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Space Debris Hazard To Defense Systems

Gregory H. Canavan¹

Abstract

Space debris could present a hazard to defense systems. Recent data indicate that impact rates from small particles at low altitudes may have been overestimated, impacts at high altitudes would only reduce the lifetimes of large satellites slightly, and fragmentation and cascade rates are small.

Introduction

Natural and man-made debris are argued to present hazards to space systems, but recent data indicate that at low altitudes, the impact rates from small particles may have been overestimated by an order of magnitude. At high altitudes, small particles only present an impact hazard to large satellites; they would not support a cascade. Large particles would apparently produce a cascade only on time scales of centuries or millennia. Radar and optical data should be capable of resolving these uncertainties, but their observations are, as yet, inconsistent. While independent analytic and numerical estimates of collision and cascade rates agree, given consistent inputs, different groups produced significantly different estimates of debris growth rates. This note examines the basis for these discrepancies.

Debris Catalogue

The U.S. Air Force Space Command maintains a catalogue of objects larger than about 10 cm, which remain in space for an extended period of time, that is distributed to users as element sets of ephemerides. NASA's Johnson Space Center (JSC) also distributes a "USAF Space Command" catalog, which gives the object flux (debris density times velocity) as a function of altitude and particle size. JSC's catalogue is the Air Force Space Command catalogue (Kessler 1995), reduced to a function of altitude and size with algorithms derived by JSC (Kessler 1981). After independent derivation and testing, these algorithms, were used to independently reduce a typical Air Force Space Command catalogue. The results agreed with JSC fluxes to within a factor of two at Shuttle and Space Station altitudes and even more closely at higher altitudes, which indicates that the source of discrepancy does not

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arise from differences between the catalogues and algorithms, which are essentially identical.

Impact rate at 350-450 km

Shuttle or Space Station collisions with catalogue size objects are very unlikely. The principal threat is collisions with ≈ 1 cm objects, because they are more numerous by orders of magnitude, but still large enough to defeat affordable shielding. To estimate the threat from ≈ 1 cm objects, JSC extended its catalogue from that for > 10 cm objects by extrapolation. Only the MIT Lincoln Laboratory Haystack narrow-beam, x-band radar has enough sensitivity to measure the distribution of small particles, because scattering cross sections decrease even faster than their sizes for longer wavelengths. JSC has measured debris in the range of roughly 3 mm to 3 m over the last five years and disseminated the measurements through threat models.

The relationship between the data and model is somewhat unclear. For observations of > 1 cm debris at 350-450 km, Haystack measurements lie factors of 3 to 20 below the model predictions that are used to define the environment for Space Station (Stansbery). JSC has argued that the NASA model is a "worst case" model built on a number of factors, but that does not explain the discrepancy between the model and the data on which it is supposedly based. Using the Haystack data rather than the model theoretical collision rates reduces the expected impact rate from about 0.03 to 0.003 per year. That gives a collision time of 300 years or a 3% probability of impact per decade of habitation, which might not require additional shielding. Thus, this discrepancy between the Haystack data and the model is the key factor in determining whether there is a low altitude threat.

Interpretation of radar data

This discrepancy is compounded by the difficulty of inferring the size of the scattering objects in the beam from the radar return for the centimeter particles of interest. The radar scattering cross sections of objects whose size is comparable to that of the radar show large Mie resonances whose magnitude and structure depend on the size and orientation of the scattering particle (Judd). The composite scattering function is not a monotonic function of particle size, so it cannot be inverted to determine the size or distribution of the scattering objects uniquely. JSC has an empirical prescription for converting radar returns into the sizes of equivalent debris spheres through the incoherent addition of the measured cross sections of a collection of typical objects, but that process appears uncertain by factors of 2 in amplitude and size due to the resonances, which differ for each particle size, shape, and orientation. Further Haystack measurements would not resolve the issue, as it has to do with proper averaging over cross sections rather than with the total number of particles observed. However, further measurements should resolve why the Haystack data do not agree with catalogue values for larger particles, which are thought to be well known.

Impact rate at 850-950 km

At 850-950 km altitudes, the Haystack data roughly agrees with JSC's $\approx 5 \times 10^{-5}/\text{m}^2\text{-yr}$ flux for > 1 cm particles, which would give ≈ 0.002 impacts/year on a 40 m^2 satellite (Stansbery). That rate would reduce its ≈ 10 year design lifetime by about a percent, which is small compared to other operational factors considered in

its amortization. It would give 0.2 collisions per year in a 100 satellite constellation, or 2 collision per year in a 1,000 satellite constellation. However, impacts by ≈ 1 cm particles would damage the satellites, but they would not produce significant numbers of additional particles to start a cascade (McKnight). They would only reduce expected lifetimes to an extent that is independent of the sizes of the constellations deployed now or in the future.

For the > 10 cm particles that could produce significant numbers of secondary particles in collisions, Haystack data lie a factor of 3 to 10 below the JSC model, giving an impact rate of $\approx 4 \times 10^{-5}$ /year on a 40 m^2 satellite, or ≈ 0.04 collisions/year in a 1,000 satellite constellation. As discussed below, such collisions would produce about 100 catalogue particles/collision or a total of about 4 catalogue particles per year, which is small compared to orbital decay losses. Thus, collisions of debris with existing or proposed satellite constellations would not lead to cascading.

Mass in LEO

Total mass in low Earth orbit (LEO) determines collision and cascade rates. Most of the mass is in catalogue particles, which, as noted above, are the only ones that can produce significant secondary particles in a collision. JSC estimates there is 2,000 tons in LEO on the basis of the difference between the inventories of launched and decayed material (Reynolds). An estimate of 800 tons results from direct integration (Canavan 1995a) of the curves in the National Research Council report on Orbital Debris (Cleghorn), using the mass-area ratio relationship established by JSC (Kessler 1978) and still used in their recent calculations of regions of potential instability (Kessler 1991).

JSC's empirical relationship gives an average mass per unit area about a factor of 2 below that of actual catalogue objects. The JSC differencing of launched and decayed material should be more accurate, but uncertainties in the decay model could be of that order. In any case, the total mass is the product of the number of catalogue particles and the mass of an average particle, which is related to the mass of the largest particles. The estimates can be brought into consistency by doubling the area and mass of the largest particles from those indicated in the NRC plots. That doubling would also bring the catalogue collision frequencies into agreement while altering the predicted number of fragments per collision by only $\approx 60\%$ (Canavan 1995a).

Explosion and collision physics

In addition to the influx of particles from space, there are two known means of production of objects in LEO: explosions of rockets or payloads and collisions of particles with other particles or satellites. The two differ in detail, but produce broadly similar distributions of particles (McKnight). For explosions, the mixing of residual fuel and oxidizer produces a pressure spike, rupturing the tank, which fragments during expansion. The few characterized explosive ground tests produced large numbers of objects of low velocities. Most observations of explosions are on orbit, where only the catalogue sized objects can be detected and tracked. The particle distributions produced by these explosions are consistent with those from ground explosion and impact experiments. However, JSC uses the largest number of particles observed in explosions rather than the distribution average in estimates, for "conservatism," which increases their estimate of the number of particles from explosions by about a factor of three.

Hypersonic collisions between objects whose masses are within about a factor of 10,000 of each other produce showers of particles containing the total mass

of the colliding partners. A small number of large particles contain most of the mass. A continuous distribution of intermediate masses contains most of the particles large enough to multiply in collisions. A large number of small particles contain most of the number but little of the area or mass of the collision partners. These trends are generalized from a few dozen instrumented experiments, which were not at full velocity or scale. There is no evidence of fragmentation through collisions on orbit. That is consistent with the discussion of collision rates below, which suggests that there should not have been any.

Fragment production

JSC's analysis predicts fragment production to be "480 fragments larger than 10 cm..." per collision between catalogue objects (Kessler 1991). That is about a factor of 6 greater than that from analytic (Canavan 1995a) and numerical (Canavan 1995b) calculations, which actually average over cross sections, debris distributions, and collision products to predict the average number of particles. JSC does not use the results of these impact experiments; instead they scale from the empirical result of 480, or now "about 300 fragments per energetic explosion." (Kessler 1995) That amounts to using the *largest* number of fragments observed from *explosions* to estimate the *average* number of fragments produced per *collision*. The effect is the factor of 4 to 6 increase in JSC's estimate cited above.

The NRC report on Orbital Debris states that for "a 420 kg spacecraft struck by a 0.5 kg piece of debris at 13 km/s...models predict that 50 to 100 fragments with masses of greater than 0.5 kg—massive enough to cause similar catastrophic breakup—would be produced (Cleghorn)." These values are consistent with those in the analytic and numerical calculations, which give 85 catalogue fragments for that case. Thus, the issue is not one of how to interpret the collision or explosion data or of how to average it. It is a matter of whether the proper debris-averaged collision fragment production will be used or replaced with the maximum explosion fragment production. The latter can be used if it is clearly understood that it is done for additional conservatism and that there is no basis for it in the data.

Growth rates

Using the collision rates and fragment production discussed above, JSC estimates a catalog fragment production rate of $\approx 480 \text{ fragments/collision} \times 0.05 \text{ collisions/year} \approx 24 \text{ fragments/year}$ (Kessler 1991) Since there are currently $\approx 8,000$ catalog objects in LEO, this implies a growth rate of $\approx 24 \text{ objects/year} / 8,000 \text{ objects} \approx 0.3\%/yr$. That gives a doubling time of ≈ 230 years, which is so long that by itself cascading would not appear to be a serious near-term consideration. Moreover, this doubling times is much shorter than the 800-2,000 years from more recent calculations using the experimental average number of fragments per explosion and collision discussed above.

JSC does not disagree with the inference of a 240 year cascade doubling time from their calculations and agrees that cascading is not an immediate problem. JSC is "concerned about the possible growth due to increased launches and explosions" in the near term, when their doubling times are dominated by the debris from launches and explosions. "Cascading would only become important in subsequent centuries." (Kessler 1995)

A recent JSC figure (Reynolds) shows the catalogue debris increasing from $\approx 70,000$ to 1,000,000 particles in a century. That gives a growth rate of 2.7%/yr, which is a factor of 10 greater than that inferred in the previous paragraph. It corresponds to a doubling time of about 25 years rather than the 240 estimated above. There appear

to be three factors that could produce such a discrepancy: the rate of launch, explosion, and fragments per explosion; the number of fragments per collision; and the rate of decay of debris. JSC' assumes continued growth of debris from normal launch activities at 5%/yr. That causes growth from 70,000 to 350,000 objects in a century, or 1.6%/yr, which accounts for about half of the total growth. This increase due to launch operations is dominant in the first half of the century; cascading is dominant during the latter half.

The product of the rates of launch, explosions per launch, and fragments per explosion dominates the near-term growth of debris. None of the terms is known with precision. Launch rates have fallen sharply in the last decade. It is not known whether they will recover to cold war levels. Current Air Force estimates indicate they will not. Moreover, the most bothersome past explosions can be traced to a few unique mission. Some, such as Soviet use of 1,200 to 1,500 km orbits, have probably been ended. There have only been 3 explosions in that altitude regime in the last 15 years.

Other orbits, such as sun-synchronous orbits, will be continued, although the trend is to fewer explosions per launch to that orbit as well. There have been a number of explosions at 800-900 km, but those explosions inject less material into the less stable 900-1,000 km region, where there have been none in the last decade. There are plans for large communications constellations at these altitudes, but those satellites are not a direct concern for the impact reasons discussed above, and the launchers planned are fairly clean and tested. Overall, there is no fundamental reason for the assumption of a continued 5%/year growth from deployment. If launch trends continue and boosters continued to be burned to completion to eliminate the major source of explosion energy, the amount of debris in LEO would decrease even without the imposition of measures to deorbit boosters or payloads.

The number of fragments per explosion is discussed above. There is an empirical average number; JSC uses the maximum, which is about a factor of three higher. That is acceptable so long as it is identified as an excursion.

The number of fragments per collision is also reviewed above. JSC uses the maximum number, which is about a factor of 6 above the weighted average. Again, this is acceptable as long as it is understood that this value is not implied by the data. The number of fragments per explosion and per collision are essentially multiplicative at the level of JSC's analysis. Thus, their treatment of collision physics is apparently conservative by about a factor of 18.

Rate of decay refers to detailed technical differences between how the Air Force and JSC treat the lifetime of collision fragments, which apparently decreases JSC's estimate by about a factor of 3 of the size of particles that can remain in orbit long enough to multiply.

If the maximum values for each of these parameters are used in the analytic and numerical calculations, JSC's results are recovered. If any of them are reduced, debris growth is pushed off into following centuries. If Air Force projections are used for launch and explosion rates, the debris never gets to a level where cascading can take place. If the properly averaged number of fragments per explosion is used, the linear phase of debris growth is similarly retarded. If the properly averaged number of fragments per collision is used, the quadratic phase of cascading is delayed several centuries. If decay is treated normally, the threshold for instability is pushed up to levels that would only be reached some centuries out. From this discussion it appears that cascading is a slow and possibly hypothetical process. However, it has received national and international prominence. To fully resolve the issue, it would be necessary to find a consensus on likely launch and collision rates, explosion and collision fragment production, and debris decay rates.

Summary

Natural and man-made debris are argued to present a hazard to space systems, but recent data indicate that small particle impact rates may have been overestimated at low altitudes, impacts at high altitudes would only reduce the lifetimes of large satellites slightly, and that fragmentation and cascade rates are probably small. The low altitude discrepancy between the Haystack data and the model supposedly based on it is large enough to determine whether there is a problem at low altitudes. Its resolution is difficult because of ambiguities in reducing the data from the only relevant radar.

Particle impacts on satellites at 900-1,000 km are a lifetime issue, not a cascade issue, and apparently not a dominant one. Debris growth would require the continuation of historical rates of launch, explosion, and fragmentation. Cascading from current debris levels would take centuries, even assuming the maximum number of fragments per collision and the minimum rate of decay.

If the maximum values for each of these parameters are used, JSC's results are recovered. If any are reduced, debris growth is pushed into following centuries. It would appear that most of the important measures to reduce deployment debris and explosions have already been implemented. Before pressing for others, it would be appropriate to resolve how much conservatism should be built into the treatments of fragmentation in explosions and collisions, much of which could be done through cross comparisons of existing data and models.

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