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Identification of a debris cloud from the nuclear powered SNAPSHOT satellite with haystack radar measurements

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Abstract

Data from the Massachusetts Institute of Technology Lincoln Laboratory Long Range Imaging Radar (known as the Haystack radar) have been used in the past to examine families of objects from individual satellite breakups or families of orbiting objects that can be isolated in altitude and inclination. This is possible because, for some time after a breakup, the debris cloud of particles can remain grouped together in similar orbit planes. This cloud will be visible to the radar, in fixed staring mode, for a short time twice each day, as the orbit plane moves through the field of view. There should be a unique three-dimensional pattern in observation time, range, and range rate which can identify the cloud. Eventually, through slightly differing precession rates of the right ascension of ascending node of the debris cloud, the observation time becomes distributed so that event identification becomes much more difficult.

Analyses of the patterns in observation time, range, and range rate have identified good debris candidates released from the polar orbiting SNAPSHOT satellite (International Identifier: 1965-027A). For orbits near 90° inclination, there is essentially no precession of the orbit plane. The SNAPSHOT satellite is a well known nuclear powered satellite launched in 1965 to a near circular 1300 km orbit with an inclination of 90.3°. This satellite began releasing debris in 1979, with new pieces being discovered and cataloged over the years. Fifty-one objects are still being tracked by the United States Space Surveillance Network. An analysis of the Haystack data has identified at least 60 pieces of debris separate from the 51 known tracked debris pieces, where all but 2 of the 60 pieces have a size less than 10 cm. The altitude and inclination (derived from range-rate with a circular orbit assumption) are consistent with the SNAPSHOT satellite and its tracked debris cloud.

Keywords: Orbital debris; Space debris; Nuclear; Radar; Haystack; SNAPSHOT

1. Snapshot

The SNAPSHOT satellite was the first, and so far only, launch of a US nuclear reactor into space. (All other nuclear power sources launched by the US have been Radioisotope Thermoelectric Generators, or RTGs.) The payload, also known as SNAP-10A (System for Nuclear Auxiliary Power), was launched on 3 April 1965 on an Atlas/Agena D rocket from Vandenberg Air Force Base. The payload, by design, remained attached to the Agena D upper stage (see Fig. 1). It was launched into a near-circular polar orbit with an inclination of 90.3° and a mean altitude near 1300 km. The Agena also housed a small experimental cesium ion thruster and a secondary payload, SECOR-4 (SEquential COllation of Range), which was deployed after the Agena reached its orbit.

At launch, the reactor was dormant. It was activated only after ground tracking and telemetry stations verified its orbit. After the reactor was activated, a two-piece heat shield was released from the conically shaped radiators. The reactor started and operated normally for 43 days. Then, unexpectedly, all ground command and telemetry contact with the vehicle was lost. Two days later the telemetry system came back on and functioned for four days

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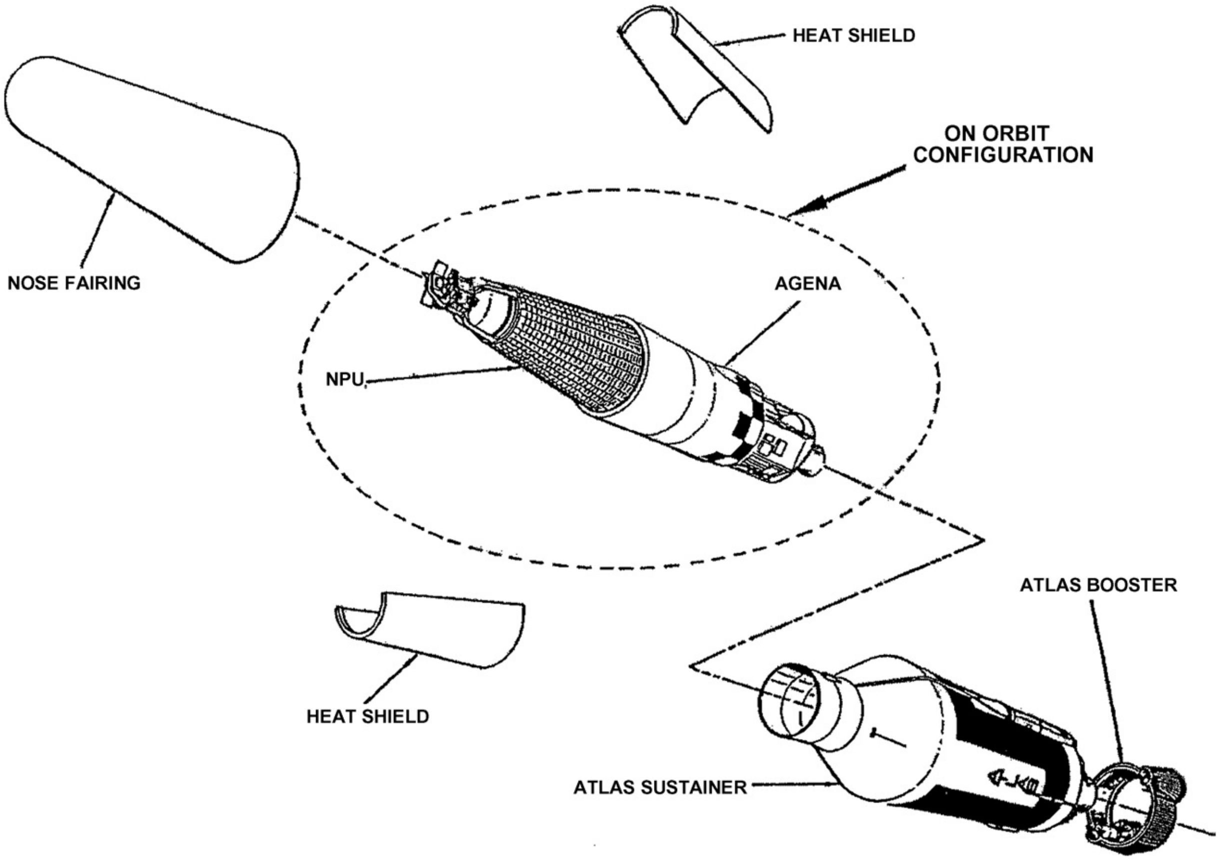

Fig. 1. On orbit configuration of the SNAPSHOT/Agena D payload.

providing partial data on the status of the spacecraft. The telemetry indicated "that some of the on-board safety shutdown devices … had activated" and that the reactor was shut down (Wilson et al., 1965).

The ion thruster also had problems. The ion engine was supposed to be operated using batteries for about 1 h and then the batteries were to be charged for approximately 15 h using power generated by the SNAP reactor. However, "flight data indicated a significant number of HV (high voltage) breakdowns, and this apparently caused sufficient EMI (electromagnetic interference) to induce false horizon sensor signals leading to severe attitude perturbations of the spacecraft" (Sovey et al., 2001).

Sometime prior to 1980, but after more than 10 years in space, the SNAPSHOT/Agena combination began shedding debris at irregular intervals (Johnson, 2004; Whitlock, 2004). The phenomenon is different from a classic breakup of an on-orbit satellite. In a classic breakup, a single energetic event occurs which produces numerous pieces and imparts some delta velocity (Δv) to them so that they disperse in altitude and (to a lesser degree) inclination from the parent satellite. In the case of SNAPSHOT, small numbers of debris have separated from the parent at very low Δv on at least 7 separate occasions (Whitlock, 2004). SNAPSHOT is not unique in terms of shedding pieces in this manner. The SEASAT payload, which is also attached to an Agena rocket body, has experienced several shedding events and the COsmic Background Explorer (COBE) has experienced at least 12 such events.

In 1985, after two Soviet satellites with nuclear power supplies reentered the earth's atmosphere, the US Air Force attempted to determine the cause of the SNAPSHOT debris. In an unclassified report with a classified appendix, the Air Force concluded that "based on data in the classified appendix, there appears to be several extraneous objects associated with the rear of the payload/rocket body structure" (DeVere, 1985). In other words, the debris appears to be coming from the Agena rocket rather than the SNAP-10A reactor.

It should be noted that the SNAP-10A reactor design is similar to the Bouk nuclear reactors which powered some Soviet Radar Ocean Reconnaissance SATellites (RORSATs), in that both used liquid metal Sodium–Potassium (NaK) in heat transfer loops. It was standard procedure for a time to eject the nuclear core from the Bouk reactors into a higher disposal orbit. The ejection apparently breached the heat transfer loops and the NaK leaked out in spherical droplets at low relative velocities (Stansbery et al., 1996; Sidharan et al., 1999). This does not appear to be the source of the SNAPSHOT debris. Very few of the RORSAT NaK droplets are large enough to be seen and cataloged by the US Space Surveillance Network (SSN) whereas over 50 SNAPSHOT debris have been cataloged. Also, the liquid metal forms into spheres when released. Conducting spheres have a highly polarized radar return from circularly polarized radars such as Haystack. This is true of RORSAT debris, but is not true of SNAPSHOT debris. Finally, the core of the SNAP-10A reactor was not ejected.

2. SSN observations

The US Department of Defense operates a worldwide network of radar and optical sensors for tracking earth satellites (including payloads, rocket bodies, and debris) of the size 5–10 cm and larger. Tracked objects are maintained in two lists. Objects in the official catalog are given, along with their international designator, a sequential number starting with satellite number 1, the Sputnik 1 rocket body. Currently there are over 29,000 objects in the regular catalog including more than 19,000 objects which have reentered the earth's atmosphere or have left earth orbit. There are many objects which are tracked by the SSN but which have not yet been included in the regular catalog. This includes many small debris fragments. These objects are maintained in an "Analyst" list using numbers from 80,000 to 89,999. Objects in the analyst catalog are often transient in that they are discovered, tracked, identified, and then transferred to the regular catalog. The number in the analyst catalog is then reused.

In addition to the SNAPSHOT payload (SSN Satellite Number 1314) and the SECOR-4 satellite (SSN 1315), the SSN cataloged three debris objects within about 2 month of the launch (SSNs 1316, 1389, and 1399). SSN 1399 was either initially or subsequently misidentified as originating from SNAPSHOT. The other two objects are likely the two piece heat shield released after reactor activation.

The first piece of debris (SSN 11631) associated with the shedding events was cataloged near the end of November, 1979. Since that time, 50 additional pieces have been included in the regular catalog. Fig. 2 shows the orbital period history for all of the cataloged debris associated with SNAPSHOT from 1975 to 2006. From this plot, it is obvious that a great deal of cross tagging of observations has occurred over the years as evidenced in the discontinuities in individual orbital histories. Many of the debris objects have similar decay profiles from atmospheric drag. The effects of periods of high or low solar activity are evident in this figure by looking at the rate of change of orbital period. Several debris were added to the catalog near the beginning of 1988. Several of these pieces had orbital periods shorter than pieces cataloged in 1979. It is likely that at least one of the debris cataloged in 1988 was shed from SNAPSHOT prior to the first recognized shedding event. Hence, the first shedding event probably occurred prior to November, 1979.

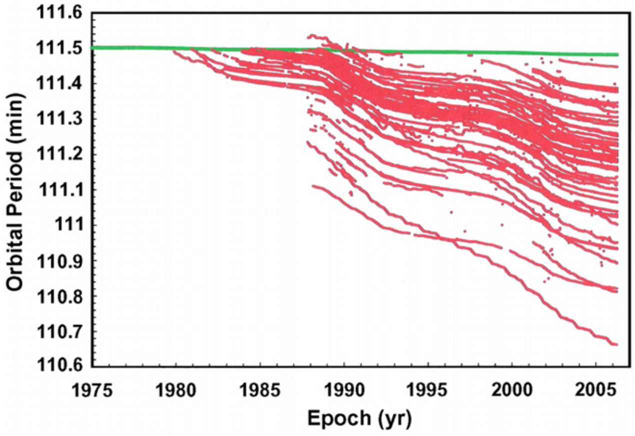

Fig. 2. Orbit period for SNAPSHOT (SSN1314) and associated cataloged debris.

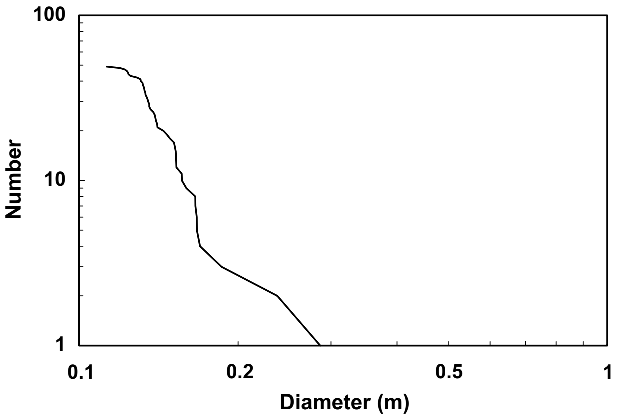

Fig. 3. Size distribution of cataloged SNAPSHOT debris. Size is estimated using the NASA Size Estimation Model.

Most of the cataloged debris from SNAPSHOT is near the threshold of detectability for the SSN. Fig. 3 shows the size distribution for the debris using the NASA Size Estimation Model to convert radar cross section to characteristic length (Stansbery et al., 1996).

The orbital element history of each of the cataloged SNAPSHOT debris was used with NASA's Prop3D orbit propagator (Whitlock and Johnson, 2005) to curve fit the decay rate to estimate an effective area-to-mass ratio

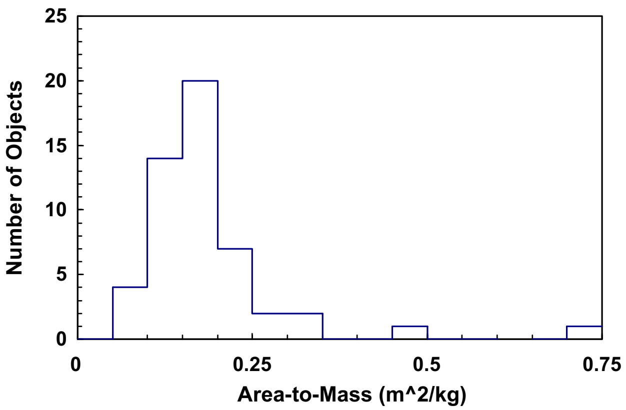

Fig. 4. Area-to-mass histogram of cataloged SNAPSHOT debris.

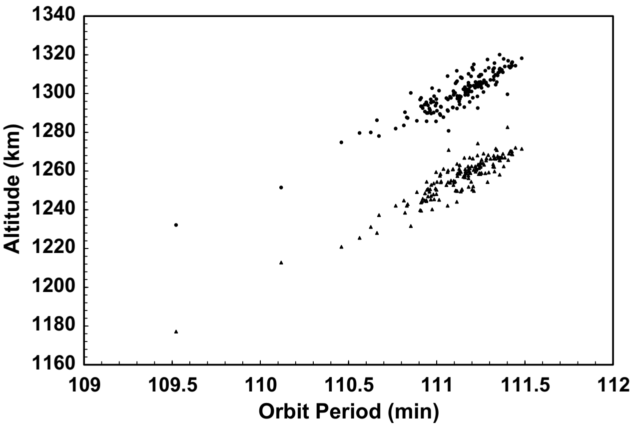

Fig. 5. Gabbard diagram of all SNAPSHOT debris tracked in May 2006, including both cataloged and analyst objects.

(assuming a coefficient of drag of 2.2). Most of the debris show an area-to-mass of between 0.1 m^2/kg and 0.2 m^2/kg (Fig. 4).

In addition to the 51 SNAPSHOT debris in the regular catalog, in May, 2006, the SSN was tracking about 100 analyst objects in orbits which indicate that they also originated from SNAPSHOT. No size information is available for analyst objects, however. Fig. 5 shows the Gabbard diagram for both the analyst and regular cataloged objects.

3. Haystack observations

The Haystack Long Range Imaging Radar (LRIR) has been NASA's primary source of data on the orbital debris population for sizes between 0.5 cm amd 10 cm. It began collecting debris data in late 1990. Haystack is a high-power, X-band (3 cm wavelength), monopulse tracking radar with very high sensitivity. For debris observations, Haystack is operated in a staring, or "beam park," mode in which the antenna is pointed at a specified elevation and azimuth and remains there while debris objects randomly pass through the field of view. By operating the radar in a stare mode and not tracking detected debris objects, a precise measurement of the object's orbit is sacrificed. However, by examining the signals from the monopulse angle channels operating in an open-loop mode (*i.e.,* no feedback of the monopulse signals to the antenna tracking servos), position in the radar beam for each pulse can be estimated. The time history of the positions in the beam along with range and range rate information can be used to estimate the object's orbital elements. The beam positions are also used to correct the radar signal return for antenna beam shape loss.

In October, 2002, the Haystack Processing and Control System (PACS), used for debris detection and near real time processing, was upgraded. The new system extended the range window from 900 km to 1580 km. Prior to the upgrade, Haystack was seldom used in the debris mode to search the altitudes where SNAPSHOT debris reside.

Table 1
Debris mode operating parameters

Operating parameter	Haystack
Peak power (kW)	400
Transmitter frequency (GHz)	10.0
Transmitter wavelength (cm)	3.0
Antenna diameter (m)	36.6
Antenna beam Width (deg)	0.058
Antenna gain (dB)	67.23
System temperature (K)	246
Total system losses (dB)	4.9
Waveform code	4
Number range gates	20
Intermediate frequency bandwidth (kHz)	1000
Independent range/Doppler samples	12,126
FFT size	2048
Number of non-coherent integrated pulses used for detection	16
Pulse width (ms)	1.6384
Pulse repetition frequency (Hz)	60
Receiver window (ms)	12.126
Single Pulse SNR on 0 dB m^2 target at 1000 km range (dB)	59.7

The new operating parameters are listed in Table 1 (Stokely et al., 2003).

Unfortunately, the "upgraded" system also introduced an error that was not discovered until much later. This error resulted in missed detections of some smaller objects. It is estimated that the detection of objects of about 1 cm and larger was unaffected by this error (Stokely et al., 2003).

During the time from October 2002 to September 2003, Haystack collected 633 h of debris staring data at pointing angles of 75° elevation and 90° azimuth over an altitude range of 350–1750 km. Evident in plots of the altitude versus inclination of the debris detections was a concentration near 1300 km altitude and 90° inclination.

When orbital objects are released from a parent body such as after a breakup event, or in this case a series of shedding events, the fragments distribute themselves around the orbit while the right ascension of ascending node (Ω) of the fragments slowly disperses. With the dispersal of the right ascension, the association of the fragment with the orbital plane is lost. The precession of the right ascension of ascending node is given by

$$\Delta\Omega = -0.585^\circ \left(\frac{R_\oplus}{p}\right)^2 \cos(\theta_{\mathrm{inc}})$$

per orbit, where θ_{inc} is the inclination, $R_\oplus$ stands for the Earth radius of 6378 km, and $p = a(1-e^2)$ is the semi-latus rectum, with semimajor axis a and eccentricity e. For a circular orbit, the semi-latus rectum p is equal to the sum of the Earth's radius, $R_\oplus$, and the altitude of the satellite. Because $d\Omega/dt$ is proportional to $\cos(\theta_{\mathrm{inc}})$, objects in a debris cloud (with a distribution in altitude) near 90° orbital inclination, such as SNAPSHOT, precess very slowly. The debris will therefore remain time correlated with the orbital plane of the parent body for a very long time. The debris cloud associated with the SNAPSHOT satellite at an orbi-

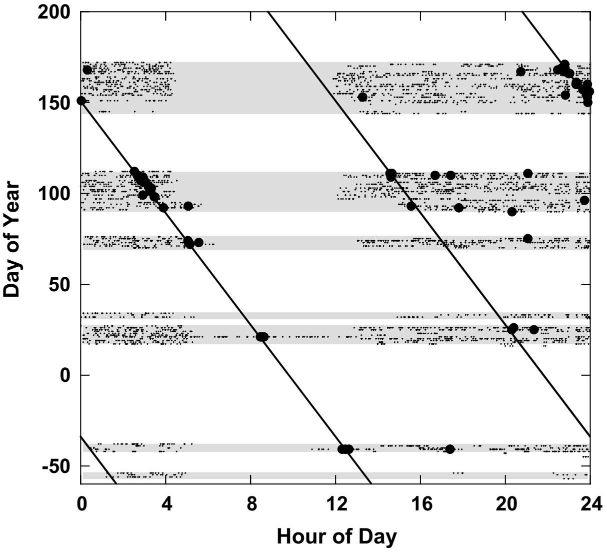

Fig. 6. Diagram showing time of day of all Haystack detections (small dots) and Haystack detections between 1200 km and 1400 km altitude and inclinations from 89° to 94° (large dots). The diagonal lines show the time of orbit plane passage of SNAPSHOT. (Day of Year is from 1 January 2003.)

tal inclination of 90.1° should still be intact even after many years of releasing objects.

To identify the SNAPSHOT debris, a plot of day (of the year) versus the time-of-day of detections within 1200 km to 1400 km and inclination from 89° to 94° is shown in Fig. 6. The large dots are within this altitude and inclination window. The small dots are all detections to indicate when the radar was actually taking data. The shaded areas are a guide to indicate roughly when the radar was acquiring data. As shown in the figure, the radar has about 8 h of down time each day with the exception of a 24 h campaign conducted on January 20–21, 2003. There are two lines shown since the orbit plane will pass through the radar twice each day. The slope of the line indicates the debris orbit plane is being observed approximately 236 s earlier each day as would be expected for the SNAPSHOT orbit.

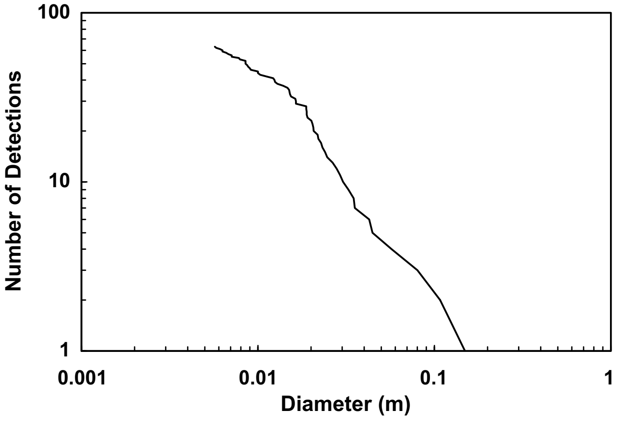

Fig. 7. Size distribution of Haystack detections determined to be SNAPSHOT debris.

Using this technique, 61 detections were determined to be associated with SNAPSHOT debris with the smallest being about 5 mm in diameter. Of the 61 detections, three were correlated to cataloged SNAPSHOT debris. The size distribution of the detections is shown in Fig. 7.

4. Population estimation

The simplest method to estimate the population of SNAPSHOT is to simply ratio the total number of objects detected by Haystack with the number of cataloged objects. Since three of the 61 detections were cataloged debris then Haystack detected 20 times the cataloged population (about 50 objects) giving a total population of about 1000 objects larger than 5 mm in diameter.

The number of three cataloged detections, however, has a large associated uncertainty due to the statistics of small numbers. In order to estimate a more expected cataloged detection rate, a series of simulations was run using the SATRAK software package. SATRAK can be used to determine when a satellite is in the field-of-view of a ground based sensor and is certified to produce the same answers as software in the SSN's Cheyenne Mountain Operations Center (Grissom and Guy, 2002). SATRAK was run using the orbital elements for the cataloged SNAPSHOT debris and a 1° field-of-view simulated radar beam at Haystack's location and pointing angles. The simulation was run for five continuous days of radar time. This corresponds to 10 SNAPSHOT plane crossings. This process was repeated for 20 different 5 day intervals in FY 2003. An average of 4.2 cataloged detections per 10 plane crossings was found. Using the data presented in Fig. 6, Haystack observed 55 plane crossings during 2003. If Haystack had a 1° field-of-view, then it should have detected 23.1 cataloged SNAPSHOT debris. However, since Haystack's beamwidth is 0.058° that number should be adjusted by the ratio of 0.058 to 1, giving an expected number of detections of 1.3.

The estimate of population at 5 mm diameter has additional problems, however. As the debris size approaches the threshold of detection for Haystack, the probability of detection drops. In other words, not every 5 mm debris object passing within Haystack's field-of-view will be detected. There is also the issue of the error discussed in the previous section which increased the number of missed detections for small particles. Therefore, the estimate of 1000 objects larger than 5 mm is a lower limit and the actual number may be several times larger.

A more reliable number would be the estimate of the population larger than 1 cm. Haystack detected about 45 objects in this size range. Using 1.3 as the number of detected cataloged objects provides an estimate of approximately 1700 SNAPSHOT debris larger than 1 cm in orbit.

5. Summary

SNAPSHOT, the only US launched nuclear reactor, and its attached Agena D rocket body have been shedding debris at irregular intervals since at least 1979 or earlier. The SSN is currently tracking about 150 debris objects and has included 51 of these in its regular catalog. Haystack observed 45 detections associated with the SNAPSHOT debris larger than 1 cm in diameter. Using a simple ratio technique, this number of detections gives a total orbital population estimate of 1700 SNAPSHOT debris larger than 1 cm.

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