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ORBITAL DEBRIS ENVIRONMENT CHARACTERISTICS OBTAINED BY MEANS OF THE HAYSTACK RADAR

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ABSTRACT

This paper describes the collection and analysis of space debris data. Sizes down to less than 1-cm diameter were detected by the Haystack radar during a collection period between October 1990 and October 1992. A "beam park" mode of operation was used whereby the radar was held in a fixed position and debris passed through the field of view. The analysis includes physical size estimates from the obtained radar cross sections (RCS), orbital debris flux calculations based upon the probability of detections within the half-power radar beam volume, and the occurrence of debris "clusters" within the general population.

1. INTRODUCTION

Orbital debris is becoming an increasingly important consideration for the design of spacecraft operating in low earth orbit (LEO). The Haystack radar has been periodically observing the debris population in LEO since October 1990. Knowledge of the orbital debris environment prior to 1990 was broken into two size regimes. For orbiting objects larger than about 10-cm. diameter, the USSPACECOM maintains a catalog which includes debris as well as intact satellites and rocket bodies. The catalog is maintained by the use of ground-based radars for objects in LEO. The 10-cm. diameter limit is somewhat arbitrary, but is mainly the result of the radars having relatively long wavelengths (70-cm. or longer). Knowledge of debris smaller than about 0.1-cm comes from analysis of surfaces that have been exposed to space for a period of time and then returned to the earth. The practical size limit of these data result from limitations of the surface area exposed and the length of time of the exposure. No statistically significant measurements of the debris environment in the size range from 0.1-cm to 10-cm existed prior to the Haystack measurements.

The Haystack debris measurements address a near-term requirement to improve the estimate of the orbital debris flux at Space Station Freedom (SSF) altitudes (nominally 350-450 km). Current designs are based on NASA's orbital debris model (Ref. 1) which has a large uncertainty. The goal for the Haystack measurements is to reduce the uncertainty in the debris environment to within ±50% before the SSF Critical Design Review.

2. EXPERIMENT DESCRIPTION

2.1 Data Collection

The Haystack observatory is located in Tyngsboro, Massachusetts. Operation of the Haystack radar is conducted by M.I.T. Lincoln Laboratory for the U.S. Air Force and other elements of the Department of Defense. Operation of the radar for NASA debris measurements is provided through a Memorandum of Agreement between USSPACECOM and NASA.

The Haystack radar is a high power, X-band (3-cm. wavelength), monopulse tracking radar with very high sensitivity (Ref. 2). To detect debris, a pulsed, single frequency waveform has been selected for use. The operating parameters for the Haystack radar during the debris measurements are shown in Table 1. Single pulse signal-to-noise ratio on a 1-m.^{2} target at 1000-km. is 56.8 dB. Objects as small as 1-cm. in diameter can be observed at ranges greater than 1000-km.

For debris observations, the Haystack radar is operated in a staring, or beam park mode in which the antenna is pointed at a specified elevation and azimuth and remains there while debris objects randomly pass through the radar's field of view. This operational mode provides a fixed detection volume critical to the measurement of the debris flux, or number of objects per unit area per unit time. By not tracking individual debris objects, a precise measurement of the object's orbit is sacrificed. However, position in the radar beam and rough orbital elements can be determined by examining the signals from the monopulse angle channels operating in an open-loop mode. A Processing and Control System (PACS) has been programmed to record data in a rotating buffer which is saved only when the integrated signal exceeds a predetermined threshold above system noise. In this way many hours of debris observation can be performed without an impractical amount of recording.

Orbital debris data has been collected with the radar directed vertically overhead and at low elevation angles. With the radar directed vertically, it can only detect orbits with inclinations between 42° and 138°. In order to sample orbits of lower inclination, the radar antenna was directed at an azimuth of 180° (due south) and at low elevation angles. At an elevation angle of 10° above the horizon, the radar can sample orbits as low as 28° inclination at 500-km. altitude. This increases the slant range to an altitude and reduces the sensitivity of the radar for smaller objects.

Calibration of the radar is a major concern for debris data collection. Currently, two types of calibrations are performed using orbiting calibration spheres of known size. The first is an absolute calibration performed by tracking a sphere at the center of the radar beam. Second, the relative sensitivity of the remainder of the antenna pattern is measured by scanning the antenna around the location of the sphere as it moves across the sky in orbit. However, spheres only return radar energy in the primary polarization (PP). Therefore, no true calibration exists for the orthogonal polarization (OP) channel (some laboratory measurements have been made which estimate the OP calibration constant). NASA is planning to deploy orbiting dipoles from an up-coming Space Shuttle flight for calibration of the OP channel.

Peak Power (KW)	400
Pulse Width (msec)	1.023
Pulse Repetition Frequency (Hz)	40
Antenna Gain (dB)	67.2
System Temperature (°K)	246
Total System Losses (dB)	4.9
Single Pulse SNR on 1 cm diameter target at 500 Km Range (dB)	27.8
Number of Non-Coherent Integrated Pulses Used for Detection	12

Table 1. Haystack Debris Mode Operating Parameters.

2.2 Data Processing and Analysis

Orbital Debris data from the Haystack radar recorded by the PACS are transmitted to NASA/Johnson Space Center (JSC) via 9-track, 6250 BPI tapes. The data are processed at JSC on a Silicon Graphics Inc. computer by a team of NASA and contractor personnel.

In the beam-park operational mode, consider an orbiting object passing through the radar field-of-view. The key step in the data processing is determining the location of a debris object in the radar beam for each radar pulse. From these locations, the motion of the object through the beam can be recreated and used to estimate rough orbital elements. Also, the signal strength can be augmented by the relative antenna gain determined by the antenna pattern calibration discussed above. Thus, the returned signal strength can be estimated as if the object were at the center of the radar beam. The radar cross section (RCS) is determined by applying the absolute radar calibration.

A separate study was done to develop a Size Estimation Model (SEM) to relate RCS to physical size. Thirty-nine "representative" debris objects were selected from two hypervelocity impacts of simulated satellites conducted by the Department-of-Defense. The RCSs of these debris objects were measured at a controlled RCS radar range operated by System Planning Corp. The RCS of each object was measured for all physical orientations. At each orientation, the frequency of the radar was stepped from 2.0 - 18.0-GHz (15 - 1.67-cm. wavelength). Figure 1 shows the relationship between the measured RCSs and the object's physical size. Each point on this plot shows a single object at a single frequency.

Physical size for this plot is defined as the average of the largest dimensions measured along three orthogonal axes. The first axis was chosen to coincide with the largest dimension, the second axis to coincide with the largest dimension in a plane orthogonal to the first axis, and the third axis to be orthogonal to the first two axes. Figure 1 also shows a scaling curve which represents the mean of the measured RCSs for each size/wavelength. For debris sizes much smaller or larger than the radar wavelength, the scaling curve approaches the Rayleigh or optics region curves, as expected. In the resonance region, the scaling curve deviates from the optical curve such that for a given RCS, the object is smaller than it would have been interpreted to be by using the optical approximation.

Further work has shown that the scaling curve in Figure 1 is not the best curve to use. The reason for this is that for any given size there is a distribution of RCS values returned. This means that sometimes the object will appear to be larger than the mean value and sometimes it will appear to be smaller. From the radar's point of view, it measures a number of similar RCS's, some of which will be from small objects which happen to look big, objects that appear to be the correct size, and big objects which happen to look small. A bias occurs because the population of orbital debris increases with decreasing size. Therefore, for a number of similar RCS's, there will be more small objects which appear large, than there will be large objects which appear small. The amount of bias introduced depends on the rate that the population increases with decreasing size and the details of the distributions of RCS's for a given size.

Figure 2 (Ref. 3) shows the measured distributions of RCS for a given size/wavelength ratio from the RCS range tests. A computer model was developed that assumes a known population (i.e. the number of debris objects in orbit vs. size). As the RCS values are stepped through, the distributions shown in Figure 2 are used to see how different sizes will be expected to contribute to that RCS measurement. These contributions are then weighted by the assumed size distribution and integrated over all possible sizes. The resulting function will reproduce the distribution of measured RCS values expected from the assumed size distribution. Historically, interplanetary dust, and certain on-orbit breakups have been modelled as simple power-law functions. Figure 3 shows the RCS vs. size relationships that would be used for a variety of power-law slopes.

A Radar Performance Model (RPM) was developed to relate the flux of objects passing through the radar's antenna beam to the number of objects detected by the radar. The RPM uses a straight forward, brute force approach. It initially calculates the trajectory of an object through the center of the radar beam. The model considers 12 points along the trajectory spaced appropriately to be the individual radar return pulses given the pulse-repetition-frequency (PRF) of the radar and altitude of the object (assuming a circular orbit). The model calculates the SNR of each of the 12 points corrected for the antenna gain at that point. It then integrates the SNR from the points and calculates the probability-of-detection (P_d) for the trajectory. The P_d is calculated assuming Swerling 2 scintillation statistics for sizes in the optical scattering regime, Swerling 1 statistics in the Mie or resonance regime, and Swerling 0 scintillation statistics for sizes in the Rayleigh scattering regime. The model repeats the P_d calculations for many parallel trajectories stepping away from beam center towards the edge of the beam. Once the beam edge is reached, the RPM calculates the average P_d and the beam edge-to-beam edge distance. The RPM repeats this calculation for object sizes from 1-mm. to 10-m. diameter in 1 dBm steps. For 90° elevation data, there is no variation in average P_d as a function of orbital inclination. However, at other elevation angles, an altitude slice of the radar beam gives an ellipse. Therefore, objects with different inclinations will have different antenna beam corrections and beam edge-to-edge distances.

The computer program then calculates the orbital debris flux that would pass through the antenna beam as a function of object size, altitude, and orbital inclination from the NASA debris environment

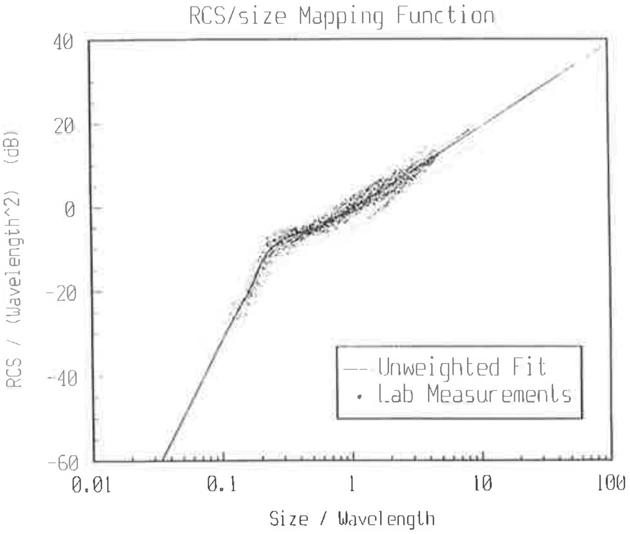

Figure 1. Results of the RCS-to-physical size measurements. Also shown is the "mean" or unweighted scaling function.

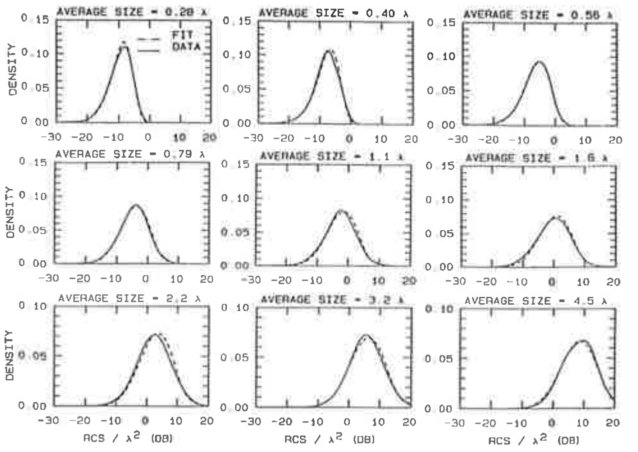

Figure 2. Distributions of single RCS measurements for various size/wavelengths.

model (i.e. the "engineering" model). The program uses the appropriate P_d and edge-to-edge distance and calculates the expected detection rate.

The NASA debris model is a function solar activity ($F_{10.7}$). All of the Haystack measurements to date have been made during a period with high solar activity. The predicted curves in the following section used a value of $F_{10.7} = 205$.

3. RESULTS

Table 2 provides a tabulation of the hours of Haystack data collect at each elevation angle through September 1992. A total of 1489.8 hours of "beam-park" data has been collected and processed.

A rational has been developed for creating a composite plot of the size distribution using data from the three primary beam park angles, 10°, 20°, and 90°. Basically, this rationale is that the longer a debris object remained in the radar beam, the more accurately the size could be determined. This is particularly true for large objects which would be very sensitive to its orientation to the radar. Therefore, the 10° data should be used for large objects since for a given altitude, it will have the largest collecting area due to its having the largest slant range to that altitude. However, the increased slant range also means less sensitivity. The 10° data are only used down to sizes for which the probability of detection begins to fall below ~100%. Below that size the 20° data would be used until its probability of detection also falls below ~100% beyond which the 90° are used. The cross-over size from the 10° data to the 20° data is 8-cm and the cross-over to 90° data is 5-cm. For the 90° elevation angle data, the altitude range used to build the composite plot is constrained to 350 to 1000-km altitude.

The composite size distribution was first plotted using the unweighted RCS scaling function. Then, different power-law distributions were used to "fit" the observed data. The RCS distribution measured by Haystack was best fit using a size distribution that is the sum of two power-law functions (diameter in m.):

$$0.000162*dia^{-2.0} + 0.026*dia^{-0.5}. \qquad (1)$$

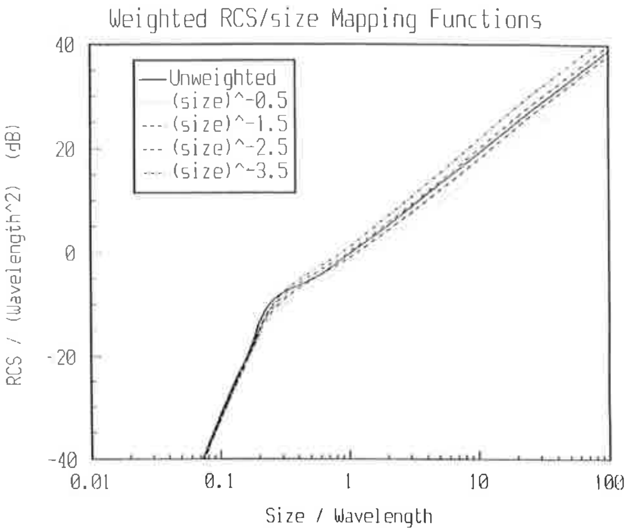

Figure 3. "Weighted" scaling function for different power-law slopes.

Using this distribution, a new mapping function is derived to transform the Haystack RCS measurements into properly weighted size measurements. Figure 4 shows a comparison of the weighted and unweighted distributions.

Figure 5 compares the weighted size distribution with the results of the RPM using the NASA "engineering" debris model. The main difference between the measured and modeled size distributions occurs between 3-cm. and 2-m. in diameter. Much of this difference is the result of an erroneous model assumption: The average RCS reported by the Eglin Radar in 1988 was equal to the cross-sectional area of the object. We now know that in 1988, all Eglin RCS's were biased by nearly 3 dB toward larger sizes. Consequently, all cataloged objects were modeled too large by a factor of 1.4 in diameter. Since the results of the optical observations (i.e. the "Henize factor") were ratioed to the Eglin RCS, these objects were also too large in the model. Consequently, there is a need to reduce the modeled size of larger debris.

This correction accounts for most of the difference between the Haystack measurements and the model in this size regime. However another factor that contributes as well is the difference in the type of measurement. In the case of Haystack, the object is in the radar beam for only a very short period of time, and much work has been done to determine the relationship between the measured RCS and true size distribution in orbit for this type of measurement. In the case of the Eglin radar, objects are tracked for a much longer

Beam Park Elevation	1990	1991	1992	Total
10°	123.3	246.1	163.0	532.4
20°	---	239.5	312.8	552.3
90°	40.0	147.7	158.1	345.9
Other	3.0	56.2	---	59.2
Total	166.3	689.5	633.9	1489.8

Table 2. Haystack debris data collection hours.

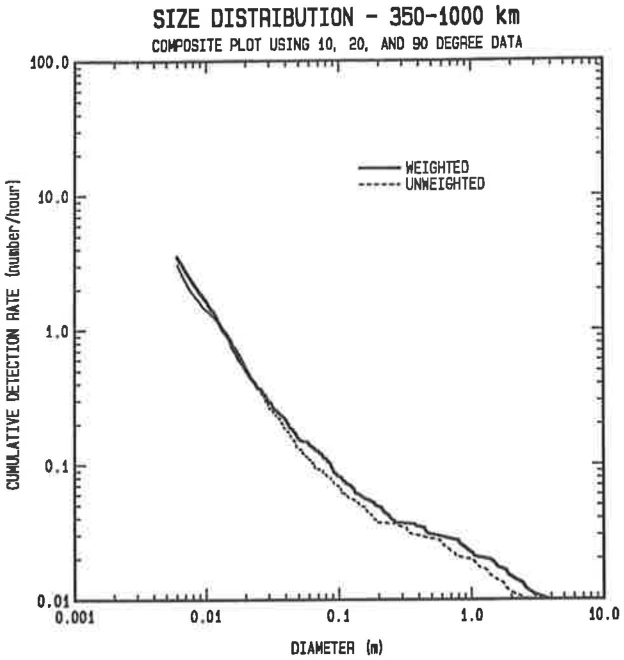

Figure 4. Comparison of weighted and unweighted composite size distributions.

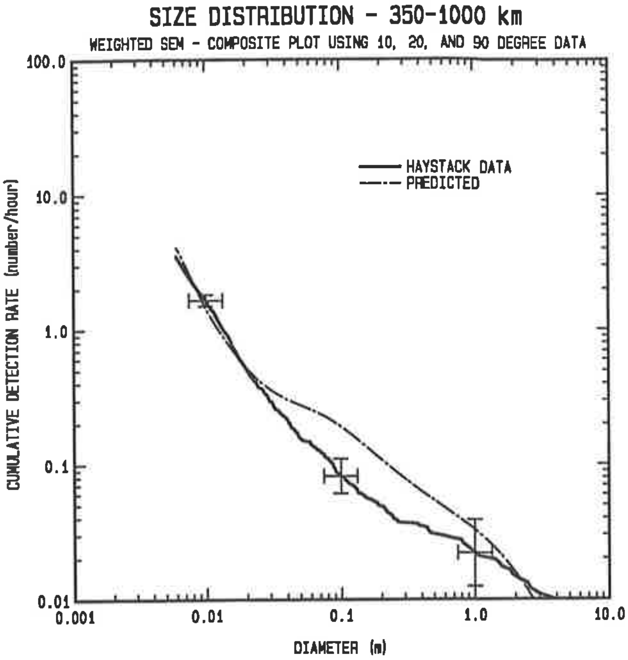

Figure 5. Comparison of measured and modeled debris size distributions.

interval of time, and RCS is "averaged" over this interval. Exactly how the RCS is averaged and how this relates to the true size distribution in space is not currently well understood.

Figure 6 shows the weighted size distributions for Space Station altitudes for each of the primary beam park angles. It should be noted that the weighting function is only correct if the true size distribution in derived for the 350-1000 km altitude band holds for the more restrictive band of 350-450 km. The data indeed appear to follow the size distribution, but the ratio of the observed debris population to the predicted population varies by a significant amount when comparing different beam park angles. The "Engineering Model" assumes that the population of orbital debris follows the same inclination distribution that is found in the USSPACECOM Catalog of orbiting satellites and debris. However, there has been evidence for some time to indicate that the catalog is biased against low inclination objects due to the relative lack of radars located at low latitudes. Figure 6 also shows the predicted curves from the RPM using the NASA debris model but with different inclination distributions. The original model results shown use the Catalog distribution summed over all altitudes up to 2000 km. Also shown are predicted results with a simple altitude dependent inclination distribution (inclination is broken into two altitude regimes: 300-600 km and 600-1500 km). The other predicted curves use the altitude dependent inclination distributions with inclinations below 33° multiplied by factors of 2, 4, and 8. Using the altitude dependent distribution with low inclinations multiplied by a factor of 4 comes closest to making the ratios of measured to predicted consistent over all beam park angles. However, this work is very preliminary and much more work needs to be done to justify this hypothesis.

Other possible contributing factors are that the RPM may not adequately model the probability of detection for the 90° beam park at low altitudes where the dwell time of an object in the radar beam may only allow the object to be detected with one or two pulses. Data will soon be collected to test this hypothesis.

4. CLUSTERS

Some orbital debris data has been collected by Goldstein and Randolph using a bi-static radar utilizing dishes at the Goldstone Deep Space Communications Complex (Ref. 4). During 48 hours of

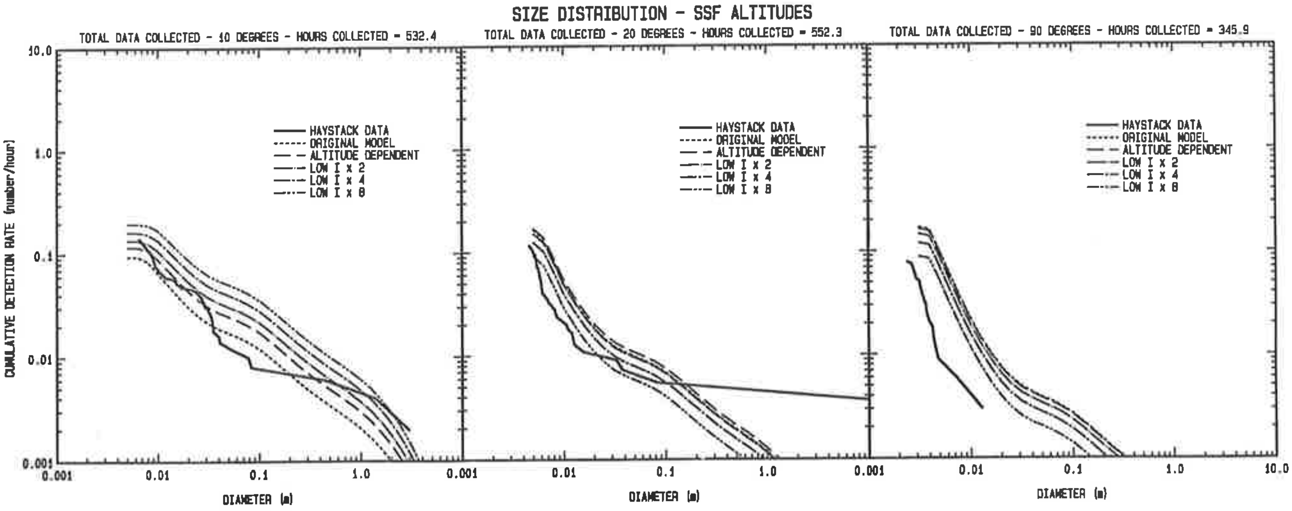

Figure 6. Size distributions for the three primary beam park angles at Space Station Freedom altitudes.

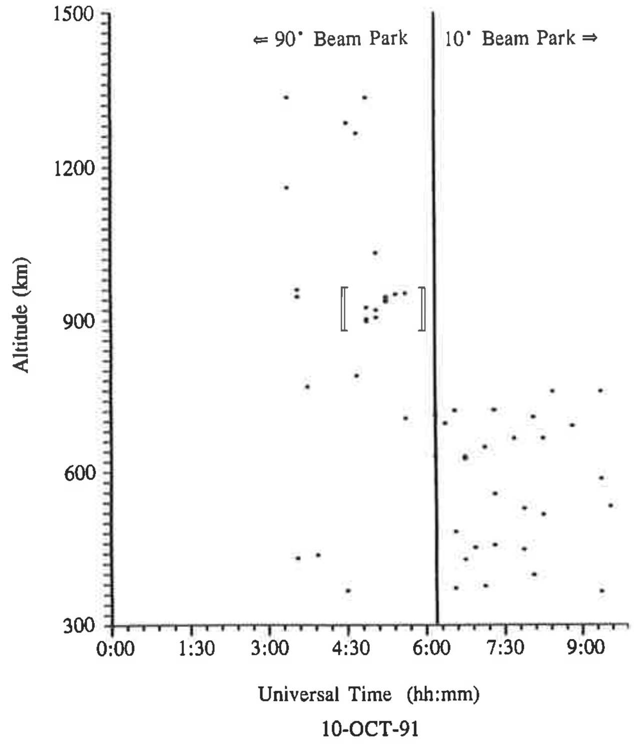

Figure 7. Detection plot showing altitude vs. time. Cluster is shown in brackets.

beam park data collected over 15 separate collection periods in 1989, swarms or clusters of small orbital debris were detected at the intersection of the transmitter and receiver antenna beams near 600-km. The experimental setup allowed detection of objects as small as 1.8-mm diameter. It obtained RCS data and range rate only, no monopulse information or range information other than that the objects were near 600-km was obtained. One reported cluster contained 15 objects and had a duration of ~1 hour.

We have searched the Haystack data for similar clusters. All of the Haystack data collected at the three primary beam park angles has been searched and no clusters were detected near 600-km. However, 6 clusters were detected in the 90° beam park data between 850 - 1000-km altitude. Figure 7 shows a plot of time vs. altitude for a section of data collected on October 10, 1991. The cluster, shown in brackets, has 10 detections between 890 - 960-km spanning about 45 minutes. The number of objects and duration of the cluster agree favorably with the streams seen at the Goldstone complex. The calculated sizes of the objects are generally between 1 and 3-cm diameter. Figure 8 shows the monopulse tracks indicated through the radar beam for 9 of the 10 objects within the brackets of Figure 7. The large dots indicate the start of the tracks. The indicated inclinations run from about 66° to 72°. The indication that the altitude increases from the start of the stream to the end as a breakup that has formed a toroid and that precession rate of the orbits is slightly different for different altitudes.

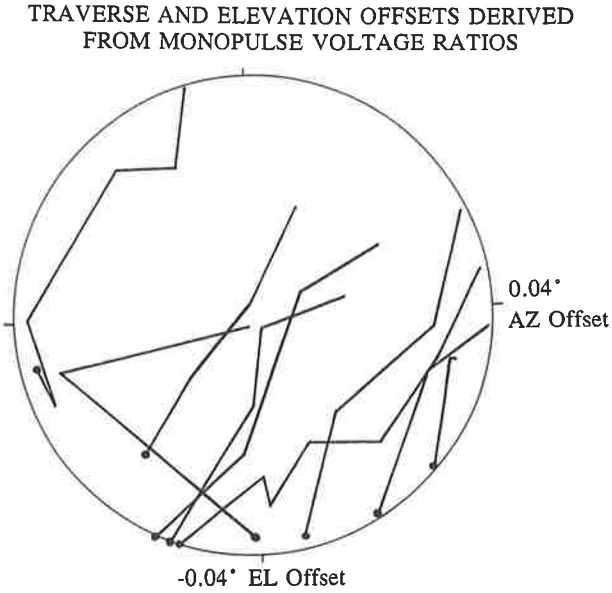

Figure 8. Plot of monopulse data for cluster showing direction of motion across the Haystack beam.

5. CONCLUSIONS

The orbital debris data collected in 1992 add significantly to the confidence in our characterization of the orbital debris environment for small debris sizes down to <1-cm. diameter. Significant progress has also been made in understanding the relationship between the RCS distribution measured by Haystack and the true size distribution of objects in orbit. Further work needs to be done to understand the inclination distribution.

6. REFERENCES

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