ANALYSIS OF THE EGLIN RADAR DEBRIS FENCE

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BACKGROUND

The Eglin FPS-85 space surveillance radar is a bi-static phased array radar system located in Northern Florida. In 1994, when a new radar control computer was installed at Eglin, the software for the debris fence was not budgeted. The radar only maintained the capability to erect low elevation angle surveillance fences. The software was upgraded in 1999 to create the debris fence, which extends from 155 to 205 degrees in azimuth and is scanned at 35-degrees elevation. This higher elevation angle enables the detection of smaller-sized debris objects at manned space flight orbits. In this configuration, the radar system has a 0.99 probability of detection for all objects that have a radar cross-section greater than -35 dBsm. The new debris fence is intended to enhance the AFSPC's and NASA's ability to detect small debris objects, which are not currently part of the SSN satellite catalog. This paper presents data collected during software version 99-1 development testing.

RADAR OPERATIONS

Introduction: The Eglin radar site located at 30.72N, 273.79E, transmits horizontal polarization and receives both horizontal and vertical polarization. The radar's operation is controlled by its resource period, which is normally 50 msec. During a resource period the radar can transmit a maximum total pulse length of 250 μsec. This energy can be transmitted in one pulse or several. The Eglin radar's primary mission is space track and object identification. Currently, there are several surveillance fences that the radar operator can erect; the two discussed in this paper are the S1 and the debris fence. Their coverage limits are shown in Fig. 1.

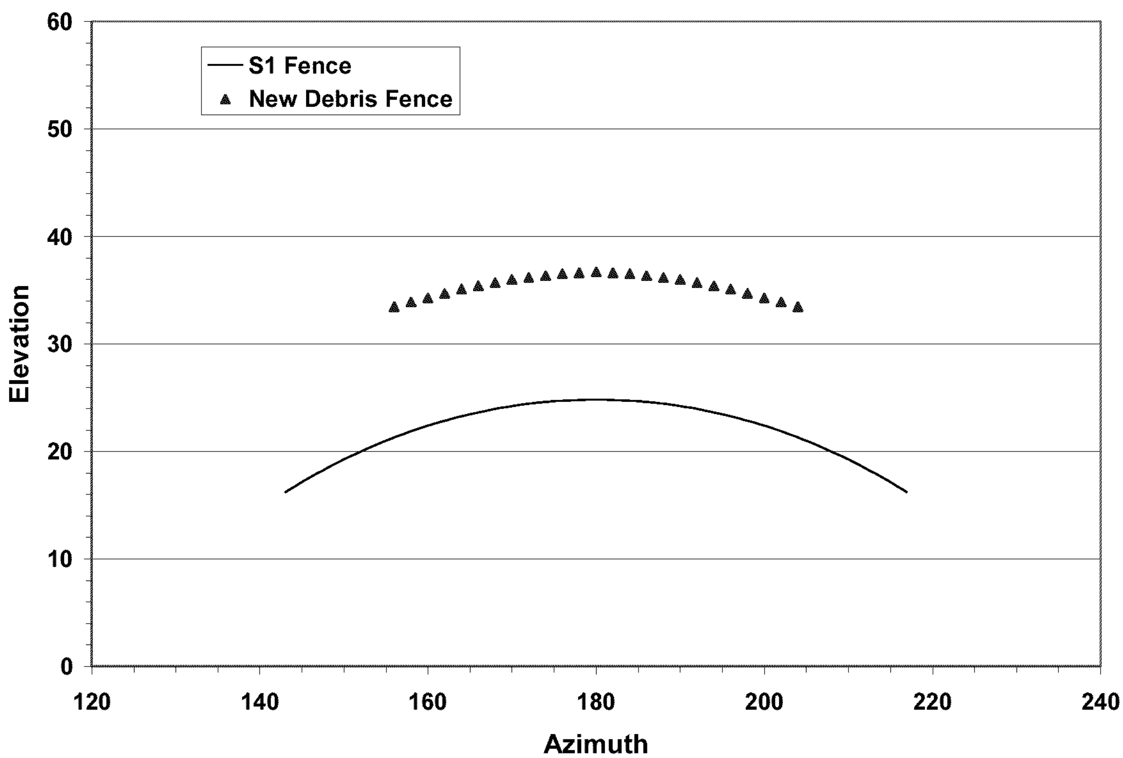

Figure 1. Eglin Fence Coverage

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14. ABSTRACT
The Eglin FPS-85 space surveillance radar is a bi-static phased array radar system located in Northern Florida. In 1994, when a new radar control computer was installed at Eglin, the software for the debris fence was not budgeted. The radar only maintained the capability to erect low elevation angle surveillance fences. The software was upgraded in 1999 to create the debris fence, which extends from 155 to 205 degrees in azimuth and is scanned at 35-degrees elevation. This higher elevation angle enables the detection of smaller-sized debris objects at manned space flight orbits. In this configuration, the radar system has a 0.99 probability of detection for all objects that have a radar cross-section greater than -35 dBsm. The new debris fence is intended to enhance the AFSPC?s and NASA?s ability to detect small debris objects, which are not currently part of the SSN satellite catalog. This paper presents data collected during software version 99-1 development testing.

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Nominal Operations: The Eglin radar's primary space mission operations are surveillance, search, and track. Surveillance is the process of examining or observing a region of space for the presence of objects for which there is no position information. This is the primary function of the S1 and new debris fence. Search is designed to locate objects when some information is available. Search is the use of a short-term keyed fence usually intended to collect observations from known space objects. This includes catalog maintenance and new launches. Once an object is detected during the surveillance or search mode, a confirmation process determines if the object detected is noise or an actual target. Confirmation serves three purposes: 1) it reduces processing time for false tracks, 2) it verifies the presence of a target, and 3) it initiates the actions required for tracking. Then depending on the radar's priorities and operating mode, several events can occur. In general, an object may be tracked to collect metric observations, signature data, or the track is dropped. Since this paper is focused on the detection of uncorrelated targets (UCT) from the S1 and debris fences, a brief chronological sequence of the operations process is presented.

a. Following a confirmed detection (by the S1 or debris fence), an initial observation is formed. The observation results from the information collected from several pulse returns. If the processing determines the object is a UCT, the radar attempts to increase the signal-to-noise ratio (SNR) to what is considered a quality observation (QO). If a QO is not achieved the track is deleted.

b. Once a QO is achieved, the observation is used to calculate an initial (osculating) element set. Simultaneously, various processing tests are used to minimize false tracks. Usually, velocity tests are considered the most reliable. If the UCT is determined to be of interest, a satellite identification (SID) is assigned to the object.

c. Second and third observations are collected approximately a few Earth-centered degrees later to provide additional data to calculate a mean element set. Additional velocity checks are made to determine if the object is an untasked known satellite, in which case tracking is dropped.

d. The UCT's time in coverage is calculated and scheduling operations are performed to determine when additional observations should be taken on the current pass. Additional observations are made approximately three Earth-centered degrees apart.

e. An estimate of the UCT's cross section is calculated once adequate data is collected. An orbital element set is calculated and several additional tests are performed to decrease the probability that a false UCT will be entered into the orbital element file. The system is then automatically tasked to collect additional observations from future passes.[1]

Figure 2 illustrates an example of an UCT fence detection and subsequent tracking. The individual points are pulse data from logical records (discussed later) #2 and #5. The data of interest is between 57140 and 57420 see the heavy line at the top of the graph. First, there is an S1 fence detection at approximately 3358-km range (57138 seconds) then, a track confirmation. Next, tracking is initiated, which is culminated in observation #1. This is followed by a brief period of signature data collection, followed by more metric data that is combined into observation #2. The metric pulse data are combined into one observation that is normally transmitted to Cheyenne Mountain. After observation #2 is complete the radar continues to collect signature data until it is time to collect metric data for observation number #3. Following observation #3, the radar resumes collecting additional signature data until the tracking is dropped. Note that during this specific time interval (and time around it, shown on the entire graph) there are many fence detections, followed by track confimations, some of which yield observations and others where track is dropped.

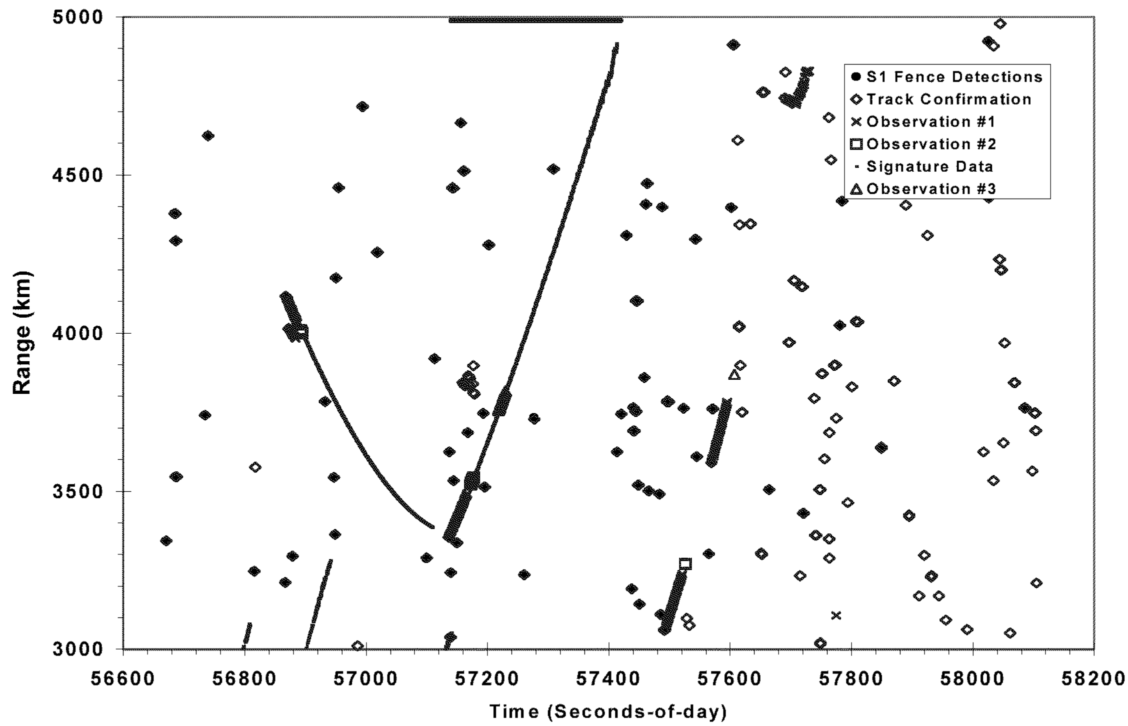

Figure 2. UCT Acquisition and Tracking

Figure 3 shows a known object acquisition and tracking example. Initially, there is minimum cost acquisition (which is the minimum transmit power required to product a QO). This is followed by a track confirmation then, a short period of metric observations followed a longer period of signature data collection.

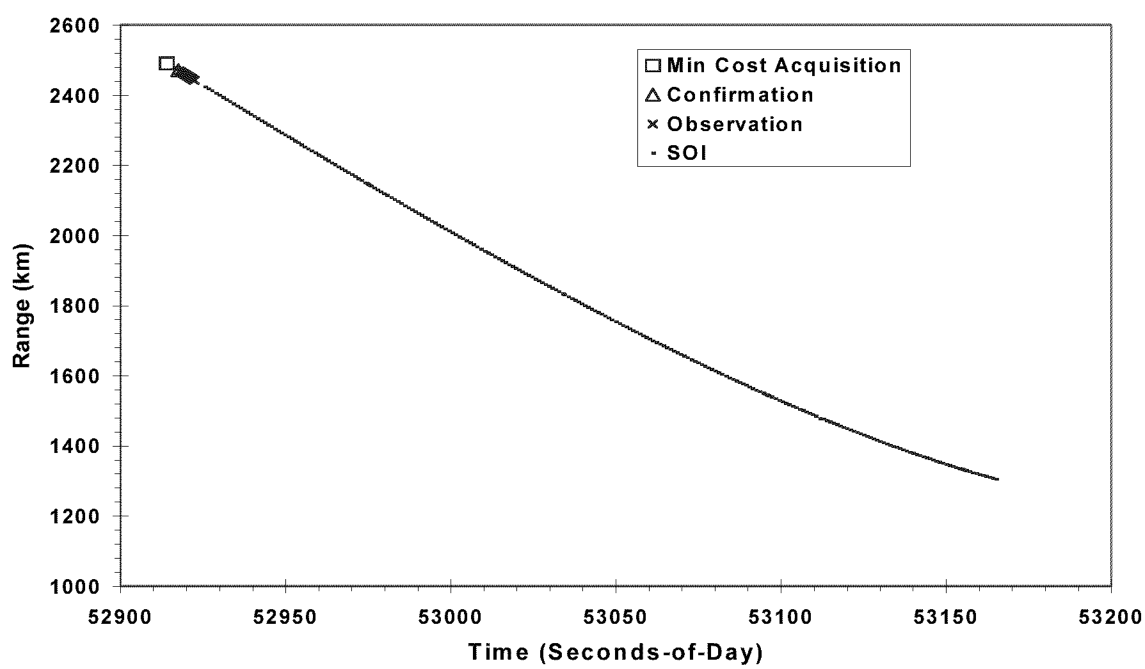

Figure 3. Known Object Acquisition and Tracking

Debris Fence Operation

The debris fence was implemented because it is expected to detect more smaller-sized objects than the S1 fence. The primary reason is better sensitivity, since the slant range to a target at the point of closest approach is greater for the S1 fence then the for debris fence. Second, the S1 fence is erected at a lower angle elevation angle, which makes it more difficult to confirm detections from debris objects that are on the descending node of their orbit. For these satellites, range is increasing which is likely to hinder a QO or after detection the object may drop below the horizon before tracking can be established. Both of these factors overshadow the fact that the S1 fence covers a larger azimuth angle extent.

There are three operational modes envisioned for the Eglin Debris Fence: Mode 1 background operations, the debris fence is generated only when surplus power is available. Mode 2, the debris fence is used part-time. Mode 3, the fence is fully operational to the exclusion of other tracking except for priority objects.

Background Fence Operations (Mode 1)

The normal mode of utilization for the Eglin debris fence will be Mode 1, background. In this mode, the debris fence will not have any dedicated radar energy devoted to its use; but will be configured to use any excess radar energy not used for normal space surveillance operations. It is recognized that in this mode the debris fence may not be active for significant amounts of time.

Part Time Fence Operations (Mode 2)

The second mode of operations is dedicated use of the fence for limited time periods. This mode may be used every day, every other day, or perhaps once per week. The intent is dedicated use on a regular, recurring basis to detect small objects, thereby establishing the basis for routine debris detections without creating a large workload at the site, the Space Control Center or the Alternate Space Control Center. During these short periods of activation, the debris fence will have priority over other surveillance fence(s) and routine tasking for low priority objects. High priority objects will still be tracked.

Full Time Fence Operations (Mode 3)

The third mode is the dedicated use of the fence for extended periods, such as during debris campaigns or when operational conditions dictate. Specifically, if a break-up occurs at space station altitudes there would be a need to rapidly assess the threat to manned space flight. In this mode, the fence has priority over other surveillance fence(s) and routine tasking for low priority objects. High priority objects will still be tracked.

DATA COLLECTION, REDUCTION, AND ANALYSIS

The Eglin radar system has over 450 logical records that can be stored to disk during operation. Each logical record is written depending on a particular action: after an event occurs, after a prescribed amount of time, after a statistic or summary event has been calculated, or when a buffer is full. The operator selects which logical records will be recorded or a standard set can be enabled. Some logical records are written after each pulse burst period or resource period. The resource period for the Elgin radar is 50 msec. Within a resource period, the radar can transmit up to 8 pulses with a total pulse duration of 250 μsec. Once the data have been written an analyst can select which logical records and data fields within a record are important.

The data is extracted using a FORTRAN program that specifies the desired records and fields. Over 30 logical records (LogR) were reduced and analyzed for the results discussed in this paper. The data was first formatted for import into Excel, then reduced and analyzed to extract the relevant information. The data collected was designed to calculate fence detection rates, false alarms, missed detections, confirmed detections, targets tracked, percent power expended for the S1 and debris fence, know satellites (correlations), correlation method, miss distance, uncorrelated targets, orbital element sets, and radar cross section. The primary logical records analyzed are shown in Table 1.

Table 1. Logical Records

Logical Record	Title	Fields
2	Search/track processor return for other than surveillance	Time, Range, AZ, EL, pulse width
5	Search Fence Detections	Fence, fence retransmission
6	Track Confirmation Request	Special tracks, unknowns tracked knows tracked, #satellite tracked, unique satellites
7	Correlation report	Satellite, next closest satellite, average, max, min, and sigma miss distance
8	Unknown Track Initiations	SNR, quality, range
241	Osculating orbital element set calculation	Satellite, eccentricity, inclination, mean motion
245	Orbital element set calculated	Satellite, epoch, eccentricity, inclination, mean motion
255	Time-of-day, 1-minute message	Percent fence pulse burst period, percent fence power expended
288	Cross section	Satellite, previous value & new radar cross section
437	Radar Cross Section	Satellite, samples, sum, max, min, average, and sigma RCS

Notes:
LogR 6 is generated to confirm an object was tracked.
LogR 241 is calculated from the first quality observation and is used to determine if the object is of interest.
LogR 245 is calculated after tracking is complete.

The logical records analyzed in this report were collected on 11 and 12 May 2000. During those two days the radar was operated in Mode 1 and 3. Table 2 below is a summary of the data collected.

Table 2. Data Collection Summary

Day	Mode	Hours HH:MM:SS	S1Fence Detections	Debris Fence Detections	Known Satellite Correlations	Average Correlation Distance (km)	Unique Satellites	Multiple Correlations	Element Sets Generated	RCS Reported
11-May	3	7:53:25	9596	48414	7414	18.79	2239	142	336	1032/513
12-May	1	3:15:01	9146	4096	2236	22.75	1226	82	73	382/215
12-May	3	5"03:24	8276	29077	5950	21.65	1801	109	190	683/352
Total		16:11:50	27018	81537	15600		5266	333	599	2097/1080

RESULTS

Objects that did not correlate with Space Surveillance Network (SSN) catalog were declared uncorrelated targets and were locally tasked during testing. The biggest challenge associated fence detections, of small debris following the initial observation, is reacquisition on subsequent passes. It is extremely important that the Eglin radar attempt reacquisition on the new debris objects at the first available opportunity; specifically the first visible pass following the initial detection. Finding small debris after several orbits can be very difficult due to atmospheric drag. If the accuracy of the initial element set is such that other sensors in the SSN can track a new debris object, the object may become part of the catalog. In addition, SSN radar sensors collect Radar Cross Section (RCS) data to estimate future resource allocation during search and tracking.

Fence Detections

The data displayed in Table 2 are totals for the hours shown. The two numbers shown for RCS reports are from logical record 288 (larger of horizontal or vertical polarization receiver channel return) and logical record 437 (average RCS, both polarizations) respectively.

Table 2 shows the total number of detections (and false alarms) for the S1 and debris fence during mode 1 and 3 operation. Not shown are retransmission detections. Often there are multiple returns from a surveillance fence transmission. To determine if multiple targets are present, a retransmission is made, where additional pulses are transmitted to the same location where possible multiple targets exist. In addition to the nominal fence detections, approximate 0.5 to 1 percent of the detections were made from a retransmission.

Note the number of fence detections are quite large. This is because false alarms are included in these columns. From the logical records available it is a very tedious task to determine which fence detections are false alarms. If a detection is determined to be a false alarm logical record 22 is recorded. But unfortunately, there is no logical path to determine the fence detection to which it is associated. The false alarm rate is function of the pulse repetition frequency, the number of independent range samples, the number of integrated pulses (coherently or non-coherently), and the voltage threshold or SNR. The primary action that will change the false alarm rate is adjusting the FFT Doppler weights, normally a technician's function. It was assumed that during version 99-1 development, test, and evaluation these coefficients remained unchanged so that the same false rate was maintained.

Critical to the new debris fence's operation is effectiveness. As discussed above the radar is controlled by the resource period. In addition, the radar's operating mode determines the priority of the pulse scheduler (what a pulse or burst of pulses are assigned to do, i.e. surveillance, search, or track). From Table 2, it can be seen that during Mode 1 the S1 fence had more than twice (2.26) the number of detections than the debris fence. Whereas in Mode 3, the debris fence had more than four (4.34) times the number of S1 fence detections. But, by itself, the total number of detections does not indicate relative performance. Comparing the ratio of fence detections to the ratio of the resource period activity and the ratio of the percent of expended energy is a better measure of fences' relative sensitivity/ effectiveness. Table 3 shows this comparison.

Table 3. Surveillance Fence Performance Comparison

Day	Mode	Debris Fence/ S1 Fence Detections	Debris Fence/ S1 Fence % Resource period	Debris Fence/ S1 Fence % Expended Energy
11 May	3	5.59	4.20	4.99
12 May	1	0.42	0.35	0.41
12 May	3	3.60	3.05	3.51

In all cases, the debris fence detects a greater percentage of objects with respect to the percent utilization of the resource period and percent power expended. Examining the viewing opportunities and minimum range; however, should also be folded into the investigation. Recall, the S1 fence azimuth field-of-view (FOV) is nearly 30-degrees greater than the debris fence.

However as previously discussed, the debris fence has two advantages. First, the debris fence is erected at an elevation angle 10-degrees higher than the S1 fence. This provides the debris fence with greater sensitivity. Second, the debris fence has a higher probably of detecting and tracking satellites that pass through the radar's FOV on their descending node. These later effects are not quantified in this report because the data shown in Table 3 are the overall result of these effects.

Radar Cross Section Measurements

The radar cross section of an object is a complex function of the size and shape of the object, the wavelength of the electromagnetic (EM) energy reflected from the object, and to a lesser degree the polarization of the transmitted energy. There are three distinct regions where the RCS can be characterized as a function of object size and wavelength. These regions are discussed in more detail because the Eglin radar detects objects that fall into all three categories. The Rayleigh region is defined where the wavelength (λ) is much greater than the object size. The object acts as a volume scatterer where there is little phase variation as the impinging EM wave is reflected from the object. In this region, the individual scatterers react simultaneously to the incident EM wave. The relationship between a sphere's radius and its RCS is shown in equation 1.

$$RCS = 114 * \pi^5 * r^6 / \lambda^4 \qquad \text{Eq. 1}$$

where r = radius of the sphere.

The Mie or resonance region is defined where the wavelength is on the same order as the object's size. The behavior of the reflected wave is oscillatory because creeping waves are created by the incident EM energy interacting constructively and destructively to create the specular reflection. The mathematical relationship between the RCS and object size is very complex; readers are referred to reference 2. The third region defined is known as the optical region where the wavelength is much smaller than the object size. The object can be modeled as the sum of many independent scattering centers. The RCS in this region is independent of wavelength. An object will have the same RCS regardless of the wavelength. Equation 2 describes the relationship for a sphere.

$$RCS = \pi * r^2 \qquad \text{Eq. 2}$$

Radar Cross Section Results

The data collected during the Eglin debris fence testing resulted from quality observations following fence detections, confirmation, and subsequent tracking. The data presented is only from UCTs. Figure 4 is a histogram (5dB bins) of the data collected during Mode 1 and 3 operations. The plot shows the RCS from the sum of the V- and H-polarization channels versus count. The corresponding size, which was estimated using the NASA Size Estimation Model is shown in the table on the plot[3].

The results, although similar to other orbital debris measurements made by other radar sites, are not intuitive. The peak in the count is between -15 to –10 dBsm. But the count decreases as RCS gets both larger and smaller. The decrease in count as RCS increases is attributable to fewer larger-sized UCTs. The decrease in count as RCS gets smaller is due to the sensitivity of the radar. Reports from more sensitive L-band or X-band radars and in-situ measurements, have shown that the number of debris objects increases as the size of the debris objects decreases.

Of a different interest are the V- and H-polarization returns. Figure 5 shows the ratio of the V/H to the sum of V and H receiver channels for the UCT fence detections. This scatter plot shows an even distribution about V/H = 1. Hence, the mean of the RCS distribution is one or for the data collected; the debris population returned an equal amount of energy in both polarization receiver channels.

Figure 6 shown the track data from the same object as Figure 3. Note the change in SNR as this target is track over this five-minute period. At several instances, the object reflects over 100 times (-20 dB) less energy in one polarization receiver channel than the other. Unfortunately linear polarization (unless both V and H polarizations are transmitted and received) doesn't provide much information about the shape of the object. Whereas with radars that transmit circular polarization, the ratio of the principal to orthogonal polarization is often a fair indicator of whether an object's shape is spherical or cylindrical.

CONCLUSION

This report has shown that the new Eglin debris radar surveillance fence performs as expected. The debris fence detects more objects than the S1 fence compared to the energy expended. The radar cross section measured from uncorrelated targets compares favorably with previous studies.[3]

Due to the elevation of the S1fence most data is collected on satellites during the ascending node of a satellite's orbit. This is probably also true for the debris fence. However, if the fence were erected at 45 degrees elevation, it would be equi-likely to detect and track satellites on descending or ascending nodes and the debris fence would have better sensitivity.

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3. Settecerri, T. J., et. al., *Radar Measurements of the Orbital Debris Environment: Haystack and HAX Radars October 1990 – October 1998,* NASA, Lyndon B. Johnson Space Center, Houston, TX, October 1999

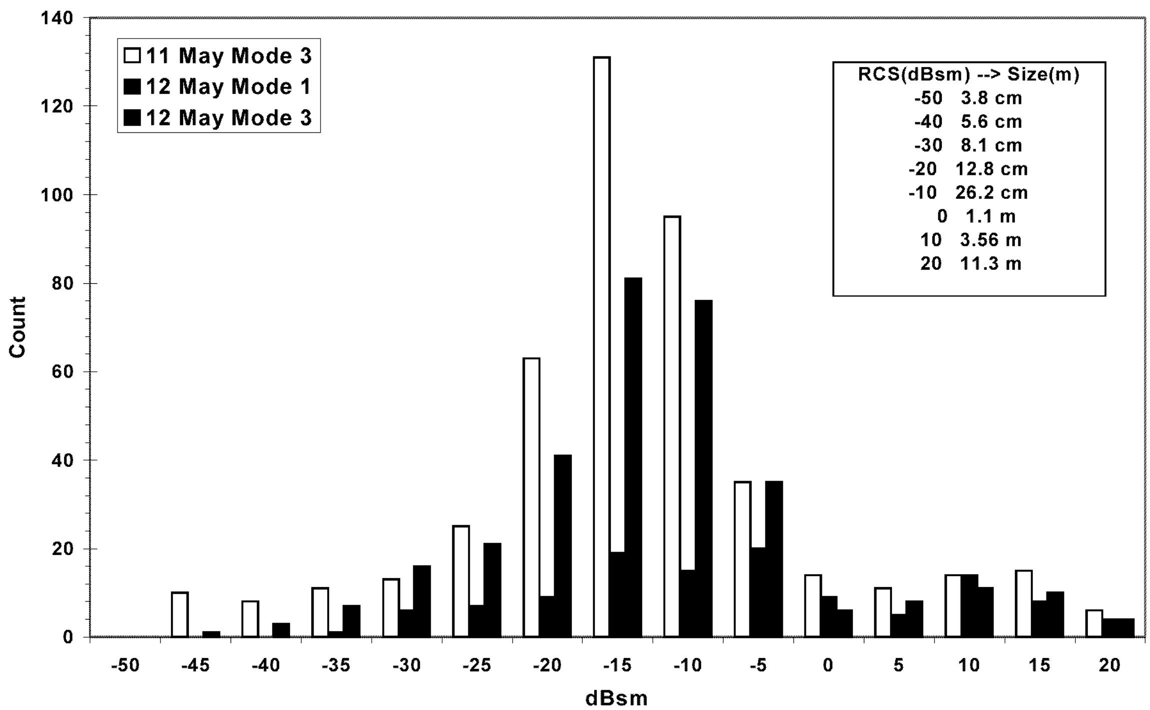

Figure 4. RCS Histogram

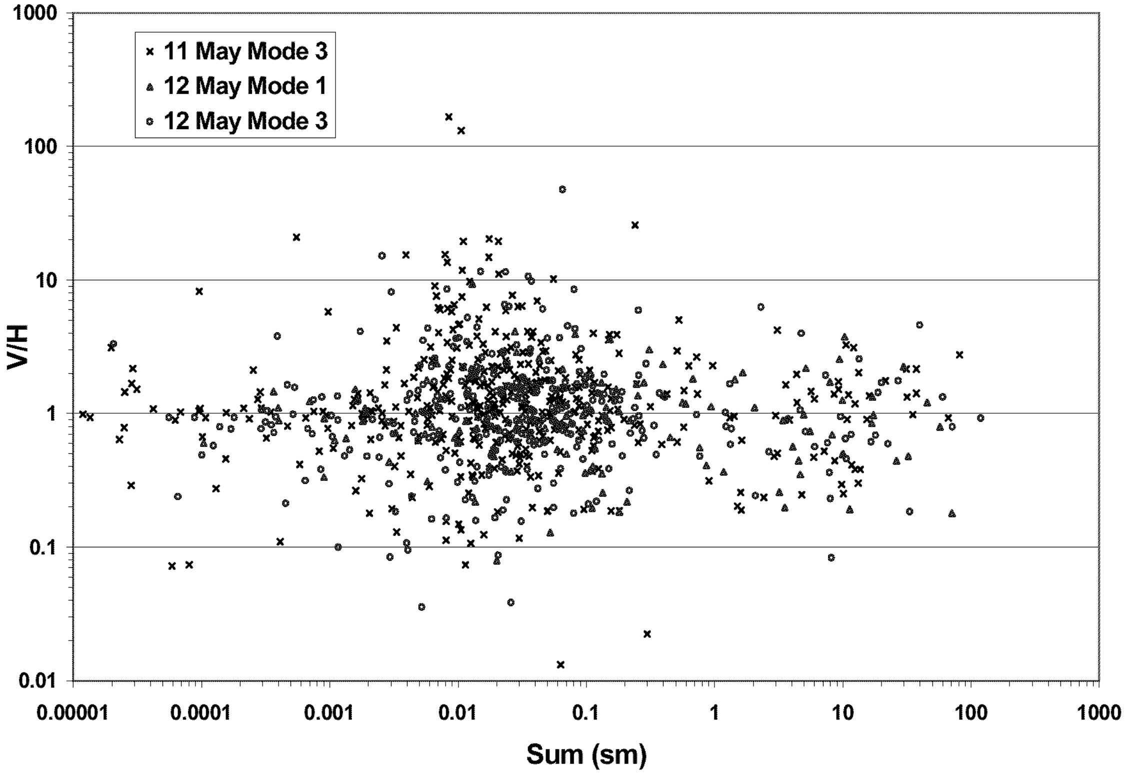

Figure 5. V/H Polarization Ratio versus Sum Polarization

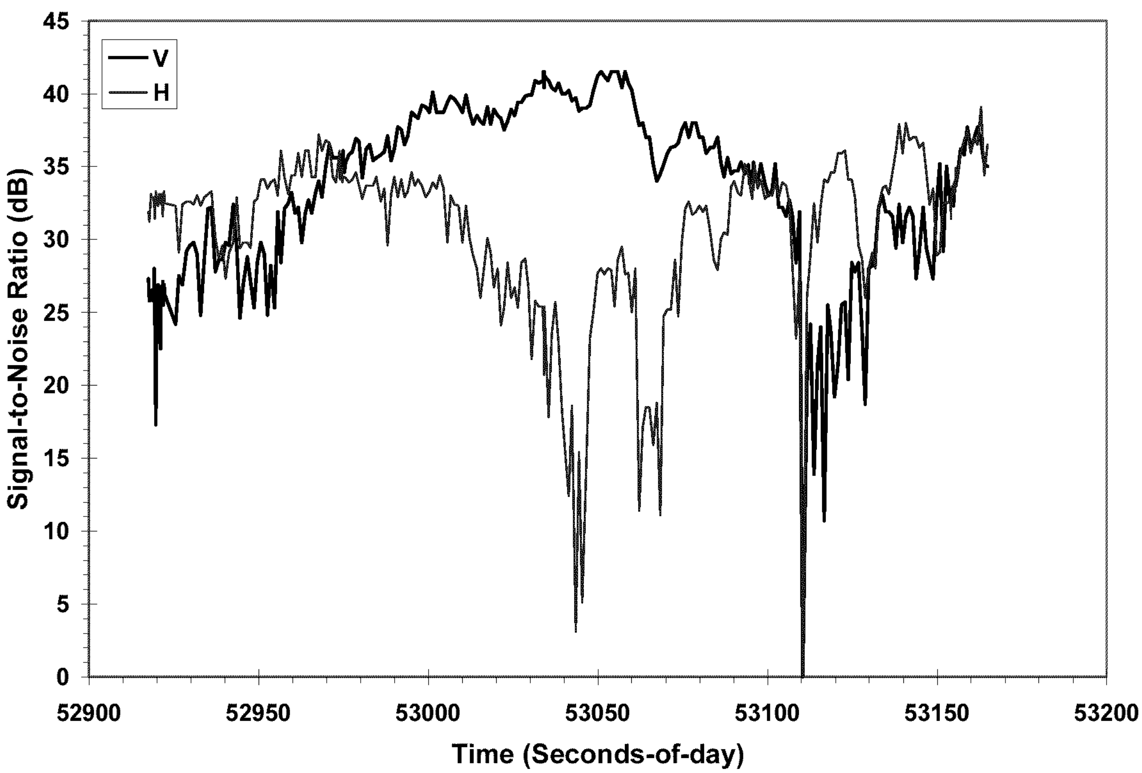

Figure 6. Polarization Comparison for a Catalog Object