Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

ORBITAL DEBRIS ENVIRONMENT PROJECTIONS FOR SPACE STATION

BY: ROBERT C. REYNOLDS AND DONALD J. KESSLER

***LOCKHEED ENGINEERING & SCIENCE COMPANY/HOUSTON, TX.**
****NASA JOHNSON SPACE CENTER/HOUSTON, TX.**

ABSTRACT

Since the release of the NASA orbital debris engineering model, which was modified and adopted as the design environment for SpaceStation Freedom, a major effort has been made to improve supporting models for the debris environment. The improvements result primarily from significant additional data that have been acquired by the Haystack radar and the ability to accurately model debris mitigation measures.

In this paper a comparison will be made of results from EVOLVE with the design environment. The use of EVOLVE to characterize the eccentricity and inclination distribution of the debris fragments less than 10cm in diameter and to support the development of new engineering models for low-earth orbit debris environments will also be discussed.

1.0 INTRODUCTION

From the early work of Kessler and Cour-Palais it has been known that the debris environment characteristics of most concern to operating spacecraft will be small fragments associated with on-orbit breakups (Ref. 1). Large objects (>10cm) will have the potential to inflict much more damage on impact but the probability of such an occurance is very small; smaller debris (1mm-1cm) is large enough to cause functional failure on almost any spacecraft and occurs with much higher probability.

Data on the velocity characteristics of numerous small debris created during breakup of a satellite, which is important for understanding the region of space transited by the debris and the duration of its effect, have been extremely limited as have direct observations of debris in this size range. Consequently, the velocity distribution to be used for debris environment modeling is somewhat uncertain. New measurements of the environment in the 1mm to 10cm size range will be important in reducing this uncertainty.

The EVOLVE debris environment projection model (Ref. 2) developed at NASA/JSC generates a catalog of element sets for objects placed into the environent by space operations and by breakups. The size and dynamical characteristics of fragmentation debris created by breakups is determined from the standard size distribution (Ref. 3) taken from ground test data. Using the EVOLVE model the orbit distributions are related directly to the breakup model. Results from EVOLVE will be compared to flux characteristics defined in the Space Station Freedom (SSF) design environment (Ref. 4).

2.0 DISCUSSION

The debris environment is generally characterized by the expected debris flux as a function of altitude, debris size, and time. The flux has units of impacts per unit area per unit time which this paper will be impacts/m^2/yr. The cross-sectional area flux, which will be used in this paper, measures the number of impacts per year onto a sphere of unit cross-sectional area; it is the spatial density multiplied by a characteristic flow velocity on the order of the orbital velocity. The flux density function retains the directional flow information for the debris environment and has units of impacts/m^2/yr/deg^2. The cross-sectional area flux is the flux density integrated over solid angle.

EVOLVE is a model for the evolution of the orbital debris environment. It has as components predictions for future use of space, represented as mission models containing specific launch schedules and orbit and satellite characteristics, breakup models for collision- and explosion-induced breakups, an orbit propagator, and statistical models to calculate the random occurance of future collision and explosion events. Environment projections are made using Monte Carlo techniques so that future debris states can be characterized in terms of an expected state with some measure in uncertainty in that state. The environment is characterized at any time as an ensemble of debris fragments having orbital elements, size, area-to-mass ratio, and various support information. EVOLVE uses the historical record of launches and breakups to establish a current environment and can therefore either predict the environment when there is no data or use new measurements to validate or correct its source terms.

In modeling the environment below 10cm in size, the breakup models provide the most important source of particles. The current NASA/JSC breakup models consist of a size distribution and a velocity distribution as a function of debris size (Ref. 3). The size distribution depends on the type of breakup event, of which there are 3 - collision, low intensity explosion, and high intensity explosion - and on the mass of the object or objects involved in the breakup. Low intensity explosions occur when the source of energy is not in close contact with the structure - for example pressure tank rupture or ignition of residual fuels. High intensity explosions occur where high explosive material is in contact with the structure - e.g ignition of range safety systems. The size distribution data is based on ground tests and are considered to be well-established. Velocity data is much more difficult to collect; the only test in which specific provision was made to do this ware the tests conducted in the last year by Defense Nuclear Agency (Ref. 5) and these data are not yet available. In consequence, and also to verify that the velocity distributions from the tests are valid for on-orbit breakups, there is a need to acquire environment data in this same size regime.

The velocity perturbation imparted to a debris object at breakup will cause a change in its orbit plane, energy, and angular momentum. These changes can be stated in terms of change in inclination, semi-major axis, and eccentricity. If values for these three orbital elements are obtained for breakup fragments from a known breakup point, the delta-v vector for each debris fragment can be obtained (Ref. 6). However, if small debris are being observed in the context of the general environment such specific information cannot be obtained except in an average sense. That is, the larger the magnitude of the velocity perturbation on breakup, in general the greater the change in angular momentum and the more eccentric the orbits into which the debris is scattered. This trend to greater eccentricity manifests itself as a characteristically broader distribution in radial velocity, i.e. velocity directed toward or away from the center of the earth, that will be reflected in measurements of radial velocity using ground-based sensors.

While there can be significant eccentricity changes caused by breakups, since the velocity perturbations are much smaller than the orbital velocity even at the smallest sizes, plane change angles and therefore inclination changes are always small.

The first extensive measurements of the debris between sizes of 1mm and 10cm are currently being obtained using the Haystack radar (Ref. 7). The range and range rate data are the best determined of the Haystack data - range from the time delay between transmit and receive of a detection signal and range rate from the Doppler shift. The range measurement accurately provides the altitude and latitude at which the debris was observed given the azimuth and elevation of the radar. The range rate measurement gives the line of sight velocity that, in general, has a contribution from both the radial velocity and the horizontal velocity. However, for the radar pointed to the zenith there is no contribution to range rate from the horizontal component of the debris velocity. Although only radial velocity and not total energy or eccentricity can be obtained directly from these data, the data can be used to establish consistency between the models and measurements.

3.0 RESULTS

The debris inclination distribution from EVOLVE follows very closely the distribution of orbits in which breakups have occured, as might be expected given that the velocity perturbations even for 1mm debris are considerably smaller than the orbital velocity. The distributions (shown in Figures 1-4) reflect orbits crossing through 450km altitude, and are weighted by the spatial density for the orbits at that altitude; note that each of the figures is normalized by the peak value of the distribution. The Catalog is the Space Surveillance Network (SSN) Satellite Catalog epoch 1990.0, which is the same epoch as the EVOLVE results.

The Catalog distribution (Figure 1) is similar to the EVOLVE distribution for objects larger than 10cm (Figure 2) as might be expected. The differences in these distributions reflect the larger than 10cm fragmentation debris that EVOLVE places in the environment via the breakup model but that have not beencataloged by the SSN. The distributions for 1-10cm and 1mm-1cm debris (Figures 3 and 4) show a major contribution from breakups in orbits of inclination 60-70°. High intensity explosions account for essentiallyt all of the 1mm-1cm debris, but remnants of the P-78 breakup are still seen in Figure 4 below 100°

Significant trends in the EVOLVE data is also seen in the eccentricity distributions. As with inclination, the eccentricity distribution is for orbits passing through altitude 450km and is weighted by the spatial density for each orbit at that altitude. The Catalog (Figure 5) shows that most orbits have eccentricity less than 0.01 and almost no orbits have eccentricity >0.1; although there are a number of cataloged objects in geosynchronous transfer or other highly elliptical orbit, they make very little contribution when weighted by spatial density. The distribution for the 10cm and larger EVOLVE data (Figure 6) is similar to the Catalog except for the excess of objects at eccentricities between 0.04 and 0.08. The broader distributions for the smaller debris (Figures 7 and 8) reflect the large changes in eccentricity during breakup caused by the in-plane component of the velocity perturbation.

These results are different from the assumptions made in formulating the design environment for SSF. In this environment, a velocity distribution was derived for the 1mm to 1cm debris that was based on averaging for larger objects from the Catalog; this is essentially equivalent to assuming the inclination distribution for this debris is similar to the Catalog. Also, the assumption was also made that debris was in nearly circular orbit, so that all debris encounters occur very nearly in the local horizontal plane. Given that the EVOLVE results are different, are the differences significant for SSF?

The velocity distribution as defined in SSP 30425 is compared to the distribution as defined by the Catalog (Figure 9) for the reference orbit of 450km altitude and 28.5° inclination. As can be seen, the averaging process using data from an earlier Catalog gives the design environment velocity distribution more weigh for encounter velocities above 11.5km/sec, but generally gives less weight for velocities in the range of 4-11km/sec. The EVOLVE data for the larger than 10cm debris matches the Catalog rather well (Figure 10) but partially fills in the excess at high velocity. The smaller debris (Figures 11 and 12) shows a strong cutoff in impact velocities greater than 12km/sec, with a strong peak at 11.5-12km/sec. In the size region of concern, EVOLVE predicts SSF will see a lower velocity flux.

A second issue is the encounter geometry relative to the local horizontal plane. The next set of figures presents flux density contours as a funtion of pitch and yaw in the spacecraft rest frame. Yaw is the angle measured in the local horizontal plane; the zero point is the intersection between the local horizontal plane and the orbit plane in the down-range direction. The pitch angle is the angle above or below the horizontal plane, with positive pitch angles denoting directions away from the earth. For the reference orbit, the velocity vector points to 0deg in both pitch and yaw.

In these figures, there is symmetry about both the 0° yaw and 0° pitch lines. There is a trend to lower encounter velocities as the encounter moves farther away from 0° yaw; the gap between the footprints across 0° yaw is a direct result of the absence of high velocity encounters shown in Figures 9-12. Each of the figures presents contours of 90%, 50%, 10%, and 1% of the peak flux density.

For the design environment, all encounters occur in the local horizontal plane. For the Catalog (Figure 13) and the EVOLVE data for the largest sizes (Figure 14), the peak in the flux density distribution occurs at ~43° yaw angle, and the 10% flux density contour lies within 1° of the local horizontal plane. With increasing eccentricity for the 1cm to 10cm EVOLVE debris, the peak in the flux density moves to ~45° yaw, and the pitch distribution opens slightly (Figure 15); however, the 10% flux density contour remains within 2° of the local horizontal plane except for some lower velocity impacts near 90° yaw. The 1mm to 1cm EVOLVE data opens the pitch distribution somewhat more (Figure 16), but still the 10% contour is within 3deg of the local horizontal plane. The peak in the distribution has moved to ~50° yaw.

4.0 CONCLUSIONS

EVOLVE results have been presented that allow a comparison of the debris environment as defined from the design environment with that produced by EVOLVE that make direct use of the breakup models. EVOLVE predicts a somewhat lower characteristic impact velocity than does the design environment and would reduce the average impact velocity from ~10km/sec to ~9km/sec. While this would reduce the penetrability of the debris somewhat, it might be equally important that characteristically smaller velocities will require less extrapolation of hypervelocity impact experimental data and increase confidence in penetration equations derived from them (Ref. 8). There does not appear to be any way that a source of higher velocity impactors will be found as this would require debris to populate orbit inclinations above 110deg, and there is no known source for such debris.

The spread in pitch angle shown by EVOLVE with smaller sizes also does not seem to be significant. It will only increase the flux on surfaces facing near the zenith or nadir, but these impacts will be at very low incidence angle and therefore not be very penetrating. Equally important, SSF will not remain in a constant pitch profile, but will experience pitch excursions much larger than the few degrees of spread at least while the STS is docked. The greatest penetrating exposure for the nominally nadir and zenith-facing surfaces might be expected to occur while the STS is docked.

It is probable that in future modeling the pitch spread will be less than that shown in this paper. Recently acquired data from the Haystack radar indicates that the breakup velocities in the current model are somewhat too high for the small debris. Haystack observations at 90deg elevation angle provide a sensitive indicator of eccentricity distribution. These data are presented in Figure 17. Modeled data for 5mm and larger debris, a good characteristic size for Haystack operating in this mode, shows the EVOLVE data for the standard breakup model. The significantly broader EVOLVE distribution is indicative of the EVOLVE debris being in characteristically higher eccentricity orbits than what is observed, and implies that the velocity perturbations for the small debris in the breakup models are too large. If the velocity distribution is reduced so that 90% of the debris of sizes below 10cm has the velocity distribution of the 10cm debris, the EVOLVE data becomes consistent with the Haystack measurements, as seen in Figure 18. This reduction in the velocity distribution implies that the small debris is more closely coupled with the large debris during the breakup process. With this velocity distribution, the pitch spread for the smaller debris will be more like that shown in Figure 14, which is very little different from the design environment.

The issue of new sources for 1mm and larger debris, which could affect the debris inclination distribution and therefore the impact velocity distribution, needs to be investigated. In analyzing the LDEF crater distribution with surface orientation, Kessler has shown in previous work (Ref. 9) that the observed crater distribution can be explained by increasing the percentage of debris in high eccentricity (apogee altitude > 10000km) orbit relative to the catalog. In so doing, for flux to a limiting size the ratio of front surface (yaw=0°, pitch=0°) flux to side surface (yaw=0°, pitch=90°) flux is 0.91:1; the ratio for front surface flux to rear surface (yaw=0°, pitch=180°) flux is 2.8:1. For EVOLVE with the standard breakup velocity distribution the front to side flux ratio is 1.4:1 and the front to back ratio is 30,000:1 for 1mm and larger debris. For EVOLVE with the velocity distribution to agree with Haystack data, the front to side flux ratio is 1.3:1 and the front to rear flux ratio is 400,000:1 for 1mm and larger debris. The very large difference in the front to rear flux ratios is indicative of a very different inclination distribution for the scaled up catalog when compared to the breakups, and would indicate that breakups do not contribute significantly for the sizes of debris represented in the LDEF data. It may be, however, that both the Haystack data at the small debris end of its range and LDEF data at the large end of its range will point to new sources that will need to be modeled by EVOLVE.

5.0 REFERENCES

1. Kessler, D. and B. Cour-Palais. Collision Frequency of Artificial Satellites: Creation of Debris Belt, Journal of Geophysical Research, 83, A6, 1978, 2637-2646.

2. Reynolds, R. Documentation of PROGRAM EVOLVE: A Numerical Model to Compute Projections of the Man-Made Orbital Debris Environment, Suystem Planning Corp. Report OD91-002-U-csp, February, 1991.

3. Bess, T. Mess distribution of Orbiting Man-Made Debris NASA Langley Research Center, Report L-10477, December, 1975.

4. Space Station Program Natural Environment Definition for Design, NASA SSP 30425 Rev. A, 1992.

5. Tedeschi, W. Private Communication, 1992.

6. Badhwar, G., A. Tan, and R. Reynolds. Velocity Perturbations in the Breakup of Artificial Satellites, Jnl. of Spacecraft and Rockets, 27, 3, May, June, 1990, 299-305.

7. Stansberry, E., J. Stanley, D. Kessler, T. Tracey, M. Matney, L. Hock, K.McIntyre. Orbital Debris Environment Characteristics Obtained by Means of the Haystack Radar, Presented at the First European Conference on Space Debris.

8. Anderson, J. Private Communication, 1993.

9. Kessler, D. Origin of Orbital Debris Impacts on LDEF Training Surfaces, Presented at the Second LDEF Post Retrieval Symposium, June, 1992, San Diego. To be published in NASA CR xxxx.

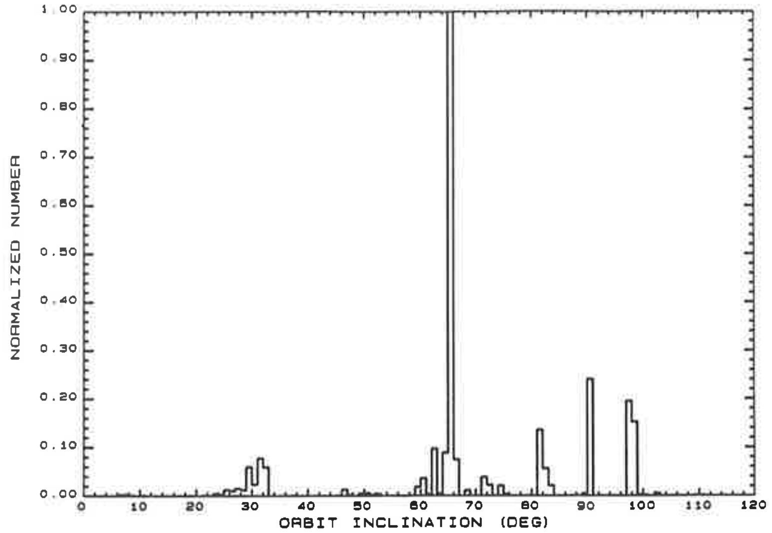

Figure 1. Orbit Inclination Distribution at 450km; Source: Catalog; Normalizing Constant = 2.05e-8 impacts/m^2/yr/deg

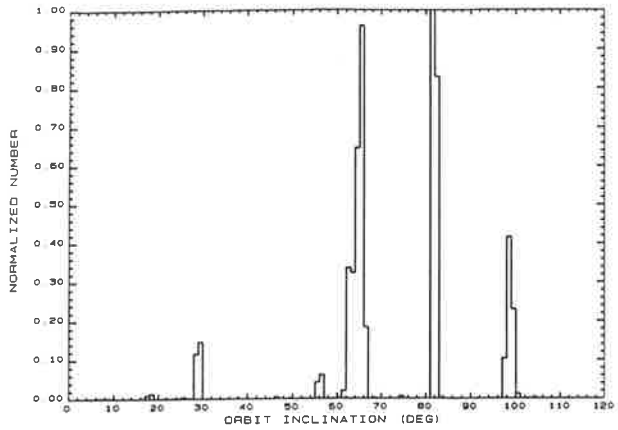

Figure 2. Orbit Inclination Distribution at 450km for Debris Larger than 10cm; Source: EVOLVE; Normalizing Constant = 5.45e-8 impacts/m2/yr/deg

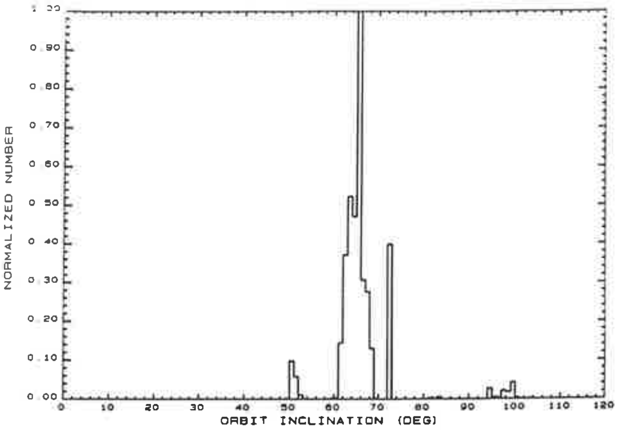

Figure 3. Orbit Inclination Distribution at 450km for Debris in Size Range 1 - 10cm; Source: EVOLVE; Normalizing Constant = 1.13e-6 impacts/m2/yr/deg

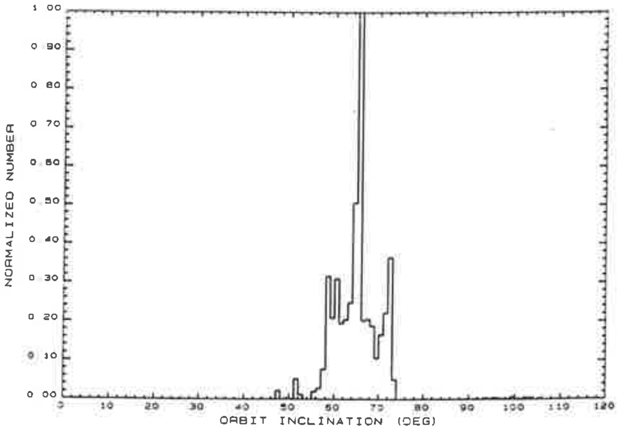

Figure 4. Orbit Inclination Distribution at 450km for Debris in Size Range 1mm - 1cm; Source: EVOLVE; Normalizing Constant = 1.54e-4 impacts/m2/yr/deg

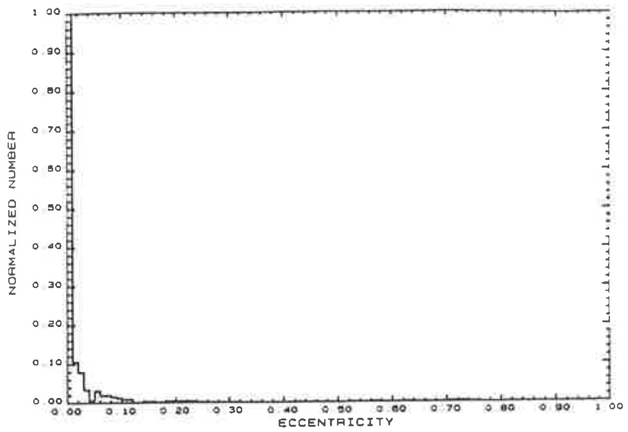

Figure 5. Orbit Eccentricity Distribution at 450km; Source: Catalog; Normalizing Constant = 3.71e-6 impacts/m2/yr/(0.01 delta-e)

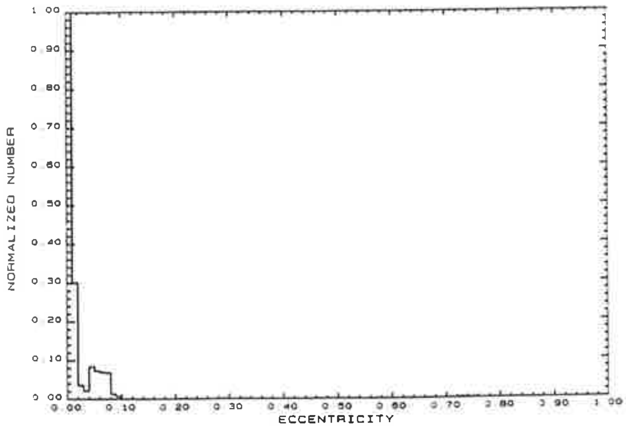

Figure 6. Orbit Eccentricity Distribution at 450km for Debris Larger than 10cm; Source: EVOLVE; Normalizing Constant = 1.76e-5 impacts/m2/yr/(0.01 delta-e)

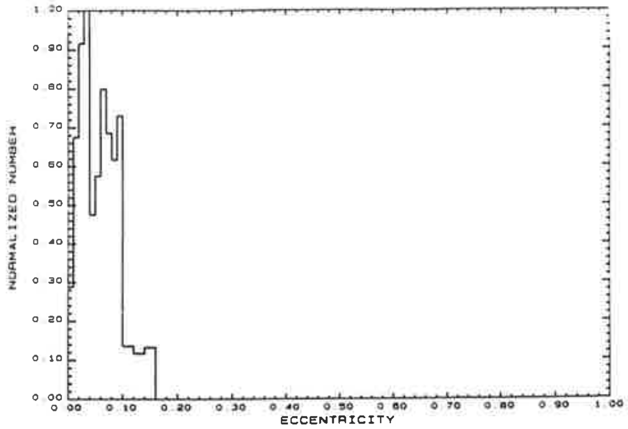

Figure 7. Orbit Eccentricity Distribution at 450km for Debris in Size Range 1 - 10cm; Source: EVOLVE; Normalizing Constant = 5.92e-5 impacts/m2/yr/(0.01 delta-e)

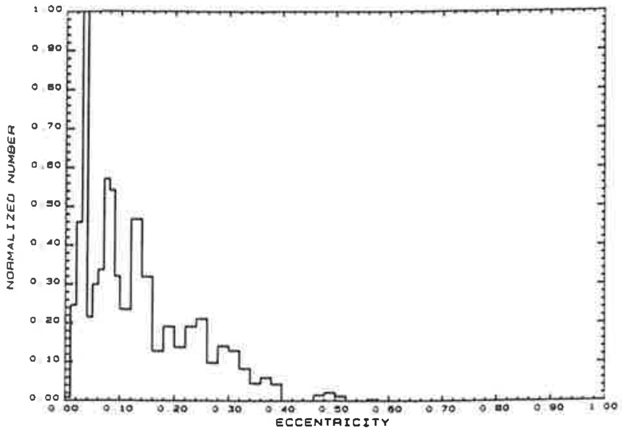

Figure 8. Orbit Eccentricity Distribution at 450km for Debris in Size Range 1mm - 1cm; Source: EVOLVE; Normalizing Constant = 8.10e-3 impacts/m2/yr/(0.01 delta-e)

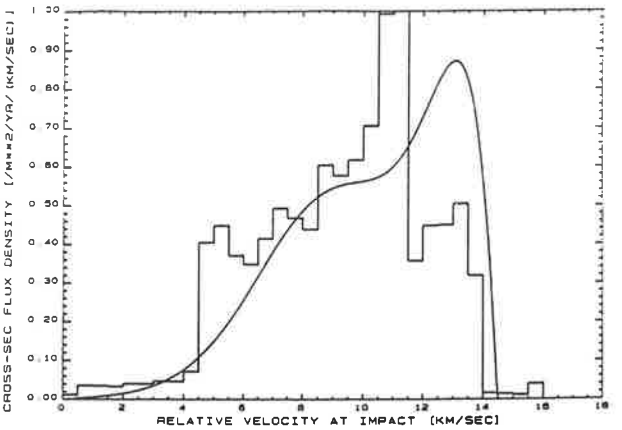

Figure 9. Collision Velocity Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Data: Catalog Compared to SSP 30425; Normalizing Constant = 2.73e-7

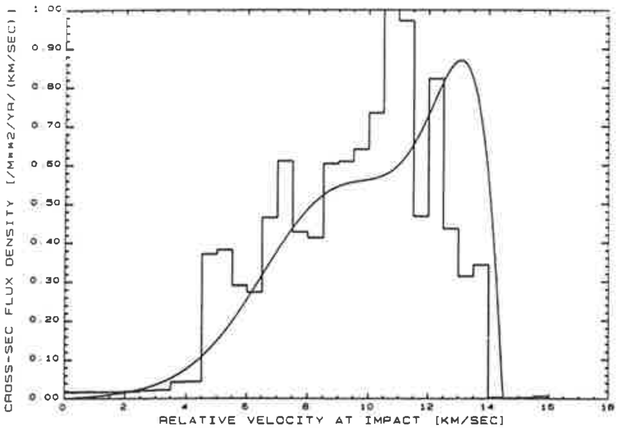

Figure 10. Collision Velocity Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Data: EVOLVE Debris Larger than 10cm Compared to SSP 30425; Normalizing Constant = 2.87e-7

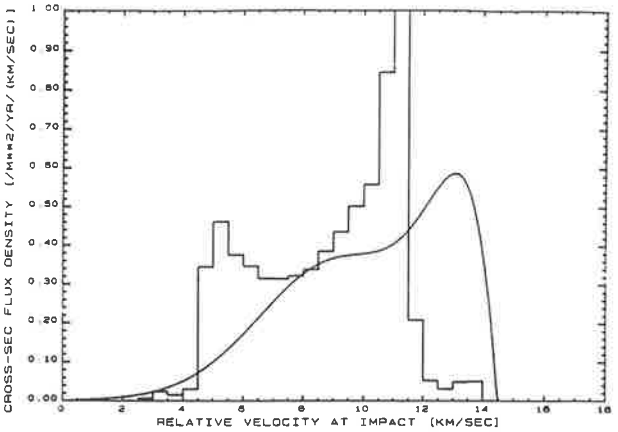

Figure 11. Collision Velocity Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Data: EVOLVE Debris in Size Range 1 - 10cm Compared to SSP 30425; Normalizing Constant = 6.27e-6

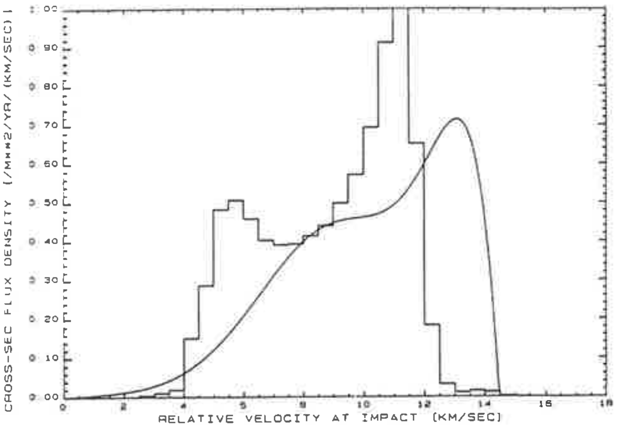

Figure 12. Collision Velocity Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Data: EVOLVE Debris in Size Range 1mm - 1cmm Compared to SSP 30425; Normalizing Constant = 8.26e-4

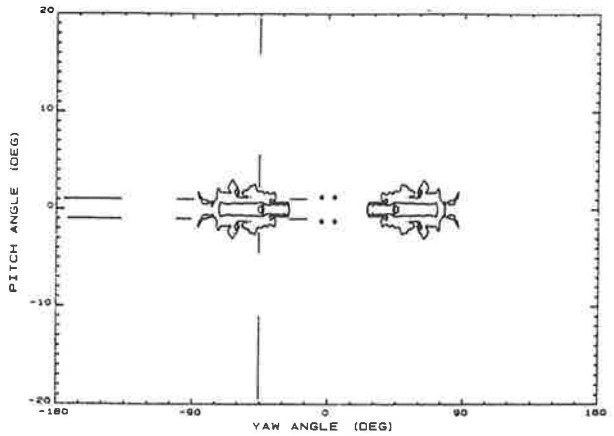

Figure 13. Flux Density Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Source: Catalog; Normalizing Constant = 3.69e9 impacts/m2/yr/deg2

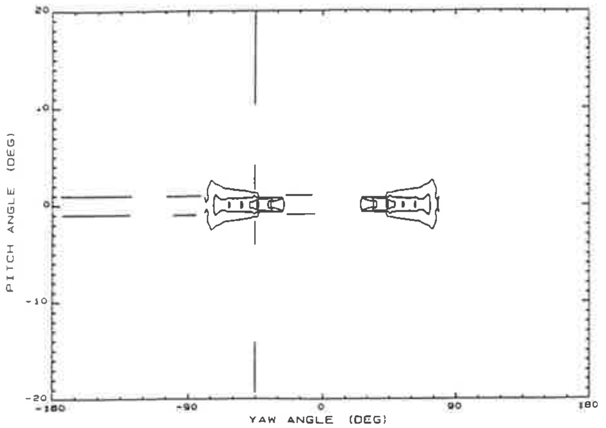

Figure 14. Flux Density Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Source: EVOLVE Debris Larger than 10cm Normalizing Constant = 1.72e-8 impacts/m2/yr/deg2

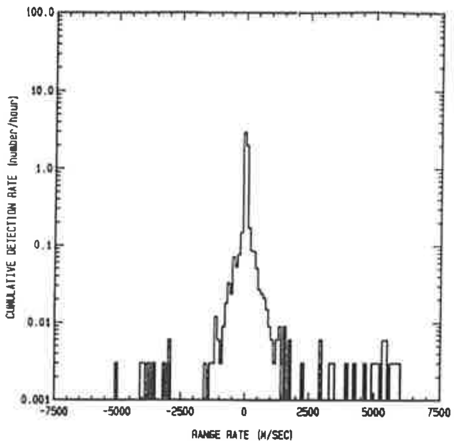

Figure 17. Haystack Range Rate Data in Zenith Starring Mode (Ref. 7)

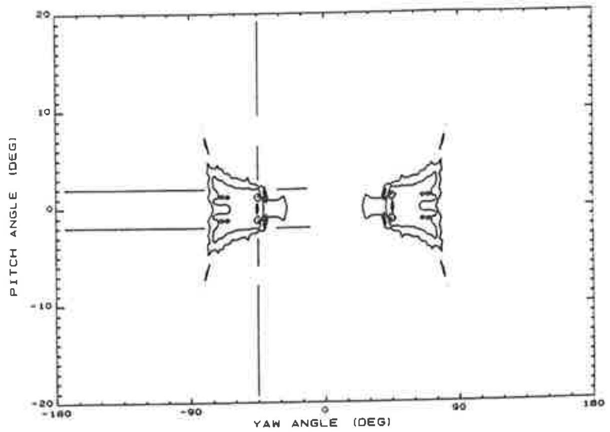

Figure 15. Flux Density Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Source: EVOLVE Debris in Size Range 1 - 10cm Normalizing Constant = 1.54e-7 impacts/m2/yr/deg2

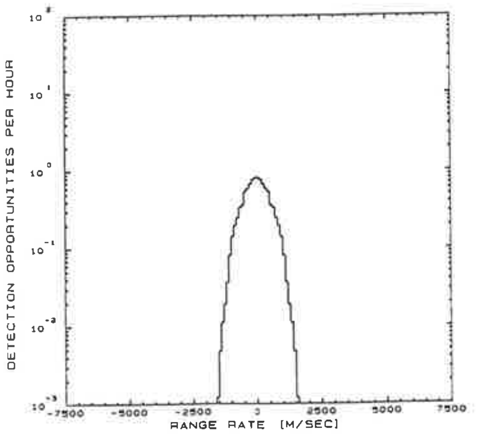

Figure 18. EVOLVE Range Rate Distribution Predicted for Haystack for Debris Larger than 5mm - Baseline Breakup Velocity Distribution

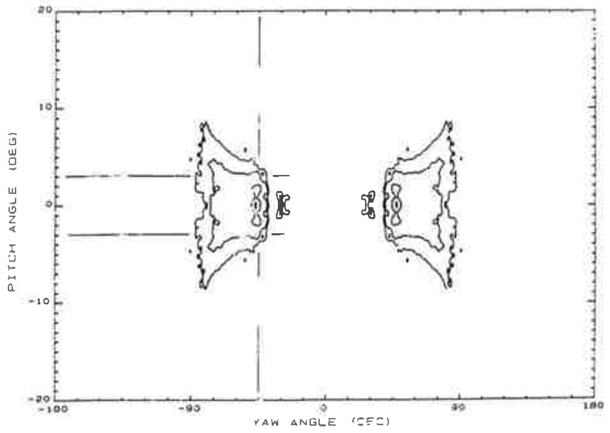

Figure 16. Flux Density Distribution for an Orbit of Altitude 450km and Inclination 28.5deg; Source: EVOLVE Debris in Size Range 1mm - 1cm Normalization Constant = 1.23e-5 impacts/m2/yr/deg2

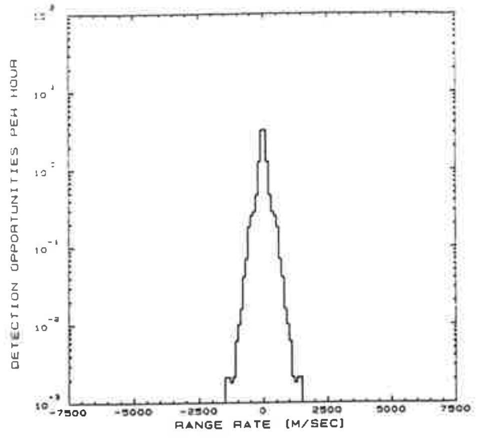

Figure 19. EVOLVE Range Rate Distribution Predicted for Haystack for Debris Larger than 5mm - Modified Breakup Velocity Distribution