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Space-Based Space Surveillance with the Space-Based Visible

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Space surveillance is the activity of keeping a current catalog of information on manufactured, Earth-bound resident space objects. Some necessary functions to perform this task are search and detection, acquisition and tracking, tasking and scheduling, and data reduction and processing. The Midcourse Space Experiment satellite, launched 24 April 1996, carries the Space-Based Visible sensor package designed for conducting space surveillance from a space platform. Other contributions to this issue discuss Space-Based Visible operations, data reduction, and accuracy. The Space-Based Visible provides high-accuracy angle measurements (right ascension and declination). Based on these data, space-based space surveillance catalog maintenance can be demonstrated. To this end, orbits are calculated based on ground-based data, space-based data, and various combinations of these data. From these results a number of surveillance functions can be demonstrated, for example, compatibility and fusion of space-based and ground-based metric (position) data. When an independent, high-accuracy orbit is available, an assessment of the orbit accuracy is made. In other cases, differences between the orbits are computed. In addition, access to the complete geosynchronous belt and catalog maintenance for geosynchronous satellites will be demonstrated. Effectiveness of space-based space surveillance data is assessed.

Introduction

OPTICAL space surveillance from the ground started with the launch of Sputnik I in 1957.[1] The Massachusetts Institute of Technology (MIT) Lincoln Laboratory has been involved in the field from the very beginning, with radar tracking from Lincoln's Millstone Hill in Westford, Massachusetts.[2] It is a mature discipline. Since then, both optical- and radar-tracking techniques have developed and matured. An elaborate data analysis system, with conventions, procedures, communications, and practices, has evolved over the years. The system has expanded from low-altitude surveillance, tracking satellites that range in altitude from a few hundred to several thousand kilometers, to deep space surveillance, tracking objects far beyond the 36,000-km altitude geosynchronous belt. Currently, the resident space object (RSO) catalog contains more than 8000 objects, consisting of active and inactive satellites, rocket bodies, and debris, with an active subset of over 800 objects. Capabilities exist today to measure positions of low-Earth-orbit (LEO) objects with sizes as small as a few tens of centimeters, and geosynchronous-orbit objects with sizes on the order of a meter. The deep space radars at Millstone Hill and on the Kwajalein atoll in the Pacific Ocean are able to track geosynchronous satellites with an accuracy of a few meters. These results clearly indicate the considerable progress that has been made in past 40 years. We are on the verge, however, of the next major technological change in space surveillance, namely, space-based space surveillance.

In 1987, the Midcourse Space Experiment (MSX) was initiated. The MSX had a number of objectives supported by a suite of optical sensors[3] ranging from the ultraviolet (280 nm) to the long-wave infrared (LWIR) (26 μm). The breadth of the program is illustrated by the eight principal investigator teams representing different phenomenologies, objectives, and disciplines. Space surveillance is one of these disciplines. The intervening 10 years has been devoted to building, launching, and operating the MSX satellite. This paper is intended to discuss the space surveillance results available after approximately two years of operation. Although the space surveillance experiments make use of the full complement of MSX sensors, the primary sensor for space surveillance is the Space-Based Visible (SBV) built at MIT Lincoln Laboratory,[4] which will be the focus of this discussion.

The 10 years between a program's inception and its producing results is not unusual, before the days of faster, better, cheaper, and the goals and objectives of these experiments have been described a number of times in these years. After two years of operation, data collection and analysis are fully underway. However, it is important to note that these results are built on the outstanding work by the designers and integrators of the spacecraft at the Johns Hopkins Applied Physics Laboratory (APL)[5] and the SBV payload at Lincoln Laboratory. They, in turn, built on the unique vision that led to technology development of the focal plane arrays used,[6] the onboard signal processor,[7] and many other subsystems that make up the instrument now being used so successfully. These results truly usher in the next phase of space surveillance. There are unique challenges, great opportunities, and exciting results in store in this new era of space-based space surveillance.

Space Surveillance Issues

Space surveillance can be described in a number of ways. Such a description ought to include a broad definition; identification of the objectives, possibly including success criteria; a list of the elements of space surveillance and their relationship, perhaps a functional description of these elements; and of course a list of requirements. Beginning early in the MSX program, each investigator team developed documentation that addressed some of these issues. This documentation was consolidated and continues to be revised, updated, and expanded. The MSX system-derived requirements document (SRD) laid out the basic program requirements. The SRD included quantitative specifications for instrument performance and virtual experiments. The MSX science modeling requirements document (SMRD) reviewed the basic scientific objectives and addressed details of the necessary measurements. The SMRD is the most useful document for describing the vision of space surveillance represented by the MSX experiments. However, these documents address implementation issues regarding MSX surveillance experiments, but do not give a full description of space surveillance. Flowing from these documents were actual experiment plans that the satellite operators could use to develop command packages for satellite operations. Each command sequence was known as a data collection event (DCE). Unique among the MSX investigators, the surveillance investigators were located at the SBV processing, operations, and control center (SPOCC) at Lincoln Laboratory, one of the two centers generating the MSX command sequences and controlling the satellite during every surveillance DCE. Because the space surveillance objectives are described in Ref. 3, the SRD, the SMRD, and Ref. 8, the following is confined to a few remarks.

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We define space surveillance as the task of keeping a current catalog of information on manufactured, Earth-bound, RSOs, to support military and civilian needs.

The following descriptors for space surveillance are from U.S. Space Command as they have the national responsibility for the U.S. space surveillance effort. Therefore, we frame the space surveillance missions as 1) new launch processing, 2) catalog maintenance, 3) catalog augmentation, 4) mission and payload assessment, and 5) treaty monitoring.

To accomplish these missions, the space surveillance system must be able to perform, among others, the following functions: 1) search and detection, 2) acquisition, 3) tracking, 4) data processing, 5) tasking and scheduling, and 6) integration with the space surveillance network (SSN). At a minimum, we need to have the technology, communications infrastructure, data processing and analysis, and procedures to perform these functions. We will describe the present MSX/SBV capability.

Implementation

To implement a space surveillance system, we need to identify critical issues. The characteristics of space surveillance begin with short timelines. This means that there is limited usefulness of old data. One needs to know the space order of battle today, not last week. For reacquisition of uncorrelated targets (UCTs), rapid response is necessary because of the limited prediction accuracy based on discovery observations. In addition, rapid initiation of tracking is necessary to respond to launch and satellite maneuvers. The wide range of target size, target geometry, and relative velocity places requirements on the sensor, network, communications, and data processing system. Targets of interest range in size from centimeter debris to hectometer payloads. RSOs exist in LEO, to deep space (DS), geosynchronous (GEO), and beyond. The angular velocity of the targets relative to the SBV ranges from approximately 0 to more than 2400 arc-s/s. Finally, the SSN is made up of many different sensors with different operational characteristics and capabilities. With the exception of three ground-based electro-optical deep space surveillance system (GEODSS) camera sites and three PAVEPAWS radar sites, none of the surveillance sensors is the same. This leads to complex issues of tasking, scheduling, and merging data. A new sensor system, in this case space based, should both supplement and complement the existing capability to make use of strengths and ameliorate weaknesses. Only do things from space that are better done there.

The early objective for the MSX/SBV to demonstrate space-based space surveillance was, of course, to show what could be accomplished from a space-based asset. However, this was performed in the context of existing realities. There are some current issues with the existing SSN. Where appropriate, these issues were addressed in constructing the MSX/SBV experiments. For example, the gap time between tracks for the current SSN is significantly longer than present requirements state. The MSX/SBV could not address this due to the communications architecture. However, the present tracking-resource shortfall could be mitigated with the MSX/SBV. The shortfall is especially acute in DS, which is where the MSX/SBV is particularly powerful. The MSX/SBV has access to all space. Its complete coverage of the geosynchronous belt, coupled with the wide field of view, would allow it to provide data on all GEO satellites with multiple observations in each look. The current network also has a coverage hole in the Eastern Hemisphere, which can be filled with the MSX/SBV. The detection sensitivity of MSX/SBV allows for the tracking of some debris, for which there were two experiment plans, and small satellites. In addition, the use of specular phenomena, due to the long specular season enjoyed by SBV, allowed for the tracking of satellites currently not tracked, as well as the gathering of signature data on the physical properties of satellites. Finally, many of the current SSN sites are on foreign territory. This process of maintaining these sites can be operationally complex and, at times, politically sensitive. A space-based asset provides complete geographical coverage while operated and controlled from the continental United States. With these issues in mind, MSX/SBV has alleviated or greatly mitigated a number of problems facing the SSN today.

Technology Demonstrations

There has been a lot of planning for space-based space surveillance with a visible-band optical sensor. Flowing from these considerations, the SBV was based on technologies available in 1988 when the MSX/SBV project was initiated. It is fair to say that the system on orbit today has been a success and a tribute to the vision of those planners.

The SBV characteristics can be summarized as follows. The SBV is a staring sensor. The principal mode of operation is to point in space, sidereal tracking, such that background stars are point sources in the focal plane and the target RSO is streaking. Of course, the SBV can also be operated in ephemeris track, where the pointing follows the target and the stars streak. Both types of data have been taken.[9] The SBV uses a wideband, charge-couple device (CCD) array (3000–9000 A), with a quantum efficiency for each device of about 28%. This performance is in comparison with the S20 ebsicon-tube technology currently used in the GEODSS cameras, which has a quantum efficiency of about 7%. The telescope has a 15-cm aperture, and an off-axis reimaging design to maximize out of field-of-view rejection. This allows for tracking within 100 km of the earthlimb. The camera consists of four (420×420 pixels) three-side abuttable CCD arrays. This results in a 1.4×6.4 deg total field of view (FOV), although only one CCD array can be used at a time. Each pixel is 60 μrad on a side (12.1 arc-s). Success in subdividing the pixel signature data by a factor of 3 and the boresight star-match determination by a factor of 15 has been demonstrated. Nominal integration time is 0.4 or 1.6 s. There is also a 1.0-s integration time used when data are stored on the tape recorder onboard the MSX. A critical technology for space-based space surveillance is the onboard signal processor (SP). The SP processes multiple frames of data to extract the target streak and star positions, rejecting background clutter and single proton events. For example, a 16-frame frameset consists of 5.6×10^6 B. The SP will produce a report containing star and streak signatures of 3.2×10^3 B, a reduction in the required data downlink capacity by a factor of as much as 2000:1. In addition, there is a programmable computer, the experiment controller (EC), for running the SBV. The on-orbit detection sensitivity of the SBV is somewhat better than expected, allowing for the tracking of a geosynchronous target (range = 36,000 km) with $\rho A = 0.5$ m^2 (cross-sectional area A scaled by the satellite's reflectivity ρ). This is equivalent to a 2-cm sphere at 1000-km range. Finally, there are two modes of recording data. The first, shared with other sensors on MSX, is the 25-Mbps tape recorder. This is used for the prime science data for the MSX satellite. Data are stored on the tape and downlinked at a later time to the single ground station at APL, in which equipped to receive the data. This mode of data acquisition often results in a delay of several days in downlinking data to the ground, with further delays following as the data are processed and distributed through APL. By collecting data in the so-called signal processed mode, SBV is able to download images through the U.S. Air Force (USAF) 1-Mbps space ground link system (SGLS). In this mode, the SBV images that are generated on the focal plane are processed in SBV's onboard SP. These data are stored in the electronic RAM of the SP or the EC and downloaded during one of the nearly 50 opportunities each day to downlink to a SGLS station. Once downloaded, the data are electronically transmitted to Lincoln Laboratory/SPOCC for analysis. This architecture results in data availability within hours of the event and in timelines that are consistent with performing space surveillance functions.

An observation is the result of several steps. Full-frame images, which are processed by the SP, produce a streak signature and a collection of star detections. For each detected streak, a swath (5 pixels wide) of the pixels associated with the streak is saved and downlinked. For each detected star, a 7×7 pixel array is saved and downlinked. On the ground, star centroids are calculated in pixel coordinates. These stars are then matched to a star catalog, and the astrometric positions are used to obtain the sensor boresight pointing. Usually, approximately 30 stars are detected, of which 10–20 are matched to the catalog. For routine work, "The Astrographic Catalogue of Reference Stars (ACRS)"[10] is used. The ACRS has approximately 320,000 stars, and when more stars are needed, for example, when studying optical distortion the "Guide Star Catalogue"[11] is used. The star centroids are matched to the star catalog with an rms accuracy better than 1 arc-s (Ref. 12), subdividing the pixel by a factor of about 15. The statistical estimate of the boresight pointing is a fraction of that, due to the number of stars matched. However, given that the ACRS catalog has systematic errors at the 0.2-arc-s level, SBV-boresight determination is limited by the errors in the star catalog. The second part of the process is to take the streak endpoints and determine the pixel coordinates of the satellite. For this purpose, a swath of pixels (5 pixels wide) centered on the streak is saved and downlinked. The streak signature is processed on the ground. For example, SBV tracking of GPS satellites gives an estimate of the sensor metric accuracy. The accuracy of the GPS orbit, determined using laser-ranging and radar data, is decimeters, and the orbit error is negligible in computing the residuals. We see the rms residuals of approximately 4 arc-s, our metric accuracy goal, again subdividing the pixel by a factor of 3. Note that the GEODSS accuracy requirement was 10 arc-s. The last part of the process is knowledge of the MSX platform position or ephemeris. To obtain the ephemeris requires careful analysis of SGLS ranging data. This modeling was made more challenging by the cryogen venting from the LWIR dewar cooler, which provided a significant thrusting. The goal of a 15-m orbit has been achieved. These all provide the principal technology demonstrations with SBV. The SP and data reduction,[9] metric calibration,[13,14] and platform ephemeris[15] are described more thoroughly elsewhere in this issue.

Functional Demonstrations

The MSX/SBV is an experimental platform, with eight principal investigator teams. For the first year of operation, satellite resources were distributed among these teams, based on priorities established by the MSX program office through the mission planning team. The satellite operations were scheduled by DCE. The baseline mission had approximately four DCEs each day. The surveillance principal investigator team allocation for is given Table 1 for data collection from launch through January 1997. In an attempt to make best use of the allocated DCEs, the surveillance team established a methodology of combining a number of experiment objectives into each DCE. Nevertheless, this amounts to about two DCEs each week.

The data collected, therefore, allowed demonstration of what a space-based sensor can provide. It is possible to give examples of all of the functions mentioned and to show some aspects of catalog maintenance.

Tasking

The tasking test experiment emphasized DS satellites. A set of satellites were chosen as high priority, mostly geosynchronous and calibration satellites, and the remaining opportunities were selected from the USAF 1st Command and Control Squadron (1CACS) in Cheyenne Mountain near Colorado Springs, Colorado, which has responsibility for tasking the SSN. The optimizing scheduler[16] attempts to make an observing schedule that respects the spacecraft operating constraints, for example, spacecraft slew rates and avoidance of the sun, taking into account the RSO observability. This is a static scheduler that preplans every DCE from beginning to end.

The first example of a tasking event is given in Fig. 1, which shows the data obtained for the active geosynchronous payload, Eutelsat II (21803). During mission planning, the spacecraft is pointed such that the tasked object falls near the center of the focal plane, as is seen in the image. This frameset leads to another important point. In this wide-field camera, one often finds other satellites. Here we have the serendipitous observation of another active geosynchronous payload, the Italian Italsat.

A second example (Fig. 2) is an observation of the geosynchronous belt. In this case we see a group of satellites in one frameset, and the SBV detected all objects at once.

Catalog maintenance, of course, results in updating orbital element sets for catalog objects. Table 2 gives the results for a variety of satellites. The results are given for an orbit based on merging both the SSN and SBV data and again for an orbit based only on the SBV data. For the various cases, there was typically a factor of 10 more SSN observations than SBV observations. In both the SSN + SBV orbits and the SBV-only orbits, the rms residuals of the SBV data and the number of SBV observations that were accepted in the fitting process are tabulated. The SBV data are consistent with the SSN data and can be used with SSN data to obtain optimal orbits. Radar data from Millstone and Advanced Research Projects Agency Long Range Tracking and Instrumentation Radar

Table 1 Surveillance DCEs

Result	Number	Percentage
Successful	108	89
Failed or canceled	14	11
Total	122	100

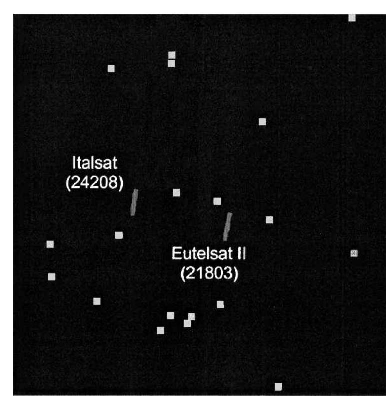

Fig. 1 Routine tasking with SBV.

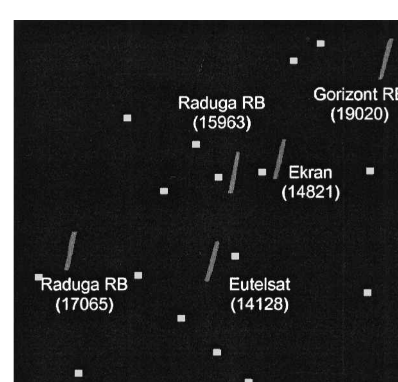

Fig. 2 Geosynchronous belt tracking.

Table 2 Catalog maintenance with SBV

Satellite	SSN + SBV rms, m deg	SSN + SBV No. of SBV observations	SBV only rms, m deg	SBV only No. of SBV observations	Difference in semimajor axis, m	No. SBV passes	Arc length, day
LAGEOS II	3.48	32	1.87	31	6	3	28
Glonass	0.9	22	1.3	23	56	4	37
Glonass	0.8	28	0.8	28	11	4	25
Molniya	1.4	41	0.9	41	24	6	28
Ekran	1.2	20	0.7	20	30	4	97

Table 3 Catalog IOD capability

Satellite	Nominal orbit			SBV IOD orbit			24-h prediction error, deg
	a, km	e	I, deg	a, km	e	I, deg	
LAGEOS II	12,159.2	0.01366	52.68	12,162.0	0.0142	52.66	0.84
Molniya	26,554.5	0.7124	65.03	26,554.4	0.7126	65.00	0.05
FEO rocket body	42,205.6	0.0022	0.579	42,121.8	0.0030	0.564	1.09

(ALTAIR) can be combined successfully with SBV data, and space-based data have been successfully fused with ground-based optical data as well. In some cases the GEODSS data does not fit, and we believe that the GEODSS data have significant biases; this is consistent with the calibration results obtained at Millstone Hill. Furthermore, the difference between the SSN + SBV orbits and the SBV-only orbits is at most about 55 m in semimajor axis. This shows the power of high-fidelity orbital mechanics models combined with high-accuracy (unbiased) data. At geosynchronous ranges, 1 s of arc (5 μrad) amounts to 180 m. Therefore, the agreement for these cases is much better than the intrinsic accuracy of the SBV data.

Catalog Augmentation

Catalog augmentation occurs when measurements that did not correlate with the RSO catalog, an uncorrelated target or UCT, are used to obtain an initial element set that leads to reobserving the object at a later time. With a series of observations, over several days, a reliable orbit is then established that can be used for reacquisition and catalog maintenance. The key step in this process is determining an orbit of sufficient accuracy to be used for reacquisition, also known as initial orbit determination (IOD). IOD based only on angular measurements is notoriously difficult. The methods used today are derived from two methods, one developed by Gauss and augmented by Gibbs, the Gauss–Gibbs method, and a second attributed to Laplace (see Ref. 17). These IOD methods are notoriously dependent on data geometry and noise. They are also suboptimal in that they use only three of the observed points, generally chosen to obtain the longest time interval between the first and last. Therefore, the IOD process is done in two steps: the IOD is performed, followed by an iterated differential correction (including 3-sigma data screening) using all available data. This leads to an optimal estimate of the orbit based on the available data.

To investigate what can be done with catalog augmentation, short arcs of SBV data, on the order of several hours, have been selected. Each one was processed to obtain 1) the initial orbit (using the Gauss–Gibbs method), 2) the differential correction, and 3) an estimate of the prediction error of this corrected orbit 24 h later. The revisit time was chosen as 24 h because this is reasonable for SBV as a sensor contributing to the SSN. Of course, the element set could potentially be handed off to another sensor for an earlier attempt at acquisition. Table 3 gives the satellite identification, the semimajor axis, eccentricity and inclination for the nominal orbit and for the IOD orbit, and the prediction error after 24 h. In these three cases, namely, that of a geosynchronous, a semisynchronous, and a LEO object, the SBV data could be used to reacquire UCTs within 24 h.

Clusters

Clusters present a unique challenge to the space surveillance system. Many of the members of clusters are active payloads and, therefore, of high interest. Being active, they are maneuverable, and orbit maintenance is correspondingly more difficult. There are at least 25 clusters of satellites in the geosynchronous belt. The primary difficulty is correctly associating an observation with an RSO. Mistaken association, or correlation, of satellite observations on satellites in clusters is a continuing problem in maintaining the DS catalog. The three sources of error in this process are 1) the observation error, 2) the element set error, and 3) the orbit model error. Of course, the system feeds on itself. If an observation is incorrectly associated, then the orbit resulting from combining it with the existing data will be degraded. Use of this degraded orbit will cause further incorrect associations, and so on. On the other hand, correctly associated high-accuracy metric observations, combined with good orbit models, will give improved orbital elements and increase the ability to associate observations correctly. Then, if an orbit maneuver takes place, as it often does in the geosynchronous belt, one can determine the maneuvered object with greater confidence and concentrate on tracking it.

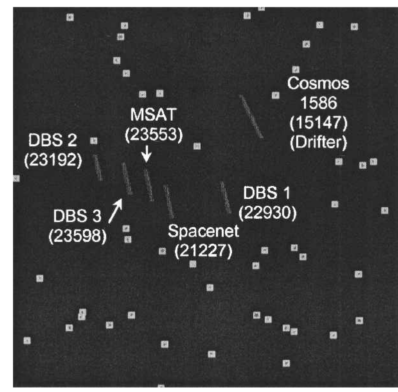

Fig. 3 Geosynchronous cluster tracking.

To illustrate the use of SBV for maintaining the orbits of clusters, measurements of a cluster are shown in Fig. 3. This cluster consists of five direct broadcast and mobile telecommunications satellites located at 259°E longitude. For legal reasons, each satellite must remain in a 0.1° box that makes it necessary to use surveillance sensors with high resolution and sufficient metric accuracy to separate the objects. It is clear from Fig. 3 that SBV is able to support cluster discrimination. By the using of tracking data from the SSN and the SBV, these orbits are well determined. Continued observation by SBV of this cluster, coupled with analysis tools for clusters, will likely allow for maintenance of all objects in this cluster. With these capabilities, it is anticipated that SBV can be used to associate correctly the observations and to maintain the orbits of the geosynchronous clusters.

Routine Space Surveillance

It has been shown that the MSX/SBV can make accurate metric observations and that these observations can be used to determine precise orbits, both by itself and when combined with SSN data. Also, SBV data can be used to obtain useful initial orbits to support catalog augmentation, as well as to maintain the orbits of cataloged objects. In addition, it is sufficiently powerful to be used for maintaining the orbits of each object in a cluster. With these technology demonstrations, the remaining issue is the ability to operate the sensor for extended periods to provide a continuous flow of data. Though beyond the scope of this discussion, DCEs of greater complexity and duration have been run successfully as part of an advanced concept technology demonstration (ACTD).[18] A number of important results have been obtained. It has been demonstrated that there is sufficient power, communications, and onboard data storage to support at least 8 h of continuous operations per day, and it is likely that the vehicle could support up to 16 h per day. The principal limitation is excessive heating of portions of the spacecraft from the sun. It has also been shown that the data collected during long duration events are of the same high quality as those obtained from shorter data collections.

Implications for Future Space Surveillance

Space-based space surveillance is here. It has been demonstrated that space surveillance from a space-based platform is possible. It is also clear that the current issues raised can be addressed with sensors such as SBV. As earlier mentioned, the SBV has recently been established as a contributing sensor within the SSN through an ACTD. As part of this effort, the SPOCC responds daily to satellite tasking from the 1CACS in the Cheyenne Mountain, supplying observations on approximately 200 distinct DS objects every day. Whereas discussion of this topic is beyond the scope of this text, the reader is referred to Ref. 18 for more details.

Conclusions

The SBV sensor has achieved its primary objective of successfully conducting both a technical and functional demonstration of space-based space surveillance. The sensor has demonstrated the operation of a wide range of technologies, including staring focal planes, high off-axis rejection optics, and on-orbit signal processing. In addition, it has been shown that it is not only possible, but highly effective, to operate a space-based space surveillance sensor for maintenance and augmentation of the resident space object catalog and for monitoring of the geosynchronous belt. It is now clear, from actual on-orbit data, that a space-based sensor with a wide FOV and high metric accuracy is able to make a significant contribution to the field of space suveillance.

References

[1]Whipple, F. L., "The Optical Tracking of Artificial Earth Satellites," *Proceedings of the American Philosophical Society*, Vol. 102, No. 3, 1958, pp. 215–220.

[2]Freeman, E., "MIT Lincoln Laboratory Technology in the National Interest," Lincoln Lab., Massachusetts Inst. of Technology, Lexington, MA, pp. 111–127.

[3]Mill, J. D., O'Neil, R. R., Price, S., Romick, G. J., Uy, O. M., Gaposchkin, E. M., Light, G., Moore, W. W., Jr., and Murdock, T. L., "The Midcourse Space Experiment: Introduction to the Spacecraft, Instruments and Scientific Objectives," *Journal of Spacecraft and Rockets*, Vol. 31, No. 5, 1994, pp. 900–907.

[4]Harrison, D. C., and Chow, J. C., "Space-Based Visible on the MSX Satellite," *Aerial Surveillance Sensing Including Obscured and Underground Object Detection*, *Proceedings of the International Society for Optical Engineering*, 2217, 1994, pp. 377–387.

[5]Peterson, M., "Midcourse Space Experiment: Technology," *Johns Hopkins APL Technical Digest*, Vol. 17, No. 2, 1996, pp. 200–217.

[6]Burke, B. E., Mountain, R. W., Daniels, P. J., and Harrison, D. C., "420 × 420 Charge-Couple Device Imager and Four-Chip Focal Plane," *Optical Engineering*, Vol. 26, No. 9, 1987, pp. 890–896.

[7]Chu, P., "Efficient Detection of Small Moving Objects," Lincoln Lab., TR 846, Massachusetts Inst. of Technology, Lexington, MA, July 1989.

[8]Gaposchkin, E. M., "Space-Based Space Surveillance with MSX," *Advances in the Astronautical Sciences: Spaceflight Mechanics*, Vol. 89, Pt. 2, 1995, pp. 1681–1690.

[9]Sharma, J., von Braun, C., and Gaposchkin, E. M., "Space-Based Visible Data Reduction," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 1, 2000, pp. 171–175.

[10]Corbin, T. E., and Urban, S. E., "Astrographic Catalogue Reference Stars," Documentation for Computer Readable Version, Doc. No. NSSDC/WDC-A-R&S 91-10, 1991.

[11]Lasker, B. M., Sturch, C. R., McLean, B. J., Russel, J. L., Jenkner, H., and Shara, M. M., "The Guide Star Catalog I. Astronomical Foundations and Image Processing," *Astronomical Journal*, Vol. 99, No. 6, 1990, pp. 2019–2058.

[12]Sharma, J., "Space-Based Visible Space Surveillance Performance," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 1, 2000, pp. 154–159.

[13]von Braun, C., Gaposchkin, E. M., and Sharma, J., "Space-Based Visible Metric Accuracy," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 1, 2000, pp. 176–182.

[14]von Braun, C., and Gaposckin, E. M., "Metric Accuracy Improvements of Space-Based Visible Using Spacecraft Attitude Drift Corrections," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 1, 2000, pp. 183–186.

[15]Abbot, R. I., Gaposchkin, E. M., and von Braun, C., "Midcourse Space Experiment Precision Ephemeris," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 1, 2000, pp. 187–191.

[16]Burnham, R., and Sridharan, R., "Geosynchronous Surveillance with a Space-Based Sensor," *Advances in the Astronautical Sciences: Spaceflight Mechanics*, Vol. 93, No. 2, 1996, pp. 295–303.

[17]Batten, R. H., *Introduction to the Mathematics and Methods of Astrodynamics*, AIAA Education Series, AIAA, New York, 1987, p. 796.

[18]Stokes, G., von Braun, C., Sridharan, R., Harrison, D., and Sharma, J., "The Space-Based Visible Program," *Massachusetts Institute of Technology Lincoln Laboratory Journal*, Vol. 11, No. 2, 1998, pp. 205–238.