WHAT ARE RADAR OBSERVATIONS TELLING US ABOUT THE LOW-EARTH ORBITAL DEBRIS ENVIRONMENT?

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ABSTRACT

NASA has been observing the low-Earth orbital debris environment with high power radars for more than a decade, and the observations continue to reveal valuable information about the character of the debris particles. Instruments such as the Haystack, Haystack Auxiliary (HAX), and Goldstone radars have been used to observe debris particles smaller than are normally visible using only the US Space Command resources. Haystack can routinely detect objects less than 1 cm in size in LEO. HAX can routinely detect debris objects less than about 3 cm in LEO. Goldstone, while limited in capability compared to HAX and Haystack, can detect objects only a few millimeters in size in LEO.

By making statistical observations of the debris, however, we have given up the possibility of tracking these objects. So, in order to enhance our information on the orbital distribution of debris in LEO, several unusual radar geometries have been employed. These have been used to identify families of orbital debris with similar orbital inclinations and altitude distributions. In addition, polarization measurements have allowed us to probe the characteristics of the debris – primarily the shape of the particles. New statistical data analysis techniques reveal information on the elliptical orbit distributions, and allow us to make the first direct estimates of the contributions of elliptical orbits of centimeter objects to the flux in LEO and to characterize the sources of these debris.

This paper updates the results of measurements made by the Haystack, Haystack Auxiliary, and Goldstone radars and how NASA is finding new ways to use these instruments to answer questions about the orbital debris environment.

1. INTRODUCTION

Ground-based radar provides a powerful tool for analyzing the LEO orbital debris environment. Radar can operate in most types of weather and at all times of the day or night. Radars make very precise measurements of position and of the reflected energy of the detected objects (computed as radar cross section – RCS).

Because of these properties, US Space Command uses radars as the "work horses" of the Space Surveillance Network to maintain accurate orbital elements on the population of satellites in Earth orbit down to about 10 cm in size (see below for definition of "size"). Space Command records the RCS values for tracked objects, but only uses the values to aid in tracking tasks (e.g., allocating radar power). NASA has been able to use these RCS values to estimate size-dependent populations.

Tracking objects smaller than 10 cm in size is difficult using current resources. NASA instead uses radar systems to statistically sample the environment. The radars point in a particular direction and count the objects that go through the beam, measuring whatever properties the particular radar can measure. Typically, we can measure the time of detection, the position of an object, its Doppler range-rate (the velocity along the line-of-sight), and its RCS value and variations while it is in the beam. For some systems, we can measure the RCS polarization, and the path and speed through the beam.

Radars do not directly measure the sizes of objects, but instead measure RCS computed from the reflected power. The RCS of an object is a function of the object's size, its shape, material properties, and orientation. As most of these properties of the objects are unknown, determining a size for each object is a difficult task. Fortunately, most orbital debris particles are created by random processes (e.g., explosions), so many of these properties can be dealt with using statistical tools. For instance, debris objects probably do not show any orientation preference. Also the size distribution is assumed to be continuous, as we do not expect any preferred size of the random shards. The material properties are somewhat more difficult to ascertain, but we know the material properties of the parent bodies (rockets and payloads), so we can make reasonable inferences about the materials of the debris. The shapes probably fall into broad categories (e.g., plate-like, sphere-like, needle-like), but these, too, will have considerable variation (e.g., plates will be bent and twisted).

In order to obtain a mapping of RCS to size, NASA did

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ground hypervelocity impact tests. The "size" of such irregular objects was defined as the average of the three orthogonal lengths (longest length, longest length in plane perpendicular to that, and the length in the remaining orthogonal direction). For each of the test objects, the RCS was measured for a variety of frequencies and orientations. From these tests, functions were created to describe the distribution of RCS expected for an irregular object of a given size. One of the results of this study was that irregular objects give well-behaved random distributions in RCS. It is regular, symmetric objects such as spheres that exhibit specialized resonant behavior. Using this data NASA also created a Size Estimation Model (SEM) that gives a one-to-one mapping of RCS to size [1]. This method has some limitations, but works well for many applications to create size distributions.

In order to model the orbital debris environment, information about the debris distributions in orbit parameters, size, and (for shielding calculations) shape of the objects is needed. The frustrating thing is that none of this information is directly measured by the radars. Fortunately, the debris properties radar does measure can be used to tell us a great deal about these distributions.

2. RADAR SYSTEMS

NASA primarily uses three radar systems to regularly survey the LEO orbital debris environment at sizes less than about 10 cm. Each radar system has its own strengths and weaknesses.

NASA's primary orbital debris radar has been Lincoln Laboratory's Long Range Imaging Radar (LRIR) known as Haystack. This radar, located in Massachusetts (latitude 42.62^{o} N), is an pulsed X-band system (3 cm wavelength) that has the capability of seeing debris objects less than 1 cm in size in LEO. The 36 meter dish has a FWHM beam width of 0.058^{o} and can operate in a number of stare mode directions [1].

The Haystack Auxiliary (HAX) radar (collocated with Haystack) is similar to Haystack, but operates at higher frequency (1.8 cm wavelength), has a smaller dish (12.2 meters), and has a wider field of view (0.1^{o}). This means that the radar is less sensitive, but the collecting area is larger. HAX can detect debris objects only down to around 3 cm. Because of its lower sensitivity, HAX is generally only used in a near-vertical stare mode [2].

Goldstone radar is a large bistatic system located in California (latitude 35.24^{o} N). It operates at a slightly lower frequency than Haystack or HAX (3.523 cm), but is quite sensitive because the receiver is isolated from the transmitter. The transmitter is a 70-meter dish and the receiver is a 34-meter dish located 497 meters away. The overlapping beams create a complex pattern, but FWHM of the equivalent beam is about 0.03^{o}. Goldstone can detect objects down to a few millimeters in size in LEO. Goldstone uses a chirped signal to determine the range and range-rate of the target [3].

Both Haystack and HAX have a monopulse capability that is used to map the path of the debris particles through the beam to correct for the beam shape so that the true radar cross section can be computed directly. Goldstone does not have this capability, however, so the path of each particle through the beam is unknown. The true radar cross section must then be computed statistically.

3. ORBIT DISTRIBUTIONS

One of the most important characteristics of the debris environment is how the particles are distributed in orbital elements. Early in NASA's radar program, it became clear that mapping the path of particles through the Haystack beam using monopulse data did not always give good results for the orbital elements. The paths derived from the monopulse data show a general degredation for decreasing signal-to-noise ratio. In general, the monopulse inclinations can be up to ten or more degrees in error in some cases, and the derived eccentricities (which are very sensitive to the angular rate through the beam) are often useless. However, experimentation with beam pointing direction and use of the Doppler range-rate (measuring the component of the velocity along the beam direction) have shown that much of the debris environment is in "families" of near-circular orbits. It is believed, however, that at least some of the debris population being measured is in more eccentric orbits.

In an effort to estimate the distributions in orbit populations, a statistical analysis tool was incorporated. For the purposes of this analysis, only the range and range-rate data were used to estimate the orbit distributions. In order to make the problem tractable, the populations were estimated for objects 1 cm and larger (estimated using the SEM model).

For an orbit with given semi-major axis, eccentricity, and inclination and with randomized argument of perigee and ascending node, there is a certain probability that a radar at a particular location pointed in a particular direction will detect the object at a particular range and range-rate. For each orbit, radar, and pointing direction a probability "map" can be constructed that shows the rate of detection per unit time in the range/range-rate plane. Each orbit thus has a unique "fingerprint" over multiple pointing geometries.

The actual data represents a superposition of many such orbit "fingerprints" that represent the environment. In these distributions. If an infinite amount of time were used to collect an infinite amount of data, it might be possible to formally invert the problem to arrive at the populations. In practice, however, a best-fit solution is used to estimate the populations – this is termed a Maximum Likelihood Estimator (MLE). The metric used for the "best fit" was the Kullback-Leibler information divergence. This MLE lends itself to the use of an iterative algorithm known as the Expectation Maximization (EM) method [4].

The data to be fit was created by binning the Haystack data in range/range-rate bins for a variety of pointing directions. The expected detection rate within each bin was computed for a large number of orbit population family distributions in inclination, perigee, and eccentricity. The "best fit" populations were then computed using the EM method. These population fits were used to construct the debris populations in the ORDEM 2000 engineering model [5].

Using the orbit population fits, estimates of the proportion of eccentric orbits distributed in altitude and inclination can be obtained. These are shown in fig.1-fig. 3 compared with the catalog population representing objects larger than about 10 cm in size.

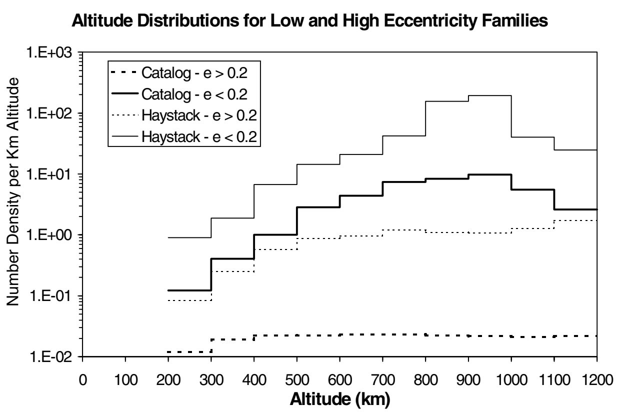

Fig. 1. This chart shows the altitude distribution of the catalog population (> ~10 cm in size) compared to the orbit populations derived from the Haystack data (> 1 cm) by the method described in the text. The populations are divided into low and high eccentricity families. The low-eccentricity populations show the greatest jump in population from 10 cm to 1 cm between 800 and 1000 km altitude due to the RORSAT populations. The elliptical orbit spatial densities show a marked jump (up to two orders of magnitude) from 10 cm to 1 cm in size.

Two major features are evident in this data. The first is the jump from the 10 cm to the 1 cm population for low-eccentricity orbits between about 850 and 1000 altitude. This debris population is associated with the Russian RORSAT reactors and is believed to be composed of droplets of sodium-potassium coolant [6]. The other interesting feature is the dramatic jump in elliptical populations from 10 cm to 1 cm in size. For low-eccentricity orbits the increase is typically a factor of ~10, but for elliptical orbits, the jump in some regimes is closer to ~100. This difference has been noted before, but this data is confirmation that the population of eccentric orbits grows more dramatically with decreasing size than does the circular orbit population.

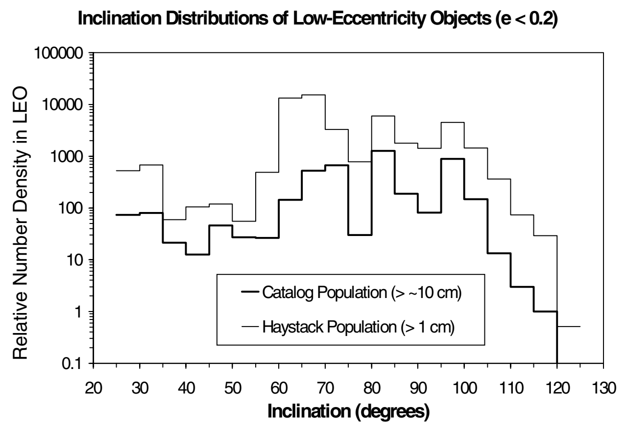

Fig. 2. This chart shows the inclination distribution of low-eccentricity orbits for the 10 cm and 1 cm populations. The RORSAT population shows up in the 60° to 70° inclination band.

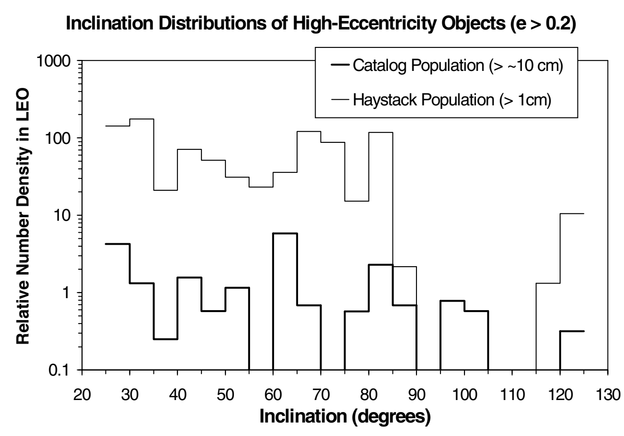

Fig. 3. This chart shows the inclination distribution of high-eccentricity orbits for the 10 cm and 1 cm populations. The strongest contributions of 1 cm orbits are in the 30° inclination region associated with launches from Cape Canaveral, but other populations show enhancement at smaller sizes as well. Note that these curves are a function of the spatial density in LEO, not the actual population

4. SIZE DISTRIBUTIONS

A number of different techniques have been used to compute the size distributions derived from the Haystack and HAX radars [7]. In this study, the EM method is applied to the size distributions from these two radars and combined with the size distribution from the Goldstone radar to show the debris populations over several decades in size. This method finds the size distribution that best matches the observed RCS distribution after applying the instrument response model.

A size-dependent RCS distribution (the distribution in RCS an object of a given size would be expected to have) based on the 39 test objects is given by formulae derived empirically by Bohannon [8]. For Haystack and HAX, it is a straightforward matter to apply the MLE to the cumulative distributions of RCS. For Goldstone, the problem is more complex.

The reduction of the Goldstone data takes into account the effects due to the non-overlap of the beams (the two beam centers only coincide at one point in space). In addition, there is some signal loss for objects with higher Doppler shift. This is corrected for as well.

There are two factors for the Goldstone detections that cannot be directly removed. The Goldstone system can only detect one type of circular polarization at a time (see below, section 5). Usually, the system is set to detect the Principal Polarization (PP) signal. As will be discussed in section 5, the polarization of small debris is not uniform, so for objects with a sizable Orthogonal Polarization (OP), the total RCS will be underestimated.

The biggest problem with the Goldstone data has been how to correct for the path of the debris objects through the beam. Goldstone does not have a monopulse capability, so we don't know whether a given detection is of a large debris object going through the edge of the beam, or a smaller object going through the center of the beam. Fortunately, where the object crosses the beam will be a random process, so we can use the EM method for this problem as well.

For the Goldstone data, instead of using the simple distribution of RCS for each size, a mapping of the *measured RCS that Goldstone would see* as a function of size is used. This "Goldstone RCS" distribution is created by integrating possible paths through the beam and using a model of polarization distributions consistent with that seen in the Haystack data.

The EM method is then applied using these distributions as the instrument response functions. A Bootstrap method is used to estimate the confidence limits on the inferred size distributions [9].

Fig. 4 and Fig. 5 show composite surface area flux from all three radars after the size distributions have been computed using the EM method. Overall, the radars give a consistent picture of the size distribution of the debris environment using different radar frequencies. Note that each curve is cumulative, so the right-hand side of each curve is based on the lowest number of detections, and therefore has the highest uncertainty. Also, for each of these curves, there has been no effort to carefully model the "rolloff" as the sensitivity of each radar system drops off at small sizes.

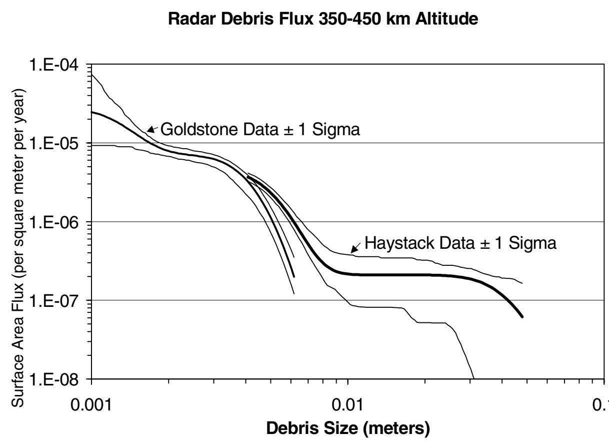

Fig. 4. This chart shows the estimated size-dependent flux in the 350-450 km altitude band. The marked increase in flux for decreasing size below about 1 cm is seen in both radar systems. Goldstone has a problem with undercounting objects with larger RCS, so the right side of the Goldstone curve has larger uncertainties than what is shown. Note that each of the curves shows a "roll-off" on the left corresponding to a loss in sensitivity at small RCS.

Each of the datasets used to make these charts was a composite of multiple years – so the relative time each radar observed each year is different. Goldstone is at a lower latitude than Haystack and HAX, but this should not greatly affect the total flux from these systems. Reference [7] has more detailed comparisons of the HAX and Haystack data broken out by time and altitude.

As can be seen in the Goldstone data, there appears to be an undercount in the number of objects with higher RCS values. This causes the Goldstone curve to drop off quickly at larger sizes. We have not yet identified the cause of this problem. This does not appear to affect the fluxes at lower sizes, however.

While there are some differences between the curves as is noted above, the different radars show the same overall behavior. The debris population begins to sharply increase with decreasing size below about 10 cm in size. The size curve changes again and becomes steeper below about 1 cm in size and continues to increase to the limits of the radar sensitivity.

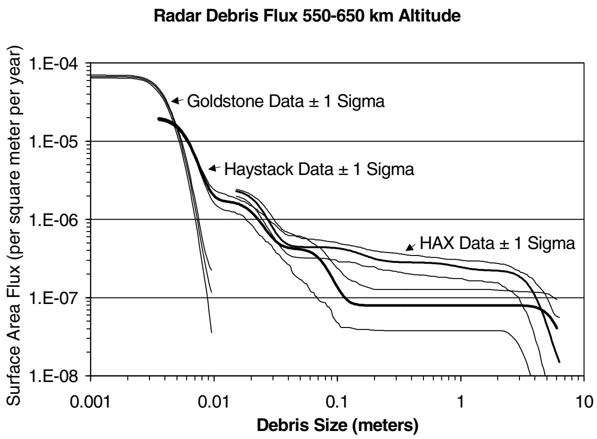

Fig. 5. This chart shows the estimated size-dependent flux in the 550-650 km altitude band for all three radar systems. There are two regions where the size distribution shows a change in slope – around 10 cm and around 1 cm in size. The three radars do not agree precisely in all regimes because this data set represents an amalgamation of several years of data and each radar system was used in differing amounts each year. Nevertheless, the three radar systems display the same overall behavior. As in fig. 4, the right hand side of the Goldstone curve has higher uncertainties than is shown.

5. SHAPE DISTRIBUTIONS

The most difficult property to ascertain is the shape of the objects seen by the radars. The shape, combined with the material properties of the debris, is the biggest unknown we have about the debris environment. Knowledge of the shape is important in calculating collision penetrability of the debris.

Both the Haystack and HAX radars broadcast right-hand circularly polarized beams and receive both right hand and left hand circularly polarized signals. The left-hand polarization return signal is know as the Principal Polarization (PP) and is associated with "specular" reflections such as the return from a sphere. The right-hand polarization return signal is known as the Orthogonal Polarization (OP), and usually indicates more complex structure – corner reflectors, etc.

If the debris object in the beam is spherical, then the polarization will be primarily PP. If the object is a dipole, then the received signal will be linearly polarized, which is an equal mix of PP and OP. If the object is a plate in the Rayleigh regime (the size of the plate is much smaller than the wavelength) the polarization varies evenly from sphere-like (high PP) for face-on illumination to dipole-like (PP = OP) for edge-on illumination. But for larger plates, diffraction off the plate edges causes constructive and destructive interference that can be different for the PP and OP signal. This results in the polarization varying wildly with different orientations of the plate. This transition from simple plate behavior to much more complex behavior occurs in the Mie region where the wavelength and size of the debris object are comparable.

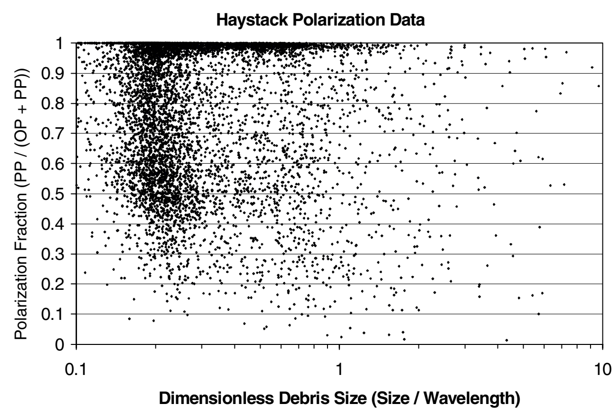

Fig. 6. This chart shows the polarization fraction (the fraction of the RCS contributed by the PP signal) of debris seen in the Haystack data as a function of the dimensionless size. The family of objects with polarization fractions near 1 is primarily due to sphere-like objects, mostly in the RORSAT family. The band of objects with polarization fractions distributed between 0.5 and 1 probably represents plate-like objects. If there were a significant population of dipole-like objects present, they would appear as a band with polarization fraction values near 0.5.

Fig. 6 shows the polarization fraction (PP / RCS) as a function of dimensionless size (size / wavelength) for Haystack. Two families are clearly visible in the data. The first is a large concentration of objects with polarization fraction near 1. These are the RORSAT spheres between about 850 and 1000 km altitude thought to be the sodium-potassium coolant from the Russian reactors [6]. The second family is at dimensionless sizes around 0.2 and has a polarization fraction distribution evenly distributed between about 0.5 and 1. This is the pattern expected from flat plates.

distribution is more evenly distributed between 0 and 1. This pattern is not uncharacteristic of plate-like objects, although it could also indicate that larger objects are simply more complex in a shape. Note that if there were a large concentration of objects with polarization fraction near 0.5, then this would indicate a large population of dipoles. While there appear to be some dipole-like objects, they are clearly not a major fraction of the LEO population.

6. CONCLUSIONS

In this paper, we have presented an overview of the NASA orbital debris radar data. We have shown how using more sophisticated statistical techniques can shed light on debris orbit distributions, including being able to resolve eccentricity families. In addition, by using multiple radars at different frequencies, it is possible to extend the measured size distribution over several orders of magnitude. Also, by looking at the polarization data, it is possible to make conclusions about the shapes of debris particles in LEO.

NASA will continue to use radar systems in the future to monitor changes in the orbital debris population. We will also seek new and better ways to use the existing radar systems to improve our knowledge of the orbital debris environment.

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