DEEP STARE TECHNICAL ADVANCEMENTS AND STATUS

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ABSTRACT

The Deep-space Surveillance Technology Advancement & Replacement for Ebsicons (Deep STARE) program is a sustainment effort designed to replace aging Ebsicon analog video cameras and mount control subsystems in the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system. The program includes design and development of highly sensitive digital Charge-Coupled Device (CCD) arrays, camera electronics, and mount control hardware as well as software upgrades necessary to support the modification. The Deep STARE implementation uses the state-of-the-art CCD, combined with new algorithms and an enhanced image processing capability, to significantly boost the performance of the GEODSS system and improve the space situational awareness mission.

This paper provides a brief background on the overall architecture of the Deep STARE upgrade, a description of the key system components, and the new system-level capabilities that will be provided to GEODSS. We will present and discuss the design challenges of the upgrade and the Deep STARE technical performance measurements related to Space Situational Awareness (SSA). We will also present measured data from the Deep STARE integration test bed and compare the data to current GEODSS operational capabilities. The resulting performance gains and expected contribution to the Space Surveillance Network (SSN) is summarized.

1. BACKGROUND

The GEODSS system consists of nine (9) telescopes worldwide that are dedicated sensors in the Space Surveillance Network (SSN). Three telescopes are located at each of three geographically dispersed sites: Socorro, NM on White Sands Missile Range (WSMR), shown in Fig. 1; Diego Garcia, British Indian Ocean Territory; and Mt. Haleakala on the island of Maui, HI. Each telescope is a passive electro-optical visible wavelength sensor used to detect, track and identify deep space artificial satellites, defined in this case as those satellites having periods greater than 225 minutes. Metric data is reported to US Strategic Command's Space Control Center (SCC), located in Cheyenne Mountain, CO, to support new object detection as well as routine catalog maintenance. Photometric data is reported to the Joint Intelligence Center (JIC) at Offutt AFB, NE to facilitate Space Object Identification (SOI). Currently all GEODSS telescopes are remotely tasked and scheduled by the GEODSS Optical Command, Control, and Communications Facility (OC^3F) at Edwards Air Force Base, CA.

Fig. 1. GEODSS Site, Socorro, NM[1]

A GEODSS sensor is composed of a one-meter aperture f /2.15 telescope of basically Ritchey-Chretien design. Ebsicon (Electron-Bombarded Silicon) vacuum tubes are the basis of the Low-Light Level Television (L3TV) cameras presently fielded in the system. Each tube fills the 80 mm diameter circular focal plane, and provides 832 pixels of horizontal and vertical resolution across the center of the focal plane. A portion of the energy, within approximately 20 arc-seconds of the bore sight, can be directed to a photo-multiplier tube for photometric brightness measurements, i.e., SOI.

[1] Courtesy U.S. Air Force

Ebsicon tubes became unsustainable when Westinghouse shut down its manufacturing line in 1991. Subsequent efforts to find an alternate production source, and then later to reliably refurbish existing Ebsicon tubes, were unsuccessful. Similarly, several components of the mount control subsystem fell out of production and are no longer available to replenish the dwindling supply of spares.

Deep STARE enables the sustainment of the GEODSS system by eliminating these aging, outdated components and by incorporating new capabilities that will contribute to the SSA mission. The upgrade replaces the existing L3TV camera, SOI subsystem, and telescope mount control subsystem used in each sensor with a CCD camera, CCD photometer, and Modular Precision Absolute Control System (MPACS), respectively. The CCD will greatly improve the sensitivity of each GEODSS sensor, as well as the accuracy of both its metric and photometric data.

2. SYSTEM COMPONENTS

Northrop Grumman Mission Systems (NGMS), the Prime Deep STARE contractor, is responsible for the systems engineering, the modifications to the image processor and the sensor controller (SC), the upgrades to the tracking and the search algorithms, integrating and installing the modification kits, updating the applicable Air Force Technical Orders (T.O.s) and the system documentation, providing end user training, and procuring initial spares. Two subcontractors are contributing major subsystems as part of the upgrade. Sarnoff Corporation is responsible for designing and building the CCD and camera, and Goodrich Corporation is responsible for designing and building the telescope mount control algorithms and hardware.

Sarnoff's CCD design, modeled on the MIT/LL CCID-16 device, has a monolithic array of 1960x2560 pixels, with 100% active area.[3] Each of the pixels is 24 μm square, providing an angular resolution of 2.27 arc-seconds. The array covers approximately 60% of the 80 mm GEODSS telescope circular focal plane, providing a Field of View (FOV) of 1.23x1.61 degrees. This back-illuminated device has 8 channel outputs enabling approximately a 3 frame per second read-out rate. The chip also has a 32x32 array of the same pixel architecture to be used for obtaining the photometric SOI signatures. Fig. 2 is a photo of the feature side of the Sarnoff CCD.

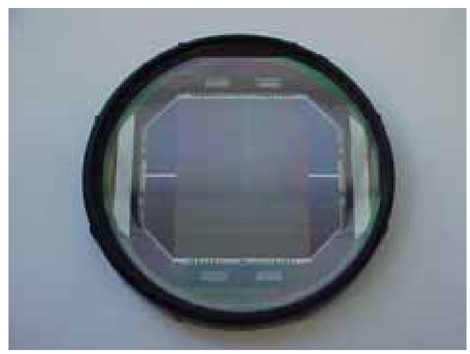

Fig. 2. Sarnoff CCD[2]

The MPACS subsystem maintains status and control of the telescope mount and dome motors. The control algorithm software, developed by Goodrich Corporation, is designed to drive the GEODSS telescope in a manner that takes advantage of the upgraded system's speed, while minimizing jitter and following errors during steady-state tracking. As a benchmark, the MPACS performs a 2 degree step-and-settle maneuver in less than 1.1 seconds with a pointing accuracy of ±1.5 arc-secondsP.[4] This helps minimize the telescope slew time and allows for faster system throughput.

As part of its integration effort, NGMS is upgrading significant portions of the GEODSS system software. Aside from software modifications required to accommodate the new hardware described above, NGMS is delivering several capability improvements, including the introduction of in-frame metrics, enhanced search capabilities, and enhanced streak detection (ESD) algorithms.

3. NEW SYSTEM LEVEL CAPABILITIES

Sensitivity

Probably the most discussed and appreciated improvement introduced by CCDs is the ability to detect and track far dimmer objects. With the introduction of CCD there is an estimated improvement of 2.5 visual magnitudes (m_v) of

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[2] Courtesy Sarnoff Corporation

[3] Tower, J.R., et al, "Large Format Backside Illuminated CCD Imager for Space Surveillance," *IEEE Transactions on Electron Devices*, Vol. 50, Iss. 1, 218-224, Jan 2003..

[4] Hough, M.E., "Modular Precision Attitude Control System (MPACS)," MITRE Corporation briefing, Aug 2001.

sensitivity. As with any system there is a need to normalize performance. GEODSS has historically rated sensitivity performance against a background sky of 19.5 m_v per square arc-second. GEODSS will be able to detect objects as dim as 17.9 m_v within this environment.

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-seconds 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.

Metric 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 is being tasked, GEODSS will generate either orbital metrics of time and pointing angle (sent to the SCC) or Space Object Identification (SOI) data (sent to JIC), 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 bore sighted, is also used to develop metric obs, in the observation of dimmer objects.

Metric obs are reported within an accuracy of 0.001 seconds. Pre Deep STARE the pointing angle data are derived from the mount angular encoders. All positional accuracy ultimately is derived from the robustness of the mount model. Deep STARE will introduce in-frame metrics. In-frame metrics utilizes the well-known position of the stars present in the FOV to accurately determine the location of the target objects.

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. 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. Deep STARE is incorporating upgraded astrometric and photometric catalogs using catalog data from the USNO B star catalog which also contains data from the Tycho 2 star catalog.

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 (FOR). 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-seconds rms.

In the present GEODSS, 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 FOV.

The incorporation of the CCD does not significantly change the present approach. Given that the CCD pixels are fixed in space, and that there is no electron path through free space (the Ebsicon read-out mode) to vary as a function of the earth's electro-magnetic field, the concerns of off-axis metrics are eliminated with the use of the CCD. Introduction of an enhanced Plate Model further improves positional metrics.

Plate Model

For the Deep STARE CCD system, there is a single plate model which addresses both the camera alignment and optical distortion effects. The CCD has a much more stable and accurate plate model calculated by observing 150-180 known stars in one of about 25 reference star fields. Third order effects are incorporated in the model. This calibration is only required whenever the camera is replaced in the telescope; the model provides an accurate and stable template across the entire sensor field of view.

Fig. 3. In-Frame Metrics[5]

During each sidereal detection set, the system looks for about 10 reference stars in the field of view and "registers" those stars using the plate model template. This provides a very accurate estimate of the bore sight location and, because the template is accurate across the entire sensor field of view, ensure that metric obs anywhere on the sensor field of view are equally accurate. Fig. 3 shows the detection of a cluster of geosynchronous satellites along with several registration stars.

The angular predictability gained by the use of CCDs over that of Ebsicons enables a couple of significant improvements in operations. When tasked in the Ebsicon environment, the system will image a track and perform a re-centering of the streak before recording obs. This is necessary due to the lack of accuracy off bore sight. The initial set of image frames does not directly contribute to the generation of the obs. For the CCD with its geometric repeatability and thus its full FOV angular accuracy, re-centering is not necessary. This eliminates the imaging and processing time it takes to re-center. Further, and more significantly, if another object or objects appear in the same FOV, with the CCD, GEODSS will now generate an equally accurate 'ob' for those off axis objects. These obs have been termed serendipitous. Their immediate reporting will also save time because these obs can be credited against the task lists.

Field-of-View

Another improvement: Ebsicons are normally (sidereal metrics mission) used in electronic zoom mode, i.e., observing only half of the telescope's 2.1° FOV or 1.05°, circular in shape. With this zoom the individual FOV of an Ebsicon pixel is ~4.4 arc-seconds. Using the CCD, the FOV grows to 1.23° by 1.61°, which is a 235% improvement in the observed area of the sky within the FOV. That's at a greatly improved resolution of 2.27 arc-seconds and at a greatly improved detection sensitivity.

Mount Model

The mount model is a least squares fit algorithm. The least squares fit mount model simultaneously fits data from 54 observed star locations which are evenly distributed over the FOR.

Streak Detection Algorithms

The manner in which the SC records metrics observational data is being changed within Deep STARE. Presently a streak is culled from a series of 11 to 15 time contiguous images of a FOV from which an observation is generated. Two sets of 5 such streaks are executed. From each set of these streaks a minimum of 3 obs must be generated to satisfy the typical sidereal track command. The two sets of three obs are temporally and spatially separated. The three obs within each set are separated by at least 10 seconds.

[5] Courtesy Northrop Grumman Mission Systems

Within Deep STARE a composite series of images against a star field will be used to generate a streak of a tracked object. It will record images of exposure length ~0.3 seconds for a period of ~6 seconds, go quiescent for approximately the same period, and then re-image, again for ~6 seconds, for a total period of 20 seconds. The Deep STARE enhanced system will generate an 'ob' from the beginning and end of each generated streak. Thus, for each 20 second observational period, 4 obs will be generated.

The streak is generated by a maximum value projection to identify signals above a certain threshold thus affecting background rejection. A second algorithm filters for clustering and determines the moment of the identified streaks.

Step Stare Surveillance

The search capabilities, now capable of area and orbit based searches, are being enhanced by Deep STARE. The four basic existing search patterns are: equatorial, fixed box raster / spiral, along orbit, and moving box raster. The first two are area searches, equatorial covers a fixed location in Earth based latitude / longitude coordinates, and fix boxed raster covers a celestial inertially fixed box. The along orbit searches, as the name implies, along the direction of an ElSet as depicted in Fig. 4. The moving box raster searches along and across an object's trajectory. Today's searches are task based, i.e., they are executed in pursuit of finding a particular missing object. Once found, the search is stopped.

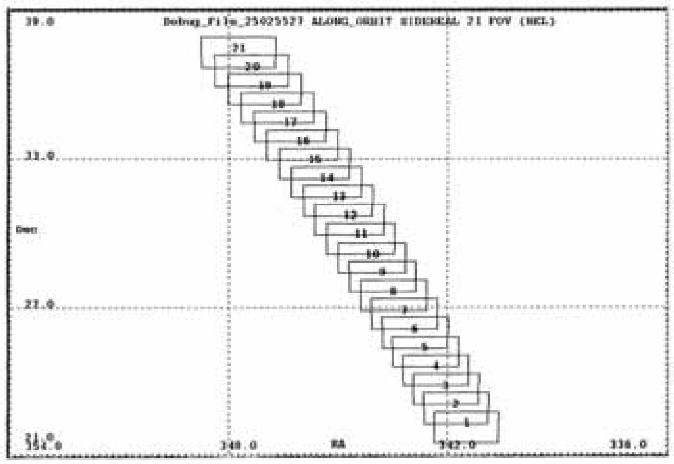

Fig. 4. Along Orbit Search Pattern[6]

The SSA driven approach to space surveillance is evidenced in the Deep STARE enhancements to search. Deep STARE introduces the "Step Stare" capability into GEODSS. The Step Stare mode enables a surveilling capability. Each Step Stare search is executed through to its completion of the configured search pattern. Object tracks imaged during the search's execution will be correlated and their obs reported to the Space Control Center (SCC). Uncorrelated tracks (UCTs) can also be reported. This mode enables directing searches to cover areas of high object density, for example, the Geo Belt. Clusters could efficiently be monitored by executing either the Step Stare enhanced equatorial or moving box raster searches. If the Step Stare search mode proves effective, objects will be frequently detected, thus reducing the tasking. The authors recommend that one telescope at each of the three sites operate in this mode while the other two remain within the present tasking regime. This mode will enable the operational evaluation of Step Stare. Performance data can be recorded over some nominal period of time, say one year. Analysis will indicate what changes would enable a more efficient utilization of the GEODSS sensors.

The present search mode capability is being maintained in GEODSS so that with the addition of Step Stare, GEODSS will have a hybrid search capability.

SOI Sensitivity

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 ($Q_e \cong 0.65$) are expected to be about 2 visual magnitudes. Assuming, both

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[6] Courtesy Northrop Grumman Mission Systems

the improved sensitivity and the 35% improvement in energy throughput, our ability to track dim objects should improve by about 2.5 visual magnitudes. Table 1 contains a comparison of Ebsicon and CCD performance for a variety of parameters. In sum, there will be an improvement in signal strength resulting in the improvement in SOI data quality for objects already being tracked, and the ability to track far dimmer objects. Data will be accessible over a greater useful range of visual magnitudes.

SOI Calibration and Accuracy

For the SOI data processing 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-seconds in diameter. It also measures the sky background brightness. The background sky correction is also applied to the SOI data. In Deep STARE the SOI data processing, while using the 32 X 32 photometer array, remains somewhat the same. Within the photometric array data processor an algorithm generates a virtual aperture centered on the image centroid. The elimination of non signal producing pixels lowers the noise level thus improving the SNR.

Table 1. Comparison of Ebsicon and CCD Performance

	Ebsicon	CCD
Field-of-View / Resolution	@ 2.1° FOV: 8.8 arc-sec/pixel @ 1.05° FOV: 4.4 arc-sec/pixel	@~2° diagonal: 2.27 arc-seconds for all conditions
Electronic Zoom	Full field (2.1° FOV, seldom used) 2x Elec Zoom (1.05° FOV)	2.03° diagonal (~1.23° by 1.61°) full time ops
Detection Sensitivity	15.3 m_v with 19.5 m_v background	17.9 m_v with 19.5 m_v background
Centering	Necessary	Not necessary
Serendipitous Obs	Not acceptable	Accurate & Reportable
Number obs/streak	1 per 10 second streak	2 per 6 second streak
SOI limiting m_v	12.8 m_v @ 19.5 mv background	16.3 m_v @ 19.5 mv background

4. DESIGN CHALLENGES

While developing and integrating the GEODSS modification, Deep STARE team members encountered difficulties with limitations inherited in the legacy GEODSS software and, more significantly, with the manufacturability of the new CCD technology. The present GEODSS system contains search algorithms that do not adequately cover the intended FOR, and do not have the intended leak-proof robustness. Since several enhancements were to be built upon the existing search algorithm foundation, many of the algorithms required corrections. The necessary modifications are now being deployed in a GEODSS software version release.

The two most significant design challenges were related to the manufacturability of the large-format CCDs, which caused subsequent program schedule delays. The first issue occurred in the CCD foundry process. Each of the 10 CCD ports, including 8 for the main array and two for the photometric arrays, has a signal amplifier on-board the chip. The architecture includes a buried contact where the signal is transferred from the chip's surface structures, through a poly-silicon layer, to a contact on the opposing side. The construction of the buried contacts involves etching a hole which is then filled with conductive material. The chosen method for 'boring' the hole was a plasma etch. Plasma etch is a highly energized and directed flow of particles, which in this case included carbon, to abrade material and thus 'drill' a hole. At the hole's bottom the carbon interacted with the silicon to form silicon carbide, an excellent insulator, and, just the opposite of what was prescribed. The single step plasma etch was replaced with a two step etch. The first 60% of depth remained the plasma etch. For the remaining 40% a wet etch was introduced. This technique prevented the formation of silicon carbide and enabled the construction of the desired non-ohmic contact to the amplifiers.

The second issue involved the construction of the CCD package residing within the Dewar, which was complicated by the size of this device. Because only one CCD can reside on a 4 inch silicon wafer, Sarnoff decided to avoid excessive handling by not dicing (cutting) the CCD out of its wafer. In addition, to achieve a rapid frame rate, critical electronic components were positioned on a printed wiring board (PWB) proximate to the CCD. For efficiency of packaging the PWB was epoxied directly to the CCD silicon wafer, but the assembly was exposed to the thermal extremes of getter firing and the -50°C operational temperature. The thermal and structural loads of the PWB on the silicon wafer were excessive. A redesign of the assembly (dicing the CCD, attaching the PWB to another layer in the cold head assembly, and lowering the mass of the PWB) driven by thermal structural analysis resolved the packaging issue, resulting in a successful First Article CCD.

5. TECHNICAL PERFORMANCE MEASUREMENTS

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 is performed 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).[7] Presently the three GEODSS sites have consistent accuracy in the vicinity of 4 to 6 arc-seconds. Deep STARE performance at the Yoder, CO test site has been evaluated by HQ AFSPC/XPY and has demonstrated a two-dimensional accuracy of 1.9 arc-seconds rms for automatic sidereal observations.[8] When fielded, Deep STARE is expected to have consistent operational accuracy less than 2 arc-seconds.

In addition to sidereal accuracy, there are several other technical performance measurements of interest to the Government. The key system level parameters include: detection sensitivity, metric obs accuracy, SOI detection sensitivity, SOI accuracy, search rates, and track rates. Table 2 summarizes the present system level performance versus the estimated performance post Deep STARE incorporation.

Table 2. Deep STARE Key Technical Performance Measurements

	Present GEODSS	GEODSS with Deep STARE
Detection sensitivity	15.3 m_v with 19.5 background	17.9 m_v
Sidereal metric obs accuracy	4 to 6 arc-seconds	< 2 arc-seconds
SOI detection sensitivity	12.8 m_v	16.3 m_v
SOI accuracy		13.6 m_v relative 12.9 m_v absolute
Search rates	600 sq degrees / hour	840 sq degrees / hour
Track rates	~1800 obs/sensor/8 hours	4600 obs/sensor/8 hours

With Deep STARE's introduction GEODSS will be able to track objects that are ~2.5 m_v dimmer, and track them with a factor of two improvement in positional accuracy. First Article installation commences in late November 2003, followed by sequential installations at each GEODSS site. System-wide operational acceptance and certification is scheduled for January 2005.

6. SUMMARY

The Deep STARE upgrade provides new space surveillance capabilities that will contribute to more timely and comprehensive SSA. Its dramatic increase in sensitivity enables the detection and characterization of smaller, dimmer objects than previously possible. Robust, leak-proof search algorithms provide for timely notification of satellite maneuvers and a more complete description of the battlespace. Deep STARE's contributions to SSA give commanders the insight they need for well-informed, time critical assessments, which in turn, helps advance the space control mission.

[7] Faccenda, W.J., "GEODSS: Past and Future Improvements," The MITRE Corporation, Dec 2000.
[8] Williams, C.M., "Data Scoring Report," NGMS Technical Report A024G-DS-0058, Draft, 1 Oct 2002.