SEARCHING FOR SATELLITE EJECTA WITH GROUND-BASED RADARS

Susan E. Andrews, Dennis Hall, and R. Sridharan

MIT Lincoln Laboratory
244 Wood Street
Lexington, MA, USA 02173

Three sensor calibration experiments have provided the opportunity to develop and test strategies for searching for small debris ejected from orbiting satellites. Two Orbital Debris Radar Calibration Spheres experiments (ODERACS I and II) and the MSX calibration spheres experiments called for well characterized targets to be deployed from space craft under highly controlled circumstances. Ground-based sensors were tasked to find, track, and characterize the objects. While the goal of the experiments was to calibrate select sensors, execution required development of strategies for finding the targets. Therefore, these experiments have implications for debris searches around newly launched satellites or disintegrating satellites.

1. INTRODUCTION

Characterization of the orbital debris environment for objects of sizes greater than 1 cm in diameter has become of great concern to spacecraft designers. The workhorse systems that collect metric data on space objects are generally assessed to only routinely collect data on low Earth orbit (LEO) objects larger than 10 cm. While a variety of sensors (e.g., the Haystack radar) have conducted sampling experiments on objects much smaller, this still leaves needs in two areas unanswered:

1) The sampling supports models of the debris environment, but not deterministic characterization.
2) The sampling may not allow for timely characterization of break-ups

The first deficiency means that objects such as lens caps or other material ejected during a launch may never be tracked - the same holds for pieces breaking off of a satellite. The second means that objects may decay before the opportunity exists to observe the results of a break-up. In addition to yielding an incomplete characterization of the orbital environment, this also yields incomplete data for characterization of the break-up event. Such characterizations are used to support models of break-ups, which are then used to help model the general debris environment.

The capability to observe objects near the time of separation from a larger spacecraft or a break-up event has two benefits: 1) smaller search space and 2) opportunity for observation prior to orbital decay. Given the limited coverage of objects in the 1-10 cm sizes and the limited search capabilities of sensors used to find and track objects of such sizes, the reduction of the search space is critical. Experiments stressing the ability to find and track small objects ejected from a spacecraft provide an opportunity to evaluate capabilities and to develop strategies for tracking objects in the event of a break-up or ejection.

Section 2 will give background on ejecta characterizations, the primary sensors providing data for this report, and the three experiments. Section 3 will briefly describe the results of the ODERACS I experiment, and Section 4 will describe the results of the ODERACS II experiment. Section 5 will describe the results from three of the MSX sphere deployments. Section 6 will provide conclusions, a summary, and concepts for future work.

2. BACKGROUND

Three critical parameters of ejecta are the size, the differential velocity, and the time of ejection. The angle of ejection is also important but search spaces can be designed around an angle uncertainty if the search is conducted near the time of ejection (break-up) and the other parameters are well known or hypothesized. Extensive work has been done (Refs. 1- 4) characterizing differential velocities and debris sizes from known breakups and modelling break-up phenomenology.

Three key sets of break-ups have provided velocity and size data. Table 1 shows estimated velocity and size distributions, based on observational data (which naturally limits minimum size). The Solwind breakup was due to hypervelocity impact, the others are hypothesized to be the result of explosions.[1,2-] Figure 1 shows a plot of estimated radar cross-section as a function of velocity and inclination for an Ariane third stage break-up. Note that the higher velocity objects are typically the smaller objects. Theoretical differential

Proceedings of the Second European Conference on Space Debris, ESOC, Darmstadt, Germany, 17-19 March 1997, (ESA SP-393, May 1997)

velocities for break-ups range from meters/second to kilometers/second, depending on size and break-up mechanism.[1,2,3,4]

OBJECT	VELOCITY RANGE (m/sec)	SIZE RANGE (cm)
SOLWIND	10 - 320	15 - 90
ARIANE 3RD STAGE	1 - 280	15 - 200
DELTA	7 - 500	15 - 400

Table 1. Estimated differential velocity and size ranges from observed break-ups[1,2]

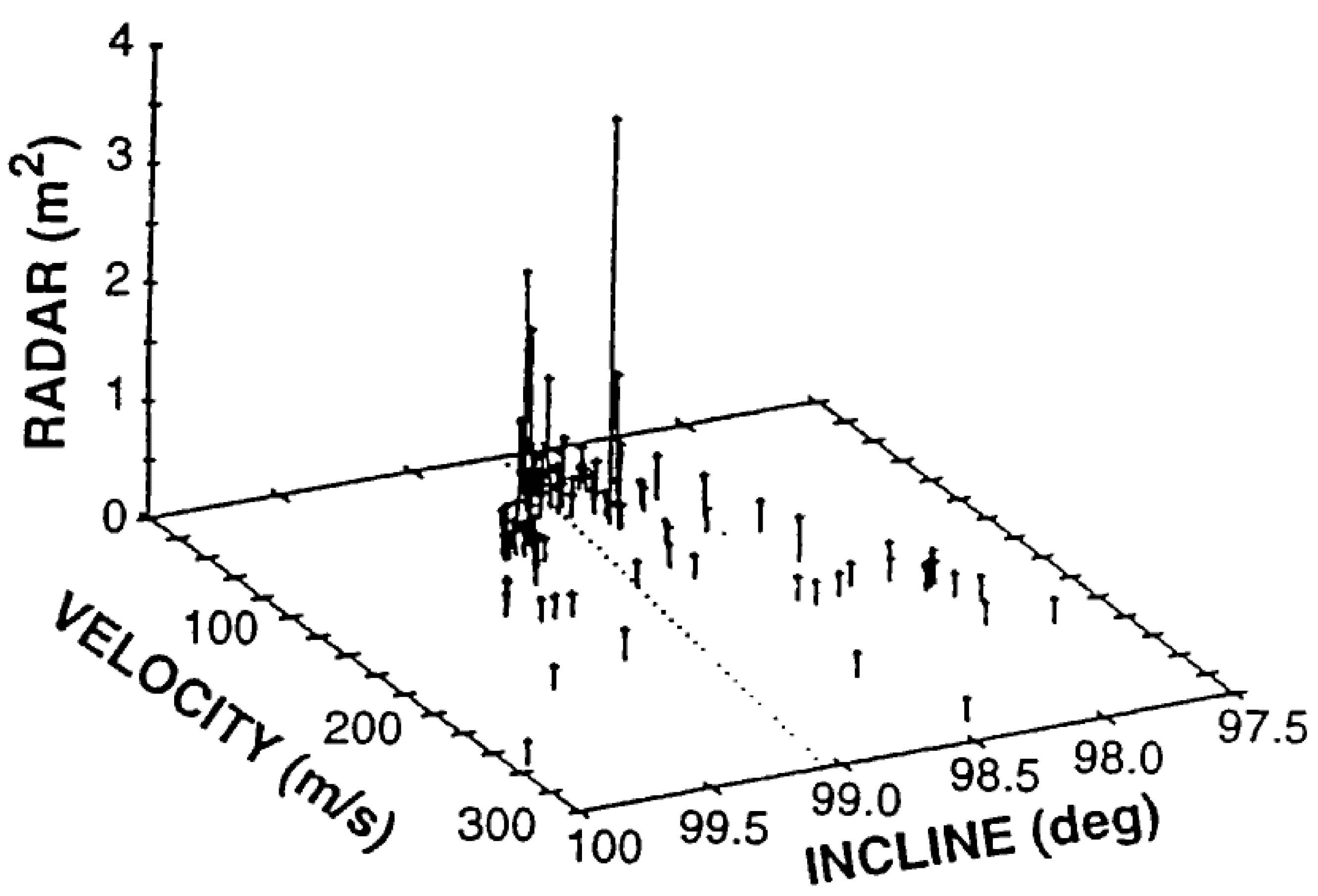

Figure 1. Estimated radar cross section, differential velocity, inclination distribution of Ariane third stage break-up[1]

Differential velocities for intentional small ejecta during launch and early orbit phases of satellites tend to be much smaller than for break-ups. Ejection velocities for things such as lens covers tend to be on the order of 1 - 2 m/s and are generally less than 5 m/s.[5]

A variety of radars participated in the experiments, but the two of interest for this report are the Haystack Long Range Imaging Radar and the Millstone Hill Long Range Tracking Radar, both operated by MIT Lincoln Laboratory (MIT/LL) in Massachusetts. The Haystack radar is an X-band radar, used for satellite imaging and statistical sampling of the orbital environment. The Millstone radar is primarily used for collection of metric data on semi-synchronous and geosynchronous objects, but also participates in debris studies. Both transmit in the right circular polarization and receive in both. Table 2 gives the primary characteristics of these radars and the nominal expected signal-to-noise (SNR) on a sphere of 10 cm in diameter.

PARAMETER	MILLSTONE	HAYSTACK
WAVELENGTH (cm)	23	3
BEAMWIDTH (deg)	0.44	0.05
SENSITIVITY (SNR dB, OdBsm @ 1000 km)	48	58
SNR per PULSE 10 cm sphere @ 2000 km	17.9	25.5
SHUTTLE (15dBsm)	51	61

Table 2. Radar Characteristics

The two radars are located within a kilometer of one another and their pointing can be linked so that the pointing of one is slaved to the pointing of the other. This is an important capability for search, since it allows one radar to search while the other anchors the search on a known object. It also allows the radars to search independently, taking advantage of each radar's distinct capabilities, while allowing for quick boresiting of either radar on a target found by the other.

These radars both have the capability to track multiple objects within the angle of the beam, as long as they are sufficiently separated in range. The finest range separation used commonly by these sensors is 20 m for Millstone and 25 cm for Haystack. While metric data can be collected only on one object at a time, it is possible to change which object is being tracked. This capability enhances the ability of these sensors to find and track closely spaced objects. The primary difficulties in finding small objects close to a normally sized satellite or the shuttle are the dynamic range required for the system, the dynamic range of the user display, and sidelobes.

The ODERACS experiments were efforts to calibrate the cross section (RCS) measurements of the Haystack (and other) radars on objects with linear sizes on the order of centimeters. Such calibration is critical to the use of the sampling data as input to the debris environment models. Haystack is well calibrated in its RCS measurements, but the calibration is based on objects of larger sizes (e.g., a 35.5 cm sphere, a 340 cm cable). Prior to the ODERACS experiments there were no calibration targets in the size regime of interest. Calibration in both the principal and orthogonal polarizations were desired, and the two experiments were developed to provide both.

In the first ODERACS experiment, six spheres were deployed from the U.S. Space Shuttle, two with 15.25 cm (6-inch) diameter, two with 10 cm (4-inch) diameter, and two with 5 cm (2 inch) diameter. One sphere of each diameter had a rough (diffuse) surface and the other a polished surface. Different materials were used to support studies of decay in atmospheric drag. Spheres return a constant (adjusted for range) signal in the principal polarization, and thus the targets supported calibration of the RCS estimated from the principal polarization return.

In the second ODERACS experiment, One of each size sphere was deployed. In addition, two dipoles of length 13.27 cm (5.225 inch) and one dipole of length 4.4 cm (1.74 inch) were deployed. These dipole lengths were chosen to provide a large maximum RCS at L-band (the longer dipoles) and X-band (the short dipole). The dipoles would provide calibration of the RCS estimated from the orthogonal polarization return.

In both experiments, deployment occurred within one revolution of a pass over Haystack. Furthermore, the deployment time was selected to allow a minimum of three consecutive passes of the objects over Haystack prior to a break in viable passes. Table 3 shows the objects, their nominal peak RCS values (dBsm), and their ejection velocities. The object column shows order in the ejection and object type, S for sphere and D for dipole. (Experiment I versus experiment II.) An asterisk indicates that the object was the same type for both experiments. Note that experimental results on the 5 cm spheres and the short dipole will not be discussed in this paper.

OBJ	DIAM /LEN	VEL (m/s)	RCS MHR	RCS HAYSTACK
1 S*	4 in	3.39	-18.15	-20.49
2 S	4 in	2.85	-18.15	-20.49
2 D	5.225 in	2.45	-23	-25
3 S*	2 in	2.13	-24.66	-28.3
4 S	2 in	1.85	-24.66	-28.3
4 D	1.74 in	1.85	-53	-33
5 S*	6 in	1.61	-16.21	-17.45
6 S	6 in	1.40	-16.21	-17.45
6 D	5.225 in	1.40	-23	-25

Table 3. ODERACS I and II object characteristics.

Note that these velocities are in the range of those observed for small objects intentionally ejected during orbital phases of launch and early satellite life. Figure 2 shows the radar cross section of the dipoles as a function of aspect for the Millstone (L-band), Haystack (X-band), and HAX (Ku-band, another sensor used in this effort). Due to the sharp nulls, this target provides a "worst-case" test target from the viewpoint of debris with cross sections that vary greatly with aspect.

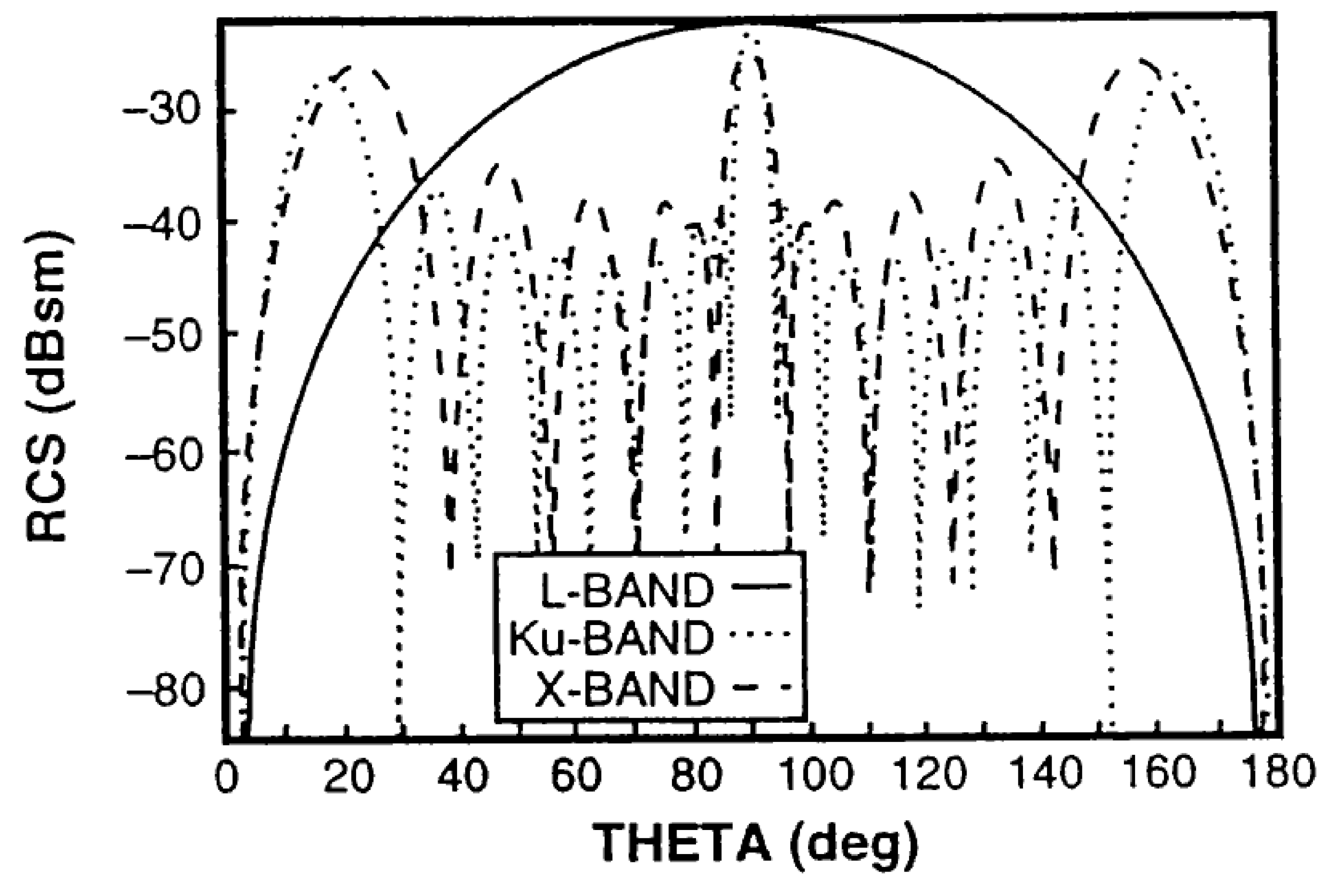

Figure 2. RCS of long dipole as a function of aspect angle and sensor band.

To support calibration of the sensors on the MSX, six spheres, each 2 cm in diameter, were carried on board. The spacecraft flies at an altitude of approximately 900 km. The calibration plan called for deploying the spheres individually, on a one per month basis, with a nominal deployment velocity of 14 m/s and an ejection angle 15 deg. off of the velocity vector in the plane of the orbit. The Haystack radar was tasked to find and track the objects to provide "ground-truth" for the data collected by the on-board sensors. Five of the spheres were coated with Martin-Black and one surfaced in gold, so ground-based visible-band optical observation was practical for only one sphere (not launched at the time of writing). The predicted radar cross sections for each sphere were -48.20 dBsm at Millstone and -33.48 dBsm at Haystack.

3. ODERACS I EXPERIMENT RESULTS

The ODERACS I spheres were deployed in February of 1993 by the STS-60 at an altitude of approximately 350 km and inclination of 57 deg.. Prior to the deployment, predictions were made of the first pass geometry for Millstone and Haystack observation of ODERACS I. Figures 3 and 4 show the predicted angular and range separations, respectively. Capabilities of the Millstone and Haystack sensors supported discrimination between the objects in range shortly after range cross-over of the objects, but the objects were all within one beamwidth for both sensors for the first pass. This yielded a reasonable search space.

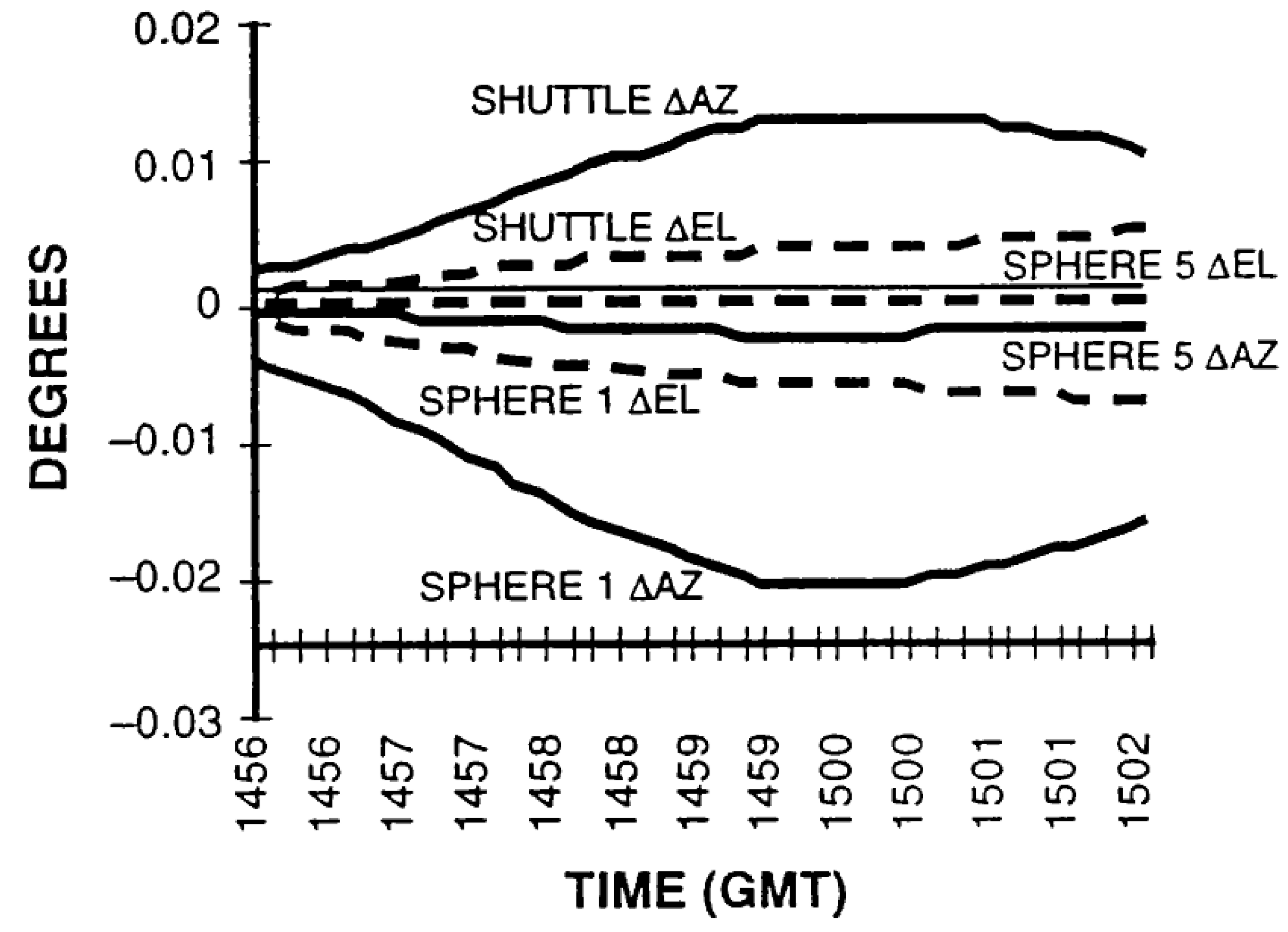

Figure 3. ODERACS I first pass separation of objects in angle, referenced to sphere 6

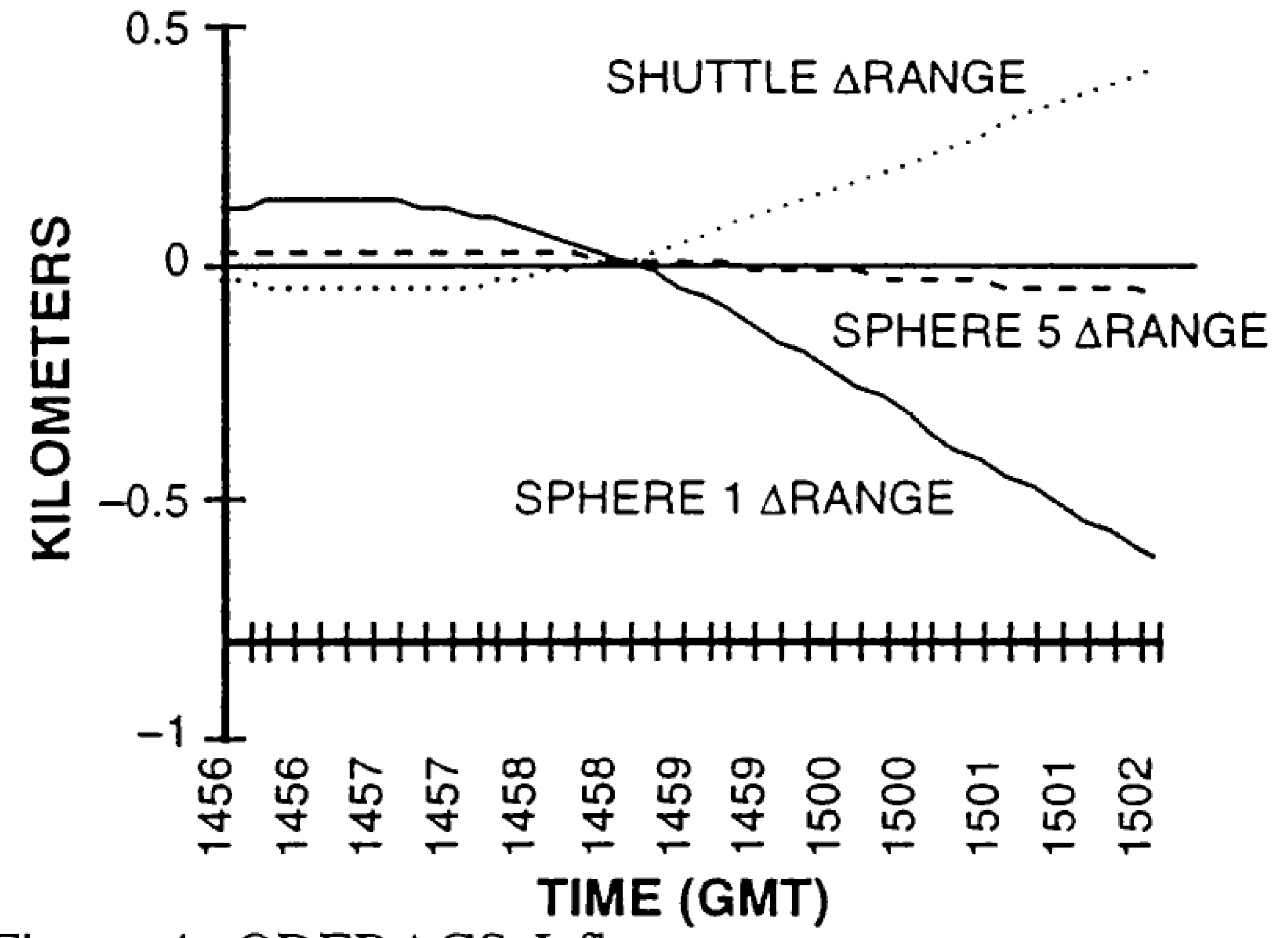

Figure 4. ODERACS I first pass separation of objects in range, referenced to sphere 6

The search strategy was to find the shuttle using established orbital elements as the shuttle rose over the horizon. Using geometry predictions for where the spheres would be relative to the shuttle, the sensors searched in the expected direction of the spheres, using the shuttle to anchor the search. In later passes, spheres found and tracked earlier were to be used to anchor the searches, using anticipated differences between the sphere orbits to guide the searches. The fact that the orbital ellipse of the spheres was similar to that of the shuttle was a significant help, since most searches could be conducted along the shuttle orbit.

The Millstone and Haystack radars were successful at finding both 4-inch and both 6-inch spheres in ODERACS I. During the first pass, Millstone was actually able to observe four objects simultaneously. Figure 5 shows a recreation of the tracking display showing the relative RCS of the four objects as a function of range and time. In later passes when the objects were not all within one beamwidth, Millstone was able to locate a sphere, bypass it for tracking, and then acquire a new sphere by searching near the known sphere in a predicted direction. Some spheres were first tracked many hours after deployment.

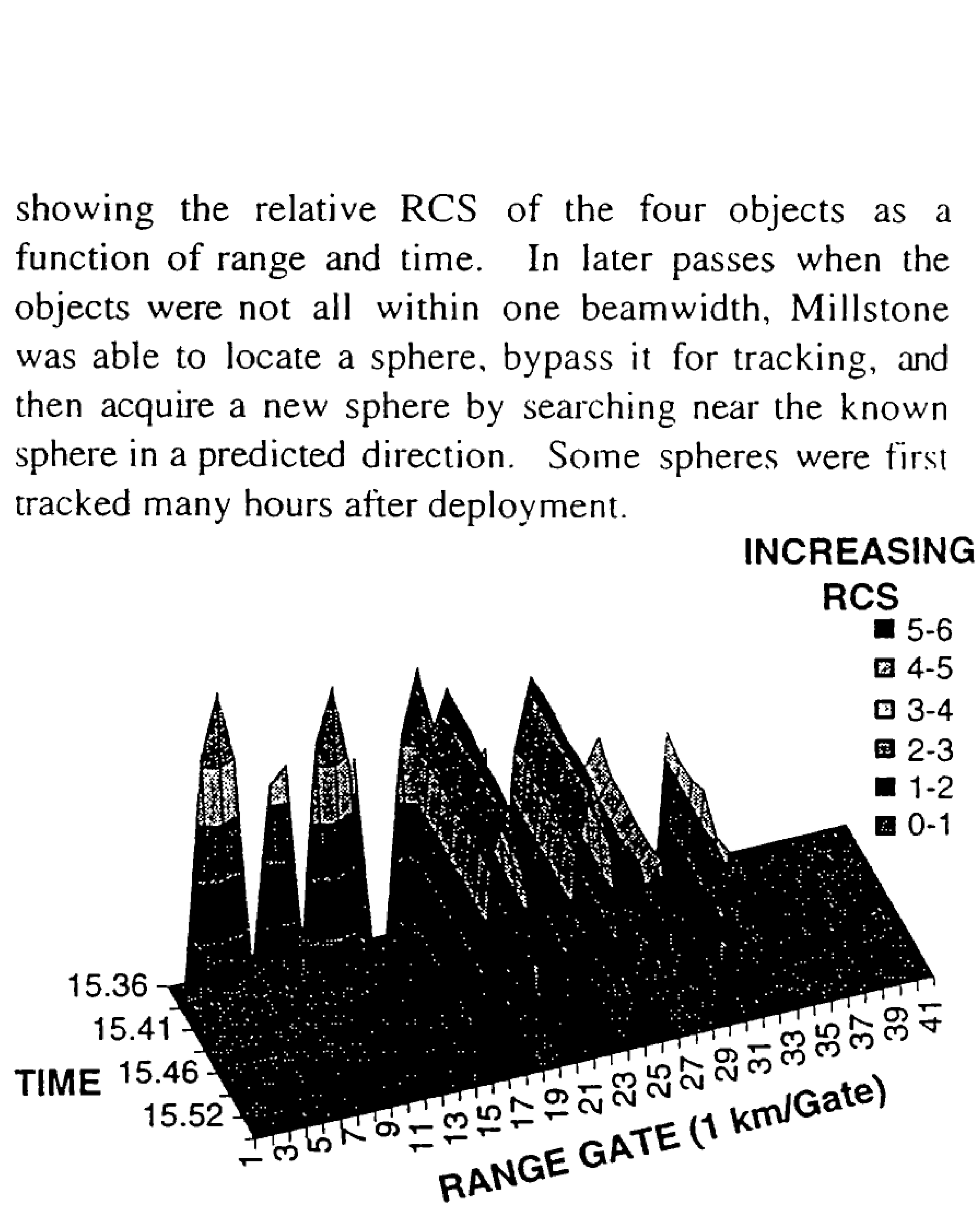

Figure 5. Millstone tracking display for ODERACS I first pass.

4 ODERACS II EXPERIMENT RESULTS

The ODERACS II spheres were deployed in February of 1994 by the STS-63 at an altitude of approximately 350 km and inclination of 52 deg.. As with ODERACS I, prior to the deployment, predictions were made of the pass geometries for Millstone and Haystack observation of ODERACS I. Figures 6 and 7 show the predicted angular and range separations, respectively, of the objects from the shuttle for the first three passes. Because the deployment was planned for earlier in the revolution prior to Haystack/Millstone visibility than in ODERACS I, separation of the targets was greater. Therefore, not all targets would be within one beam of the sensors for the entirety of the first pass. The objects were still sufficiently closely spaced during the first pass, however, to allow reasonable coverage.

Search strategies for ODERACS II were similar to those for ODERACS one, but the emphasis was on tracking the dipoles as early as possible. The dipoles were expected to be affected significantly more by drag than the spheres, so characterizing them early was considered to be vital. Millstone's goal for the first pass was to find the 6-inch sphere, guide Haystack to it (if necessary), and to stay with the sphere while Haystack searched for the dipoles.

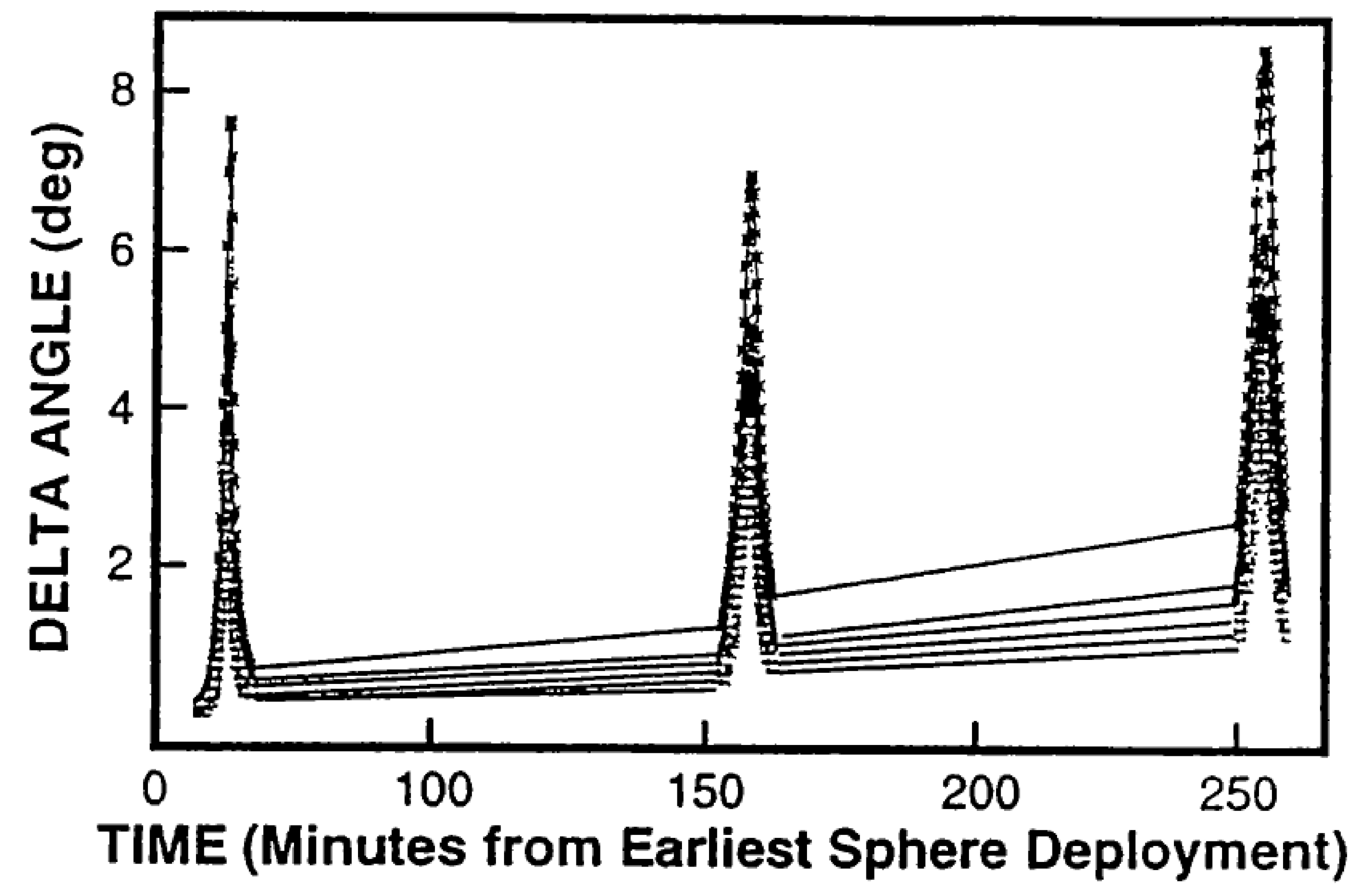

Figure 6. ODERACS II separation of objects in angle, first 3 passes, referenced to the shuttle

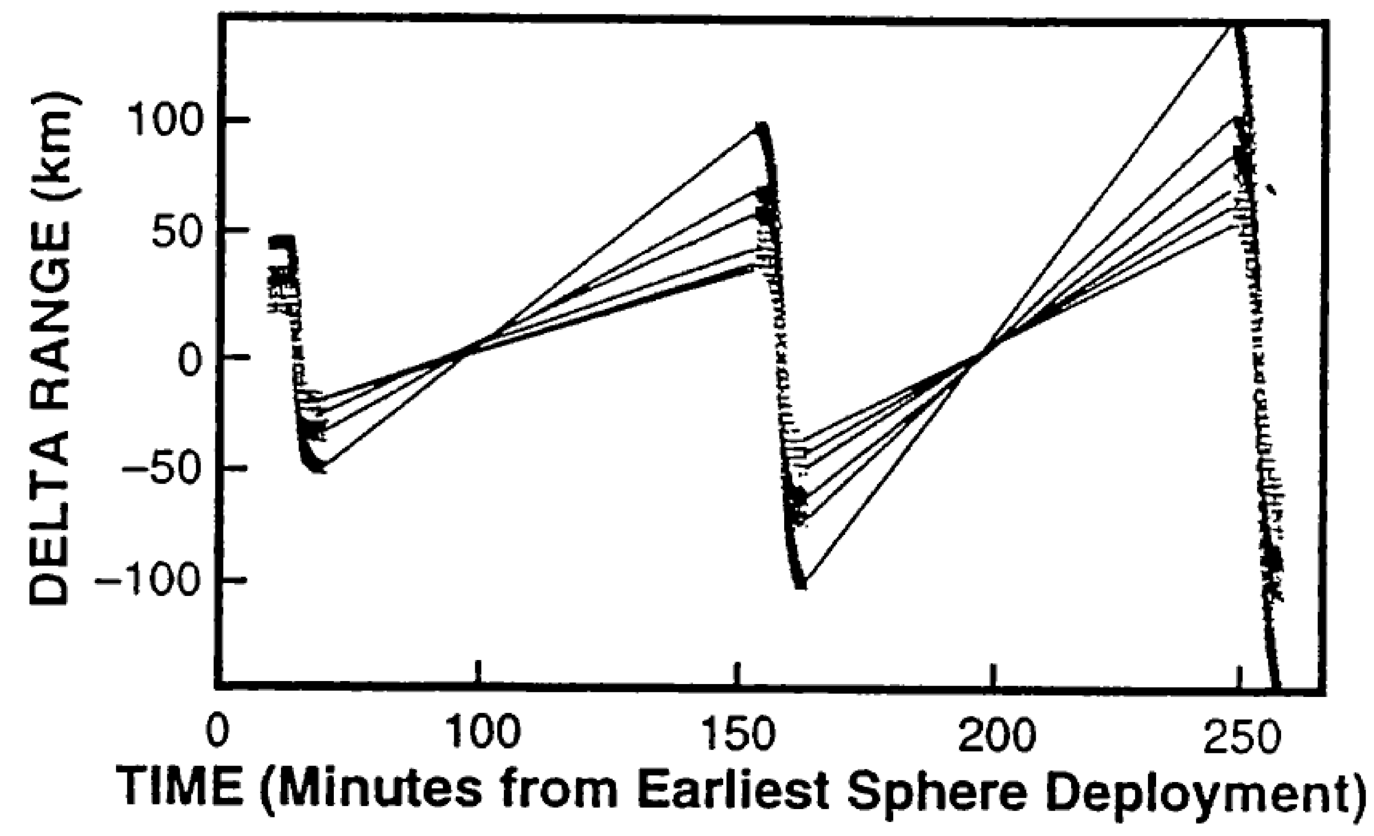

Figure 7. ODERACS II separation of objects in range, first 3 passes, referenced to the shuttle

Millstone and Haystack were successful in tracking the 6-inch sphere, the 4-inch sphere and the two long dipoles. Figure 8 shows a plot of RCS as a function of time from the Millstone operator's display while tracking one of the long dipoles. The variation in target amplitude is very clear, but the sensors were still able to find the dipole, despite the size and variability of the target.

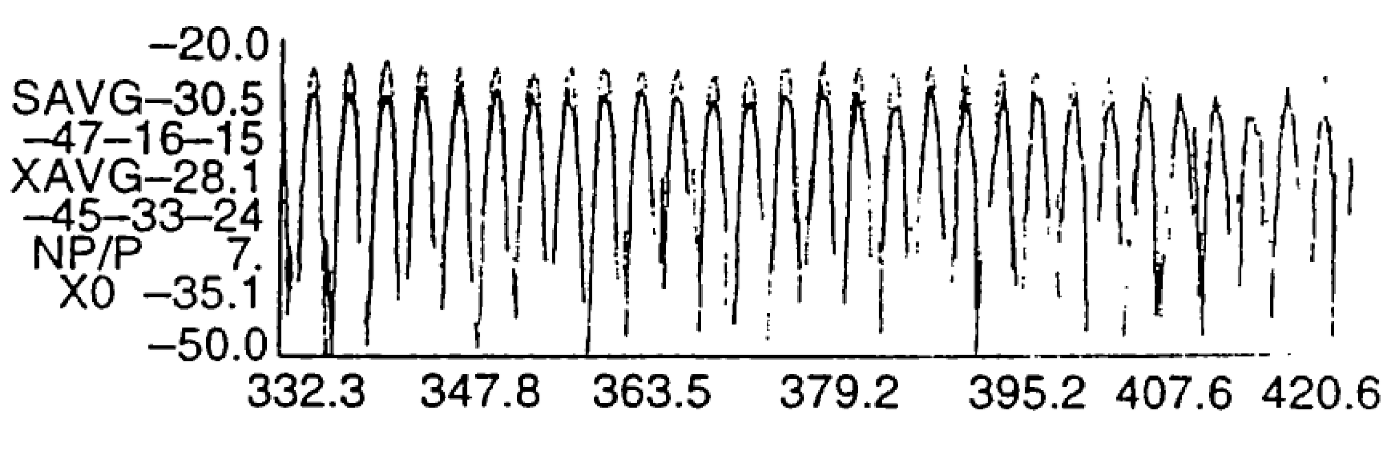

Figure 8. Millstone tracking display RCS vs. time for long dipole.

5. MSX SPHERE DEPLOYMENTS

At the time of writing, three of the MSX spheres had been deployed, and Haystack and Millstone attempted to find all three. Three factors made finding and tracking the MSX spheres much more difficult than the ODERACS targets. First, the predicted cross-sections were much lower. Second, minimum ranges were on the order of 1000 km and often around 2000 km for a pass rather than down to the 650 km of some of the ODERACS passes. Third, experiment constraints led to more difficult geometries.

For the first sphere, deployment was nearly five hours prior to the first pass, and the first pass had a 10 deg maximum elevation and 2600 km minimum range. The sphere was separated from the MSX by a minimum of 10 deg and up to 900 km over the first pass. The first search strategy was to predict a set of orbital elements for the sphere, based on the deployment parameters, and to use that as the basis for the search. Haystack conducted searches around that element set during the first pass, while Millstone anchored on the MSX. In later passes, both sensors searched around the predicted element set and along the MSX orbit.

There were several times when it appeared that Haystack had found the target, but it was never possible to acquire and track the first sphere. It was assessed that there were too many uncertainties in our prediction procedures to make search around predicted element sets practical. A strong request was made for deployment geometry better suited to Haystack/Millstone for the second deployment.

For the second deployment, the geometry was different, but not much better. The sphere was ejected shortly prior to a pass of the MSX over Haystack, but the pass had a maximum elevation of 17 deg and minimum range of 2100 km. The next viable pass occurred eight hours later. There was no successful tracking of the sphere.

For the third deployment, the geometry was ideal. Deployment occurred shortly prior to a high elevation pass over Haystack and the next pass occurred less than two hours later. Early in the first pass, the sphere and the MSX were expected to be sufficiently close that Millstone would not be able to discriminate between the targets. The search strategy was to have Millstone anchor the search early on using the MSX and to have Haystack search around the MSX, biasing the search in the direction predicted using the nominal deployment information. Millstone could search later in the pass, when the ranges were lower and separations greater.

Haystack again found a target that could have potentially been the sphere, but could not acquire and track it. Haystack also attempted to find the target using the stare mode used for other debris collection, but had no success. At Millstone, the sidelobes of the MSX likely swamped any potential return from the sphere during the first pass. The second pass, while having greater separation between targets, had a maximum elevation of 13.5 deg and minimum range of 2300 km. The combination of the shortness of the pass, the range, and the limits to the dynamic range of the Millstone operator's display confounded efforts to acquire and track the sphere.

6. SUMMARY AND CONCLUSIONS

The Haystack and Millstone sensors were highly successful at finding the higher RCS, shorter range, lower deployment velocity targets of the ODERACS experiments (4-inch spheres, 6-inch spheres, and long dipoles). The combination of lower RCS, longer ranges, and tougher geometries confounded the efforts to find the MSX spheres. The ODERACS objects are more representative of objects ejected during launch or early in a satellite's lifetime. The MSX spheres represent a moderate sized fragment and the low differential velocity end of a break-up.

There are changes to experiment planning and operations that could be made that might significantly increase the chances of success. First, despite their utility for normal operations and even the ODERACS experiments, there are aspects of the displays at both Haystack and Millstone that limit the opportunity of the operator to recognize a small target found in a search and then to act quickly on it. Second, better prediction routines could be developed and coded to predict and propagate an orbit based on specified deployment parameters (the one used for our effort was a low level-of-effort package). This would aid the specific experiment, but would not be of benefit in observing random ejecta. Third, some changes to the signal processing algorithms, such as upgrades to the coherent integration processes, could enhance the chance of success and of tracking precision. Fourth, simple practice could improve the chance of success, since the operations were distinctly different than the norm for these sensors. Even with the good geometry passes, opportunities to familiarize experimenters with what to search for and how to search on actual displays and with actual equipment was limited.

The ODERACS and MSX experiments have provided excellent opportunities to test strategies for searching for satellite ejecta. In the regime of orbits with altitudes less than 500 km, it appears very practical to find objects ejected at velocities on the order of 1 - 4 m/s, even many hours after ejection. More work is required if the altitude and velocities are raised significantly while reducing the size of the objects. Improvements in prediction algorithms, signal processing algorithms, and operator displays could improve the chance of success, but a high sensitivity, high search rate sensor might be required to have a high probability of success at finding and tracking the majority of objects larger than 1 cm (length) resulting from a break-up in LEO.

7. REFERENCES

1. Benz, F.J., Kays, R.L., Bishop, C.V., and Eck, M.B., Explosive Fragmentation of Orbiting Propellent Tanks, *Orbital Debris from Upper-stage Breakup* Editor J. P. Loftus, American Institute of Aeronautics and Astronautics, Inc, 1989.
2. Badhwar, G.D., Tan. A., and Reynolds, R.C., Velocity Perturbation Distributions in the Breakup of Artificial Satellites, NASA Johnson Space Center, 1989.
3. Smirnov, N.N., Nikitin, V.F., Kiselev, A.B., Dimitrienko, I.D., and Dushin, V.R., Generation of Space Debris from Explosions of Spacecafts' Fuel Tanks - Final Report, Moscow M.V. Lomonosov State University, Moscow, 1994
4. Chobotov, V.A., Spencer, D.B., Schmitt, D.L., Gupta, R.P., and Hopkins, R.G., Dynamics of Debris Motion and the Collision Hazard to Spacecraft Resulting From an Orbital Breakup, *Report SD-TR-88-96* , The Aerospace Corporation, 1988.