CHARACTERIZATION OF THE BREAKUP OF THE PEGASUS ROCKET BODY 1994-029B

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ABSTRACT

The breakup of a Pegasus Hydrazine Auxiliary Propulsion System (HAPS) [Satellite Number 23106, International Designator 1994-029B] on 3 June 1996 is now officially recognized as the worst satellite breakup on record in terms of cataloged debris. The number of debris produced by the relatively small vehicle (<100 kg) and debris decay characteristics have posed serious debris modeling difficulties. One noteworthy aspect of the Pegasus HAPS, which was not passivated at the end of mission, was its use of graphite-epoxy overwrap of aluminum liners for the propellant and pressurant tanks. The low altitude of the breakup and the large range of ejection velocities have also presented special concerns for other spacecraft in low Earth orbit, in particular the US Space Shuttle and the Hubble Space Telescope. In addition to orbital data collected by the US Space Surveillance Network, special observations of the debris cloud have been conducted by the Haystack and Goldstone radars. These observations have shown that the overabundance of debris is not limited to the trackable population, but also extends down to debris with sizes well below 1 cm. Attempts to detect the debris with optical sensors have been less successful. This paper presents NASA Johnson Space Center's analysis of the Pegasus HAPS fragmentation event and how these debris contribute to the current and future near-Earth space environment.

1. INTRODUCTION

The recent breakup of the Pegasus Hydrazine Auxiliary Propulsion System (HAPS) [Satellite Number 23106, International Designator 1994-029B] on 3 June 1996 demonstrates the uncertain nature of breakup events. Because the altitude regime of the HAPS debris was uncomfortably close to that used by the Shuttle, an unprecedented series of NASA experiments was conducted to characterize the cloud and assess its hazard to manned space flight. The greatest concern was over the STS-82 Hubble Space Telescope (HST) servicing mission scheduled for February of 1997. The HST orbits just below 600 km altitude, potentially exposing the Shuttle and crew on EVAs to unacceptable risks.

In order to quantify these risks, three basic questions needed to be answered. First, did the unusually large number of debris particles extend down to smaller sizes or was the cloud primarily composed only of objects with trackable sizes? Second, what was the best estimate of the total population down to sizes of interest to the Shuttle program and how did that compare with the predicted background flux? Third, what was the long-term prognosis of the cloud evolution?

What follows is an example how timely use of the diverse instruments available to study orbital debris can be used to obtain complementary data to present a much more complete view of a breakup event. The lessons learned can be used in the analysis of any future breakups in low Earth orbit.

2. BREAKUP

The Pegasus HAPS stage was about one meter long and one meter in diameter, with a dry mass of about 97 kg. Inside are four tanks, the largest of which contains the hydrazine monopropellant and the smaller ones the helium pressurant and nitrogen for the control systems. Each of the tanks is constructed of graphite-epoxy overwrapped aluminum liners. After its launch on May 19, 1994 the HAPS upper stage responsible for this breakup unexpectedly shut down prematurely, and the payload was not delivered to its desired orbit. As a result, there was as much as 10 kg of hydrazine propellant left in the main tank and helium left in the pressurant tank. The HAPS represents the first known explosive breakup of a carbon-composite tank in Earth orbit.

At the time of the explosion, the HAPS stage was in a 585 x 820 km altitude, 82^d inclination orbit. US Space Command put the breakup time at June 3, 1996, 15:18 GMT, at altitude 630 km, latitude 65° S, and longitude 58° E. It became clear in the first few weeks after the HAPS breakup that the number of pieces created was far in excess of the number that would normally be expected from such a small rocket body. Breakup models used by NASA's EVOLVE model (based on ground tests and the historical behavior of breakups) to predict the effects of on-orbit explosions indicated that an object with a mass around 100 kg should produce

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only about 60 objects large enough to be seen by the tracking network. Yet, by mid-summer, it was clear that the network was tracking ten times that number of HAPS debris, and has since produced the most tracked pieces of any known breakup. This breakup was clearly not an ordinary rocket body explosion.

3. MEASUREMENTS

The first data of the HAPS debris cloud were obtained from US Space Command. This included detailed orbit information of the larger pieces that was used to determine the time of breakup and to characterize the spatial extent of the debris cloud. Fylingdales in the UK was able to provide detailed radar cross section (RCS) data on more than 200 of the tracked HAPS debris pieces for NASA. By the end of 1996, the tally had reached nearly 660 pieces in orbit (with more than 85 already decayed).

In July and August, one of NASA's optical instruments was used to try to observe parts of the HAPS debris cloud. The 12.5" Schmidt system CCD Debris Telescope (CDT) made observations on the nights of July 13-16. It had only limited success in observing some of the tracked HAPS pieces. On the night with the best observing conditions, the CDT attempted to observe 18 tracked HAPS objects but was only able to acquire 2. In addition, observations intended to look for other debris in the orbit plane were not successful. Either the debris were smaller than calculated from the radar data, or they were darker than anticipated. It was clear that the debris were not going to be easily characterized by optical observations.

Lincoln Laboratory's Haystack radar became available in early August as part of NASA's normal annual debris observation campaign, so an observation session was carefully planned to observe the debris "ring" as it passed over Massachusetts on August 6 and 7. Haystack observed at 20° and 75° elevations chosen to maximize the coverage of the debris "ring" over the two days and counted a number of objects that were clearly part of the HAPS cloud (Fig. 1). Most of the debris detected was seen in the 75° mode, primarily because the smaller debris that dominates the cloud were only seen at close range. At this elevation, the Haystack radar can observe objects down to 6 mm in size in the altitudes of interest.

In a fortuitous turn of events, the Goldstone radar had been previously scheduled to make debris observations in October and November of 1996. The Goldstone radar operated in an 88.5° elevation bistatic mode and was able to observe debris smaller than 4 mm in size in the altitudes of interest. Goldstone data sets were taken on October 2 and 8 and on November 1, and all show the clear pattern of the HAPS debris cloud (Fig. 2).

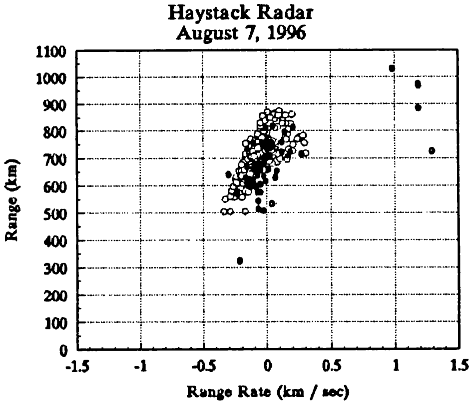

Figure 1 - This is a sample of data from the Haystack radar. The black dots represent individual particle detections and the white circles indicate the predicted values for the tracked HAPS debris population. This 1.7 hour observing window was timed to observe the HAPS debris "ring", and the majority of the detections are clearly are associated with the HAPS cloud.

4. ANALYSIS OF DATA

In order to derive the actual population of debris from count rates in a detector, some knowledge of the orbital parameters of the population of debris is needed. Unlike the background population, where the orbit planes are thoroughly randomized, debris from recent breakups cluster in a distinct orbital "ring". As a result, the observing time and geometry of a ground-based detector is critical. Consequently, a detailed model of how the debris "ring" is distributed is needed in order to accurately determine its actual debris population.

The orbital parameters of the cloud can be estimated by using the tracked population of HAPS debris. In order to use this information, it must be determined whether the small debris population has similar orbit distributions as the large population. Figure 1 shows a sample data set from the Haystack radar, and Figure 2 shows a sample data set from the Goldstone radar. The open circles represent points calculated using the tracked HAPS population that show how each tracked object would have appeared (using its known ascending node and argument of perigee) had it passed through the beam. Each point represents a "ghost object" in the same orbit as the tracked HAPS object, but with just the right mean anomaly to carry it through the radar beam. These computed points outline the time, altitude, and range-rate limits where the debris cloud should be expected to be seen. As can be seen in Figures 1 and 2, the measured data correspond well to the cloud predicted from the tracked HAPS population.

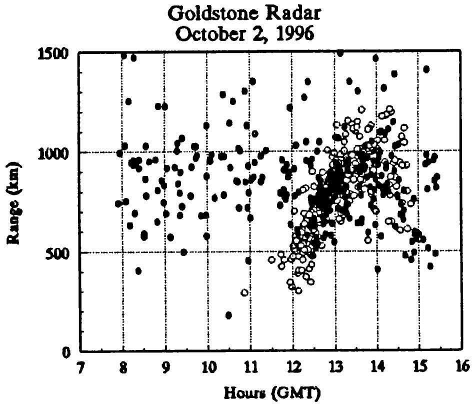

Figure 2 - This is a sample of data from the Goldstone radar. The black dots represent individual particle detections and the open circles indicate the predicted values for the tracked HAPS debris population. Goldstone observed a sharp increase in the count rate during the passage of the debris "ring" through the field of view.

Once it has been shown that the small untracked debris has similar orbits to the tracked HAPS population, the orbits of the tracked debris can be used to scale the actual detection rate to the predicted rate of a known population to arrive at the true population for a given size. In the Haystack data, HAPS cloud particles were distinguished from background objects if they fell in the range and range-rate windows defined by the tracked HAPS population. For the Goldstone data, the range and time windows were used to identify the HAPS cloud. As can be seen in Figure 2, the Goldstone radar detected a large number of background objects in addition to the HAPS cloud. Consequently, an average background rate was determined for each debris size from the observations when the cloud was not in the beam and was subtracted from the debris cloud measurements.

Figure 3 represents a composite cumulative size distribution based on the Goldstone, Haystack, and US Space Command RCS data. The error bars represent one sigma variation based only on the sampling errors. The data from the different sources agree very well over many orders of magnitude and show a distribution that increases with decreasing size. The models that NASA uses to transform RCS measurements into size distributions are based on laboratory analysis of metallic breakup pieces with certain material and RCS properties. If a population of debris has physical properties very different from those of normal breakup debris, it is possible that the size estimates may not be accurate.

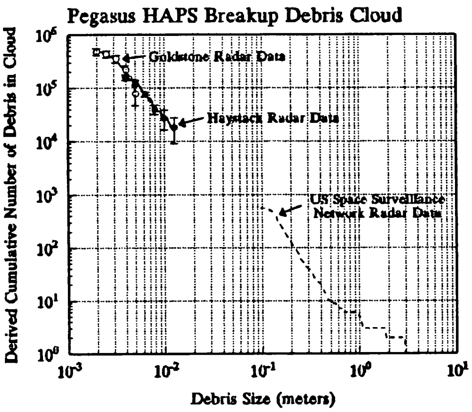

Figure 3 - This composite data set shows the computed size distributions based on radar cross section (RCS) data from the Goldstone (white circles), Haystack (black dots), and US Space Command radars. Each of the detectors can only observe objects down to some limiting size, below which the cumulative curves "roll off". The error bars represent only the estimated uncertainties due to finite sampling errors. The method for transforming RCS to size is the same as is used for the Haystack radar experiment, where the sizes represent an average length of the debris pieces based on ground test of metal fragments.

In addition to RCS measurements, the Haystack radar also records the polarization characteristics of each target object. Haystack emits a circularly polarized beam and receives both polarizations of the reflected signal. The principle polarization (PP) is characteristic of specular reflections from objects such as spheres, and the orthogonal polarization (OP) is characteristic of retroreflections. In Figure 4, the polarization is plotted as a function of size for the detections associated with the HAPS cloud. The polarization is defined as the difference between the PP and OP signals divided by their sum. This method minimizes the effects of noise on the polarization determination. Objects with a high PP/OP ratio will have a polarization near one. Dipoles will have a polarization value near zero ($PP \approx OP$). Many of the small HAPS debris (< 1cm) seem to have polarization values indicative of dipoles. It is possible that the breakup of the graphite-epoxy tank created a number of small graphite needles. If that is true, then the size distribution may have an over-estimate of the debris size. In such a case, the size distribution in Figure 3 would represent an upper limit.

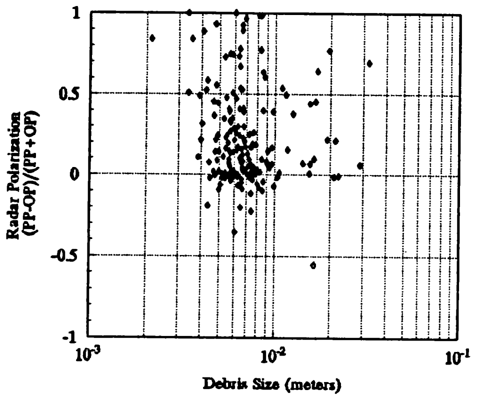

Figure 4 - The points in this graph represent Haystack polarization data of the HAPS cloud. The sizes are calculated from the RCS, and the polarization value is explained in the text. The HAPS cloud shows a large fraction of debris with polarization values around 0, especially in the 0.5 to 1.0 cm size range. This would be consistent with a large population of small dipoles, possibly from the fragmentation of the graphite-epoxy overwrap. If the HAPS debris population is predominantly composed of dipoles, then the sizes computed from the RCS may be an upper limit.

Using the size distribution a flux on an orbiting spacecraft can also be computed. The flux on the target spacecraft is computed for the tracked HAPS cloud population and then scaled by the size distribution for a given size. Safety issues for the Shuttle mostly concern debris objects 1 mm or smaller in size, so the size distribution must be extrapolated into the smaller size regime. For the safety calculations, we determined the number of 1 mm objects to be $7\text{x}10^6$ and the number of 0.4 mm objects to be $5.5\text{x}10^7$.

The altitude distribution of the tracked HAPS debris peaks around 600 km altitude. This means that the addition of the HAPS flux to the normal debris background is strongly dependent on altitude. Shuttle missions that are well below Mir altitudes (390 km) do not see a significant increase from the HAPS cloud. Calculations for Mir altitudes indicate the 5 mm debris flux will be increased about 30% over the background. HST orbits at an altitude (590 km) very near the densest part of the cloud, and our calculations indicate that the 0.4 mm debris flux would be 35% above the model background at HST altitudes, the 1 mm debris flux would be 69% above the model background, and the 5 mm debris flux about 100% over the background. Fortunately these rates were within safety guidelines for the February, 1997 HST servicing mission (STS-82), but the analysis performed by NASA were absolutely necessary in order to quantify those risks.

5. PROGNOSIS FOR THE FUTURE

In order to relate the sensor observations of debris to an actual population in orbit, all of these methods make the assumption that the small measured debris must have orbit distributions similar to those of the larger tracked population. In reality, even if this condition were initially true, debris particles with larger ballistic coefficients would be expected to decay faster due to atmospheric drag. Consequently, observations of the small debris need to be conducted as soon as possible after the breakup events in order to understand the original size and orbit distribution of the breakup cloud. In addition, measurements need to be maintained over a period of time to monitor the decay of the debris cloud.

The HAPS breakup occurred during solar minimum, so the decay rates have been slower than would occur during average solar activity. Nevertheless, the HAPS debris in the lower Shuttle operating altitudes (200 to 350 km) have cleaned out somewhat in the time since the breakup, but at Mir altitudes (around 400 km) and higher, the HAPS cloud continues to be a major contributor to the debris flux and will continue to do so for years to come due to rain down of debris from higher altitudes.

6. CONCLUSIONS

The HAPS breakup shows the need to be able to monitor new and unusual breakups that may affect low-Earth orbit. It shows how data from different sensors can be used to paint a clearer picture of the debris cloud and to assess its risks. Because of the unusual number of debris of the breakup, there is reason to believe that graphite-epoxy overwrap tanks may have undesirable properties. It is clear that with the growing use of such tanks more study needs to be conducted on their behavior in the space environment.