Haystack and HAX Radar
Measurements of the
Orbital Debris Environment: 2006-2012

Astromaterials Research and Exploration Science Directorate
Human Exploration Science Office
Orbital Debris Program Office

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May 2014
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Appendices

A1  Attitude Versus Range Rate, Haystack 75° Elevation, East Pointing .............................................. A1-1
A2  Integrated SNR, Haystack 75° Elevation, East Pointing ................................................................. A2-1
A3  Altitude Versus Total RCS, Haystack 75° Elevation, East Pointing .................................................. A3-1

B1  Attitude Versus Range Rate, HAX 75° Elevation, East Pointing .................................................. B1-1
B2  Integrated SNR, HAX 75° Elevation, East Pointing ...................................................................... B2-1
B3  Altitude Versus Total RCS, HAX 75° Elevation, East Pointing ...................................................... B3-1

C1  Attitude Versus Range Rate, Haystack 20° Elevation, South Pointing ................................................ C1-1
C2  Integrated SNR, Haystack 20° Elevation, South Pointing ............................................................. C2-1
C3  Altitude Versus Total RCS, Haystack 20° Elevation, South Pointing ............................................. C3-1

D1  Attitude Versus Range Rate, Haystack 10° Elevation, South Pointing ............................................... D1-1
D2  Integrated SNR, Haystack 10° Elevation, South Pointing ............................................................. D2-1
D3  Altitude Versus Total RCS, Haystack 10° Elevation, South Pointing ............................................. D3-1

E1  Flux Versus Altitude, Referenced to RCS_{\text{noise eq avg}}, Haystack 75° Elevation, East Pointing ............ E1-1
E2  Flux Versus Inclination, Haystack 75° Elevation, East Pointing ..................................................... E2-1
E3  Flux Versus Characteristic Size, Referenced to RCS_{\text{noise eq avg}}, Haystack 75° Elevation, East Pointing E3-1

F1  Flux Versus Altitude, Referenced to RCS_{\text{noise eq avg}}, HAX 75° Elevation, East Pointing ................. F1-1
F2  Flux Versus Inclination, HAX 75° Elevation, East Pointing ........................................................... F2-1
F3  Flux Versus Characteristic Size, Referenced to RCS_{\text{noise eq avg}}, HAX 75° Elevation, East Pointing F3-1
Figures

Figure 2-1 Debris observations waveform characteristics.......................................................... 4
Figure 2-2 Haystack and HAX debris signal processing by PACS.......................................... 7

Figure 4-1 Historical acquisition of satellites used for calibration by Haystack and HAX radars.................................................................................................................. 11
Figure 4-2 Orbital debris data collection and pre- and post-data collection timeline.......... 12
Figure 4-3 Traverse and elevation angle offsets (in angular degrees) relative to the calibration satellite position versus time from a Haystack calibration performed on 31 March 2009.................................................................................................... 12
Figure 4-4 Elevation versus traverse angle offsets in degrees (top) and the corresponding voltage ratios (bottom), from the same calibration as in Figure 4-2.................... 13
Figure 4-5 Elevation angle offset versus voltage ratio; the solid line represents the elevation fit third order polynomial................................................................................. 14
Figure 4-6 An example of a calibration model paraboloid created from the same calibration spiral scan as shown in Figs. 4.3 - 4.5................................................................. 15
Figure 4-7 NASA SEM model polynomial fit (smooth curve) is plotted as a function of scaling parameters $x$ and $z$, while the oscillating line is the RCS for a spherical conductor.................................................................................................................... 16
Figure 4-8 Polar plot with an example of beam path estimate for Haystack detection........ 18
Figure 4-9 Haystack SNR dependence on range for different RCS ($\sigma$, dBsm) at Haystack maximum sensitivity of 59.2 dB................................................................. 20
Figure 4-10 Haystack sensitivity (PP SNR for 1 m$^2$ object at 1000 km), averaged over events contained on each tape for FY2007......................................................... 21
Figure 4-11 Haystack sensitivity (PP SNR for 1 m$^2$ object at 1000 km), averaged over events contained on each tape for FY2009......................................................... 22
Figure 4-12 HAX sensitivity averaged over events contained by each tape for FY2006................................................................. 23
Figure 4-13 HAX sensitivity averaged over events contained by each tape for FY2011 and FY2012................................................................. 23
Figure 4-14 Single pulse SNR versus range of a 1-cm size object for several Haystack and HAX sensitivities......................................................................................... 25
Figure 4-15 $\text{RCS}_{\text{noise_eq_avgPP}}$ for Haystack Radar at 75° east-pointing from FY2006 to FY2012................................................................. 26
Figure 4-16 $\text{RCS}_{\text{noise_eq_avgPP}}$ for HAX Radar at 75° east-pointing from FY2006 to FY2012.... 26
Figure 5-1  Uncorrected Haystack cumulative NaK debris count rate for 75° elevation;
east azimuth observations for FY2006–FY2010. ..........................................................  29

Figure 5-2  Haystack cumulative NaK debris count rate for 75° elevation, corrected
for RCS bias; east azimuth observations for FY2006 – FY2010 .................................  30

Figure 6-1  Altitude and range-rate observations for Haystack at 75° east-pointing
over FY2010, with circular orbit, ascending and descending node;
constant-inclination lines superimposed. ........................................................................  32

Figure 6-2  Altitude versus range rate count rates during FY2010 for Haystack at
75° east-pointing.  Constant inclination lines superimposed as in Figure 6-1. ...... 32

Figure 6-3  Altitude and range-rate observations over FY2012, for HAX
at 75° east-pointing, with circular orbit, ascending and descending node;
constant-inclination lines superimposed. ........................................................................  33

Figure 6-4  Altitude versus range rate count rates during FY2012, for HAX at
75° east-pointing.  Constant inclination lines superimposed as in Figure 6-3. .... 34

Figure 6-5  PP channel integrated SNR during FY2010, for Haystack at 75° east-pointing... 34

Figure 6-6  PP channel integrated SNR during FY2012, for HAX at 75° east-pointing. ..... 35

Figure 6-7  Total RCS during FY2010, for Haystack at 75° east-pointing,
with RCS\(_{\text{noise eq avg}}\) reference. ..............................................................................  35

Figure 6-8  Total RCS during FY2012, for HAX at 75° east-pointing,
with RCS\(_{\text{noise eq avg}}\) reference. ..............................................................................  36

Figure 6-9  Total RCS versus characteristic size during FY2010,
for Haystack at 75° east-pointing. ................................................................................  36

Figure 6-10 Altitude versus polarization for observations during FY2010,
Haystack Radar at 75° east-pointing. ..........................................................................  37

Figure 7-1  FY2010 Haystack, 75° east, total observed flux,
characteristic size for RCS\(_{\text{noise eq avg}}\). ........................................................................  40

Figure 7-2  FY2012 HAX, 75° east, total observed flux,
characteristic size for RCS\(_{\text{noise eq avg}}\). ........................................................................  40

Figure 7-3  FY2006 through FY2010 Haystack, 75° east, total observed flux. .....................  41

Figure 7-4  FY2006 through FY2012 HAX, 75° east, total observed flux. ............................  41

Figure 7-5  FY2006 through FY2010 Haystack, 75° east,
characteristic size equivalent to RCS\(_{\text{noise eq avg}}\). .........................................................  42

Figure 7-6  FY2006 through FY2012 HAX, 75° east,
characteristic size equivalent to RCS\(_{\text{noise eq avg}}\). .........................................................  42
Figure 7-7  FY2010 Haystack, 75° east, 400-1800 km, total observed flux versus inclination................................................................. 43
Figure 7-8  FY2012 HAX, 75° east, 400–1800 km, total observed flux versus inclination..... 43
Figure 7-9  FY2010 Haystack, 75° east pointing, 400–1800 km, divided by characteristic size equivalent to RCS_{\text{noise}_\text{eq_avg}}. .............................................. 44
Figure 7-10 FY2012 HAX, 75° east pointing, 400–1800 km, divided by characteristic size equivalent to RCS_{\text{noise}_\text{eq_avg}}. .................................................. 44

Figure 8-1  Haystack staring data collected from January - May 2007................................. 47
Figure 8-2  Cumulative size distribution of FY-1C debris during an orbit plane track conducted by the Haystack radar within 24 hours of the ASAT test........... 47
Figure 8-3  Altitude versus time-of-day for FY-1C debris during Haystack orbit plane track. ........................................................................................................... 48
Figure 8-4  Catalogued FY-1C debris as of 11 July 2007...................................................... 49
Figure 8-5  Altitude versus Doppler inclination for all Haystack valid detections at 75° elevation............................................................................................... 50
Figure 8-6  Number of pre-collision and post-collision debris, but before the Haystack power loss, detection rate versus Doppler inclination (histogram, 2° bins) for Haystack detections of sub-centimeter objects. ........................................... 51
Figure 8-7  Detection count rate per hour versus SEM size (for 1-mm bins) for pre-collision data, for post-collision but pre-power loss, and for post-collision and post-power loss ................................................................. 52
Figure 8-8  Virtually all of the objects generated by this Briz-M breakup population (SSN 38746) de-orbited within a year due to the low perigee of the orbits........... 53
## Tables

Table 2-1  Radar Debris Mode Operating Parameters .......................................................... 5

Table 3-1  Haystack Data Collection Hours and Number of Detections .............................. 8
Table 3-2  HAX Data Summary for 75° Elevation, East Pointing ........................................ 9

Table 4-1  Haystack Historic Sensitivity Data Averaged by Fiscal Years ............................. 22
Table 4-2  HAX Historic Sensitivity Data, Averaged by Fiscal Year .................................... 24

Table 7-1  Haystack Total Cumulative Flux (#/m²/year) ...................................................... 39
Table 7-2  HAX Total Cumulative Flux (#/m²/year) ............................................................. 39
Table 7-3  Haystack Minimum Characteristic Sizes (cm), for RCS_{noise\_eq\_avg} ............ 39
Table 7-4  HAX Minimum Characteristic Sizes (cm), for RCS_{noise\_eq\_avg} ..................... 39

Table 8-1  Haystack 75° East Debris Staring Mode Measurements,
    Probability of Detection .............................................................................................. 52
Table 8-2  Haystack and HAX 24-Hour Campaign Observations ........................................ 54
Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASAT</td>
<td>anti-satellite</td>
</tr>
<tr>
<td>AZ</td>
<td>azimuth</td>
</tr>
<tr>
<td>CFAR</td>
<td>Constant False Alarm Rate</td>
</tr>
<tr>
<td>CLDT</td>
<td>calibrated Long Range Imaging Radar data tape (format)</td>
</tr>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>dB</td>
<td>(unit) decibel</td>
</tr>
<tr>
<td>dBsm</td>
<td>(unit) decibel referenced to 1 m$^2$</td>
</tr>
<tr>
<td>DPCS</td>
<td>digital pulse compression subsystem</td>
</tr>
<tr>
<td>EL</td>
<td>elevation</td>
</tr>
<tr>
<td>EM</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>FY</td>
<td>Fiscal Year</td>
</tr>
<tr>
<td>FY-1C</td>
<td>Fengyun-1C</td>
</tr>
<tr>
<td>GEO</td>
<td>geosynchronous orbit</td>
</tr>
<tr>
<td>GUI</td>
<td>graphical user interface</td>
</tr>
<tr>
<td>HAX</td>
<td>Haystack Auxiliary (radar)</td>
</tr>
<tr>
<td>IADC</td>
<td>Inter-Agency Space Debris Coordination Committee</td>
</tr>
<tr>
<td>LEO</td>
<td>low Earth orbit</td>
</tr>
<tr>
<td>LRIR</td>
<td>Long Range Imaging Radar</td>
</tr>
<tr>
<td>MIT LL</td>
<td>Massachusetts Institute of Technology Lincoln Laboratory</td>
</tr>
<tr>
<td>NaK</td>
<td>Sodium-Potassium</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NCI</td>
<td>non-coherent integration</td>
</tr>
<tr>
<td>OD</td>
<td>orbital debris</td>
</tr>
<tr>
<td>ODAS</td>
<td>Orbital Debris Analysis Software</td>
</tr>
<tr>
<td>ODPO</td>
<td>Orbital Debris Program Office</td>
</tr>
<tr>
<td>OP</td>
<td>orthogonal polarization</td>
</tr>
<tr>
<td>PACS</td>
<td>Processing and Control System</td>
</tr>
<tr>
<td>PP</td>
<td>principal polarization</td>
</tr>
<tr>
<td>RCS</td>
<td>radar cross-section</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>RORSAT</td>
<td>(Russian) Radar Ocean Reconnaissance Satellite</td>
</tr>
<tr>
<td>RSO</td>
<td>resident space object</td>
</tr>
<tr>
<td>RTP</td>
<td>real-time processing</td>
</tr>
<tr>
<td>SEM</td>
<td>Size Estimation Model</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SSN</td>
<td>Space Surveillance Network</td>
</tr>
<tr>
<td>TWT</td>
<td>traveling wave tube</td>
</tr>
<tr>
<td>WFC</td>
<td>Wave Form Code</td>
</tr>
<tr>
<td>WGS 84</td>
<td>1984 World Geodetic System</td>
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</table>
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1.0 Introduction

1.1 Purpose

This report is a summary of observation data from the Haystack and the Haystack Auxiliary (HAX) radars provided to the NASA Orbital Debris Program Office (ODPO) by the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL).

1.2 Scope

This report covers the period from Fiscal Year (FY)2006 through FY2012. The report includes observation results that are used to improve various models that estimate the risk to spacecraft and predict future debris populations, but it does not include the results of such models. For convenience, the NASA Size Estimation Model (SEM) was used to translate radar cross-section (RCS) measurements into characteristic size estimates.

1.3 Overview

The Haystack radar, operated by MIT LL, has been collecting orbital debris data for the ODPO since 1990 under an agreement with the U. S. Department of Defense. The ODPO also receives data from the HAX radar located next to the main Haystack antenna. Both radars operate in a stare mode designed to statistically sample objects in low Earth orbit (LEO) that are smaller than those typically tracked and cataloged by the Space Surveillance Network (SSN).

The dynamic nature of the environment requires continual monitoring. Over the period of this report, many events happened that changed the orbital debris environment. In addition to the accumulation of derelict spacecraft, rocket bodies, and operational debris, the SSN cataloged over 7000 debris, created by more than 40 breakup events, in orbits having the potential to threaten operational spacecraft in LEO. These events include both standard and aerodynamic breakups; standard breakups consist of explosions and collisions producing debris. Anomalous events have been excluded from this accounting, as the nature of their production of debris is not understood.
One of those events was a Chinese anti-satellite test in 2007, which left many pieces in persistent orbits at an altitude near 850 km when the Fengyun-1C (FY-1C) (SSN 25730) target spacecraft was destroyed. Another major debris-generating event occurred in 2009 when an inactive Russian communication satellite, Cosmos-2251 (SSN 22675), collided with an active U.S. commercial communication satellite, Iridium-33 (SSN 24946), at an altitude of 790 km.

The ODPO relies heavily upon ground-based radar observations, such as those radars operated by MIT LL, to estimate the distribution of small debris objects in LEO. Annually, MIT LL collects approximately 1000 hours of radar data at random times throughout the year, not including special surveys. These observation hours are necessary to measure the small object population. The ODPO processes these data, taking problems into account that degrade performance and maintenance/upgrades that improve performance. These validated results are used to improve models that estimate the risk to spacecraft.

The MIT LL’s large dish radars generate narrow beams that are very sensitive but cover a small region of space at any given time. Less sensitive than Haystack, the HAX radar operates at a different wavelength (1.8 cm for HAX versus 3 cm for Haystack) and has a wider beam. Normally, data collection would be split between the two radars with 600 hours from Haystack and 400 hours from HAX. When the Haystack radar became unavailable for debris data collection in May 2010, MIT LL increased observation hours on HAX to compensate. The Haystack radar is expected to resume debris observations in early 2014.

Chapter 2 provides a detailed description of the Haystack and HAX radars. Chapter 3 contains a summary of the data collected by MIT LL each year, except for special surveys listed in Chapter 8. Chapters 4 and 5 explain how the data were processed, calibrated, and validated. Chapters 6, 7, and 8 provide the results and discuss the implication of selected measurements. The appendices present a broad range of plots representing the radar data.
2.0 Radar System and Data Collection Overview

2.1. Location

The Haystack and HAX radars are of Cassegrain configuration. Located in Westford, Massachusetts, each radar has a Cassegrain focus at the following coordinates:

Haystack: Latitude: 42.623287° N; Longitude: 288.511846° E; Elevation: 115.69 m
HAX: Latitude: 42.622835° N; Longitude: 288.511709° E; Elevation: 101.11 m

These coordinates are relative to the 1984 World Geodetic System (WGS 84) Earth model.

2.2 Radar Configurations

The Haystack and HAX radars are high powered, right-circularly polarized, amplitude-sensing, monopulse tracking radars with very high sensitivity. The Haystack radar operates at a 3 cm wavelength (X-band) and the HAX radar operates at a 1.8 cm wavelength (Ku-band). Debris measurements are obtained using a pulsed continuous wave (CW) waveform.\(^1\)

The Haystack 36.6-m parabolic main reflector is a solid aluminum surface shell composed of 96 light, stiff aluminum panel sections. The root-mean-square (RMS) deviation from a perfect paraboloid is 0.25 mm. At 10 GHz, the antenna gain is 67.23 dB with a 0.058° half-power transmitted beam-width (termed also as 3-dB width, one way). Haystack’s pointing accuracy is approximately 1.5 millidegrees during stable thermal conditions. This has been determined using naturally occurring astronomical maser sources. The first, second, and third side lobes reduce the measured RCS by approximately -41 dB, -49 dB, and -55 dB, respectively.

The HAX radar is a scaled-down version of the Haystack radar. Its 12.2-m parabolic main reflector deviates from a perfect paraboloid by 0.46 mm RMS and its pointing accuracy is approximately 2.0 millidegrees during stable thermal conditions. The HAX radar antenna’s first sidelobe reduces the two-way measurement of RCS by approximately -38 dB. Like Haystack, HAX is a monopulse tracking radar; however, it emits less power than Haystack.
2.3 Data Collection

Calibration measurements are taken before and after each series of orbital debris (OD) observations. The calibration process includes RCS magnitude and beam pattern measurements using orbiting calibration objects of known RCS. First, the radar tracks the calibration objects on its orbit using Wave Form Code (WFC)-10, which is a narrow band chirp. To evaluate the beam pattern, the beam then spirals about the estimated object trajectory while obtaining an RCS measurement employing WFC-1, a CW waveform. It then returns to tracking (WFC-10). The waveform designated as WFC-1 is similar to the OD measurement mode (WFC-4). WFC-1 sampling comprises three range gates, each with 2048 Doppler samples with 50% overlap, which are concatenated into one range gate of 4096 samples during processing.

The radar’s primary operational waveform for debris data collection, WFC-4, is a CW waveform and has a receive window of 12.1264 ms, which is sampled by 16 overlapping range gates (see Figure 2-1). Each gate is converted to the frequency domain with 2048 Doppler samples. The gates have an overlap of 874 samples. When a range gate is determined to contain a detection, it is concatenated with the two adjacent gates. Then the result is converted back to the frequency domain to perform matched filter detection, which produces the detected range and the signal amplitude.

Figure 2-1. Debris observations waveform characteristics (used with permission of MIT LL).
The principal operating parameters for the Haystack and HAX radars during debris measurements (using waveform WFC-4) are shown in Table 2-1. This waveform was introduced in FY2003 for both Haystack and HAX. It increases the pulse duration and energy on targets by 60% as compared to the waveforms used in prior years. With WFC-4, the nominal sensitivity, which is determined as a single pulse signal-to-noise ratio (SNR) from a target with RCS = 1 m² at 1000 km, is 59.2 dB and 40.56 dB for Haystack and HAX, respectively. With Haystack, objects smaller than 1 cm diameter can be observed in LEO.

Table 2-1. Radar Debris Mode Operating Parameters

<table>
<thead>
<tr>
<th>Operating Parameter</th>
<th>Haystack</th>
<th>HAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power (kW)</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>Transmitter frequency (GHz)</td>
<td>10.0</td>
<td>16.7</td>
</tr>
<tr>
<td>Transmitter wavelength (cm)</td>
<td>3.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Antenna diameter (m)</td>
<td>36.6</td>
<td>12.2</td>
</tr>
<tr>
<td>Antenna beam width (deg)</td>
<td>0.058</td>
<td>0.10</td>
</tr>
<tr>
<td>Antenna gain (dB)</td>
<td>67.23</td>
<td>63.64</td>
</tr>
<tr>
<td>System temperature (K)</td>
<td>186</td>
<td>161</td>
</tr>
<tr>
<td>Total system losses (dB)</td>
<td>3.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Waveform code</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Range gates</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Intermediate frequency bandwidth (KHz)</td>
<td>1250</td>
<td>1250</td>
</tr>
<tr>
<td>Independent range/Doppler samples</td>
<td>15158</td>
<td>15158</td>
</tr>
<tr>
<td>FFT size</td>
<td>2048</td>
<td>2048</td>
</tr>
<tr>
<td>Number of non-coherent integrated pulses used for detection</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Pulse width (msec)</td>
<td>1.6384</td>
<td>1.6384</td>
</tr>
<tr>
<td>Receive window (msec)</td>
<td>12.1264</td>
<td>12.1264</td>
</tr>
<tr>
<td>Pulse repetition frequency (Hz)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Single pulse SNR on 0 dBsm target at 10³ km (dB)</td>
<td>59.2</td>
<td>40.6</td>
</tr>
<tr>
<td>Average power (kW)</td>
<td>24.6</td>
<td>4.9</td>
</tr>
<tr>
<td>Doppler extent (km/second)</td>
<td>± 7.5</td>
<td>±4.5</td>
</tr>
</tbody>
</table>
For debris observations, both radars operate in a staring mode with the antenna pointed at a specified elevation and azimuth while debris objects randomly pass through the field of view. Antenna elevations of 75°, with an azimuth of 90° (east-looking), and elevations of 20° and 10° with azimuth of 180° (south-looking), were used for debris observations. The staring operational mode provides a fixed detection volume for the measurement of the debris flux, which is defined as the number of objects detected per unit area, per unit time. By operating the radar in a staring mode, a precise measurement of the object’s orbit cannot be obtained. However, by processing signals from the monopulse angle channels, the object’s position while passing through the radar beam can be determined for each pulse. Subsequently, from the sequence of pulse positions, the object’s path through the beam can be estimated. Then the orbital parameters can be derived from this path. However, it has been determined that for detections with small SNR (less than around 10 dB), the derived orbital parameters are not reliable, and that range/range rate analysis is preferable in this case.

2.4 Real-Time Processing

Both Haystack and HAX implement monopulse acquisition and processing techniques; hence, the radar antennae focal plane feeds use a multi-flared horn design, operating as an amplitude-sensing monopulse four-horn feed. The radars transmit right-hand circular polarization and receive both right- and left-hand circular polarization. As the signal returned from conducting calibration spheres is primarily left-handed, this polarization is termed principal polarization (PP), and the right-handed polarization return is named the orthogonal polarization (OP). For monopulse processing, the PP channel is fed by the sum of the left-handed circular, polarized signal received from all four horns; the OP channel is fed by the sum of the orthogonal right-handed circular polarized signals. The traverse (also referred to as azimuth [AZ]) sensing channel is fed by the difference of the horizontally located horns normalized to the PP sum; and the elevation (EL) sensing channel is fed by the difference of the vertically located horns normalized to the PP sum. Both the AZ and EL channels use only the PP signal. For these channels, data are converted into traverse and elevation angle offsets relative to the antenna boresight for each return pulse, which is subsequently used to generate the object’s path through the main lobe. The OP traverse difference and OP elevation difference channels are not available.

The Processing and Control System (PACS) at the MIT LL has been programmed to record data in a buffer, where only a sequence of pulses is saved when the integrated signal exceeds a predetermined threshold above the system estimated noise (detection event). In this way, many hours of debris observation can be performed without using an impractical amount of the recording medium. The OD data recorded by PACS are delivered to the ODPO on high-density, 8-mm magnetic tapes in calibrated Long Range Imaging Radar (LRIR)/HAX data tape (CLDT) format. Using Orbital Debris Analysis Software (ODAS), the ODPO can choose a different threshold for data processing, higher than that used by the MIT LL PACS.
Each of the four (PP, OP, AZ, and EL) amplified signals centered at 10 GHz are mixed with a 6-GHz CW signal to produce a signal centered at 4 GHz. After a series of down-conversions, the resulting signal is sampled with a 12-bit analog-to-digital converter at a 1.25-MHz rate (corresponding to the 0.8-μs timespan between the 15,158 independent samples, per pulse).

Further processing develops digital in-phase (I) and quadrature-phase (Q) signals that are correctly balanced. The I and Q samples are fast Fourier transform (FFT) to the frequency domain (2048 samples per gate, with 874 samples overlapping between adjacent gates). Complex FFT data for each channel are sent to a memory buffer containing data for the previous 12 to 20 pulses. To minimize the archiving of data with no detections, a non-coherent integration (NCI) 16-pulse running sum of the PP sum channel data is performed. Only when a threshold is exceeded are the spectral data for all four channels permanently recorded to tape. The initial recording threshold is intentionally set lower than allowed in subsequent processing to ensure that no usable data are missed (currently around 5.0 dB in comparison to a 5.45-dB threshold maintained by ODAS). A significant number of pulses, before and after the declared detection event, are also recorded to ensure that no useful data are missed. The MIT LL then sends the ODPO the digitized-frequency domain data, which are recorded in the CLDT format.

Figure 2-2. Haystack and HAX debris signal processing by PACS.

The digital pulse compression subsystem is abbreviated as DPCS in the figure. Match-filtering, non-coherent integration, and detection are performed by the real-time processing software (used with permission of MIT LL).
3.0 Data Collection Summary

3.1 Haystack

Most of the OD data were collected at 75° elevation, 90° azimuth. Objects detected in this configuration are in orbits with inclinations that are at or larger than the latitude of the radar and its complement. The 15° offset from vertical provides enough Doppler discrimination to estimate some of the orbital parameters. During the timespan of this report, Haystack began collecting data at 180° azimuth with staring elevations of 20° and 10° to detect objects in lower inclination orbits. The increased slant range for a given altitude reduces the ability to detect small objects.

Table 3-1 presents the number of OD observation hours at 75°-, 20°-, and 10°-elevations and the number of detections collected for each Haystack antenna elevation angle throughout the reported time period. The “Other” column reflects observation hours and detections collected at specially requested azimuths and elevations (for specific breakup event follow-ups). All detections contained in the table are above the threshold of integrated SNR (> 5.45 dB), which ensures less than a 10^-9 probability of false alarm and a 0.38 false alarm rate per hour; the corrected pulses are all inside the 3-dB region of the transmitted signal.

For 75° elevation, east-looking measurements were conducted with a minimum altitude of 302.6 km and a maximum altitude of 1837.2 km, which corresponds to ranges from 312.4 km to 1885.4 km during FY2006. However, for FY2007 through FY2010, the minimum altitude was 401.5 km and the maximum altitude was 1937.4 km, which corresponds to ranges from 414.5 km to 1885.4 km.

For 20° elevation, south-looking measurements were conducted with a minimum altitude of 333 km and a maximum altitude of 1178 km, which correspond to ranges from 834 km to 2407 km. For 10° elevation, south-looking measurements were conducted with a minimum altitude of 337 km and a maximum altitude of 1046 km, which corresponds to ranges from 1250 km to 2827 km.

Table 3-1. Haystack Data Collection Hours and Number of Detections

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>75° East</th>
<th>20° South</th>
<th>10° South</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hours of Observation</td>
<td>Number of Detections</td>
<td>Hours of Observation</td>
<td>Number of Detections</td>
</tr>
<tr>
<td>2006</td>
<td>350.3</td>
<td>3304</td>
<td>157.9</td>
<td>1210</td>
</tr>
<tr>
<td>2007</td>
<td>401.0</td>
<td>4249</td>
<td>151.5</td>
<td>1261</td>
</tr>
<tr>
<td>2008</td>
<td>332.2</td>
<td>5272</td>
<td>201.1</td>
<td>2108</td>
</tr>
<tr>
<td>2009</td>
<td>547.0</td>
<td>6959</td>
<td>76.8</td>
<td>916</td>
</tr>
<tr>
<td>2010</td>
<td>657.0</td>
<td>6368</td>
<td>0.0</td>
<td>NA</td>
</tr>
</tbody>
</table>
3.2. HAX

During FY2004 through FY2012, HAX collected data at 75° east, with the exception of several hours devoted to special observations of debris clouds after breakup events (1.7 hours in FY2007 and 3.62 hours in FY2009). Table 3-2 shows the hours of observation and all detection event totals sorted by fiscal year. Included detections are above the threshold (integrated SNR > 5.45 dB) and inside the 3-dB zone. All measurements were conducted with a minimum altitude of 301.5 km and a maximum altitude of 1834.4 km, which corresponds to ranges from 311.7 km to 1884.7 km.

Table 3-2. HAX Data Summary for 75° Elevation, East Pointing

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Hours of Observation</th>
<th>Number of Detections</th>
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</thead>
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<tr>
<td>2006</td>
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<td>819</td>
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<tr>
<td>2007</td>
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</tr>
<tr>
<td>2011</td>
<td>717.4</td>
<td>1512</td>
</tr>
<tr>
<td>2012</td>
<td>1011.2</td>
<td>1734</td>
</tr>
</tbody>
</table>
4.0 Data Reduction Procedures

4.1 Calibration

Phase correction and calibration procedures are used to ensure reliable and consistent OD measurement results. Phase correction is achieved using averaged biases found over portions of the higher SNR debris measured data. Calibration of the beam is achieved in two steps, using orbiting calibration objects. Both processes are essential in ensuring the highest quality RCS measurements of unknown objects encountering the radar beam.

4.1.1 Phase Correction

Reliable angular offset measurements in the radar beam are obtained by ensuring proper monopulse amplitude processing. The complex voltage ratios, both traverse and elevation, should have an imaginary component of zero and hence a phase difference close to 0° or 180° to ensure correct amplitude comparison of the monopulse signals. Any deviation due to hardware or noisy signal issues may cause erroneous elevation or traverse voltage ratio magnitudes leading to wrong angular offsets. Therefore, phase differences for each channel for high-enough SNR detections (more than 12 dB) from each dataset are examined and phase corrections are manually introduced to the relevant dataset to cancel out the derived offset.

4.1.2 Radar Cross-Section Measurement Bias

The absolute RCS calibration bias, obtained from observations derived from an ensemble of calibration satellites, is the product of work performed by MIT LL during observation runs. These spacecraft, some hollow metallic spheres in LEO, some larger spacecraft of more complex structure in geosynchronous orbit (GEO), provide the basis for determining the apparent system bias of the radar, which results in an absolute difference in measured RCS. The LEO objects are in the geometrical optical scattering region for both Haystack and HAX; GEO objects behave as point sources.

Each radar measures the RCS of the calibration object to calculate a "system sensitivity constant," used to maintain the system calibration. If the measured constant drifts sufficiently from the accepted value, it is adjusted (this ΔRCS is provided by MIT LL as auxiliary data to each dataset). The revised value is typically the average of the measured values from the past several days. The data tapes recorded at the Haystack facility contain only the averaged constant.
4.1.3 Beam Pattern Measurement

As introduced in Section 2.3, current operating guidelines require that the calibration measurements be taken before and after each series of observations to ensure reliable and consistent results. A list of satellites of sufficient measurement quality used for calibration over seven report years is presented in Figure 4-1.

![Figure 4-1. Historical acquisition of satellites used for calibration by Haystack and HAX radars.](image)

The pre- and post-data collection calibration procedure consists of three parts: (1) the radar tracks the calibration object, or “object track” mode; (2) the radar conducts a spiral scan around the calibration object’s propagated position; and (3) object track (Figures 4-2 and 4-3). The first and third parts assure track quality, whereas the second part is performed to obtain beam-pattern calibration data.
During the spiral scan, the antenna motion is such that the relative location of the calibration object appears to be a “spiral” about the beam center. The result is a pattern of observations that cover the 3-dB portion of the beam sufficient for the calibration of OD RCS measurements.

The LEO calibration satellites are metallic spheres of known size, material, and surface properties; hence, the return signal is primarily PP. A limitation in the calibration process is that the OP channel cannot be truly calibrated. The data reduction procedure used to generate this report assumes a calibration pattern identical to PP for the OP observations. On a regular basis, the OP channel is internally calibrated by injecting known test signals in both channels and measuring the results.

Each data point corresponds to one radar pulse.
Gain across the radar beam, or beam shape, must be mapped in order to perform corrections to RCS measurements taken away from the center of beam, since only a measurement at the maximum gain would be free of beam pattern loss. The monopulse feature of both radars enables detected pulse angle offsets from the center of beam to be measured. These measurements yield the position in beam of each pulse, which provides the information necessary to correct the measured RCS for the transmitted beam power loss off-boresight.

The beam pattern is measured by scanning around the location of the calibration object during the second, spiral stage of the antenna motion (Figure 4-4). The spiral motion of the Haystack antenna around the calibration satellite in terms of traverse (azimuth) and elevation angle offsets is shown in the left-hand chart, where each data point corresponds to the antenna boresight offset from the satellite at the pulse time on target. Corresponding voltage ratios are presented in the right-hand chart, where the spiral is not clearly visible due to system noise. Each data point here represents one pulse. For a correct object path through the beam, it is important to achieve reliable measurements of the traverse and elevation angle offsets; therefore, the beam shape model should be updated and reliable from observation period to observation period. Thus, it is always necessary to have calibrations performed as close as possible to observing times.

![Figure 4-4. Elevation versus traverse angle offsets in degrees (left) and the corresponding voltage ratios (right), from the same calibration as in Figure 4-2. Each data point represents one radar pulse.](image)

Two models are used for the beam pattern characterization, which are applied using the results of the spiral scan measurements. The first connects the target angle offsets from the boresight with the acquired elevation and traverse voltage ratios (Figure 4-5). This model uses third order polynomials to connect the actual elevation and traverse offsets with the voltage ratios. If mechanical and electrical construction of the radar
were perfect, the expected voltage ratio-to-angle offset mapping functions would be linear; also, elevation angle would depend only on elevation voltage ratio, whereas traverse angle would depend only on the traverse voltage ratio. However, due to various conditions that affect the radar (such as weather, thermal, or electrical instabilities), this is not the case. Therefore, the elevation and traverse offsets each depend on both elevation and traverse voltage ratios.

Figure 4-5. Elevation angle offset versus voltage ratio; the solid line represents the elevation fit third order polynomial.

The second calibration model used for beam characterization describes the return signal loss versus both angle offsets, in comparison to the maximum gain (which should be very close to the boresight) by a second order polynomial versus elevation and traverse angles (Figure 4-6). This model fits a paraboloid to the spiral scan measurements; however, only returns from inside the 3-dB region for transmitted energy (which corresponds to a maximum 6-dB loss for the received return in comparison to the beam center) are taken into account by ODAS to estimate trajectories and to calculate the corrected RCS of measured objects. The coefficients of the paraboloid derived from the calibration procedure are used for both the PP and OP RCS correction procedure.
Figure 4-6. An example of a calibration model paraboloid created from the same calibration spiral scan as shown in Figs. 4.3-4.5. Note that some points lie on the interior of the best fit paraboloid and therefore are not visible here.

4.2 NASA Size Estimation Model

The NASA SEM, which was developed to relate RCS to the physical size of a debris fragment on orbit, is now in general use by the OD and space situational awareness communities. Size (or diameter) refers to the characteristic length of an object, which is defined as the average of the largest dimensions for an object measured along three orthogonal axes. The first axis coincides with the largest dimension, the second axis coincides with the largest dimension in a plane orthogonal to the first axis, and the third axis is orthogonal to the first two axes.

By using Maxwell’s equations, electromagnetic (EM) waves scattered by an object can be compared for different wavelengths by normalizing the object’s size by the wavelength and its total RCS by the wavelength squared. This results in two scalable parameters: $x = \text{size}/\lambda$ and $z = \text{RCS}/\lambda^2$, where $\lambda$ is the wavelength of the EM wave.

The scaling curve (seen as a smooth solid line in Figure 4.7) is derived from the RCS measurements of debris objects over four radar frequency bands at a controlled RCS radar range. The oscillating line represents the computed RCS of a spherical conductor for comparison. For debris sizes much smaller or larger than the radar wavelength, the scaling curve approaches the Rayleigh or geometrical optics region curves, as expected. Between the Rayleigh and optics scattering regions lies the Mie resonance region. These oscillations in the Mie resonance region result from the constructive and destructive interference of induced EM waves on the surface of a conducting sphere or target object.
Figure 4-7. NASA SEM model polynomial fit (smooth curve) is plotted as a function of scaling parameters \( x \) and \( z \), while the oscillating line is the RCS for a spherical conductor. Results of RCS measurements on 39 representative debris objects over the frequency range 2.0–18 GHz (15–1.67-cm wavelength) are shown by points, where each point represents an average RCS over many orientations for a single object measured at a single frequency.

The three types of scattering regions of the scaling curve in Figure 4-7 may be expressed as:

\[
\frac{4z}{\pi}, \text{ for } z > 5, \text{ Optical Region;}
\]

\[
\frac{4z}{9\pi^5}, \text{ for } z < 0.03, \text{ Rayleigh Region;}
\]

\[x = g(z), \text{ for } 0.03 < z < 5, \text{ a piecewise continuous approximation function in the Mie Resonance Region.}\]

Note that the NASA SEM is a simple model for one-to-one RCS-to-size mapping and does not provide an uncertainty estimate for the derived size distribution, nor does it take into account the specific distribution of RCS values for a given size or specific materials.

4.3 Orbital Debris Analysis Software Processing

Radar data provided to the ODPO by MIT LL are associated with four channels: the PP and OP sum channels, and the traverse and elevation difference channels. The PP and OP sum channel data are used to acquire a detected object’s parameters and the difference channel data (normalized by the PP sum channel) are employed for target angle offset from the boresight estimation. Each complete data record corresponding to a single transmitted pulse is comprised of these four channels. For each channel, the complex signature data contains a two-dimensional matrix with range (or time) along
one dimension (in terms of the range gate identification), and 2048 frequency domain (or range rate) data cells along the other dimension.

The ODAS, as well as real-time processing (RTP) of PACS, non-coherently averages 16 consecutive pulse amplitudes for each range/Doppler cell to compute integrated SNR. After comparison with the given threshold, it can trigger a detection event (hereafter referred to as “detection”) that represents a possible beam transit. The detection is considered terminated when a given time gap is exceeded between two successively read pulses (i.e., above the threshold). The detection data also contain extra pulses, which are noise, leading and trailing the detection pulses in time.

To compute a consistent SNR, it is important to estimate the correct noise floor magnitude. This is performed by averaging amplitudes of 16 pulses (in each range/Doppler cell) before the detection triggering pulse. A fading memory filter is used to: (a) predict the noise floor value that is used for NCI SNR calculation and (b) provide a smoothed noise floor for use in determining each pulse’s SNR of a detection event. Additionally, the noise floor across the Doppler span of each range gate is corrected with the help of a shape factor file, which is designed to normalize uneven noise power due to hardware or software issues. This method of real-time noise power estimation can be referred to a known technique of clutter removal using the Constant False Alarm Rate (CFAR) algorithm.4-6

Measurements that relate range and range-rate are addressed by ODAS Range/Doppler Processing, which implements the match-filtering technique to compute detection ranges. It uses the Doppler domain data from the range-gate, which triggered the detection, concatenates it with two adjacent range gates in the time domain, and then compares it to the transmit pulse after conversion to the frequency domain. The computed range, range gate, Doppler cell, SNR, phase, complex traverse, and elevation voltage ratios for each pulse are saved in the ODAS database for subsequent processing, detection validation, and analysis.

To correct the pulse RCS measurements, it is necessary to calibrate them according to the known beam gain pattern, as well as determine the observed path through the beam. Because the monopulse angles are measured from pulse voltage ratios that have a range of uncertainties, it becomes necessary to estimate statistically the trajectory of an object through the beam. This is accomplished using a method of statistical evaluation of the measured pulse ratios. Each measurement, along with computed uncertainties, is transformed into associated beam angle offset form, as illustrated in Figure 4-8 by the scattered data points in traverse and elevation coordinates. It is assumed that an orbiting object passing through the beam will take a straight line path, thus the task of fitting a straight line to them is attempted.

Initially, the fitting process takes the data point with the highest SNR, along with two others closest in time. It then progressively adds neighboring measurements, in terms of pulse time, while computing goodness-of-fit statistics with each addition. The purpose of the procedure is to expand the available fitted points to include only those that are believed to be consistent with a transit through the main lobe. The data that pass the goodness-of-fit test, and are determined to be statistically inside the main lobe, are then fitted as a first order function of time. Weighted traverse and elevation residuals are then calculated.
The final step is to compute Beta statistics as functions of the mean and variance of the weighted residuals. The residuals are compared to the Beta statistics; if they pass this test, then new pulses are added. The pulses that fail this test are removed and the remaining pulses are used for the fit. The earliest point in time is marked as the start of beam transit of the object, and each measured monopulse value in this subset is given a traverse and elevation bias to place the measurement in-line with the fitted path. These new values of pulse positions are now used to compute RCS corrections, which are subsequently used to calculate the detection average PP and OP RCS. Note that only pulses with corrected positions inside the 3-dB region of the beam are used for average RCS estimation.

![Polar plot with an example of beam path estimate for Haystack detection. The 3-dB region ellipse is shown along with the uncorrected monopulse position of the pulses (blue dots) and corrected positions (red dots). Only pulses marked by large red dots are used for the statistical evaluation of the straight path through the beam. Note that the red dot farthest to the right is outside of the 3-dB region and, therefore, RCS of this pulse will not be used for the average RCS calculation.](image)
Once the path is determined, the RCS measurements of the PP and OP channels are scaled up to counteract the effects of off-boresight measurements, based on location on the path and the beam pattern derived from the calibration routine. The RCS scale factors are limited to the 3-dB region of the transmitted signal. With the beam position effects gone, the PP and OP RCS of the accepted pulses are averaged, and the RCS measurement bias is applied, resulting in the final calibrated average RCS measurements from the PP and OP channels. The total average RCS (in square meters) is then calculated as

\[
\text{RCS}_{m^2} = \text{PPRCS}_{m^2} + \text{OPRCS}_{m^2}
\]  

(4.2)

Size estimation of the object is then performed using the NASA SEM. Finally, ODAS compares the detection state vector with the SSN catalog of resident space objects (RSOs). For a given RSO, orbital elements are propagated from its pre-detection epoch time to the detection time (RSOs with epoch times greater than 30 days old are excluded). If a correlation is found, the SSN number is attached to the detection data.

4.4 Noise Floor and Radar Sensitivity

For the Haystack and HAX performance evaluation, first consider the radar equation:

\[
\text{SNR} = \frac{P_t G_t G_r \lambda^2 E_n}{(4\pi)^3 k T B F L R^4} \sigma
\]  

(4.3)

where SNR is measured at the antenna terminal, \(P_t\) is the peak transmit power (W), \(G_t\) is transmit antenna gain on axis, \(G_r\) is receive antenna gain on axis, \(\lambda\) is transmitter wavelength (m), \(E_n\) is pulse integration efficiency factor, \(\sigma\) is target RCS (m\(^2\)), \(k\) is Boltzmann’s constant (J/K), \(T\) is the system temperature (K), \(B\) is bandwidth (Hz), \(F\) is a noise figure (the receiver’s figure of merit), \(L\) is total system losses, and \(R\) is antenna to target range (m).

Figure 4-9 illustrates the Haystack SNR for different RCS magnitudes resulting from the transmitted peak power of 250 kW. Note that an SNR below 5 dB is not useful due to noise interference. However, during the 7-year period covered in this report, the parameter \(P_t\) deviated from that given in Table 2-1. Thus, for Haystack’s transmitted peak power figures (as provided by MIT LL), maximum peak power was 265.9 kW on 28 August 2006 and minimum peak power was 25.8 kW on 6 April 2010. For HAX, maximum peak power was 75.4 kW on 11 August 2009 and minimum peak power was 19.6 kW on 2 February 2010.
It is widely accepted that a radar sensitivity is measured in terms of SNR on its antenna terminal returned from a 1.0 m$^2$ RCS target at a range of 1000 km (in dB units):

$$\text{SNR}_{1000 \text{ km}} = \text{RCS}_{1m}^2 (= 0 \text{ dBsm}) - \sigma_{\text{Noise}} \ (\text{Range}=1000, \text{Dataset}) \ [\text{dBsm}] \ (4.4)$$

Within standard conditions, Haystack and HAX have sensitivities of 59.2 dB and 40.56 dB, respectively. However, because there are noticeable variations of power on a daily basis, it is necessary to know the radar sensitivity for a given set of measurement data. This equation makes it possible to infer a reliable estimate of the probability of detection for this dataset.

As SNR, by definition, is the ratio of the target returned power to the noise power, it can be interpreted as the target RCS ratio to the noise-equivalent RCS for this range. Therefore, the noise floor of a dataset is estimated statistically by applying the SNR definition to the noise itself, defining the “noise equivalent” RCS as the achieved RCS for SNR = 1. This means analyzing pulse measurements taken outside the observation of an object, as any signal other than a target return, is considered noise. The noise level (or noise equivalent RCS magnitude) of an event is calculated by averaging magnitudes of all pulses that are not qualified as signal pulses (with SNR below the threshold).
Plots showing the mean sensitivity estimation for consecutive Haystack tapes from FY2007 and FY2009 are shown in Figures 4-10 and 4-11. In FY2007, Haystack experienced a loss of sensitivity due to loss of transmit power (Figure 4-10), which occurred in May 2007 (tape designated as #18 in Fig. 4.10). Therefore, in Table 4-1, where the data by fiscal years are summarized, results before this loss (from 1 October 2006 to 3 May 2007) are labeled as 2007a and after the loss (from 4 May 2007 to 30 September 2007) as 2007b. Furthermore, a significant loss of sensitivity occurred in March 2009 and then a major drop in May 2009.

In March 2009, Haystack lost one of four microwave transmitter power traveling wave tubes (TWTs). To achieve symmetrical power generation, the transmitter operated with two tubes rather than three. Consequently, transmission power fell from the regular 240 kW to 120 kW. The following May, another TWT became defective, dropping the power to 31 kW. These events correspond to a loss of sensitivity around 3 dB seen in Figure 4-11 (from tape numbers 3 to 4), and the larger drop between datasets 9 and 10 (which belong to one tape). Therefore, in Table 4-1, the sensitivity data before this drop (from 1 October 2008 to 18 April 2009) is labeled as 2009a and after the drop (from 19 April 2009 to 30 September 2009) as 2009b.
Figure 4-11. Haystack sensitivity (PP SNR for 1 m² object at 1000 km), averaged over events contained on each tape for FY2009. Abscissa represents consecutive tape data. Vertical brackets show 95% confidence intervals.

Table 4-1. Haystack Historic Sensitivity Data Averaged by Fiscal Years

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>SNR of 1 m² target at 1000 km, dB</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Weighted Mean</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>56.9</td>
<td>60.3</td>
<td>59.2</td>
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<td>2010</td>
<td>50.0</td>
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</table>

HAX mean sensitivity calculation results for FY2006 and FY2011 through FY2012 are presented in Figures 4-12 and 4-13. The drastic drop of HAX sensitivity that happened in FY2011 (see dip at tape #12 in Figure 4-13) was caused by the transmitter TWT tube loss. Although the transmitting power was restored by replacing the faulty TWT, the replacement tube could not achieve the operational performance of the
Mean sensitivity values for HAX, summarized by fiscal years, are presented in Table 4-2.

Figure 4-12. HAX sensitivity averaged over events contained by each tape for FY2006. Abscissa represents consecutive tapes. Vertical brackets show 95% confidence intervals.

Figure 4-13. HAX sensitivity averaged over events contained by each tape for FY2011 and FY2012. Abscissa represents consecutive tapes. Vertical brackets show 95% confidence intervals.
Table 4-2. HAX Historic Sensitivity Data, Averaged by Fiscal Year

<table>
<thead>
<tr>
<th>FY</th>
<th>SNR, dB</th>
<th></th>
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<td>Min</td>
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<td>Weighted Mean</td>
</tr>
<tr>
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<td>----------------</td>
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<td>2008</td>
<td>38.1</td>
<td>40.0</td>
<td>39.3</td>
</tr>
<tr>
<td>2009</td>
<td>38.2</td>
<td>40.2</td>
<td>39.5</td>
</tr>
<tr>
<td>2010</td>
<td>37.2</td>
<td>40.1</td>
<td>39.0</td>
</tr>
<tr>
<td>2011</td>
<td>37.7</td>
<td>40.6</td>
<td>39.4</td>
</tr>
<tr>
<td>2012</td>
<td>37.1</td>
<td>38.5</td>
<td>37.6</td>
</tr>
</tbody>
</table>

Variations of sensitivity significantly influence the probability of detection for small OD (of less than 1 cm size for Haystack and less than 3 cm for HAX). Calculating probability of detection as a function of SNR at a given probability of false alarm \( P_{fa} \) is a well-established procedure in radar signal processing that is widely described in the literature.\(^4\)\(^-\)\(^7\) The false alarm probability of \( P_{fa} = 10^{-9} \) is routinely used by MIT/LL for Haystack and HAX operations during routine observations.

For evaluating the SNR of a detection, the sensitivity value for the specific dataset to which this detection belongs was estimated by transforming it to a standard detection range of 1000 km:

\[
\text{SNR}_{\text{Target}}(R) = \frac{\sigma_{\text{Target}}(R)}{\sigma_{\text{Noise}}(R)} = \frac{\sigma_{\text{Target}}(R)}{\sigma_{\text{Noise}(1000\text{km}, \text{dataset})}} \left( \frac{1000\text{km}}{R} \right)^4
\]  

(4.5)

Here \( \sigma_{\text{Target}} \) is an average of the corrected PP RCS including only pulses inside the 3-dB region of the beam. The SNR (1000 km, dataset) is the sensitivity of the dataset that contains this particular event.

Figure 4-14 relates theoretical Haystack and HAX SNR measurements for a 1-cm characteristic size (due to SEM) object versus range with different values of radar sensitivity. Data shown is for optimal (FY2007a) and reduced (FY2009b) Haystack sensitivities, along with optimal (FY2007) and reduced (FY2012) HAX sensitivities during the time period covered in this report.
4.5 Noise Equivalent Radar Cross-Section

Detection performance of a radar depends on the amplitude of return signal relative to that of the noise (as determined from SNR) and the detection threshold settings. That is why it is important to estimate noise and its variations over time. This variability is especially important when estimating the debris environment, to be certain that variation in the detection rate of objects of a given size at a given altitude is the consequence of a change in the environment and not the result of variation in signal gain or loss. Here we present estimation of the noise level dependence on altitude, which defines a minimum object size (in terms of its RCS) that is likely to be detected by the radar during a given fiscal year.

The effects of signal loss in the measurement process, including internal radar losses, the atmosphere, and equipment power levels, result in a composite loss term with respect to altitude. The PP channel noise equivalent RCS was measured for each detection and the results grouped by time period and radar. These groupings were then fitted over the observable range to determine a range-dependent RCS equivalent of noise and losses, or :math:`\text{RCS}_{\text{noise_eq_avgPP}}`.

The result of this work is a reference by altitude and fiscal year of the threshold at which the PP channel RCS measurements are equivalent to the average noise, which are presented in Figures 4-15 and 4-16 for all pertinent time periods. Note that the variability in Haystack sensitivity is visible in Figure 4-15, as compared to the relatively stable HAX performance over the same time periods. The average performance of the radar at a given time within the periods presented in each figure can vary considerably.

This analysis is important for two reasons: (1) each radar triggers on a detection by monitoring the SNR of the PP channel alone, and (2) the collection of measurements has an implied minimum size attributed to it by the condition of the radar and
environment at the time of observation. This reference criterion is not intended to represent the minimum size detectable, but it is intended to provide the reader with a reference from which to infer the population size measured. In the process of analysis of the measured data, it is useful to infer from the NASA SEM the noise equivalent-derived characteristic size. This is convenient to illustrate a reasonable estimation of the size threshold, and is accomplished by the same method as with debris size estimation, where the total noise equivalent RCS is given by:

\[
\text{RCS}_{\text{noise_eq_avg}} = \text{RCS}_{\text{noise_eq_avg_PP}} + \text{RCS}_{\text{noise_eq_avg_OP}}
\]  

(4.6)

These will be presented in concert with the altitude-dependent flux in a later section.

Figure 4-15. \(\text{RCS}_{\text{noise_eq_avg_PP}}\) for Haystack Radar at 75° east-pointing from FY2006 to FY2012.

Figure 4-16. \(\text{RCS}_{\text{noise_eq_avg_PP}}\) for HAX Radar at 75° east-pointing from FY2006 to FY2012.
5.0 Data Validation

The Haystack and HAX radar data have been examined thoroughly to ensure the quality and reliability of the reported results. Data gathered during more than 20 years of operation are collected in the database, which is regularly audited, scanned for faulty data cells, and updated or corrected as necessary.

5.1 Detection Validation and Threshold

A manual data review was performed by using a custom graphical user interface (GUI) that displays the ODAS polar detection plot, and PP and OP SNR for each pulse of the pulse train. The GUI also displays the uncorrected and corrected PP and OP RCS, elevation and traverse voltage ratios, and phase differences. The displayed information provides an opportunity to qualify the event as a valid detection or reject it using one of the following criteria: (1) the integrated SNR is below the noise threshold, (2) the path is outside the 3-dB region, (3) it is a side-lobe detection, (4) there is a noise spike in a pulse (possibly due to a hardware failure), (5) there are unacceptable phase differences between pulses, or (6) the measured range exceeds the limit for reliable data. Recently, a new automated classification software tool was developed that can reject detections below the desired integrated SNR threshold and detections that are outside of the 3-dB beam width. It can also flag detections that produce possibly unreliable orbital parameters. All of the data presented in this report use the automated classification scheme.

The detection threshold is set low enough to ensure a high probability of detection and high enough to maintain a low probability of false alarm.\textsuperscript{3-6} This threshold is applied to the computed non-coherently integrated SNR for a set of 16 consecutive pulses. The probability of a false alarm is set by the MIT LL-developed algorithm to $10^{-9}$ during radar data acquisition and RTP pre-processing. The original detection threshold for 16 NCI pulses was set for an SNR = 5.168 dB; this corresponds to 4.72 false alarms per hour.\textsuperscript{7,8}

For this low threshold, a large number of false alarms were expected. Based on a thorough analysis of correlating debris sizes with SNR values, the NASA ODPO concluded that a threshold of 5.45 dB would not reduce the Haystack radar’s capability to detect debris less than 1 cm, or the HAX radar’s capability to detect debris less than 4 cm, but it would eliminate almost all detections containing only noise. Therefore, the 5.45 dB value was used for ODAS processing of all FY2006 – FY2012 data. This threshold produces about 0.38 false alarms per hour, which is sufficient to ensure the required detection sensitivity. On average, Haystack yields approximately nine valid detections per hour, and HAX yields three valid detections per hour.
5.2 Sodium-Potassium Population Measurements

Haystack and HAX radar detection data produces PP and OP polarization components. The polarization parameter is defined as:

$$P = \frac{\text{RCS}_{PP} - \text{RCS}_{OP}}{\text{RCS}_{PP} + \text{RCS}_{OP}}$$ (5.1)

An object with $P$ near +1 indicates that its shape is close to spherical and it is highly conductive. Because the same noise level is assumed to be in both the PP and OP channels, the measured polarization ratio is unlikely to be an artifact of system noise.

In previous studies,$^9$-$^{11}$ highly polarized OD, with near 65° inclination and an altitude from 700-1000 km were identified as spherical, eutectic, Sodium-Potassium (NaK) nuclear reactor coolant droplets from ejected cores of the Soviet/Russian Radar Ocean Reconnaissance Satellites (RORSATs). In contrast, debris at other altitudes and inclinations show a wide distribution of polarization, an indication that they represent a large variety of debris shapes, which is consistent with the fragments generated in laboratory explosion and collision tests.

Debris objects with an altitude from 700–1000 km, with a Doppler inclination between 62° and 68°, and with a measured polarization parameter $P$ in excess of 0.84 are interpreted to be spherical NaK debris. These debris are unique since there are no new sources of NaK. Also, since no appreciable fraction of the debris is lost to reentry, and sublimation is a relatively slow process, the NaK population is highly stable. This stability is demonstrated by Haystack’s previous measurements from the 1994 to 2003 time period.$^{12}$

Figure 5-1 shows the cumulative NaK population for the reporting time period from FY2006 to FY2010 as a function of total RCS. The FY2008 NaK population had an apparent bias of approximately 2 dBsm compared to all other fiscal years examined. The source of this bias is unknown and under investigation, but for purposes of this report we introduce a + 2 dBsm bias to all Haystack FY2008 data, as shown in Figure 5-2.
The corrected cumulative NaK population plots in Figure 5-2 confirm that after applying the RCS bias correction to the FY2008 data, the NaK RCS distribution exhibits a very stable behavior in the -30 to -50 dBsm region. These RCS values correspond to a size distribution with a wide range of NaK droplets from 3.4 cm down to 0.5 cm. In estimating these sizes from the RCS data, we have applied the standard SEM, inverted to express characteristic size as a function of RCS. While this is technically incorrect, there is no way to invert the RCS distribution in the Mie region, due to its multi-valued nature for perfect conducting spheres (shown as a blue line in Fig. 4-7).

Note that count rate differences for sizes less than 0.5 cm (RCS < -50 dBsm) are explained by variations in Haystack’s probability of detection due to sensitivity loss, which was caused by a transmitter power failure in April 2009; this is reflected in the FY2010 curves. As a result, the overall debris detection rate in FY2010 was noticeably lower than for previous years.
Figure 5-2. Haystack cumulative NaK debris count rate for 75° elevation, corrected for RCS bias; east azimuth observations for FY2006 – FY2010.
6.0 Radar Measurements

For both the Haystack and HAX radars, the majority of observations are taken in a
fixed antenna configuration, also referred to as a staring mode. The favored orientation
is to point each radar due east (AZ = 90°) with an elevation angle of 75° from horizontal.
In this configuration, radar measurements of the debris environment are obtained in a
range from 426-1863 km. This corresponds to an altitude range of 400-1800 km.

This section provides only a brief introduction to the measurements obtained by the
Haystack and HAX radars. For a comprehensive presentation of the data across each
of the fiscal years covered in this report, please refer to the appendices. There, altitude
versus range rate, integrated SNR histograms, and altitude versus characteristic size
are presented for each radar and pointing direction. Appendices A and B contain
Haystack and HAX 75° east data, respectively. Appendix C includes data for Haystack
20° south and Appendix D includes data for Haystack 10° south.

6.1 Range/Range Rate Data

Objects that pass through the radar beam are detected by passing a set threshold in
the PP channel, and are measured in range from the radar, as well as the Doppler shift
of the returned transmitted radar signal. This measurement is better known as the
range rate, which relates the relative velocity of the object with respect to the measuring
radar.

6.1.1 Haystack Radar

A scatter plot of the range and range rate measured from the Haystack radar over
the FY2010 time period is shown in Figure 6-1. The data are plotted across a +/- 4 km/s
range rate and from 400-1800 km in altitude. Not all objects in orbit are in circular
orbits, but many are closer to circular than eccentric; therefore, the computed circular
orbit inclinations are overlaid in 10-degree increments for reference. Each inclination
overlay has two lines that intersect near the bottom of the chart. This represents the
ascending versus descending nodes of the circular orbit curves. As orbits become less
regularly circular, the range/range rate relationship becomes more complicated.

In terms of number of observations, it is useful to go beyond simple scatter plotting
techniques. Dense clusters of detections in this figure can obscure how many
detections are represented by the scatter-plotted points. Figure 6-2 portrays the density
detections in Figure 6-1, using a bin size of 0.1 km/s in range rate, and 100 km in
altitude. The count rate is illustrated using a color value, and is simply the number of
detections in each bin divided by the total number of observed hours for the fiscal year.
The four large peaks represent four of the most highly trafficked altitude/inclination
regions in LEO.
Figure 6-1. Altitude and range-rate observations for Haystack at 75° east-pointing over FY2010, with circular orbit, ascending and descending node, and constant-inclination lines superimposed.

Figure 6-2. Altitude versus range rate count rates during FY2010 for Haystack at 75° east-pointing. Constant inclination lines superimposed as in Figure 6-1.
6.1.2 HAX Radar

A scatter plot of the HAX altitude and range rate measured over the FY2012 time period is shown in Figure 6-3. When comparing Haystack and HAX data, a reduced number of detections is noticeable. This is due to the reduced sensitivity of HAX when compared to Haystack. Nevertheless, the data over the fiscal year shown in Figures 6-3 and 6-4 clearly show three of the four peaks Haystack records from 700-1000 km.

Figure 6-3. Altitude and range-rate observations over FY2012, for HAX at 75° east-pointing, with circular orbit, ascending and descending node; constant-inclination lines superimposed.
6.2 Signal-to-Noise Ratio Measurement

For each recorded detection, a value in both the PP and OP channels for SNR is obtained. For a detection event to be recorded, the PP channel integrated SNR must be greater or equal to 5.0 dB. The OP channel SNR is ignored. Because the radar triggers detections by the integrated SNR of the PP channel, this value is used to filter measurements for further analysis. Figure 6-5 shows the PP SNR values observed for all ranges over the FY2010 timeframe. A bin size of 0.05 dB was used for illustrative purposes, and to demonstrate the high amount of detections, particularly as the SNR goes below 6 dB.

Figure 6-5. PP channel integrated SNR during FY2010, for Haystack at 75° east-pointing.

HAX has a similar SNR profile, but with a much lower count rate. Figure 6-6 shows the PP SNR values observed for FY2012 at 75° east-pointing.
For the purposes of data analysis in this report, the minimum SNR threshold was set at a value of 5.45 dB. This eliminates a sufficient amount of suspected noise measurements, and yields a cleaner dataset from which to compare other fiscal years.

### 6.3 Radar Cross-Section Measurement

Once a detection is registered by the radar, the monopulse measurements are used to characterize details of the observation. The observations, along with the $\text{RCS}_{\text{noise_eq_avg}}$ curve for FY2010 by Haystack at the 75° east-pointing angle, are shown in Figure 6-7. Detections with a size greater than this curve represent sizes above the noise magnitude, whereas those to the left of the curve are a size that makes them much less likely to be detected. HAX observations from FY2012 are shown in Figure 6-8. The SEM uses total RCS to estimate characteristic size.
Using the NASA SEM, the total RCS is used to estimate the characteristic size of the object. Figure 6.9 depicts total RCS versus characteristic size for the FY2010 timeframe, with the Haystack radar pointed at 75° east. Comparison with the NASA SEM will show that size estimation is simply the total RCS applied to the SEM curve.
The OP and PP RCS observations provide polarization (refer to section 5.2), yielding clues to the shape of debris objects. Though no shape estimation model has been derived yet, basic physics implies that the closer observations tend toward the +1 value, the more spherical an object becomes. Figure 6-10 shows the polarization measurements obtained by the Haystack radar for FY2010 at 75° east-pointing. Of particular interest is the region from 700 km –1000 km, which is the NaK region. It is clear there are many sphere-like objects in this region.

Figure 6-10. Altitude versus polarization for observations during FY2010, Haystack radar at 75° east-pointing.
7.0 Environment Characterization

The radar data in this report present a snapshot of what was seen during each observational fiscal year. Quantities are presented as total cumulative flux rates, but must be tempered by the awareness of the radar sensitivities at observation time. Therefore, variations in flux from fiscal year to fiscal year must be further analyzed by the reader before environmental conclusions may be drawn.

As in Chapter 6, Chapter 7 is a primer to introduce the reader to the comprehensive data presented in the appendices. Flux estimates for both radars at 75° east pointing are available, with Haystack included in Appendix E and HAX included in Appendix F. Due to inadequate statistics, estimates of flux derived from Haystack 20° and 10° south-pointing data are not presented in this document.

7.1 Flux by Altitude

Flux is defined as the number of observations, divided by the product of the altitude bin surface area and number of hours observed during a given time period. Cumulative flux is the summation of detections for a given altitude range, summed from largest to the smallest observable characteristic size. The characteristic size in this report is based on the mean value obtained from the NASA SEM. While this yields a value of size, it does not capture the sample variation that contributed to the SEM derivation. Uncertainty estimation is necessary to analyze fully the characteristic size, and is outside the scope of this document. Instead, the size threshold discussed as $\text{RCS}_{\text{noise eq avg}}$ is provided as a reference. Each set of observations has a subset of detections with size estimates that fall below what is physically observable by Haystack or HAX.

The total cumulative flux, meaning flux for all observations regardless of characteristic size, for both radars at the 75° elevation east-pointing direction is presented in Tables 7-1 and 7-2. To understand the flux calculation, it is necessary to account for sensitivity across the entire observation range. Tables 7-3 and 7-4 present the minimum size threshold according to the $\text{RCS}_{\text{noise eq avg}}$ criteria. It is clear that for any given time period, the $\text{RCS}_{\text{noise eq avg}}$ size increases with altitude. Variation in $\text{RCS}_{\text{noise eq avg}}$ size between time periods is due to variations in the radar sensitivity.

By combining the information represented by total cumulative flux with that of noise equivalent size, a better picture of what the radar detected during a given time period emerges. As altitude increases, the minimum detected size also increases. Thus, when flux is plotted across altitudes, variations due to population as well as radar sensitivity are at play. The Haystack FY2010 and HAX FY2012 data are presented in Figures 7-1 and 7-2. Note how the reduced sensitivity of Haystack during FY2010 presents quite clearly as altitude increases.
### Table 7-1. Haystack Total Cumulative Flux (#/m²/year)

<table>
<thead>
<tr>
<th>Fiscal Year Period</th>
<th>AltitudeMin (km)</th>
<th>AltitudeMax (km)</th>
<th>Total Cumulative Flux (#/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>400</td>
<td>500</td>
<td>1.05E-05</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>500</td>
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<td>700</td>
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</tr>
<tr>
<td></td>
<td>800</td>
<td>500</td>
<td>3.73E-05</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>500</td>
<td>3.53E-05</td>
</tr>
<tr>
<td></td>
<td>1000</td>
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<td>1100</td>
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</tr>
<tr>
<td></td>
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<td>2.64E-04</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>1700</td>
<td>500</td>
<td>4.93E-03</td>
</tr>
</tbody>
</table>

### Table 7-2. HAX Total Cumulative Flux (#/m²/year)

<table>
<thead>
<tr>
<th>Fiscal Year Period</th>
<th>AltitudeMin (km)</th>
<th>AltitudeMax (km)</th>
<th>Total Cumulative Flux (#/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>400</td>
<td>500</td>
<td>2.87E-06</td>
</tr>
<tr>
<td></td>
<td>600</td>
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<td>6.00E-06</td>
</tr>
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<td>700</td>
<td>500</td>
<td>1.11E-05</td>
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<td></td>
<td>1700</td>
<td>500</td>
<td>5.11E-03</td>
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</table>

### Table 7-3. Haystack Minimum Characteristic Sizes (cm), for RCSnoise_eq_avg

<table>
<thead>
<tr>
<th>Characteristic Size(cm)</th>
<th>AltitudeMin (km)</th>
<th>AltitudeMax (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>2007</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2007a</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2007b</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2007c</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2008</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2009</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2009a</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2009b</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2010</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Table 7-4. HAX Minimum Characteristic Sizes (cm), for RCSnoise_eq_avg

<table>
<thead>
<tr>
<th>Characteristic Size(cm)</th>
<th>AltitudeMin (km)</th>
<th>AltitudeMax (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>2007</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2008</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>2009</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>2010</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>
A comparison of all time periods observed by the radars is shown in Figures 7-3 and 7-4. The flux for each time period is related both to environment and radar sensitivity, thus Figures 7-5 and 7-6 summarize capabilities according to the $RCS_{\text{noise_eq_avg}}$ during these periods. It is important that although flux appears to go up or down, the radar’s condition during an observation period must be taken into account before concluding what variation is actually being seen in the orbiting debris environment.
Figure 7-3. FY2006 through FY2010 Haystack, 75° east, total observed flux.

Figure 7-4. FY2006 through FY2012 HAX, 75° east, total observed flux.
Figure 7-5. FY2006 through FY2010 Haystack, 75° east, characteristic size equivalent to RCS\textsubscript{noise\_eq\_avg}.

Figure 7-6. FY2006 through FY2012 HAX, 75° east, characteristic size equivalent to RCS\textsubscript{noise\_eq\_avg}.

7.2 Flux by Inclination

Charting flux by binned altitude does not illustrate sufficiently the sources of detected populations. The fluxes shown, so far, describe the overall summation of flux across all observable inclinations, 40°-140°. When these total flux summations are sectioned by inclination, the non-uniform distribution of detections becomes apparent.

As flux is examined over a range of detections, the object inclinations suggest which historic launches and fragmentation events contributed to the debris. Figures 7-7 and 7-8 show flux broken down by inclination, in 1° bins, for both Haystack and HAX radars at the 75° east-pointing direction, for FY2010 and FY2012, respectively.
To give a better picture of what was observed, two vertical axes are used. Flux is on the left-hand side, and actual number of detections observed is on the right. The value of flux is number of detections divided by surface area and time.

![Figure 7-7. FY2010 Haystack, 75° east, 400–1800 km, total observed flux versus inclination.](image)

![Figure 7-8. FY2012 HAX, 75° east, 400–1800 km, total observed flux versus inclination.](image)

### 7.3 Size Distribution

Size distributions by altitude were computed in a manner similar to the NaK-cumulative size distribution. Because the uncertainties of size estimation are still under study, the presumption is that the cumulative flux summed to some minimum size may provide an approximation to the limits of reliable measurement. Here the \( \text{RCS}_{\text{noise \_eq \_avg}} \) term is presented as this metric. Though differential breakdowns of the size distribution are still useful, they require a much greater degree of interpretation.
The cumulative summation of flux by size for both radars is shown in Figures 7-9 and 7-10 for detections from 400–1800 km, for FY2010 and FY2012, respectively. These size distributions are split by the characteristic size equivalent to $R_{\text{CPSnoise_eq_avg}}$ for each time period. An estimate of the Poisson sampling uncertainty, that of $\sqrt{\text{flux}}$, is charted to determine how likely these data were to be observed. However, this is only a primitive approximation of uncertainty that requires further statistical analysis, as the number of detections does not necessarily represent the true Poisson mean.

Figure 7-9. FY2010 Haystack, 75° east pointing, 400–1800 km, divided by characteristic size equivalent to $R_{\text{CPSnoise_eq_avg}}$.

Figure 7-10. FY2012 HAX, 75° east pointing, 400–1800 km, divided by characteristic size equivalent to $R_{\text{CPSnoise_eq_avg}}$. 
7.4 Summary

The fluxes shown in this section illustrate how comprehensively observations ranged over altitude, inclination, and size. Both the Haystack and HAX radars observed a variety of orbits and size distributions, which emphasizes the dynamic and diverse nature of LEO debris measurements. Further illustrations may be found in appendices E and F, where flux versus altitude, inclination, and characteristic size from both radars is addressed.
8.0 Special Surveys

The Haystack and HAX radars have played an important role in data acquisition for special space events, such as significant satellite breakups. Both Haystack and HAX radar resources are made available to the ODPO by MIT LL for dedicated space debris event measurements, on request.

8.1 On-orbit Breakup Measurements

In the critical hours after a breakup, timely measurements of a debris cloud can yield information on the magnitude and nature of the breakup. Depending upon the parent body's initial orbit and the characteristics of the event, a debris cloud may be distributed about the parent orbit plane in a matter of days. Because of this, the availability of two large radar observatories to collect orbital debris data is a critical component in the ODPO measurement resources.

Upon detection of a breakup event by the SSN, the ODPO issues an initial risk assessment to selected space assets. The assessment is conducted using the NASA standard breakup model to create an initial, model debris cloud; propagating the cloud forward in time; and determining the risk associated with modeled conjunctions. NASA software also determines model cloud orientation with respect to the radar observatories and optimal observation windows in time. Then the ODPO requests special observations from Haystack and HAX to observe the real cloud. Deviations between the model and actual clouds are common, and actual measurements are helpful for adjusting risk assessments and for identifying areas to improve the model for future breakups.

8.2 Fengyun-1C Anti-Satellite Test

One particularly large breakup occurred when the Chinese FY-1C spacecraft was the object of an anti-satellite (ASAT) test conducted on 11 January 2007. The target satellite was a weather satellite in a circular polar orbit at 98.8° inclination, with a mean altitude of approximately 850 km. As of 6 January 2014, the SSN had cataloged 3381 FY-1C fragments, of which 3020 were on orbit. The debris generated by this nearly 960-kg object had substantial repercussions to the LEO debris environment, with many altitudes experiencing an elevated debris risk that is projected to exist for decades to come. Observations were conducted in staring mode before and after the breakup by both Haystack and HAX. Figure 8-1 shows a sample of this data.13 The clustering of debris can be seen spread about the parent body’s inclination.

In an attempt to gauge the magnitude of debris generated, the Haystack radar was tasked to a special “orbit plane tracking” configuration approximately 24 hours after the test. From 10:30 - 11:40 UTC on 12 January 2007, 859 objects were detected. Then, from 20:00 - 21:54 UTC, another 667 objects were detected. Figures 8-2 and 8-3 depict the measurements of the cloud during these track observations, originally reported in The Characteristics and Consequences of the Break-up of the Fengyun-1C spacecraft.14
Another follow-up track was performed on 23 January from 20:20 - 22:30, when 31 detections were observed. By then, the debris cloud had become less concentrated, and thus fewer objects were detected. These data were essential in establishing an early analysis of the magnitude of this breakup.

Figure 8-2. Cumulative size distribution of FY-1C debris during an orbit plane track conducted by the Haystack radar within 24 hours of the ASAT test.
By the end of FY2007, the SSN had catalogued 2246 pieces from the event. The Gabbard diagram, devised in 1971 by Mr. John Gabbard of the U.S. Department of Defense to categorize debris by parent event or source, provides a quick means of assessing three cloud traits: the qualitative number of cataloged debris; the extent in altitude of the debris cloud; and the evolutionary state of the cloud. The diagram plots both the apogee and perigee altitudes of a given object as a function of its period (Figure 8-4) or semimajor axis. In Figure 8-4, the cloud extends from altitudes of 250 to over 4000 km, with the densest concentration spanning altitudes from 300 to 1600 km. In the 6 months since the event, atmospheric drag is evident as apogees below a period of approximately 100 minutes have begun to “collapse” to lower altitudes.
8.3 Iridium-Cosmos Collision

On 10 February 2009, an inactive Russian communication satellite, Cosmos-2251 (SSN 22675), collided with an active U.S. commercial communication satellite, Iridium-33 (SSN 24946), at an altitude of 790 km. Both spacecraft were in nearly circular orbits with inclinations of 86.4° and 74°, respectively. At the time of the collision, the two orbital planes intersected at nearly right angles, resulting in a collision velocity of more than 11 km/s. This was the first on-orbit accidental hypervelocity collision of this magnitude. It left two distinct debris clouds and 823 of the larger debris pieces were identified and cataloged by the SSN network during the following month.

As of 6 January 2014, 2204 fragments from both spacecraft had been cataloged by the SSN and 1706 of them were in orbit. In addition to the cataloged objects, it is estimated that hundreds of thousands of fragments, down to the millimeter size, were also generated. These objects are too small to be tracked by the SSN, but are still large enough to be a safety concern for human space activities and robotic missions in LEO. Only objects larger than 5–10 cm are tracked by the SSN; the Haystack radar historically is able to detect centimeter-size objects at LEO, and objects of 0.5-cm size at ranges of less than 1000 km. However, beginning in April 2009, the transmitting power of Haystack was reduced, and this resulted in a drastic loss of sensitivity.

Therefore, all FY2009 75°-elevation observation data are divided into three collection segments: (1) October - December 2008 (110.3 hours of observation), which is the pre-collision period; (2) January - April 2009 (85.0 hours), which is the post-collision, but pre-power loss period; and (3) May - September 2009 (352.4 hours), which is both the post-collision and post-power loss period. Finally, in April 2010, Haystack was shut down completely for significant upgrades.
Figure 8-5. Altitude versus Doppler inclination for all Haystack valid detections at 75° elevation: blue dots are dated to pre-collision period (October - December 2008, 224 detections) and red dots are dated to post-collision period (January - September 2009, 753 detections).

It is evident from Figure 8-6 that Haystack observed a significant increase in detections with inclinations from 71°-79°, and 84°-89°, at an altitude range of approximately 550–950 km. The conclusion is that objects at these altitudes can belong to both the Iridium-Cosmos collision and the FY-1C event. Objects with altitudes from 710–800 km are likely to be Iridium-Cosmos collision fragments. These objects were extracted from the data set and plotted separately in Figure 8-6, which shows the inclination distribution of the pre-collision and post-collision debris, before the Haystack power loss. This figure demonstrates that the number of sub-centimeter debris dramatically increased between 74° and 86° inclinations after the Iridium-Cosmos collision. In addition, the total detection rate increased from 2.0 to 2.8 numbers per hour.
Figure 8-6. Number of pre-collision and post-collision debris, but before the Haystack power loss, detection rate versus Doppler inclination (histogram, 2° bins) for Haystack detections of sub-centimeter objects; blue is for the pre-collision period (October - December 2008) and black is for the post-collision period (January - September 2009).

The Haystack count rate per hour for detections versus SEM size (for 1-mm bins) is presented in Figure 8-7. This size distribution is shown for pre-collision data in the solid black line (224 detections), for post-collision but pre-power loss in the dashed violet line (237 detections), and for post-collision and post-power loss in the blue dotted line (516 detections). The first two lines show a drastic increase in count rates for particles of 3.5-mm SEM size (1.23 times), 4.5-mm (1.89 times), and 5.5-mm (1.47 times). However, for the "post-collision, post-power loss" line, a significant loss of sensitivity occurred, and the probability of detection dropped, as shown in Table 8-1. Following this occurrence, the radar was not able to detect particle populations with pieces less than 5.5 mm in size at altitudes above 700 km.
Figure 8-7. Detection count rate per hour versus SEM size (for 1-mm bins) for pre-collision data (solid black line), for post-collision but pre-power loss (dashed violet line), and for post-collision and post-power loss (blue dotted line); the last data curve was obtained after a significant loss of sensitivity by the Haystack radar and, therefore, should not be compared with the previous two.

Table 8-1. Haystack 75° East Debris Staring Mode Measurements, Probability of Detection

<table>
<thead>
<tr>
<th>Characteristic Size</th>
<th>3.5 mm</th>
<th>4.5 mm</th>
<th>5.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>750 km</td>
<td>800 km</td>
<td>750 km</td>
</tr>
<tr>
<td>Prior to Loss</td>
<td>64%</td>
<td>26%</td>
<td>100%</td>
</tr>
<tr>
<td>After Loss</td>
<td>0%</td>
<td>0%</td>
<td>20%</td>
</tr>
</tbody>
</table>
8.4 Briz-M Breakup

On 16 October 2012, the explosion of a Briz-M upper stage (2012-044C, SSN 38746) created a cloud of debris pieces posing a risk to LEO spacecraft, including the International Space Station. The HAX radar conducted special observations, requested by the ODPO, to characterize the size distribution of objects from the breakup. Results were compared to the NASA breakup model prediction and the SSN cataloged objects. The comparison, shown in Figure 8-8, indicates that the NASA standard breakup model over-predicted the population of objects less than 10 cm in characteristic size. This indicates that the event does not follow the standard breakup model, leading to the conclusion that the actual hazard posed ISS and other space assets is less than is indicated by standard risk assessment models.

Figure 8-8. Virtually all of the objects generated by this Briz-M breakup population (SSN 38746) de-orbited within a year due to the low perigee of the orbits. Dotted lines indicated the ±1σ uncertainties in the HAX radar measurements.
8.5 Twenty-Four-Hour Campaigns

The Haystack and HAX radars occasionally participate in a coordinated, international debris observation effort, commonly known as the “24-Hour Campaigns.” This is a cooperative effort with the European Space Agency (ESA), under the guidance of the Inter-Agency Space Debris Coordination Committee (IADC). Although all IADC member organizations are encouraged to participate, the ESA has historically been the only other active member. Radars across the world are active during overlapping periods, with the goal of gathering 24 hours of continuous observations at each radar. All data between radars are grouped in time within about a day of each other, with the benefit of observing the debris environment at multiple wavelengths and from geographically dispersed observatories.

Over the time period reported in this document, there were three sets of Haystack and HAX contributions to campaigns, as described in Table 8-2. The jump in detections from 2006 to 2008 is partially due to the ASAT event in 2007, while the drop in detections from 2008 to 2010 is due to a significant drop in sensitivity in Haystack.

Table 8-2. Haystack and HAX 24-Hour Campaign Observations

<table>
<thead>
<tr>
<th>Radar</th>
<th>Observation Date 1</th>
<th>Observation Date 2</th>
<th>Detections (#) Date 1</th>
<th>Detections (#) Date 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haystack and HAX</td>
<td>06 Jul 2006</td>
<td>07 Jul 2006</td>
<td>187</td>
<td>188</td>
</tr>
<tr>
<td>Haystack and HAX</td>
<td>18 Nov 2008</td>
<td>19 Nov 2008</td>
<td>323</td>
<td>324</td>
</tr>
<tr>
<td>Haystack and HAX</td>
<td>27 Mar 2010</td>
<td>28 Mar 2010</td>
<td>86</td>
<td>87</td>
</tr>
</tbody>
</table>
9.0. Conclusion

The LEO environment was observed by the Haystack and HAX radars and their measurements were analyzed. This report covers seven years of observations; 3285 hours were collected by Haystack at the 75° elevation, east-pointing; 20° elevation, south-pointing; and 10° elevation, south-pointing directions, while HAX collected 4222 hours at the 75° elevation, east-pointing angle. Additional special observations were conducted for critical break-up events, and in coordination with the IADC 24-hour campaigns. Objects detected by both radars were measured for RCS, range, and range-rate. These data were analyzed to produce orbital parameter, size, and flux distributions.

Three advances were made in the methods used to reduce and analyze the radar data presented in this report: (1) historic accounting of power loss with respect to sensitivity, (2) size-based limits with respect to sensitivity variation from year to year, and (3) implementing an automated classification scheme. The first, using historic power-loss information to account for loss of sensitivity was necessary to compare data across multiple years. During the timespan of this report, both Haystack and HAX experienced multiple, significant power losses, which complicated comparison of small object observations. These power losses led to the further study of the $\text{RCS}_{\text{noise_eq_avgPP}}$ threshold. By establishing a standard for measuring $\text{RCS}_{\text{noise_eq_avg}}$, the complications in small-size measurement over time were mitigated by allowing general size thresholds to be established as a function of range and power. Finally, the work of accepting and rejecting detections, based on measured data, was transitioned from a human-in-the-loop subjective process to an automated method using objective metrics. This method uses a standard set of conditions from which to evaluate detections, and was applied throughout the data, thus eliminating some of the guesswork introduced by human-based evaluation.

As described in this report, the debris environment in LEO is diverse, heterogeneous, and not trivial to analyze. The data reduction and analysis conducted in writing this report has yielded interesting preliminary results, and it is anticipated, valuable information for the orbital debris community and a unique resource for further study.
10.0 References


Appendix A1

Altitude Versus Range Rate

Haystack 75° Elevation, East Pointing
Figure A1.1. Altitude versus range rate detection count rate, Haystack 75° east, FY2006, with circular orbit inclination lines superimposed.

Figure A1.2. Altitude versus range rate detection counts, Haystack 75° east, FY2006, with circular orbit inclination lines superimposed.
Figure A1.3. Altitude versus range rate detection count rate, Haystack 75° east, FY2007a, with circular orbit inclination lines superimposed.

Figure A1.4. Altitude versus range rate detection counts, Haystack 75° east, FY2007a, with circular orbit inclination lines superimposed.
Figure A1.5. Altitude versus range rate detection count rate, Haystack 75° east, FY2007b, with circular orbit inclination lines superimposed.

Figure A1.6. Altitude versus range rate detection counts, Haystack 75° east, FY2007b, with circular orbit inclination lines superimposed.
Figure A1.7. Altitude versus range rate detection count rate, Haystack 75° east, FY2008, with circular orbit inclination lines superimposed.

Figure A1.8. Altitude versus range rate detection counts, Haystack 75° east, FY2008, with circular orbit inclination lines superimposed.
Figure A1.9. Altitude versus range rate detection count rate, Haystack 75° east, FY2009a, with circular orbit inclination lines superimposed.

Figure A1.10. Altitude versus range rate detection counts, Haystack 75° east, FY2009a, with circular orbit inclination lines superimposed.
Figure A1.11. Altitude versus range rate detection count rate, Haystack 75° east, FY2009b, with circular orbit inclination lines superimposed.

Figure A1.12. Altitude versus range rate detection counts, Haystack 75° east, FY2009b, with circular orbit inclination lines superimposed.
Figure A1.13. Altitude versus range rate detection count rate, Haystack 75° east, FY2010, with circular orbit inclination lines superimposed.

Figure A1.14. Altitude versus range rate detection counts, Haystack 75° east, FY2010, with circular orbit inclination lines superimposed.
Appendix A2

Integrated SNR

Haystack 75° Elevation, East Pointing
Figure A2.1. Integrated SNR, Haystack 75° east, FY2006.

Figure A2.2. Integrated SNR, Haystack 75° east, FY2007a.

Figure A2.3. Integrated SNR, Haystack 75° east, FY2007b.
Figure A2.4. Integrated SNR, Haystack 75° east, FY2008.

Figure A2.5. Integrated SNR, Haystack 75° east, FY2009a.

Figure A2.6. Integrated SNR, Haystack 75° east, FY2009b.
Figure A2.7. Integrated SNR, Haystack 75° east, FY2010.
Appendix A3

Altitude Versus Total RCS

Haystack 75° Elevation, East Pointing
Figure A3.1. Altitude versus total RCS, Haystack 75° east, FY2006.

Figure A3.2. Altitude versus total RCS, Haystack 75° east, FY2007a.

Figure A3.3. Altitude versus total RCS, Haystack 75° east, FY2007b.

Figure A3.4. Altitude versus total RCS, Haystack 75° east, FY2008.
Figure A3.5. Altitude versus total RCS, Haystack 75° east, FY2009a.

Figure A3.6. Altitude versus total RCS, Haystack 75° east, FY2009b.

Figure A3.7. Altitude versus total RCS, Haystack 75° east, FY2010.
Appendix B1

Altitude Versus Range Rate

HAX 75° Elevation, East Pointing
Figure B1.1. Altitude versus range rate detection count rate, HAX 75° east, FY2006, with circular orbit inclination lines superimposed.

Figure B1.2. Altitude versus range rate detection counts, HAX 75° east, FY2006, with circular orbit inclination lines superimposed.
Figure B1.3. Altitude versus range rate detection count rate, HAX 75° east, FY2007, with circular orbit inclination lines superimposed.

Figure B1.4. Altitude versus range rate detection counts, HAX 75° east, FY2007, with circular orbit inclination lines superimposed.
Figure B1.5. Altitude versus range rate detection count rate, HAX 75° east, FY2008, with circular orbit inclination lines superimposed.

Figure B1.6. Altitude versus range rate detection counts, HAX 75° east, FY2008, with circular orbit inclination lines superimposed.
Figure B1.7. Altitude versus range rate detection count rate, HAX 75° east, FY2009, with circular orbit inclination lines superimposed.

Figure B1.8. Altitude versus range rate detection counts, HAX 75° east, FY2009, with circular orbit inclination lines superimposed.
Figure B1.9. Altitude versus range rate detection count rate, HAX 75° east, FY2010, with circular orbit inclination lines superimposed.

Figure B1.10. Altitude versus range rate detection counts, HAX 75° east, FY2010, with circular orbit inclination lines superimposed.
Figure B1.11. Altitude versus range rate detection count rate, HAX 75° east, FY2011, with circular orbit inclination lines superimposed.

Figure B1.12. Altitude versus range rate detection counts, HAX 75° east, FY2011, with circular orbit inclination lines superimposed.
Figure B1.13. Altitude versus range rate detection count rate, HAX 75° east, FY2012, with circular orbit inclination lines superimposed.

Figure B1.14. Altitude versus range rate detection counts, HAX 75° east, FY2012, with circular orbit inclination lines superimposed.
Appendix B2

Integrated SNR

HAX 75° Elevation, East Pointing
Figure B2.1. Integrated SNR, HAX 75° east, FY2006.

Figure B2.2. Integrated SNR, HAX 75° east, FY2007.

Figure B2.3. Integrated SNR, HAX 75° east, FY2008.
Figure B2.4. Integrated SNR, HAX 75° east, FY2009.

Figure B2.5. Integrated SNR, HAX 75° east, FY2010.

Figure B2.6. Integrated SNR, HAX 75° east, FY2011.
Figure B2.7. Integrated SNR, HAX 75° east, FY2012.
Appendix B3

Altitude Versus Total RCS

HAX 75° Elevation, East Pointing
Figure B3.1. Altitude versus total RCS, HAX 75° east, FY2006.

Figure B3.2. Altitude versus total RCS, HAX 75° east, FY2007.

Figure B3.3. Altitude versus total RCS, HAX 75° east, FY2008.

Figure B3.4. Altitude versus total RCS, HAX 75° east, FY2009.
Figure B3.5. Altitude versus total RCS, HAX 75° east, FY2010.

Figure B3.6. Altitude versus total RCS, HAX 75° east, FY2011.

Figure B3.7. Altitude versus total RCS, HAX 75° east, FY2012.
Appendix C1

Altitude Versus Range Rate

Haystack 20° Elevation, South Pointing
Figure C1.1. Altitude versus range rate detection count rate, Haystack 20° south, FY2006.

Figure C1.2. Altitude versus range rate detection counts, Haystack 20° south, FY2006.
Figure C1.3. Altitude versus range rate detection count rate, Haystack 20° south, FY2007a.

Figure C1.4. Altitude versus range rate detection counts, Haystack 20° south, FY2007a.
Figure C1.5. Altitude versus range rate detection count rate, Haystack 20° south, FY2007b.

Figure C1.6. Altitude versus range rate detection counts, Haystack 20° south, FY2007b.
Figure C1.7. Altitude versus range rate detection count rate, Haystack 20° south, FY2008.

Figure C1.8. Altitude versus range rate detection counts, Haystack 20° south, FY2008.
Figure C1.9. Altitude versus range rate detection count rate, Haystack 20° south, FY2009a.

Figure C1.10. Altitude versus range rate detection counts, Haystack 20° south, FY2009a.
Appendix C2

Integrated SNR

Haystack 20° Elevation, South Pointing
Figure C2.1. Integrated SNR, Haystack 20° south, FY2006.

Figure C2.2. Integrated SNR, Haystack 20° south, FY2007a.

Figure C2.3. Integrated SNR, Haystack 20° south, FY2007b.
Figure C2.4. Integrated SNR, Haystack 20° south, FY2008.

Figure C2.5. Integrated SNR, Haystack 20° south, FY2009a.
Appendix C3

Altitude Versus Total RCS

Haystack 20° Elevation, South Pointing
Figure C3.1. Altitude versus total RCS, Haystack 20° south, FY2006.

Figure C3.2. Altitude versus total RCS, Haystack 20° south, FY2007a.

Figure C3.3. Altitude versus total RCS, Haystack 20° south, FY2007b.

Figure C3.4. Altitude versus total RCS, Haystack 20° south, FY2008.
Figure C3.5. Altitude versus total RCS, Haystack 20° south, FY2009a.
Appendix D1

Altitude Versus Range Rate

Haystack 10° Elevation, South Pointing
Figure D1.1. Altitude versus range rate detection count rate, Haystack 10° south, FY2006.

Figure D1.2. Altitude versus range rate detection counts, Haystack 10° south, FY2006.
Figure D1.3. Altitude versus range rate detection count rate, Haystack 10° south, FY2007a.

Figure D1.4. Altitude versus range rate detection counts, Haystack 10° south, FY2007a.
Figure D1.5. Altitude versus range rate detection count rate, Haystack 10° south, FY2007b.

Figure D1.6. Altitude versus range rate detection counts, Haystack 10° south, FY2007b.
Figure D1.7. Altitude versus range rate detection count rate, Haystack 10° south, FY2008.

Figure D1.8. Altitude versus range rate detection counts, Haystack 10° south, FY2008.
Figure D1.9. Altitude versus range rate detection count rate, Haystack 10° south, FY2009a.

Figure D1.10. Altitude versus range rate detection counts, Haystack 10° south, FY2009a.
Appendix D2

Integrated SNR

Haystack 10° Elevation, South Pointing
Figure D2.1. Integrated SNR, Haystack 10° south, FY2006.

Figure D2.2. Integrated SNR, Haystack 10° south, FY2007a.

Figure D2.3. Integrated SNR, Haystack 10° south, FY2007b.
Figure D2.4. Integrated SNR, Haystack 10° south, FY2008.

Figure D2.5. Integrated SNR, Haystack 10° south, FY2009a.
Appendix D3

Altitude Versus Total RCS

Haystack 10° Elevation, South Pointing
Figure D3.1. Altitude versus total RCS, Haystack 10° south, FY2006.

Figure D3.2. Altitude versus total RCS, Haystack 10° south, FY2007a.

Figure D3.3. Altitude versus total RCS, Haystack 10° south, FY2007b.

Figure D3.4. Altitude versus total RCS, Haystack 10° south, FY2008.
Figure D3.5. Altitude versus total RCS, Haystack 10° south, FY2009a.
Appendix E1

Flux Versus Altitude

Referenced to RCS_{noise_eq_avg}

Haystack 75° Elevation, East Pointing
Figure E1.1. FY2006 Haystack, 75° east, total observed flux versus altitude, characteristic size for RCS$^{\text{noise_eq_avg}}$.

Figure E1.2. FY2007a Haystack, 75° east, total observed flux versus altitude, characteristic size for RCS$^{\text{noise_eq_avg}}$. 
Figure E1.3. FY2007b Haystack, 75° east, total observed flux versus altitude, characteristic size for RCS_{noise_eq_avg}.

Figure E1.4. FY2008 Haystack, 75° east, total observed flux versus altitude, characteristic size for RCS_{noise_eq_avg}.
Figure E1.5. FY2009a Haystack, 75° east, total observed flux versus altitude, characteristic size for RCS\textsubscript{noise_eq_avg}.

Figure E1.6. FY2009b Haystack, 75° east, total observed flux versus altitude, characteristic size for RCS\textsubscript{noise_eq_avg}.
Figure E1.7. FY2010 Haystack, 75° east, total observed flux versus altitude, characteristic size for RCS_{noise_eq_avg}.
Appendix E2

Flux Versus Inclination

Haystack 75° Elevation, East Pointing
Figure E2.1. FY2006 Haystack, 75° east, total observed flux versus inclination.

Figure E2.2. FY2007a Haystack, 75° east, total observed flux versus inclination.
Figure E2.3. FY2007b Haystack, 75° east, total observed flux versus inclination.

Figure E2.4. FY2008 Haystack, 75° east, total observed flux versus inclination.
Figure E2.5. FY2009a Haystack, 75° east, total observed flux versus inclination.

Figure E2.6. FY2009b Haystack, 75° east, total observed flux versus inclination.
Figure E2.7. FY2010 Haystack, 75° east, total observed flux versus inclination.
Appendix E3

Flux Versus Characteristic Size

Referenced to RCS_{\text{noise_eq_avg}}

Haystack 75° Elevation, East Pointing
Figure E3.1. FY2006 Haystack, 75° east, total observed flux versus characteristic size.

Figure E3.2. FY2007a Haystack, 75° east, total observed flux versus characteristic size.
Figure E3.3. FY2007b Haystack, 75° east, total observed flux versus characteristic size.

Figure E3.4. FY2008 Haystack, 75° east, total observed flux versus characteristic size.
Figure D3.5. FY2009a Haystack, 75° east, total observed flux versus characteristic size.

Figure E3.6. FY2009b Haystack, 75° east, total observed flux versus characteristic size.
Figure E3.7. FY2010 Haystack, 75° east, total observed flux versus characteristic size.
Appendix F1

Flux Versus Altitude

Referenced to RCS_{\text{noise_eq_avg}}

HAX 75° Elevation, East Pointing
Figure E1.1. FY2006 HAX, 75° east, total observed flux versus altitude, characteristic size for RCS_{noise_eq_avg}.

Figure E1.2. FY2007 HAX, 75° east, total observed flux versus altitude, characteristic size for RCS_{noise_eq_avg}.
Figure E1.3. FY2008 HAX, 75° east, total observed flux versus altitude, characteristic size for $\text{RCS}_{\text{noise_eq_avg}}$.

Figure E1.4. FY2009 HAX, 75° east, total observed flux versus altitude, characteristic size for $\text{RCS}_{\text{noise_eq_avg}}$. 
Figure E1.5. FY2010 HAX, 75° east, total observed flux versus altitude, characteristic size for RCS_{noise_eq_avg}.

Figure E1.6. FY2011 HAX, 75° east, total observed flux versus altitude, characteristic size for RCS_{noise_eq_avg}.
Figure E1.7. FY2012 HAX, 75° east, total observed flux versus altitude, characteristic size for RCS
\textsuperscript{noise_eq_avg}.
Appendix F2

Flux Versus Inclination

HAX 75° Elevation, East Pointing
Figure E2.1. FY2006 HAX, 75° east, total observed flux versus inclination.

Figure E2.2. FY2007 HAX, 75° east, total observed flux versus inclination.
Figure E2.3. FY2008 HAX, 75° east, total observed flux versus inclination.

Figure E2.4. FY2009 HAX, 75° east, total observed flux versus inclination.
Figure E2.5. FY2010 HAX, 75° east, total observed flux versus inclination.

Figure E2.6. FY2011 HAX, 75° east, total observed flux versus inclination.
Figure E2.7. FY2012 HAX, 75° east, total observed flux versus inclination.
Appendix F3

Flux Versus Characteristic Size

Referenced to $\text{RCS}_{\text{noise_eq_avg}}$

HAX 75° Elevation, East Pointing
Figure E3.1. FY2006 HAX, 75° east, total observed flux versus characteristic size.

Figure E3.2. FY2007 HAX, 75° east, total observed flux versus characteristic size.
Figure E3.3. FY2008 HAX, 75° east, total observed flux versus characteristic size.

Figure E3.4. FY2009 HAX, 75° east, total observed flux versus characteristic size.
Figure E3.5. FY2010 HAX, 75° east, total observed flux versus characteristic size.

Figure E3.6. FY2011 HAX, 75° east, total observed flux versus characteristic size.
Figure E3.7. FY2012 HAX, 75° east, total observed flux versus characteristic size.
This report summarizes methods of orbital debris radar data collection, reduction and analysis by the NASA Orbital Debris Program Office (ODPO), with data gathered from the Haystack and the Haystack Auxiliary (HAX) radars. Both radars are operated by the Massachusetts Institute of Technology Lincoln Laboratory, and have been collecting orbital debris data for the ODPO since 1990. They operate in a stare mode designed to statistically sample objects in low Earth orbit that are smaller than those typically tracked and cataloged by the U.S. Space Surveillance Network. Seven years of observations, beginning in fiscal year 2006, were processed and analyzed to obtain this report’s results. Three major advances in orbital debris radar data reduction and analysis represented in the report are (1) correlation of historical power loss with respect to radar sensitivity variation, (2) establishment of limits to size variation estimates caused by sensitivity variation from year to year, and (3) an automated data quality classification process. Results are presented in terms familiar to both radar and orbital debris analysts.