CHARACTERIZATION OF THE 2012-044C BRIZ-M UPPER STAGE BREAKUP

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ABSTRACT

On 6 August 2012, Russia launched two commercial satellites aboard a Proton rocket, and attempted to place them in geosynchronous orbit using a Briz-M upper stage (2012-044C, SSN 38746). Unfortunately, the upper stage failed early in its burn and was left stranded in an elliptical orbit with a perigee in low Earth orbit (LEO). Because the stage failed with much of its fuel on board, it was deemed a significant breakup risk. These fears were confirmed when it broke up 16 October, creating a large cloud of debris with perigees below that of the International Space Station.

The debris cloud was tracked by the U.S. Space Surveillance Network (SSN), which can reliably detect and track objects down to about 10 cm in size. Because of the unusual geometry of the breakup, there was an opportunity for the NASA Orbital Debris Program Office to use specialized radar assets to characterize the extent of the debris cloud in sizes smaller than the standard debris tracked by the SSN.

This paper describes the observation campaign to measure the small particle distributions of this cloud and presents the results of the data analysis. We shall compare the data to the modelled size distribution, number, and shape of the cloud, and what implications this may have for future breakup debris models. We shall conclude the paper with a discussion about how this measurement process can be improved for future breakups.

1 INTRODUCTION

Validation of satellite breakup models can be very challenging for debris smaller than the (approximately) 10 cm minimum size tracked by the U.S. Space Surveillance Network (SSN). Debris tracked by the SSN can be monitored over a period of time, yielding information on the breakup that produced it and the particle's ballistic coefficient and radar cross section (RCS) − from which the debris size can be estimated. Details of the debris orbit, especially soon after the breakup, can establish its initial delta-velocity as well. All of this information is needed for the construction of a complete breakup model.

For untracked debris smaller than 10 cm, this information is much more difficult to obtain. While NASA uses radars such as Haystack, HAX, and Goldstone in staring mode to make statistical samples of the environment down to centimeter and even millimeter sizes, it is very difficult to associate any particular debris object observed in this manner with any particular breakup. Usually these radars can only characterize the small debris environment as a whole or in broad inclination or altitude bands, which limits the ability to isolate and study individual breakups.

Occasionally, however, large breakups occur under conditions that leave the debris in distinct orbit planes for a period of time so that special observations, by one or more of these radars, can use the correlations in time and space to isolate and study debris specifically from that breakup. The details of when, where, and how to observe these clouds are dependent on the specifics of the parent satellite's orbit and time of breakup, so that any observation campaign must be custom designed for that particular breakup and observation opportunity.

The recent breakup of a Russian Briz-M upper stage presented an opportunity for just such an observation campaign, and demonstrates the challenges and idiosyncrasies of these kinds of observations.

2 BRIZ-M BREAKUP

On 6 August 2012, a Proton Briz-M upper stage was left stranded in an elliptical orbit with a perigee in LEO. The launch malfunction occurred when the Briz-M upper stage (2012-044C, US satellite number 38746) carrying the Telkom 3 and Express MD2 spacecraft unexpectedly shut down shortly after the start of the third of its planned four maneuvers. This left it in a 265 km by 5015 km, 49.9° inclination orbit. The two satellites were later autonomously released from the stage without reaching their designed orbit.

A Briz-M stage is composed of two parts: a core section with a central tank carrying 5.2 metric tons of propellant mass and a donut-shaped auxiliary propellant tank (APT) with an initial propellant mass of 14.6 metric tons (Fig. 1). During a nominal mission, the APT is separated after the initial burns, and the central

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Figure 1 – The Briz-M upper stage is composed of a central engine surrounded by a donut-shaped auxiliary propulsion tank, which is ejected part-way through a nominal mission. The Briz-M stage described in this paper failed with the donut-shaped tank still attached and containing substantial amounts of fuel.

tank completes the delivery of the payloads. In the 6 August mishap, the APT had not yet separated, leaving more than 5 metric tons of propellant in the integrated 2.6 metric ton (dry mass) stage.

Two previous Briz-M stages had experienced similar failures, leaving the integrated stages stranded in orbit with substantial amounts of fuel aboard. Both later exploded (one in 2007 and one in 2010), so there was concern that this stage was also a candidate for explosion, which occurred on 16 October 2012. The fragmentation occurred when the stage had a perigee altitude of 290 km, with as many as 700 large debris detected by the SSN.

Because the perigee was in the northern hemisphere at the time of breakup, the debris orbits were well-placed to be observed by U.S. radar assets in a timely manner

3 STUDYING BREAKUP CLOUDS

To study the evolution of a debris cloud, one needs a mathematical model of the particles of the cloud. NASA uses the Standard Breakup Model (Johnson, et al., 2001) which creates a Monte Carlo cloud of debris particles characterized using model distributions in size, ballistic coefficient, and delta-velocity. Using data from the SSN, the parent body state vector at the time of breakup is used to "create" an initial cloud based on the mass and type of the parent satellite, which is then propagated to observation time of interest. The NASA Standard Breakup Model is based on a variety of empirical data sources – both in-orbit and ground tests – but the data, especially for small debris, is limited. In addition, all breakups are treated in an average sense based on past experience, and the model does not factor in the possibility that new types of vehicles different from those used to create the model might break up differently. Therefore, the model needs to be regularly updated with new information.

For these studies, NASA uses the Standard Breakup Model as a reference model to explore how the actual breakup deviates from the baseline. For example, the overall number of detected objects can be compared to the total predicted to see if the actual cloud is larger or smaller in number than that predicted.

When a satellite breaks up, the debris are given a delta-velocity from the explosion, and each object proceeds to evolve on its own orbit. There are three time scales that define this evolution. For the first hours to days after a breakup, the debris are still clumped in a single cloud. Over time, however, different orbital periods cause the debris in the cloud to "lap" each other, until the cloud begins to form a single ring around the Earth. After a period of months to years, differential precession of the orbit planes randomizes the ascending nodes of this ring until the debris orbit planes become evenly distributed around the Earth. It is during the time that the debris is in a distinct ring that radars used in a stare mode are best able to uniquely identify and characterize the debris cloud.

Fig. 2 shows the early evolution of a model Briz-M cloud (based on the NASA Standard Breakup Model). The chart shows the number of debris making their ascending equatorial crossing in each 5-minute interval. As can be seen, the debris cross the equator in distinct clumps for the first few days, but after a short time the debris become thoroughly randomized in mean anomaly and are evenly distributed around the orbit. Once this randomization has occurred, an observation of the ring at any point will obtain an unbiased random sample of the debris in that ring.

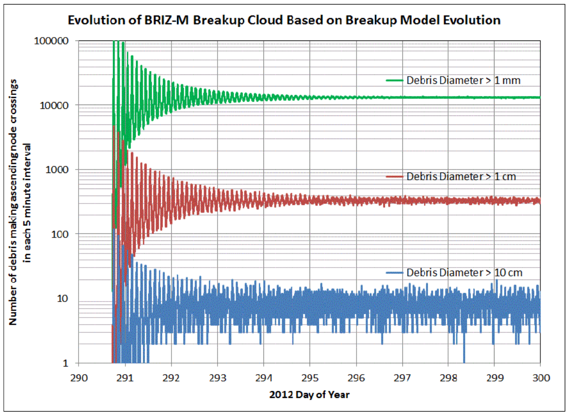

Figure 2 – The evolution of a model simulation of the Briz-M breakup shows that the equator crossing times of the breakup debris are correlated at first because the debris are grouped together in a large "clump". After some time; however, the differential orbital periods randomize the positions of the debris within their orbits, leading to "rings" of debris around the Earth that are easier for staring radars to measure and characterize.

4 OBSERVATIONS

NASA regularly uses three radar tools for centimeter and millimeter debris observations. The Massachusetts Institute of Technology's Lincoln Laboratory operates the Haystack and Haystack Auxiliary (HAX) radars. These X-band instruments operate in a staring mode. Haystack is the more sensitive of the two because of its larger dish, and can see debris as small as 5 mm under the right conditions. Unfortunately, Haystack is currently unavailable as it undergoes upgrades, so only HAX was available for these observations. HAX has a 12.2-meter dish and operates with a wavelength of 1.8 cm. Because its dish is smaller than Haystack, it has a wider beam and larger collecting area, but is not as sensitive. Nevertheless, at shorter ranges it can regularly see debris down to approximately 1 cm in size.

NASA also has access to the 70-m dish radar at the Goldstone facility. Using a bistatic configuration with the 70- and 35-meter dishes, Goldstone can detect debris as small as 2 mm. But these instruments must be shared with the Deep Space Network, which limits when we can use it in debris radar mode. Unfortunately, even though Goldstone made a number of debris observations over the last several months, none were at the right times or ranges to see the Briz-M cloud.

Because the Briz-M broke up near perigee, the cloud of debris had its "pinch point" – the narrow part of the debris ring near the breakup location – at low altitude also. The breakup occurred in such a way that this location was very near the latitude of HAX, and in addition, the inclination of the Briz-M was very close to the latitude of HAX. This made for a very fortuitous geometry for debris options, albeit with its own complications.

Normally, HAX and Haystack operate in a mode pointing east (90° azimuth) at 75° elevation. For general observations, this direction provides a nice balance between short range to the debris (for maximum sensitivity) and information on the debris orbital parameters using the Doppler velocity measurements along the beam sight. However, the perigee of the Briz-M cloud passed close overhead of HAX during the days following the breakup, and the computed debris ranges for 75° east mode would actually have been too close to the radar. Many of the debris were computed to pass at ranges shorter than the nearest range bin of the radar.

A careful study was conducted to optimize the staring angle of HAX to maximize collection area and collection time, but to minimize range so as not to sacrifice sensitivity. If the elevation angle was too high, some of the debris would pass too close to the radar. If the elevation angle was too low, portions of the debris cloud could pass above or too far from the radar so that some orbits might not be observable at all. The measurements had to be custom-planned for each day, limited by the time windows available on the HAX radar, and by the rapid evolution of the cloud. Also, because of the low perigee altitude, it was important to make measurements as soon as possible before the smallest particles began to decay.

5 PREDICTIONS

The model for predicting detection rates is based on the assumption of random mean anomaly (Horstman, et al., 2005 and Matney, et al., 2008). Under this assumption, one only needs five of the standard Kepler elements (semi-major axis, eccentricity, inclination, right ascension of the ascending node, and argument of perigee). The orbit is treated like a "structure" in space, and the staring beam sweeps across it as the Earth rotates. While an orbit is in the beam, the rate of detecting a single object in that orbit is once per orbit period (assuming it has a high enough RCS to be detected by the radar). Therefore, if the orbit is in the beam for a period of time much less than the orbit period, the probability of detecting a single object in an orbit is the ratio of the time the orbit arc is physically in the beam divided by the object's orbital period. The individual orbits of the Monte Carlo debris objects are computed using the Standard Breakup Model described above, then their orbits are propagated to the time of the planned observations. For each Monte Carlo object, the time it will be in the beam is computed, plus its expected range, Doppler range-rate, and probability of being detected (assuming random mean anomaly). This

Monte Carlo ensemble of time, range, and range-rate creates a three-dimensional probability distribution unique to that observation run that can be used to distinguish between cloud debris and conventional background debris objects from other breakups.

Fig. 3 shows the orbit geometry on day-of-year (DOY) 296. The location of the perigee was ideally situated for the HAX latitude, but to observe the highest concentration of orbits around the so-called "pinch point", the best geometry was to point the radar to the north.

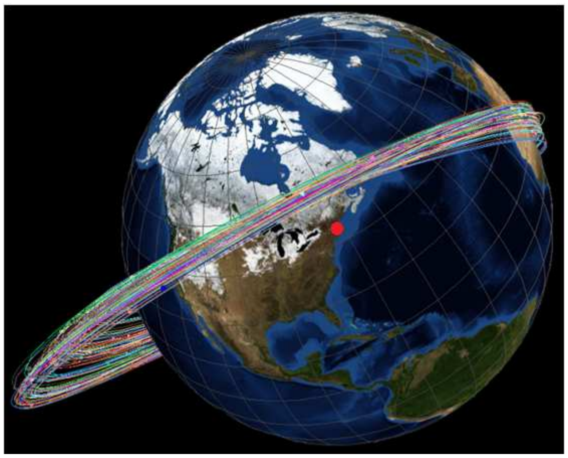

Figure 3 – This image represents a snapshot of the orbits of the catalogued debris from the Briz-M breakup on 22 October 2012 (DOY 296). The viewpoint is positioned directly above the location of the HAX radar, shown as a red mark on the east coast of the United States. Note that the highest concentration of orbits, roughly corresponding to the "pinch point" of the debris cloud, passes to the north of the radar site. At least some of the observations were made with the HAX radar pointing north to take advantage of this fortuitous geometry.

Fig. 4 shows how different pointing elevations affect the observations. If the observations are at too low an angle, some of the debris pass too high to be observed by the radar. However, the longer the cloud is in the beam, in general, the higher the expected rate of detection. If the beam is pointed too high, then some of the debris will pass too close to the radar to be seen in even the shortest range bin. In general, longer range means a higher detection probability per object (longer range = wider beam), but also a drop off in sensitivity. Therefore, a variety of modes were attempted.

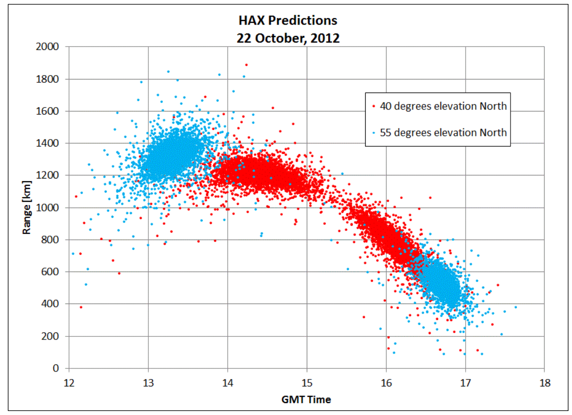

Figure 4 – Predictions of HAX observations based on the NASA Standard Breakup Model. Each point represents a range/time at which a particular Monte Carlo orbit might be detected. Note that the probability of any one object being detected is significantly less than one, so that the patterns can be thought of as representing a probability distribution. Note also that the detection "clumps" are paired – corresponding to an ascending and a descending pass. Different elevation angles offer different advantages. The lower angles offer longer viewing times and a higher probability of detection per object, but at longer ranges and lower sensitivity. For this date, observations below about 40° elevation would have put the beam too low to see parts of the cloud. Higher than about 55° elevation, some of the cloud would have been at ranges too short to have been seen by HAX, at least for the observations after about 16:00 GMT. Tools like this were used to design an observation campaign.

6 RESULTS

Several observation runs were planned using the HAX radar in the days following the breakup. Because of the low altitude of the parent body perigee, the observations had to be made in a timely manner to catch the smaller debris before they began reentering in large numbers. While NASA requests had a high priority, the HAX radar is shared with other users, so not all observation periods requested were available. In the end, a subset of observations that had high-quality data from the complete time and range coverage of the cloud passage were compiled. The data chosen had wide-enough time windows that, even if the actual cloud was somewhat different from the predicted cloud (e.g., the delta-velocities were asymmetric), there was still a high probability that the radar would have measured a complete pass of the cloud.

Fig. 5-7 show a sample set of data from an observation run on 26 October 2012 (DOY 300).

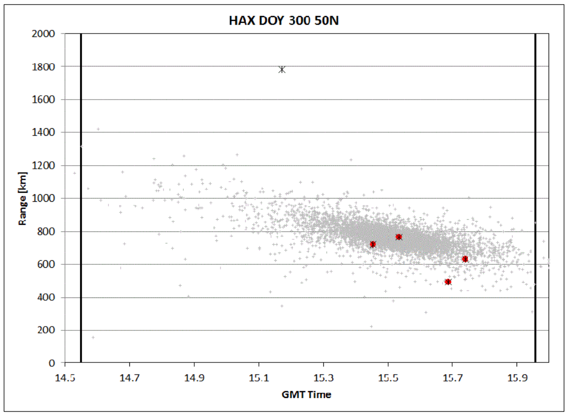

Figure 5 – This is a plot of data taken on 26 October 2012 (DOY 300) showing range as a function of time. This particular observation run was at 50° elevation pointed due north (azimuth 0°). The lines on the left and right represent the beginning and end of the observation run. The grey points are predictions based on the NASA Standard Breakup Model. The stars are all observations. The red dots are observed objects identified as possible debris cloud candidates. One object detected at just below 1800 km range is most probably a background debris object and not associated with the cloud. The two candidates on the right are in regions with relatively low predicted probability (viewing the grey points as a predicted probability distribution). Nevertheless, there is always the possibility that the breakup cloud may be asymmetrical or these may represent objects that are dragging out of the atmosphere faster than predicted (note they are at the lowest range).

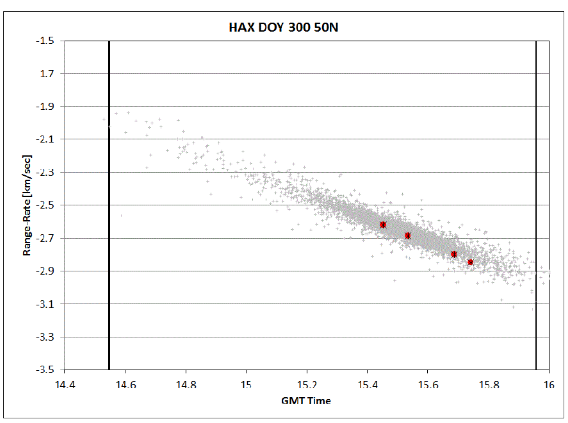

Figure 6 – This chart is identical to Figure 5, but showing Doppler range-rate (velocity along the radar beam) instead of range. The two candidates on the right now look much more likely to be related to the other cloud objects.

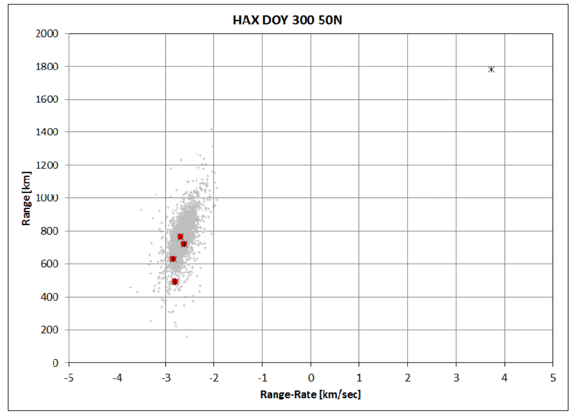

Figure 7 – This chart shows a combination of the data from Figures 5 and 6, but showing the range/range-rate scatter plot, again showing the correlations between these candidate objects and the predicted cloud.

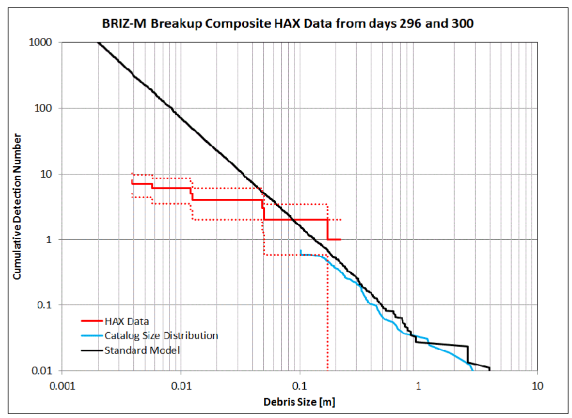

Figure 8 – This plot shows cumulative size distribution of the objects detected in the HAX data that were identified as part of the Briz-M breakup cloud. This distribution is shown in red with simple +/- 1-sigma Poisson sampling error bars. Also plotted is the size distribution curve predicted by the NASA Standard Breakup Model. In addition, the graph shows the size distribution of all catalogued debris from this breakup. All measured sizes were computed from the RCS based on the NASA Size Estimation Model. Note that the HAX data and the catalog data give similar answers to the model in the 10-20 cm range. As has sometimes been seen in other explosion measurements, the size distribution appears to "turn over" below about 10 cm, and rise at a lower rate than the model predicts. This agrees with other measurements that seem to indicate that the explosion models may sometimes overestimate the debris population in the range between about 1 cm and 10 cm.

Because there are three parameters (range, range-rate, and time), there must be correlation in all three parameters to be identified as a possible member of the breakup cloud. Sometimes, candidate objects were on the edge of the predicted distribution. This might be due to differences in the breakup cloud from the model assumptions. Also, these more ambiguous objects tended to be at lower altitudes. This may indicate a possible variation in the estimates of the drag from the model assumptions.

In all, nine objects were identified as part of the breakup cloud. Fig. 8 shows the size distribution of these nine objects compared to the predicted size distribution from the model. In addition, the equivalent calculations for the catalogued population are shown. The detection rate for the catalogued objects is computed in the same manner as the debris – the mean anomalies are assumed random. Note that the model predicts the mean number of catalog debris objects from this cloud expected to be seen was less than one. No catalogued objects were actually observed during these runs, as expected.

7 CONCLUSIONS

While the model (as expected) matches the size distribution of the catalogued population reasonably well, the sampled population of debris below 10 cm shows a change in overall slope, “turning over” below 10 cm. This indicates that our model for smaller particles, partially based on extrapolations of existing data, over-predicts the centimeter population for this breakup. A similar phenomenon has been observed for other on-orbit explosion breakups, and may indicate that certain classes of explosions may have reduced small particle production. Note that this is not the case with observed collision debris, where analysis indicates a continuation of the steep distribution of catalogued objects well below 1 cm.

There are some indications from the catalog population that this particular breakup may have been asymmetric in nature. Unfortunately, the paucity of HAX detections made it difficult to see if such behaviour was reflected in the centimeter size debris.

Further studies will be needed to see if the differences between the observed and modelled size distributions are characteristic of explosions. However, this study indicates the value of timely observations of breakups using sensitive radars.

This breakup, in particular, was particularly challenging because of the high eccentricity and low perigee. Creative observation configurations were used to optimize finite time resources to maximize detection probability and sensitivity. Such planning requires flexible three-dimensional tools to understand the evolving configuration of the orbit cloud and observing instruments.

There are also on-going studies to see if using a moving beam to track the evolving cloud, instead of a fixed staring mode, can increase the number of debris detections and still provide useful statistics.

Any satellite breakup has its own specific properties depending on the specifics of the parent orbit and when the breakup occurs, so it is difficult to come up with any single procedure that would be applicable to all breakups. However, the tools developed over the years for these kinds of studies make each successive breakup study campaign easier to plan and execute than the previous one.

8 REFERENCES

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