# Space Surveillance Catalog Growth During SBIRS Low Deployment

Charles P. Hoult and Robert P. Wright
The Aerospace Corporation
P.O. Box 92957 MS: M5/644
Los Angeles, CA 90009
310-336-1791 310-336-5051
charles.p.hoult@aero.org robert.p.wright@aero.org

Abstract--The Space Surveillance Catalog is a database of all Resident Space Objects (RSOs) on earth orbit. It is expected to grow in the future as more RSOs accumulate on orbit. Potentially still more dramatic growth could follow the deployment of the Space Based Infrared System Low Earth Orbit Component (SBIRS Low). SBIRS Low, currently about to enter development, offers the potential to detect and acquire much smaller debris RSOs than can be seen by the current ground-based Space Surveillance Network (SSN). SBIRS Low will host multicolor infrared/visible sensors on each satellite in a proliferated constellation on low earth orbit, and if appropriately tasked, these sensors could provide significant space surveillance capability. Catalog growth during SBIRS Low deployment was analyzed using a highly aggregated code that numerically integrates the Markov equations governing the state transitions of RSOs from uncataloged to cataloged, and back again. It was assumed that all newly observed debris RSOs will be detected as by-products of routine Catalog maintenance, not including any post breakup searches, and if sufficient sensor resources are available, be acquired into the Catalog. Debris over the entire low to high altitude regime were considered. Findings include: 1) Catalog extension will not require much searching. Incidental discovery will get the job done very nicely; 2) Depending on the signal processing design chosen and tasking policy followed, the Catalog could grow from about 8,000 RSOs today to roughly 80,000 by the time SBIRS Low is fully deployed. Most of this growth is due to the ability of SBIRS Low to see much smaller debris than can be currently detected; 3) It is uncertain whether SBIRS Low can affordably detect and track the bulk of the small debris hazardous to the International Space Station (ISS) after it decays to ISS altitudes; and 4) It is unlikely that SBIRS Low plus the current SSN will have enough capability to acquire all detectable debris. As a result, the daily rate of Uncorrelated Targets will increase somewhat from present levels. However, the daily Lost Satellite Rate will be much smaller.

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## 1. INTRODUCTION

As the population of all objects on earth orbit has increased over the years, so also has the population of space debris increased. Today, the current debris population is large enough to cause a discernable risk of collision with operational spacecraft. This concern has been extensively described in the literature [1, 2 & 3]. A hypervelocity collision with a millimeter size debris particle is potentially catastrophic for many spacecraft. It is possible, of course, to provide some protection for spacecraft. The International Space Station [1], for instance, will have bumper shields sufficient to maintain hull integrity against impacts of debris smaller than one centimeter. And, if the debris has been tracked, it will sometimes be possible to maneuver to avoid a predicted collision.

This paper explores the ability of a new Air Force program, the Space Based Infrared System-Low Earth Orbit Component (SBIRS Low), to detect, acquire and maintain track on debris smaller than that now tracked by ground based radars and optical sensors. Every satellite in the SBIRS Low proliferated constellation carries a robust multicolor sensor suite. In this paper, we will show how these sensors can be used while SBIRS Low is being deployed to find a great deal of the smaller debris.

## 2. Space Debris

A good point of departure is Reference 1. Its conclusions are still valid even though its data are now three years old. Table 1 summarizes the known Resident Space Objects (RSOs) as of 1 November 1995. It includes all debris on low earth orbit (LEO) larger than about 30 cm and some as small as 10 cm. For geosynchronous orbits (GEO), the table includes all debris larger than about 100 cm. Debris size estimates were inferred from measured radar and optical signatures. About 72% of the objects listed in Table 1 are on LEO, not surprising since they are the closest to the existing ground based sensors and because more satellites are launched into LEO orbits than elsewhere. There are another 1,500, or so, larger debris RSOs which have been occasionally seen, but not tracked well enough to establish good orbits.

**Table 1. Cataloged RSOs by Orbit (Ref. 1)**

| | Spacecraft | Rocket Bodies | Debris Fragments | Total |
|---|---|---|---|---|
| LEO | 1292 | 712 | 3743 | 5747 |
| MEO | 107 | 24 | 3 | 134 |
| GEO | 465 | 133 | 3 | 601 |
| Transfer | 75 | 276 | 147 | 498 |
| Other | 359 | 361 | 229 | 940 |
| TOTAL | 2298 | 1506 | 4125 | 7929 |

Table 2, from Ref. (1), shows the estimated population of smaller debris on orbits below 2,000 km as of 1 November 1995. Its most striking feature is the overwhelming numerical preponderance of the smallest objects.

**Table 2. Estimated Total Debris Population Below 2000 km (Ref. 1)**

| Size | Number | Type |
|---|---|---|
| >10 cm | 7,247 | "Large" Objects |
| 1-10 cm | 110,000 | "Risk" Objects |
| 0.1-1 cm | 35,000,000 | "Small" Debris |

The historical growth of Catalog size by year is shown in Figure 1. The dashed straight line shows an annual growth of 238 RSOs per year. When this rate is applied to Table 1, there will be a total of 11,024 known RSOs in 2008, a representative epoch for the deployment of SBIRS Low. The major caveat relevant to this prediction is that for some time the major space faring nations have been implementing policies designed to mitigate creation of new space debris.

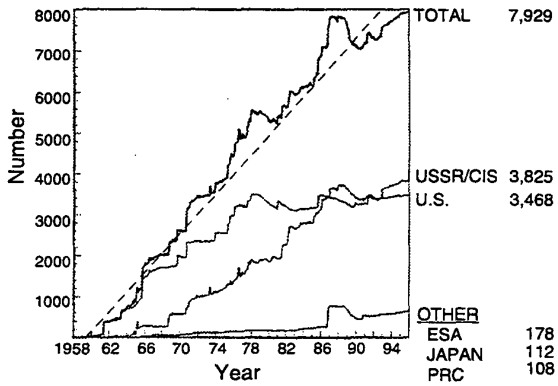


**Figure 1. Number of Cataloged Satellites by National Origin (Ref. 1)**

To extrapolate to unknown, smaller debris, some consideration of debris genesis is needed. Some of these objects are associated with normal spacecraft deployment and operation. Examples are lens caps, explosive bolt fragments, and a variety of clamps and fittings discarded after a satellite is ready to perform its mission. But, by far the most important current source of new debris is satellite explosions. In the future, collisions between satellites are expected to take on increased importance. Any source of energy, such as high pressure gas or propellant stored onboard, can, under the wrong conditions, cause an RSO to explode. The distribution of fragment sizes after a single explosion/collision (see Ref. (1)) is shown in Figure 2. The solid straight line has been used to fill in the details in Table 2 by fitting it with

$$\log_{10}(N) = 4.097 - 2.244\log_{10}(D), \text{ where} \qquad (1)$$

N = Number of fragments larger than D, and
D = Debris diameter, cm.

It has been assumed that this relative size distribution applies to space debris that are the product of many explosions.

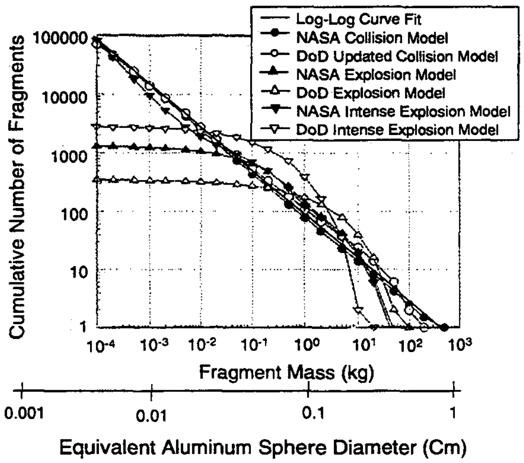


**Figure 2. Single Event (Explosion or Collision) Particle Size Distribution (Ref. 1)**

Debris altitude is important because distance between a sensor and debris can have a major bearing on whether or not it appears bright enough for detection, and the relative sensor-debris altitudes affect viewing geometry. Figure 3 shows the distribution of LEO RSOs with altitude in 1997. This curve has been used knowing that it is biased toward larger debris. Smaller debris are more readily affected by atmospheric drag, the major debris removal mechanism. Therefore, the altitude distribution curve for smaller debris would tend to have fewer objects in the lower altitude regions. Since more debris on lower orbits is more challenging to SBIRS Low, using Figure 3 will provide a conservative estimate on the number of new debris RSOs found.

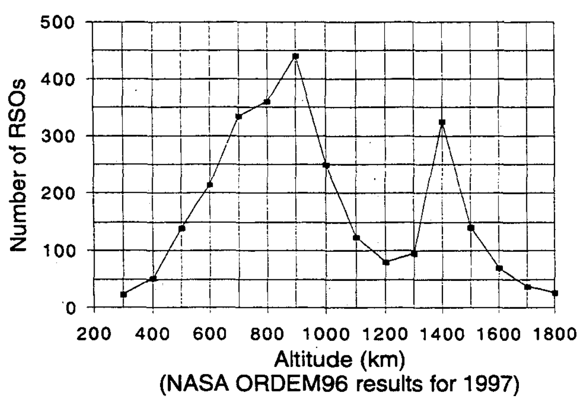


**Figure 3. Trackable Objects (>10cm) vs. Altitude (Ref. 10)**

The situation for GEO debris is somewhat different. To begin with, Figure 4 shows that most of the GEO RSOs are on low latitude orbits. For this paper a ±15 deg latitude limit was used. Secondly, all GEO debris are about the same distance from a SBIRS Low sensor. That is, GEO orbits are much higher than any combination of earth's radius and SBIRS Low altitude, and therefore, all GEO RSOs are more or less equidistant from SBIRS Low sensors.

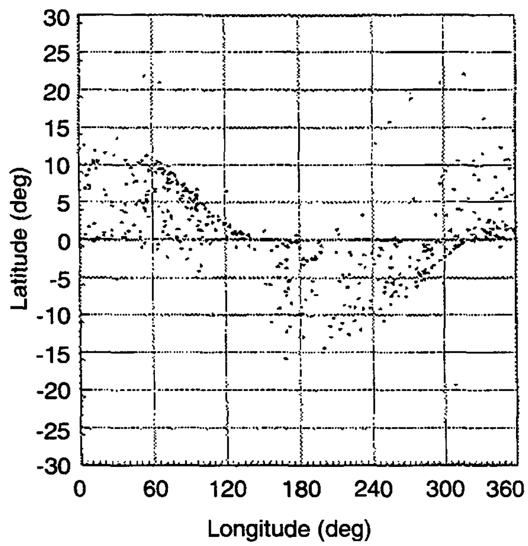


**Figure 4. 1995 Distribution of Debris In and Near Geosynchronous Orbit (Ref. 1)**

The projected debris populations in 2008 are shown in Tables 3 and 4. These were developed by first extrapolating the current debris data in Table 1 and Figure 3 forward in time using the growth rate obtained from Figure 1. Interpolation of the smaller (LEO "risk") debris populations was based on the simplified explosion model given by Equation (1). The debris model used in the remainder of this paper is summarized in Table 3 for the LEO debris, and in Table 4 for the GEO debris. This theoretical data clearly demonstrates the quantitative preponderance of smaller debris RSOs.

**Table 3. Projected LEO Debris in 2008**

| Lower Size Limit, cm | Altitude, km | Cataloged # Debris RSOs | Total # Debris RSOs | Lower Size Limit, cm | Altitude, km | Cataloged # Debris RSOs | Total # Debris RSOs |
|---|---|---|---|---|---|---|---|
| 10.00 | 400 | 284 | 284 | 4.00 | 400 | 0 | 75 |
| 10.00 | 650 | 1340 | 1340 | 4.00 | 650 | 0 | 355 |
| 10.00 | 900 | 2816 | 4243 | 4.00 | 900 | 0 | 1125 |
| 10.00 | 1050 | 503 | 1403 | 4.00 | 1050 | 0 | 372 |
| 10.00 | 1450 | 238 | 2414 | 4.00 | 1450 | 0 | 640 |
| 10.00 | 1750 | 23 | 493 | 4.00 | 1750 | 0 | 132 |
| 8.00 | 400 | 0 | 16 | 3.00 | 400 | 0 | 173 |
| 8.00 | 650 | 0 | 75 | 3.00 | 650 | 0 | 818 |
| 8.00 | 900 | 0 | 237 | 3.00 | 900 | 0 | 2591 |
| 8.00 | 1050 | 0 | 79 | 3.00 | 1050 | 0 | 857 |
| 8.00 | 1450 | 0 | 135 | 3.00 | 1450 | 0 | 1474 |
| 8.00 | 1750 | 0 | 28 | 3.00 | 1750 | 0 | 301 |
| 6.00 | 400 | 0 | 37 | 2.00 | 400 | 0 | 541 |
| 6.00 | 650 | 0 | 173 | 2.00 | 650 | 0 | 2554 |
| 6.00 | 900 | 0 | 547 | 2.00 | 900 | 0 | 8085 |
| 6.00 | 1050 | 0 | 181 | 2.00 | 1050 | 0 | 2674 |
| 6.00 | 1450 | 0 | 311 | 2.00 | 1450 | 0 | 4600 |
| 6.00 | 1750 | 0 | 64 | 2.00 | 1750 | 0 | 940 |
| 5.00 | 400 | 0 | 39 | 1.00 | 400 | 0 | 3387 |
| 5.00 | 650 | 0 | 184 | 1.00 | 650 | 0 | 15977 |
| 5.00 | 900 | 0 | 581 | 1.00 | 900 | 0 | 50587 |
| 5.00 | 1050 | 0 | 192 | 1.00 | 1050 | 0 | 16733 |
| 5.00 | 1450 | 0 | 331 | 1.00 | 1450 | 0 | 28784 |
| 5.00 | 1750 | 0 | 68 | 1.00 | 1750 | 0 | 5883 |

**Table 4. Projected GEO Debris* in 2008**

| Lower Size Limit, cm | Cataloged Number Debris RSOs | Total Number Debris RSOs |
|---|---|---|
| 100 | 531 | 1878 |
| 30 | 0 | 11223 |

*Note that the "GEO" category includes RSOs on geosynchronous orbits, Molniya orbits, semisynchronous (12 hour) orbits and GEO transfer orbits. These RSOs spend most of their time at high altitude and are most likely first detected there.

## 3. Space Based Infrared Systems (SBIRS)

SBIRS is an ongoing Air Force program being deployed in multiple Increments. Increment 1 is based on the Defense Support Program (DSP) that has been operational for many years. It consists of a new Mission Control Station (MCS) and DSP satellites on geosynchronous orbits observing events on, or near, the earth with infrared sensors. The most interesting of these events are launches of ballistic missiles and spacecraft.

Increment 2 adds the SBIRS High satellites, also on geosynchronous orbit. SBIRS High incorporates a number of technical advances over DSP. It uses the same MCS as DSP. At this time, SBIRS High has had its Preliminary Design Review (PDR) and is scheduled for a first launch in Fiscal Year (FY) 2004.

Increment 3 brings in SBIRS Low, the only component capable of making a significant impact on the space debris problem. The SBIRS Low family tree began with Brilliant Eyes in 1991, and carried through the Space and Missile Tracking System that was merged with DSP and SBIRS High in 1995 to form SBIRS. SBIRS Low is just beginning its Program Definition (PD) phase on the way to a scheduled first operational launch in FY 2006 (three test bed satellites are scheduled for launch in the spring of 2000).

The PD phase has two parts, each lasting about 15 months, namely requirements development and then, subsequently, initial system design. Requirements will be developed for four mission areas: 1) Missile Defense (MD); 2) Technical Intelligence; 3) Battlespace Characterization; and 4) Missile Warning North America. Battlespace Characterization includes Space Surveillance, Major Regional Conflict Situational Awareness, and Weather support.

At this time a definitive Increment 3 SBIRS Low system configuration does not exist. That design is still three years into the future. However, eight years of studies provide some solid insights into what features that system might have. The constellation will probably be 24 to 30 satellites orbiting below the inner Van Allen belt. It is expected the space surveillance observation data will be flood routed back to a ground station in the U.S. The large constellation provides a multiplicity of communications routes. Each satellite will have two sensors on a common optical bench, one with a wide below-the-horizon (BTH) field of regard for initial detection and acquisition of missile launches, and the other, a gimbaled Track Sensor, with a narrow Field of View (FOV) for precision tracking. Track sensors are tasked devices. Each Track Sensor will have a variety of wavebands likely including visible light, short wave infrared (SWIR), mid wave infrared (MWIR), mid/long wave infrared (MLWIR) and long wave infrared (LWIR). Each Track Sensor will have about a $2\pi$ field of regard, both BTH and above-the-horizon (ATH). For purposes of finding space debris, the principal data source will be the Track Sensor visible band with some use of the LWIR band to find dark debris. Finally, note that a few, limited studies [4] have traded Track sensor aperture, and hence minimum detectable debris size, against system Life Cycle Cost. It was concluded that apertures much larger than those used in this paper provided small performance improvements at large cost increases, and therefore will not likely be used in the final design.

Figure 5 shows one version of the SBIRS Low deployment schedule. In this figure, the satellites are launched three per booster, with three months between booster launches. Launch and early orbit checkout takes approximately one month for each satellite, and in this paper, is assumed to occur serially. After the first two launches, there will be a one year pause to conduct Development Test and Evaluation (DT&E).

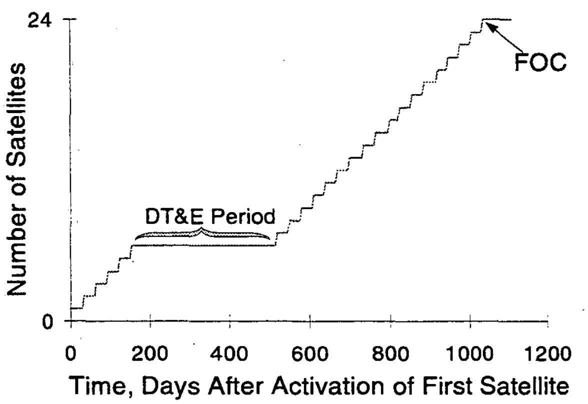


**Figure 5. Evolution of SBIRS Low Constellation During Deployment**

Figure 6 displays the coverage of one fully deployed constellation currently under investigation. It shows, for example, that for RSOs located anywhere globally at 200 km altitude, the probability that they could be observed by three SBIRS Low satellites is approximately 56.6%. The 90 km line of sight tangent altitude limit is imposed by background radiation, both visible and LWIR, which reduces the contrast signatures of objects in space. As can be seen, a proliferated constellation provides proliferated observing opportunities.

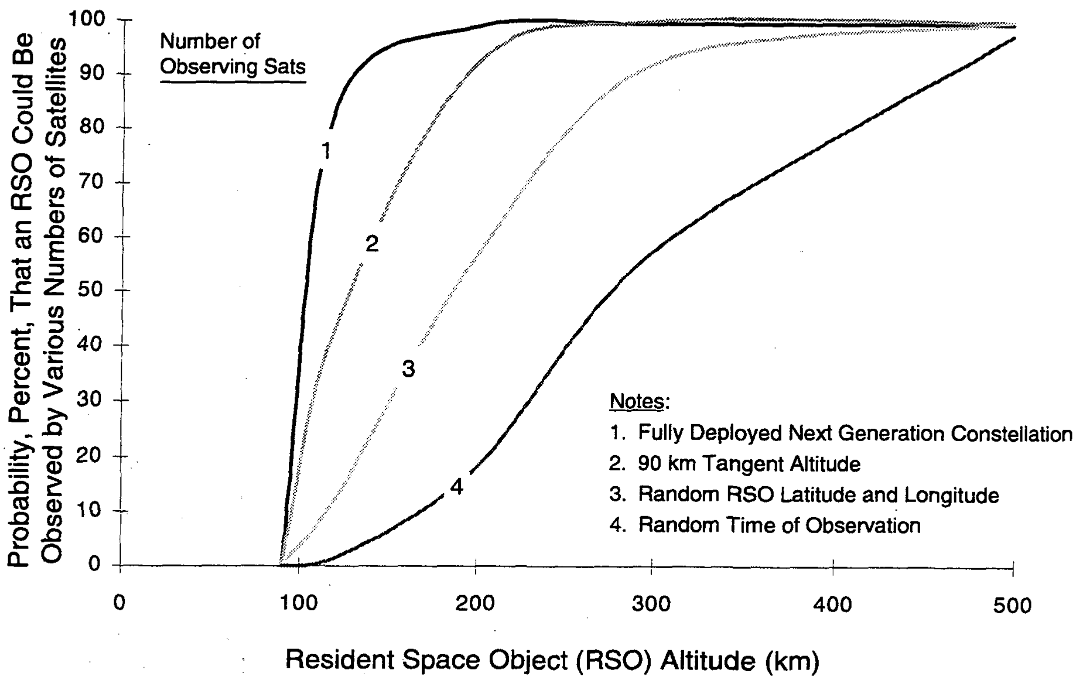


**Figure 6. Observational Coverage (Ref. 9)**

## 4. Operations Approach

It is important to keep in mind that since SBIRS Low has not yet been deployed, all discussion of how it might be operated is very preliminary in nature. While it is being developed, the operator, Air Force Space Command, will also evolve, in parallel, its formal Concept of Operations (CONOPS).

Space surveillance has been going on for a long time. More than 25,000 RSOs have been observed since the Sputnik launch in 1957. Processed observational data is documented in the Space Surveillance Catalog, also known as the Catalog, a database of all known RSOs including their orbits and characteristics. At the start of SBIRS Low deployment there will be an Initial Space Surveillance Catalog, developed and maintained by SSN ground based radars and optical sensors. This Initial Catalog includes all the large, interesting satellites, the so called Defense Intelligence Space Order of Battle (DISOB), expended upper stages, and much of the larger debris. And, the SSN will continue to maintain the Initial Catalog at least during the early part of SBIRS Low deployment.

However, and this is very important, calculation shows that SBIRS Low will have far better coverage, as well as greater sensitivity than most of the SSN sensor assets. For example, Figure 6 shows that RSOs at 300 km altitude can be observed by three SBIRS Low satellites most of the time and by four about half the time. The corresponding SSN assets can only observe RSOs at 300 km altitude with one sensor, and then much less than half the time. Based on data from the open literature, it appears that the best of the ground based sensors can only track debris larger than 8 cm. We considered operations approaches using a notional SBIRS Low system with the capability to detect much smaller debris.

System Operators place all RSOs into two groups, ordinary RSOs and Special Interest RSOs. Ordinary RSOs need only be observed a few times every day to maintain their Catalog data currency. Special Interest RSOs, as the name implies, must be monitored far more closely. Examples of Special Interest RSOs are:

- Newly launched RSOs
- Maneuverable RSOs
- RSOs docking and undocking
- Large Reentering RSOs (those in the DISOB list)
- Close encounters/collisions between RSOs (if at least one is in the DISOB list)
- RSOs whose Mission-Payload Assessment (MPA) status has recently changed

One way to judge operations is to examine the relevant Measures of Effectiveness (MOEs), top level metrics that indicate how well things are going. In the present case, suggested MOEs are:

- Orbit determination accuracy
- Uncorrelated target rate
- Lost satellite rate
- Minimum debris size cataloged at a specific altitude

In addition, Catalog completeness for minimum size debris, while not suitable as an operations metric because the true total debris population is unknown, has clear relevance to the collision avoidance issue.

An Uncorrelated target (UCT) is an observed RSO that cannot be associated with any cataloged object. A lost satellite is a cataloged RSO no longer observable at its cataloged position.

Earlier studies [5] considered a space surveillance operations approach in which new debris RSOs were discovered by deliberate, systematic searches. These studies mainly focused on the minimum detectable debris size and the time required to find a new debris RSO of specified class (each class defined as a combination of debris size and altitude). In the present paper planned searches are never used. Instead, all space surveillance observations will be tasked on RSOs already cataloged. From time to time in the course of collecting these observations uncataloged objects will be detected, and if possible, acquired into the Catalog. As will be shown in this paper, incidental discovery of debris RSOs is a very efficient technique. In fact, when the other space surveillance functions must be done concurrently with debris discovery, debris discovery processes other than incidental detection have poorer performance.

Now imagine that SBIRS Low deployment has just begun, and only a few satellites are operational. Since there are several space surveillance functions supported by SBIRS Low, a priority scheme for allocating scarce resources is needed. For purposes of this paper, the scheme used was:

1. MPA observations
2. Supplementing the Existing SSN with additional observations on Special Interest RSOs, e.g., in the southern hemisphere
3. Maintaining the Catalog of newly acquired debris RSOs
4. Acquiring newly detected debris RSOs into the Catalog
5. Maintenance of the Initial Catalog (off loading SSN radars and optical sensors)

Those few MPA observations that overlap the Special Interest Observations have been neglected in this paper. Also note that the Initial Catalog will be in place when the first SBIRS Low launches because it has been developed and maintained with radar and optical observations since the early days of space flight.

A key system element is the sensor scheduler, the software that generates sensor commands, including pointing angles, stare time, waveband, etc. The scheduler is assumed to follow the above priority scheme while ensuring that each observation will result in detection of its targeted RSO by satisfying the criteria discussed next. In this paper the scheduler is assumed to be 100% efficient. That is, when observations are needed, no sensor will ever be idle given MCS direction to support the space surveillance mission.

The definition of detection is: an RSO is said to be detected when its image falls on the sensor focal plane with intensity greater than, or equal to, the Signal to Noise Ratio (SNR) threshold that is taken to be six in this paper. For most practical purposes, it can be assumed that nearly all space surveillance observations will use the visible band.

Based on [5] there are four preconditions for a detection to occur. First, the RSO's image must fall on a sensor's focal plane. Second, the debris RSO be sunlit. This is clearly necessary when the visible band is used. But, it also applies when the LWIR band is used to detect very dark debris because small RSOs come to radiative thermal equilibrium very rapidly when crossing the terminator. In practice, only when sunlit will the temperature and LWIR signature of such RSOs be high enough for detection. Third, visible band detection requires that the RSO be more or less illuminated from the front. For Low Earth Orbit (LEO) RSOs, this is rarely a problem because there will eventually be many potential observers, each with different viewing geometry with respect to the sun. However, for RSOs on Geosynchronous Orbit (GEO) the viewing geometry differences among potential observers are expected to be minor. In this paper, it has been assumed that detection of GEO RSOs requires that the sun lie within 60 deg. of the line of sight from the earth to a point on geosynchronous orbit. Lastly, SBIRS Low's passive electrooptical sensors will be constrained against looking too closely to the sun or moon. As with the front illumination issue, the multiplicity of potential viewing geometries makes this easy to neglect for LEO RSOs while demanding its inclusion in any analysis of GEO detections.

The definition of acquisition is: an RSO is said to be acquired when its orbit is determined with sufficient accuracy to enable its later detection without recourse to search procedures. For systems with the line of sight accuracy typical of SBIRS Low, analysis [6] shows that about ten observations spaced over a quarter orbit (fully sunlit, of course) are sufficient to acquire a newly discovered RSO such that it may be reacquired on the first look a day later. Debris RSOs so acquired must subsequently be treated like any ordinary RSO in terms of observations needed for Catalog maintenance.

A first come, first served model has been used in this paper. When a new debris RSO is first detected, an attempt will be made to acquire it by tasking the ten observations needed. Then, if the sensor resources needed to acquire another subsequently detected debris RSO have already been committed, the second acquisition attempt will be aborted, and its initial detection reported as a UCT. It is assumed in this paper that such initial detections, and all other observations not resulting in acquisition, will be discarded without any further attempt to associate them to a Cataloged RSO. Operationally, this data will be retained in hope of supporting future acquisitions.

Two detection modes for the sensor were considered: First, in the streak mode, the RSO image during the observation is allowed to move across the focal plane, typically by ten pixels, or so. Second, in the stare mode, the sensor is moved to keep the RSO image fixed on the focal plane during the observation. Both modes have signal processing implications [7] if RSOs on unknown orbits are to be detected. Requirements for signal processing features, like velocity filters, will be established during the PD phase. From the perspective of this paper, the key parameter is the observation duration.

## 5. ANALYSIS

The major analysis issue is the prediction of future Catalog growth via detection and acquisition of small debris RSOs. As a secondary matter, the analysis should also be able to predict the behavior of the space surveillance MOEs identified in Section 4, Operations Approach. Since the details of the undiscovered debris RSOs and their orbits are unknown, it seems only reasonable that a simplified, highly aggregated analysis be used. Clearly, more detailed analyses could be made, but this should be sufficient for a first exploratory study designed to elucidate the salient features of the problem.

Space limitations preclude describing, in detail, the analyses used. Therefore, this section only presents an abbreviated overview illustrating the analysis processes used. For example, the mathematical description below has been simplified to address only one notional class of debris. The actual computer code used for this paper grouped debris into 48 LEO classes and two GEO classes.

The rates of debris detection and acquisition and Uncorrelated Target events are described here by their expected, or mean, values. Since all debris classes have large populations, the rate probability distribution functions will be very narrowly centered on their expected values. Each debris RSO can be in one of three possible states: Uncataloged, detected, and acquired/ Cataloged. The analysis proceeds by integrating the Markov rate equations for state transitions.

There are two time scales of importance, that for acquisition given detection (the orbital period), and that for Catalog growth (the SBIRS Low deployment time). In this paper, the focus is on the latter. Acquisition is assumed to happen instantaneously when studying deployment scale events. The unit of time is the day.

The Markov rate equations for each debris class have the general form of:

$$\text{Debris Detection Rate} = \text{Nobs} \times \text{Prdet}, \tag{2}$$

where

Nobs = Number of space surveillance observations tasked per day, and
Prdet = Probability that a previously Uncataloged debris RSO is detected in a single observation.

The key assumption behind Equation (2) is that the lines of sight for space surveillance observations are assumed to be randomly oriented over the celestial sphere with a uniform probability distribution. While not true for observations on GEO RSOs, it can be argued that this will be approximately true for the more numerous LEO RSO observations.

$$\text{Debris Acquisition Rate} = \text{Nobs} \times \text{Prdet} \times \text{Pracq} - \text{Lost Satellite Rate}, \tag{3}$$

and

$$\text{UCT Rate} = \text{Nobs} \times \text{Prdet} \times (1 - \text{Pracq}), \tag{4}$$

where

Pracq = Probability that a newly detected debris RSO will be acquired given that sensor resources are available.

Whenever a newly detected debris RSO has been acquired, the number of undetected RSOs is decremented and the Catalog size incremented by one. No searches for lost satellites were considered in this paper.

Next, each of the four terms in Equation (3) will be discussed in turn. First, consider the observation rate. When a new RSO is first detected, its motion towards or away from the terminator is unknown. If all newly detected RSOs were blindly tracked until they were acquired or lost in the earth's umbra, and if there were sufficient sensor resources to attempt acquisition of all newly detected RSOs,

$$\text{Debris Observation Rate For Acquisition} = \text{Nobs} \times \text{Prdet} \times (1 + \text{Pracq}) \times \text{Obac} \;/\; 2, \tag{5}$$

where

Obac = Number of observations needed to establish an orbit for a newly discovered RSO.

Equation (5) is obtained assuming a uniform probability density function for the number of observations for failed attempts at acquisition.

Now compare the demand for SBIRS Low space surveillance observations with its observational capacity:

$$\text{Nobd} = \text{Nobm} + \text{NSIS} \times \text{DObsi} + \text{NDEB} \times \text{Obor} + \text{Noba}\,, \tag{6}$$

where

Nobd = Demanded number of SBIRS Low space surveillance observations per day,
Nobm = Demand for MPA observations per day,
NSIS = Number of Cataloged Special Interest RSOs demanding frequent observation,
DObsi = Demanded increase in MPA observations per day beyond those supplied by the SSN per Special Interest RSO,
NDEB = Number of debris RSOs added to the Catalog by SBIRS low,
Obor = Demanded observations per day per ordinary RSO for Catalog maintenance, and
Noba = Observations per day used for attempted acquisition of debris RSOs.

and,

$$\text{Nobc} = \text{NSAT(t)} \times 86400 \times \text{DC} / \text{Tobs}, \tag{7}$$

where

Nobc = SBIRS Low space surveillance observational capacity per day,
NSAT(t) = Number of operational SBIRS Low satellites as a function of time after the start of deployment,
DC = Duty cycle, the fraction of time devoted to collecting space surveillance observations,
Tobs = Slew, settle and observe time, seconds, for a single observation.

When demand and capacity are compared, several distinct operating regimes can be identified:

1. Early in deployment as satellites become operational, support to the various space surveillance functions is added in the order described in the section on Operations Approach. Initially, there may not be sufficient capacity to acquire new debris RSOs, or, if they were acquired, to maintain their Catalog data. Thus, it is possible that there will be a period after the start of deployment during which the Catalog does not change size.

2. Later on, as more SBIRS Low satellites become operational, resources for new debris acquisitions will become available, although initially not at the full rate demanded. The observation rate for new debris acquisition can be found by equating demand and capacity (Equations (6) and (7)), and solving for Noba. The acquisition and UCT rates are found by setting Nobs = Noba in Equations (3) and (4).

3. As still more satellites come online, the point can eventually be reached when the new debris acquisition rate is not limited by sensor resources, but only by the debris detection rate. If any more SBIRS capacity were added, it could be used to take over some of the SSN Catalog maintenance work. An important cautionary note: This does not necessarily mean that it would be possible to shut down ground based SSN assets. Only a few of these are dedicated to the space surveillance mission; most also have other, important work to do.

Finally, the complex operating regime transitions described above are the major reason for numerically integrating Equations (3) and (4). A fourth order Runge-Kutta integrator was used.

Probability of detection is governed by three processes: First, the probability that an unknown debris RSO will be found in a sensor's FOV in a single observation; Second, whether or not it is close enough (and has enough source brightness) to be detected; and Third, the probability that it will be illuminated appropriately. Because the probabilities of being found in a sensor FOV and of being illuminated are independent, they may be multiplied to estimate Prdet, given that the RSO is close enough.

Consider a sensor observing remote stars brighter than some threshold of detectability. If the stars are randomly located on the celestial sphere, and the sensor line of sight is randomly oriented, then it can be shown that the number of stars detected in a single observation has a Poisson distribution. For the debris detection problem, it turns out that detecting more than one is a rare event, and, therefore, the important relation is

$$\text{Pr (exactly one star detected in an observation)} = \exp(-\text{FOV}^2 \times \text{Nstar} / 4\pi), \tag{8}$$

where

FOV = Sensor field of view, square radians, and

Nstar = Total number of stars brighter than detection threshold.

When Equation (8) is corrected for non-central viewing of unknown debris randomly located on a nearby sphere, and averaged over all Track Sensor viewing nadir angles, the probability that an unknown debris is in the field of view can be estimated.

A simple "cookie cutter" detection range model has been used. An important parameter here is the observation time. The same sensor characteristics and two times used in [5] were used in this paper, 0.1 second (streak mode) and 5.0 seconds (stare mode).

Finally, the probability that an RSO is sunlit was based on a standard model [8] averaged over all beta angles (the angle between the solar line of sight and the orbit plane of the undiscovered RSO). This is consistent with a multiyear deployment schedule. For GEO debris RSOs, the probability that an RSO will be illuminated is very high, but only a fraction of the orbit, typically directly down sun from the earth by about ±60 deg [5], provides sufficient signature for detection. By its very nature, this restriction makes the solar exclusion angle limit moot. For sunlit LEO debris, Figure 6 shows that there is a good chance that there will always be at least one satellite viewer with favorable observing geometry.

Acquisition, given initial detection and sufficient sensor resources, is limited by the probability that the requisite tracking arc will be curtailed by a terminator crossing. Simple geometric considerations lead to

$$\text{Pracq} = (\text{Prill} - \text{Trarc} / 2\pi) / \text{Prill}, \qquad (9)$$

where

Prill = Average probability that an RSO will be illuminated by the sun, and

Trarc = Minimum orbital tracking arc needed to acquire a new RSO, radians.

The lost satellite rate has two components, the rate at which sensor line of sight pointing errors and RSO ephemeris errors combine to extend the RSO image beyond the sensor FOV, and lost satellites resulting from explosions, collisions, etc. A simple Gaussian error model was used for the former; the latter must be estimated from experience.

## 6. Analysis Results

First, SBIRS Low will be capable of collecting a vast amount of space surveillance data, far more than the SSN. Consider the deployment schedule of Figure 5. The corresponding SBIRS Low capability to generate space surveillance observations for two different times is shown in Figures 7 and 8. The two observing times chosen, 0.1 and 5.0 seconds, are probably not the absolute minimum and maximum for SBIRS Low. However, we believe that these are representative of lower and upper bounds on observing time. Note that streak and stare imply different signal processing techniques for detection. In both cases, SBIRS Low generates far more observations than the current SSN. Also shown in these figures is the demand for Catalog maintenance observations from the SSN (by no means all of the demand for SSN observations). It has been assumed that together the SSN and SBIRS Low must attempt to satisfy the need for observations. SBIRS Low resources were assumed to be tasked to collect observations according to the priority order presented in the Operations Approach section. For the short observing time streak mode, the demand for SSN observations quickly drops to zero and stays there. In this case SBIRS Low can replace, in part, the SSN. On the other hand, the longer observing time stare mode must always be supplemented by SSN observations at a constant level. The sensitivity of demand for SSN observations to SBIRS Low operational tasking is demonstrated by Figures 7 and 8.

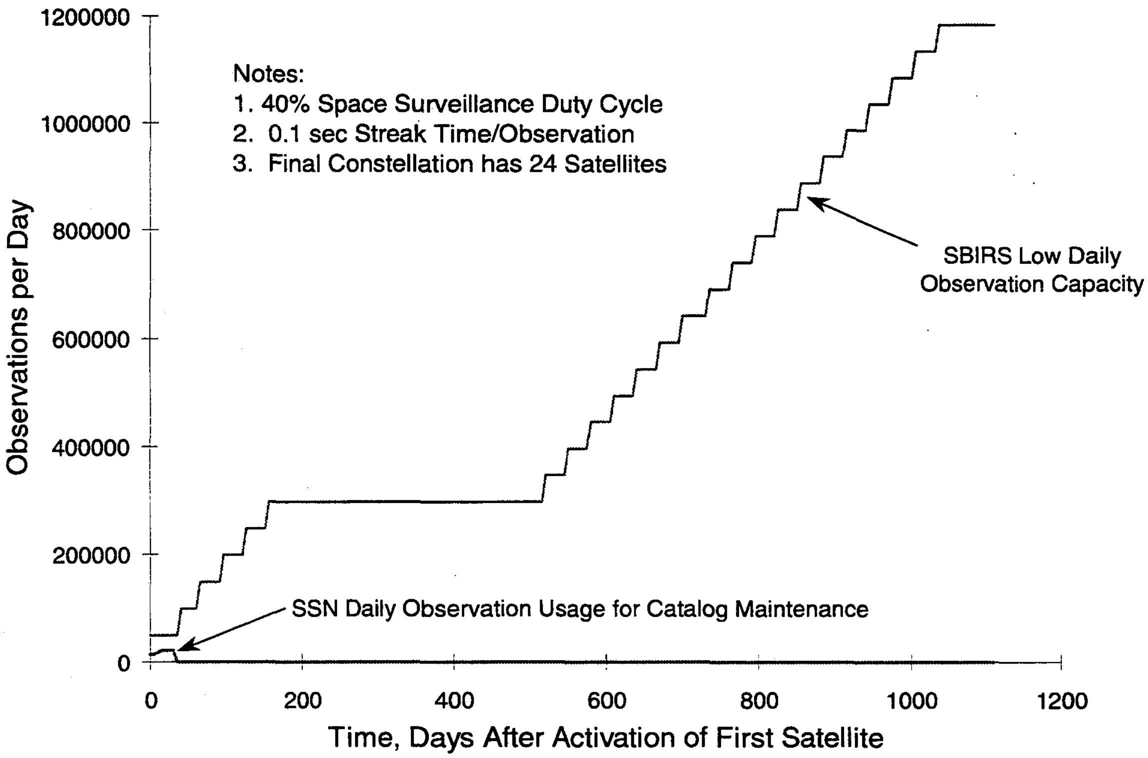


**Figure 7. Space Surveillance Observation Capacities**

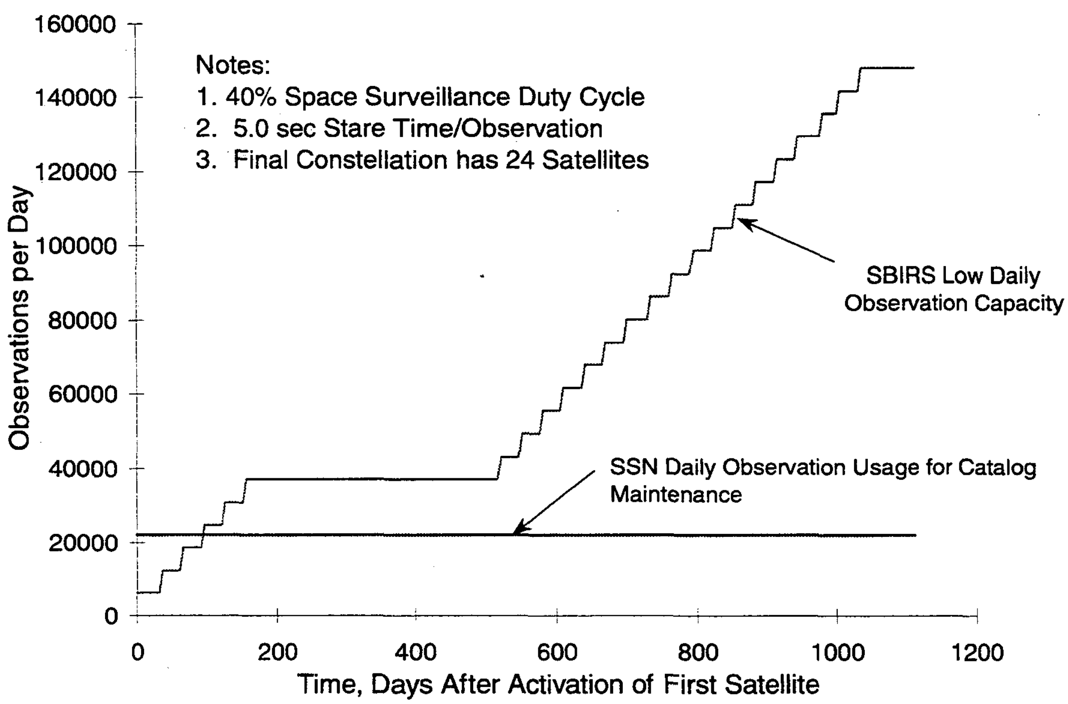


**Figure 8. Space Surveillance Observation Capacities**

Now examine Figure 9 which shows how the total Catalog will grow as SBIRS Low is deployed. The three curves show some interesting behaviors. To begin, consider the impact of increasing the space surveillance duty cycle from 40% to 60% while operating in the streak mode. The increase in new debris RSOs added to the Catalog with increased duty cycle is so small as to be negligible. This is because acquisitions are primarily limited by the number of debris detections, which in turn is limited by the instantaneous Catalog size. Increasing the duty cycle does not materially increase the number of observations because no searches are modeled, and because, with 40% of its total resource allocated to space surveillance, SBIRS Low acquires nearly all the debris it can detect.

However, the stare mode curve displays entirely different characteristics. The reason nothing happens for about a year and a half is that the deployed SBIRS Low Track Sensor resources are fully occupied executing tasks of higher priority than acquiring newly detected debris. And, the reason the stare mode curve crosses the streak mode curves is that the longer observing time provides increased sensitivity resulting in detection of many more smaller debris RSOs.

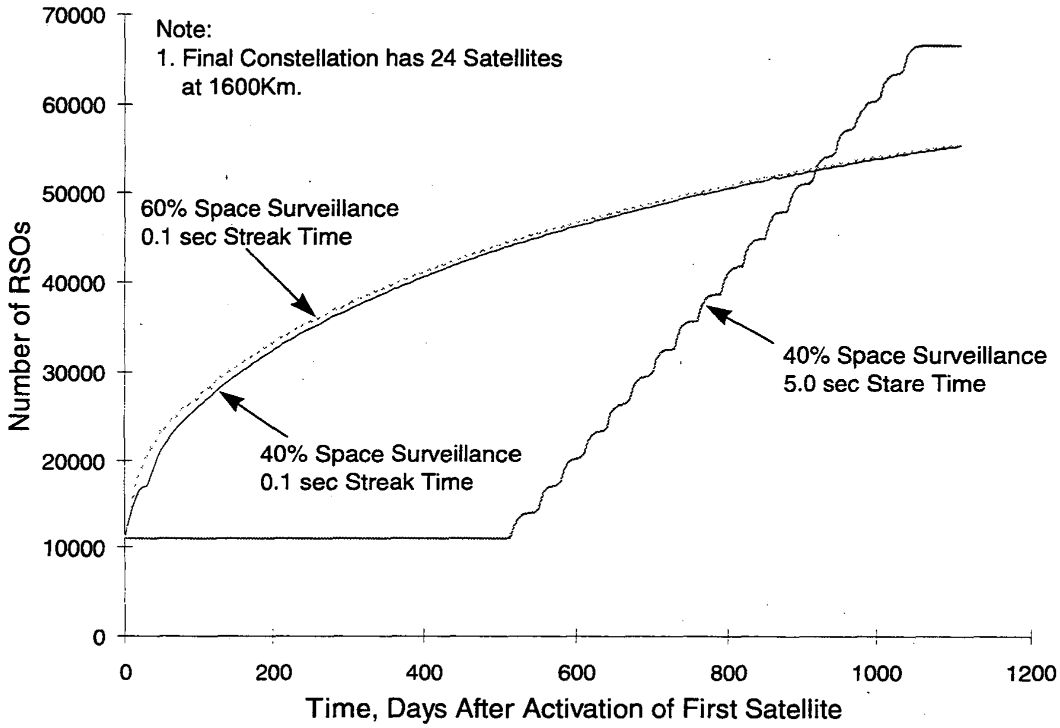


**Figure 9. Space Surveillance Catalog Growth**

Figures 10 and 11 address the issue of Catalog completeness for various debris altitudes. Completeness is relative to the predicted total debris populations in Table 3. It is strikingly apparent that the Catalog, initially void below 10 cm, will be extended downward with good completeness to about 4 cm (streak mode) and to about 2.5 cm (stare mode) at the end of deployment. While this is certainly encouraging, the minimum debris size still does not approach the International Space Station bumper shield upper limit of 1 cm.

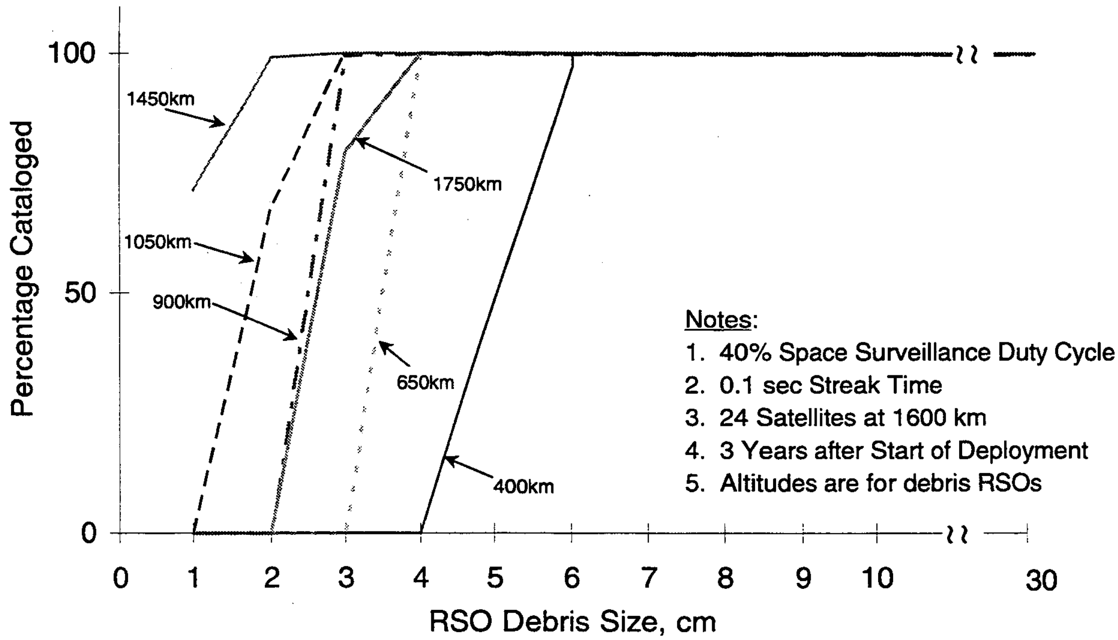


**Figure 10. Debris Catalog Completeness**

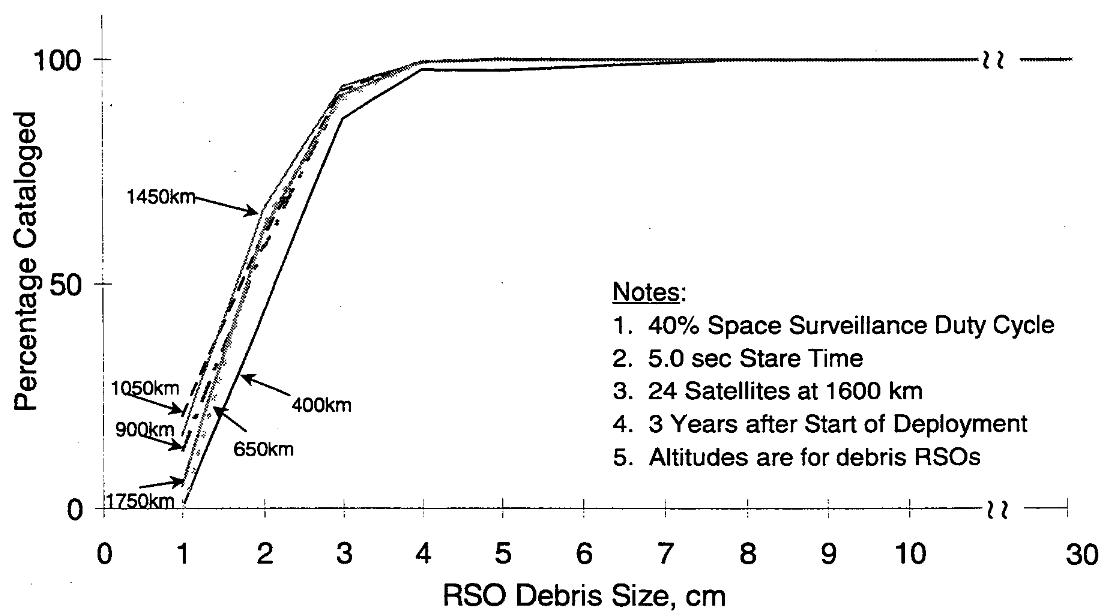


**Figure 11. Debris Catalog Completeness**

Table 5 shows the analogous situation for Catalog completeness of geosynchronous debris. Due to the remoteness of geosynchronous orbit, the minimum debris sizes are far larger than for those on low earth orbit.

**Table 5. Cataloged GEO Debris Three Years After Start of Deployment**

| | Minimum Debris Size, cm | Cataloged # Debris RSOs | Total # Debris RSOs |
|---|---|---|---|
| 40% Space Surveillance, 0.1 sec Streak Time | 100 | 1878 | 1878 |
| 40% Space Surveillance, 5.0 sec Stare Time | 30 | 12496 | 13101 |

The Uncorrelated Target rate, Figure 12, displays features consistent with the remarks above. The stare mode curve increases as each new satellite comes on line until there are enough resources to begin acquisition. After that, the curve drops to about 1,660 per day at the end of deployment where it remains. No further reduction occurs because the sensor resources for more acquisitions is lacking. The streak mode curve, after showing a brief transient blip when the second satellite becomes operational, quickly drops to a very low level of about five per day at the end of deployment. If the simulation were extended in time, this rate would eventually drop to zero. In both cases, sensor resource availability, or lack thereof, determines the long term debris acquisition rate and its detection complement, the UCT rate.

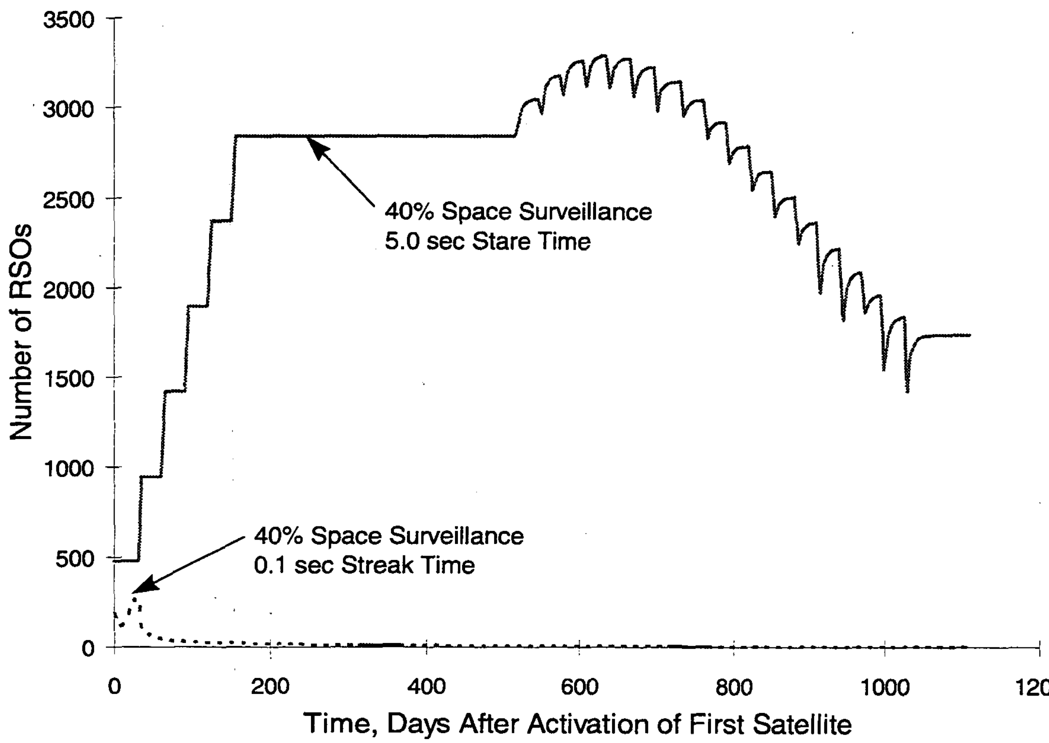


**Figure 12. Daily Uncorrelated Target Rate**

An attempt to estimate the Lost Satellite rate was made. Two possible sources of lost satellites have been identified. First, lost satellites could happen when an RSO image does not fall on a SBIRS Low sensor focal plane during multiple tasked observations on it. Since RSO steady state angular ephemeris errors are of the same order of magnitude as the focal plane pixel size, a 128 × 128 focal plane array would associate to a failure to detect an RSO, per observation, of about 64 standard deviations...a probability too small to estimate with any meaning. The second source, however, has been with us a long time. It is satellite breakup, or explosion, events. Figure 13 [1] shows that in spite of the introduction of procedures to eliminate stored energy on dead satellites, we should plan on a Lost Satellite Rate of two to five per year. SBIRS Low will detect and acquire the larger debris fragments which result. The bottom line is that the Lost List is expected to be very short after SBIRS Low is deployed.

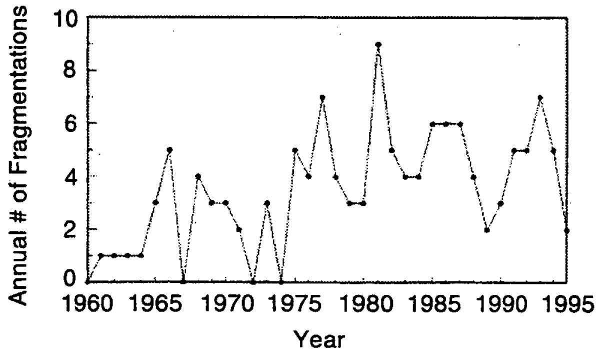


**Figure 13. Lost Satellite Rate (Ref. 1)**

## 7. Conclusions

SBIRS Low offers the potential to revolutionize the way we do space surveillance. First, it will provide an unprecedented volume of space surveillance observations covering the entire globe. Also, its multicolor observations will enable detection of debris with wide compositional variations. Given appropriate tasking and signal processing, the Catalog could grow by order of magnitude by the time SBIRS Low is fully deployed. It appears likely that the bulk of the small debris RSOs added to the Catalog by SBIRS Low will be a by product of routine Catalog maintenance observations. Consequently, it may well *not* be necessary to conduct extensive SBIRS Low searches to find small debris RSOs.

The ultimate detection capability of the SBIRS Low system will result from upfront cost versus performance trades early in the program definition process. These trades will help establish an affordable set of space surveillance requirements which will establish the foundation for future capabilities. The critical cost versus performance trades studies will be those addressing minimum debris size and Catalog completeness at that size. These trades will address system design features including a velocity filter [7] in the signal processing, track sensor aperture, constellation size, and space surveillance duty cycle.

Finally, it appears that while SBIRS Low will greatly enhance our capability to Catalog smaller debris, it may not be able to detect and acquire the bulk of the debris posing a collision hazard to the International Space Station.

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## 9. Biographies

Charles P. Hoult is a Senior Project Engineer with The Aerospace Corporation working in the SBIRS Program Office. His previous Aerospace experience includes work in the Antisatellite (ASAT) and Titan Program Offices as well as renewable energy studies done while part of Government Support Operations. Prior to joining Aerospace he consulted in the areas of sounding rockets, wind power, and surface effect ships. He has an S.B. and S.M. degrees from M.I.T.

Robert P. Wright is a Section Manager with the Aerospace Corporation working in the Modeling and Simulation Department, within the Systems Engineering Division. He is currently involved in architecture-level space systems simulation development for a variety of Air Force Programs. His previous experience includes infrared sensor design and performance analysis and infrared detector material characterization. He received B.S., M.S., and Ph.D. degrees in Solid State Physics from UCLA.