Contributions of the GEODSS System to Catalog Maintenance

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The Electronic Systems Center completed the Ground-based Electro-Optical Deep-Space Surveillance (GEODSS) Modification Program (GMP) in 1999 with new mission critical computer resources, including sensor controllers at the GEODSS sensor sites and an Optical Command, Control, and Communications Facility (OC3F) at Edwards AFB. The GEODSS system with the GMP configuration became operational on 3 August 1999, with the OC3F dynamically scheduling the three GEODSS sites in response to tasking from the Space Defense Operations Center (SPADOC). SPADOC still tasks the individual GEODSS sites, Socorro, Maui, and Diego Garcia, based on site visibility and capacity, but the site tasking messages are transmitted to the OC3F instead of the individual sites. The OC3F combines the individual site tasking messages into a single database and dynamically schedules the individual sites in near real-time, independent of which site SPADOC tasked. For example, a high-priority satellite may be tasked by SPADOC to Socorro and not Maui, even though it has visibility, but the dynamic scheduler may schedule Maui to track the satellite because Socorro is clouded over during the satellite pass. SPADOC tasks the optical sites hours before their shooting periods begin, assuming clear skies, because it cannot predict the weather in advance.

The OC3F also converts track requests from SPADOC into several tracklets of three obs each, separated in time by at least ten minutes, to achieve better orbit distribution of the observations. This benefits catalog maintenance by producing more accurate element sets. In accordance with U. S. Space Command Instruction UI 10-40, SPADOC tasks satellites to sensors at a category 1 through 5 (category 1 has the highest priority) and a suffix A through Z, indicating the number of tasked tracks and the number of observations per track. As a hypothetical example, consider a semi-synchronous satellite that is visible to all three GEODSS sites. Suppose SPADOC determines that the satellite only needs to be tasked to two sensors, which could be any combination of radar and optical sensors with visibility. Suppose SPADOC tasks Socorro at 2K and Diego Garcia at 2K, i.e. category 2 and suffix K, indicating one track of five observations. K is the most frequently used suffix by SPADOC for ground-based optical sensors. When the OC3F receives Socorro s tasking message from SPADOC, it converts the suffix for each satellite into the number of 3-ob tracklets necessary to provide at least as many observations in SPADOC s track request. For the K suffix, this would be two tracklets, providing SPADOC one more observation than requested but in two tracks or tracklets. When the OC3F receives Diego Garcia s tasking message, it does the same conversion to tracklets. So the hypothetical satellite would have a requirement of four tracklets in the dynamic scheduler s database. The OC3F would attempt to obtain the four tracklets for this satellite from any site that has visibility, based on the real-time optimization and prioritization of all other requests. It is possible that Socorro could be scheduled to provide one of the tracklets, Maui two of the tracklets, and Diego Garcia one of the tracklets to satisfy SPADOC s tasking request. This would result in a total of 12 observations in four tracklets, two more observations than SPADOC requested.

GEODSS with the GMP configuration now produces more tracks, on more objects, and provides more observations per day, on average, than the legacy GEODSS system. The purpose of this paper is to show the effect of this increased throughput on catalog maintenance.

The throughput of GEODSS under GMP from August 1999 through December 1999 is compared with the throughput of the GEODSS legacy system from August 1998 through December 1998, so that the time intervals cover the same months of the year. Figure 1 shows the track response for these two time intervals from all deep-space sensors. The other deep-space sensors include the Maui Space Surveillance System (MSSS), the Space Based Visible (SBV) sensor on board the MSX satellite, the Moron Optical Space Surveillance (MOSS) system, the ALTAIR and Millstone (MIL) radars, and the passive RF sites, Feltwell (FLT) and Misawa (MSW). The post-processing software that reconstructs tracks from SPADOC observation files defines a track to be a contiguous collection of observations on a satellite from a sensor over a short time interval. Thus, GEODSS tracklets are counted as tracks by this software.

Given that the OC3F converts SPADOC 5-ob track requests into two 3-ob tracklets, one would expect GEODSS under GMP to produce twice as many tracks as legacy GEODSS, based on this post-processing software. It is evident from Figure 1 that the GEODSS track throughput has more than doubled (legacy GEODSS provided 40,658 tracks and GMP provided 116,052 tracks for a 185 percent increase). The legacy GEODSS system did have red time from August through December 1998 due to GMP testing. However, the third cameras, both on auxiliary telescopes at Socorro and Maui, were available for spacetrack under the legacy GEODSS system, but are not available under GMP. These auxiliary telescopes will be replaced with main telescopes in the future and scheduled by the OC3F. This will further increase the GEODSS throughput under GMP. The SBV track throughput essentially remained the same for these two time intervals, 26519 and 27563, respectively. It is also evident from Figure 1 that the MSSS track throughput has decreased (from 29577 to 18534 for a 37 percent decrease), and the MOSS track throughput has increased (from 15376 to 25532 for a 66 percent increase). The decrease from MSSS is due to the refurbishment of the 1.2 meter telescope to support Near Earth Asteroid Tracking (NEAT) during the latter part of 1999. In 2000, the 1.2 meter telescope will be used three weeks per month supporting NEAT and only available one week per month for spacetrack. The spacetrack throughput from MSSS will only decrease further in 2000. The increase from MOSS is due to two factors. The site was exhausting its tasking list before the end of its shooting period and just revisiting previously attempted satellites with no success. On 7 February 1999, the daily number of tracks tasked by SPADOC was increased from 250 to 400 at the site s request. On 13 April 1999, operational changes were made at the site to improve the scheduling efficiency by adjusting the miss weight so that satellites would not continue to be scheduled after several missed acquisitions.

Figure 2 shows the object response from the deep-space sensors. The GEODSS object throughput went from 35454 to 51289 for a 45 percent increase. The SBV object throughput essentially remained the same for these two time intervals, 22372 and 21363, respectively. The MSSS object throughput went from 28738 to 17866 for a 38 percent decrease. The MOSS object throughput went from 12445 to 22237 for a 79 percent increase.

Figure 3 shows the observation response from the deep-space sensors. The GEODSS observation throughput went from 202545 to 385753 for a 90 percent increase. The SBV observation throughput essentially remained the same, 81734 and 83454, respectively. The MSSS observation throughput went from 157221 to 97994 for a 38 percent decrease. The MOSS observation throughput went from 80668 to 126669 for a 57 percent increase.

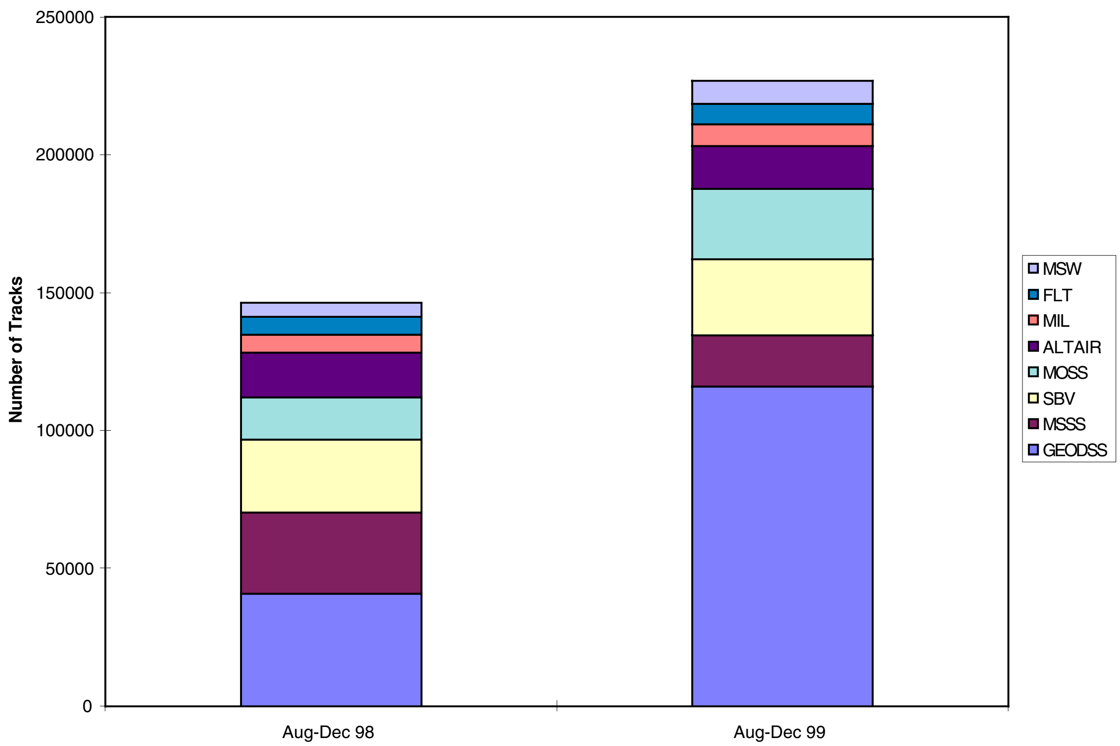

Figure 1. Track Response from the Deep-Space Sensors

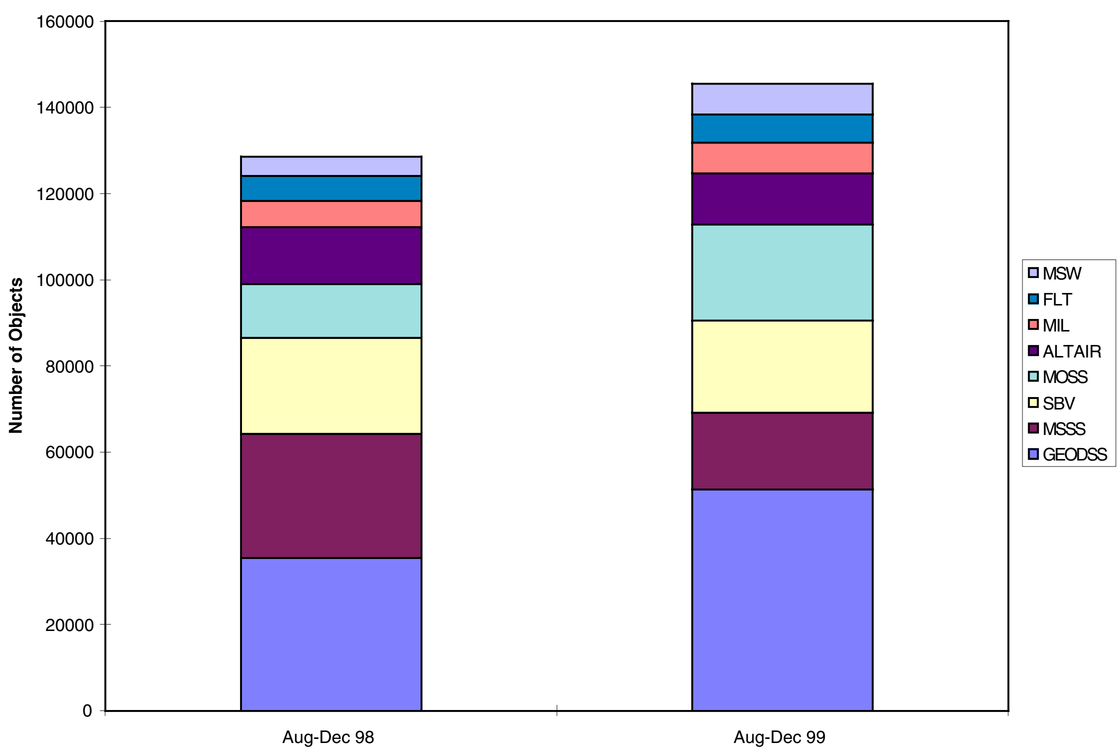

Figure 2. Object Response from the Deep-Space Sensors

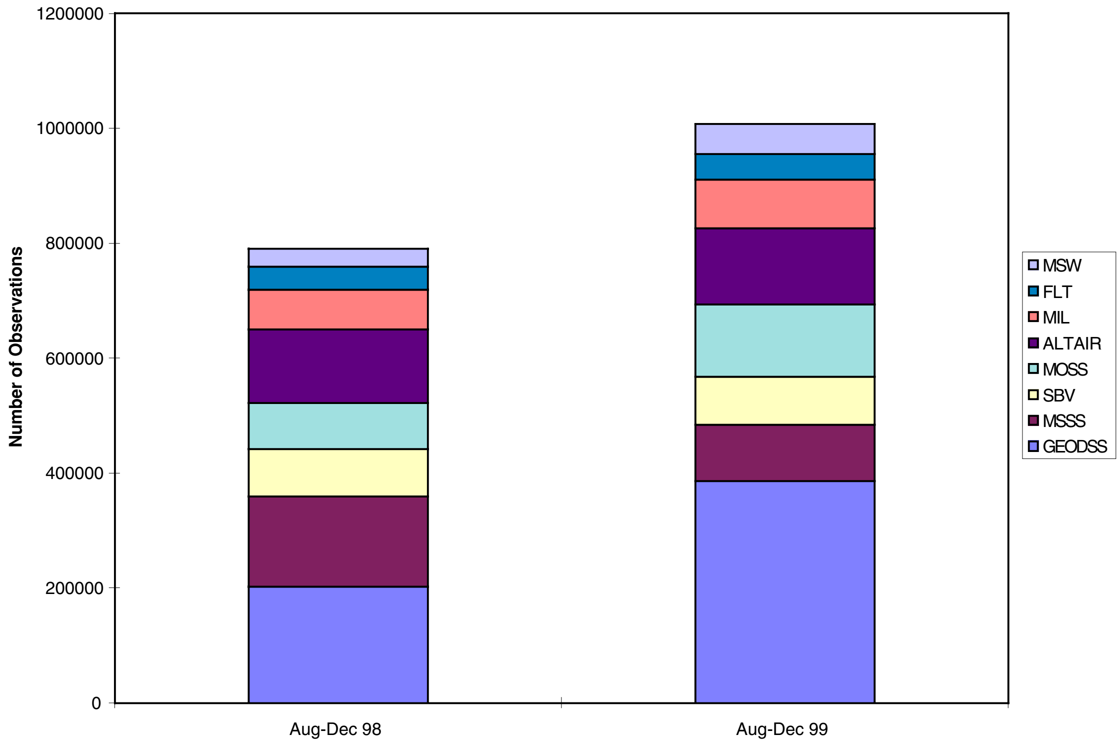

Figure 3. Observation Response from the Deep-Space Sensors

From August 1998 through December 1998, the average number of observations per track from the legacy GEODSS system was 5.0. From August 1999 through December 1999, the average number of observations per track from GEODSS under GMP was 3.3, agreeing with the 3-ob tracklet scheduling by the OC3F for most of the objects. For SBV, the average number of observations per track was 3.0 for both time intervals. The most frequently used tasking suffix for SBV by SPADOC is C, which specifies one track of four observations. The frame processing from SBV s signal processor produces two observations from the endpoints of a streak on the focal plane array. It takes two streaks on the same satellite to produce the four observations requested by SPADOC. For half of the satellites tracked by SBV, a second streak is not obtained, thus explaining the average 3.0 observations per track. For MSSS, the average number of observations per track was 5.3 for both time intervals. For MOSS, the average number of observations per track for these two time intervals was 5.2 and 5.0, respectively.

The GEODSS track response over time is shown in Figure 4. An operational assessment of GMP was done in May 1999. The OC3F s conversion of SPADOC tasked tracks to 3-ob tracklets is clearly seen in the increased track throughput. The increased track throughput is seen again in the beginning of August 1999 when GMP became operational. The GEODSS object response over time is shown in Figure 5. The upper curve in Figure 5 is the number of unique objects tasked to the GEODSS system, which has remained fairly constant except for the fall of 1998. The same object may be tasked by SPADOC to multiple GEODSS sites on a given day, and these objects are counted only once. The bottom curve is the number of unique objects tracked by the GEODSS system. If more than one GEODSS site tracks the same object or the same site tracks an object multiple times on a given day, the object is counted only once. The increase in May 1999 and again in August 1999 is evident in Figure 5, but it is not as significant as the increase in track throughput. Many of the additional tracks (or tracklets) are on the same object in order to satisfy SPADOC s total observation request. The GEODSS observation response over time is shown in Figure 6 with increased throughput under GMP.

The MOSS track response over time is shown in Figure 7. The increase from 250 to 400 tasked tracks by SPADOC on 7 February 1999 is clearly seen in the upper curve with a corresponding increase in track throughput. Since the sensor tasking function in SPADOC uses a maximum track limit as a measure of a site s capacity, the upper curve is a step function that changes when the track limit for a site is updated in the SPADOC database. The site requested an increase from 400 to 600 tasked tracks per day on 23 April 1999. There seems to be no immediate change in the MOSS track response after 23 April 1999. The only effect is to reduce MOSS percentage track response (number of tracks acquired divided by the number of tasked tracks times 100). A site s percentage response can be very misleading without looking at the absolute response numbers. There is an increase in track throughput beginning in August 1999, which cannot be explained. It appears that MOSS is over tasked at 600 tracks per day and that 500 tracks per day would be more appropriate. There needs to be a balance between providing an optical site with enough tasking so that it does not run out of objects to schedule during its shooting period and not over tasking the site, in which case the percentage response will decrease. In the latter case, objects will not get tracked that could have been tasked by SPADOC to other sites.

The MOSS object response over time is shown in Figure 8. An increase in object throughput is noticeable beginning in February 1999, with a further increase beginning in August 1999. The number of tasked objects per day by SPADOC is not constant because some objects are tasked to a site for multiple tracks. The number of tasked objects will always be less than or equal to the number of tasked tracks.

The MOSS observation response over time is shown in Figure 9. An increase in observation throughput is noticeable beginning in February 1999, with a further increase beginning in August 1999.

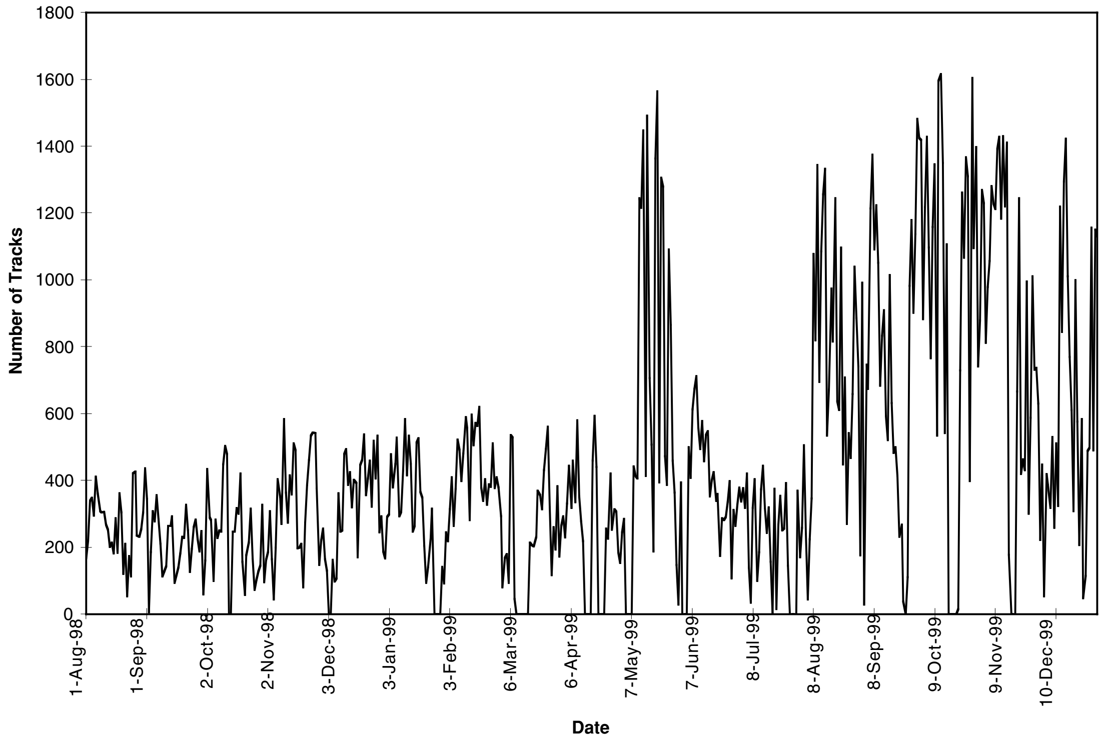

Figure 4. GEODSS Track Response

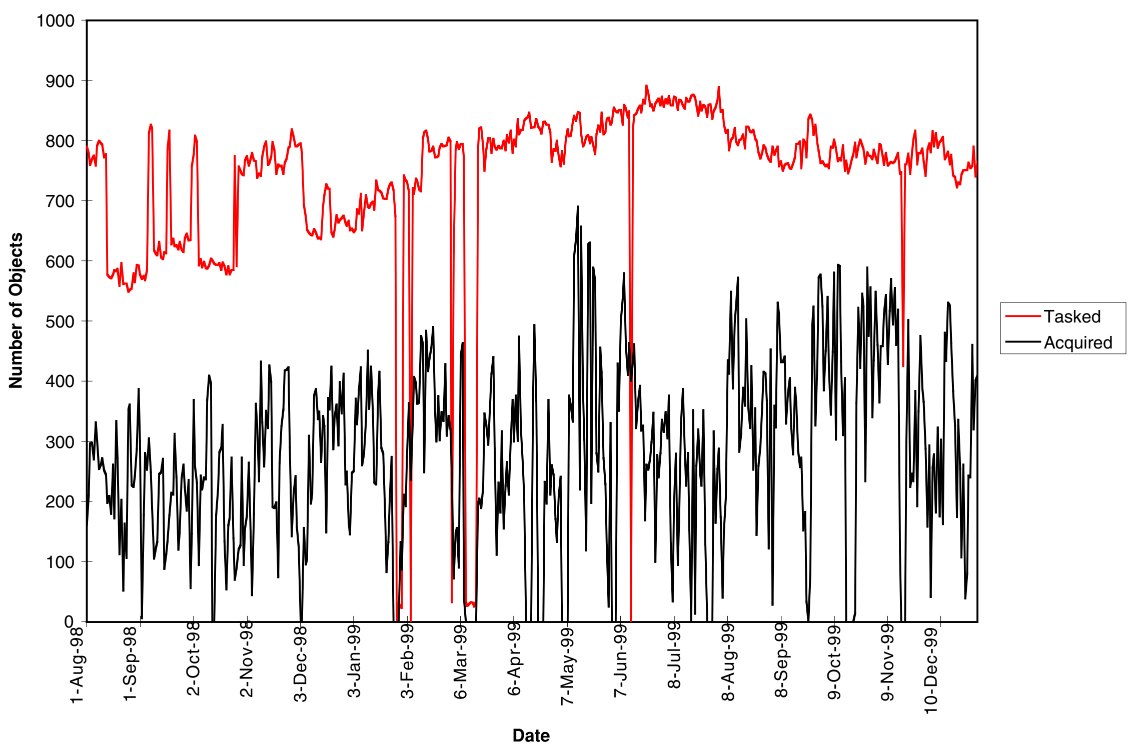

Figure 5. GEODSS Object Response

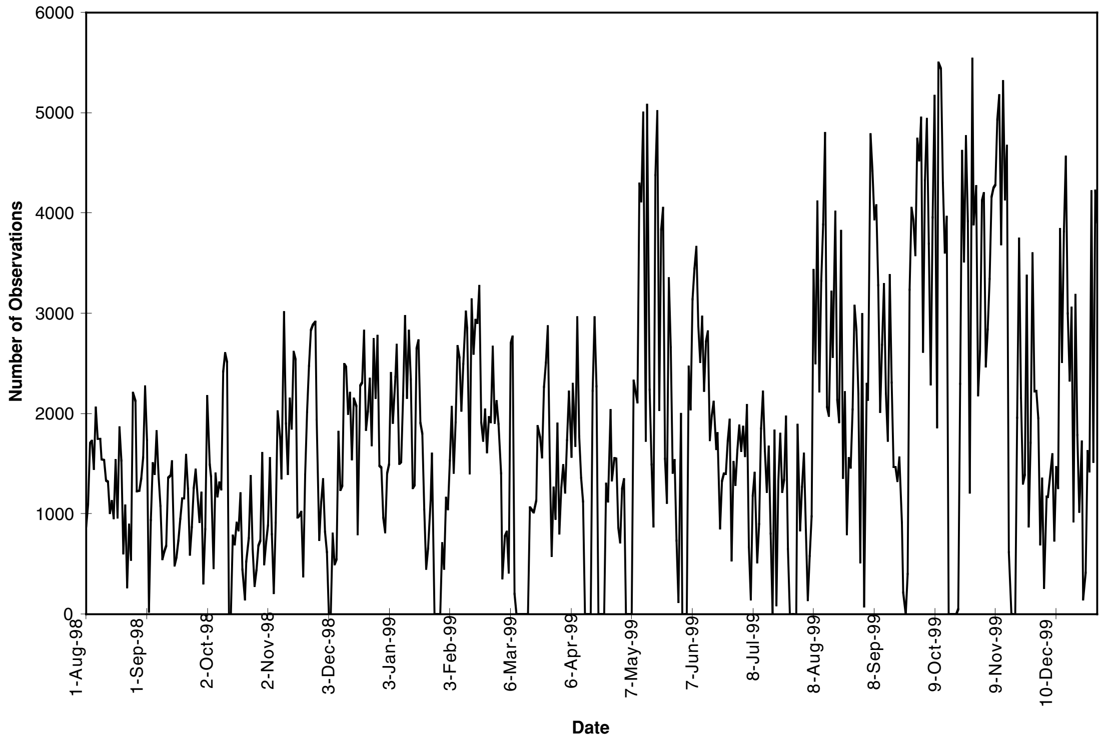

Figure 6. GEODSS Observation Response

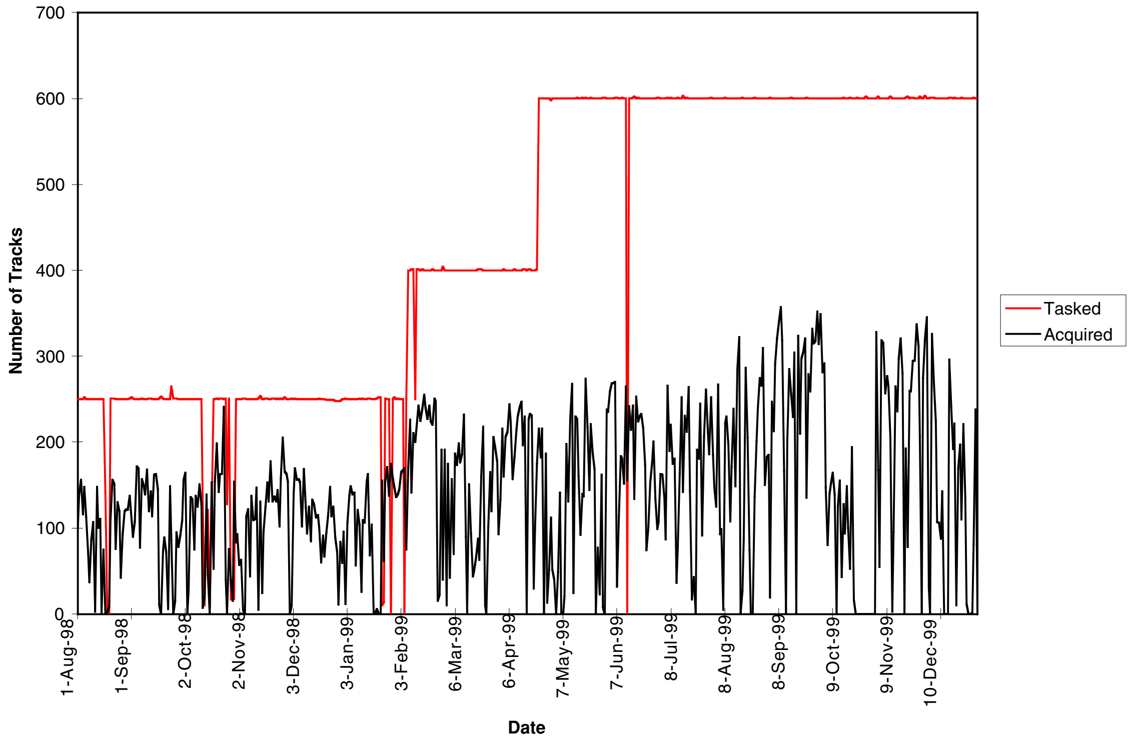

Figure 7. MOSS Track Response

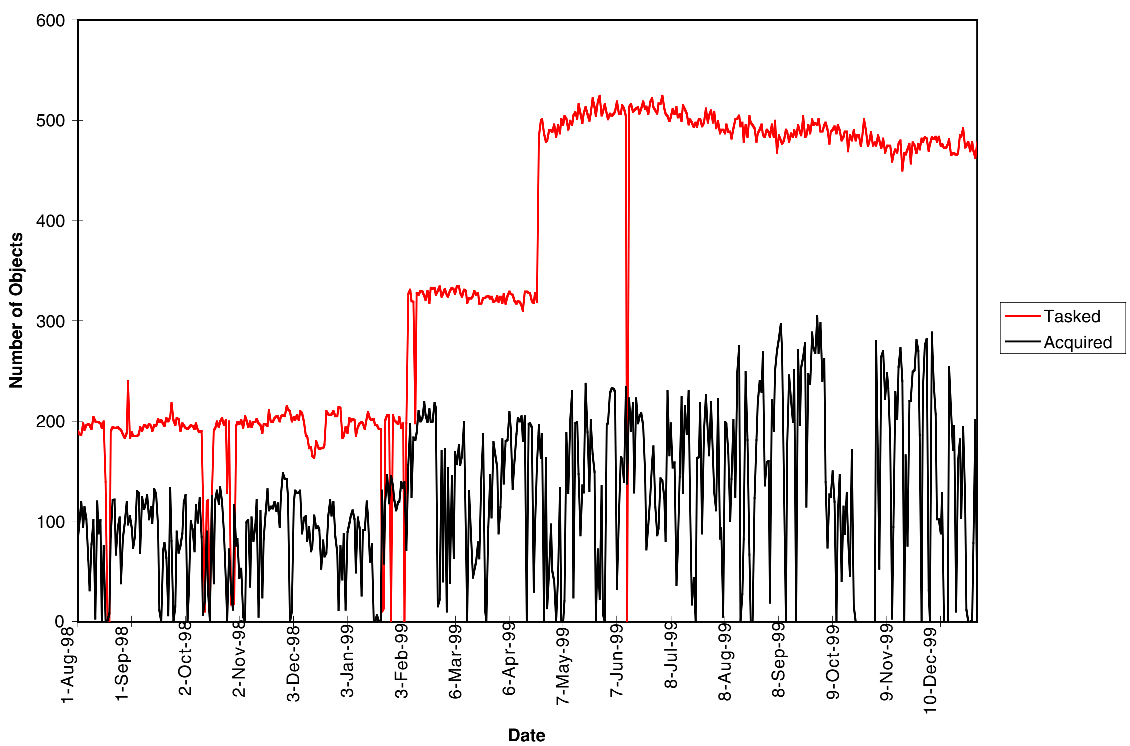

Figure 8. MOSS Object Response

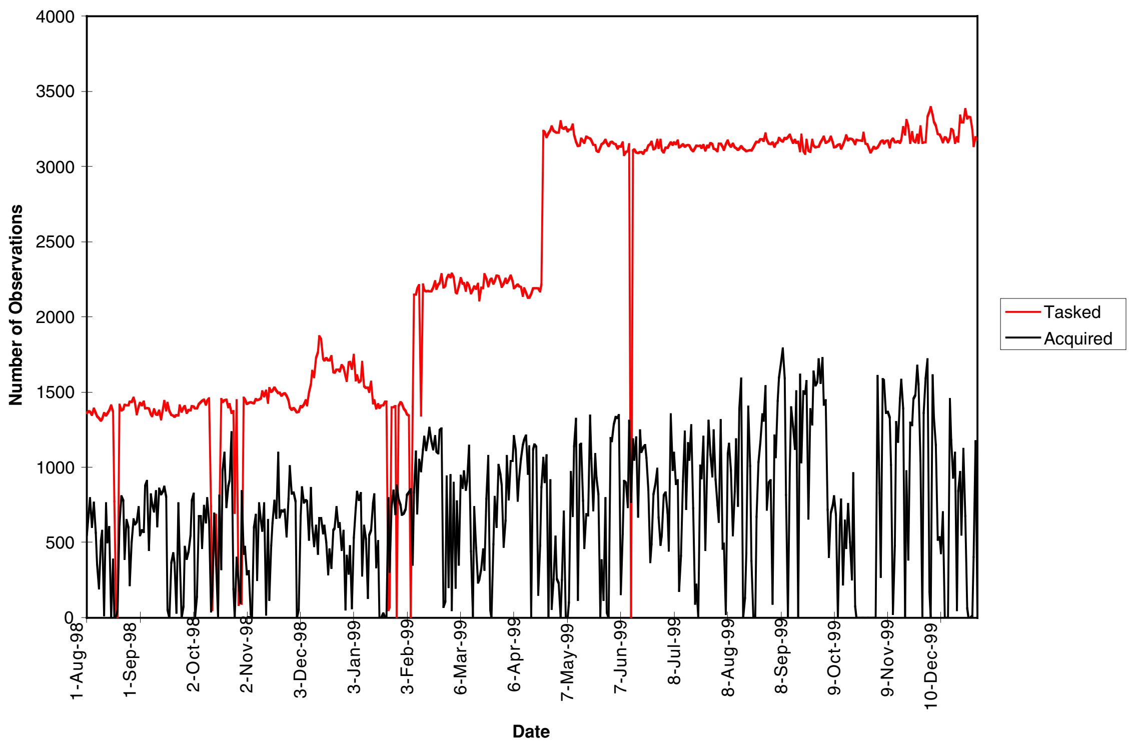

Figure 9. MOSS Observation Response

The impact of the increased throughput from GEODSS under GMP and from MOSS on the deep-space satellite catalog is now investigated. Table 1 shows the number of deep-space satellites (period greater than 225 minutes) on 31 December 1999, broken down by cataloged and analyst satellites and by orbit type. The Naval Space Command Fence and the Eglin radar contribute by far the most tracks on deep-space satellites, even though they are near-earth sensors. Most of these deep-space tracks from the Fence and Eglin are on satellites in highly eccentric orbits and are obtained near perigee. The impact of GMP and MOSS on the subset of the catalog consisting of all deep-space satellites will be minimal because their tracking data constitutes such a small percentage of the total data.

Table 1. Number of Deep-Space Satellites on 31 December 1999

	Deep-Space	Geosynchronous	Deep-Space Other
Cataloged Satellites	1812	736	1076
Analyst Satellites	674	98	576
Total	2486	834	1652

GEODSS provides the most tracking data on geosynchronous satellites. It might be expected that a significant improvement in the GEODSS throughput by GMP would be reflected in the statistics of the geosynchronous satellites. The number of analyst satellites fluctuates daily due to uncorrelated track (UCT) processing. Statistics on the geosynchronous cataloged satellites will be shown because this subset of the catalog represents known objects and is rather stable over time.

The long-term average epoch age of the geosynchronous cataloged satellites dropped from 5.0 days to 4.2 days after SBV became operational in April 1998 as a contributing sensor to the Space Surveillance Network. Figure 10 shows the daily average epoch age of geosynchronous cataloged satellites, which is around 4.0 days in August 1998. However, the daily average epoch age increased the latter part of 1998 even with the observations from SBV. This increase in average epoch age is strongly correlated with the increase in the geosynchronous work list. The work list consists of satellites whose element set has failed an automatic differential correction (DC) on SPADOC. The epoch age of these satellites is not current, yet there are recent observations in the database that have not been used to update the element set. If human resources are not applied to manually update the element sets of satellites on the work list, the age of the element sets continue to grow older and the work list increases from new failures from the automatic DC process on SPADOC.

The daily average epoch age did drop in early 1999, which is correlated with the drop in the number of satellites on the work list. The increased MOSS throughput beginning in February 1999 may have also contributed to the decrease in average epoch age. The decrease in average epoch age in May 1999 correlates with the operation assessment of GMP. However, there is no decrease in average epoch age beginning in August 1999 when GMP became operational. In fact, there is an increase in average epoch age in November and December 1999, but this appears to be correlated with an increase in the number of satellites on the work list. The impact of the increased throughput of GEODSS under GMP and from MOSS appears to be minimal and can be offset by increases in the work list.

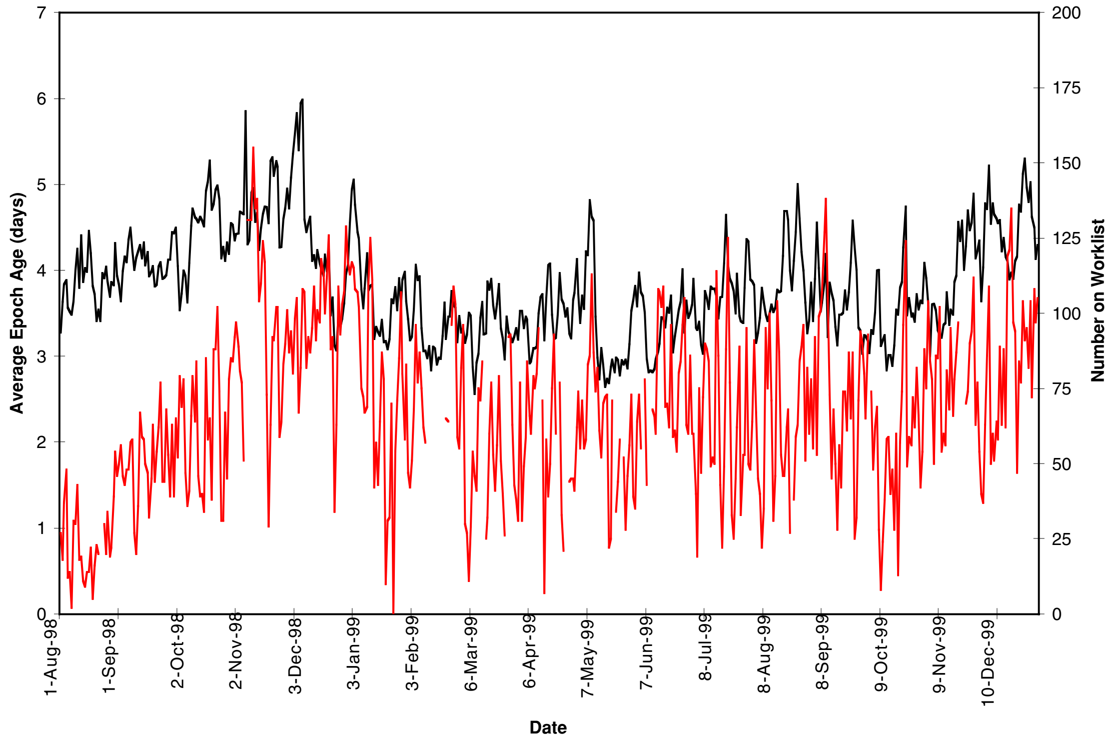

Figure 10. Average Epoch Age of Geosynchronous Cataloged Satellites

The increase in object throughput of GEODSS under GMP is not as nearly as large as the increase in the track and observation throughput. An increase in object throughput will have a greater impact on the average epoch age than an increase in track or observation throughput because more satellites will be updated with a current epoch. If all the GEODSS 3-ob tracklets were taken on different satellites, the average epoch age would probably decrease but the SPADOC observation request would not be satisfied as well. More satellites can always be tracked at the expense of providing fewer observations per satellite. SBV has taken the approach of maximizing the object throughput at the expense of not always getting a second streak on the same satellite. GMP maximizes observation throughput by scheduling enough tracklets for each satellite to satisfy SPADOC s request.

The long-term average error growth rate of the geosynchronous cataloged element sets dropped from 10.6 km/day to 9.6 km/day after SBV became operational in April 1998. Figure 11 shows the daily average error growth rate and long-term average of the geosynchronous cataloged satellites. The long-term average dropped from 9.6 km/day to 8.9 km/day after GEODSS with the GMP configuration became operational in August 1999.

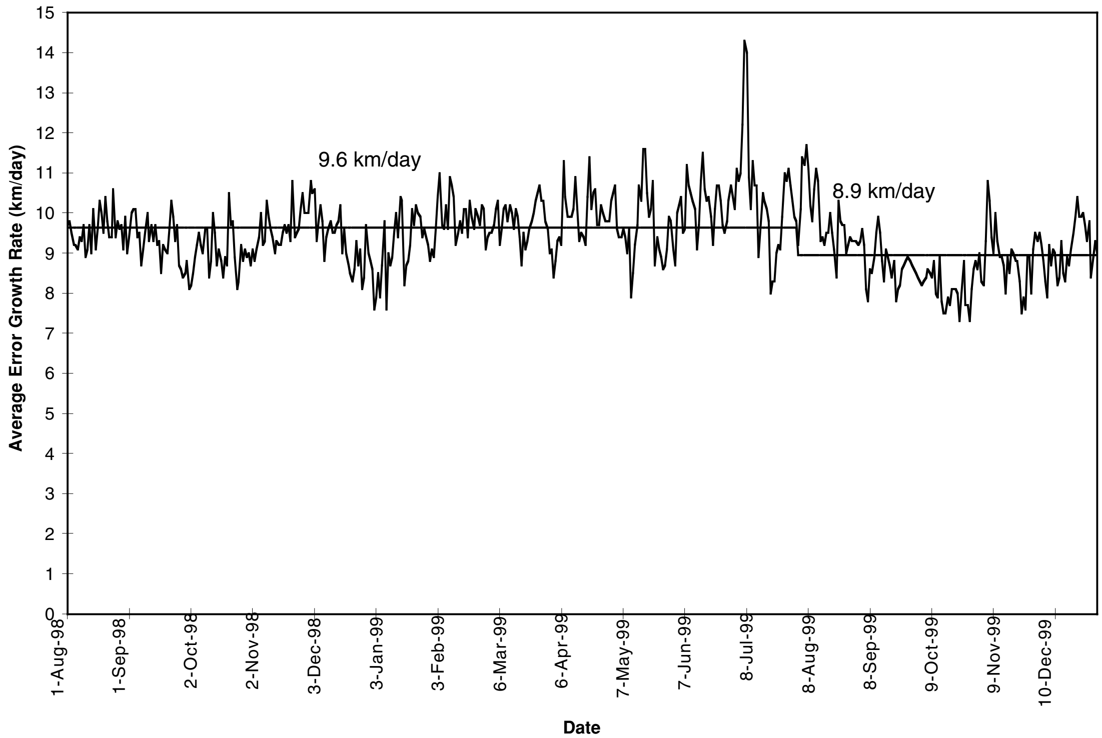

Figure 11. Average Error Growth Rate of Geosynchronous Cataloged Satellites

Two reasons may account for this drop in error growth rate. Two 3-ob tracklets spread over time provide better orbit distribution of the observations and should provide a more accurate element set than a 5-ob track taken at one point in the orbit. Also, an observational coordinate system mismatch between GEODSS and SPADOC was corrected in GMP. SPADOC was expecting right ascension and declination to be in topocentric coordinates, and legacy GEODSS was using a heliocentric coordinate system. The computation of aberration is coordinate system dependent, and this coordinate system mismatch for the observational data caused SPADOC to compute a significant bias in right ascension, which was not really present in the site data but an artifact of the coordinate system. Average biases and sigmas for right ascension and declination for each sensor before and after GMP are displayed in Figures 12 and 13, respectively. Note that MOSS and MSX were not changed by GMP, but their biases before and after GMP (3 August 1999) have been included for comparison sake.

Reference orbits for the calibration of the optical deep-space sensors are generated using 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 (SATNO 08820), Lageos 2 (SATNO 22195), Etalon 1 (SATNO 19751), and Etalon 2 (SATNO 20026). Additionally, declassified 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). The deep-space sensors are routinely tasked to track these satellites, and then those observations are compared against the reference orbits. Calibrations are performed using two weeks of sensor observations and calculating the residuals against the reference orbits.

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.

Note that prior to GMP, the three GEODSS sites display a noticeable bias in right ascension. After GMP the bias has become negligible. Even more significant is the improvement in the right ascension and declination sigmas after GMP. In some cases there is a 400 percent improvement. The third cameras, both on auxiliary GEODSS telescopes at Socorro and Maui, have yet to be replaced by main telescopes and therefore have yet to produce post-GMP data. MOSS has not yet corrected the reference frame in which it provides its data to SPADOC, and thus has not shown the improvement that the post-GMP GEODSS sensors have. A software release at MOSS in the spring of 2000 will correct this problem. MSX has always provided its data in the correct reference frame and thus does not show any biases. Its average sigmas appear to be higher than that of the GEODSS sensors, but this could be due to its low response to calibration tasking. MSX only provides about 10 to 12 observations on the calibration satellites in any two-week period.

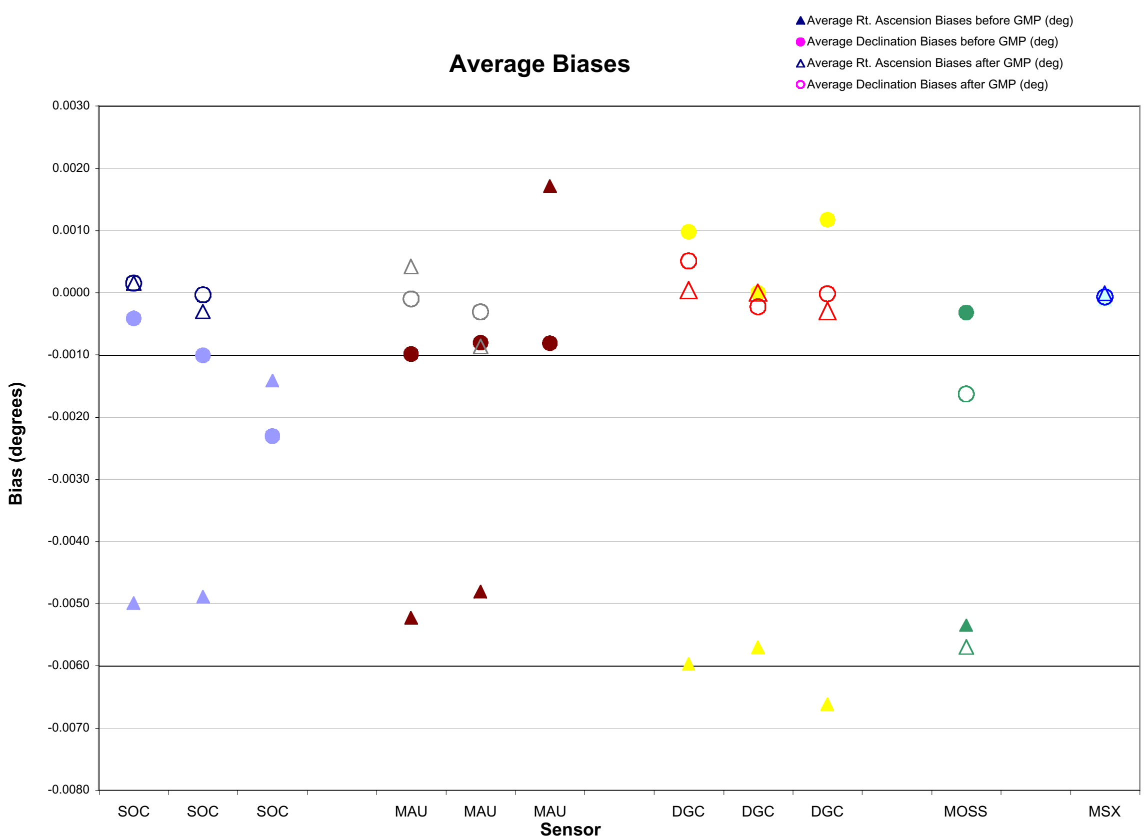

Figure 12. Average Biases of Optical Sensors

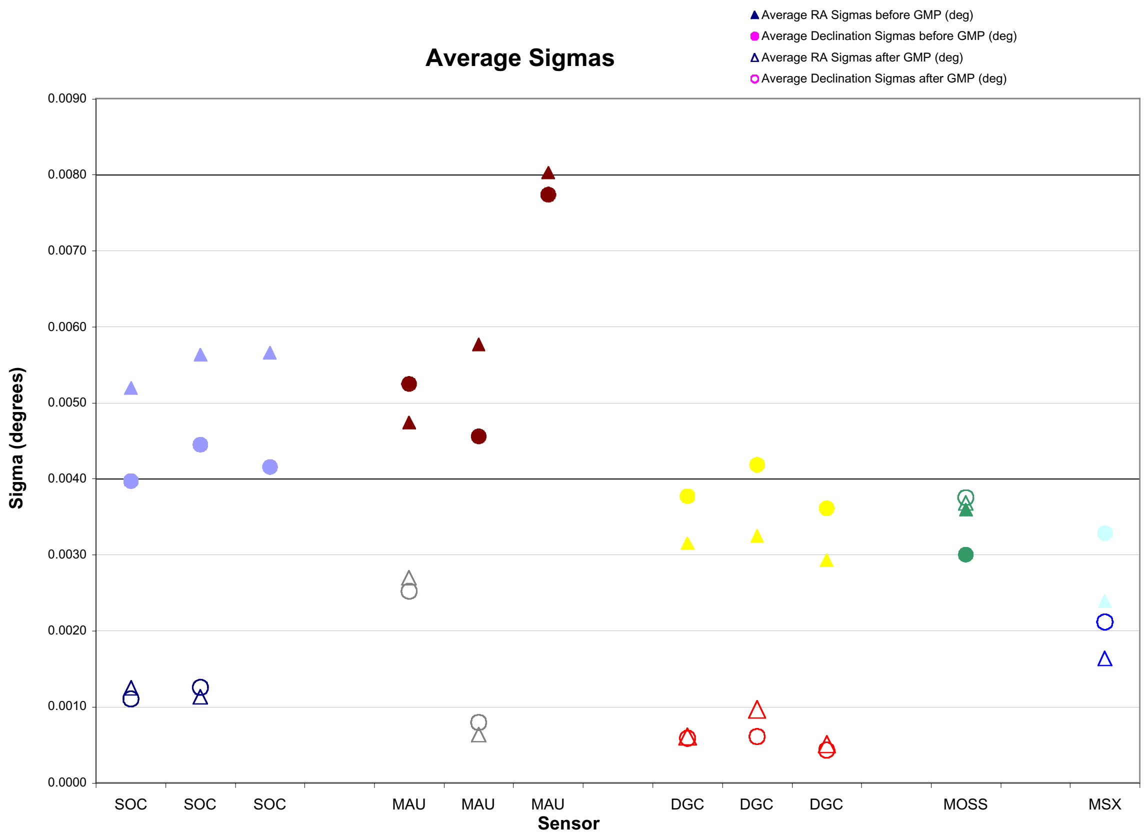

Figure 13. Average Sigmas of Optical Sensors

Figure 14 shows the first pass residuals for Camera 1 at Socorro. This is typical of a standard calibration run except that the time scale has been greatly extended beyond the usual 14 days of observations. Notice the drastic improvement in the right ascension and declination residuals after the post-GMP changes beginning 3 August 1999 (day 215).

Although sensor bias can be corrected in satellite orbit determinations, the larger sigmas generally result in a less accurate orbit fit. Thus, the smaller right ascension and declination sigmas of the post-GMP GEODSS are also contributing to a more accurate deep-space satellite catalog.

Figure 14. First Pass Residuals for Camera 1 at Socorro