A Comparison of Catastrophic On-Orbit Collisions

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Orbital debris environment models, such as NASA's LEGEND model, show that accidental collisions between satellites will begin to be the dominant cause for future debris population growth within the foreseeable future. The collisional breakup models employed are obviously a critical component of the environment models. The Chinese Anti-Satellite (ASAT) test which destroyed the Fengyun-1C weather satellite provided a rare, but not unique, chance to compare the breakup models against an actual on-orbit collision. Measurements from the U.S. Space Surveillance Network (SSN), for debris larger than 10-cm, and from Haystack, for debris larger than 1-cm, show that the number of fragments created from Fengyun significantly exceeds model predictions using the NASA Standard Collision Breakup Model. However, it may not be appropriate to alter the model to match this one, individual case. At least three other on-orbit collisions have occurred which have produced significant numbers of debris fragments. In September 1985, the U.S. conducted an ASAT test against the Solwind P-78 spacecraft at an altitude of approximately 525 km. A year later, in September 1986, the Delta 180 payload was struck by its Delta II rocket body in a planned collision at 220 km altitude. And, in February 2008, the USA-193 satellite was destroyed by a ship launched missile in order to eliminate risk to humans on the ground from an on-board tank of frozen hydrazine. Although no Haystack data was available in 1985-6 and very few debris pieces were cataloged from Delta 180 due to its low altitude, measurements were collected sensors in the days after each test. This paper will examine the available data from each test and compare and contrast the results with model predictions and with the results from the more recent Fengyun ASAT test.

Introduction

On 11 January 2007, the Fengyun-1C satellite (1999-25A) was destroyed in an anti-satellite test conducted by the Chinese government by collision with a ground-launched, sub-orbital interceptor. The resulting debris cloud, measured by the number of trackable fragments, was the largest in the history of spaceflight. The U.S. Space Surveillance Network (SSN) has tracked approximately 2800 objects from this on-orbit fragmentation and more than a factor of two above the number of 10-cm and larger fragments predicted by the NASA Standard Breakup Model for collision of a satellite of the Fengyun mass[1]. Statistical sampling of the debris cloud by the Haystack and Goldstone radars indicate that this trend continues for sizes at least as small as 2 – 3 mm diameter (see Figure 1).

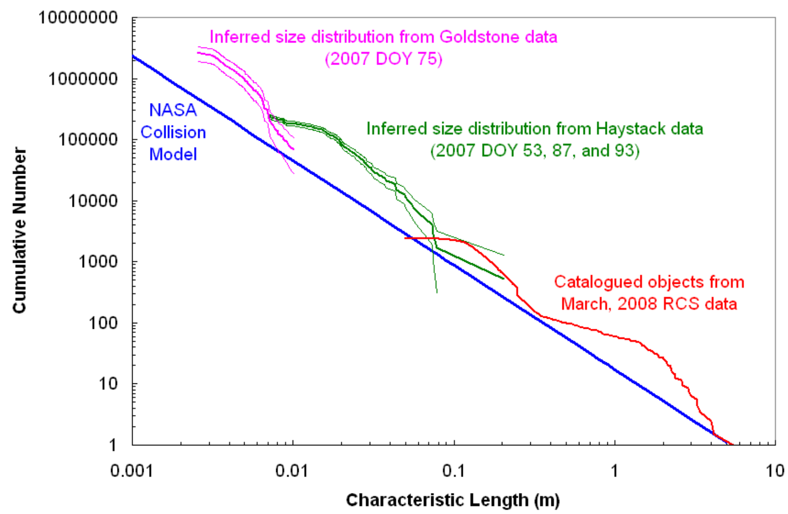

Figure 1. Size distribution from the Fengyun-1C collision. Data from the SSN catalog and the Haystack and Goldstone radars compared with the NASA Standard Breakup Model for collisions.

Other discrepancies exist as well. Since the event in early 2007, about 2200 of the fragments have been tracked long enough and well enough to estimate their area-to-mass (A/M) ratios by monitoring their orbital decay. Distributions of the A/M show a larger proportion of high A/M objects than is predicted by the model.

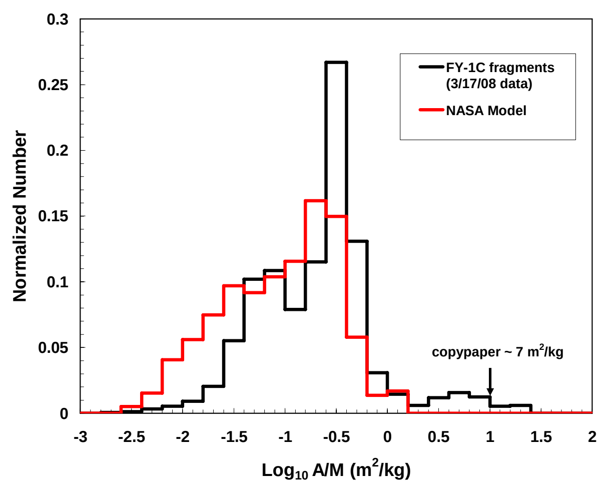

Figure 2. A/M distribution of Fengyun-1C debris for sizes 10-20 cm.

The NASA Standard Breakup Model is an important sub-model used in the NASA orbital debris environment evolution model, LEGEND (LEO-to-GEO Environment Debris). LEGEND is used to predict long-term trends in the orbital debris environment and can be used to test the effectiveness of various debris mitigation actions. LEGEND has shown that even if no new satellites were launched in the future, collisions between already existing on-orbit satellites and debris would continue to increase the number of 10-cm and larger objects for at least the next 200 years[2]. Collision probability is relatively straightforward to calculate. But the size, orbit, and A/M distributions of the resulting fragments are key components to predicting future populations and are much more difficult to determine. Because of the large discrepancy between measurements and the model, some have questioned the need to update the collision model. However, it may not be appropriate to alter the model to match this one, individual case.

NASA Standard Breakup Model

The NASA Standard Breakup Model[3] is a data driven model. The model was developed in the late 1990's and was based on available on-orbit explosions and collisions as well as a number of controlled, ground-based explosions and hypervelocity collision tests. The breakup model defines the size, area-to-mass ratio, and ejection velocity of each generated fragment. Different size distributions are modeled for explosion events versus collision events.

In the NASA model, collisions are considered to be catastrophic if the relative kinetic energy of the smaller object divided by the mass of the larger object is equal to or greater than 40 J/g. Each of the collisions considered in this paper meet this criterion and are considered catastrophic. For collisions, the cumulative size distribution is modeled as a power law:

$$N(L_c) = 0.1(M)^{0.75} L_c^{-1.71}$$

L_c = characteristic length of the fragment (average of the three longest orthogonal dimensions) and M = mass of the satellite.

Different A/M distributions were developed for upper stage rocket bodies and for satellites. However, it was determined there was insufficient data to support a distinction between A/M for explosions vs. collisions.

The distribution function for upper stage fragments with L_c larger than 11 cm is given by

$$D_{A/M}^{R/B}(\lambda_c,\chi) = \alpha^{R/B}(\lambda_c) N(\mu_1^{R/B}(\lambda_c), \sigma_1^{R/B}(\lambda_c),\chi) + (1 - \alpha^{R/B}(\lambda_c)) N(\mu_2^{R/B}(\lambda_c), \sigma_2^{R/B}(\lambda_c),\chi)$$

where $\lambda_c = \log_{10}(L_c)$

$\chi = \log_{10}(A/M)$ is the variable in the distribution

N = the normal distribution function: $N(\mu,\sigma,\chi) = [1 / \sigma(2\pi)^{0.5}]\, e^{-(\chi-\mu)2 / 2\sigma2}$

$$\alpha^{R/B} = \begin{cases} 1 & \lambda_c \le -1.4 \\ 1 - 0.3571(\lambda_c + 1.4) & 1.4 < \lambda_c < 0 \\ 0.5 & \lambda_c \ge 0 \end{cases}$$

$$\mu_1^{R/B} = \begin{cases} -0.45 & \lambda_c \le -0.5 \\ -0.45 - 0.9(\lambda_c + 0.5) & -0.5 < \lambda_c < 0 \\ -0.9 & \lambda_c \ge 0 \end{cases}$$

$\sigma_1^{R/B} = 0.55$

$\mu_2^{R/B} = -0.9$

$$\sigma_2^{R/B} = \begin{cases} 0.28 & \lambda_c \le -1.0 \\ 0.28 - 0.1636(\lambda_c + 1) & -1.0 < \lambda_c < 0.1 \\ 0.1 & \lambda_c \ge 0.1 \end{cases}$$

The corresponding distribution function for spacecraft fragments with L_c larger than 11 cm is given by

$$D_{A/M}^{S/C}(\lambda_c,\chi) = \alpha^{S/C}(\lambda_c)N(\mu_1^{S/C}(\lambda_c), \sigma_1^{S/C}(\lambda_c),\chi) + (1 - \alpha^{S/C}(\lambda_c))N(\mu_2^{S/C}(\lambda_c), \sigma_2^{S/C}(\lambda_c),\chi) ,$$

where

$$\alpha^{s/c} = \begin{cases} 0 & \lambda_c \le -1.95 \\ 0.3 + 0.4(\lambda_c + 1.2) & 1.95 < \lambda_c < 0.55 \\ 1 & \lambda_c \ge 0.55 \end{cases}$$

$$\mu_1^{s/c} = \begin{cases} -0.6 & \lambda_c \le -1.1 \\ -0.6 - 0.318(\lambda_c + 1.1) & -1.1 < \lambda_c < 0 \\ -0.95 & \lambda_c \ge 0 \end{cases}$$

$$\sigma_1^{s/c} = \begin{cases} 0.1 & \lambda_c \le -1.3 \\ 0.1 + 0.2(\lambda_c + 1.3) & -1.3 < \lambda_c < -0.3 \\ 0.3 & \lambda_c \ge -0.3 \end{cases}$$

$$\mu_2^{s/c} = \begin{cases} -1.2 & \lambda_c \le -0.7 \\ -1.2 - 1.333(\lambda_c + 0.7) & -0.7 < \lambda_c < -0.1 \\ -2.0 & \lambda_c \ge -0.1 \end{cases}$$

$$\sigma_2^{s/c} = \begin{cases} 0.5 & \lambda_c \le -0.5 \\ 0.5 - (\lambda_c + 0.5) & -0.5 < \lambda_c < -0.3 \\ 0.3 & \lambda_c \ge -0.3 \end{cases}$$

Solwind P-78

Solwind P-78 (1979-017A) was an Orbiting Solar Observatory type satellite, with a solar-oriented solar panel section and a rotating section roughly cylindrical in shape. The cylindrical section had a diameter of 2.1 m and a length of 1.3 m. The solar panel was 4.37 m^2 and the total mass of the satellite was 878 kg.

The satellite was the target for a sub-orbital ASAT interceptor launched from an F-15 aircraft. The Solwind P-78 collision occurred on 13 September 1985 at approximately 20:43 GMT. At the time of the intercept, P-78 was in a 97.6° inclined, nearly circular orbit of 518 x 548 km.

Early observations of the breakup cloud were captured during two passes through the coverage of the Perimeter Acquisition Radar Characterization System (PARCS), located at Cavalier Air Force Station in North Dakota, within 12 hours of the fragmentation. PARCS is a north-facing, UHF phased-array radar with broad area coverage. It has a nominal detection limit of about 10 cm equivalent diameter (or the more accurate description, characteristic length). Teledyne Brown Engineering (TBE) processed the data from these two passes and presented the results in a technical report, *Postmortem of a Hypervelocity Impact*[4].

The first pass in PARCS coverage started on 14 September a little before 6:20 GMT. All of the debris determined to have come from P-78 passed through PARCS coverage in 41 minutes. The number of debris pieces detected during the first pass was 133. The second pass started just before 7:40 GMT, lasted 53 minutes, and detected a total of 267 objects.

Although the TBE report mentions that the second pass over PARCS was closer to passing directly over the radar and hence the radar would be more sensitive due to the shorter slant range to the P-78 orbit, experience would indicate that more pieces were seen during the second pass due to them being spread out further along the orbit. If multiple objects are closely spaced, the radar is unable to discriminate between them and would count them as a single object. Also, a phased array radar is sometimes resource limited. In other words, if too many objects are passing through its field of view at one time, it may not have the time or transmit power to track all of the objects detectable by the radar. Therefore, 267 may not be the ultimate count of objects larger than 10 cm. Also, given the altitude of the P-78 satellite at the time of the collision, some 10-cm and larger debris would have reentered prior to either of the PARCS passes, although this was probably not a significant fraction of the total piece count.

Another dedicated test using PARCS was conducted on 9 January, 1986, some 118 days after the fragmentation. During this test, PARCS was operated using software which slightly increased the sensitivity of the radar to small objects. During this test 288 individual detected objects were determined to have originated from P-78. (Nine additional cataloged debris had reentered the atmosphere before the date of this test.)

Eventually, 285 debris objects were cataloged by the SSN, the last piece cataloged in the first week of August, 1988. All of these data sources (PARCS second pass, PARCS small satellite test, and the SSN catalog) consistently indicate that total number of debris larger than 10 cm is on the order of 300 objects, less than half of the ~800 predicted by the NASA model.

The TBE report lists the radar cross section (RCS) of the detected objects during both the first and second passes. In Figure 3, the size distribution for fragments from P-78 for the PARCS second pass along with the size distribution of the SSN cataloged objects and the results of the NASA Standard Breakup model are plotted. For the measured data, the RCS has been converted to equivalent characteristic length using the NASA Size Estimation Model[5] (SEM). The SSN sizes were collected over time and involve the averages of many passes of the debris through different radars. Therefore, it is not surprising to see the variation in the two measured size distributions.

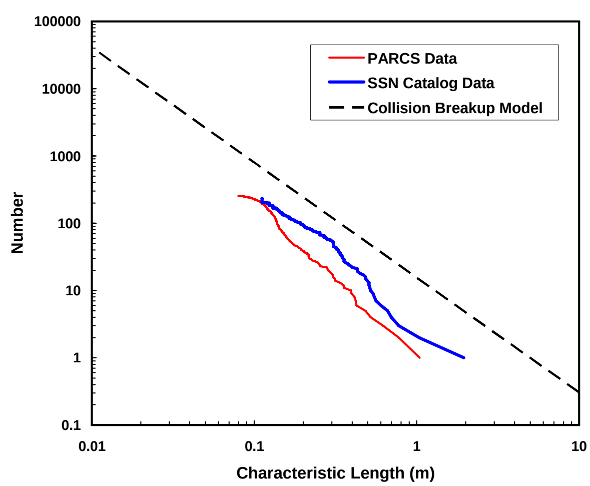

Figure 3. Size distribution from PARCS data as well as the SSN catalog compared against the NASA Standard Breakup Model for collisions.

It can be seen from Figure 3 that the slope of the cumulative size distribution using either the PARCS data or the SSN data is approximately the same as the model, but is at least a factor of 2-3 lower than the model prediction. It must be noted that P-78 SSN catalog data was one of the data sets used to create the NASA Standard Breakup Model. However, the data was converted to mass using the size information and A/M values prior to fitting the data even though the model is formulated to provide a size distribution.

The early PARCS data was not sufficient to determine area-to-mass, or drag data from the P-78 fragments. For that, the SSN data is used. The orbital element history of each of the cataloged debris was used with NASA's Prop3D orbit propagator[6] to curve fit the decay rate to estimate an effective area-to-mass ratio (assuming a coefficient of drag of 2.2). Figure 4 shows a histogram of the A/M distribution of the SSN cataloged objects between 10 and 20 cm characteristic length while Figure 5 shows the distribution of all of the SSN objects. Although showing some variation from the model, the model seems to be a reasonable fit to the data and the data is not skewed towards the high A/M values as seen in the Fengyun distributions.

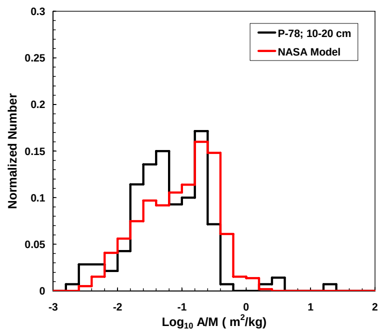

Figure 4. A/M distribution of P-78 debris for sizes 10-20 cm.

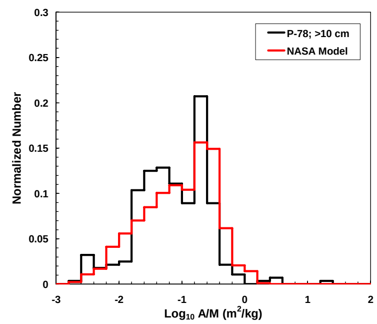

Figure 5. A/M distribution of all P-78 debris larger than 10 cm.

Delta-180

Another planned on-orbit collision occurred on 5 September 1986 at 17:53 GMT during the Delta-180 mission. This collision was between a Delta II second stage (1986-069B) and the Delta-180 Payload Adaptor System (PAS) (1986-069A; also known as USA 19) at an altitude of 218 km altitude about 600 km north of the Kwajalein Atoll. At the end of a short mission, the engines on the Delta second stage and PAS were fired and the seeker head on the PAS directed it to the intercept of the thrusting Delta stage. At the time of the impact, the relative velocity between the two vehicles was ~ 3 km/sec. The Delta second stage was in an orbit of 210 x 550 km with an inclination of ~23° while the PAS was in a 210 x 590 km orbit with an inclination of ~39°. There is some confusion on the masses of the two payloads. But using the most authoritative references available, the dry mass of the Delta stage[7] was 1455 kg and the dry mass of the PAS[8] was 725 kg.

The principal author of this paper was an eyewitness to this collision from his location on Kwajalein Island. The collision was timed to occur just before dawn so that the satellites and resulting debris could be observed by ground-based and airplane mounted passive optical systems. As the satellites cleared the northwestern horizon, they were already firing their engines and so were very bright. The collision looked very similar to a large fireworks bomb detonating. The initial debris cloud looked perfectly spherical in shape from the observer's line-of-sight which was almost directly behind the PAS and nearly parallel to the relative velocity vector between the two stages. As the debris continued moving towards the eastern horizon, the debris appeared to begin to separate and follow the two parent body orbits. The two debris clouds also appeared to have slightly different colors although that could have been caused by the different phase angles between the sun, the debris, and the observer.

Because of the low perigees of the orbits for both stages, the lifetimes of the resulting debris were relatively short. The SSN cataloged only 16 debris pieces from the collision, 12 from the PAS and 4 from the Delta second stage. Part of the low number of objects detected in the 23° orbit has to do with the lack of sensors at low latitudes. Fortunately, some sensors were specially tasked to observe the debris clouds. Data from debris clouds created by the collision was gathered and reported by NASA in *Hazard Analysis for the Breakup of Satellites 16937 and 16938*[9].

Several optical and radar sensors were tasked with observing the clouds in the days immediately following the collision. The optical sensors yielded few observations which led to the conclusion that the albedo values of the resulting debris were lower than anticipated. These measurements were some of the earliest indications that the albedo values of orbital debris are on the order of 10%. (Similar optical instruments were used in Alaska during the P-78 data campaign. The low detection rate in that campaign was initially attributed to interference from bright auroral background. It was not until after Delta 180 that the low detection rate was attributed to the low albedo of collision debris.)

As mentioned before, the low perigees of the orbits for both stages meant that debris began to reenter the atmosphere almost immediately. In fact, a meteor radar located on the island of Kauai in the Hawaiian Islands detected reentering debris during the first orbit, ~3600 km downrange from the collision[9]. Estimates are that as much as half the debris would have reentered within the first day.

The two debris clouds had orbital inclinations which were too low to be observed by the PARCS radar. The Eglin radar, located in Florida and south pointing, was utilized instead. The Eglin FPS-85 is also a large phased array radar with similar sensitivity as PARCS. Both parent orbits entered into Eglin coverage approximately 16 hours after the collision. During the next 90 minutes, Eglin detected 190 debris in the Delta (23°) orbit and 191 objects in the PAS (39°) orbit. This was a surprising result since the Delta had about twice the mass of the PAS. Another Eglin pass was collected on 12 October, 37 days after the event, and 132 debris from the Delta and 69 debris from the PAS were detected. Unfortunately, debris sizes were not reported from Eglin for these passes although the accepted sensitivity limit is approximately 10 cm.

The SSN, as a whole, did track enough of the debris to develop area-to-mass values on 57 objects[10]. These are shown in Figure 6.

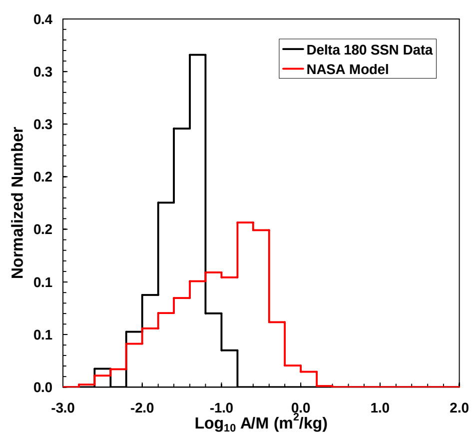

Figure 6. A/M distribution of debris tracked by the SSN from the Delta-180 collision.

The only debris sizes reported came from the ALTAIR radar. The ALTAIR radar is a dish radar located on Kwajalein Atoll. ALTAIR operates simultaneously in two wavelength bands, VHF (center frequency of 162 MHz, wavelength = 185 cm) and UHF (center frequency of 422 MHz, wavelength = 71 cm). At VHF the beamwidth of the radar is 2.8° and at UHF 1.1°. These nominal fields of view are relatively wide for dish type radar antennas, but still much smaller than the wide area coverage provided by phased arrays. For three successive days after the collision, ALTAIR was pointed at the intersection of the orbit planes for the two debris clouds as the intersection passed near the radar. The intersection was close to the location in inertial space where the collision occurred, so that the debris clouds were relatively narrow at this point. It is unknown if either of the beamwidths covered the entire width of the clouds as seen from the radar, but it was decided that this was the best way to sample the largest percentage of debris from both clouds. No attempt was made to determine if any objects repeated. But, since each data collection was approximately 90 minutes in duration (similar to the orbital period of the parent bodies), significant contamination from double counting is not likely.

NASA received the ALTAIR VHF data in both a digital format and as range-time-intensity (RTI) plots while the ALTAIR UHF data was received only as RTI plots. Although ALTAIR is sensitive to smaller debris in UHF, the only recorded size information was from the VHF digital data. Even the original digital data is now lost, probably having been discarded along with the now ancient VAX 11/780 computer it was originally processed on. The size data only survives in the form of histogram plots in the original NASA report. The original analysis was done prior to development of the NASA SEM, so the RCS was interpreted using the optical scattering approximation. In other words the RCS was interpreted as a physical cross section without regard to the wavelength of the radar. For the current analysis, the size histogram was converted back to RCS and then size was estimated using the SEM. The data are replotted in Figures 7, 8, and 9 in the more standard cumulative size distribution.

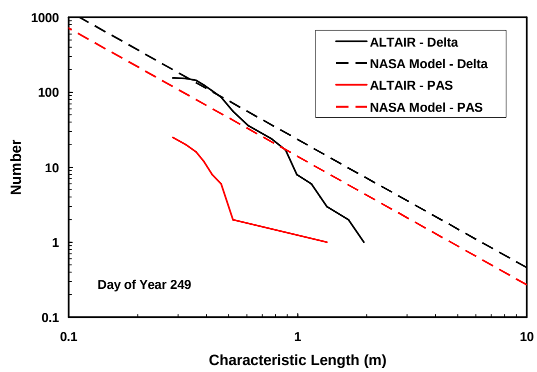

Figure 7. ALTAIR VHF data collected 1 day after the Delta 180 collision.

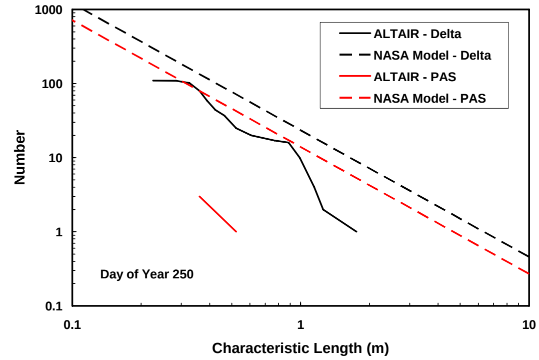

Figure 8. ALTAIR VHF data collected 2 days after the Delta 180 collision.

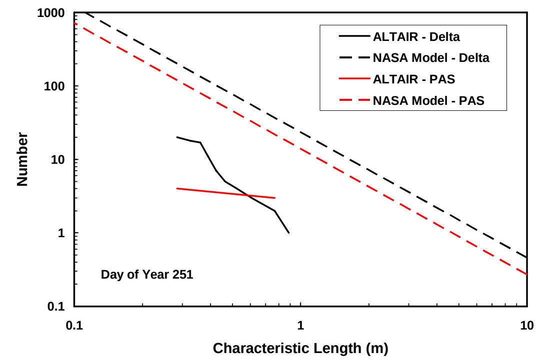

Figure 9. ALTAIR VHF data collected 3 days after the Delta 180 collision.

The only other size information that can be gleaned from the ALTAIR data is a comparison of the VHF and UHF total counts for each of the three days. At the slant ranges and waveforms used for the beam park data collection, the limit of the VHF waveform is about 35 cm and about 11 cm for the UHF data. Table 1 summarizes the number of detected objects from each data set. Figure 10 shows the number of detections normalized to a uniform 90 minute collection window against model prediction for the Delta plus PAS combined size distribution. These data points are behaving as one would expect. The total numbers of detected objects is lower each day which would be expected from the low perigee altitude of the orbits. In addition, the 11-cm population is dropping at a higher rate than the 35-cm population because one would expect the smaller objects to have higher A/M. Extrapolating this trend backwards to the time of the collision would indicate that the NASA model probably under-predicted the total number of objects produced in the collision, but the slope of the data points is probably very close to the predicted slope.

Table 1. ALTAIR UHF and VHF total detections

	UHF		VHF	
Day of Year	Number of Objects	Duration of Observations	Number of Objects	Duration of Observations
249	470	0:47	212	1:39
250	498	1:46	148	1:51
251	228	1:30	99	1:44

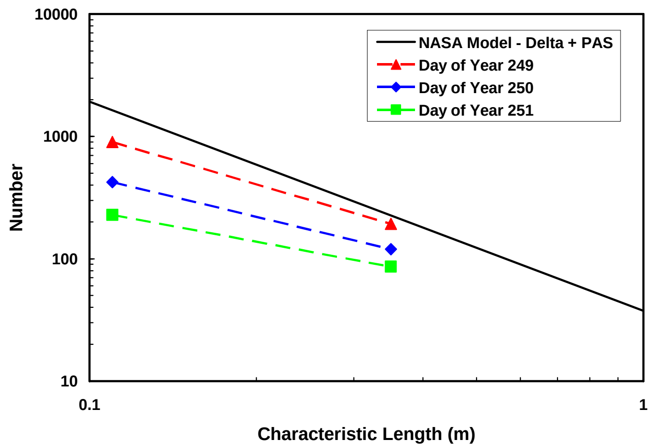

Figure 10. ALTAIR UHF and VHF total counts scaled to 90 minute detections windows for each of three days following the Delta 180 collision.

The low altitude of this collision makes interpretation of the data very difficult. Some of the debris reentered the Earth's atmosphere almost immediately. It is not known what biases that may have introduced to the subsequent A/M and size distributions. Certainly, the higher A/M objects reentered the atmosphere faster than other objects in similar orbits, skewing the distribution of the few objects for which A/M was developed. Also, the total number of objects measured in the subsequent days after the event does not reflect the true number of objects created. Figures 7 and 10, along with the knowledge that up to half of the debris reentered in the first day, would indicate that NASA model under-predicted the total number of 10-cm and larger debris created in the collision. But again, the degree to which the model under-predicted is nearly impossible to quantify.

USA-193

On 21 February 2008, USA-193 was intercepted by a missile launched from an Aegis cruiser. The satellite was in a low, ~250 km, near-circular orbit. Data for this event is very limited in due in part to the classified nature of the mission and, in part, to the low altitude of the collision. Assuming a reported mass of ~1800 kg, the NASA Breakup Model would yield ~1400 debris larger than 10 cm diameter. Similar to Delta-180, many debris pieces probably reentered almost immediately. On 22 February, the SSN was tracking 360 objects. On 25 February, this number had dropped to ~275. 174 objects eventually made it into the SSN catalog. And, at the time of this paper, one USA-193 fragment remains in orbit but is expected to reenter before the end of 2008.

Haystack was tasked to observe the orbit plane of the parent body within a few hours of the collision. Detection rates for Haystack were very high during the data collection. Because of this, the normal Haystack data processing programs do not work properly. This data set is still being processed. Because of the low altitude of the USA-193 orbit, most of the debris was below the altitude of Haystack's range window during normal debris staring operations. So, little data was collected in this mode.

Conclusions

There have now been four on-orbit collisions which can be classified as catastrophic upon which future improvements to collision breakup models can be based. Two of the events, Delta-180 and USA-193, occurred at low altitudes designed to shorten the life of the resulting debris clouds and hence protect the low Earth orbit environment. The low altitudes complicate the collection and interpretation of data because so many of the debris pieces reenter the Earth's atmosphere before they could be measured. Of the two remaining collisions, Fengyun produced more fragments than predicted while P-78 produced less than predicted. In terms of A/M, Fengyun was more biased towards high A/M objects while P-78 seemed to match the predicted distributions more closely.

The Fengyun collision is certainly a data point which indicates that the NASA Standard Breakup Model may need modification to predict a higher piece count along with a component of higher A/M debris. But it is preferable to know why this breakup is different from ground tests and P-78 in order to understand how to modify the model. The possible causes are: 1) differences in construction and makeup of the spacecraft; 2) differences in the geometry of the collision; and 3) statistical or random variation. It is clear from available information that the Fengyun had much larger solar panels than P-78 and was also covered in multi-layered insulation (MLI) material. It has been postulated that the differences in the Fengyun debris cloud are due to these construction elements[1]. Planning is currently underway to perform ground hypervelocity tests on simulated spacecraft that have MLI components. It would also be prudent to measure the radar cross section of different MLI configurations to understand the size range that SSN radars could detect. However, since the model over-predicts the number of fragments from P-78 and under-predicts the number from Fengyun, it is not prudent to change the breakup model until more information is available either from more realistic ground tests or from additional on-orbit collisions. Furthermore, in terms of total overall risk to the environment, the higher number of objects produced in the Fengyun breakup is offset by their shorter lifetimes resulting from the higher A/M distribution[1].

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