<u>Contributions of the Space-Based Visible Sensor to Catalog Maintenance</u>

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The Space-Based Visible (SBV) sensor, built by Massachusetts Institute of Technology Lincoln Laboratory for the Ballistic Missile Defense Organization's (BMDO) Midcourse Space Experiment (MSX), was one of a suite of sensors on board the MSX satellite to collect data over a wide-wavelength range on ballistic missiles and the earth's background. When the infrared sensor's cryogenic coolant was depleted, the BMDO experiments were concluded. Not needing cryogenic coolant, SBV has become a contributing sensor to the Space Surveillance Network (SSN) as an Advance Concept Technology Demonstration (ACTD).

The Space Defense Operations Center (SPADOC) system was modified in vertical release 97-1 to process space-based observations, i.e., observations from a sensor on board a satellite. The Space Control Center (SCC) at Cheyenne Mountain Air Station began tasking the SBV sensor from SPADOC on 13 April 1998. The sensor tasking software in SPADOC was not modified to handle space-based sensors, but instead a set of fictitious ground-based optical sensors was added to SPADOC's database to simulate the global coverage of a space-based sensor.

Since the ACTD only provided for eight hours of operation six days a week, the visibility constraints of this schedule did not give the SBV sensor global coverage of the geosynchronous belt. Due to the time of the eight-hour period of operation, the SBV sensor could not see the geosynchronous belt from approximately 80 degrees east to 220 degrees east. Two fictitious optical sensors on the equator were entered in SPADOC's database to represent SBV's coverage. One was placed at 21 degrees east with a minimum elevation of 23 degrees. Its coverage of the geosynchronous belt is from 322 degrees east to 80 degrees east. The other ground-based sensor was placed at 271 degrees east with a minimum elevation of 31.6 degrees. Its coverage of the geosynchronous belt is from 220 degrees east to 322 degrees east. See Figure 1 for a depiction of the SBV sensor coverage. Although near-earth satellites are visible to SBV, it has only been utilized for deep-space satellites (periods greater than 225 minutes). Since 15 December 1998, the daily eight hours of operation has been changed to two separate four-hour periods of operation, with the effect of providing global coverage of the geosynchronous belt.

Table 1 shows the number of deep-space satellites on 31 December 1998, broken down by cataloged and analyst satellites and by orbit type. Figure 2 shows that the number of deep-space satellites has grown slowly in 1998. The number of analyst geosynchronous satellites (difference between the two lower graphs in Figure 2) is a small proportion of the total number of geosynchronous satellites. However, the number of deep-space analyst satellites (difference between the upper two graphs in Figure 2) is a large proportion of the total number of deep-space satellites. This is due to the Uncorrelated Track (UCT) processing at the Alternate Space Control Center (ASCC) from Naval Space Command Fence detections on deep-space objects with low perigee. The ASCC generates analyst satellites from these UCTs, and the SCC tasked them to the SSN for more observations from other sensors. If these analyst satellites cannot be maintained by observations from the SSN, they are deleted from the catalog when the epoch age exceeds 60 days. Such analyst satellites are constantly being added and deleted from the satellite catalog, and this accounts for the daily fluctuations in the upper graph in Figure 2.

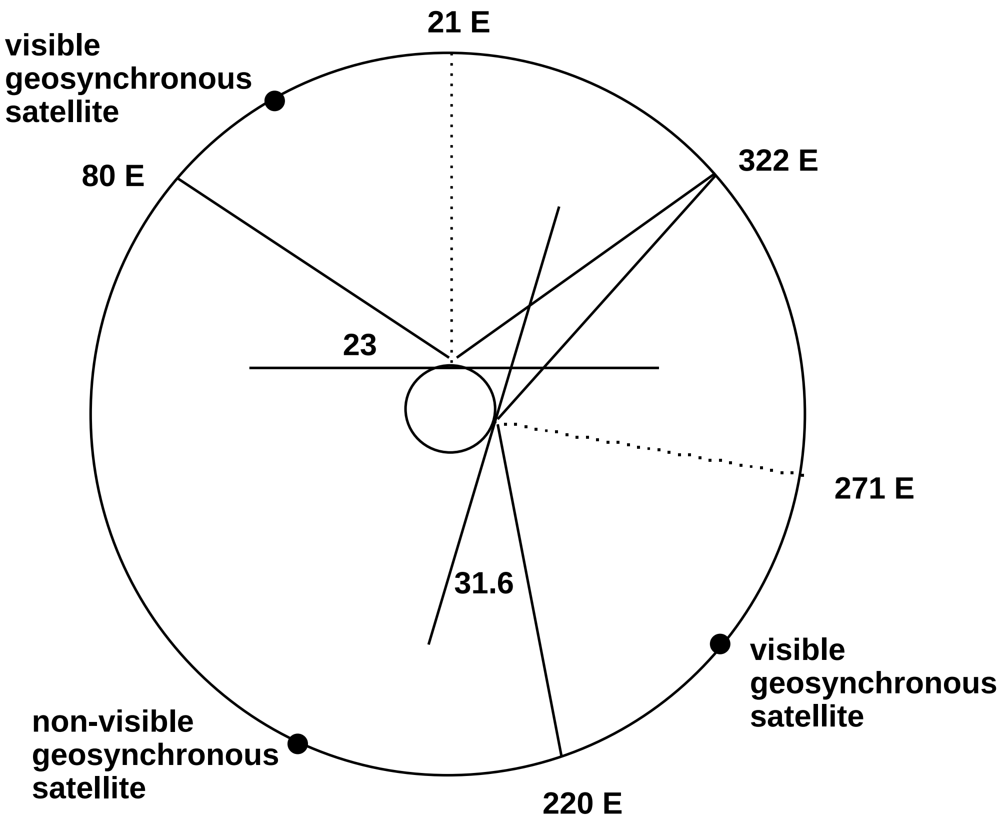

Figure 1. SBV Sensor Coverage

Table 1. Number of Deep-Space Satellites on 31 December 1998

	Deep-Space	Geosynchronous	Deep-Space Other
Cataloged Satellites	1772	711	1061
Analyst Satellites	883	102	781
Total	2655	813	1842

This paper attempts to show SBV's contributions to catalog maintenance. It is difficult to show how any one sensor impacts the satellite catalog. It is even more difficult to show that SBV has made significant contributions to catalog maintenance because the Transportable Optical Sensor (TOS) came on line in Moron, Spain at about the same time as SBV. The SCC began tasking TOS for observations on 18 March 1998. Figure 3 shows the number of tracks from SBV and TOS from their initial operations through 31 December 1998. TOS has contributed nearly as many tracks as SBV. With the addition of two new deep-space sensors to the SSN in 1998, one would expect improvements in the catalog maintenance of deep-space satellites. Our analysis shows that the SBV sensor has contributed significantly to improvements in the catalog maintenance of a subset of the deep-space satellites, namely geosynchronous satellites.

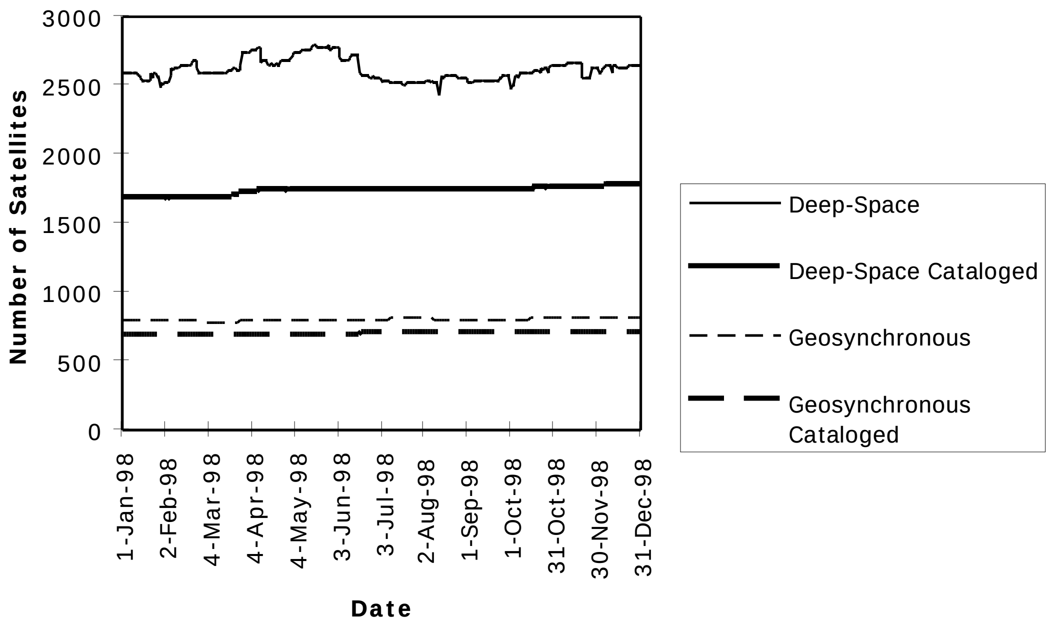

Figure 2. Deep-Space Catalog Growth During 1998

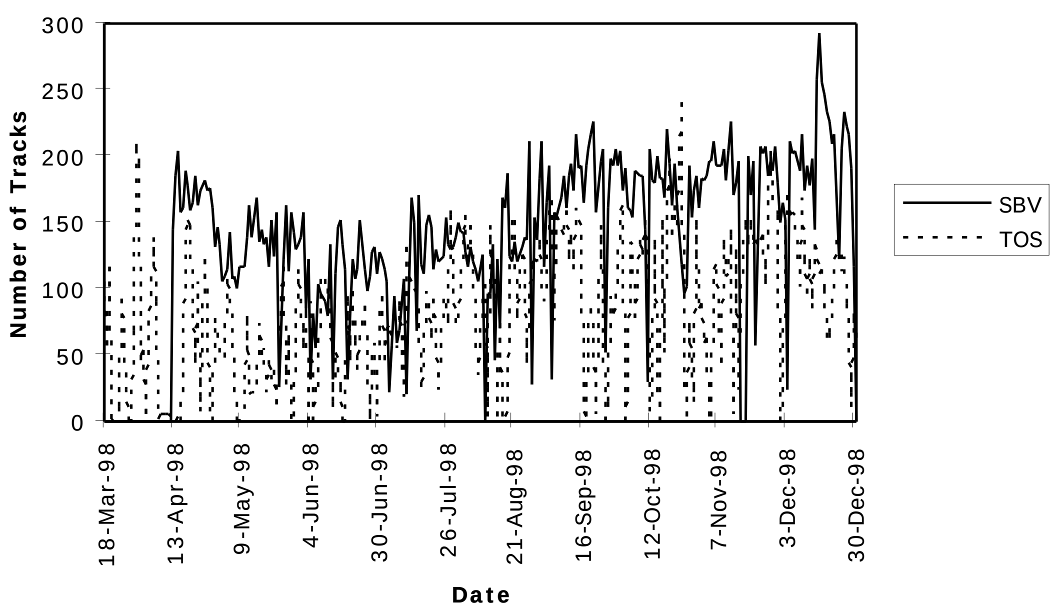

Figure 3. SBV and TOS Tracks

Figure 4 shows the contributions of each SSN site in tracking deep-space satellites from 13 April through 31 December 1998. The Naval Space Command Fence (NAV) and the Eglin radar have contributed by far the most tracks on deep-space satellites. However, most of the tracks in Figure 4 from these two sensors are on non-geosynchronous satellites. The contributions of TOS and SBV to tracking deep-space satellites are small compared to the rest of the SSN. Therefore, statistics on the deep-space subset of the satellite catalog have not significantly changed since the addition of TOS and SBV to the SSN. However, statistics on just geosynchronous satellites have shown improvements since SBV became operational. Sensors that can track geosynchronous satellites are the Eglin (EGL), Millstone (MIL), and ALTAIR (ALT) radars; the RF passive sites at Feltwell (FLT) and Misawa (MSW); the Ground-Based Electro-Optical Deep-Space Surveillance (GEODSS) sites at Socorro (SOC), Maui (MAU), and Diego Garcia (DGC); the Maui Space Surveillance System (MSSS); and TOS and SBV. Among these sensors, SBV's contribution to tracking deep-space satellites is second only to MSSS.

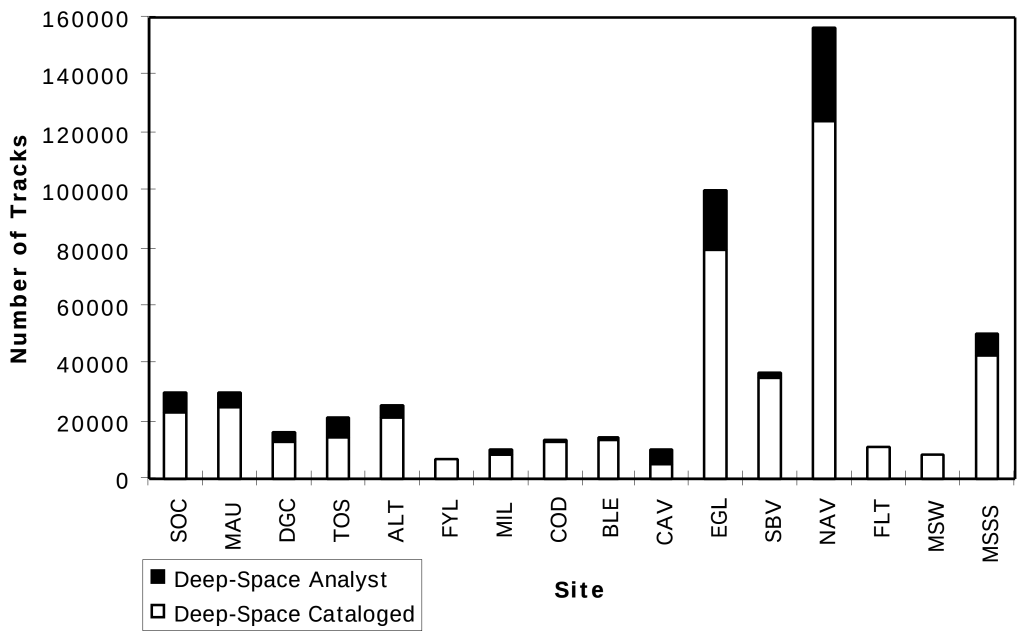

Figure 4. Tracks on Deep-Space Satellites from 13 April through 31 December 1998

Figure 5 shows the contributions of each site in tracking geosynchronous satellites from 13 April through 31 December 1998. SBV's contribution on this subset of the catalog exceeds MSSS, and is rather large compared to the rest of the SSN. Statistics on the epoch age and error growth rate of geosynchronous cataloged satellites show dramatic improvements after 13 April 1998 when SBV became operational. Figure 6 shows a drop in average epoch age of geosynchronous cataloged satellites by 0.8 days. Figure 7 shows a drop in the average number of geosynchronous cataloged satellites on the attention list (epoch age between 5 and 30 days) by 44 satellites. Figure 8 shows a drop in the average error growth rate (EGR) of geosynchronous cataloged satellites by 1.0 km/day.

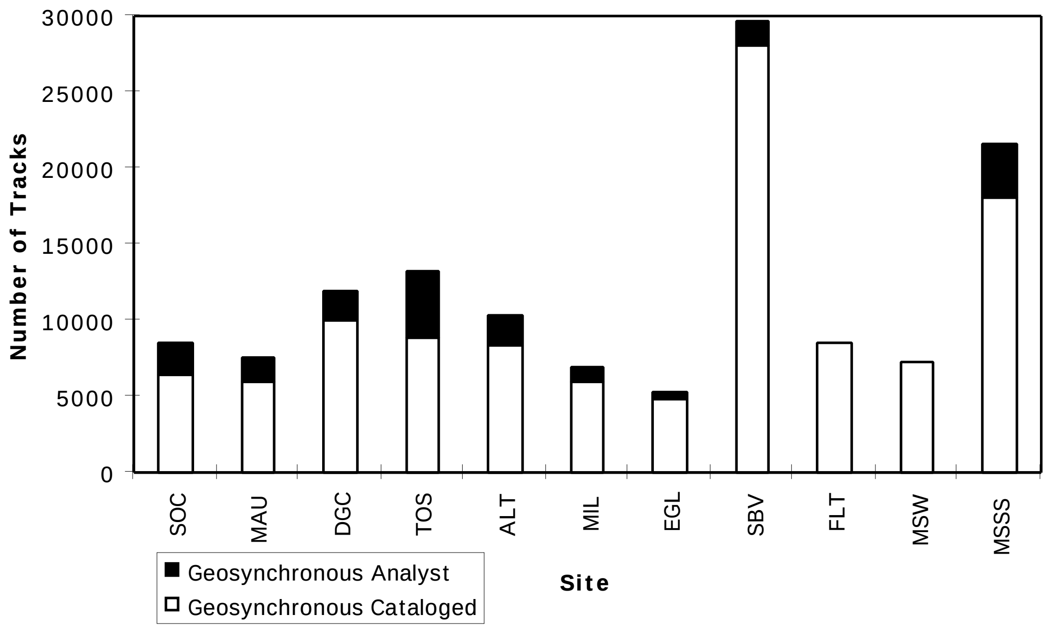

Figure 5. Tracks on Geosynchronous Satellites from 13 April through 31 December 1998

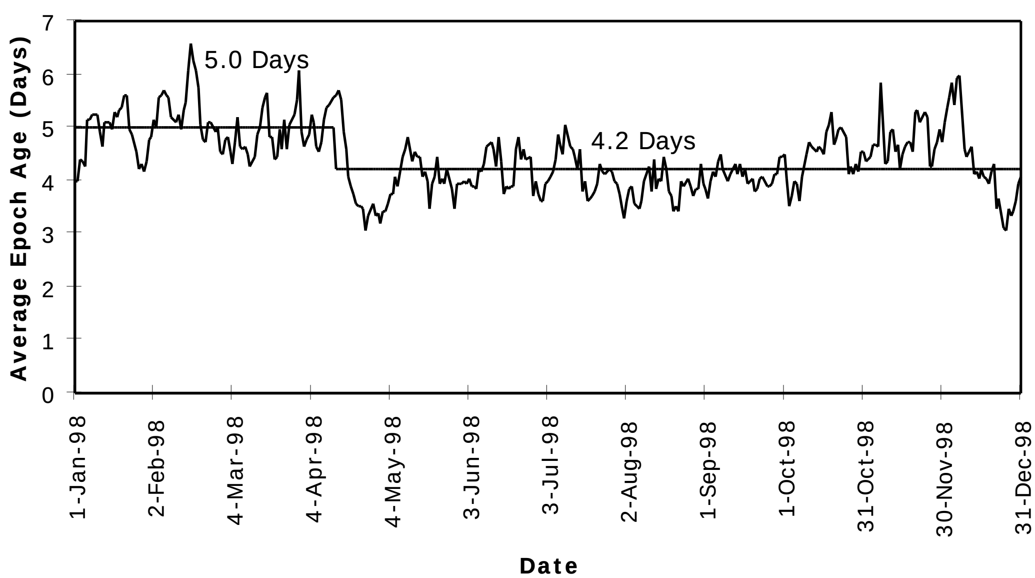

Figure 6. Average Epoch Age of Geosynchronous Cataloged Satellites

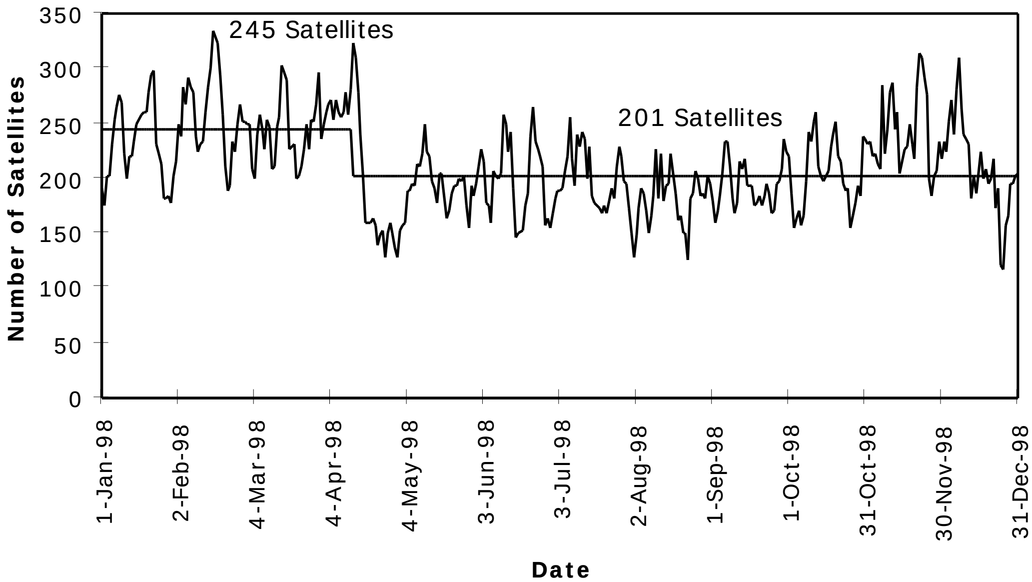

Figure 7. Number of Geosynchronous Cataloged Satellites on Attention List

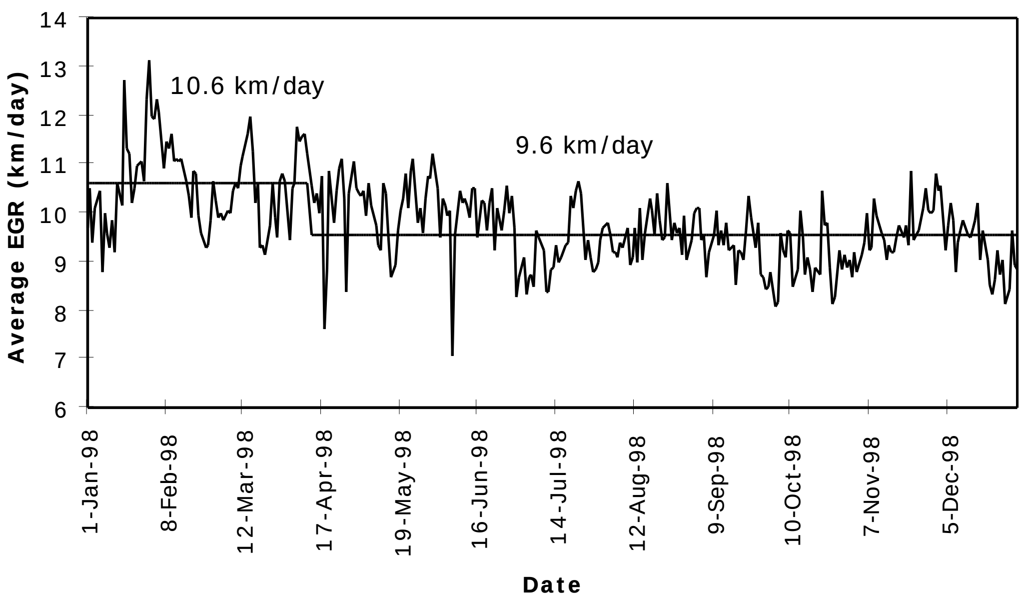

Figure 8. Average Error Growth Rate of Geosynchronous Cataloged Satellites

An EGR value for each satellite in the catalog is computed once a day in SPADOC using a previous element set and the observations from all sensors since the epoch time of the element set. The element set is propagated by Simplified General Perturbations 4 (SGP4) to the time of each observation, and the vector magnitude (VMAG) between the propagated point and observation is computed. A linear least-squares fit to the VMAGs is computed. The EGR value is the slope of the regression line, measured in km/day. The observations are also used in a differential correction to update the epoch time and element set parameters. The element set is saved for the computation of the satellite's EGR the next day as new observations are received by SPADOC. EGR is more a measure of the propagation errors of SGP4 than a measure of the observation errors of the sensors, although the latter does influence EGR. For a given EGR value, it would be difficult to separate the errors due to SGP4 and the observation errors of the sensors. Individual sensor errors are determined from the sensor calibration program developed by ITT.

The sensor calibration program uses reference orbits generated from laser ranging observations obtained from NASA's Crustal Dynamics Data Information System. Reference orbit fits of centimeter-level root mean square (RMS) are generated for Lageos 1 (SSC satellite number (SATNO) 8820), Lageos 2 (SATNO 22195), Etalon 1 (SATNO 19751), and Etalon 2 (SATNO 20026). Additionally, declassified Global Positioning System (GPS) precise ephemeris files are obtained from the National Imagery and Mapping Agency (NIMA) for GPS satellites 34, 35, and 36 (SATNOs 22779, 22877, and 23027, respectively). The deep-space sensors are routinely tasked to track these satellites, and observations on these satellites are compared against the reference orbits. Residuals are calculated against the reference orbits, using two weeks of sensor observations. The mean, one sigma standard deviation, and RMS of all the individual observables are computed from the residuals. Where sufficient observational data are available, the results (biases and sigmas) were very consistent for 1998. The average biases and sigmas for right ascension (RA) and declination for 1998 for each sensor are displayed in Figures 9 and 10, respectively. MSSS consists of three different telescopes, MOTIF(MOT), AMOS(AMS), and the Beam Directed Tracker (BDT). By far, most of the observations from MSSS are from the BDT telescope. AMOS did not provide sufficient observations to accurately determine its bias and sigma.

Note that SBV had no discernable bias for either right ascension or declination, while the other optical sensors definitely displayed biases, especially in right ascension. By accounting for sensor biases in the differential corrections of element sets, the biases can be removed. However, SPADOC does not use sensor biases in the differential correction of element sets, and the biases introduce errors in the differential correction process. The one-sigma standard deviations also reflect upon the quality of the observations going into the orbit determinations. Figure 10 shows that SBV observations are of higher quality than the ground-based optical sensors. This is consistent with the improvement in the average error growth rate of geosynchronous cataloged satellites since SBV became operational, as seen in Figure 8.

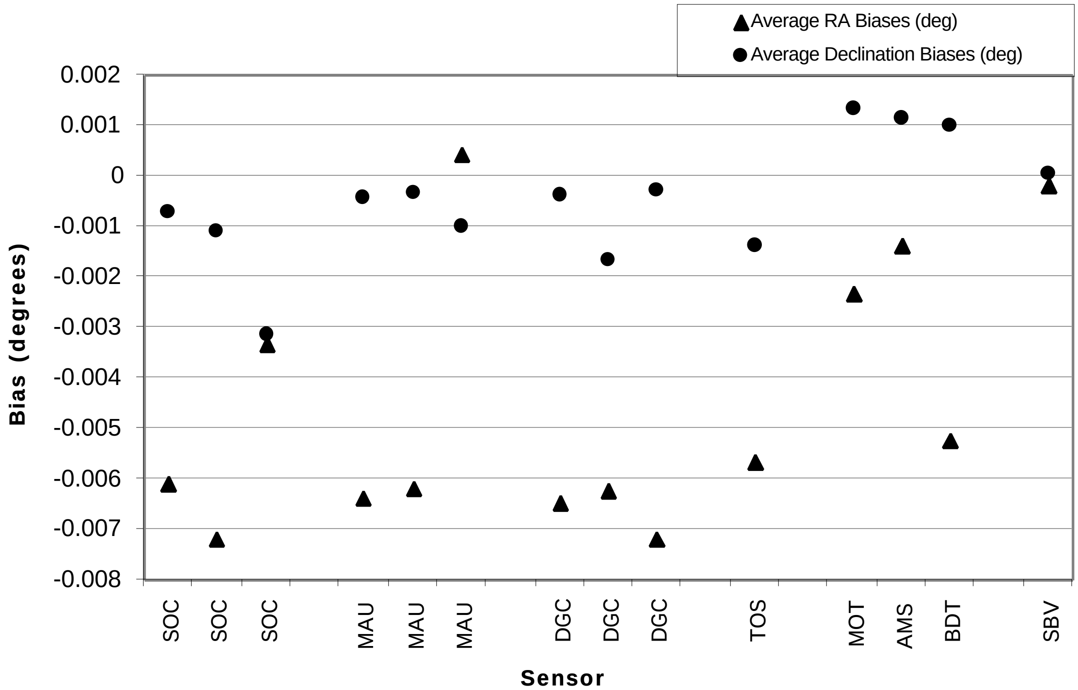

Figure 9. Average Biases of Optical Sensors for 1998

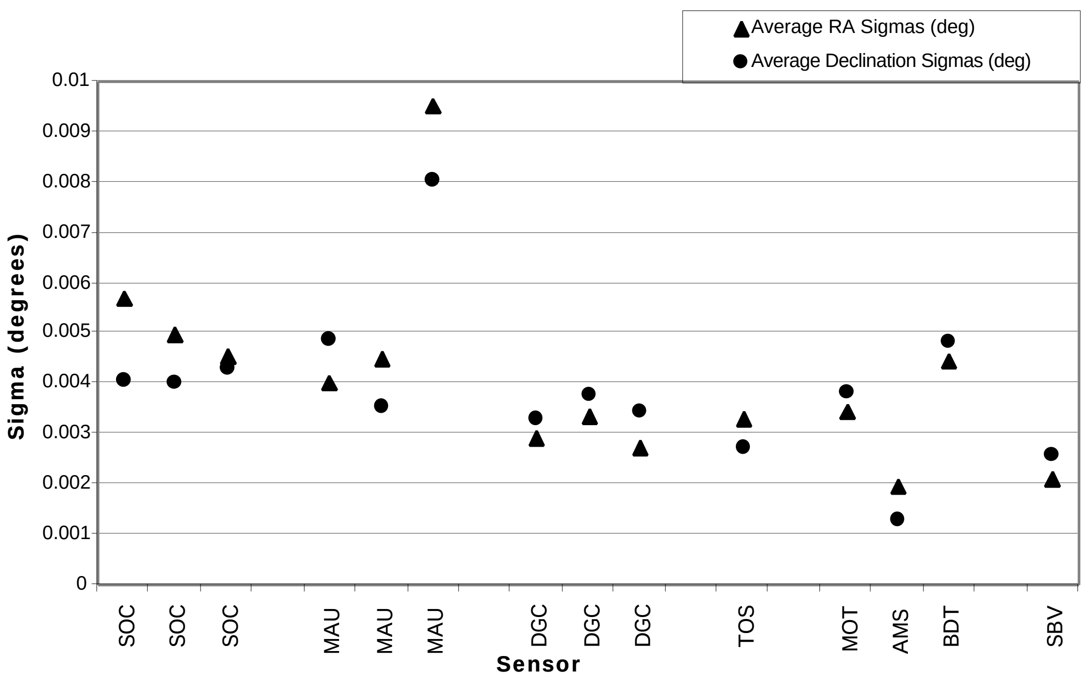

Figure 10. Average Sigmas of Optical Sensors for 1998

Finally, the optical sites' response to tasking is considered. After SBV was operational, Lincoln Laboratory developed a Conjunction-Optimized Look-Ahead (COLA) scheduler to optimize track throughput. The COLA scheduler gives higher priority to tasked objects that are on the focal plane of SBV at the same time, generating streaks on multiple objects from the charged coupled device (CCD). This produces tracks on multiple objects for the cost in time of one slew of the SBV sensor, which is done by reorienting the MSX satellite since SBV is not gimbaled. In order to provide SBV a large enough set of objects to feed the COLA scheduler with opportunities to simultaneously track objects, the sensor tasking from SPADOC was changed from 300 to 800 tracks per day. Beginning in September 1998, the increased track throughput of the COLA scheduler to over 200 tracks per day can be seen in Figure 3. Although SBV's percentage response to tasking decreased when the number of tasked tracks increased from 300 to 800, the actual track throughput increased.

There was some concern that the optimization in the COLA scheduler for simultaneous tracks would not appropriately consider the tasking category, which prioritizes the importance of the satellites to the user. In particular, category 1 tasking occurs on high priority satellites and a higher response rate from the sensors is expected. Lincoln Laboratory's COLA scheduler also prioritizes the satellites by category based on a weighting scheme to ensure the appropriate response on high priority satellites, even though this conflicts with the priority to get simultaneous tracks on multiple objects. Figure 11 shows SBV's response to tasking by category from September through December 1998. Although the number of tasked tracks on category 1 satellites is small, the percentage response has been high.

SPADOC tasked TOS for 250 tracks per shooting period (time site is in darkness). Figure 12 shows TOS's response to tasking by category from September through December 1998. TOS is also responding appropriately to category 1 tasking. TOS is not tasked for category 4 and 5 satellites because its capacity is filled by the time SPADOC attempts to task category 4 and 5 satellites. SPADOC orders the satellite catalog by tasking category before each daily tasking run. Although TOS's percentage response to tasking is higher than SBV's percentage response, SBV's track throughput is higher, as can be seen from Figure 3.

Figure 13 shows the track and observation throughput from SBV and TOS on deep-space satellites from September through December 1998, broken down by acquired tracks/observations in response to tasking and extra tracks/observations (either more tracks/observations than required on a tasked satellite or tracks/observations on an untasked satellite). The large number of extra tracks/observations from SBV is due to the fact that 2 hours per day are spent searching the geosynchronous belt and only 6 hours per day are devoted to responding to SPADOC's tasking. SBV has the greater track throughput, but the observation throughputs are nearly equal.

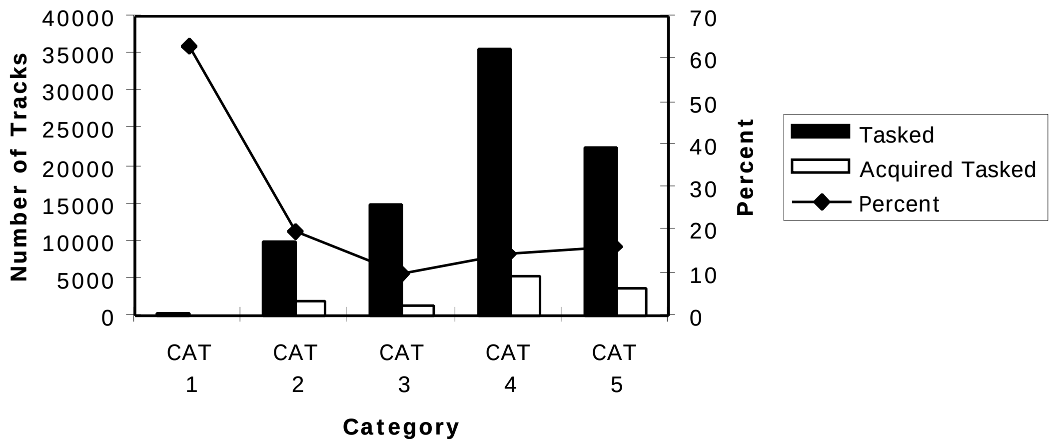

Figure 11. SBV's Tasking Response by Category from September through December 1998

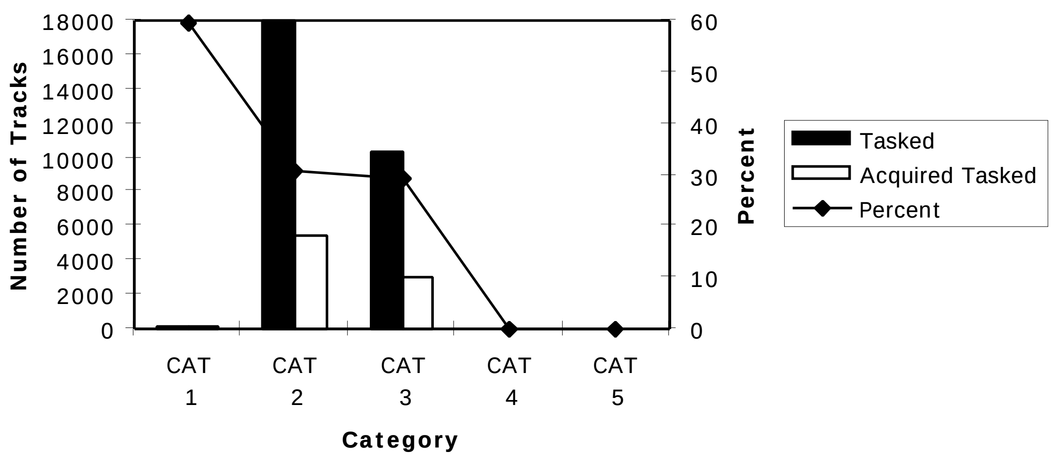

Figure 12. TOS's Tasking Response by Category from September through December 1998

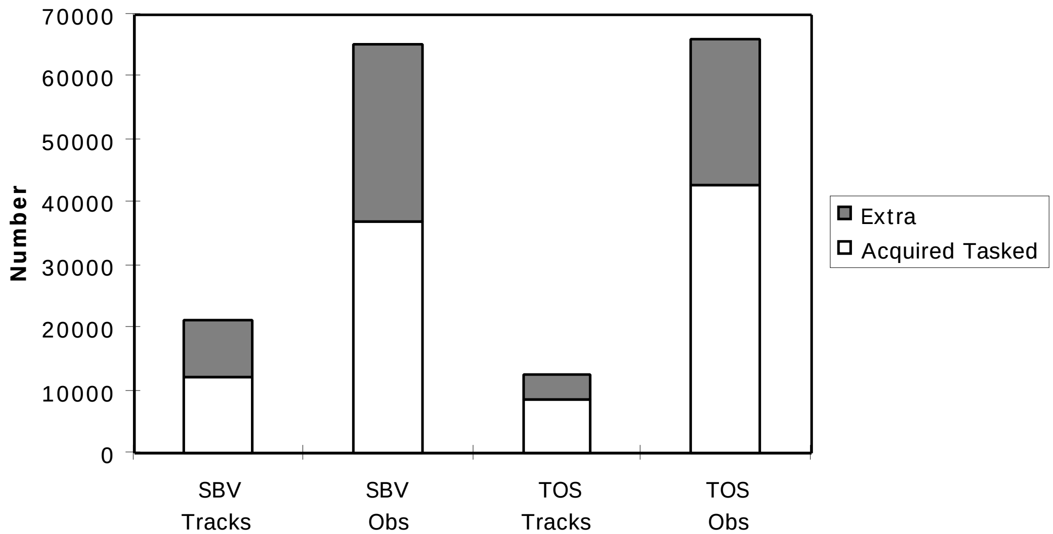

Figure 13. Track and Observation Throughput from September through December 1998

Figure 14 shows the histogram of SBV's observations per track from September through December 1998. SBV is being tasked by SPADOC according to Regulation 55-12, and the most commonly used tasking suffix by SPADOC requires 4 observations per track. Each streak on the CCD produces two observations, corresponding to the endpoints of the streak. To get the 4 required observations on a satellite, two streaks must be processed. Figure 14 shows that SBV is providing more one-streak tracks than two-streak tracks. Two reasons account for the one-streak tracks with only two observations: (1) two hours per day are spent searching the geosynchronous belt and the continuous scanning prevents acquiring the second streak, and (2) the COLA scheduler centers the focal plane array on the primary tasked object and the serendipitously tracked object may only be in the field of view for one streak.

The ground-based optical sites are being tasked by SPADOC according to UI 10-40, which superseded Regulation 55-12. The most commonly used tasking suffix used by SPADOC for the ground-based optical sites requires 5 observations per track. Figure 15 shows the histogram of TOS's observations per track from September through December 1998. Most of TOS's tracks contain 5 observations.

In conclusion, the SBV sensor has contributed to improvements in the statistics on the epoch age and error growth rate of geosynchronous satellites. Since SBV became operational, it has contributed more tracks on geosynchronous satellites than any other sensor in the SSN. SBV's track throughput has increased with the development of the COLA scheduler. SBV's observation throughput has been comparable to TOS's observation throughput. The accuracy of SBV's observations has exceeded the accuracy of the ground-based optical sites.

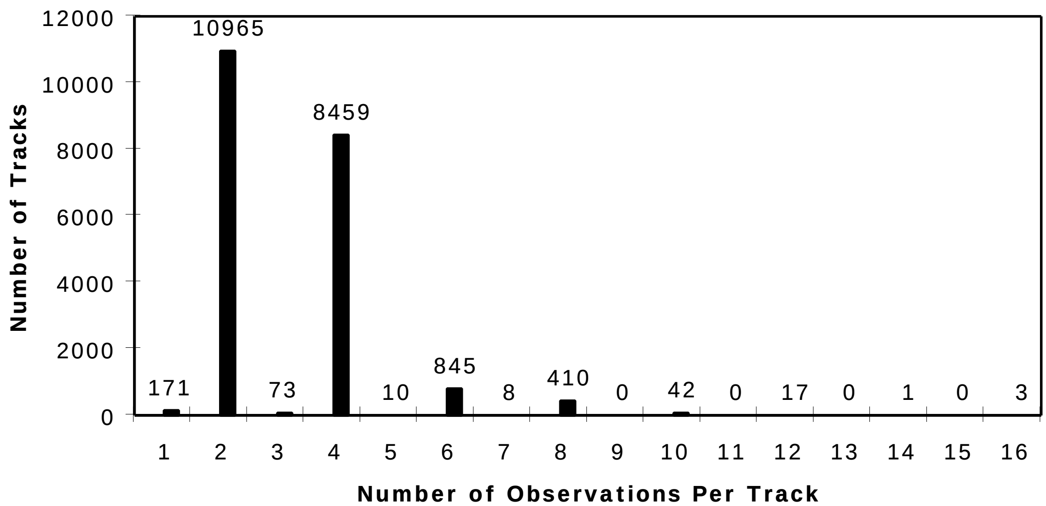

Figure 14. SBV's Obs Per Track from September through December 1998

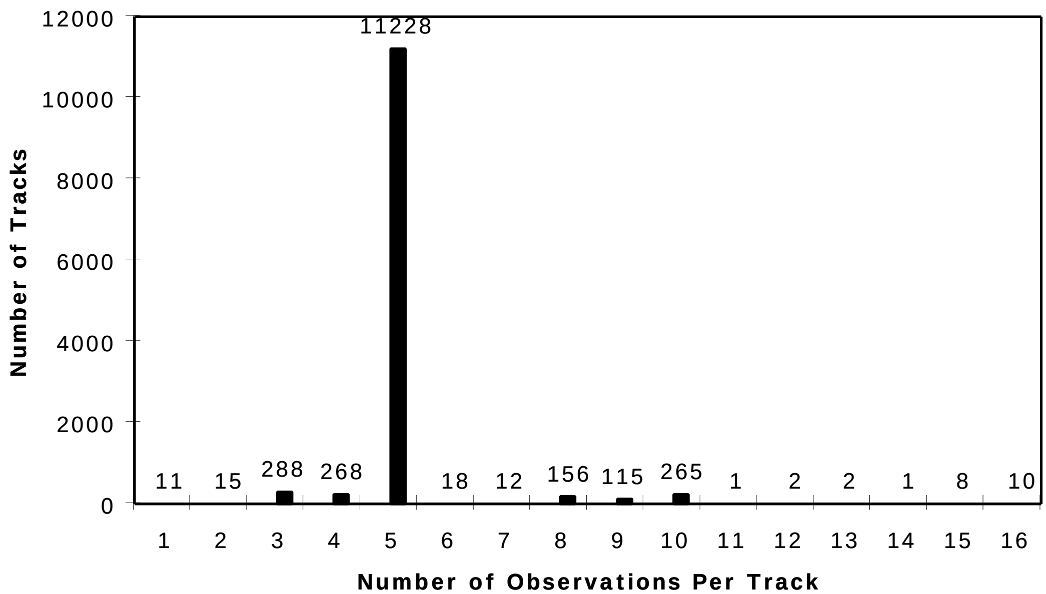

Figure 15. TOS's Obs Per Track from September through December 1998