Toward Operational Space-Based Space Surveillance

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On 1 October 2000, the Space-Based Visible (SBV) sensor on the Midcourse Space Experiment (MSX) satellite was transitioned to operational status as a Space Surveillance Network (SSN) sensor for the U.S. Air Force. This transition continues a long Lincoln Laboratory history of technology insertion into the nation's space control capability, which started in 1957 with the advent of satellite tracking at the Millstone Hill radar. The transition is an important milestone for the Advanced Concept Technology Demonstration (ACTD) program, which allowed the use of a "residual" experimental/demonstration asset in an operational role directly supporting the warfighter. The information developed during the ACTD was also critical to the definition of and advocacy for a follow-on operational constellation of space-based space-surveillance satellites, which is now planned for funding starting in the 2003 fiscal year.

The space-based visible (SBV) sensor was launched on the Midcourse Space Experiment (MSX) satellite in April 1996. The MSX program was sponsored by the Ballistic Missile Defense Organization (BMDO) primarily to gather phenomenology data for missile-defense applications [1]. Initial operations of the MSX satellite demonstrated the efficacy of using the SBV sensor for space surveillance. Following the completion of the BMDO measurements, the MSX satellite was incorporated into the Space-Based Space Surveillance Operations (SBSSO) Advanced Concept Technology Demonstration (ACTD) sponsored by the Office of the Secretary of Defense, the BMDO, and U.S. Air Force Space Command. The goal of the ACTD was to demonstrate operational space-based space surveillance, and to leave behind an effective system for Space Command to operate.

The first operational space-based space-surveillance observations were supplied to Space Command in April 1998, during the first year of the ACTD. During the following two years, the SBV sensor's operations became progressively more capable, and its observations substantially improved the quality of the deep-space object catalog maintained by Space Command. In addition, the SBV sensor validated the capability of space-based space-surveillance sensors to provide assured access to militarily important objects, by demonstrating a greater than 90% response to tasking for targets of highest priority (Category 1 objects in Space Command's parlance).

This article provides a summary overview of the MSX/SBV satellite and the ACTD program, and presents the operational lessons learned during the second half of the three-year-long ACTD. A detailed description of the SBV sensor and the results of the first half of the ACTD appear elsewhere [2]. The productivity and effectiveness of the SBV are also described by Space Command in the accompanying sidebar entitled "Space Command Becomes New Owner of Space-Based System," which contains the Air Force statement describing the transition of the MSX/SBV from ACTD status to the operating command. An overview of the intent of the ACTD program in general is provided in the subsequent sidebar entitled "What Is an ACTD?"

SPACE COMMAND BECOMES NEW OWNER OF SPACE-BASED SYSTEM

The following press release was issued at Peterson Air Force Base, Colorado (AFPN, 25 October 2000) [1]. Air Force Space Command here became the new owner of the Midcourse Space Experiment satellite and its associated ground support infrastructure, recently. The system provides deep space surveillance and has been operating since its launch in April 1996 under the Ballistic Missile Defense Organization.

The MSX space-based system improves AFSPC's mission of collecting data related to deep space orbits of military and commercial satellites without the limitations inherent in ground systems. These ground system limitations include location sensitivity, dependence on weather and time-of-day requirements.

For the last three years, AFSPC worked with the Ballistic Missile Defense Organization, Johns Hopkins University, Maryland, and the Massachusetts Institute of Technology to extend the MSX satellite's life and ensure its viability as a space-based system for continued deep space surveillance.

"The Space-Based Space Surveillance Operation has helped to increase our revisit rates on militarily significant objects by 50% and has helped us to reduce our list of lost satellites by 80%," said Master Sgt. Steve Ferner, AFSPC Space Control Mission Team. "It has also enabled us to develop search techniques that will be the standard used in operations for many generations to come."

Reference

1. This press release came from web site http://www.af.mil/news/Oct2000/n20001025_001612.shtml.

While the SBV sensor was used extensively and productively during the missile tracking and phenomenology experiments [2–4], the primary aim of the SBV sensor was to validate the feasibility and efficacy of space-based space surveillance. Following the depletion of the cryogen in the MSX's SPIRIT 3 long-wave infrared sensor, ten months after launch, the space-surveillance activities became the primary focus of the satellite operations. The space-surveillance activities were intended to fulfill the following three broad goals:

(1) Demonstrate the specific hardware and software included on the SBV, including the focal-plane cameras [5], the signal processor [6] and the signal processor algorithms [7].

(2) Develop an effective concept of operations for space-based space surveillance, including (a) understanding the trade-offs between search-based and tasking-based operations [8], (b) achieving sufficient productivity from the MSX/SBV to significantly improve the space-object catalog maintained by Space Command, and (c) demonstrating the power of high-accuracy angle/angle measurements to contribute significantly to initial orbit determination and maintenance of the space-object catalog.

(3) Convince the operational components of Space Command that space-based space surveillance represents an effective way to achieve their objectives, and work with Space Command to integrate a space-based capability into the surveillance operations at Cheyenne Mountain.

Over the past five years of on-orbit operations the SBV program clearly and unambiguously achieved all three of these goals.

The MSX Satellite

The MSX satellite is an observatory-class spacecraft developed by the BMDO primarily to collect phenomenology data in support of missile-defense efforts. The satellite hosts three primary imaging/spec-

WHAT IS AN ACTD?

ADVANCED CONCEPT TECHNOLOGY Demonstrations (ACTD) exploit mature and maturing technologies to solve important military problems. A declining budget, significant changes in threats, and an accelerated pace of technology development have challenged our nation's ability to respond adequately to rapidly evolving military needs. In addition, the global proliferation of military technologies, resulting in relatively easy access to these technologies by potential adversaries, has further increased the need to rapidly transition new capabilities from the developer to the user.

In early 1994 the Department of Defense (DOD) initiated a new program designed to help expedite the transition of maturing technologies from the developers to the users. The ACTD program's goal was to help the DOD acquisition process adapt to today's economic and threat environments. ACTDs emphasize technology assessment and integration rather than technology development. The goal is to provide a prototype capability to the warfighter and to support the evaluation of that capability. The warfighters evaluate the capabilities in real military exercises and at a scale sufficient to fully assess military utility.

ACTDs are designed to allow users to gain an understanding of proposed new capabilities for which there is no user experience base. Specifically, they provide the warfighter an opportunity to (1) develop and refine a concept of operations to fully exploit the capability under evaluation; (2) evolve operational requirements as the user gains experience and understanding of the capability; and (3) operate militarily useful quantities of prototype systems in realistic military demonstrations, and on that basis, make an assessment of the military utility of the proposed capability.

There are three potential outcomes at the conclusion of the ACTD operational demonstration. The user sponsor may recommend acquiring the technology and fielding the residual capability that remains at the completion of the demonstration phase of the ACTD to provide an interim and limited operational capability. If the capability or system does not demonstrate military utility, the project is terminated or returned to the technology base. A third possibility is that the user's need is fully satisfied by fielding the residual capability that remains at the conclusion of the ACTD, and there is no need to acquire additional units.

Reference

1. This material was taken from web site http://www.acq.osd.mil/at/intro.htm.

troscopic sensors, which cover the wavelength range from long-wave infrared to the ultraviolet band [1]. The SBV provides broadband visible coverage of the spectral region from 300 nm to 900 nm. Figure 1 shows the MSX satellite during its final integration and test at Vandenberg Air Force Base, California, from which the satellite was launched. The core of the MSX contains the long-wave infrared sensor, called the SPIRIT 3. The SPIRIT 3 focal plane is cooled below 10 K by solid hydrogen cryogen, which is stored in the dewar visible at the center of the spacecraft. The apertures of all the MSX sensors are located at the top of the satellite, along with the sunshade for the SPIRIT 3 sensor.

Figure 2 shows the entire suite of MSX instrument telescopes during integration of the satellite with the booster. The first half of the booster faring, or nose cone, is shown already installed. The MSX satellite is seventeen feet long and weighs nearly six thousand pounds. As shown in Figure 1, the SBV sensor is composed of two elements: the seventy-three-pound telescope, which is co-boresighted with all the other

MSX sensors, and the one-hundred-pound electronics assembly toward the rear of the satellite.

The MSX satellite and sensors were integrated by and are operated by the Johns Hopkins University Applied Physics Laboratory (APL). During space-surveillance operations of the satellite, the command information for the SBV sensor and the MSX bus systems is developed at Lincoln Laboratory in a facility called the SPOCC (SBV Processing Operations Control Center) [9] and forwarded to APL for upload to the spacecraft. Data resulting from on-orbit operations are returned to the SPOCC for calibration and processing into observations, which are provided to the 1st Space Control Squadron (1SPCS), formerly known as the 1st Command and Control Squadron, (1CACS), located in Cheyenne Mountain, Colorado. Figure 3 shows the flow of tasking, commands, and data among the various organizations involved in the operations. Since the MSX satellite was designed for missile-defense measurements, rather than space-surveillance operations, a number of constraints and complex system features must be accommodated in order to conduct effective space-surveillance operations. More detailed discussions of these constraints are provided elsewhere [8–10].

Operational Impact of Space-Based Space Surveillance

After completing a successful demonstration of its ability to perform space-based space surveillance, the SBV sensor began contributing sensor operations in April 1998, routinely responding to 1CACS tasking

FIGURE 1. The Midcourse Space Experiment (MSX) satellite undergoing final integration and test at the Vandenberg Air Force Base launch processing facilities. The Space-Based Visible (SBV) sensor is composed of a telescope assembly, shown at the top of the satellite, and the electronics assembly, shown near the bottom of the satellite.

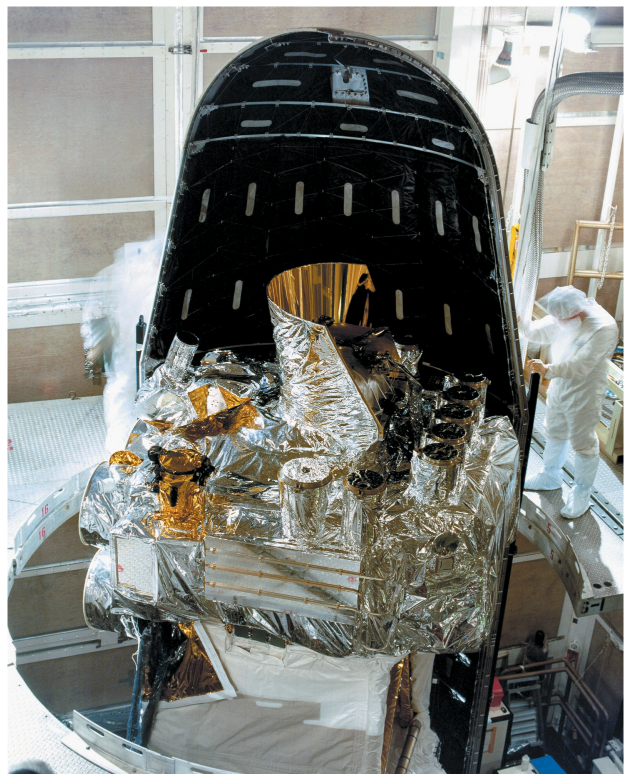

FIGURE 2. The MSX satellite undergoing booster integration on the launch pad. All of the sensors on the MSX are aligned along a common boresight. The SBV telescope is visible to the left of the picture, covered with gold-colored multilayer insulation. An openable cover, used to maintain cleanliness of the optics during launch and early operations, protects the SBV telescope. The SPIRIT 3 long-wave infrared sensor sunshade is visible at the center of the picture, and the ultraviolet/visible telescopes are located at the right of the picture. The first half of the booster faring (nose cone), which protects the satellite during launch, is shown being installed.

and operational commands for eight hours per day. SPOCC, which receives daily tasking requests from Space Command, operates the spacecraft eight hours per day, seven days per week. Descriptions of space-surveillance operations and data processing are provided in previous publications [9, 11]. Table 1 summarizes sensor characteristics relevant to routine space surveillance.

Two unique properties of the SBV sensor are being exploited for space surveillance [12–14]. First, the SBV sensor is on an orbiting platform and has access to the entire geosynchronous belt. Second, the wide field of view of the sensor allows efficient search operations and simultaneous multiple detections of resident space objects (RSO). Surveillance data are collected in a sidereal track mode, in which the stars appear as point sources and the RSOs appear as streaks. Routine surveillance data are then processed through the onboard signal processor to extract the star and streak information, as illustrated in Figure 4.

The SBV sensor demonstrates the unique capabilities of a space-based space-surveillance sensor. The unique nature of this sensor, however, has not precluded improvements from being made to the entire SBV system. Modifications have been made to both ground and spacecraft systems and components. Improvements undertaken early in the ACTD focused on increasing the efficiency of scheduling observations by collecting data on multiple RSOs simultaneously and reducing the maneuver time required by the MSX spacecraft. These efforts are described in detail in previous papers [2, 9]. The primary impact of the operational improvements has been to increase the quantity and quality of SBV observations. The increase in productivity has not only allowed improved surveillance of deep-space objects but has also aided in the collection of data on high-value RSOs.

The SBV sensor also provides a valuable contribution in the identification of uncorrelated targets and in the detection of high-priority tasked RSOs. The SBV sensor can make these contributions in regions

Table 1. SBV Sensor Characteristics

Spectral range	300–900 nm
Spatial resolution	12.1 arcsec/pixel
Field of view per CCD	1.4° × 1.4°
Aperture *f* number	15 cm, *f*/3
Number of frames per frameset	4–16 frames
Frame integration times	0.4, 0.625, 1, 1.6 sec
Frame sizes	420 × 420 pixels

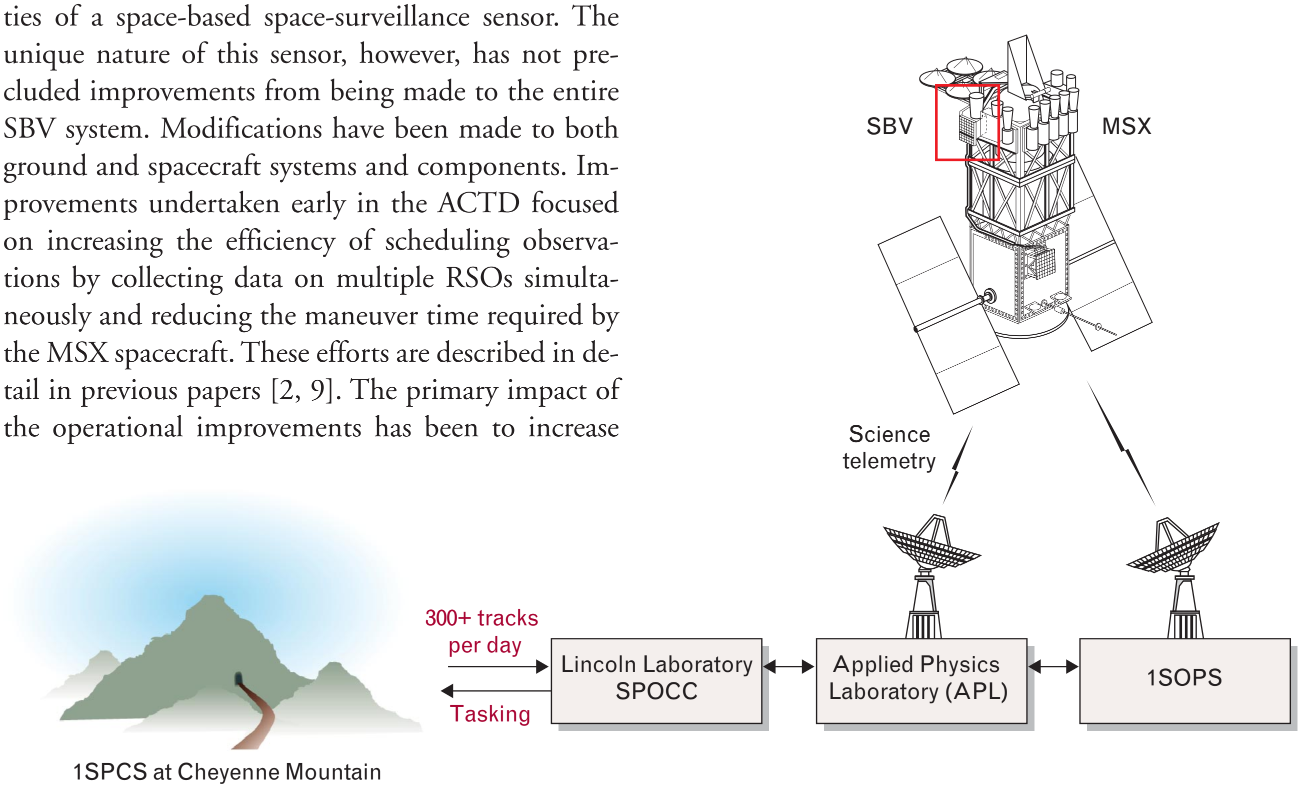

FIGURE 3. The MSX/SBV ground network. The 1st Space Control Squadron (1SPCS) in Cheyenne Mountain, Colorado, the Applied Physics Laboratory (APL) at John Hopkins University, the 1st Space Operations Squadron (1SOPS) at Schriever Air Force Base in Colorado Springs, Colorado, and the SBV Processing and Operations Control Center (SPOCC) at Lincoln Laboratory make up the ground-based operations of the MSX satellite and the SBV sensor.

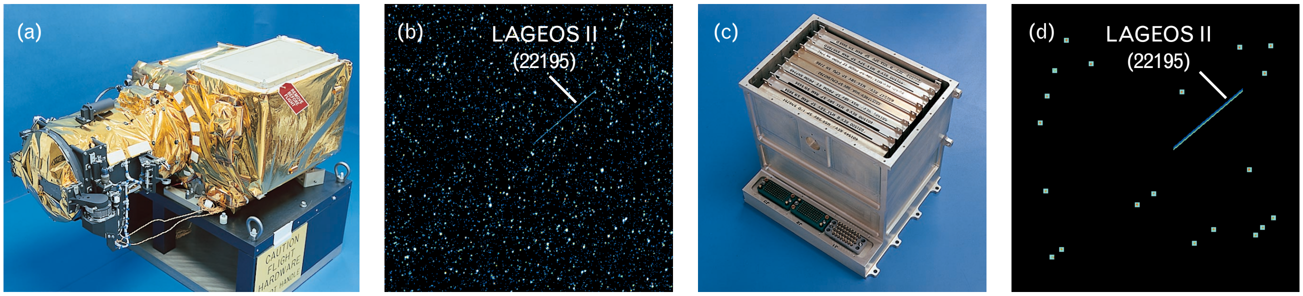

FIGURE 4. (a) The SBV sensor consists of a high-quality stray-light rejection telescope that contains four 420 × 420-pixel charge-coupled devices (CCD) that generate (b) a raw frameset. (c) The onboard signal processor processes the focal-plane images to yield star and streak reports that are used to construct (d) the signal-processed frameset image. The signal-processed data are used for routine space surveillance of resident space objects (RSO).

that are not well covered by the current Space Surveillance Network (SSN), which is a worldwide distribution of optical and radar sensors. Finally, the SBV sensor is also useful in generating observations that result in highly accurate position estimates of geosynchronous earth orbit (GEO) satellites.

Increasing Productivity

The impact of the modifications of both the ground-based and spacecraft systems has produced significant increases in the productivity of the SBV sensor. Figure 5 shows the average number of daily deep-space tracks collected by SBV. In October 1997 the SBV sensor produced approximately 50 deep-space tracks per day; by October 2000 this number had increased to nearly 400 tracks per day.

The productivity of the SBV sensor was increased through a combination of efficient data collection and efficient use of MSX spacecraft capabilities. Figure 6 illustrates the increasingly effective time management of the SBV system by showing the percentage of time the SBV spends collecting data. This percentage is the fraction of time the charge-coupled device (CCD) sensors are collecting photons and producing framesets. The remaining fraction of the time is spent maneuvering the satellite and processing the data through the signal processor. A satellite maneuver is initiated immediately following the data collection, and signal processing is performed during the maneuver. The effectiveness of the SBV sensor has been increased by reducing the time the spacecraft spends maneuvering, and by reducing the effective processing time on board the spacecraft.

Efforts to increase the productivity of the SBV sensor focused initially on reducing the amount of time the MSX spacecraft spent maneuvering. As a start, the maneuver durations were reduced from five minutes to three minutes for all maneuvers, independent of maneuver angle. With a shorter maneuver time, the first increase in productivity resulted from exploiting the SBV sensor's wide field of view to collect data on multiple objects simultaneously. This wide observational capability permitted the detection of more objects with the same number of maneuvers. Productivity was further enhanced by additional decreases in maneuver duration and by an increase in MSX-spacecraft data processing capability produced by a dual signal processing upgrade.

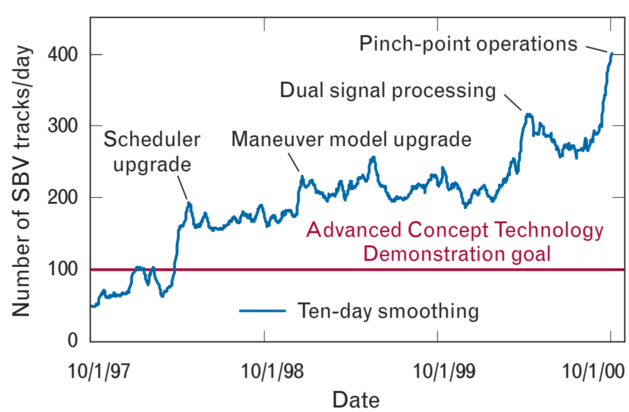

FIGURE 5. The increasing average number of daily deep-space tracks collected by the SBV sensor have resulted from increasingly efficient use of spacecraft resources. Modifications of both ground and onboard software have increased the efficiency of maneuver scheduling and onboard signal processing.

The final boost in productivity resulted from the addition of so-called pinch-point operations, which enhance the efficient data collection of the MSX spacecraft by searching a small region of space with small quick maneuvers, and by placing the search region in dense regions of the GEO belt. The effect of the quicker maneuver time is apparent in Figure 6, which shows the increased fraction of time spent collecting data. A more thorough description of pinch-point operations is provided in a later section.

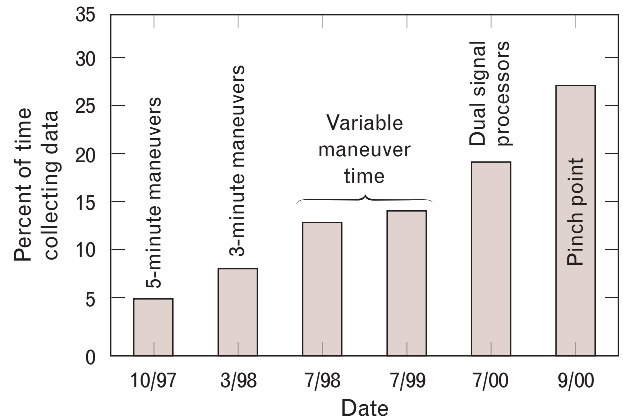

FIGURE 6. The fraction of time used for collecting data is a measure of how efficiently the MSX/SBV system is used. The data-collection time is the time required for collecting a frameset on a CCD. As the spacecraft maneuver time and signal processing time have been reduced, the amount of time devoted to data collection has increased from 5% to nearly 30% of the eight hours per day that is used for space-surveillance operations. The high efficiency of pinch-point operations is a result of performing short maneuvers.

Uncorrelated Target Discovery and Recovery

It is commonplace for the SBV sensor to detect streaks that do not correlate with any known objects in the catalog. This process occurs if a detection does not correspond to the predicted position of any known object to within a threshold of 125 millidegrees. Such a detection is called an uncorrelated target, or UCT. In many cases, a UCT is actually a detection of an object currently in the catalog but whose predicted position possesses significant errors. These errors may exist because (1) the satellite has not been tracked for a long period of time and its cataloged element set is no longer accurate; (2) the satellite has recently maneuvered and has not been tracked since the maneuver occurred; or (3) the satellite was erroneously associated with another satellite, commonly referred to as a corrupted or mistagged element set. A UCT is also possibly a detection of a satellite that was recently placed into orbit but for which no element set exists in the catalog. Finally, a UCT may be a detection of an object that has never before been seen by any sensor within the SSN, due to the object's small physical size. Any UCTs that cannot be classified in any of these ways are likely to be false detections, caused by such factors as radiation events or anomalies in the signal processor of the SBV sensor.

The U.S. Space Command has developed a classification scheme for objects that have been lost to the SSN, objects that need to be tracked for a variety of reasons, or objects that are misassociated with another object. This classification scheme, called the Attention List, is also associated with the way in which tasking priorities are given to sensors within the SSN on a daily basis, and it can be used to classify the successful association of UCTs. These categories are as follows: (1) *Lost*, an RSO that has not been tracked by any SSN sensor within the last thirty days; (2) *Attention List*, an RSO that has not been tracked within at least five days, but which is not officially a Lost object; (3) *Maneuvered*, an RSO that has recently maneuvered and can no longer be associated with its cataloged position; (4) *New Launch*, an RSO that was recently placed into orbit but for which no element set has been established; (5) *Corrupted*, an element set in the catalog that is seemingly misassociated with another object; or (6) *Uncataloged*, an RSO that has never been previously cataloged.

Objects on the Attention List have a well-defined problem, and action can be taken to track these objects and remove them from the list, given the adequacy and availability of SSN sensors. In many cases, however, such as those associated with lost objects, maneuvered objects, new launches, corrupted element sets, and uncataloged objects, an object cannot be classified until after it has first been discovered or recovered. Once this discovery or recovery step is accomplished, SSN sensors can then be tasked to gather more information on that object, thus improving the quality of its element set. The SBV sensor has made a significant contribution to the SSN by detecting and properly classifying numerous UCTs. With its wide field of view, the SBV sensor is able to recover objects whose predicted positions deviate considerably from their actual positions.

Specialized UCT processing software, which was developed at Lincoln Laboratory, can successfully associate a detection with a previously cataloged object [15]. The SBV sensor has been highly successful in properly cataloging UCTs, to a large degree specifically because of its wide field of view. This capability allows for the successful detection of an RSO, even if its actual position is far from its predicted location. In the case of the Ground-based Electro Optical Deep Space Surveillance (GEODSS) system, which is the collection of nine telescopes comprising most of the ground optical sensors within the SSN, the effective fields of view of these sensors are a factor of three times smaller than that of the SBV sensor, and, in the case of the deep-space radars, the fields of view are an order of magnitude smaller than that of the SBV sensor. Since the inception of the ACTD in October 1997, the SBV sensor has exploited its wide field of view by successfully assigning 160 detected UCTs to objects in the catalog. During the ACTD, the SBV and Space Command teams reduced the Lost list associated with the GEO belt from 63 objects, which were detectable to the SBV sensor, to merely 13.

Figure 7 shows the distribution in longitude of the objects discovered or recovered by the SBV sensor, clearly indicating that most of the activity, particularly with respect to maneuvering satellites, occurs over Europe. This region of the world has an unusually high number of geosynchronous satellites that are frequently maneuvered, or station-kept, in order to maintain their restricted positions along the belt. It is also important to note the significant support given by the SBV sensor to new launches over central Asia.

High-Priority Object Tasking

For many years now, U.S. Space Command has used a system of prioritization to establish its daily tasking of the sensors within the SSN. Objects of highest priority are referred to as Category 1 objects, and these are the objects on which Space Command needs data that day, with a high probability of success. These so-called Cat 1 objects may be satellites that are operated by U.S. adversaries; they may be satellites that have recently maneuvered and will be lost if they are not tracked immediately; or they may be satellites nearing reentry into the atmosphere, and updates are required at a high rate in order to establish a good prediction on their reentry point. The categories decrease in priority to Category 2, 3, 4, and 5, with suffixes associated with each, to indicate how many observations and over what duration tracking data are requested. In theory, any given sensor within the SSN is sup-

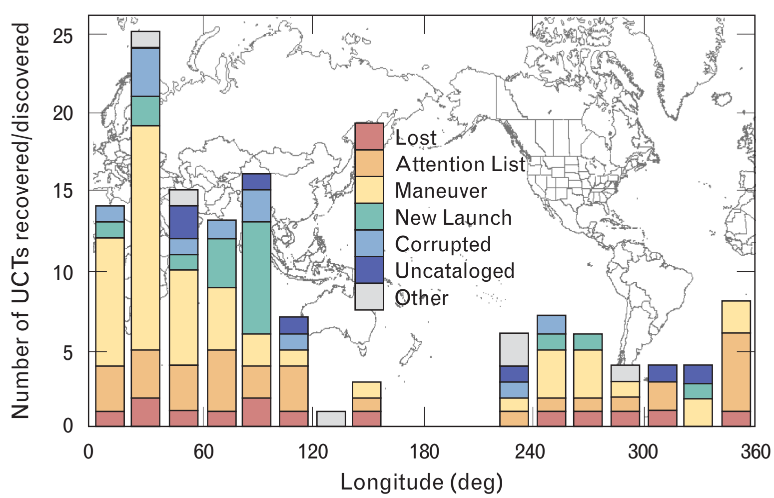

FIGURE 7. Geographic distribution of high-priority uncorrelated target (UCT) objects discovered or recovered by the SBV sensor. This histogram clearly shows that the SBV sensor has had a significant impact on supporting maintenance of the catalog over Europe and Asia.

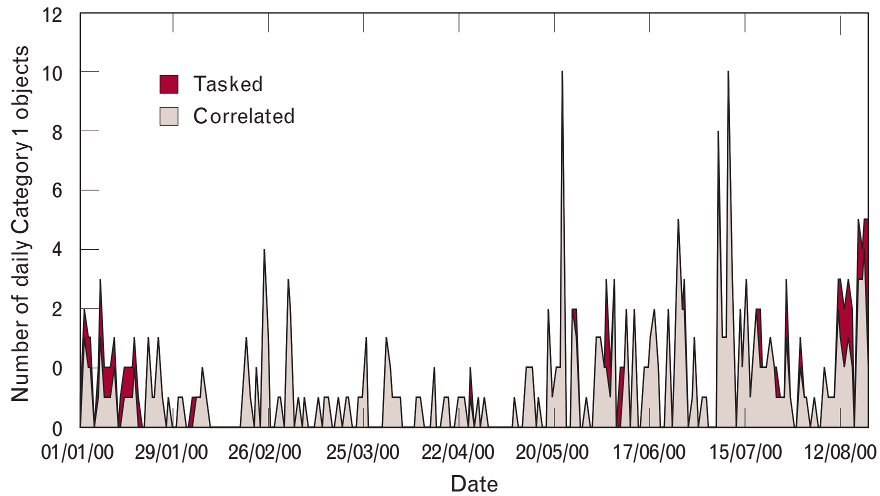

FIGURE 8. The reliability of the SBV sensor in response to tasking of high-priority (Category 1) objects. This diagram shows a comparison of the number of high-priority satellites that were tasked to the SBV sensor on any given day, and the success to which data were gathered on that object. In comparison with the ground-based optical sensors in the Ground-based Electro Optical Deep Space (GEODSS) system, the SBV sensor performs approximately three times more reliably in response to tracking these critical objects.

posed to respond to Category 1 objects with a very high degree of success, Category 2 to a lesser degree, and so on down to Category 5.

Unfortunately, this goal is not reached in practice, with the one exception of the SBV sensor. Figure 8 shows that the SBV sensor responds routinely to Category 1 tasking at or above the 90% level. So there is a high probability that U.S. Space Command will receive tracking data on these objects when it tasks the SBV sensor. In contrast, the GEODSS system averages around 30% in response to tasking of Category 1 objects. The success rate of the GEODSS system is due principally to its restriction to nighttime viewing and weather outages. As a consequence, Air Force Space Command has come to depend on the SBV sensor in the last three years to gather data on these high-interest objects.

In addition to the 90% success rate of the SBV sensor in response to Category 1 objects, the sensor has complete global coverage, unlike any ground-based sensor. Figure 9 shows where the SBV sensor has gathered observations in response to Category 1 requests. The red triangles show the locations of current deep-space satellite-tracking radars. This figure illustrates the contributions of the SBV sensor for regions outside of ground-based radar coverage.

Catalog Maintenance

SBV observations have proven valuable not only because of their quantity and global coverage, but because the quality of these observations has contributed to the maintenance of an accurate catalog of RSOs. This section illustrates the utility of SBV sensor observations to perform orbit determination of geosynchronous objects [16]. Three different requirements for GEO orbit determination are explored. The first requirement is the capability to perform initial orbit determination to catalog UCTs. The second requirement is the ability to perform long-term orbit maintenance. The third and final requirement is the ability to calculate very accurate orbits.

SBV sensor observations on a selected GEO satellite were used for this analysis. The accuracy of the SBV-derived orbit solution was assessed by comparing it to a more accurate reference orbit. The Goddard Space Flight Center routinely generates a precise orbit for their Tracking and Data Relay System (TDRS) satellites in geosynchronous orbit. The published TDRS orbits are accurate to 50 to 60 m (1 σ) in position [17, 18]. The TDRS-4 satellite was tracked frequently by the SBV sensor and the Millstone Hill radar during a sixty-day maneuver-free pe-

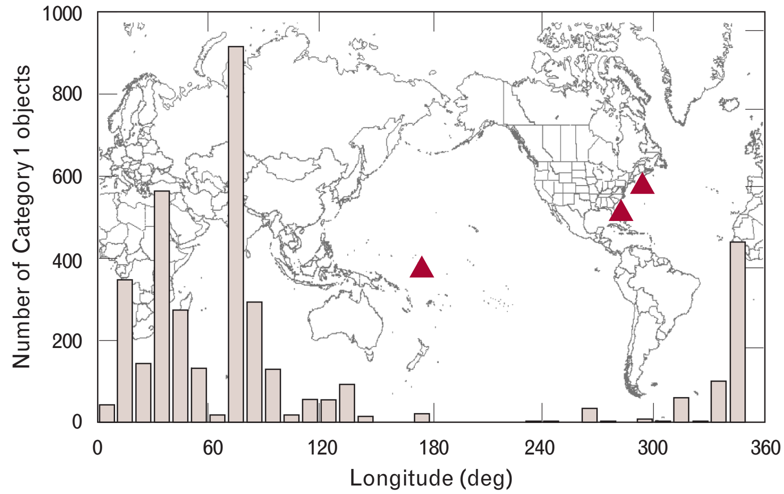

FIGURE 9. MSX/SBV coverage of high-priority objects. The red triangles show the locations of current ground-based deep-space satellite-tracking radars. The SBV sensor primarily provides data on high-priority deep-space objects that are outside ground-based radar coverage. Three additional ground-based sites would be required—most likely situated in foreign countries—to achieve the same coverage offered by the MSX/SBV.

riod. Both optical and radar tracking data were used to compute orbits for TDRS-4, and the accuracy of these orbits was determined by comparing the orbits with the reference orbits computed from Goddard Space Flight Center element sets.

The capability to perform initial orbit determination with SBV observations is necessary for the identification of UCTs. The initial orbit-determination process generates an element set for a set of UCT observations, which can be compared to other element sets, and can be used to direct sensors to observe the UCT. Figure 10 shows an example of the initial orbit-determination process. In this example, about 5% of the orbit arc was sampled by the discovery observations. The initial solution was refined by using least-squares estimation with all six observations, and Figure 10 shows the resulting orbit error. The larger amplitude of the oscillations is a result of the eccentricity of the orbit not being well determined because of the small sampling of the orbit, although the errors are small near the observations where the orbit is well constrained. The errors of the initial orbit-determination solution are small enough to allow the object to be recovered by the large field of view (1.4° × 1.4°) of

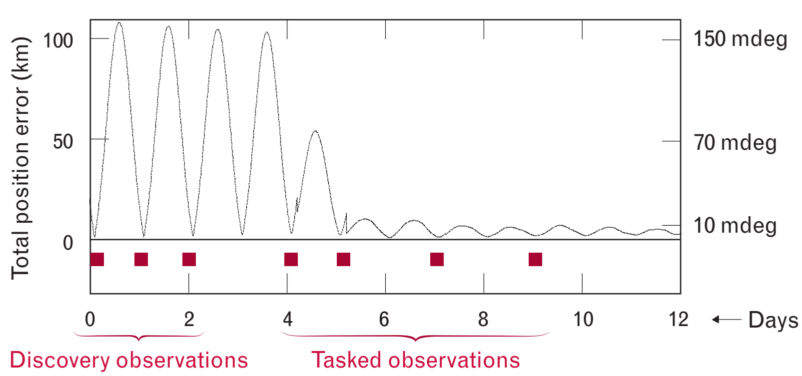

FIGURE 10. The quality of geosynchronous earth orbit (GEO) determination during the UCT discovery process increases as additional observations (indicated by red squares) are collected. Orbit error is reduced by an order of magnitude as the number of tracks increases from three to six. The right-side *y*-axis shows the orbit position error in millidegrees (mdeg).

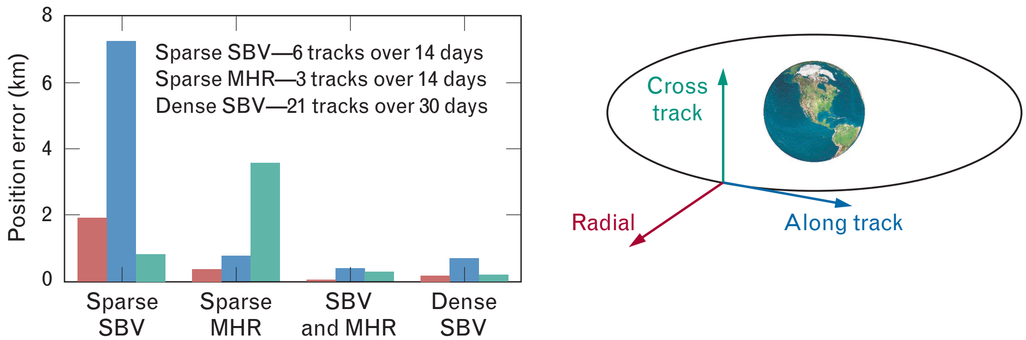

FIGURE 11. The accuracy of GEO orbit determination. For routine space surveillance, orbit quality of GEO objects is a function of type and quantity of data. The sparse SBV solution has smallest errors in the cross-track direction, and the sparse Millstone Hill radar (MHR) solution has smallest errors in the radial and along-track directions. The complementary nature of SBV optical data and MHR radar data permits an effective fusion of the two data types, resulting in accurate orbit estimates. An SBV track consists of two observations, and an MHR track consists of five observations.

the SBV sensor within a few days of the discovery observations. Once an element set is generated, further observations are collected and the orbit is improved. The errors in the orbit rapidly decrease with an increasing number of tracks.

The growth of the geosynchronous satellite population combined with the small altitude band they occupy has increased concerns about the possibility of collisions between these objects. Highly accurate geosynchronous orbits are required to address these concerns [19]. SBV sensor data has proven valuable in generating these high-accuracy orbits. Let us examine how the fusion of SBV optical and radar data efficiently produces high-accuracy geosynchronous orbits. The first two orbit solutions in Figure 11 represent sparse SBV sensor data and sparse Millstone Hill radar data, respectively. The sparse SBV-data case represents the amount of tracking necessary for routine object tracking and catalog maintenance. The bars on the left side of Figure 11 show the position errors in the three orbit components (radial, along track, and cross track). The sparse SBV-sensor solution has smallest errors in the cross-track direction because of the high angular accuracy of these observations. The accurate SBV-sensor measurement of the cross-track component permits the inclination of the orbit to be well determined. The sparse Millstone Hill radar (MHR) data solution has the smallest errors in the radial and along-track directions because of accurate range and range-rate observations. The direct measurement of range and range rate results in an accurate estimate of the semimajor axis and eccentricity of the orbit. The complementary nature of these observations can be exploited by combining sparse optical and radar observations to generate an orbit solution that is considerably better than what is achievable with data from only a single source.

Finally, if sufficient SBV-only data (dense tracking) are available, it is also possible to generate an accurate orbit solution. The SBV sensor has proven very effective in surveillance of deep-space geosynchronous objects. The SBV sensor's capability to collect accurate data on low earth orbit (LEO) objects has also been explored; it is described in the sidebar entitled "Low-Earth-Orbit Observations: Solving Today's Operational Issues While Preparing for Tomorrow's."

Improving the Capability of the SBV Sensor

During the second half of ACTD operations, additional improvements were made to both ground and spacecraft systems to enhance the capabilities of the SBV sensor. Space surveillance with the SBV sensor involves scheduling RSO observations, uplinking SBV commands, collecting data, performing signal processing, maneuvering the MSX spacecraft, and finally downloading and reducing data from SBV sensor observations. Because of funding constraints and spacecraft access limitations, SBV data collection is limited to a maximum of eight hours per day. Operational improvements to increase the productivity of

LOW-EARTH-ORBIT OBSERVATIONS: SOLVING TODAY'S OPERATIONAL ISSUES WHILE PREPARING FOR TOMORROW'S

BUILDERS OF the Space-Based Visible (SBV) sensor took great pains to develop a sensor that could gather observations covering objects in all orbit classes. To address low earth orbit (LEO) targets, which must be detected in the presence of the bright earth limb, the telescope design was optimized for high off-axis rejection. This capability entailed a unique telescope design [1] and required very clean optics. The ultimate off-axis performance of the SBV sensor exceeded the lofty goals set for off-axis rejection. However, because the operational shortfalls in the space-object catalog often involved deep-space objects (any object with an orbital period exceeding 225 minutes), little data were acquired on LEO objects over the course of the Advanced Concept Technology Demonstration. The SBV sensor, however, made considerable contributions to the deep-space catalog.

Anticipated needs in space surveillance over the next few decades include a requirement for short timeline access to the orbits of space objects. Achieving quick access to these orbiting objects (in a time period much shorter than the object's orbital period) by using ground-based sensors is difficult because the sensors must be proliferated widely across the earth's surface. This approach is costly and requires access to numerous foreign sites.

Space-based sensors are much better solutions to the requirements for short timeline access to orbiting objects, including LEO objects. In fact, the timeline requirements have been the most persuasive justification for a follow-on constellation of space-based space-surveillance sensors.

Given the long-term interest in understanding how to make space-based space-surveillance sensors most effective for all orbital regimes, Lincoln Laboratory and Air Force Space Command began an effort to gather observation data on LEO space objects. The objectives were (1) to validate that the SBV sensor could effectively access and detect LEO targets, (2) to verify that SBV target tracks could be used to generate accurate orbits for LEOs, and (3) to collect optical signature data covering a wide range of LEO target types and geometries with respect to the sun.

Achieving the first objective was critical to demonstrating that space-based space-surveillance sensors could provide the short timeline access that is required by Space Command across the entire target set. The objective was successfully achieved as a by-product of achieving the second and third objectives.

Conducting a series of observations of known LEO targets and processing the data to yield updated orbits achieved the second objective, namely, demonstrating the generation of accurate orbits with the SBV sensor data. Figure A shows an example of the result. In this case, a series of two SBV tracks were taken on space object 23463, which is a Russian navigation satellite called Tsikada 1. The resulting orbit was compared to a reference orbit generated by using ground-based radar observations; Figure A shows the resulting errors. The quality of the SBV-only orbit error for this object is on the order of a few kilometers, which translates to a timing error of less than a second and is representative of the accuracy of the LEO catalog.

Achieving the third objective, namely, generating an extensive set of signature measurements of LEO objects, has proved to be vital to the requirements analysis and design for the follow-on operational constellation of space-based space-surveillance satellites. The space-object catalog maintained by Space Command contains the radar cross section of each cataloged object. No optical signature data, however, are included in the catalog. Attempts to convert from a radar cross section, usually measured at UHF wavelengths, to optical signatures measured with wavelengths a factor of 10^7 shorter, have met with little success. However, as described above, the current operational shortfalls were most extreme in deep space, and as a result LEO observations were not generally tasked to the SBV. During the surveillance of deep-space objects, LEO objects are also captured in the SBV sensor's wide field of view. As a result of these serendipitous detections, a catalog of over 5000 measurements on over 2500 LEO objects at a wide variety of sun/object/SBV geometries was collected. This database has been critical to the requirements analysis and design of the planned follow-on system called SBSS (Space-Based Surveillance System). The capability of proposed sensor constellation architectures can be realistically estimated by using the database of measured signatures. As expected, short timeline access to objects in all orbital regimes has become a major requirement for the operational constellation, and has been the leading priority design objective.

Reference

1. D. Wang, C. Wong, and R. Gardner, "Space-Based Visible All-Reflective Stray Light Telescope," *SPIE* **1479**, *Surveillance Technologies*, 1991, pp. 57–70.

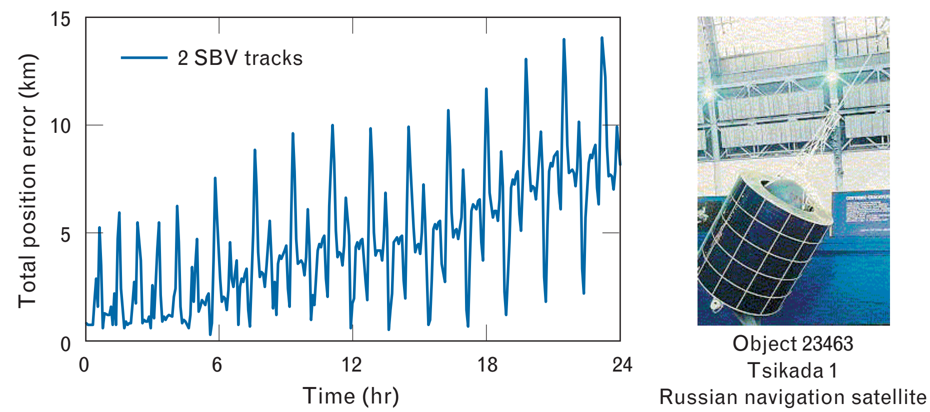

FIGURE A. SBV-only observations are capable of generating an accurate orbit of low earth orbit (LEO) satellites. The position error of an SBV-only orbit solution for the Russian navigation satellite Tsikada 1 is on the order of a few kilometers, which translates to a timing error of less than a second.

the SBV sensor are thus limited to increased efficiency in both scheduling RSO observations and in data processing onboard the spacecraft.

The remaining sections of this article discuss subsequent operational improvements that have been implemented during the second half of the ACTD period. The first of these improvements focuses on increasing the efficiency of data processing on board the spacecraft by exploiting redundant processing capability onboard the spacecraft. The second improvement further increases the effectiveness of scheduling RSO observations by concentrating data collection on dense regions of the GEO belt, and by performing these observations with a minimum number of maneuvers. These modifications represent a new mode of operations with emphasis on search operations versus tasked operations.

Dual Signal Processor Operations

The SBV sensor was designed with redundant components to allow for reliable operations in space [5–7]. The primary components of the SBV sensor hard-

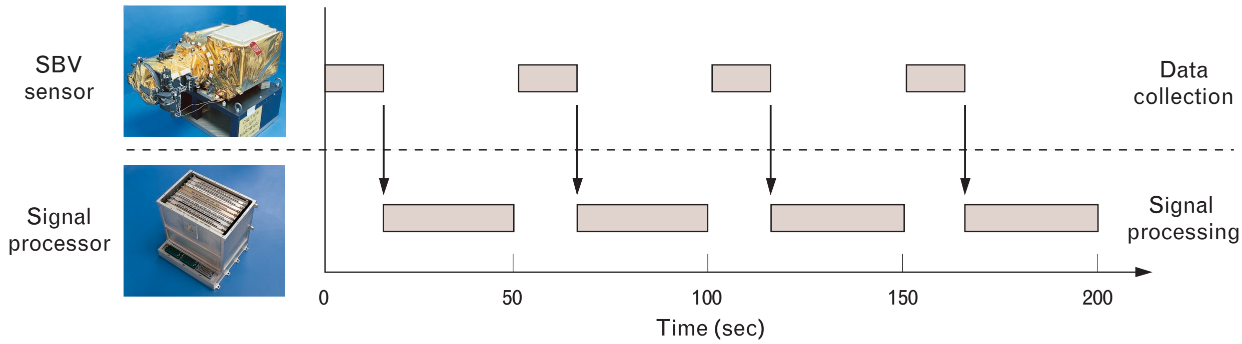

FIGURE 12. Single signal processor. With one signal processor, the SBV sensor data must be processed through the signal processor before the next frameset can be collected. The spacecraft can begin maneuvering while the last frameset is being processed.

ware consist of the camera, CCD sensor, analog electronics, experiment controller, and signal processor. The experiment controller coordinates the operation of the CCD sensor and signal processor. The focal plane is configured such that a single failure will impact only two out of the four CCDs. Both the experiment controller and the signal processor have fully redundant channels. This redundancy has been exploited in two ways in the SBV program. First, the redundant components were utilized in performing final testing of software upgrades to the onboard systems. After thorough ground testing, software modifications for the SBV hardware were uploaded and first tested on the redundant component before being implemented in routine operations. This approach permitted upgrades to the SBV system with minimal impact on operations. The redundancy of the SBV system was also utilized to increase the processing capability of the hardware. This section describes how the redundant signal processor was used to increase the capability to process data onboard the spacecraft.

In nominal operations with only one signal processor, the CCD sensor is used to collect eight frames of data with an integration time of 1.6 sec per frame. The collected data are sent to the signal processor, in which star and satellite detections are extracted and stored as reports. The reports are initially stored within the memory of the signal processor and are moved to the experiment controller before being downloaded to the ground. Data can be downloaded directly from the signal processor, although the process of downloading deletes the data from the signal processor. Once the data are moved to the experiment controller, they can be downloaded multiple times. Figure 12 illustrates the timeline of processing data with a single signal processor.

Figure 12 shows that approximately 200 seconds are needed to collect and process four successive framesets of data. As stated earlier, the SBV hardware was designed and built with a redundant signal processor for reliability. The SBV hardware is capable of operating both signal processors. Figure 13 shows how the second signal processor is utilized.

Once one frameset has been collected by the CCD sensor and sent to the signal processor, the second signal processor is immediately configured to receive the second frameset from the CCD sensor. The third frame is taken when the first signal processor is ready to receive the data. Finally, the second signal processor is ready to receive the fourth frameset. The spacecraft can begin maneuvering after the fourth frameset is taken, while the signal processor is processing these data. In dual signal processor mode approximately eighty seconds are needed to take four framesets of data, whereas approximately 160 seconds are needed to take the same amount of data with a single signal processor. In search operations all four CCDs are used sequentially, and dual signal processor search operations can cover twice as much area than single signal processor search operations.

Dual signal processor operations are implemented by modifying onboard spacecraft software to toggle the two signal processors to receive the data from the CCD sensors. Once the memory in the signal processor is filled up, the data are moved to the experiment controller after which they can be downloaded. The

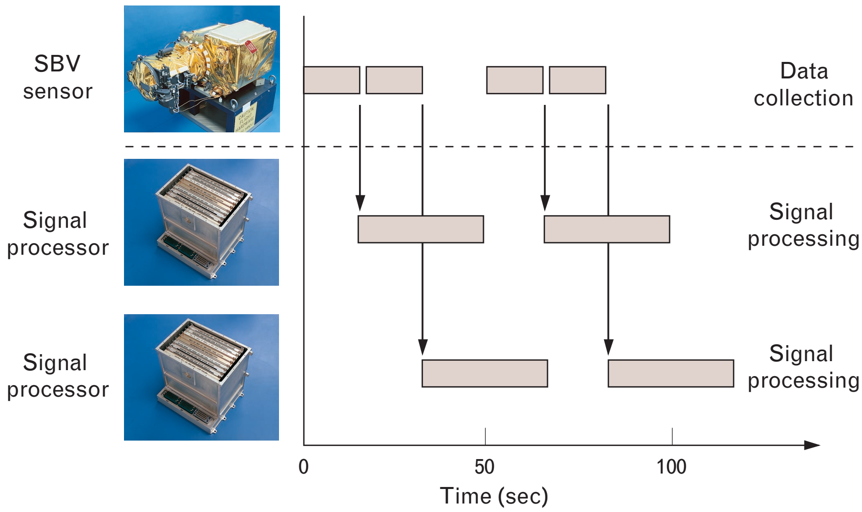

FIGURE 13. Dual signal processors. With two signal processors, a second frameset can be immediately collected and sent to the second signal processor while the first signal processor is still processing. As with the single signal processor case, the spacecraft can begin maneuvering while the last frameset is being processed.

onboard data flow is handled by a set of macros that are loaded onboard the spacecraft to redirect the data alternatively to both signal processors (a macro is a set of commands stored onboard the spacecraft and addressable by a single command from the ground).

Geosynchronous Pinch Points

The increased efficiency of dual signal processing operations has made it possible to set up a search fence for geosynchronous objects. This section motivates the location chosen for the search fence and the resulting sensor operating strategy. A geosynchronous satellite is one in which its orbital period is synchronous with the rotation of the earth. If, in addition to having a period of one sidereal day, the satellite is launched into the equatorial plane (an orbit with zero inclination), the satellite seems to stay over a fixed point on the equator, as seen by an observer standing on the ground. This type of orbit is referred to as a geostationary orbit. If, however, the satellite's orbit plane is inclined to the equator, the satellite appears to an observer on the ground to follow a figure-eight pattern in the sky. This type of orbit is referred to as a geosynchronous orbit, but it is not geostationary. Figure 14 illustrates the angles that define an orbit.

Geosynchronous and geostationary orbits are both

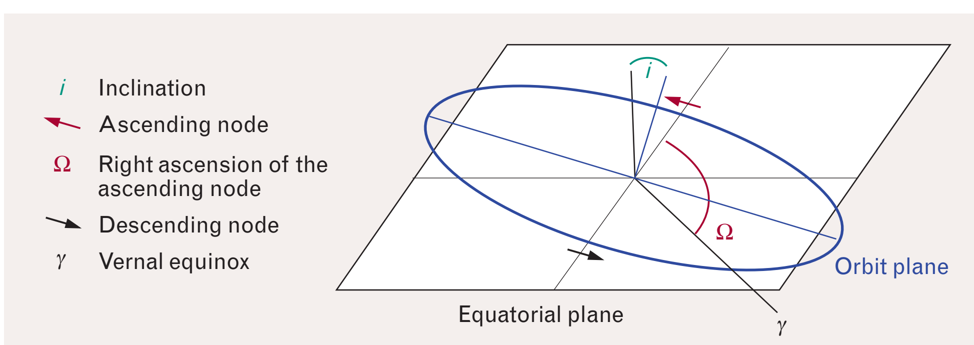

FIGURE 14. Satellite orbital elements. Six parameters are required to define the orbit of a satellite. The two shown in this diagram define how the orbit is inclined to the equator, namely, the inclination i and the right ascension of the ascending node Ω, which defines the angular location at which the orbit crosses the equator on its path into the northern hemisphere. The location is measured with respect to a fixed direction in the sky known as the vernal equinox γ.

used by the operators of communication, weather, and surveillance satellites to conduct their missions. In fact, an interesting pattern of behavior has developed over the last forty years with regard to how satellite operators launch and maintain their geostationary satellites and, ultimately, what happens to these satellites when they cease to be active. This behavior is driven by the operator's desire to exploit the natural effects of the sun, the moon, and the oblateness, or equatorial bulging, of the earth, in order to maximize the satellite's lifetime and to minimize its operational (fuel) costs. It is through a combination of these natural effects and this behavior that creates what we refer to as geosynchronous pinch points, or the systematic grouping of satellites in specific regions of the geosynchronous belt [20]. By exploiting these pinch points the SBV sensor is able to significantly increase its productivity in search mode. In order to appreciate the causes of these pinch points and recognize how best to exploit them, we must first understand the behavior of geosynchronous orbits.

Geosynchronous Orbit Characteristics

The natural effects of the sun, the moon, and the oblateness of the earth are referred to as lunisolar and J_2 geopotential perturbations. These forces produce, among other effects, a torque on the orbit plane of a satellite that results from the net out-of-plane force component that acts on the satellite. This torque produces a correlated periodic variation in the inclination and a precession of the orbit plane along the equator. The effect of precession is similar to the motion that occurs when a spinning gyroscope is suspended on one end by a string; the gyroscope precesses around the string in a direction dependent upon the spin direction of the gyroscope. This motion is quantified by the rate of change of the right ascension of the ascending node, Ω, or the angle between the location at which the orbit plane intersects the equator, on the satellite's motion into the northern hemisphere, and an inertial reference point known as the vernal equinox γ. The effects are observed as a fifty-three-year periodic variation in the inclination and the ascending node [21, 22].

Geosynchronous-satellite operators, by thoughtfully choosing the initial conditions of their satellite's orbit, establish a certain evolution of the orbit. There is a relationship between the inclination and the right ascension of the ascending node, due to the lunisolar and J_2 effects. The goal of the majority of geosynchronous satellite operations is to maintain the relative position of the satellites over a point on the earth, thus producing a geostationary satellite. This goal requires that the inclination of the orbit remain near zero, which can be accomplished only through routine orbit maneuvers. However, performing a maneuver to change the inclination of an orbit is an exceedingly fuel-intensive operation, and, since the rate of fuel consumption is the most important parameter defining the lifetime of these satellites, careful planning of these maneuvers is vitally important. As a consequence, operators choose to launch their satellites in such a way as to minimize the need to perform these expensive inclination-altering maneuvers. This effort is accomplished by launching the satellite with an initial inclination and ascending node that places the evolution along the curve shown in Figure 15. Since this philosophy is incorporated by the vast majority of geostationary satellite operators, an interest-

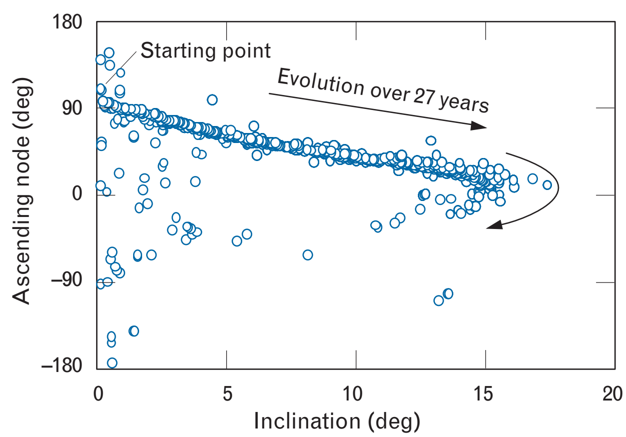

FIGURE 15. Actual satellite data for geosynchronous satellites, showing the correlation of the inclination and right ascension of the ascending node due to lunisolar and J_2 geopotential perturbations. The figure shows the initial conditions of inclination and ascending node used by most geosynchronous satellite operators. Data for satellites with inclinations less than 0.5° have been removed from the plot, since they are frequently maneuvered and because the right ascension of the ascending node becomes ill-defined if the inclination is near zero degrees (these low-inclination objects always pass through the pinch-point region).

ing pattern evolves in the orbits. It is this pattern that forms the so-called pinch points.

Over thirty years have elapsed since satellites were first launched into geosynchronous orbit. Today there are approximately 650 active and inactive geosynchronous satellites in orbit. Figure 15 shows actual satellite positions, with respect to the inclination and the right ascension of the ascending node, as they exist today. It takes approximately twenty-seven years for the inclination to increase to 15°, and nearly twenty-seven years for the inclination to decrease back to zero. Note that satellites with inclinations less than 0.5° have been removed from the plot, since they are frequently maneuvered to maintain their position over a fixed point on the earth, and they go through the pinch point as well. Furthermore, the right ascension of the ascending node becomes ill-defined if the inclination is near zero, and this angle is difficult to estimate accurately with data from the SSN.

The important feature to note is the structure of the geosynchronous population. During the active life of these satellites, their inclinations are maintained near zero and their corresponding ascending nodes are maintained between –90° and 90°. When a satellite's fuel is depleted, or when the satellite fails, it is no longer maneuvered. Over time the ascending node of the satellite rapidly evolves to 90° clockwise, and slowly evolves along the curve shown in Figure 15. This cycle is completed in about fifty-three years. Because geosynchronous satellites have been launched into earth's orbit for only about thirty years, the satellites have evolved—at most—a little greater than halfway through the cycle. Satellites with inclinations of 15° and near-zero ascending nodes, as seen in the right-most data in Figure 15, are some of the first geosynchronous satellites ever launched. These results clearly show that, while active geosynchronous satellites are maneuvered to remain their position on the equator, the inclination and ascending node of inactive satellites evolve in predictable ways.

Figure 16 shows the distribution of ascending nodes for the same set of satellites shown in Figure 15 (satellites with inclinations less than 0.5° have once again been removed from the plot). This histogram shows the high concentration of orbits with ascending nodes between 20° and 90°. It is this clustering of orbits that forms the geosynchronous pinch points. These pinch points become even more clearly visible if the population of the geosynchronous belt is viewed over a 24-hour period, as shown in Figure 17. In this figure, each satellite progresses from left to right along a sinusoidal trajectory. The contours indicate the number of distinct satellites passing through a 1.4° × 1.4° region of inertial space over a 24-hour period, which is the field of view of one charge-coupled device (CCD) on the SBV. The highest density regions, or pinch points, are centered at 0° declination and at approximately 65° and 245° in right ascension. Unlike with the data shown in the previous figures, this data set contains all the geosynchronous satellites, which explains the high concentration of those with zero declination (equatorial orbit).

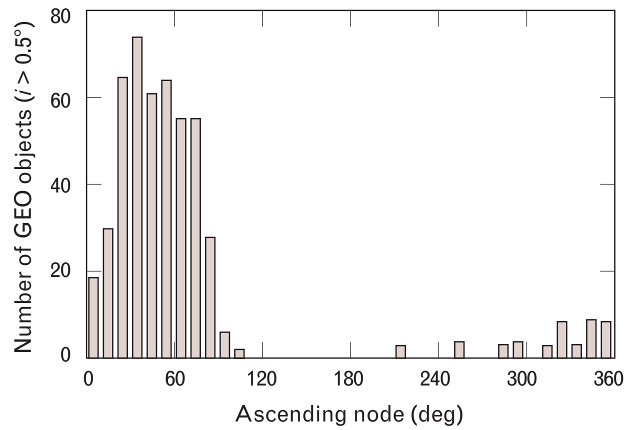

FIGURE 16. Histogram of the right ascension of the ascending node for geosynchronous satellites. The clustering of ascending nodes between 0° and 90° is the pattern referred to as the geosynchronous pinch points. Satellites with inclinations less than 0.5° have been removed.

Pinch points exist because, at these locations, active satellites on the belt are passing through these regions at the same time that older inactive satellites are crossing the equatorial plane. Note the distinct high-density "tails" extending above and below the belt near the two pinch points. This structure can easily be explained by comparing Figure 17 with Figure 18, which depicts the sinusoidal orbit tracks of fifteen inactive geosynchronous satellites. In this figure, the sinusoids have been systematically shifted in phase, so that each orbit crosses the equator at a slightly differ-

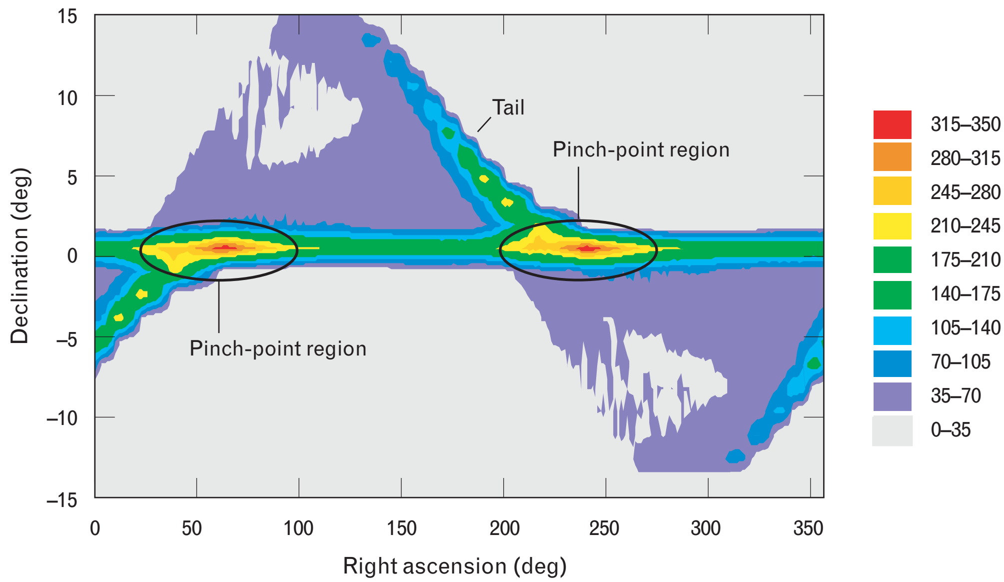

FIGURE 17. Satellite concentration in the geosynchronous belt over a 24-hour period. The concept of pinch points becomes clear if the population of geosynchronous satellites is viewed with respect to the inertial coordinates of right ascension and declination over the course of one day. These pinch points, which are illustrated as lighter colored regions in the figure, are locations on the geosynchronous belt that represent high concentrations of satellites at certain times of the day.

ent location. This shift in phase occurs in reality, since each inactive satellite is at a different location in its fifty-three-year evolution.

Once these pinch points were understood, it was the goal of the MSX/SBV team to determine an operational technique to exploit these regions, and thus increase the SBV sensor's productivity during its search periods.

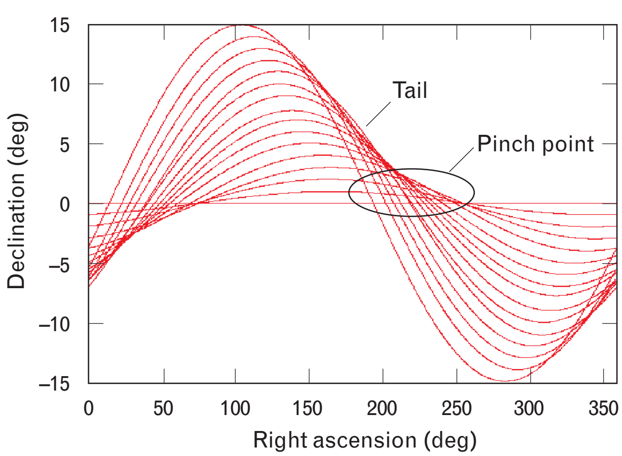

FIGURE 18. Orbit traces of fifteen geosynchronous satellites, with varying inclinations and locations of the ascending node. This diagram clearly shows the cause of the tails associated with the pinch points, as seen in Figure 17. Because of the shifted phase of the various sinusoids and the varying inclination, regions of high concentration are found both north and south of the geosynchronous belt, in addition to the main points on the belt.

Pinch-Point Implementation

Pinch-point operations require the pinch-point search region to be continuously observed over the twenty-four hours that geosynchronous objects require to complete a single orbit. In practice SBV operations are limited to eight hours per day, and the coverage of the search region has to be accomplished by searching the region in small time increments over twenty-four hours. By searching a region repeatedly with a constant revisit interval, it is possible to create a search region that covers the entire geosynchronous belt. Since the SBV sensor is orbiting the earth, a constant revisit interval implies that a given pinch-point region is searched once an orbit. The size of the search region results from a trade-off between the time required to search the region and the amount of time the region is continuously visible. Figure 19 shows the resulting search pattern.

This figure shows a coverage box that is 30° wide

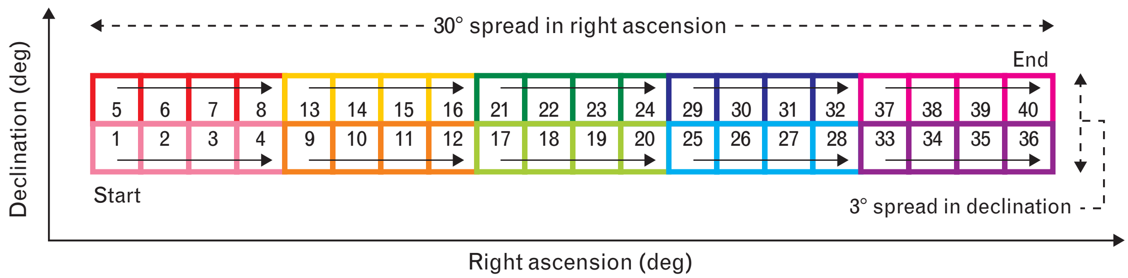

FIGURE 19. The pinch-point search region is covered by generating a pattern with the four-CCD SBV sensor array. The complete pattern consists of forty framesets, which are grouped into ten four-frameset blocks. The MSX spacecraft is maneuvered only between each of the four-frameset blocks. The resulting coverage is 30° in right ascension and 3° in declination.

in right ascension and 3° high in declination, and consists of ten groups of framesets. Each group consists of a frameset from each of the four CCDs. The spacecraft is maneuvered only between each group of framesets. The search region is covered by an array of forty framesets, and is covered from left to right. Since GEO objects move from right to left, objects that are leaving the search region are observed first, and objects that are just entering the region at the end of the search interval are observed last. This search strategy also results in a slight overlap between framesets in longitude, and the 30°-wide region in right ascension translates to a 25°-wide region in longitude. With dual signal processor operation approximately thirty minutes are necessary to cover the pattern shown in Figure 19. Figure 20 illustrates how this search region is covered every orbit revolution.

In practice, due to spacecraft operation constraints, the pinch point is revisited twelve times per day, resulting in coverage of approximately 300° of the geosynchronous belt. The twelve pinch-point revisits require approximately six hours of spacecraft operations, which leaves approximately two hours for tasked operations. Figure 21 illustrates an example timeline, showing the distribution of pinch-point revisits and the placement of two blocks of time de-

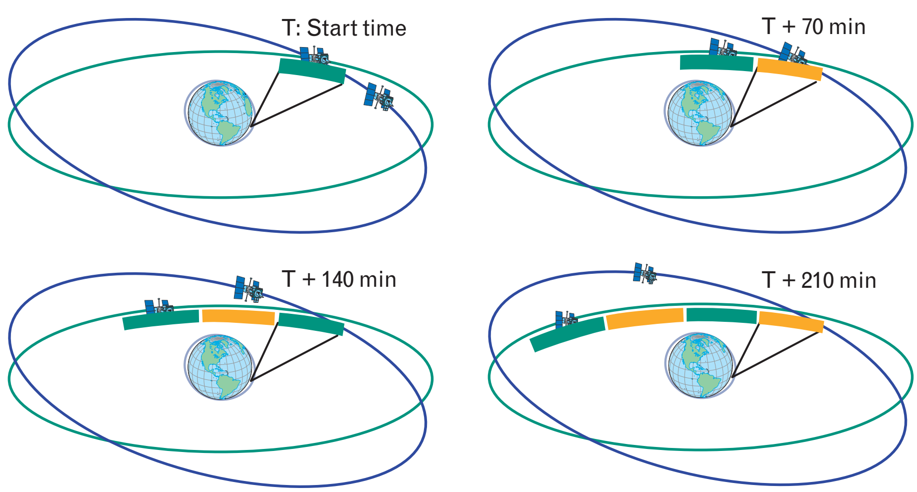

FIGURE 20. Four successive revisits of the pinch point illustrate the ability of pinch-point operations to detect objects with 0° inclination (green orbit) and with 15° inclination (blue orbit). As geosynchronous satellites orbit the earth, satellites with inclinations between 0° and 15° pass through the pinch-point region. The proper timing of twelve data collections at the pinch point allows the SBV sensor to cover up to 300° of the GEO belt.

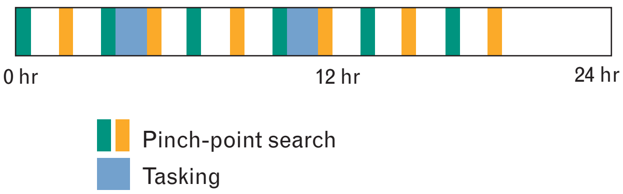

FIGURE 21. Twelve data pinch-point collection periods, distributed over 19.4 hours. Two 70-minute blocks of time between revisits of the pinch point are devoted each day to tasking operations. These blocks are used for data collection of high-priority objects and calibration objects.

voted to tasked operations. The resulting operation timeline results in six hours of search operations and two hours of tasked operations.

The scheduling of pinch-point data collection is also limited by three time constraints that must be accommodated, as shown in Figure 22. The first constraint is the time needed for contacts with the Applied Physics Laboratory (APL). These are times used by APL to upload commands and download data, and times when the MSX spacecraft is passing above APL. The second constraint is times that the MSX passes through the South Atlantic Anomaly (SAA). The SAA is a high-density region of high-energy electrons and protons. The high-density protons interact with the CCD focal plane and prevent the detection of RSOs [2]. The third constraint, as the pinch-point region is searched, are the times when lower satellite density regions are observed. The lower satellite density region is a part of the geosynchronous belt located over the Pacific Ocean. It is desirable to position this 60° gap in pinch-point coverage over this Pacific Ocean region.

These three constraints are combined with the visibility of the pinch-point region from MSX orbit, and the timing of the pinch-point data collection is adjusted by up to ten minutes to avoid conflicts. Figure 23 illustrates an example of a complete data-collection schedule.

The brief maneuvers required by pinch-point operations, combined with the faster speed of dual signal processor operations, permit a large number of framesets to be taken. The number of commands required to perform the pinch-point data collection ex-

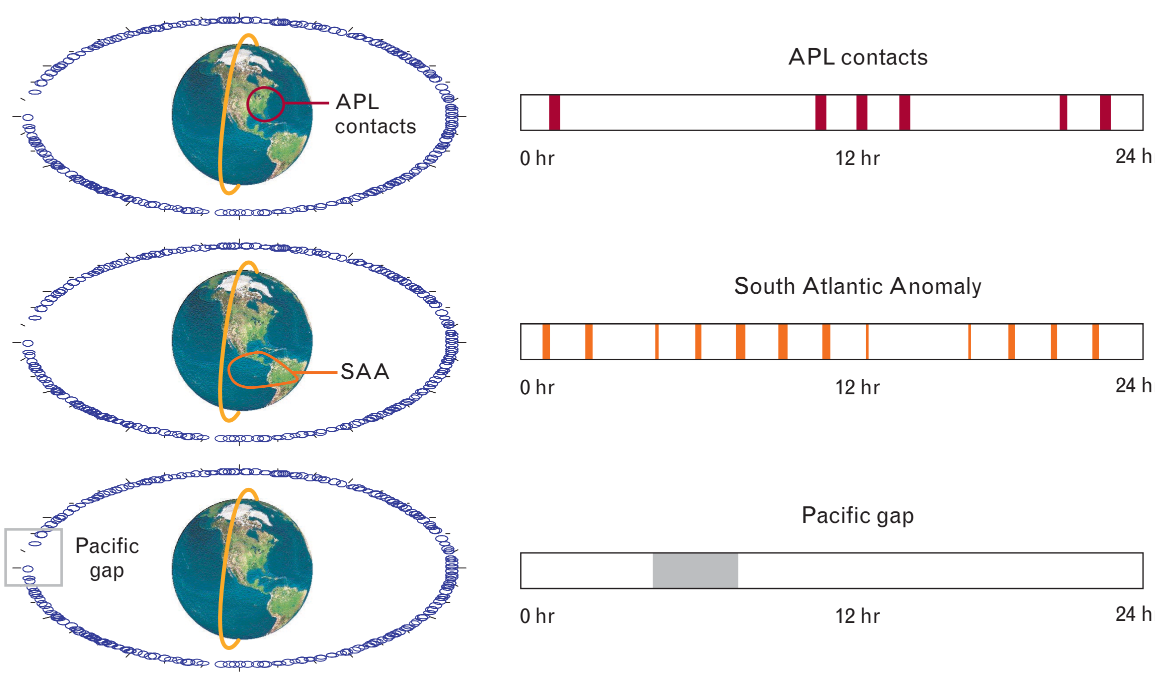

FIGURE 22. Times for the pinch-point data collection are chosen to avoid conflicts with the Applied Physics Laboratory (APL) contacts with the MSX spacecraft, since these contacts are the primary means to upload commands to the spacecraft and download collected data. For maximum productivity, data collection is also avoided when the spacecraft is in the South Atlantic Anomaly (SAA) and when the Pacific gap is passing through the pinch point.

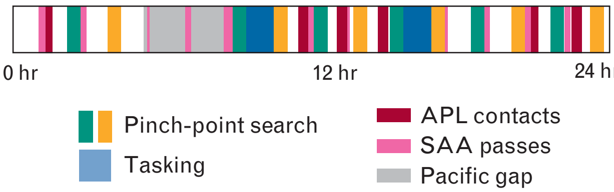

FIGURE 23. Schedule showing twelve pinch-point data collection periods, subject to operational constraints. The data collection can be scheduled to avoid APL contacts and minimize data collection in the SAA and the Pacific gap.

ceeded the command memory buffer aboard the MSX spacecraft. To reduce the number of these commands, a macro (consisting of commands to execute data collection from each set of four CCDs) was created and uploaded to the spacecraft. The macro permits four framesets to be taken with a single command instead of multiple commands.

The spacecraft data handling was modified to move the data to the experiment controller and retain it until the experiment controller memory was reset. This modification increased the robustness of data downloads. The data handling system was also modified to permit all the data in the experiment controller to be downloaded at any available ground contact. This modification permitted nearly all the data to be downloaded at least twice. These multiple downloads also required additional modifications in the ground processing system to appropriately handle the additional data downloads.

As illustrated earlier, the pinch-point coverage has resulted in increased productivity. Figure 24 illustrates the efficient capability of pinch-point operations by showing the distribution in both longitude and inclination of all geosynchronous objects detected during pinch-point operations in a single day. Data from the tasked data takes are not included in these results. Figure 24(a) illustrates the global coverage with a planned gap only over the Pacific Ocean. Figure 24(b) shows that geosynchronous objects with both low and high inclinations are being detected simultaneously at the pinch points.

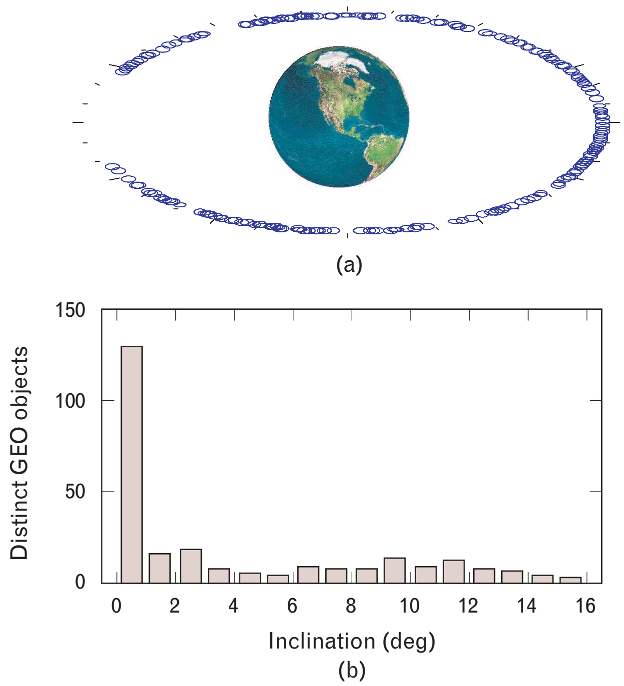

FIGURE 24. (a) The longitude distribution of detected GEO objects, and (b) the inclination distribution of these objects. This example of data collected during a 24-hour period illustrates the global coverage of pinch-point operations, and the success of these operations in detecting high-inclination GEO objects.

Metric Accuracy Improvement

In addition to increasing the productivity of the SBV sensor, we have also improved the quality of the metric observations. The metric accuracy of SBV sensor observations is evaluated by a rigorous calibration process. Observations of Global Positioning System (GPS) satellites are taken and compared to independently determined precise ephemerides for these satellites. GPS satellites are used because they provide rate and brightness characteristics that are similar to geosynchronous objects, which comprise the bulk of SBV sensor observations. Analysis of factors that degrade metric accuracy led to the identification of unwanted spacecraft motion and contaminating radiation events as primary contributors to degraded metric accuracy [23–25].

Two approaches were taken to reduce spacecraft motion. First, SBV data were used to fine-tune the time required to maneuver the spacecraft for a given maneuver angle. Unwanted spacecraft motion causes stars to streak on the focal plane. Analyzing the maneuver size and times that cause stars to streak made it possible to determine the minimum maneuver time

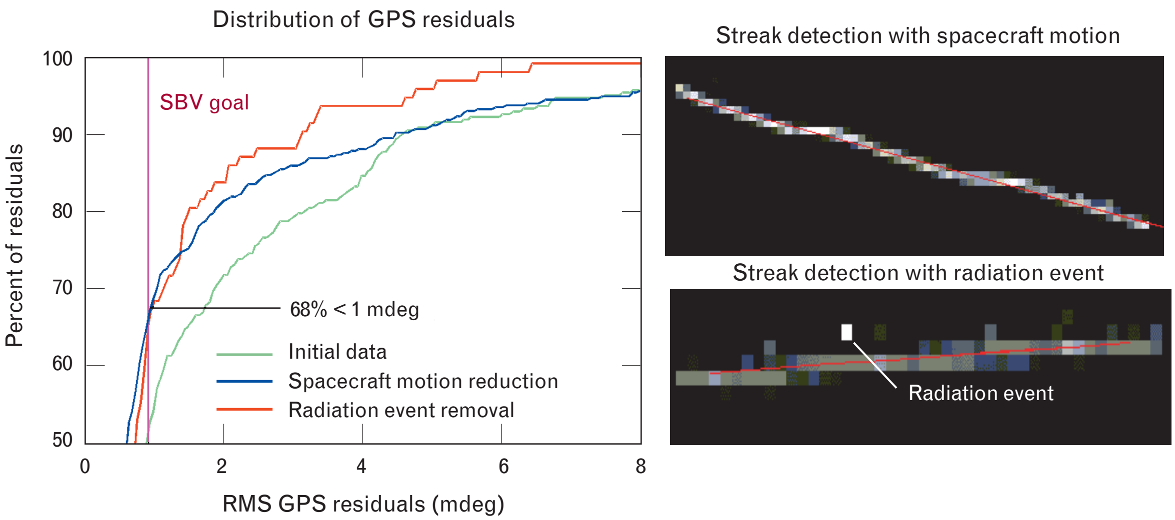

FIGURE 25. The metric accuracy of SBV sensor observations has been improved by reducing unwanted spacecraft motion through more accurate modeling of spacecraft maneuvering and settling times, as shown in the graph of the distribution of root mean square (RMS) Global Positioning System (GPS) residual data. Further improvements have been made by removing the effect of radiation events on the detected spacecraft streak.

for a given maneuver angle. Second, it was determined that the solar panels were free to track the sun during routine data collection. Locking them in place during routine data collection minimized motion of solar panel, and limited the resulting motion on the spacecraft. The results of these modifications are visible in the blue curve in Figure 25, which shows the distribution of GPS residuals after the efforts to reduce spacecraft motion were implemented. Comparing the blue curve to the green curve shows that a larger number of GPS residuals have smaller values.

Another factor that was determined to reduce the accuracy of SBV sensor observations was the effect of radiation events on the detected streak. A radiation event is the interaction of a high-energy proton with the focal plane. If a proton strikes a sensor pixel at the right time, the onboard signal processor has difficulty distinguishing the proton from the RSO detection. Metric observations are generated by fitting a line, weighted by intensity, through the RSO signature data. Since a typical radiation event has an intensity that is greater than that for a RSO, the higher intensity tends to skew the line fit. Filtering out pixels with intensity above a threshold mitigates the effect of radiation events. The red curve in Figure 25 shows the resulting improvement in metric accuracy when these radiation events are removed.

Summary

The SBV sensor has been successfully transitioned to an operational Contributing Sensor under Air Force Space Command sponsorship. Extensive operational improvements to ground systems and spacecraft systems have increased the efficiency of data collection. In three years these improvements have increased the SBV sensor's productivity from fifty deep-space tracks per day to nearly four hundred tracks per day. In addition, the SBV sensor has demonstrated its effectiveness in discovering and recovering uncorrelated targets (UCT) with its wide field of view and global coverage. The space-based sensor's immunity to surface weather outages has also led to 90% acquisition rate of high-priority objects. Accurate SBV-sensor metric observations can generate precise geosynchronous orbits for UCT discovery and recovery, catalog maintenance, and other high-accuracy applications.

The Future of Space-Based Space Surveillance

The final measure of success of a demonstration system is the acceptance of the system into operational use and the procurement of a follow-on operational system based on the results of the demonstration. The SBV sensor, via the ACTD process, has met that final measure of success. Starting in the 2002 fiscal year,

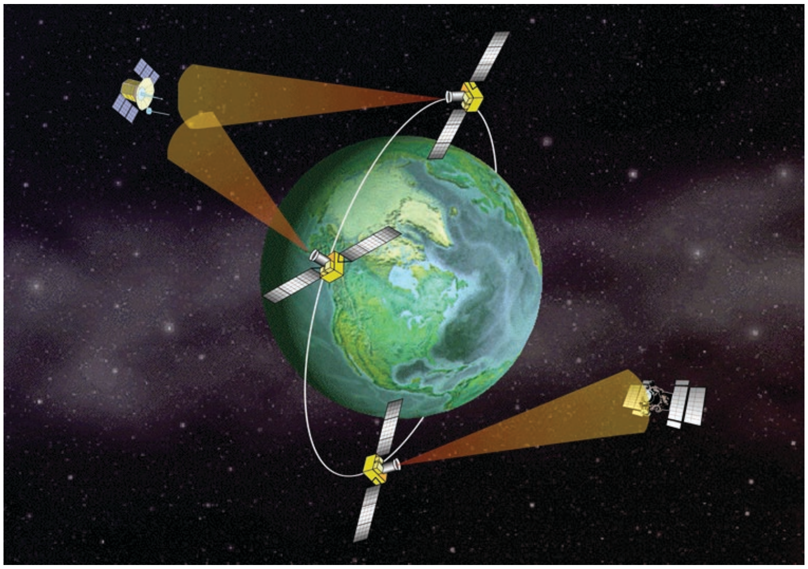

FIGURE 26. The next-generation space-based space-surveillance system, currently programmed into the U.S. Air Force planning process. This system is expected to include three to eight satellites, each hosting a wide-field visible-band sensor based on the SBV design.

the U.S. Air Force has allocated funding for long-term operations of the SBV sensor, and construction of an operational constellation of space-based space surveillance satellites. The system, now called the Space-Based Space Surveillance (SBSS) system, illustrated notionally in Figure 26, is expected to be composed of three to eight satellites, each carrying a wide-field visible sensor with heritage to the SBV sensor.

Developments in focal plane and processing technology since the 1989 SBV sensor technology freeze date have been impressive, and will allow for significantly increased sensor capability. For instance, when the SBV sensor was designed, the CCD focal planes had a limited number of pixels that had to be apportioned carefully between the objectives of maintaining good metric accuracy (each focal-plane pixel covering a small angle) and having a wide-area search capability (each pixel covering a wide area). Today's focal-plane technology, as evidenced by Lincoln Laboratory's Solid State division's five-million-pixel GEODSS upgrade CCD [26], allows enough pixels to address both search capability and metric accuracy with no compromise. In addition, the SBV signal processor was constructed with special-purpose digital signal processing chips, providing a processing capability of about ten million fixed-point operations per second. Today, many times that processing power is available in general-purpose space-qualified processors, which will be needed to process the information from the larger focal planes. When combined into the next-generation sensor, these technology improvements, along with gains in operational methods derived from the SBV sensor, offer an improvement in per-sensor productivity, beyond that demonstrated by the SBV sensor, by a factor of more than ten.

While the underlying technology has evolved considerably, the lessons learned during the SBV sensor's technology demonstration and subsequent operations endure as fundamental to the execution of space surveillance. The system engineers, designers, fabricators, and operators of the SBV sensor have achieved exactly what they set out to do—bring space surveillance to space.

Acknowledgments

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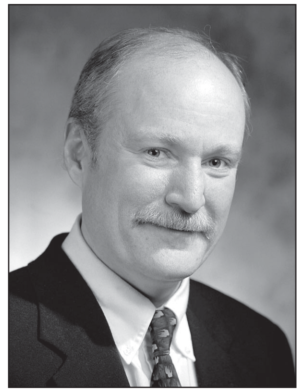

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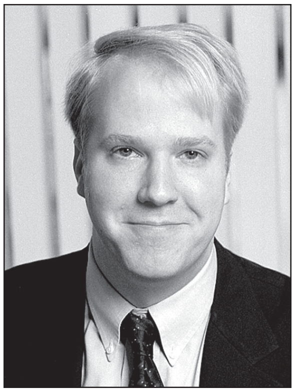

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