GEODSS: PAST AND FUTURE IMPROVEMENTS

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ABSTRACT

The Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system, a passive electro-optical visible wavelength sensor in the Space Surveillance Network (SSN), has been and continues to be upgraded. Introduction of the Optical Command, Control, and Communications Facility (OC^3F) improved efficiency. The accuracy of its metric observation data of artificial deep space satellites, greatly improved just recently, will again be substantially improved. Improvements in sensitivity in both its metric and photometric (Space Object Identification, SOI) missions will also be achieved in the present acquisition phase.

INTRODUCTION

The Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system, an asset of the Space Surveillance Network (SSN), is a passive sensor used to observe individually tasked 'deep space' artificial satellites, those having periods greater than 225 minutes. The GEODSS generated data is used by the US Space Command's Space Control Center (SCC) and the Combined Intelligence Center (CIC), both in Cheyenne Mountain, Colorado Spring, CO. The telescopes are remotely tasked and scheduled by the GEODSS Optical Command, Control, and Communications Facility (OC^3F) at Edwards Air Force Base, CA.

ASSETS

GEODSS is composed of one-meter aperture f /2.15 telescopes of basically Ritchey-Chretien design. There are three passive electro-optical visible wavelength telescopes at each of three geographically dispersed sites; Socorro, NM on White Sands Missile Range (WSMR), Diego Garcia, British Indian Ocean Territory, and Mt. Haleakala on the island of Maui, HI. Presently Ebsicon (Electron-Bombarded Silicon) vacuum tubes fill the 80 mm diameter circular focal plane, with 832 pixels of horizontal and vertical resolution across the center of the focal plane. A portion of the energy, within ~ 20 arc-sec of the boresight, can be directed to a photo-multiplier tube for photometric brightness measurements, i.e., SOI.

HISTORY

In the summer of 1999 GEODSS operationally introduced the GEODSS Modification Program (GMP) components. The GMP contractor, PRC (Colorado Springs, CO), was responsible for the introduction of the OC^3F into the GEODSS system along with its Optical Dynamic Scheduler (ODS), based on a prototype developed by the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL). PRC also developed the hardware and software for the Data Processing Group (DPG), the high level GEODSS controller of tasks. The core sensor functionality of the metrics and SOI missions resides in the Sensor Controller (SC), developed by TRW (Colorado Springs, CO). This component, developed in the GEODSS Technology Insertion Program (GTIP), was introduced at the same time, and was largely responsible for the improvement in GEODSS metric accuracy.

GEODSS Data Accuracy

The metric observations (obs) data are principally generated by sidereal track mode; recording a series of frames, which are processed using a maximum value projection method for background rejection, and cluster/moment processed for streak detection. Based on how it was tasked, GEODSS will generate either orbital metrics of time and pointing angle (sent to the SCC) or Space Object Identification (SOI) data (sent to CIC), tracking of object brightness, typically at 100 Hz. SOI data is collected in a rate-track like mode.

Rate-track, i.e., continuously moving the telescope to keep the object's image on one pixel, for SOI – within the photo-multiplier tube (PMT) aperture, is also used to develop metric obs, in the observation of dimmer objects.

Metric obs data contain time and the pointing angle. Being a passive sensor, there are no range data. The GEODSS sites maintain their time stamp from the Global Positioning System (GPS) satellites. Metric obs are reported within an accuracy of 0.001 seconds. The pointing angle data are derived from the mount angular encoders. All positional accuracy ultimately is derived from the robustness of the mount model. The Deep-space Surveillance Technology Advancement & Replacement for Ebsicons (Deep STARE) upgrade, presently in acquisition, will introduce in-frame metrics. In-frame metrics utilizes the 'well-known' position of the stars present in the field-of-view to accurately determine the location of the target objects. 'Well-known' is, of course, only as good as the star catalog used. Implementation of in-frame metrics, performed only in sidereal tracking mode, will eliminate the now-stringent dependence on the mount model and the mount encoders in the development of metric observations.

At a top level in the processing are algorithms to select and process the stars, and to locate their centers. In the present implementation the GEODSS custom star catalogs are comprised of stars from the Smithsonian Astrophysical Observatory (SAO) Catalog and the Astrographic Catalog Reference Stars (ACRS). These star catalogs are utilized within the mount calibration catalog and the SOI calibration catalog. Because the metric accuracy requirements remained the same in going to GMP, there was no need to change the star fields already in use. There was an effort made to incorporate the most recent positional data. The SOI star catalog was created using a subset of the Hubble Guide Star Photometric Catalog from which 600 to 800 solar (G2) type stars have been identified.

The mount model incorporates five high level algorithms in its execution: Calibration Data Collection, Correction (including for atmospheric refraction), Control, Read-out Interpolation, and the Mount Model Solution. The mount calibration uses an assembled grouping of 54 stars, which are evenly distributed over the field-of-regard. Each mount calibration uses the previously assembled mount model, the known star location, and the mount encoder read-out, in a least squares fit algorithm and thus improves on the residual error. Acceptable performance is achieved when, at the end of the 54 star survey, the residual error, as reported by the Mount Model Solution, is less than 6 arc-sec rms.

Accuracy in the focal plane is achieved through the implementation of Camera Geometry Models including: Ebsicon Camera Alignment and Calibration and Ebsicon Plate Model. For the camera alignment, i.e., rotation and centration, about 25 pre-identified sets of star fields, typically identifying about 10 stars each, are used. There are a sufficient number of star fields identified such that those used for the calibration are located close to zenith so as minimize the variable refractive atmospheric effects. The Ebsicon Plate Model Calibration Algorithm is used to determine 10 calibration constants used for transforming the focal plane coordinates to the pixel coordinates. This algorithm does not use stars in the present implementation in consideration of the Ebsicon vacuum tube's non-linearities. The instabilities cause a fixed-point image on the focal plane to not always get read-out in the same pixel. It does use fixed reseau points on the faceplate. These are mapped to the pixels and thus achieve a fixed focal plane dimensional reference. To ensure consistent metric accuracy the present system is limited to reporting observations centered in the field-of-view (fov).

The SSN system tracks metric accuracy by having each of the space surveillance sensors report obs on a set of calibration satellites (CalSats). The Space Surveillance Performance Analysis Tool (SSPAT) uses the reported positional data to characterize the system and sensor performance against data supplied by the NASA laser ranging office, specifically from their Crustal Dynamics Data Information System. The analysis against CalSats (Lageos 1 and 2, Etalons 1 and 2, and GPS satellites 34, 35, and 36, SATNOs 08820, 22195, 19751, 20026, 22779, 22877, and 23027, respectively) of the sensor raw data is presented in Figure 1. Prior to inclusion of GMP, the metric accuracy, as analyzed, bias plus sigma, can be seen to be roughly 40 arc-seconds. Following GMP's acceptance in the late summer of 1999 the three GEODSS sites have consistent accuracy in the vicinity of 4 arc-seconds. The improvements were accepted at face value. Insufficient effort has been made to identify and evaluate the contributing errors either in the legacy or the GMP improved GEODSS. Expanded detail of the data in Figure 1 can be found in the same web site within the PowerPoint presentation accompanying this paper.

With the introduction of GMP metric accuracy of the reported GEODSS data did improve noticeably. This change was driven by real and purposeful improvements but may be partially attributable to a serendipitous set of events associated with the treatment of annual aberration. Components and methodologies changed within the GMP installation included improvements to the mount model, a rigorous treatment of coordinate systems, a better plate model, a change in the spacing between obs, and the replacement of the streak detection algorithm. Corrections for annual aberration were included in both generations of GEODSS.

The mount model, unless the base of the mount has been moved, is used to point the telescope in the collection of the data for use in developing the subsequent model. The legacy mount model used a Kalman filter. It was replaced by a least squares fit algorithm. Unlike the Kalman filter mount model, which weights the most recent measurements heavily in achieving the model, the least squares fit mount model simultaneously fits data from all 54 observed star locations.

For the implementation of the SC processing a great deal of attention was given to the formulation of what, when, where, and how to apply coordinate transformations. TRW worked the details with the Space Warfare Center. SPAce Defense Operations Center (SPADOC) uses mean equinox coordinates (true equator, mean equinox).

The plate model incorporated a least squares fit registering reseau points to render angles off-boresight accurately.

The manner in which the SC recorded metrics observational data was changed at this time. Specifically the temporal and spatial distances between obs, was lengthened. Previously, a set of 5 obs was executed, each ob having temporal spacing of 10 seconds. Post GMP two sets, each containing 3 obs, are executed. But the two sets of three obs are temporally and, more importantly, spatially separated. Again, the three obs within each set are separated by at least 10 seconds. This improvement, the greater obs separation in true anomaly, contributed to the SPADOC and its orbit determination capability, which in turn drove an accuracy improvement in the resident space object catalog maintained by SPADOC.

The sidereal track streak detection algorithm in the legacy system recorded a series of frames, as does the GMP enhanced system. In the legacy system, the streak was generated by subtracting the first frame from each of the subsequent images. Summing the residual images generated the streaked image of the satellite. GMP introduced the maximum value projection to identify signals above a certain threshold. Each method thus affected background rejection. In both implementations a second algorithm filters for clustering and determines the moment of the identified streaks. The new algorithms likely achieve more of an improvement in detection sensitivity than in metric accuracy.

Just prior to the incorporation of the GMP there were biases, principally in right ascension (RA), evident in the GEODSS data. A component of the improvement has been credited to the incorporation of treating annual aberration within the Sensor Controller (SC). Annual aberration does manifest dominantly in RA. However, the legacy system also treated annual aberration. Changes in the processing of the calibration laser ranging data, which may have occurred at about the same time as the GMP installation, may have played a role in the quality improvement of the GEODSS data. Although this is not clearly evidenced in data accuracy changes of the other optical sensors (see Figure 1). Annual aberration is caused by the earth's motion around the sun. The positional correction is applied against non-earth-orbiting objects. The objects of interest, artificial satellites, are traveling with the earth. Thus the apparent positions of the stars are aberrated, i.e., displaced, in the same manner as the apparent location from which rain originates while one is observing it from a moving vehicle. Annual aberration in and of itself can contribute errors up to ~20 arc-sec.

Figure 1 shows the enhancement in the quality of the data when GMP came on-line in August of 1999.

The SOI data processing did not change in the implementation of GMP. The instrument calibration portion surveils a set of G2 solar type stars to estimate the device's zero value coefficient and current sky extinction value. To correct the measured data the bias and dead-time coefficients of the PMT are also determined. The present device, the PMT, is effectively a single pixel device staring at a circular portion of the sky ~40 arc-sec in diameter. It also measures the sky background brightness. The background sky correction is also applied to the SOI data.

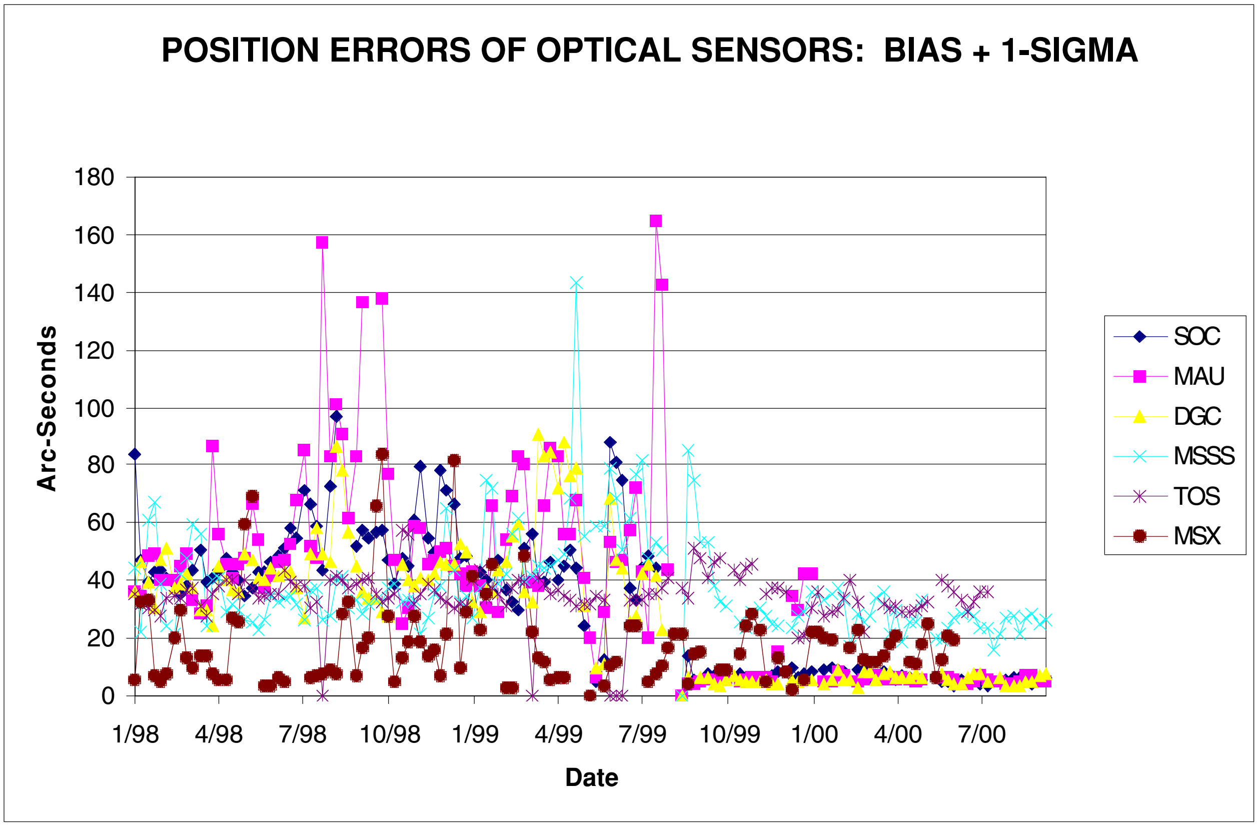

Figure 1: Geosynchronous object positional accuracy

Figure 1 shows the position errors for a number of optical sensors, which contribute to the Space Surveillance Network (SSN). Defining the legend:

SOC	GEODSS Site 1	Socorro, NM
MAU	GEODSS Site 3	Mt. Haleakelaa, Maui, HI
DGC	GEODSS Site 2	Diego Garcia, BIOT
MSSS	Maui Space Surveillance Site	Mt. Haleakelaa, Maui, HI
TOS	Transportable Optical System	Moron, Spain
MSX	Midcourse Experiment satellite	Space Based Visible (SBV)

Table 1: Figure 1 Legend

GEODSS FUTURE

TRW (Colorado Springs, CO) is presently on contract for the Deep STARE program. They are responsible for the development and installation of a charge-coupled device (CCD), the CCD camera, a replacement mount control system, and among other capability improvements, the introduction of in-frame metrics and enhanced streak detection (ESD) algorithms.

The CCD, modeled on the MIT/LL CCID-16 device, presently in the design stage at Sarnoff, will have a monolithic array of 1960 by 2560 24 μm square pixels, with 100% active area. It will cover just under 60% of the 80 mm GEODSS telescope circular focal plane. This back-illuminated device will have 8 channel outputs enabling approximately a 3 frame per second read-out rate. The chip will also have a 32 X 32 array of the same pixel architecture to be used for obtaining the photometric SOI signatures.

Sensitivity improvements for objects tracked are expected to be on the order of 2 to 2.5 m_v.

Accuracy improvements are expected to be about a factor of 2. Presently for obtaining metric observations the Ebsicons are run in Zoom mode. This affects an Ebsicon pixel of about 4.5 μm square versus 2.3μm square for the CCD.

In today's system only metric observations of objects tracked at, or across, the center of the fov are reported, due to the sum of unpredictable non-linearities, dominated by that of the Ebsicon tube. With the elimination of the Ebsicon's free electron path, the introduction of fixed location focal plane array, namely the CCD, off-axis obs positional corrections can be achieved by modeling the telescope optics' non-linearities through the introduction of an enhanced plate model. With the addition of in-frame metrics, real-time plate models should achieve metric accuracy within two arc-sec for all objects detected within the fov. Thus, enhancements to the number of objects tracked per unit time can be achieved by reporting on all objects within the telescope's fov. With multiple objects within a fov being reportable, alternate tasking methods to maximize the number of objects expected within the tasked fov, are being considered.

With the introduction of Deep STARE, GEODSS is again hoping to achieve an incremental improvement in its contribution to SPADOC and to its ability to perform orbit determination. As was done in GMP, Deep STARE is proposing to further separate the obs in true anomaly. As proposed, each sidereally generated streak will in-turn generate two obs, one from each end of the streak. Streaks of the same object will be separated by at least tens of minutes with three streaks needed to suffice a typical object's tasking. Each pair of obs intrinsically contains data on position and topocentric angular velocity.

Presently SOI data are obtained by beam-splitting the collected energy, part to the Ebsicon, to maintain closed-loop tracking, with the principle portion of the energy directed to the PMT for the object brightness signature. There is appreciable loss in the process. The Ebsicon is the limiting factor in this design. Receiving only a muted signal induces an all-too-soon loss in the ability to maintain track. With the introduction of the Deep STARE CCD camera, the photometric measurement will be performed in the telescope's focal plane, rather than having only some of the energy relayed to the PMT. This will achieve approximately a 35% improvement in the energy to the detector for a given object thus improving the signal-to-noise ratio (snr). The SOI CCD array will function as both the collector of energy for the SOI mission and will supply the signal to maintain tracking. This eliminates the limitation of closed loop tracking induced by the Ebsicon. SOI sensitivity improvements in going from the PMT (quantum efficiency $\cong 0.10$) to the CCD ($Q_e \cong 0.70$) are expected to be about 2 visual magnitudes improvement. Assuming, both the improved sensitivity and the 35% improvement in energy throughput, our ability to track dim objects should improve by about 2.5 visual magnitude. The improvement in signal strength, the resulting improvement in SOI data quality for objects already being tracked, and the ability to track far dimmer objects beg for an improvement in the accuracy of brightness calibration. Data will be accessible over a greater useful range of visual magnitudes. An improved photometric star catalog will greatly enhance the accuracy of the generated data.

The introduction of in-frame metrics gives rise for the need for an improved star catalog, which will enable positional accuracy to be achieved across the focal plane array (FPA). To improve SOI accuracy, better photometric calibration stars are required. Improvements to the existing GEODSS star catalogs will likely engender a greater benefit to the SOI photometric accuracy than that of positional metric accuracy.

Toward this goal the Deep STARE program is presently formulating sets of requirements for the customized star catalogs. The metric needs are for three sets of star 'catalogs' for performing 1) the mount calibration 2) the camera rotation calibration, as well as 3) for the in-frame metrics. Sets one and two will likely be a subset of 3 whose to-date requirements are listed.

For the astrometric catalogs;

- Single isolated stars, outside of galactic plane
- Positional accuracy ≤ 0.3 arc-sec rms
- 5 to 10 stars per square degree – uniformly distributed
- Stars of 12 to 15 m_v, color corrected for the Sarnoff supplied CCD

The SOI star catalogs will be used for the instrument calibration (zero point coefficient) and the atmospheric extinction estimation.

For the photometric catalogs;

- Single isolated stars, outside of galactic plane
- Stars of 9 to 12 m_v, color corrected for the Sarnoff supplied CCD
- Photometric accuracy ≤ 0.05 m_v
- ~1000 stars – uniformly distributed.

Conversations with the USNO indicate their ability and eagerness to provide a custom catalog by using existing tools to identify a sub-set of B1.0 of B2.0. Discussions included supplying updates to maintain positional accuracy correcting for proper motion. Through use of USNO CCD Astrograph Catalog (UCAC) star positional accuracy down to 0.1 arc-sec could be achieved.

The replacement to the present mount control system, the Modular Precision Angular Control System (MPACS), is the Telescope and Dome Control (TDC) system. The TDC is being supplied by Raytheon of Albuquerque, NM. It's pointing accuracy performance will not dramatically differ from that of the original MPACS. Nor does it really have to. With the introduction of in-frame metrics, getting the telescope to point-and-report to sub-arc-sec accuracy for the sidereal tracking mission is not a requisite to improved accuracy. However, because of the smaller pixels, the mount's drift and jitter performance will be of greater concern.

SUMMARY

GEODSS metric accuracy improved substantially late in the summer of 1999. GEODSS will hopefully continue that trend with an estimated 2 times improvement in metric accuracy with the introduction of Deep STARE. The sensitivity of the main focal plane arrays will enable tracking objects 7 to 10 times dimmer than the Ebsicon based GEODSS. SOI will also achieve an improvement in sensitivity and will likely sustain a substantial improvement in the quality of its SOI data.

Table 2 summarizes the principal components, events(?), and algorithm introductions associated with the legacy GEODSS, GMP, and the future Deep STARE.

	GEODSS	GMP	Deep STARE
Metric Accuracy		Annual aberration correction?	In-frame metrics
			ESD
Sensor	Ebsicon	Ebsicon	CCD
Pixel Size	4.4 arc-sec	4.4 arc-sec	2.2 arc-sec
Star Cat	SAO	SAO	USNO UCAC?
SOI Photometric Accuracy			
Sensor	PMT	PMT	CCD
Star Cats	?	Hbl GS Phtmtrc	USNO?

Table 2: Principal contributors to metric and SOI accuracy improvements.

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