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Title:

DEBRIS MASSES AND AREAS INFERRED FROM
THE LAUNCH CATALOG

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DEBRIS MASSES AND AREAS INFERRED FROM THE LAUNCH CATALOG

Gregory H. Canavan

Debris density and area can be determined as functions of altitude from the debris launch catalog. Those quantities can be used in an algebraic model to predict fragments and intact object density at each altitude. The measured spectrum of debris objects can be used to partition objects into fragments and intact object fractions that are consistent with the catalog and not overly sensitive to the choice of the defining boundary.

Debris particle number and areas can be determined as functions of altitude from the parameters in the debris launch catalog. A companion note discusses the determination of the total number and area of the particles launched to each altitude.¹ This note uses those quantities in a simplified model to predict the number of fragments and intact objects at each altitude. The earlier paper sorted the debris launch catalog to produce a source at every altitude by averaging each orbit over the time spent in each altitude band. Sorting particle times area produces the area launched to those bands. There has been little apparent change in the rate of launch to low Earth orbit (LEO), because the rapid buildup in 1957-67' was roughly mirrored by the rapid decay in 1985-95'. However, the average areas of the objects launched to LEO has increased by about a factor of 7.3.

The measured power law spectrum of debris objects can be used to partition objects into fragments and intact objects. A boundary between the two of about 1 m^2 produces plausible fragment and intact object fractions and areas that are not overly sensitive to the choice of boundary. Those values can be used to algebraically decompose the total distribution into fragments and intact objects in reasonable accord with observations. For most altitudes, average values of fragment and intact object areas are adequate for accurate decomposition. For the peak at 1,450 km, the observed peak of much smaller objects should be used for high accuracy. This note illustrates the decomposition for a two component decomposition, the minimum that can treat both the large objects, which have most of the mass, and the small fragments, which have most of the number. It can be extended to any number of components.

Objects launched. An earlier paper sorted every launch in the debris launch catalog to produce a debris source at every altitude. It did so by using spherically symmetric averaging kernels to average time each object spent in each of a set of 100 km altitude bands from 100 to 2,000 km. It sorted the '57-95 launch catalog in two separate halves because of the different launch patterns in the first and second part of the space era. Figure 1 shows the number of objects launched to or born in each altitude bin during '57-77 and '78-95. The two curves for the two-decade intervals each fall with altitude, though non-monotonically. Each has peaks at 200-300,

950, and 1,450 km and minima in between. At low altitudes, the two curves are very similar. The main differences are at 1,100-1,400 km and $> 1,500$ km. There were about an order of magnitude fewer objects launched into those altitudes in '78-95 than in '57-77, and there were relatively few objects there even in '57-77. The peak at 1,450 km area was about the same in the two intervals. The peak at 950 km was about 50% higher in '78-95 than in '57 to '77. Deposition fell about 50% at 550 km, but there is little growth there in either interval.

Area Launched. Figure 2 shows the "area launched," i.e., the particle number time area averaged over launch altitude intervals in '57-77 and '78-95. Like the number density curves, each has a peak at ≈ 200 , 950, and 1,450 km. Unlike the number curves, the area launched curves are quite similar at high altitudes, apart from the increased rate at 1,450 km in recent decades. The rates are similar down to about 950 km, where the rate for recent decades is higher by a factor of ≈ 2 . That ratio is maintained down to 750 km; then, the '78-95 curve increases by a factor of ≈ 2 , while the '57-77 rate moves down by a like amount, so the rates differ by a factor of $\approx 4-5$ in 650-450 km. At 350 km, the '78-95 rate jumps by a factor of 10 because of the recent deployment of large systems there, which gives a ratio of ≈ 40 . At 250 and 150 km the ratio of the rates is about a factor of 20. Together, Figs. 1 and 2 indicate that low altitude satellites were much bigger in '78-95 than in '57-77, though not necessarily more numerous.

Total launches. Figure 3 shows the total and cumulative launches in the total interval '57-95. The bottom two curves for N and A are sums of those in Figs. 1 and 2. As expected, the composite curves are close $> 1,000$ km, where the objects are typically $\approx 1 \text{ m}^2$, and further apart at lower altitudes, where the objects are larger. The cumulative curves show that few of the objects and little of the area are above 800 km. The top curve shows that only about 15% of the area is above 800 km. About half the object number and area are below 350 km. The total fragment and intact object number and area in the launch catalog are:

interval	<u>'57-77</u>	<u>'58-95</u>	<u>'57-95</u>
N	10663	10054	20717
A	8326	61026	69353

The total number N of 20717 differs from the 24,000 of the launch catalog by the number of objects above LEO and by those objects for which no ephemerides are given in the catalog. The total area of 69,353 m^2 differs from other estimates by the deletion of objects for which no RCS is given in the catalog. There were roughly equal numbers of launches in '57-77 and '78-95, but the total launched area increased by a factor of $61,026/8,326 \approx 7.3$ in the second interval, reflecting the larger objects launched to low altitude discussed above. The overall result of sorting the total launch catalogs for '57-77 and '78-95 is the observation that there has been little

change in the rate of launch to LEO, although there have been large changes in the areas of the objects launched.

Average area. Figure 4 shows the average area, i.e., $A(z)/N(z)$, for all altitudes. The bottom curve is for '57-77, when the average areas were $\approx 1 \text{ m}^2$, although they were about a factor of 2 larger at 500-1,000 km and a factor of 2 smaller below 500 km. The top curve is for '78-95, when the average areas became much larger—particularly at 350, 550, 1,250, and 1,550 km. The center curve is the average for the whole interval '57-95. It resembles the '57-77 curve above 800 km, but tracks the '78-95 curve at lower altitudes. Comparing the '57-77 and '78-95 curves indicates that there has been a growth in satellite area by over an order of magnitude at low altitudes between the two intervals. Even the mean object size has grown by about an order of magnitude at low altitudes. However, that is less of a concern for debris growth estimates, in that fragments produced at those altitudes experience too much debris to survive long. Thus, the mass in orbit is continuing to increase, but most of the increase is at low altitudes. Of greater concern is that the average object size have grown a factor of 2 at 750-950 km. It is significant that large objects now make up a larger fraction of the source at medium and low altitudes.

Fragment definition. The distributions of object number and areas from the catalog sort cannot be used directly in debris growth calculations; they must be converted into estimates of the number of large objects, fragments, etc. used in model calculations. That is a two step process. The first step is to define the average areas of the fragments and large objects. The second is to separate the total object number and area into those average object areas. The first amounts to defining the boundary between fragments and intact objects, seeking a definition that corresponds to natural divisions in the data and to which the results are not overly sensitive. The empirical measurements of the debris catalog provide most of the data needed to do that. The catalog has a distribution of particles over area A that is approximately a power law distribution A^{-c} , in which the observed value is $c \approx 1/4$ between the minimum area $R \approx 0.05 \text{ m}^2$ and a maximum object area of $M = 30 \text{ m}^2$ of catalog particles. For this distribution, the approximate normalized object distribution is

$$n(A) = c/(R^{-c} - M^{-c})A^{c+1}, \quad (1)$$

so that $\int_R^M n(A) dA = 1$. In this model, fragments are defined as objects with areas below some given value B . From Eq. (1), the fraction of such objects is

$$f(B) = \int_R^B n(A) dA = (R^c - M^c)/(R^{-c} - M^{-c}), \quad (2)$$

and the fraction of intact objects is $1 - f(B)$, which are shown in Fig. 5. The fraction of fragments is small when B is close to R , and it increases rapidly when B is small. However, by $B \approx 1 \text{ m}^2$, the rate of increase of f slows. Thus, for choices of B larger than about 1 m^2 , the fragment and intact object fractions are relatively insensitive to the specific value used for B . The average area of the fragments is

$$\langle A_{\text{frag}} \rangle = f^{-1} \int_R^B n(A) A = (B^{1-c} - R^{1-c})c / (R^{-c} - M^{-c})(1-c)f, \quad (3)$$

and the average area of the intact objects is

$$\langle A_{\text{int}} \rangle = (1-f)^{-1} \int_B^M N(A) A / f \approx (M^{1-c} - B^{1-c})c / (R^{-c} - M^{-c})(1-c)(1-f), \quad (4)$$

which are shown in Fig. 6. For a boundary area of 1 m^2 , the average area of the fragments is 0.25 m^2 , and the average area of the large objects is $\approx 8 \text{ m}^2$. For a choice of $B = 4 \text{ m}^2$, which is larger than suggested by the data, the areas increase to about 0.6 and 12 m^2 .

As the boundary area increases, the average area of the fragments increases as the $\approx 3/4$ power of the boundary area, while the average area of the large objects changes more slowly. The variations are due to the progressive shift of objects from the intact to the fragment category, which reduces the number of small objects in the latter and increases the number of large objects in the former. For fragments, a more important quantity than area is mass per unit area, which governs decay. For small fragments, the mass scales roughly as $A^{3/2}$, so their areal density scales as $A^{3/2}/A \approx \sqrt{A}$, whose average varies much more slowly than that of A . Thus, for area as well as fractions, a choice of boundary of $B \approx 4 \text{ m}^2$ produces relative insensitivity.

Decomposition of the debris distribution into fragments and intact objects is executed by resolving N , the total number of objects at z , into its components

$$N = N_f + N_i, \quad (5)$$

where N_f is the number of fragments and N_i is the number of large intact objects. Similarly, A is the total area at z

$$A = A_f + A_i, \quad (6)$$

where A_f is the average fragment area and A_i is the average intact object area. The solution to Eqs. (5) and (6) is

$$N_f = (A_i N - A)/D, \quad (7)$$

$$N_i = (-A_f N + A)/D. \quad (8)$$

where $D = A_i - A_f$. This result can be generalized to any number of components. The result for a 2 component decomposition is shown in Fig. 7. For typical areas of $A_f = 0.3$ and $A_i = 10 \text{ m}^2$, from Fig. 6, at altitudes $> 750 \text{ km}$, the fragments greatly outnumber the large objects. At $650\text{-}550 \text{ km}$, the difference is about a factor of two, although it increases to a factor of 4 at 450 km . At 350 km , the intact objects outnumber the fragments due to the large source of large objects there. At the lowest altitudes, fragments outnumber large objects by a factor of 2 to 4.

Figure 8 shows the fraction of large objects at each altitude from the model and from data. The line with open squares indicates the predictions of Eqs. (5) - (8) for $A_f = 0.3$ and $A_i = 10 \text{ m}^2$. Overall, large objects constitute about $1/3$ of the total, although much of that comes from their large contribution at low altitudes. Above $1,000 \text{ km}$, their percentage is $\approx 10\text{-}15\%$. From $1,000$ to 500 km , it is about 25% . Below 450 km , it averages about 40% .

The curve with solid squares shows the approximate fractions from *Orbital Debris* for comparison.² Those values have comparable averages, but they show much more structure, particularly at altitudes above 1,000 km. The peaks at 1,150 and 1,450 km differ markedly from model predictions. However, there are relatively few objects at the former. The latter is discussed below. Below 950 km, the *Orbital Debris* values gradually fall below those from the launch catalog. That is expected, as *Orbital Debris* presents decayed objects, while the launch catalog presents only newly launched ones.

Sensitivity. There are significant discrepancies between the model decomposition and *Orbital Debris* catalog of large fragments in Fig. 8. The main discrepancies are at 350, 550-750, 1,150, and 1,450 km. The large discrepancy at 350 km is due to the use of an average value of $A_i = 10 \text{ m}^2$ at all altitudes, which is an order of magnitude smaller than the large objects there. That could be remedied by using the value from the catalog, but it is not of concern because fragments produced at that altitude would not last long. The discrepancies at 550-850 km are due to the effect of decay on the distribution in the *Orbital Debris* catalog. The discrepancy at 1,150 km is apparently large, but there are few objects at that altitude. The discrepancy at 1,450 is probably of greatest concern. It is sensitive to model parameters.

Figure 9 shows the fraction of large, intact objects at 1,450 km as a function of A_i and A_f for the $N = 740$ and $A = 1120 \text{ m}^2$ of the catalog. For A_i and A_f small, the intact fraction approaches 0.45. For A_f small, as A_i increases, the fraction falls, reaching about 10% by $A_i \approx 12 \text{ m}^2$. As the fragment size increases, by $A_f \approx 1.6 \text{ m}^2$ the intact fraction becomes negative. However, that is not significant, as it would correspond to boundary areas larger than the largest areas in the catalog. A_f represents an average fragment area. Most catalog fragments are 10-20 cm across.³ According to Fig. 4, average areas of intact objects are $\approx 10 \text{ m}^2$; thus, an appropriate combination for the evaluation of the fraction is roughly $A_i \approx 10 \text{ m}^2$; $A_f \approx 0.3 \text{ m}^2$, which gives the intact fraction ≈ 0.1 . That is smaller than the 0.35 shown in Fig. 8. However, the intact objects at 1,450 km are much smaller than the average used above, because many small satellites have accumulated there over the last four decades. If the $A_i \approx 4 \text{ m}^2$ appropriate for them is used instead, an intact fraction of ≈ 0.35 is obtained. This indicates that in unique situations, it is useful to use the measured cross sections from the catalog at that altitude rather than the overall averages for precision. In practice, the peak at 1,450 km appears to be the only altitude at which that precision is required.

Figure 10 shows the decomposition of the large peak at 950 km. Here, the average values provide a good estimate of the intact object fraction. Figure 7 shows that $N \approx 1,000$ and $A \approx 2,500$ there; thus, the number of intact objects can be simply converted into a fraction, which according to Fig. 8 is ≈ 0.2 . For $A_f = 0.3$ and $A_i = 10 \text{ m}^2$, the model produces $N_i \approx 230$, i.e., an intact fraction of ≈ 0.23 , which is very close. The model is not sensitive to fragment parameters.

Figure 10 shows that at this altitude, increasing A_f to 1 m^2 would only decrease the fraction to about 0.17. It is more sensitive to smaller A_i , but that sensitivity saturates at about 10 m^2 , and the average objects are larger than that size at 950 km. Increasing A_i to $\approx 16 \text{ m}^2$ would again decrease the intact fraction to about 0.16. Thus, it is not necessary to know the large object area precisely for adequate decomposition when the intact fragments are large.

Summary and conclusions. This note builds on the work of a companion note that evaluates the number and area of the particles launched to each altitude to produce an algebraic model that decomposes those quantities into the number of fragments and intact objects launched to each altitude. The earlier paper sorted the debris launch catalog to produce a source at every altitude by averaging each orbit over the time spent in each altitude band up to 2,000 km. Multiplying each particle by its area produced the area launched on those bands. The number of launches in the first half of the space age was about the same as the number in the second half, because the rapid buildup in 57-67' was roughly mirrored by the rapid decay in 85-95'. Thus, there has been little change in the rate of launch to LEO, although the average areas of the objects launched there has increased by about a factor of 7.3. The measured power law spectrum of debris objects can be used to partition objects into fragments and intact objects. A boundary of about 1 m^2 produces plausible fragment and intact object fractions and areas, which are not overly sensitive to the choice of boundary. Those values can be used to decompose the total distribution into fragments and intact objects algebraically. The resulting decompositions are in reasonable accord with observations. For most altitudes, average values of fragment and intact object areas are adequate for accurate decomposition. For the peak at 1,450 km, the observed peak of much smaller objects should be used for high accuracy. The illustrations provided here are for a two component decomposition, as that is the minimum system that can treat both the large objects, which have most of the mass, and the small fragments, which have most of the number. It can be extended as a matrix algorithm to any number of components.

References

1. G. Canavan, "Rates Inferred from the Space Debris Catalog," Los Alamos report LA-UR-96-2803, August 1996.
2. G. Cleghorn, *Orbital Debris* (Washington, National Research Council, 1995).
3. G. Canavan, "Rates Inferred from the Space Debris Catalog," op. cit., Fig. 1.

to '77 & present dN/dt vs z

Fig. 1. Particles launched in 20 year intervals versus altitude.

N,A, cumN,CumA vs z; cat

Fig. 3. Local and cumulative catalog fragment density and area versus

Fig. 4. Average area of objects launched in various intervals as functions of altitude.

fractions vs boundary area

Fig. 5. Fragment and intact fractions as functions of boundary area.

Fig. 6. Average areas of fragments and intact objects versus boundary area.

N, Ni, Nf vs z

Fig. 7 Fragment, intact, and total debris density versus altitude

fract large obj vs z

Fig. 8. Large object fraction as function of altitude from 2-component decomposition.

fract large vs Af; Ai

Fig. 9 Intact object fraction at 1,450 km as a function of intact and fragment area.

Ni vs Af; Ai, 950 km

Fig. 10. Intact objects at 950 km as function of intact and fragment areas.