# A COMPARISON OF HAYSTACK AND HAX MEASUREMENTS OF THE ORBITAL DEBRIS ENVIRONMENT

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## ABSTRACT

NASA/Johnson Space Center's Space Sciences Branch has been analyzing orbital debris data collected by the Haystack radar operating at 10 GHz since 1990. The major objective of these measurements has been to characterize the debris environment for the International Space Station and the U.S. Space Shuttle. The environment has been characterized by: number, size, altitude, and inclination. The Haystack Auxiliary (HAX) radar, operating at 16.7 GHz, began collecting orbital debris data in 1994. The HAX radar is less sensitive than Haystack, but is available more often. HAX utilizes similar data collection procedures, the same real-time data collection system, and the same analysis software as Haystack. Therefore, results from the two radars should be consistent with each other after accounting for the known differences in sensitivity and wavelength. This paper will discuss the data collection and analysis of the two data sets.

## 1. INTRODUCTION

The Haystack radar first began routine collection of orbital debris data in August, 1990 (Ref. 1). Since that time, it has been NASA's primary source of data on the Space Debris environment in the 0.6–10 cm debris diameter size range. However, Haystack's availability is limited. The Haystack antenna is configured as a radio telescope most of the time. It is operated as a radar for an average of only about 1 week in 6 with significant observational gaps occurring during the winter months. The Haystack Auxiliary radar (HAX) was built to help fill in gaps in radar coverage from Haystack and began routine debris data collection in 1994. HAX operates at a higher frequency (shorter wavelength) and has a larger field of view than the Haystack radar; but, is less sensitive. The two radars share the real time control and data collection hardware, and therefore cannot be operated simultaneously. The Haystack/HAX facility provides a unique opportunity to test the effects of wavelength and sensitivity on the resulting debris environment measurements while ensuring that there are no other data collection and processing biases.

## 2. DATA COLLECTION AND PROCESSING

The Haystack and HAX radars are located in Tyngsboro, Massachusetts at a North Latitude of 42.6°. Operation of the two radars 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 radars for NASA's debris measurements is provided through a Memorandum of Agreement between USSPACECOM and NASA.

The operating parameters for the Haystack and HAX radars during debris measurements are shown in Table 1.

| | **Haystack** | **HAX** |
|---|---|---|
| Frequency (GHz) | 10 GHz | 16.7 GHz |
| Wavelength (cm) | 3 cm | 1.8 cm |
| Peak Power (KW) | 400 KW | 40 KW |
| Pulse Waveform | Pulsed CW | |
| Pulse Width (msec) | 1 msec | 2 msec |
| Pulse Repetition Frequency (Hz) | 40 Hz | 95 Hz |
| Beamwidth (degrees) | 0.05 | 0.1 |
| Antenna Diameter (m) | 36 m | 12 m |
| Polarization | Left & Right Circular | |
| Sensitivity ($1m^2$ @ 1000 km single hit) | 58 dB | 40 dB |

Table 1. Haystack Debris Mode Operating Parameters

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An overview of the entire data collection and analysis is depicted in Figure 1. For debris observations, the Haystack or HAX radar is operated in a staring, or "beam park," mode with the antenna pointed at a specified elevation and azimuth where it remains as debris objects randomly pass through the field of view. This operational mode provides a fixed detection volume important to the measurement of the debris flux, or number of objects detected 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 to tape. The PACS records system parameters plus signal strength for each received pulse from four separate channels: the Principal Polarization (PP) sum channel, Orthogonal Polarization (OP) sum channel, Traverse (TR) difference channel, and Elevation (EL) difference channel.

The PACS recorded data are transmitted to NASA/Johnson Space Center (JSC) via high density 8-mm magnetic tapes. The data are processed at JSC using the Orbital Debris Analysis System (ODAS) which is hosted on a Silicon Graphics Inc. computer by a NASA\Lockheed-Martin contractor team.

In the debris mode, the ODAS software computes/ determines the signal strength, signal-to-noise (SNR) ratio, TR and EL voltage ratios, range and range rate. Other parameters are derived from these measurements. For an orbiting object passing through the radar field-of-view, one of the key steps in the data processing is determining the location of a debris object in the radar beam for each radar pulse in the presence of noise. From these locations, the motion of the object through the beam can be estimated and used to develop rough orbital elements. Also, the signal strength can be augmented by the relative antenna gain determined by the antenna beam-pattern calibration discussed below. 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, antenna beam shape, and the slant range to the object.

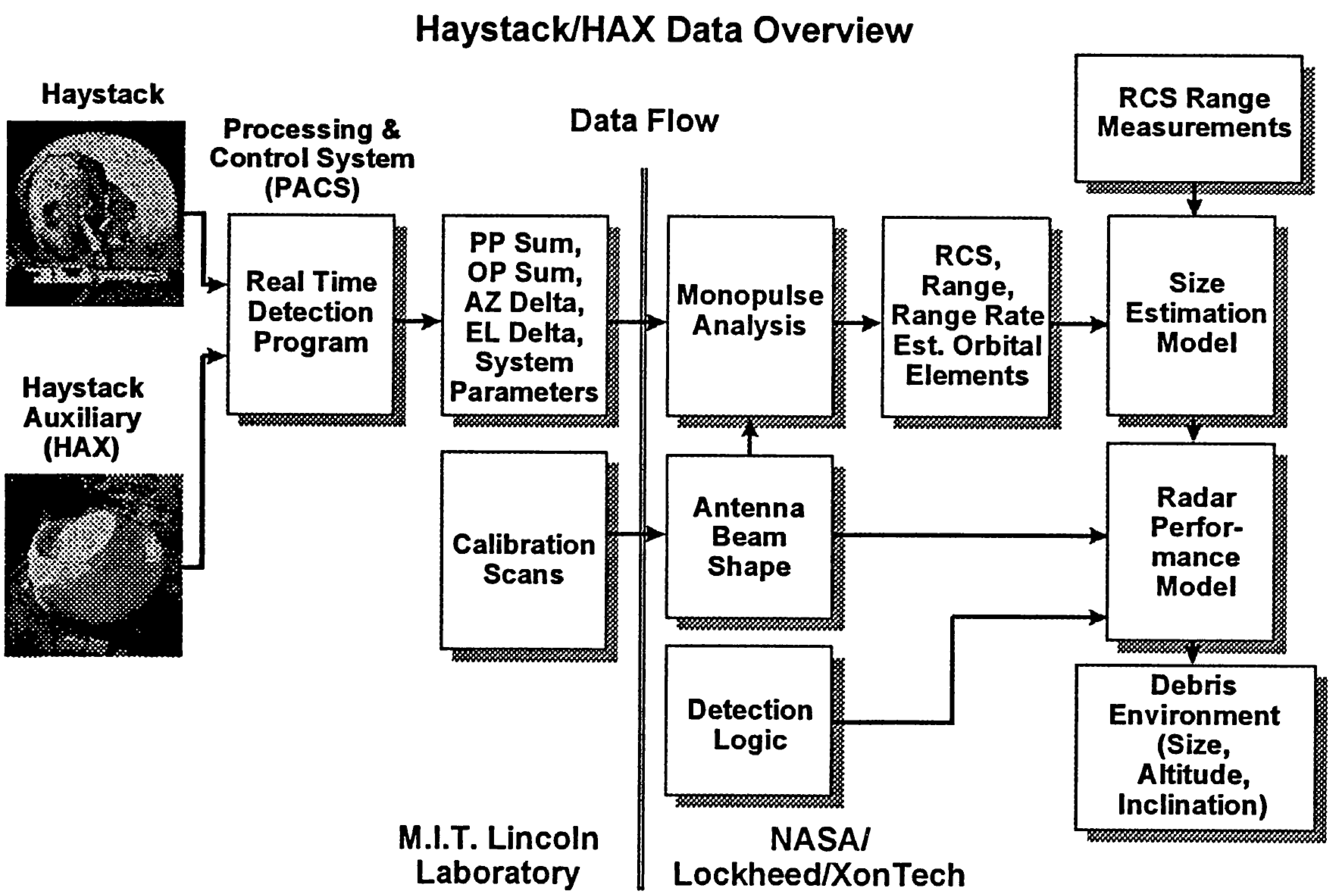


Figure 1. Overview of data collection and processing of the Haystack and HAX orbital debris data.

The size of each object detected is estimated using a separately derived Size Estimation Model (SEM) (Ref. 2,3). Thirty-nine "representative" debris objects were selected from two hypervelocity impacts of simulated satellites conducted by the Department-of-Defense. The RCS 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 2 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 averaged over all orientations. 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. From this plot a scaling curve was developed which represents the mean of the measured RCS for each size/wavelength. The SEM is scaled as a function of the radar wavelength.

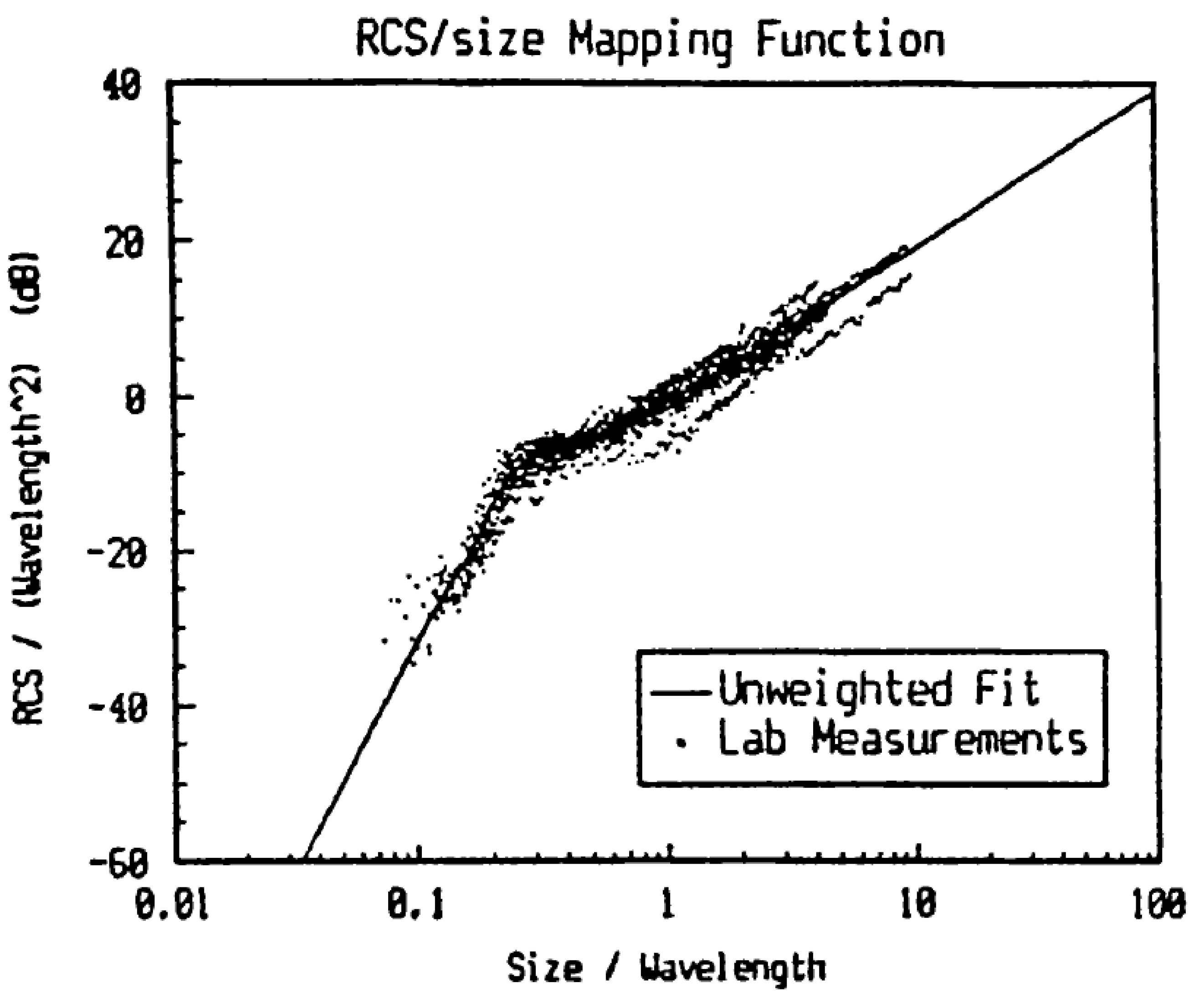


Figure 2. Results of RCS-to-Physical size measurements of 39 "representative" debris objects. Each point represents a single object measured at a single frequency.

The SEM is an empirically derived function. Therefore, the key factor in its formulation is that the 39 debris objects used to formulate the SEM are truly representative of the on-orbit debris population. For debris sizes much smaller or larger than the radar wavelength the SEM scaling curve approaches the Rayleigh or optics region curves, as would be expected. In the resonance region, the SEM can be tested by measuring the same debris population using the different wavelengths of the Haystack and HAX radars. If the measured environment estimates are consistent, then the scaling curve should be consistent with the on-orbit population.

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 each points location. 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-edge distance. The RPM repeats this calculation for object sizes from 1-mm. to 10-m. diameter in 1-dBm steps. For vertical staring, or 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 model, ORDEM96 (Ref. 4). The program uses the appropriate $P_d$ and edge-to-edge distance and calculates the expected detection rate or flux.

Calibration of the radar is a major concern for debris data collection. Two types of recurring calibrations are performed using orbiting calibration spheres of known size, typically 1 m$^2$. 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. The first determines the system gain and the second determines the antenna beam pattern.

## 3. RESULTS

Data from Haystack has been collected at a number of different staring angles since 1990. Early in the program data was collected with the radar pointed vertically and pointed south at low elevation angles. The vertical staring angle maximized the sensitivity of the radar while the south pointing sampled inclinations lower than the latitude of the radar, 42.6°. However, in 1993 it was realized that the orbital inclination of satellites could be inferred from the range rate of the detection for non vertical staring angles (Ref. 5). Further, an ambiguity existed in the Doppler derived inclinations for south pointing angles that did not exist if the radar were pointed to the east (or west). Therefore, in 1994, over 40% of the approximately 600 hours of data collected was collected at 75° elevation and 90° azimuth. This staring angle provided unique Doppler inclination data and high sensitivity.

Debris data from HAX, however, was only planned to be collected using a vertical staring beam because of the reduced sensitivity. Therefore, the radar was built without an optional hardware filter to handle the range rate span appropriate to collect debris data at 75° elevation.

The data to be compared here are 263.1 hours of Haystack data collected at 75° elevation/90° azimuth and 372.1 hours of HAX data collected staring vertically, both data sets having been collected in 1994. For comparison of debris flux measurements, the data were separated into seven 100 km altitude bins from 400 ± 50 km to 1000 ±50 km. Figures 3 and 4 show the size distribution at two different altitudes; 450-550 km and 850-950 km. The dashed lines in each plot are the ORDEM96/RPM models. The two dashed lines overlay each other for large sizes. This indicates that the probability of detection for large objects is essentially 100% over the entire radar field of view. For these large sizes, the model simply reflects the ORDEM96 predictions. These are modified as the probability of detection falls off with decreasing size. Since HAX is a less sensitive radar than Haystack, the model for HAX falls off at a larger size than the model for Haystack. In Figure 3, the two data sets overlay each other for sizes from about 1 to 4 cm diameter. Below 1 cm, the HAX data become flat as the probability of detection approaches zero while the Haystack measured flux continues to climb until it reaches 3–4 mm. Both the Haystack and HAX distributions are limited for large debris by poor counting statistics. In other words, you would not statistically expect to see very large satellites because there are few of them and the collection area (field of view) and duration (number of hours) of the data sets are limited. Of the two data sets, larger objects are seen more frequently in the HAX data because there are more HAX hours and the radar beamwidth is twice as wide as for Haystack. Error bars shown in these figures represent one sigma Poisson uncertainties.

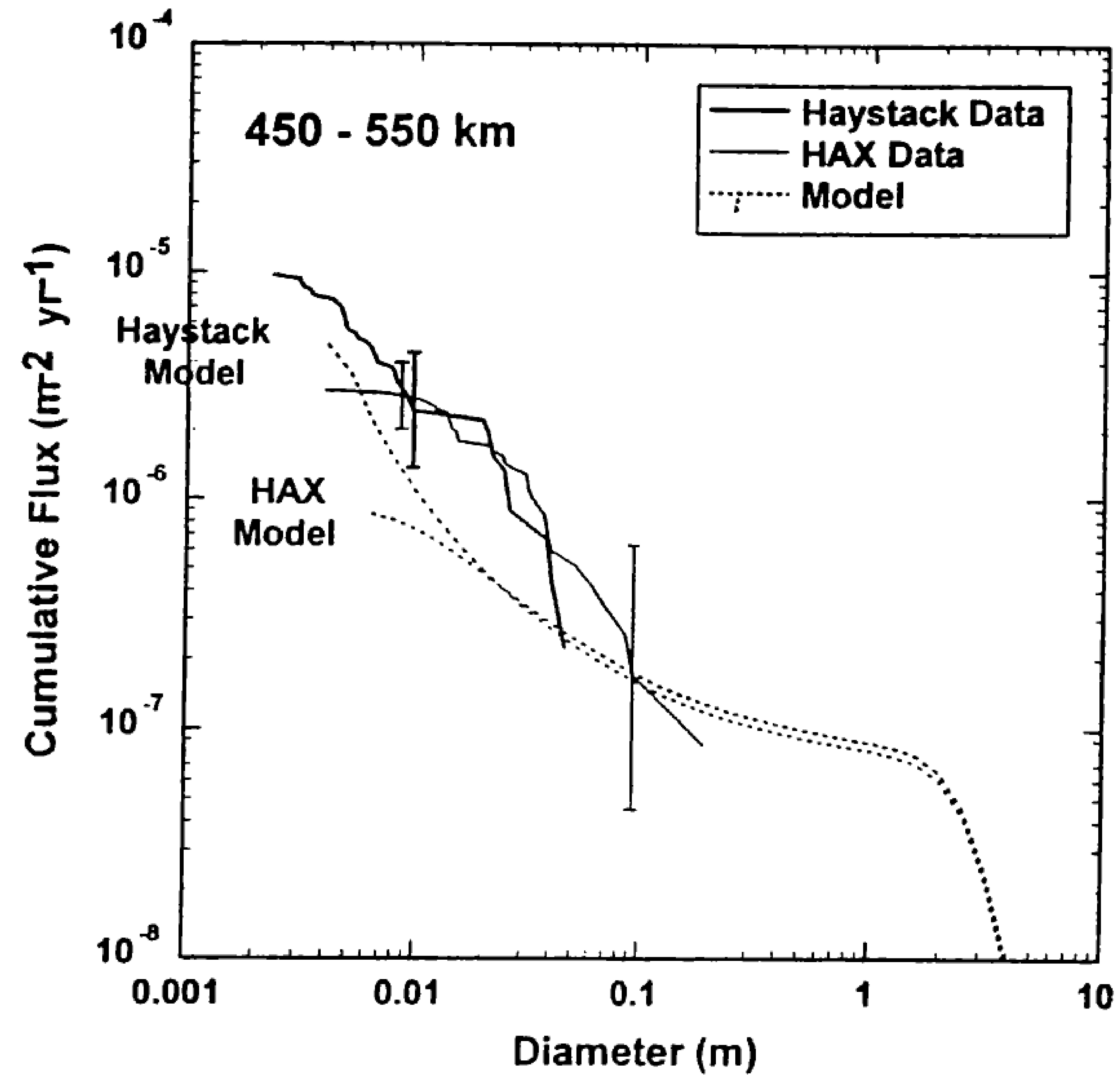


Figure 3. Comparison of Haystack and HAX measured debris size distributions for the altitude band 450–550 km.

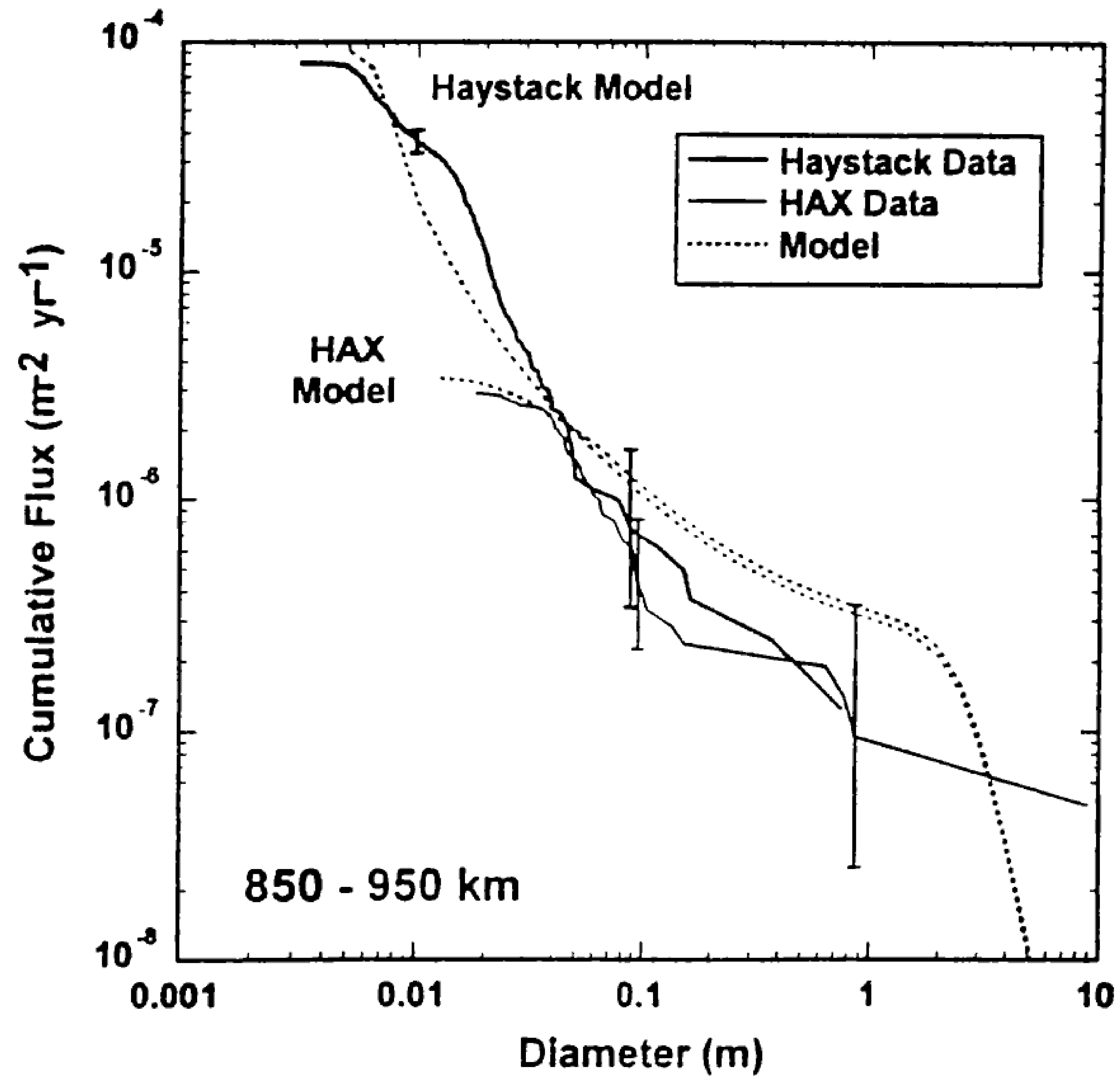


Figure 4. Comparison of Haystack and HAX measured debris size distributions for the altitude band 850–950 km.

Figure 4 shows that the two data sets overlay for diameters from about 4 to 70 cm in the 850-950 km altitude bin. Larger sizes are seen in these data sets because the flux of particles at this altitude is higher and because the collection area is larger at the longer slant range. These plots, as well as similar plots from the other altitudes, show consistent results between the two data sets.

Other types of plots are examined to check for consistency as well. Figure 5 is a scatter plot showing each detection's altitude and time of day for the HAX data set. The plot shows that the HAX was operated predominately only during two 8-hour shifts. There is a potential for biasing the data set in this manner in that not all sun synchronous orbits are sampled, but the realities of limited resources and funding dictates this constraint. Also evident in this plot are two groupings of detections near 12:00 GMT, one at altitudes near 500 km, and the second near 900 km. The lower altitude group was detected when the Haystack data was first published in April of 1996 (Ref. 6) and is attributable to the Cosmos 1484 breakup in October 1993 (Ref. 7). The second, higher altitude group occurs in the heart of the NaK debris band (Ref. 6,8,9). The NaK debris is typically below the HAX sensitivity threshold and is not detected allowing this second group of debris to be easily noticed. Although present in the Haystack data, the large number of NaK debris detected tended to hide this second group of debris. Therefore, the second group was not mentioned in the earlier Haystack report. Analysis of the combined Haystack and HAX data indicates that this higher altitude debris group probably originates from the COBE (COsmic Background Explorer) satellite which began shedding debris in January, 1993 (Ref. 7).

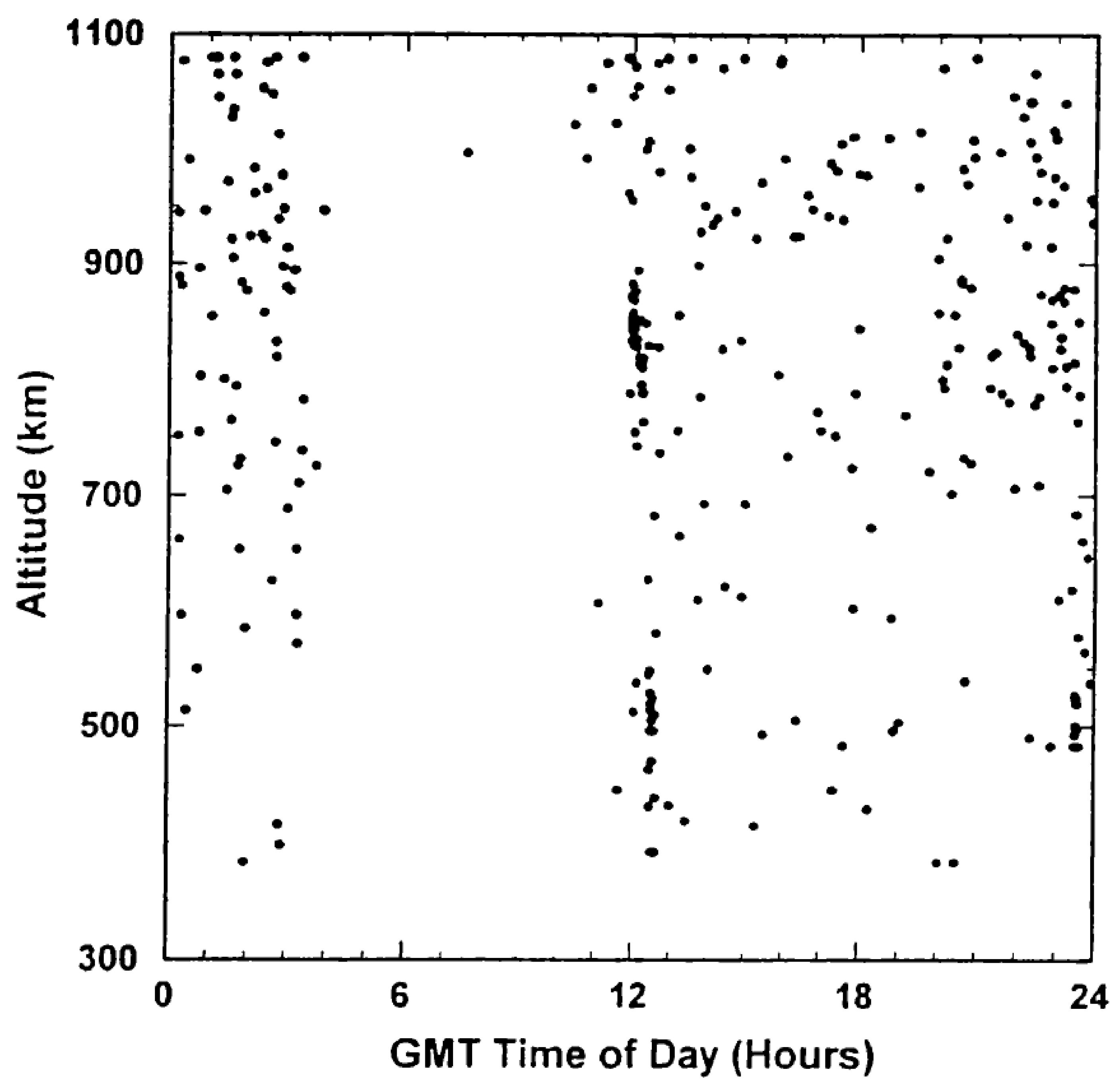


Figure 5. Scatter plot of GMT Time of Day vs. Altitude for HAX debris data.

## 4. CONCLUSIONS

The Haystack and HAX data sets, collected during the same time period in 1994 and covering similar orbital regimes, are both consistent and complimentary. The two data sets are consistent in the size ranges they have in common. They are complimentary because each set extends the size range. Due to its better sensitivity, Haystack extends our knowledge to smaller sizes. HAX, on the other hand, has a larger field of view and is more readily available. Because of the larger detection volume-duration, HAX will see more of the larger debris pieces and therefore extends the flux plots in the direction of larger sizes.

The close consistency of the two data sets collected at different wavelengths is also indicative of the validity of the Size Estimation Model which is scaled to wavelength.

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