Methods of Predicting and Processing Breakups of Space Objects

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ABSTRACT

The 18th Space Control Squadron (18 SPCS) has created new techniques to predict, detect, process, and catalog breakups. It has done so on behalf of Air Force Space Command (AFSPC), in support of U.S. Strategic Command's Joint Functional Component Command for Space, which is charged with executing USSTRATCOM's presidentially assigned Space Operations mission area. This paper presents the process of predicting propulsion system-related breakups through the detection of outgassing, which has led to the successful prediction of the breakup of a rocket body. 18 SPCS methods for tasking, correlating uncorrelated tracks (UCTs), and finding breakup pieces are shown. Also presented are existing and new approaches to finding the time and location of a breakup, which assists in determining the cause. Finally, we explore a new method for determining the parent piece of a breakup, which was essential in finding the main body of an active payload and six rocket bodies in past breakup events. These methods have optimized breakup processing and increased the responsiveness of 18 SPCS.

1. PREDICTING BREAKUPS

The 18th Space Control Squadron (18 SPCS) is the tactical unit under the 21st Space Wing (21 SW) responsible for maintaining and providing foundational space situational awareness (SSA) for the U.S. Department of Defense, as well as interagency, commercial and foreign partners around the globe. The core functions of 18 SPCS include maintaining the space catalog through space surveillance and tracking, generating spaceflight safety data, and processing high-interest events such as launches, reentries, and breakups. In years past, this role was accomplished successively by the Space Control Center (SCC), 1st Space Control Squadron (1 SPCS), and most recently the 614th Air Operations Center (614 AOC), also referred to as the Joint Space Operations Center (JSpOC).

18 SPCS defines a breakup as the usually destructive disassociation of an object, often with a wide range of ejecta velocities. A satellite breakup may be accidental or the result of intentional actions. 18 SPCS also processes anomalous debris-causing events which are the unplanned separation, usually at low velocity, of one or more objects from a satellite, which remains essentially intact. Anomalous debris-causing events can be caused by material deterioration of items such as thermal blankets, protective shields, or solar panels, or by the impact of small particles. The number of debris generated and/or the operational status of the spacecraft is not indicative of the type of event; both breakups and anomalous events may result in few or many pieces, and may or may not affect the capability of the spacecraft. This paper will focus on breakups as the destructive disassociation of an object.

Traditionally, 18 SPCS relies on the Space Surveillance Network (SSN) to deliver multiple headcount reports to detect breakups. This can take an extended period of time if an object is highly eccentric, or may not happen at all if the argument of perigee is in the southern hemisphere. Therefore, 18 SPCS cannot rely solely on headcount reports from the SSN for timely detection of breakups. This has motivated the squadron to develop a procedure for predicting breakups due to the failure of propulsion systems.

On Friday, October 1, 1999, a 1 SPCS analyst noticed outgassing by object 21734, listed in the satellite catalog as an SL-14 rocket body. The analyst increased sensor tasking before the weekend, and identified that the rocket body broke up the following Monday. This was the first prediction of an unintentional breakup in history, and demonstrated that outgassing could precede a breakup for events related to propulsion systems.

The 18 SPCS uses the Astrodynamics Support Workstation (ASW) to maintain the high accuracy catalog. ASW employs a calculated parameter, Adaptive Linear Element (ADALINE), to detect events based on user-set thresholds specific to each space object. If an object has event detection turned on and the observations that come in after the epoch of the state vector break the defined ADALINE threshold, then the object will fail automatic processing and transfer to a manual processing list. This notifies the analyst that the object has deviated

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from normal orbital motion, and requires manual intervention to update its orbital parameters in the catalog. Traditionally only active satellites have event detection turned on to detect maneuvers.

However, event detection can be used to detect other activities in addition to maneuvers. For example, if a rocket body outgasses, the resultant observations will break the ADALINE threshold. If event detection has been turned on for this rocket body, it will be placed onto the manual intervention list, which will alert the analyst that something abnormal has occurred or is occurring.

The objects designated as SL-12 (AUX MOTOR) in the space catalog have fragmented more than any other space object in history. Due to the long time between tracking by the SSN, their high eccentricity, and the rapid separation of the debris pieces from the parent, many times a multiple headcount is not detected immediately after breakup. For example, in one case, a JSpOC analyst identified a SL-12 (AUX MOTOR) breakup several months after it had taken place. Similar to the event in 1999, 18 SPCS analysts recently noticed that SL-12 auxiliary motors often outgas before breaking into pieces. In response, new procedures have been put into place that increase tasking on objects when analysts notice outgassing, which increases the likelihood that the SSN will catch a multiple headcount at the time of breakup.

During post-event analysis of the June 1, 2016 breakup of space object #33473, designated as an SL-12 (AUX MOTOR), JSpOC analysts realized they had identified outgassing prior to the breakup; they also observed outgassing by the parent piece for days after the event.

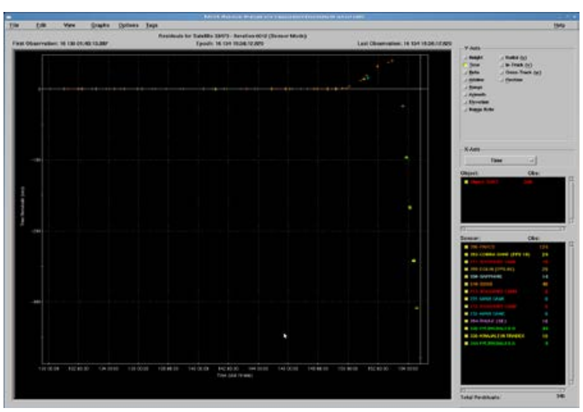

Figure 1. Delta time vs. time plot of 33473 showing outgassing prior to breakup

Based on these findings, a post-event analysis of the March 26, 2016 breakup of space object #33472, also listed as SL-12 (AUX MOTOR), was conducted. It revealed that outgassing occurred prior to the breakup and continued for days afterwards, as well.

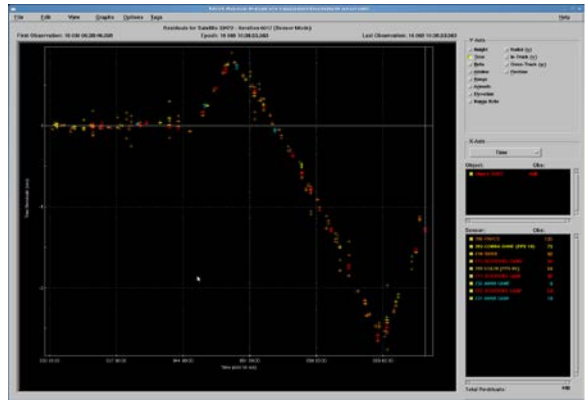

Figure 2. Delta time vs. time plot of object #33472 showing outgassing prior to breakup

On July 25, 2016, 18 SPCS analysts identified outgassing of object #29680, another SL-12 (AUX MOTOR). Analysts immediately increased tasking, and two days later, on July 27, they detected the object’s breakup. Outgassing continued for days afterwards. This demonstrated the second successful prediction of an unintentional breakup in history.

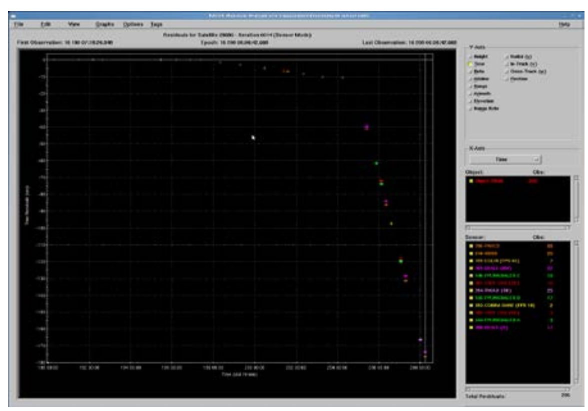

Figure 3. Delta time vs. time plot of 29680 showing outgassing prior to breakup

As of February 2017 ASW’s event detection has found three possible collisions and five outgassing events including the outgassing of SL-12 (AUX MOTOR), #33472, which previously broke up a year earlier.

Knowing that outgassing can occur before propulsion-related breakups happen allows 18 SPCS to predict that a fragmentation may occur. This is especially important when successive tracking is hours apart, such as for highly eccentric rocket bodies. By activating event detection in ASW for rocket bodies and dead payloads, 18 SPCS will be able to monitor abnormal behavior such as outgassing, and in turn, predict breakups that could threaten spaceflight safety.

2. TASKING, CORRELATION, AND FINDING PIECES OF THE BREAKUP

The first step in processing a breakup is tasking sensors to collect observations on the debris. Phased array sensors typically perform the best as they can put up a debris-sensing "fence" ahead of the parent satellite's last known orbit and collect observations for several minutes after it has passed. This effectively assesses the spread of the debris since the pieces usually disperse faster in-track than cross-track or radially. Large explosions or collisions pose exceptions because the inclination and right ascension of the node can spread several degrees due to the energy of the breakup. Unlike a mechanical tracker, a phased array radar can collect many tracks in a very short amount of time, making them invaluable in the detection of the pieces. Once adequate data is collected and assessed, the 18 SPCS Breakup Officer may confirm the event as a breakup, which results in notifications to interagency and security partners. Beginning in 2015, 18 SPCS added additional notifications specifically to all operators of active spacecraft, as well as the general public through Space-Track.org and social media, to support spaceflight safety and increase transparency on debris-causing events.

Once tasking and tracking are accomplished, 18 SPCS analysts associate the resultant uncorrelated tracks (UCTs) to the breakup. The JSpOC mission system, SPADOC, does this automatically, but 18 SPCS analysts can increase the association parameters to pull in UCTs that may have been missed. Once initial pieces are created and correlated to the breakup, the parameters can be refined so that pieces that do not belong are not correlated.

Timely identification of the breakup pieces is important so that they can be used for conjunction assessment, to refine the breakup cloud model, and to determine the time of the breakup. When a piece is found and correlated to an event, it is created in the analyst catalog, usually designated by the satellite catalog number range 80000 to 80999. Initially designating these debris pieces as analyst objects allows their two line element set (TLE) history to mature and refine. Once a piece has a sufficient TLE history and analysts are convinced that its orbit can be maintained by the mission system automatically, the piece is entered into the public catalog.

There are several methods for finding pieces of a breakup. The quickest and easiest is visually finding strings of UCTs that correlate to each other on a delta-time vs. time plot. Delta-time is the measurement of how far off the observations are from the prediction or propagation. If delta-time is negative, the object has arrived before it was expected. If positive, the object has arrived later than expected. The advantage of this method is that people can recognize a trend that computers cannot.

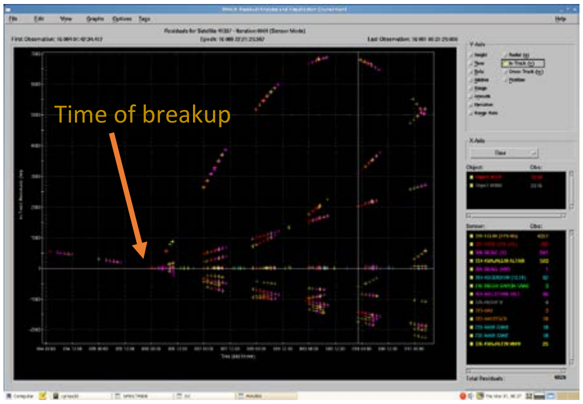

Figure 4. In-track vs. time plot of Hitomi (ASTRO-H) breakup

Other methods include UCT processing and UCT trending. UCT processing mathematically determines which UCTs correlate to each other; this is more sophisticated, but can take much longer due to the power required for computer processing. Many UCT processors use a different method, UCT trending. This method plots the Keplerian elements of the UCTs individually and visually strings them together, which can be very reliable for finding outliers of a breakup. Overall, there is no wrong way to find a debris piece as long as the end result is of good quality.

3. FINDING THE TIME AND CAUSE OF A BREAKUP

Finding the time of the breakup up is important for two reasons. First, it can be used to find the latitude, longitude, altitude, and location in the orbit of the breakup by propagating the parent object before the time of the breakup to the time of the breakup. The latitude, longitude, and altitude reveal which part of the world the satellite was over when the event happened. If the satellite broke up while intersecting with a launch trajectory when a launch occurred, there may have been a collision. The location in the orbit can also help determine the cause of the breakup. If a satellite is close to reentry and fragments on a perigee pass, then the breakup is most likely aerodynamic.

The second reason the time of the breakup is important is debris modeling. Along with the energy of the breakup, the time is needed to model the debris cloud appropriately and determine the risk to surrounding satellites. There are many methods for modeling clouds of breakup debris, but they are all useless if they do not know when and where to start modeling.

18 SPCS can determine the time of the breakup in several ways. The most straightforward is using conjunction assessment software, specifically ASW's SuperCOMBO, which implements special perturbations (SP) predictive modeling. 18 SPCS analysts have adapted it to find the mean separation time and the standard deviation or error of that time. It also gives a delta-v or separation velocity of the pieces. This directly relates to the energy of the breakup, which indicates the cause of the breakup. A highly energetic event could be due to a collision or significant explosion, whereas lower-energy events could be due to small explosions or drag. Other methods can also be employed. AFSPC's Astrodynamics Standards software has a tool named the Breakup Analysis Module (BAM) which employs pinch point analysis and has been used in breakup processing for many years.

Figure 5 shows the results of applying conjunction assessment software to NOAA 16 versus the NOAA 16 pieces after the breakup. The results are in miss distance (km) vs. time. Where the miss distances converge is the time of the breakup.

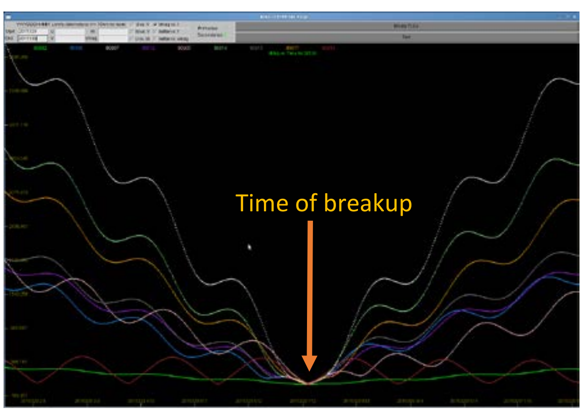

Figure 5. Conjunction assessment of NOAA 16 breakup.

Another way to determine the type of event is to evaluate the separation times of the pieces. If they separate hours or days apart, the event is most likely due to shedding or coolant leaking, as demonstrated by Cosmos 1818 and Cosmos 1867 [1]. If the pieces separate all at once, the event may have been an explosion or collision.

The easiest way to investigate the cause an event for an active payload is to communicate with the owner/operator (O/O) of the satellite. For instance, if the O/O states that they lost communication at a certain time, it can lead to identifying or confirming the time of the event. In the case of the Hitomi/Astro-H, the O/O verified that the satellite spun itself apart [2]. If an O/O maintains contact with a satellite and can still control it, the 18 SPCS Breakup Officer will not categorize it as a breakup, except in extreme cases; rather, it will be deemed an anomalous debris-causing event, and the pieces will be expeditiously catalogued for conjunction assessment purposes.

4. FINDING THE PARENT PIECE

The parent piece of a breakup is the main body of the original object or the biggest piece. Finding the parent piece of the debris is important for two reasons. First, there needs to be an object in the place of the original number in the catalog to keep the catalog in order. Second, the parent object may break up again, as has happened with several SL-12 auxiliary motors. To determine the biggest piece, 18 SPCS relies on the radar cross-section (RCS) calculated by the SSN. This has many limitations, the most significant of which is that the RCS data can be erratic and sparse depending on sensor coverage and availability. Another factor is that the RCS depends on the frequency of the radar, so two different radars will give two different values for RCS. Additionally, some radars have limits on how many objects per pass they can track. Also, for most SL-12 auxiliary motors there are usually two objects that contend for the largest RCS.

With this in mind, 18 SPCS analysts have developed a method that works extremely well to determine the parent object of a breakup. 18 SPCS maintains a history of the special perturbations state vectors which include the Ballistic Coefficient (BC) and the measurement of radiation pressure measured as Area Gamma Over Mass (AGOM). Both are functions of area-to-mass ratio. When viewing the breakup pieces' BC/AGOM histories with that of the parent object prior to the breakup, the main body should have similar BC/AGOM values to that of the original object. Note, however, that this may not always be the case for catastrophic breakups. Depending on the altitude of the perigee of the pieces and the parent, either AGOM or BC may be more definitive than the other.

This method was essential in finding the main body of Hitomi (ASTRO-H) when it fragmented. In this case, the main body was not the largest piece, marking a flaw in traditional 18 SPCS methodology. Figures 6 and 7 shows the AGOM and BC histories of the original object, #41337 (red), plotted against the largest piece, #41442 (green), and the main body after the breakup, also numbered 41337 (red). Note that the post-breakup #41337 piece matches the pre-breakup parent object closer than the largest piece. Upon realizing this, sensor resources were allocated to track the main body as opposed to the biggest piece.

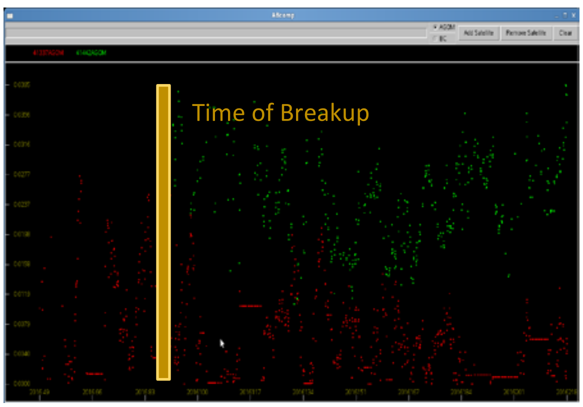

Figure 6. AGOM plot of Hitomi breakup

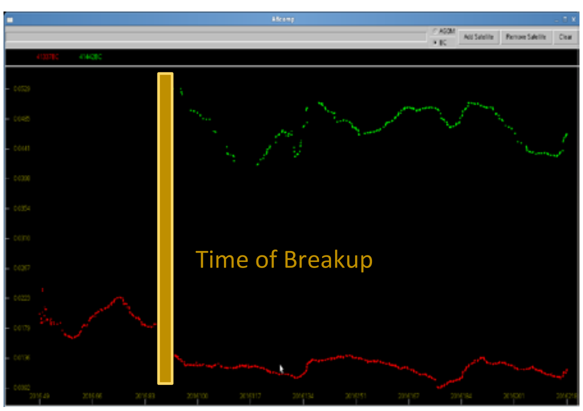

Figure 7. BC plot of Hitomi breakup

In Figures 8 and 9, the pre-breakup AGOM and BC histories of SL-12 auxiliary motor #33473 (red); is compared to the largest post-break up pieces 80503 (green), 80500 (blue), and 80504 (white), all of which have similar RCS. As seen, 80503 matches the pre-breakup parent before the breakup better than the other pieces, indicating that it is the main body.

Figure 8. AGOM plot of #33473 and biggest pieces

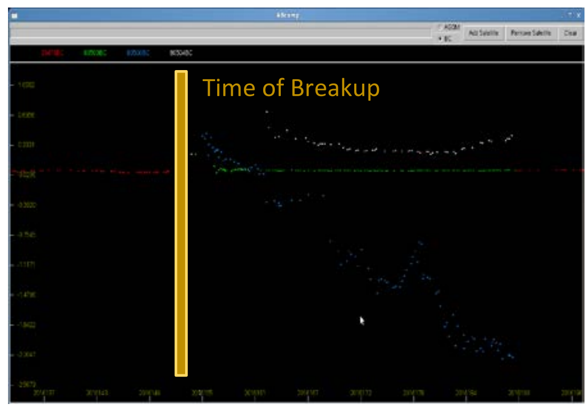

Figure 9. BC plot of #33473 and biggest piece

The primary drawback to this method is the time that it takes to build a decent AGOM/BC history for each object. Calculating a high-fidelity AGOM and BC requires a minimum span of three days of observations. This is hindered by the fact that the main body may still be outgassing for days after the breakup, which is the case of SL-12 auxiliary motors. However, despite these challenges, for the cases shown 18 SPCS was able to determine the post-breakup parent object significantly faster using BC/AGOM history correlation than they would have using traditional methods.

5. CONCLUSION

Through the development of new analytical methods, 18 SPCS can now detect, process, and catalog breakups faster than traditional approaches allowed. By using event processing for dead payloads and rocket bodies, many breakups are detected sooner, and some can even be predicted. The employment of new processing techniques in the past few years has also expedited the cataloging of post-break up pieces, as well as determining the parent piece of the event. In short, 18 SPCS is now more efficient at processing breakups than ever before.

6. REFERENCES

1. New Debris Seen from Decommissioned Satellite with Nuclear Power Source.” *Orbital Debris Quarterly News*, NASA Orbital Debris Program Office, Jan. 2009, https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv13i1.pdf

2. Foust, Jeff. " JAXA closing in on cause of Hitomi’s breakup." *SpaceNews*, 20 April 2016, http://spacenews.com/jaxa-closing-in-on-cause-of-hitomis-breakup