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A SEARCH FOR A PREVIOUSLY UNKNOWN SOURCE OF ORBITAL DEBRIS: THE POSSIBILITY OF A COOLANT LEAK IN RADAR OCEAN RECONNAISSANCE SATELLITES

D. J. Kessler, M. J. Matney, R. C. Reynolds, R. P. Bernhard, Lockheed Martin Space Mission System and Services, C23, Houston, TX, 77058, USA

and

E. G. Stansbery, N. L. Johnson, A. E. Potter, NASA Johnson Space Center, SN3, Houston, TX, 77058, USA

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D. Anz-Meador, Viking Science and Technology, Houston, TX, 77058, USA

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P.D.Anz-Meador, Viking Science and Technology, Houston, TX, USA

ABSTRACT

Measurements of objects in the size range between 1 mm and 10 cm, begun in 1989, revealed populations with distribution characteristics different from those predicted by either explosions or collisions. The measured spatial and temporal characteristics required that these new populations consist of a large number of small-debris objects injected into orbit with very low velocities relative to one another. Radar polarization of the debris suggested that this population in near-circular orbits was much more spherical in shape than debris at other altitudes. The orbital characteristics of the debris matched those of Radar Ocean Reconnaissance Satellites (RORSATs). The RORSAT design was examined to determine a possible cause of this debris and was found to contain a significant amount of coolant consisting of the liquid-metal alloy Sodium-Potassium (NaK). The leakage of this coolant from RORSATs, producing a large number of orbiting liquid metal spheres, was consistent with all observations. The Long Duration Exposure Facility (LDEF) data was then reexamined, resulting in the reclassification of hypervelocity impact craters containing only NaK. The Haystack and Millstone radars were used with telescopes to acquire and track a sample of small objects in the RORSAT orbits, resulting in detailed radar and optical measurements of nine objects. All nine objects were concluded to be metal spheres with the same mass density as NaK.

While the measurements to date cannot prove conclusively that the RORSATs have leaked NaK into Earth orbit, no other explanation is consistent with all observations. The issue has been discussed with Russia and there is an ongoing effort to reach consensus.

INTRODUCTION

Early models which predicted the small orbital debris population assumed that either explosions or collisions were the major source of small debris. [1] This was because no measurements existed which were capable of identifying any other source. The first measurements of debris in the size range between 1 mm and 1 cm used ground radar in an operational mode which sampled the orbital debris environment, rather than track individual objects. Since the early models were capable of predicting what the sample characteristics should be, this provided a valuable technique for testing the model predictions.

RADAR DATA ACQUISTITION AND THE SEARCH FOR EXPLOSION SOURCES

In July, 1987, the NASA Administrator requested JPL to use their radar background to assist JSC in the design and operation of a new radar concept to detect small orbital debris. The concept consisted of pointing the radar beam in a fixed direction and sampling the orbital debris population as objects passed through the beam, rather than track and catalogue orbital debris. JPL conducted two experiments to test JSC's concept for measuring the debris environment. One test used the Goldstone radar in California, obtaining a sample of the environment in the 2 mm to 5 mm size range. [2] For this test, an X-band (8.5 GHz) radar transmitter was connected to the 70-meter dish antenna. A receiver was connected to a smaller 26-meter antenna located 21.6 km from the transmitter. The two antennas were pointed approximately vertically, but tilted slightly toward one another so that their fields of view intersected at an altitude of 600 km with a detection cross-section area of 11.2 km^2. Between March 22 and October 16, 1989, 48 hours of data were collected over 15 separate days and nights. During this time, an average flux of 6.4 events/km^2/day was measured with a signal-to-noise ratio greater than 3.87. This signal-to-noise ratio corresponds to an expected false alarm rate of one per five hours (which was subtracted to get the measured flux) and a detection limit of 1.8 mm in diameter for a metallic sphere.

During most observation days, one or two events per hour were recorded. However, six periods were observed when the measured flux was as high as 15 per hour, lasting about one hour. The time of day (GMT) that the high flux was observed was plotted versus the day of the year of the observation and is shown in Figure 1. Five of the six periods clearly fall along a line, illustrating that the "swarm" of debris would pass overhead 0.26 hours ($\pm$ 0.01 hour) earlier every day. Also, during these one-hour periods, the measured radial velocity of most of the detected objects was less than 10 meters/sec and varied linearly from a negative to positive value during the hour. The observations indicated that the detected objects were associated with one another and the orbits of the objects in this swarm were nearly circular.

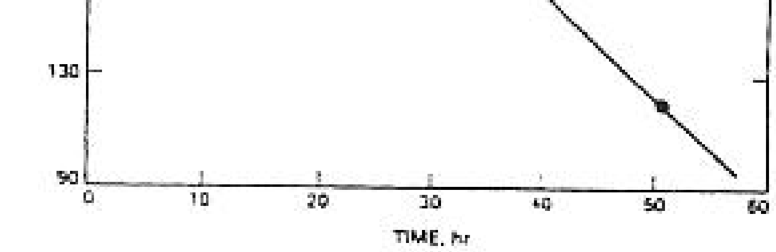

Figure 1. Time of Observed Swarms by Goldstone. Five of the six observed swarms fall along a line, indicating the swarms were in the same orbit, with a sidereal precession rate of about -2.9 degrees per day.

Figure 1 can be interpreted as a measure of the rate of change of the orbit's right ascension of ascending node. For a circular orbit, this rate depends only on altitude and inclination. A rate of -0.26 hours per day corresponds to a sidereal precession rate of -2.9 degrees per day. If the source were at 700 km, its orbital inclination would have to be near 67 degrees; if its altitude were at 900 km, its orbital inclination would be near 64 degrees. The one swarm observation which does not fit along the straight line in Figure 1 was observed about 10 hours earlier than the swarm periods represented by the other five observations. If these five observations represent the descending part of a circular orbit, with an inclination somewhere around 65 degrees, then one would expect the ascending part of the orbit to pass overhead about 10 hours earlier. Therefore, this single observation is likely to be the other half of the same swarm of debris. A search for this source was not conducted until after the Haystack observation program had acquired additional data pointing to an unknown source or sources of orbital debris.

HAYSTACK RADAR OBSERVATIONS

With the success of the JPL radar tests, NASA and the US Space Command in 1990 entered into an agreement which resulted in NASA acquiring data using the X-band Haystack radar, located near Boston, MA. [3] The primary mode of operation would be for the radar to point vertically, in a "staring mode", measuring small debris as objects passed through the radar's 0.05 degree field of view. Range, range rate, and signal strength in principal and orthogonal polarization would be measured as a function of time as the object passed through the field of view. In addition, because the radar is monopulse, the approximate position of each particle in the beam was determined.

The Haystack radar used the same antenna to both transmit and receive the signal. This resulted in a slightly reduced sensitivity for Haystack compared to Goldstone; Haystack was estimated to be able to detect a 0.5 cm diameter metal sphere at 500 km distance. However, the altitude of the measurements by Haystack was only limited by the time between the transmitting and receiving of signals, and consequently the radar could measure the environment over a much broader range of altitudes than Goldstone.

The Haystack data showed a strong concentration of approximately 1 cm orbital debris at altitudes between 850 km and 1000 km. [4] For those who had worked exclusively with the US Space Command catalogue, this concentration may not have seemed unusual since there is also a concentration of catalogued objects within this altitude range. However, for those who had used breakup models to predict the 1 cm orbital debris population, the Haystack observations introduced a problem: All breakup models assumed that smaller debris would be scattered over a larger altitude range than larger debris, reducing the concentration of smaller debris. Since the altitude profile measured by Haystack actually indicated a greater concentration than the catalogue, the measured altitude profile could not be duplicated using existing breakup models and would be difficult to duplicate using radically modified breakup models. Unlike the swarm measured by the Goldstone radar, this debris appeared to be more evenly distributed in the time of day that the debris passed over-head, characteristic of either several sources, or debris that had been in orbit for several years.

The first attempts to understand the concentration of 1 cm debris began by questioning the assumptions in the existing breakup models. These breakup models were used in NASA's EVOLVE model. [5] Smaller debris were predicted to be scattered over a large range of altitudes, resulting in a predicted population of small debris that was nearly independent of altitude for altitudes between 500 km and 1500 km. These EVOLVE model predictions were incorporated into the NASA Engineering Model, which is a different modeling approach that interpolates past direct measurements of the environment, using EVOLVE results as a basis for that interpolation. [6]

Figure 2 compares the Engineering Model predictions with the Haystack measurements after 547.6 hours of observations below 1250 km. [7] The predicted detection rates include the Haystack radar sensitivity to debris size as a function of altitude. Also shown is the predicted detection rate for catalogued objects. The figure clearly illustrates that the peak measured between 850 km and 1000 km is sharper than the peak predicted by the catalogue, and much sharper than the peak predicted by NASA models. This implies that radical changes to the satellite breakup models would be required if breakups were assumed to the source of the measured debris.

To attempt to bring model predictions into agreement with the measurements, the velocity of small debris fragments was reduced as much as satellite breakup data would allow. However, the peak in the predicted detection rate for the smaller debris was still not as sharp as the measurements and was at a lower level. This conclusion was tested further by a special observation test by the Haystack radar. The US Space Command Catalogue exhibits another peak in its altitude distribution near 1500 km altitude. This is partly due to four major

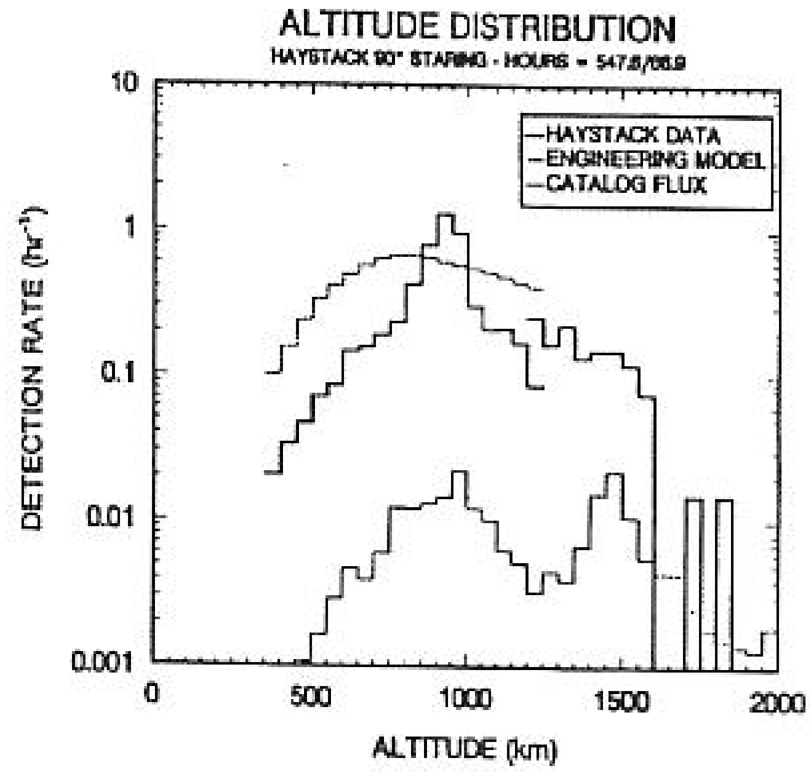

Figure 2. Haystack Radar Count Rate as a Function of Altitude Compared to Predictions. The sharp peak between 850 km and 1000 km was not predicted by NASA's EVOLVE or Engineering Model.

breakups at this altitude. If a general, radical lowering of the fragment velocity for small fragments was required in breakup models, then any Haystack observations at this altitude should also reveal a sharp peak near 1500 km altitude. Haystack was reconfigured to measure the debris environment between 1200 km and 2000 km altitude. A total of 66.9 hours of vertical staring data was obtained within the altitude interval, and the results are included in Figure 2. These results clearly do not show a peak at 1500 km. The measured count rate is only about a factor of two below the model predictions over most of the altitude band, meaning that minor adjustments to the number of fragments produced may be required, but a lower fragment velocity of breakups around 1500 km would be inconsistent with the measurements around that altitude.

The need to change the velocity distribution was tested further by examining the radar Doppler measurements by Haystack. The Doppler measurements provide an accurate measurement of the rate of change in range, or "range rate", of any detected particle. When the radar is pointed vertically, this range rate measurement becomes a measurement in the rate of change in altitude of each debris object detected. If the debris is in a circular orbit, the range rate would be zero. A concentration in range rates near zero indicates a concentration of near-circular orbits. When this data was examined as a function of altitude, a peak rate around zero at altitudes near 900 km was most pronounced, consistent with the requirement that the detected objects near 900 km be in near-circular orbits. The EVOLVE model attempted to duplicate this range rate distribution, first using the earlier, higher-velocity distribution for fragments. The resulting EVOLVE range rate prediction was that a larger number of debris should be detected with higher range rates than detected by Haystack. When the velocity of the fragments was reduced, as discussed previously, the EVOLVE range rate prediction was much closer to that measured by Haystack, although still slightly short of predicting as many objects with near-zero range rate. The fact that the modeled range rate was close to the measured range rate does introduce the possibility that one breakup, or several breakups at exactly the same altitude, caused the peak between 850 km and 1000 km.

Another parameter that Haystack measures using monopulse is direction of motion through the radar field of view. From this measurement, orbital inclination can be determined. However, this measurement is not very accurate, having an approximate uncertainty of plus or minus 5 degrees for most objects detected, and an even greater uncertainty for objects with a low signal-to-noise ratio. Figure 3 gives the resulting inclination of these measurements as a function of altitude. The figure shows that if there were a single breakup, or a family of breakups at a single altitude, then the inclination is likely to be somewhere between 60 and 70 degrees.

A search for breakups within the altitude range of 900 km to 1000 km, and inclinations between 60 and 70 degrees finds only one breakup to fit these orbital conditions. [8] When COSMOS 1375 exploded on Oct. 21, 1985, it was in a 990 km by 1000 km, 65.8 degree inclination orbit. This 650 kg satellite is believed to have been used as a Soviet "anti-satellite" target 40 months before it broke up. As of May, 1995, 58 fragments had been catalogued, with 57 still in orbit. The cause of the breakup probably was a battery malfunction, as the satellite is not believed to have contained any other energy sources. [9]

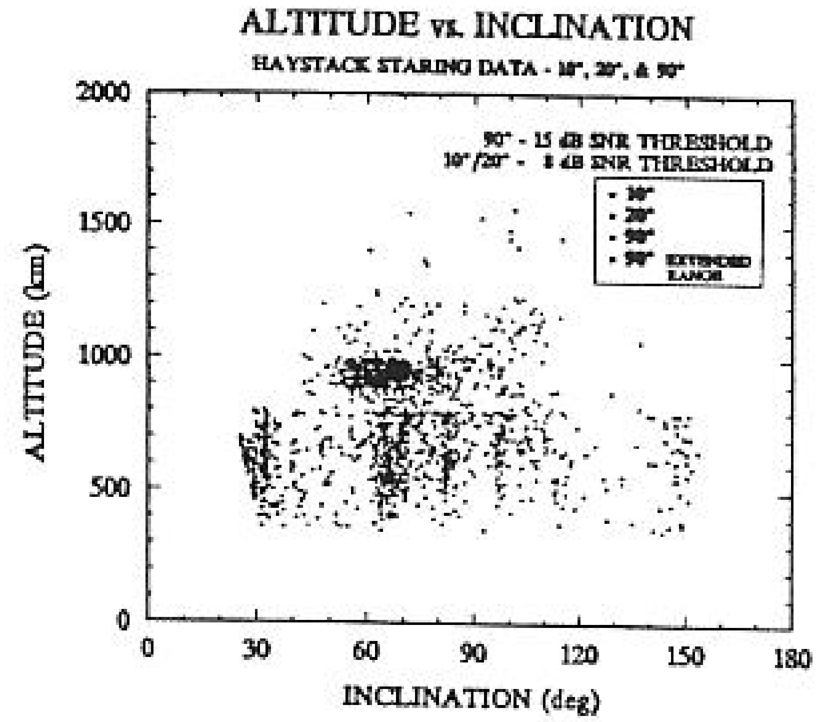

Figure 3. Inclinations Measured by Haystack. Below 850 km, inclination was measured by Doppler, which is more accurate than the monopulse used above 850 km. The inclination of debris between 850 km and 1000 km had inclinations which were most likely between 60 and 70 degrees.

To test the possibility that the COSMOS 1375 breakup could be the source, calculations were performed to determine how the orbits of the 57 fragments contributed to spatial density as a function of altitude. Results are shown in Figure 4. This figure shows that this breakup might meet the requirements for the unknown source of debris if the following conditions were met: (1) if the breakup could produce a sufficient quantity of small fragments, (2) if those small fragments were not spread in altitude over greater distance than the catalogued fragments, and (3) if the differences in peak spatial density (about 50 km higher than the peak in the Haystack count rate) could be accounted for.

The required number of fragments to be produced is found by converting the observed count rate to flux, then spatial density, and using the equations which relate spatial density to number when inclination and latitude are known. [10] The flux measurements by Haystack requires an average of 132,400 objects to be found between altitudes 750 km and 1050 km. If it is assumed that the flux measured in bins 750-800 km and 1000-1050 km represents "background" flux

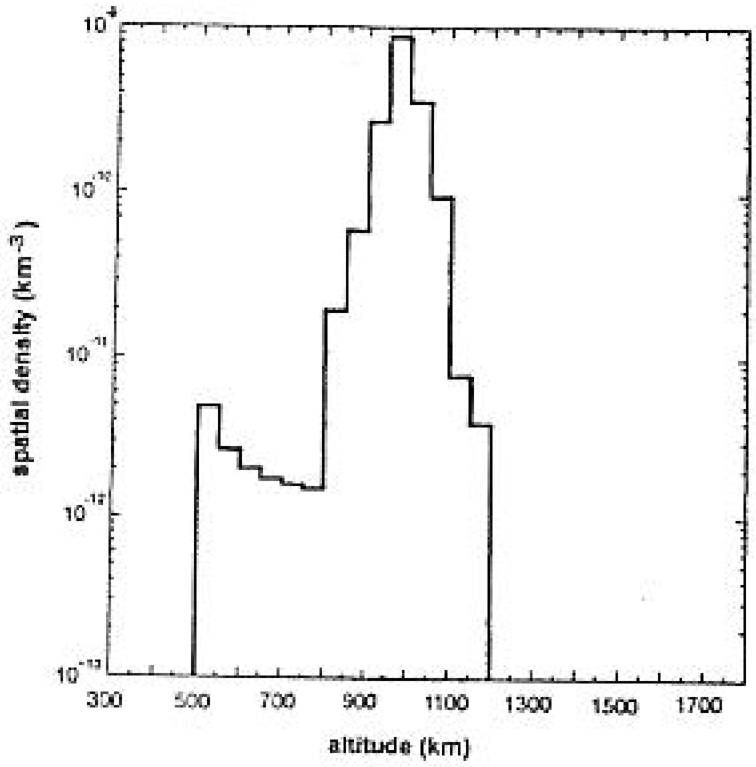

Figure 4. Altitude Profile of Catalogued Fragments from COSMOS 1375. COSMOS 1375 is the only known explosion between 60 and 70 degrees inclination, and 850 km and 1000 km altitude. The peak density of the explosion fragments is too high in altitude to be consistent with the unknown source measured by Haystack.

(not associated with the assumed source, in this case COSMOS 1375), then about 54,000 objects, should be subtracted from the total to obtain the required number of fragments, leaving 78,400 fragments to have been produced by COSMOS 1375. Based on the sensitivity of the radar near 900 km latitude, each fragment would have to have been larger than 0.6 cm in diameter to have been detected.

A low energy explosion, as might be expected from a battery failure, would not produce this many fragments. Most models place the number of fragments for this type explosion at about 1,000. More energetic breakups, as might result from detonation of a range-destruct device or from a collision with a large piece of debris, could produce the required large number of fragments; however, the same energy required to produce the large number of small fragments would also produce higher velocities, spreading the debris over a larger altitude range.

Also, still unresolved was the inconsistency of a COSMOS 1375 explosion producing a peak density about 50 km above the Haystack peak. It was considered possible that the low-energy explosion produced objects with a high area-to-mass ratio, such as might be expected from thermal insulation material or some other composite materials. That type of debris could have decayed by 50 km in the five years between the explosion and first measurements. In addition, such low-density material might produce a large number of fragments with little energy. A drop by 50 km in altitude from 1985 to 1990 should show at least a similar drop in altitude from 1990 to 1993 because lower altitude and greater solar activity would increase the decay rate. However, no change in the Haystack-measured altitude distribution could be found during the period through 1993.

The question was then reversed ... what is the minimum mass density of debris that would not measurably change the altitude profile measured by Haystack over this time interval? Using the orbital debris decay model with the observed solar activity, a value of 0.5 g/cm^3 was obtained. That is, if the mass density of the debris observed between 850 km and 1000 km were less than 0.5 g/cm^3, then the debris would decay in altitude during the period from 1990 through 1993 and result in a change in the altitude profile measured by Haystack. This change was not observed, so the mass density of the debris must be greater than 0.5 g/cm^3. This minimum mass density, combined with the measured size distribution (varying roughly inversely proportional to the mass of the debris) places the total mass released by this source to be at least 30 kg, assuming this size distribution continues over an order of magnitude in diameter (e.g., from 0.6 cm to 6 cm). If the mass density were 1 g/cm^3, then the total mass released by the source would be twice as high, or 60 kg.

Therefore, the possibility seemed remote that the COSMOS 1375 explosion was a source of the debris measured by Haystack. Its debris was not likely to meet the requirement for a large number of fragments with a small-fragment velocity, nor the requirement for the debris to have decayed by 50 km. Finally, 30 kg of small-fragment mass is an unreasonable amount for a relatively small spacecraft with little stored energy to produce.

Another Haystack observation parameter also strongly suggested that the unknown source must be very different from other orbital debris sources. Haystack also measured both the "principal polarization" (PP) and "orthogonal polarization" (OP). The ratio of OP/PP provides a measure of the type of object being detected. For example, a dipole would result in a ratio of 1.0. A metal sphere would result in a ratio near zero. Flat plates would return a variety of ratios, depending on the orientation of the plate at the time of observation. The OP/PP ratios for each of the observed objects was plotted both as a function of altitude and as a function of the monopulse-derived inclination. The results (Figures 5 and 6) show that the debris detected between 850 km and 1000 km and with inclinations between about 60 and 70 degrees have lower values, characteristic of metal spheres, while the debris at other altitudes are scattered toward higher values, characteristic of flat plates and dipoles. This suggests that the unknown source is producing much more spherical-shaped debris than other sources. These surprising results, together with the failure to identify a satisfactory explosion source, forced the consideration of a non-explosion source.

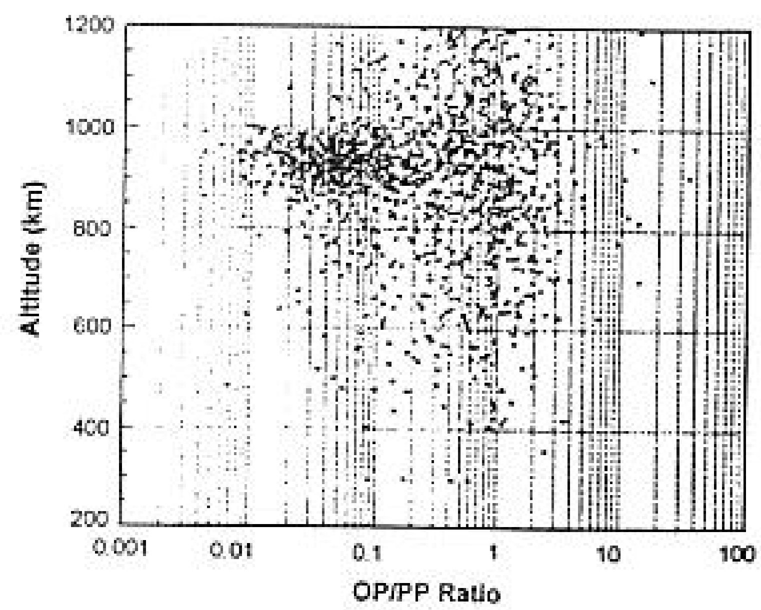

Figure 5. Altitude Distribution of Haystack OP/PP RCS Ratios. The OP/PP ratio is a measure of the object's shape. The large concentration of objects between 850 km and 1000 km has a distinctively low value for this ratio. Such low OP/PP ratios are indicative of conducting spheres.

From the data gathered and analyzed by early 1994, it was concluded that a non-explosion source of debris must exist somewhere between 850 km and 1000 km altitude. The orbital inclination of the source was probably somewhere between 60 and 70 degrees. The source released at least 30 kg of debris, consisting of nearly 80,000 objects, nearly spherical in shape, with diameters of 0.6 cm and larger, and a mass density of at least 0.5 g/cm^3. A search of the US Space Command catalogue of all payloads and rocket bodies in near-circular orbits with perigee above 800 km, apogee below 1050 km, and inclinations between 60 and 70 degrees found 52 candidate sources. However, even though most of

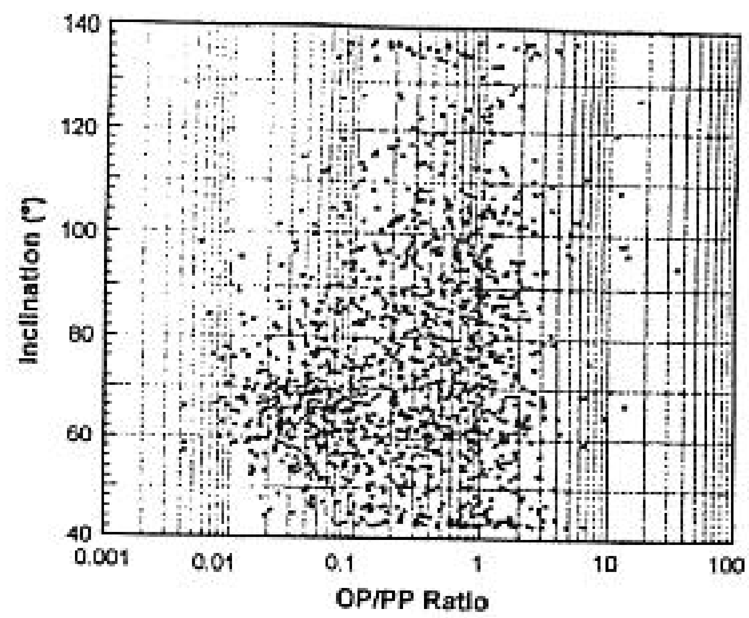

Figure 6. Inclination Distribution of Haystack OP/PP RCS Ratios. The low OP/PP ratio objects appear centered in the 60 to 70 degree inclination band.

the measured debris had inclinations between 60 and 70 degrees, the uncertainty in the inclination measurements made it possible that the unknown source was just outside this inclination range. Extending the range between 55 and 75 degrees increased the number of candidate sources to 81. More information and analysis was needed. The similarity in orbital inclination of the Haystack unknown source and the near 65 degree inclination of the Goldstone unknown source hinted that the two sources may be related.

SEARCH FOR NON-EXPLOSION SOURCES

The Goldstone Swarm

The swarm of debris was measured by the Goldstone radar for more than 150 days over a 40 km altitude band at 600 km. The altitude of the source must be at an altitude of 600 km or higher. However, the time for the debris to decay to 600 km must be short, or the ascending node of the individual particles would become randomized with respect to one another, and the particles would not be observed as a swarm. If the mass density of the debris was not exceptionally low, the altitude of the source would have to be between 600 km and 800 km.

The required source strength for these swarms can be calculated from the measured flux, the rate of orbital decay for objects at 600 km, the latitude of the measurements, and the measured inclination of the source.[10,11] The unknown source was calculated to be producing 40 g/day of 2 mm debris. If a mass density of 1 g/cm^3 is assumed, each particle has a mass of 0.0042 g or greater and the source produces 9,600 particles per day. The source strength when expressed in mass generated per unit of time, is independent of the assumed mass density. Consequently, these observations indicated that the unknown source must be capable of releasing at least 6.0 kg of debris for at least 150 days. The amount would be greater if we adopted the size distribution measured by Haystack; however, the actual Goldstone-measured size distribution may be a function of time, with smaller objects decaying through 600 km before larger objects. In any event, 6.0 kg of debris indicates that the likely source is a more-massive payload or upper stage.

Between 600 km and 800 km, only three payloads or rocket bodies were found with the proper inclination and altitude: COSMOS 44 (65.1 deg, 650 km by 768 km orbit), the COSMOS 44 rocket body (65.1 deg, 648 km by 763 km), and COSMOS 1900 (66.1 deg, 692 km by 747 km). Each of these three were located at an altitude so that their debris (with a mass density of 1 g/cm^3) would take about 100 days to decay to 600 km; consequently, the orbit plane containing the debris at 600 km would be expected to pass overhead about 40 minutes before the orbital plane of the source.

A point was picked on the line in Figure 1 (near the highest concentration of data) at 20:00 hours GMT, which corresponded to day 238. That time point was increased by 40 minutes to account for the difference in the observed particles passing overhead and the time the orbital plane of the source would be expected to pass overhead. The question then becomes, "What object's orbital plane was passing over the Goldstone radar during a descending pass at 20:40 GMT on the 238th day of 1989?" If the orbital plane of one of these three objects were found to pass overhead at this time, then it would also pass overhead at any time along the line in Figure 1. In addition, if the pass were a descending pass, then the ascending pass could be expected 10 hours earlier, explaining the single data point that does not fall on the line.

Figure 7 shows the orbital plane of these three objects at 20:40 GMT on the 238 day of 1989. COSMOS 1900 was the only one that passed over the Goldstone radar site at this time, and it was a descending pass. Consequently, the debris source being COSMOS 1900 is consistent with all of the Goldstone observations.

PREDICTED ORBIT PLANE OF 2mm DEBRIS AT 600km
(DAY 238, 20:00 GMT + 40 MINUTES)

Figure 7. Source of Goldstone Swarms. COSMOS 1900, a lower altitude RORSAT, is the only object below 800 km altitude which passed over the Goldstone radar at a time to observe all 6 swarms.

COSMOS 1900

COSMOS 1900 is a Radar Ocean Reconnaissance Satellite (RORSAT), launched December 12, 1987 by the USSR into an operational orbit of under 300 km altitude. These satellites use radar to observe ships at sea and require a nuclear power source to obtain sufficient power for the radar. If these satellites were allowed to reenter, radio-active material would contaminate the environment on Earth, as did COSMOS 954 in 1978. Consequently, before station-keeping fuel is depleted, RORSATs are placed into a nominal graveyard orbit near 900 km altitude. COSMOS 1900 did not follow the nominal profile. By May, 1988, COSMOS 1900 was obviously in trouble, and it was feared that it would reenter. On September 30, 1988, just before reentering, an apparent automatic system triggered separation of the reactor and boosted it to a 695 km by 763 km orbit. [12] This was 173 days before the Goldstone observations began.

RORSATS: Responsible For Haystack Source?

Between 850 and 1000 km altitude, with an orbital inclination of 65 degrees, are 30 non-functioning payloads associated with RORSATs, as listed in Table 1. [12] The orbital data was obtained from the US Space Command catalogue in Oct, 1991. The orbits of these 30 objects were used to calculate spatial density as a function of altitude, with the results shown in Figure 8. This altitude profile is almost identical to the profile that would be required to explain the unknown source measured by Haystack.

A more accurate measurement of the orbital inclination of the debris measured by Haystack would help resolve whether RORSATs were responsible for the debris by reducing the number of possible sources. The Haystack Doppler data, while staring vertically, had already proven that the debris was in a near circular orbit. Under the assumption that the orbit is circular, Doppler could accurately measure orbital inclination by pointing the radar toward the east, 15 degrees off of vertical. Figure 9 shows the results of such a measurement. The contour lines on the figure are the values expected for each 10 degrees of inclination. The intersecting debris between 850 km and 1000 km is grouped around 65 degrees inclination, there is still a one or two degree uncertainty in the measured inclination.

However, by reducing the uncertainty, the number of candidate sources is also reduced. A search of the US Space Command catalogue, this time limiting inclination to between 63 and 67 degrees, resulted in identification of only 12 more objects in addition to the 30 RORSATS. These 12 objects are also of Russian origin and are either anti-satellite targets, used in Russian anti-satellite tests, or rocket bodies used to put targets into orbit. [13,14] One of the 12 objects is the remains of COSMOS 1375, the previously discussed anti-satellite target. All of the anti-satellite targets and their associated rocket

Table 1. Catalogued RORSATs
Found between 850 km and 1000 km, 8 Oct., 91

COSMOS	Sat. No.	Mission End	Perigee, km	Apogee, km	Inclination
198	3081	28 Dec 67	901	933	65.1
209	3158	23 Mar 68	877	928	65.3
367	4564	3 Oct 70	913	1024	65.3
402	5105	1 Apr 71	959	1017	65.0
469	5721	3 Jan 72	934	1021	64.5
516	6154	22 Sep 72	922	1021	64.8
626	7005	9 Feb 74	904	985	65.4
651	7291	25 Jul 74	878	959	65.0
654	7297	30 Jul 74	929	1002	64.9
723	7718	15 May75	883	978	64.7
724	7727	11 Jun 75	850	946	65.6
785	8473	12 Dec 75	897	1014	65.1
860	9486	10 Nov 76	912	1006	64.7
861	9494	20 Dec 76	925	991	64.9
952	10358	7 Oct 77	928	974	64.9
1176	11788	10 Sep 80	895	941	64.8
1249	12319	18 Jun 81	914	967	65.0
1266	12409	28 Apr 81	890	964	64.8
1299	12783	5 Sep 81	915	973	65.1
1365	13175	26 Sep82	893	967	65.1
1372	13243	10 Aug 82	905	980	64.9
1412	13600	10 Nov 82	900	984	64.8
1579	15085	26 Sep 84	917	968	65.0
1607	15378	1 Feb 85	912	989	65.0
1670	15930	22 Oct 85	911	990	64.9
1677	15986	23 Oct 85	897	984	64.7
1736	16647	21 June 86	938	993	65.0
1771	16917	15 Oct 86	926	983	65.0
1860	18122	28 Jul 87	920	972	65.0
1932	18957	19 May 88	926	1002	65.0

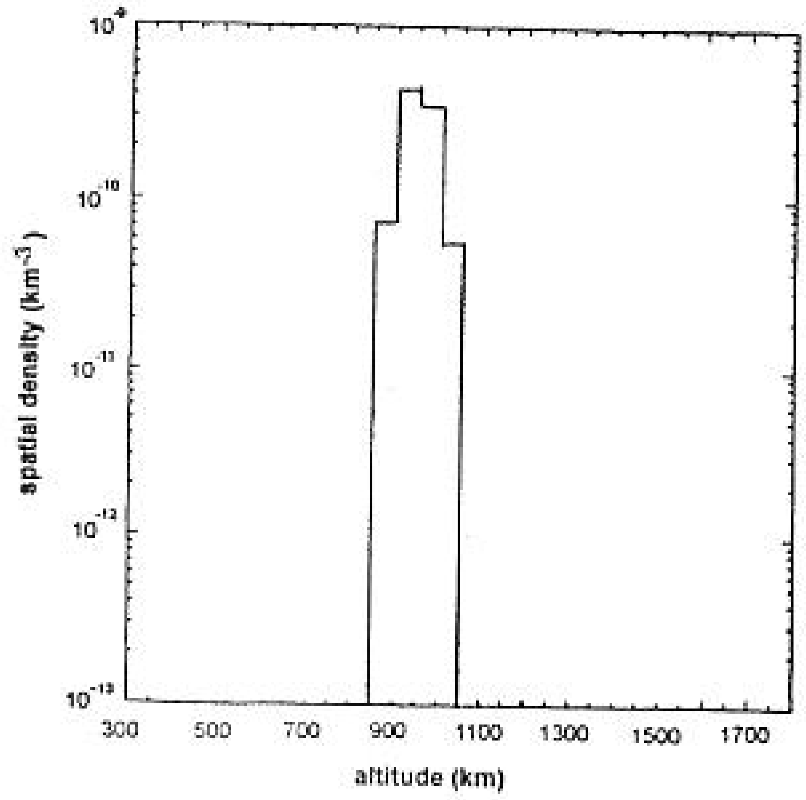

Figure 8. Altitude Profile of Catalogued RORSATs. The altitude profile from the 30 higher altitude RORSATs matches that required by the Haystack observations.

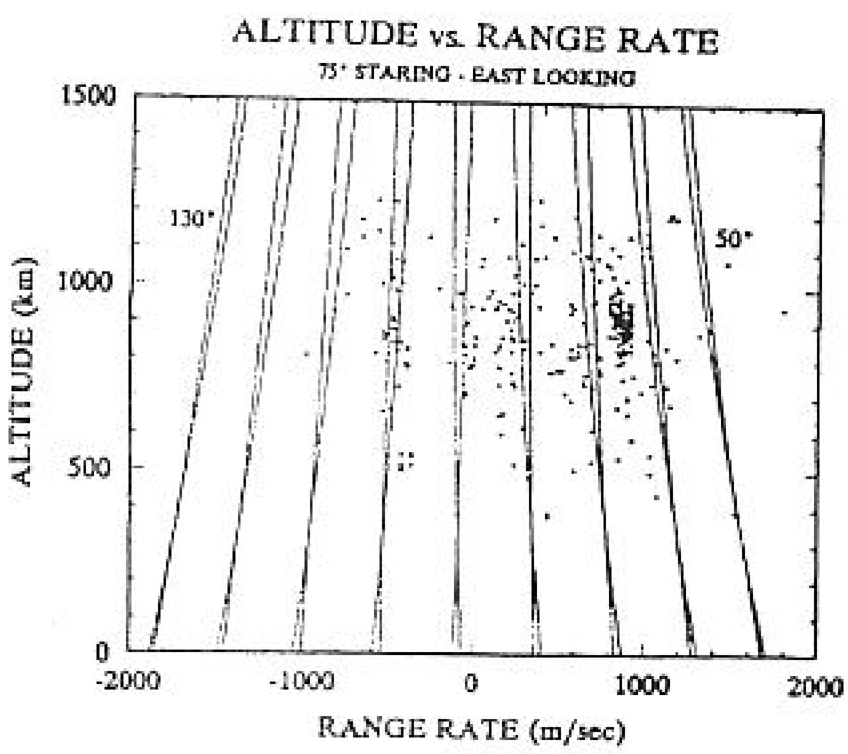

Figure 9. Using Doppler to Determine Inclination. By pointing 15 degrees to the East of vertical, Doppler was used to more accurately determine inclination. The contours (every 10 degrees) are lines of constant inclination expected for circular orbits at the given altitude. A pair of contours is shown for each inclination, depending on whether the pass is ascending or descending. Most objects detected between 850 km and 1000 km were found to have inclinations of 65 $\pm$ 2 degrees.

bodies have orbital inclination of 65.8 degrees, and an average altitude that is about 50 km higher than that of the RORSATs. Consequently, neither the altitude nor the inclination fits the data perfectly, but both are within the uncertainties of the measurements and their interpretation.

It has long been believed that Russian anti-satellite activity was likely to produce a large number of regularly-shaped projectiles, consistent with the number and shape of the objects detected by Haystack. However, it is also believed that these projectiles were ejected at high velocities and ended up in very different orbits than the either the anti-satellite interceptor or target. This property makes it totally inconsistent with the sharp peak in altitude measured by Haystack. While Russian anti-satellite activity might later be found important in understanding the Haystack data, it does not appear to be consistent with the observations in question.

Therefore, all data was consistent with the assumption that RORSATs were the unknown source of debris between 850 km and 1000 km. No other spacecraft or set of spacecraft could be found that was totally consistent. However, the mechanism that would produce the observed debris was still unknown. A study of the RORSAT design and operation was begun to determine any possible sources.

RORSAT Design And Operation

On September 19, 1994, a summary of our conclusions was discussed with a Russian representative to the Inter-Agency Space Debris Coordination Committee (IADC).[15] In addition, Los Alamos National Laboratory was contacted, since they had acquired four Topaz II reactors from Russia for testing and evaluation. After discussions with the RORSAT designer, the IADC representative reported that there was no basis for RORSATs to produce a large number of small particles.

The RORSAT uses a Bouk reactor. The Bouk reactor is different than the Topaz reactors. However, less information is available on the Bouk reactors. Consequently drawings of the Topaz reactor were examined to determine what debris might be generated by a Russian reactor in space. These drawings showed a large coolant reservoir with sodium-potassium (NaK) surrounding the rods. The NaK coolant is an alloy of sodium and potassium that is liquid at room temperature. These drawings also showed that the coolant passed though large radiators. We questioned what happens to the NaK after RORSATs are placed in their graveyard orbit.

It seemed an obvious possibility that coolant was ejected when the core was ejected. Another possibility was that the radiators, subject to punctures by meteoroids and orbital debris, could have also leaked coolant. The theory that NaK was being released by RORSATs would be consistent with all existing data; however, more details were needed to determine the physical properties of the coolant and the amount used, as well as to discover a mechanism for its release.

On October 4, 1994, the Deputy Chief General Designer of RORSATs confirmed, through the IADC member, that NaK was used as a coolant, and its drops could be released when the core was ejected in the graveyard orbit...an operational procedure adopted after COSMOS 954. However, the designer could not give us more details. By scaling the Topez drawings, it was concluded that the coolant in a RORSAT might be about 10 liters and the radiator area might be about 10 sq. meters. The optimal NaK ratio for cooling gives NaK a mass density of 0.9 g/cm^3, so 30 RORSATs could contain a total of 270 kg of NaK, much more than needed to account for the Haystack and Goldstone observations.

Los Alamos also confirmed that the Bouk reactor uses a eutectic mixture of NaK (78% sodium and 22% potassium), which has a melting temperature of -11^0 C. They estimated the amount of NaK present in the entire coolant system to be about 20 liters. [16] The wall thickness of the radiators was estimated by Los Alamos to be about 1 mm, so an orbital debris particle or meteoroid with a diameter larger than 0.2 mm could penetrate this wall. [17] At altitudes below 300 km, the operational altitude of RORSATs, the meteoroid environment dominates the orbital debris environment in this size range and would be expected to penetrate the radiator about two times per year. This would not cause an operational problem, since the operational life of a RORSAT is generally less than 3 months. However, in the graveyard orbit near 900 km, a type of cascading may have occurred: As meteoroids and orbital debris penetrated the radiators, NaK leaked out, increasing the orbital debris environment, which then increased the penetration and leakage rate. The Haystack data was extrapolated to give the current orbital debris environment near 950 km for 0.2 mm and larger debris. This extrapolation predicts debris penetration of the radiator about 20 times per year. [18] Therefore, by October 1994, there was sufficient reason to believe that NaK was the unknown debris observed by both the Goldstone and Haystack radar.

The vapor pressures of both sodium and potassium were used to determine the evaporation rate of the NaK droplets in a vacuum. At a temperature around 0^0C, the diameter of a 1 cm NaK droplet would decrease (linearly) by evaporation to zero over hundreds of years. As it would take about 80 years for this size droplet at 950 km to fully decay in altitude due to atmospheric drag, it clearly will not evaporate before reentering the atmosphere. Consequently, if NaK were released, its orbital lifetime would more likely be controlled by atmospheric drag rather than evaporation. This raised the possibility that smaller droplets might have decayed in much shorter times to lower altitudes and impacted low-altitude spacecraft.

The Long Duration Exposure Facility (LDEF) satellite was in orbit between 1984 and 1990 and, on return, was covered with millions of hypervelocity impacts. About a thousand of these craters, most due to impacting particles around 0.1 mm in diameter, have been examined for chemical composition to determine the source of the impacts. Both natural meteoroids and man-made orbital debris impacts were found; however, for about half of the craters, the source could not be determined, either because nothing was found, or only contamination was found in the craters. [19] The original examiners identified any salts as contaminates and assumed that any observed Na or K was a salt (e.g., NaCl). No one was looking for pure Na or K (or the combination of NaK).

Because of the tentative identification of orbiting NaK, those LDEF craters that contained both Na and K were re-examined to determine if they were salts. Of the 1,000 craters that had been examined, two craters were found to contain only Na and K. This smaller flux of NaK debris at LDEF altitude is consistent with the much larger predicted flux of 0.2 mm debris at 950 km after the orbits have decayed to LDEF altitude, near 400 km.[20]

In early March 1995, Los Alamos concluded that meteoroid or orbital debris penetrations of the radiators was not necessary for NaK leakage. [17] For NaK not to be ejected when the core (consisting of 37 uranium metal rods) was ejected, a special valve to limit NaK release would have to be in place. As the presence of this valve would reduce system reliability, such a valve was unlikely to exist. This would mean that every RORSAT since COSMOS 954 (i.e., 15 RORSATs between 850 km and 1000 km) could have dumped about five liters of NaK from its primary coolant loop. This operation alone could be responsible for putting 70 kg of NaK at altitudes between 850 km and 1000 km, and about five kg at 725 km, almost exactly as predicted by the Haystack and Goldstone measurements.

Russian Analysis And Modeling

While the modeling approach used by Nazarenko is different from that used by the NASA EVOLVE model, Nazarenko's results were very similar to the EVOLVE results using the lowest possible fragment velocity. [21] Therefore, just as the EVOLVE results did not, Nazarenko's results did not duplicate the "sharp" peak required by the Haystack data. Just as the EVOLVE model indicates, Nazarenko's results illustrate that, unless there is a single altitude where explosions dominate and the 1 cm fragments have the same velocity as the catalogued fragments, the sharp peak measured by Haystack cannot be reproduced. Nazarenko also predicted an inclination distribution measured by Haystack. [22] Both of these model results are shown in Figure 10. Nazarenko's model did not match either the altitude distribution or the inclination distributions measured by Haystack.

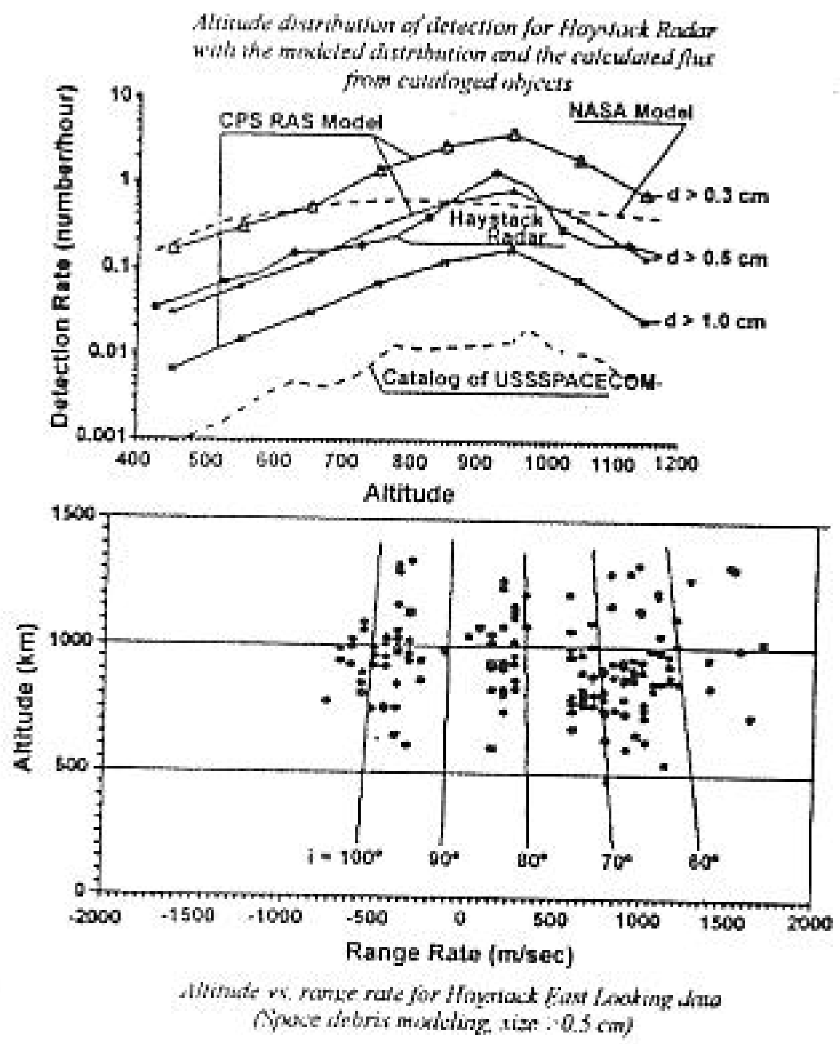

Figure 10. Russian Modeling Results. Attempts by Russia to explain the sharp peak and inclination measured by Haystack using explosions alone also failed, although they were able to obtain a rounded altitude peak near 950 km.

Another Russian analyst, Meshcheryakov, concluded that if NaK droplets were in Earth orbit, they would reach a temperature as high as 1050°K from sunlight, and evaporate in a very short time. [23] This analysis extrapolated available reflective coefficient data on sodium alone to the wave-lengths of interest. Consequently, it was not clear that pure sodium would obtain this high a temperature in sunlight; in addition the presence of potassium and possibly some impurities could easily change the results. Consequently, by July 1996, Meshcheryakov had changed the reflection coefficients so that NaK spheres would reach a temperature of only 293°K. Under these conditions, he predicted that a 1 cm sphere would evaporate to a 0.7 cm sphere in 100 years, consistent with the NASA calculations. [24]

In summary, Russian modeling has not been able to reproduce the sharp peak or inclinations measured by Haystack using only explosions. In addition, Russian analysis agrees that evaporation rates for NaK are slower than orbital decay rates from atmospheric drag. Thus, Russian modeling has not precluded the possibility of the RORSATs as a source of NaK debris.

Search For Metal Spheres In RORSAT Orbits

NASA/JSC funded MIT Lincoln Laboratory to detect, track and characterize small debris between 850 km and 1000 km, with inclinations near 65 degrees. To do this, Lincoln Laboratory used the Haystack, Millstone, and TRADEX radars, and the Firepond observatory in a "stare-and-chase" mode to acquire small objects. Once acquired, the same sensors were used to update the orbital elements and obtain radar and optical characteristics of each object. A total of 11 objects were detected, tracked and characterized. [25] A list of these objects is given in Table 2.

All of the objects detected have inclinations and altitudes that are characteristic only of RORSATs. The objects range in size from 3.4 cm to 5.7 cm in diameter. All of their radar OP to PP ratios were below 0.01, characteristic of metal spheres. Two of the objects were also characterized with the Firepond telescope, which determined both objects were highly reflective and had optical polarization characteristics of a metal sphere. The area-to-mass ratio of each object was determined by observing the rate of change in orbital elements, then calibrating changes in the atmosphere over the same period with a known area-to-mass ratio object at a similar altitude (sat. no. 5398, an MIT calibration sphere). From the measured area-to-mass ratio and object diameter, the mass density of the object could be found, also shown in Table 2. The estimated uncertainty in this mass density is about 10%. All of the mass densities clustered around 1 g/cm³, very near that of the liquid metal NaK.

Table 2. Objects Detected, Tracked and Characterized by MIT Lincoln Laboratory's Anomalous Debris Search

Object Num	PP RCS (dBsm)	Pol ratio (dB)	Incl. (deg)	Per. (km)	Apo. (km)	Radius (cm)	Density (g/cm^3)	Firepond: Albedo	Surface
81215	-20.8	-24.2	65.0	930	940	2.84	1.0	0.85	metallic
33562	-23.6	-21.6	65.0	931	939	2.55	1.1	0.8	metallic
33609	-22.4	-23.3	65.0	928	938	2.68	1.2		
33612	-22.1	-25.3	65.0	928	937	2.71	1.0		
33616	-30.7	-25.1	64.7	934	946	1.94	1.1		
39969	-34.3	-21.2	64.7	932	944	1.70	1.0		
39970	-32.3	-25.2	64.7	933	945	1.83	0.8		
39971	-21.9	-24.5	65.0	928	937	2.73	1.1		
39972	-22.1	-24.0	65.0	930	938	2.70	0.9		
39973	-25.4	-21.2	65.1	930	939	2.38	—		
39974	-25.0	-25.0	65.1	924	930	—	—		

Object numbers are temporary and not permanent catalogue numbers.
Radius determined from Millstone radar (1300 MHz) RCS (In Rayleigh Region).
The last object was tracked only once, making both the radius and mass density too uncertain.
The next to last object was tracked only 3 times, making the mass density too uncertain.

In addition to the stare-and-chase search for objects, the orbital region around each of ten RORSATs was searched for recently-released debris. None was found, indicating that none of those ten RORSATs had recently (within 30 days of the search) leaked any debris larger than 2 cm in diameter. This result suggests that most, if not all, of the NaK was released when the core was ejected, rather than by a slow leak that could be expected from meteoroid or orbital debris penetrations of the radiators.

These latest findings by Lincoln Laboratory -- confirming the presence of small metal spheres with a mass density near one, in orbits characteristic only of RORSATs -- are perhaps the most conclusive evidence that RORSATs have released significant quantities of NaK into orbit.

Use of Solid Rocket Motors

In late 1996, NASA was informed that solid rocket motors were used to boost the RORSAT reactors to their graveyard orbits. [26] The US solid rockets burn aluminum, so that about 1/3 of their exhaust is aluminum oxide particulates. More than 99% of the particulate mass is believed to smaller than 10 microns in diameter. However, there is evidence that the remaining less than 1% may be ejected as aluminum oxide slag, with sizes as large as several centimeters in diameter. [27,28] The question was raised as to whether slag from the RORSAT rockets might be a significant source of RORSAT debris.

Any slag is expected to be ejected near the end of the solid rocket motor burn and may be ejected with velocities approaching 100 meter/sec., although some slag may be ejected after the burn is complete. Two burns are required to boost the RORSATs to their graveyard orbits. Slag from the first burn would be left in an elliptical orbit, with the perigee near or below 300 km and the apogee around 950 km. These types of orbits are not consistent with any of the Haystack observations. Slag from the 2nd, or circularization burn, could be left in a near-circular orbit around 950 km, especially if most of the slag was ejected after the burn was complete. These types of orbits might be consistent with the measured Haystack altitude and inclination measurements but would still be inconsistent with other observations.

Aluminum oxide has a mass density of 4 g/cm^3. This is inconsistent with the Lincoln Laboratory observations which determined a mass density near 1 g/cm^3 for the objects they tracked. Also aluminum oxide slag is neither spherical nor a metal, which makes the polarization measurements by both Haystack and Lincoln Laboratory to be inconsistent with aluminum oxide debris. Finally, from the number of objects measured by Haystack, if the debris were aluminum oxide slag, then the total mass would be about 240 kg. This is an exceptionally large amount of slag for 30 circularization motors to produce and would raise the additional question as to why more slag is not observed in association with other operations in space. Consequently, it was concluded that aluminum oxide slag from RORSAT solid rocket motors was not likely a significant source of debris.

CONCLUSIONS

All observational evidence is consistent with the possibility that Russian Radar Ocean Reconnaissance Satellites (RORSATs) have leaked the coolant used in their reactor core, a liquid metal sodium potassium (NaK) alloy. No other identified possibility is consistent with all observations. The contribution from this leak to the orbital debris environment between 850 km and 1000 km is greater than that of any other debris source and will affect spacecraft reliability and design at those altitudes for the next hundred years.

A highly unlikely alternative is that Russian anti-satellite targets were releasing some type of debris. This possibility is only marginally consistent with the Haystack statistical measurements and is totally inconsistent with all other measurements, especially the latest observations conducted by MIT.

The available evidence indicates that the NaK in the primary coolant loop was ejected when the reactor core was ejected. In addition, a lesser amount of coolant could be expected to leak from the RORSAT radiators as a result of hypervelocity penetrations by meteoroids and orbital debris -- resulting mainly from the previous RORSAT leaks of NaK.

The possibility always exists that coolant will eventually leak from an active cooling system; this should be carefully considered in the design and operation of any cooling system. Either a passive cooling system or a coolant with a fast evaporation rate should be selected. Expected orbital lifetimes in low-Earth orbit are measured in hundreds of years, and millions of years in semi-synchronous and geosynchronous orbits. With increasing evidence that space systems do not necessarily remain intact during their orbital lifetimes, future design and operations of spacecraft should take precautions to mitigate against this possibility.

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