment with a mass estimate at less than 10 g, had a spreading speed in the 90 m/s range [2].

In the Orbcomm FM16 event all but three fragments had spreading speeds above 40 m/s, a significant departure from similar events. Being outside the typical range of events used to develop the energy estimation model it is difficult to use the model directly with confidence. Instead, an examination of some of the relevant events may suggest characteristics of the event. The very high A/m values of most of the fragments suggests that these fragments have low masses. Based on similar fragments from the Iridium 91 and other events implies masses on the order of 10s of grams or less. The two fragments with lower A/M values and lower delta-Vs likewise would have higher masses, perhaps in the 100s of grams to low kg. This would place the overall fragment mass on the order of the Iridium 91 event although likely somewhat larger. The significantly higher spreading speeds imply a possibly order of magnitude higher energy than observed in the Iridium 91 event due to the squared relationship between speed and energy. This would suggest on the order of 10 kJ of energy. The uncertainties in this are significant, although the result may be refined with further analysis. If the event was caused by the impact of a small fragment, then it would have likely had a mass in the sub-gram range. The energy range is also not inconsistent with the amount of energy that could be released from a battery breakup event.

5 CONCLUSION

The Orbcomm FM16 satellite experienced a debris-generating event on December 22, 2018 at ~05:16:55 UT. An analysis was performed on the resulting debris pieces. It was found that the average delta-V was ~91 m/s with individual values ranging from near 0 to 170 m/s. The distribution of the debris delta-V was in an unusual fan shape. While unusual for a debris-generating event, a fan shape distribution would be consistent with the disc-shaped construction of the satellite. Area-to-mass ratios estimated from the time-series of two-line element sets indicate that the debris was mostly low-density material such as MLI or pieces of solar panel. As a check on the estimation process, an analysis was performed for the other Orbcomm satellites that were launched in the same group as FM16. The results of this analysis show that the estimation process was producing consistent A/m values. In addition, examining FM16 pre- and post-event also indicated that the main satellite's A/m changed little due to the event.

Due to the unusual nature of the event, the standard energy estimation process could not be used, so analogical estimates were made. They suggest an energy release on the order of 10 kJ which would be consistent with either a small debris impact or a battery rupture. Additional analysis may be able to refine the estimates. These results indicate that useful information can be derived after an event that, in turn, can be beneficial in understanding the nature, characteristics, and source of the event.

6 REFERENCES

1. Orbital Debris Program Office, "History of On-Orbit Satellite Fragmentations, 14th edition," NASA TM-2008-214779, Johnson Space Center, June, 2008.
2. Sorge, M. E., Peterson, G. E., and McVey, J. P., "Forensic Analysis of On-orbit Debris Generation Events," Seventh European Conference on Space Debris, Darmstadt, Germany, April 18-21, 2017.
3. Peterson, G. E., "Use of Slowly Varying Orbit Elements for Spread Velocity Reconstruction of Historical Orbital Breakups," *AAS 13-845,* AAS/AIAA Astrodynamics Specialist Conference, Hilton Head, South Carolina, August 11-15, 2013.
4. Gist, R. G., and D. L. Oltrogge, "Collision Vision: Covariance Modeling and Intersection Detection for Spacecraft Situational Awareness," Paper No. AAS 99-351, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, August 16-19, 1999.
5. Thompson, R. C., G. E. Peterson, J. P. McVey, R. E. Markin, M. E. Sorge, "Blits: A Forensic Analysis of a Probable Collision," *AAS 13-907,* AAS/AIAA Astrodynamics Specialist Conference, Hilton Head, South Carolina, August 11-15, 2013.
6. McVey, J. P. "Automated Ballistic Coefficient Estimation Technique to Analyze the Debris from the COSMOS-2251 and IRIDIUM-33 Collision," *AAS/AIAA Astrodynamics Specialist Conference*, AAS 11-412, Girdwood, Alaska, July 31-August 4, 2011.
7. McVey, J.P. (2016). *Characterization of Space Debris from the Cosmos-2251 and Iridium-33 Collision Event Using Ballistic Coefficient Estimation*. Ph.D. thesis, University of Southern California, 2016.
8. Sorge, M. E., and D. L. Mains, "IMPACT Fragmentation Model Developments," *Acta Astronautica,* vol. 126, pp 40-46, 2016.
9. Hoots, F. R., and M. E. Sorge, "Satellite Breakup Parameter Determination," *Journal of Astronautical Sciences.* **59**(1&2), 123-143, 2012.