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Mission Planning for Space-Based Surveillance with the Space-Based Visible Sensor

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The Midcourse Space Experiment (MSX) satellite was built and launched to make phenomenological measurements of backgrounds in space and targets under realistic scenarios. The Massachusetts Institute of Technology, Lincoln Laboratory built a broadband visible wavelength sensor called the Space-Based Visible (SBV) sensor that is on the satellite. The primary motivation for the SBV sensor has been to demonstrate surveillance of satellites from a space-based platform. Historically, space surveillance has been conducted from ground-based sensors. The satellite was primarily designed for experiments with a long lead time for planning. However, it was essential to retain the flexibility to plan the actual space surveillance data collection events at the daily level while still abiding by the six-week planning cycle. Additionally, the system had to be automated to reduce the operational cost. Significant challenges were the design of a language for experiment design, the monitoring of the resource cost of experiments, and the significant pointing constraints on the satellite. The mission planning system that was set up for space surveillance experiments and its operational success are described.

I. Introduction

THE Midcourse Space Experiment (MSX) satellite was conceived and funded by the Ballistic Missile Defense Office (BMDO) to make phenomenological measurements of backgrounds in space and targets under realistic scenarios.[1] The satellite was launched in April 1996. The major sensor on board was the cryogenically cooled space infrared imaging telescope (SPIRIT III), built by Utah State University. Three other sensors were also onboard: a set of instruments for contamination measurements built by Johns Hopkins University Applied Physics Laboratory (APL), an ultraviolet and visible wavelength sensor (UVISI) also built by APL, and a broadband visible wavelength sensor [Space-Based Visible (SBV) sensor] built by Massachusetts Institute of Technology (MIT) Lincoln Laboratory.[2,3]

The primary motivation for the SBV sensor has been to demonstrate the ability to conduct space surveillance, that is, collect data on man-made resident space objects (RSOs), from a space-based platform. Historically, space surveillance has been conducted from ground-based radars, optical instruments, and telemetry sensors.[4,5] The MSX/SBV sensor offered the first opportunity to demonstrate the capability for space-based space surveillance.[6] The advantages of such a sensor can be summarized as follows:

1) An optical sensor in space does not suffer from weather or day/night limitations.

2) A sensor in orbit has access to all of space, unlike a ground-based sensor, which can track only a part of the important geosynchronous satellite population.

3) A sensor in orbit can make measurements over a wider range of phase angles than a sensor on the ground.

4) If detection and tracking of newly launched satellites is important in a tactical time frame, for example, within 30 min, a space-based sensor constellation offers a better option than geographical proliferation of ground-based sensors.

For all of these reasons, the U.S. Air Force is hoping to transfer substantial surveillance capability to space-based sensors. The SBV sensor is a pathfinder for such systems.

II. Mission Planning for the MSX

MSX is a spacecraft for experiments and was designed without any real-time communication capability. Thus all planning for experiments (called mission planning hereafter) had to be conducted well ahead of the actual data collection on the spacecraft. An elaborate system of three-stage mission planning was set up to ensure that experiments were fully and correctly planned prior to execution. Allocation of spacecraft resources was controlled by BMDO. The spacecraft was actually operated by APL.

Mission planning was initiated following the announcement of the experiment objectives for each principal investigator for a MSX month (of four weeks) by the mission planning team of the MSX program office. The first two stages of mission planning, monthly and weekly, enabled the operations planning team to allocate and, if necessary, adjust the use of the finite resources onboard the spacecraft so that spacecraft and sensor health and safety were maintained. The third stage, called the daily planning, created and uploaded the commands for the actual conduct of the experiment. Data were collected on tape recorders onboard. The recorded data were dumped to the ground station at APL and were processed and distributed to the experimenters.

Mission planning for seven of the principal investigators was conducted at APL's operations planning center. The experiments for the principal investigator for space surveillance were, however, planned at and executed by the SBV Sensor Processing and Operations Control Center (SPOCC) at MIT Lincoln Laboratory. Such an approach was taken because of the detailed knowledge of the SBV sensor and the long heritage in space surveillance at Lincoln Laboratory. The planning process for space surveillance involved fairly detailed interaction between SPOCC and APL at all levels of planning and is described elsewhere.[7] The rest of this paper describes the present state of the mission planning process and the techniques developed within SPOCC to design, conduct, and optimize data collection for space surveillance (an earlier version was described in a previous papers[8,9]). Note that the SBV sensor is the only sensor on the MSX designed with onboard memory for storage of science data and, hence, can operate without the tape recorder.

III. Mission Planning for Space Surveillance

The mission planning data flow is shown in Fig. 1. Essentially, SPOCC generates all of the commands for the spacecraft and sensors to conduct the experiments in accordance with the requirements of the principal investigator. The commands are checked by APL to ensure spacecraft safety before being uploaded to the spacecraft.

Fundamentally, mission planning consists of the following activities: 1) choosing the time for the experiment, 2) simulating the functioning of the experiment, and 3) generating the detailed commands for the running of the experiment. All of these steps have to be carried out with full cognizance of all constraints, both pointing

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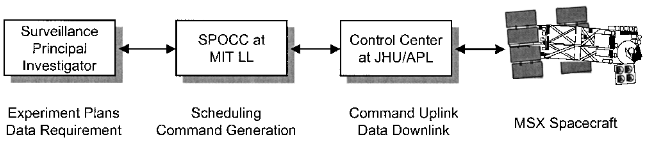

Fig. 1 Data flow for mission planning of space surveillance experiments.

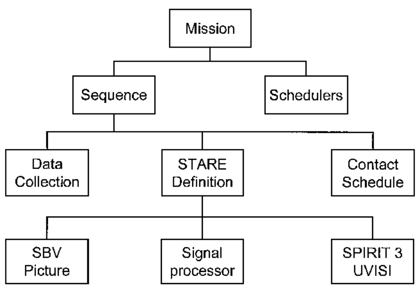

Fig. 2 Structure of SLED language.

and resources, of the spacecraft and the sensors. Furthermore, because there is no real-time communication with the spacecraft, the ground–spacecraft contact schedule also has to be considered in the mission planning. Also, because resident Earth-bound space objects were the primary targets, account has to be taken of their location in their orbits and the solar illumination conditions.

The major techniques and capabilities developed to support mission planning are 1) the surveillance language for experiment design (SLED), 2) the experiment simulator, 3) the schedulers and automated mission planning, 4) graphical data displays and automated opportunity analysis, and 5) command compliance and performance monitoring. Each of these is discussed in the subsequent sections.

IV. SLED

It became evident at the inception of the project that a human language interface was necessary for the experimenter to communicate with the mission planning system. The major purposes of such an interface were to 1) isolate the experimenter from the detailed but repetitive commands that control a sensor or the spacecraft, 2) avoid the necessity for the experimenter to understand the detailed timelines for executing spacecraft or sensor commands, and 3) preclude the experimenter from commanding the sensors or the spacecraft in an inadmissible or unsafe manner.

SLED was developed for this purpose. SLED performs the same function in mission planning as a high-level computer language on a computer; it isolates the user from the details of the machine. SLED has approximately 100 primitives and 10 macros. The logical, hierarchical structure of SLED is shown in Fig. 2.

At the top level, a mission in SLED defines the experiment. The commands at this level consist of a number of simulation directives (SIMDIRs) that define the invariant parameters of the experiment including modes of the sensors, the spacecraft, or the simulation. Examples are the absolute start time and the duration of the experiment, the type of orbital propagator to be used, the source of the ephemeris of the spacecraft, the types of output to be produced, etc. Every mission (or experiment) consists of a set of sequences or units of data collection. Each sequence consists of a data collection mode, a set of STARES that consist of commands to point the sensor (and spacecraft) and collect data. Each STARE may consist of a set of pictures. Each picture defines a charge-coupled device (CCD) number, an exposure time, and the number of such exposures to be taken on the CCD focal planes of the SBV sensor. The camera data may be sent to a tape recorder or, optionally, the signal processor may be invoked to process the camera data and store the results onboard. Ability exists within SLED to command a pause in an experiment to accommodate uplinks or downlinks as dictated by a spacecraft contact schedule.

SLED is interpreted through a parser. The parser verifies that the SLED file is valid, contains a nonnull experiment and does not violate the syntax of SLED. The parser also builds certain tables for the experiment that are used in the rest of the mission planning system.

The SLED syntax was originally defined to command and control the primary space surveillance instrument, the SBV sensor, and its interactions with the spacecraft. However, as the surveillance principal investigator's experiments evolved to include the other sensors [SPIRIT III and UVISI] onboard the spacecraft, SLED was modified to command these sensors as well. The architectural decision taken at this stage was that the SBV sensor would be the prime instrument and the other sensors would never be used in isolation. Thus, the detailed experiment timing was controlled by the operation of the SBV sensor with the other sensors affecting the timing only at the STARE level. Note that when more than one sensor was used the data are recorded on tape and the SBV sensor signal processor cannot be invoked.

SLED was initially visualized as a language to test various modes and capabilities of the SBV sensor/MSX system for space surveillance. However, it has proved a surprisingly durable and useful language.

V. Experiment Simulator

The major components of the mission planning system in SPOCC are shown in Fig. 3. The experiment simulator is the heart of the system. The major function of the simulator is to simulate the operation of the experiment in detail and to create a timed sequence of events called the instantiated mission timeline (IMT). The simulation is conducted with full regard to all of the constraints that may exist on the pointing of the spacecraft, the operational modes of the sensors, and the resources onboard. Examples of pointing constraints are the avoidance of the bright Earth, a minimum angle from the sun or the bright moon, etc. Examples of the sensor constraints are the requirement for the UVISI to avoid bright stars, the necessity to open and shut the telescope aperture door for the SBV sensor, the requirement to keep the $-Y$ axis of the spacecraft pointing to the Earth as much as possible to minimize cryogen flow from the SPIRIT III sensor, etc. Examples of resource constraints are the limit on the depth of discharge of the battery, limits on the tape recorder head temperature, monitoring of the SBV sensor RAM memory usage, etc. Note that no sensor on the MSX is gimbaled; they are all fixed to the bus and point in the same direction.

The simulator creates the following major outputs.

1) An IMT describes the sequence of events to conduct the experiment. The IMT can flow automatically to the next stage in the mission-planning pipeline or can be examined by an analyst first.

2) A variety of data for graphical display, are output such as the orientation of the spacecraft axes with respect to the sun, the moon, and the Earth, spacecraft resource usage, a variety of cost functions, etc., and are also used for automated opportunity analysis.

3) The attitude of the spacecraft during the experiment is output.

4) The list of RSOs that should have been in the field of view (FOV) of the sensor during the experiment is output.

The simulator uses, apart from the databases, a maneuver model for computing the elapsed time for spacecraft reorientation, knowledge of the constraints on the spacecraft and sensors to ensure their safe operation, and calculated or prestored values for the delays associated with spacecraft and sensor commands. It also estimates memory usage onboard the SBV sensor for data output. The simulator

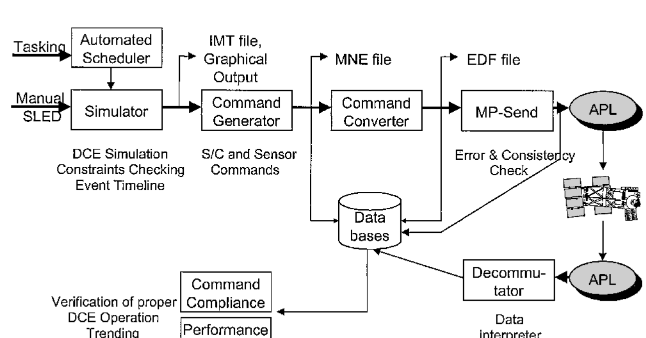

Fig. 3 Mission planning system.

optimizes the overall timeline by taking advantage of events that can be overlapped in time. All of the events pertaining to an experiment are encoded in the IMT, which is then processed by the next two stages to generate the mnemonic commands (MNE) and the event definition file (EDF). The MNE is an intermediate file that expands all of the commands pertaining to the SBV sensor. The MNE file can be run on the SBV brassboard system on the ground for verification. The EDF contains the expanded versions of all of the commands for the spacecraft and the other sensors also. The EDF is sent to the spacecraft controllers at APL via a program called MP-Send that performs a battery of tests on the EDF to ensure consistency and correctness of the EDF. The EDF is rechecked, macros are expanded, and the commands uploaded to the spacecraft for execution from APL.

VI. Schedulers

In a typical space surveillance experiment, data are collected on a large number of RSOs. The process of sequencing these operations in an organized manner is called scheduling. Three schedulers have been built to work with the SBV sensor: a space surveillance interface processor (SSIP), a geosynchronous scheduler, and a conjunction-optimized look-ahead (COLA) scheduler. Each of these will be briefly described. The schedulers are not dynamic as the MSX operates only in a stored command mode. Thus, a full experiment is planned out without any ability to respond to lack of detection of an RSO or malfunction of the sensor.

A. SSIP Scheduler

The SSIP was an adaptation of existing schedulers that were designed for ground-based narrow FOV optical and radar sensors. SSIP chooses, at any given time, the best RSO to track from a tasking list. The optimization is based on parameters such as the importance of the RSO, its detectability, its phase angle, the location of the RSO relative to current pointing of the spacecraft, its angular speed in the focal plane, the pointing constraints on the spacecraft, etc.

B. Geosynchronous Search Scheduler

Figure 4 shows that unlike a ground-based sensor, the MSX, being in low-altitude orbit about the Earth, has access to the entire geostationary belt. A ground-based sensor, on the other hand, can cover only a third of the belt. Advantage is taken of this feature of the SBV in the geosynchronous scheduler (GEO).[10] A search is created of the belt with the FOV aligned as shown in Fig. 4 with the long side oriented perpendicular to the equator. This enables a substantial range of orbital inclination to be covered. At any time, the scheduler tries to achieve the lowest solar phase angle possible to improve detectability of the RSOs.

C. COLA Scheduler

Perhaps the most interesting development is the COLA scheduler that was designed and tested recently. The major driver for COLA is the large FOV of the SBV (1.4×1.4 deg per CCD, 5.6×1.4 deg over four CCDs). A small study showed that at any time there are regions of space accessible to the SBV wherein there is more than one satellite in the FOV (hence, in apparent conjunction). Whereas this is evident for geosynchronous clusters, the study showed that other accidental clusters abound, too. The study results are in Table 1.

A set of 620 satellites in high-altitude orbits was chosen from the catalog. The study tested for apparent conjunctions (defined as being within 2.8 deg or a FOV spanning two CCDs) beginning at an arbitrary time. As can be seen, at all times there are geosynchronous clusters. However, there is also apparent clustering of nongeosynchronous with geosynchronous RSOs and, even more surprisingly, of nongeosynchronous satellites at all times examined. These results indicated strongly that taking advantage of such conjunctions would significantly enhance the productivity of the SBV as a sensor. This is exactly what COLA is intended to do.

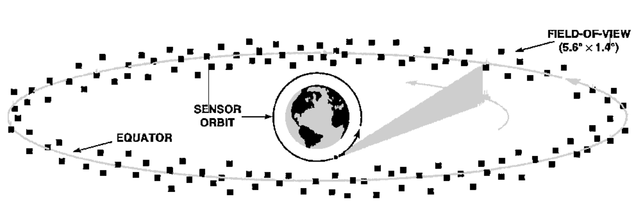

Fig. 4 SBV's access to entire geosynchronous belt; satellites in equatorial geosynchronous orbit (■). SBV's FOV is shown sweeping the belt.

Table 1 COLA study results

Time from initiation of simulation, min	Number of geosynchronous–geosynchronous clusters visible	Number of geosynchronous–nongeosynchronous clusters visible	Number of nongeosynchronous–nongeosynchronous clusters visible
0	56	10	11
2	56	11	12
4	56	8	9
6	56	7	10
8	55	9	10
10	66	11	10
12	79	8	10

Table 2 Comparison of scheduler performance

Parameter	SSIP	GEO	COLA
Framesets/h	19.8	25.3	36.1
Valid streaks/h	17.0	12.1	32.6
Number of maneuvers/h	21.0	7.7	12.1

D. Comparison of the Schedulers

The performance of the schedulers may be compared in the following ways.

1) The number of framesets per hour that are scheduled may be compared. The SBV typically operates in the onboard signal processor mode. A designated number (or a frameset) of camera exposure (or frame) data is read into the signal processor from the camera focal plane and is processed to retrieve stars and streaks representing satellites. These processed data are stored onboard and read down at an appropriate downlink contact. This is the normal mode of operation of the SBV for space surveillance experiments. Obviously, the larger the number of framesets/hour scheduled, the more productive the sensor is.

2) The number of valid streaks that result from the framesets may be compared. The purpose of each frameset is to collect data on RSOs that are detected as streaks against the background of fixed stars. Another figure of merit of a scheduler is its productivity in terms of number of valid streaks per hour.

3) The number of spacecraft maneuvers per hour may be compared. The MSX is in orbit, and its lifetime is affected by several parameters: the battery cycles, the solar panel degradation, and the mechanical wear and tear due to the constant running of the reaction wheels. Each time the satellite is asked to reorient, the wheels go through a cycle of acceleration and deceleration. Minimizing the number of cycles should conserve the life of the MSX.

Table 2 compares the performance of the schedulers on the basis of the listed parameters. It is clear that COLA is better than other schedulers in terms of productivity and is also better than the other tasking scheduler SSIP in terms of the number of the number of cycles on the wheels of the MSX.

Figure 5 compares SSIP and COLA graphically to demonstrate the effects of the introduction of new schedulers as well as operational modes. The operations of the SBV started with an average of 1 h of experiment time per day and built up to the current level of 8 h of data collection per day seven days per week. Along the way, a 12-h data collection experiment was run to validate that prolonged operations were possible with the SBV and the spacecraft. As can be seen, the number of planned framesets/day shows significant jumps with the change to full-time operations and another large jump with the introduction of COLA as the scheduler. The amount of data on RSOs that is collected by the SBV is directly related to the number of framesets that are taken, and thus the productivity of the sensor has undergone substantial improvements.

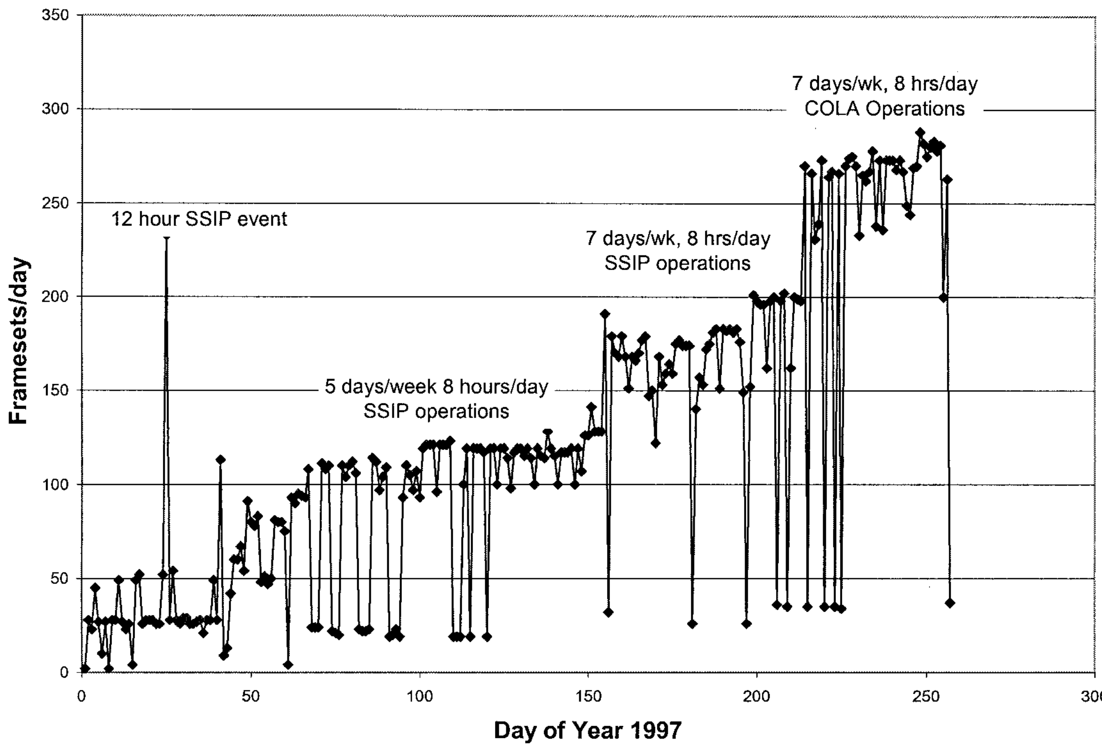

Fig. 5 Effect of new schedulers on performance of the SBV.

VII. Automated Mission Planning Pipeline

The SBV operations are carried out every day of the year for 8 h/day. Keeping the costs down by using as few operations personnel as possible is essential. Hence, substantial automation has been achieved in the operations of mission planning. The 8-h experiment is embedded in a 10-h opportunity window that is tied to the passes of the satellite over the MSX control station at APL. The window starts at the termination of the first afternoon contact of the spacecraft with APL. The 8-h experiment is divided into a short and a long event. The short event is uploaded at the first contact with APL and runs for 1.5 h. At the next contact, approximately 100 min later, the processed data from the first event are downloaded, and the commands for the second event are uploaded. The second event lasts 6.5 h. The processed data are then downloaded at the first available ground contact after the end of the 10-h opportunity window.

The mission-planning pipeline is shown in Fig. 3. Automation is achieved by going through the entire sequence without human intervention and trapping for errors prior to sending the EDF. The pipeline is triggered at a certain clock time every day. It reads in the latest tasking available, consults the daily contacts schedule to determine the appropriate starting times for the two events to be run, and runs through the entire simulation and command generation. All of these actions are carried out before operations personnel appear for the day. The operator then checks the PROGRAPH displays to verify that the events do in fact observe spacecraft and sensor safety constraints before sending the EDF on to APL. The MP-Send checks for errors in and consistency of commands before sending the EDF to APL for upload to the spacecraft. Although the process is not illustrated here, the receipt and processing of the downlinked data is also automated.

VIII. Graphical Displays and Automated Opportunity Analysis

The simulator produces a large array of graphical output. These record the evolving state during the experiment of several constraints such as spacecraft X-, Y-, and Z-axis pointing with respect to the sun, moon, and Earth tangent; resource utilization such as battery depth of discharge; cryogen usage and RAM memory usage; and ancillary information. The operations personnel ensure that gross constraint violations are not permitted by scanning these graphical outputs. Equally important, an automated opportunity analysis system uses the data for the graphs as input in deciding the time sequence of opportunities available to conduct specific experiments.[9] A number of instantiations of the same experiment can be run to choose, in an automated fashion, the experiment opportunity that minimizes cost or resource usage.

IX. Command Compliance and Performance Monitoring

SPOCC is not a round-the-clock operation. Consequently, when operators arrive on site they need the ability to quickly ascertain the success of the previous days experiments. Hence, a suite of software tools has been developed to aid in assessment of the data collection events. These tools condense large amounts of mission planning and experiment data into easily comprehensible form by extracting key information out of a large volume of data. Three of the tools that assist and assess the mission planning will be described here. All of these tools use standard Internet explorer tool NETSCAPE as a backbone, making the software easily accessible and portable.

A. Command Compliance

The first tool developed for understanding the performance of the SBV is a software package called Command Compliance that compares the experiment results with the experiment as planned. A series of tests are performed on the results of every frameset to answer questions such as the following: Was the tasked RSO in the FOV? Did the detected streak correlate with the object? A set of summary statistics is also generated including the number of objects tasked and acquired and the amount of memory used. These reports enable the operators to quickly comprehend the results of the experiments. The reports are written in HTML. A key use of the Command Compliance software is for troubleshooting because it provides an independent analysis of the mission planning and the data reduction processes.

B. Performance Monitoring

A Command Compliance report represents assessment of the performance of a single experiment. However, to assess the performance of the SBV, a series of experiments needs to be evaluated.

With this requirement in mind, another set of tools has been developed using Command Compliance as the underlying engine. The first tool is a query engine, wherein the user is able to specify a set of queries with user-defined limits for any set of attributes from the Command Compliance reports. Along with the query engine, a plotting package has been developed that can generate graphs involving many of the attributes tracked by Command Compliance enabling an analyst to identify key changes in spacecraft operations. Fox example, Fig. 5 was generated using this software.

X. Conclusions

This paper has described the successful development and operation of an automated mission planning system for space-based space surveillance. Several key techniques were developed and used in the system. In particular, three different schedulers were developed and their relative merits were demonstrated. The most innovative scheduler uses the fortuitous but frequent conjunction of RSOs in the FOV of the sensor to enhance productivity by a significant factor over conventional scheduling as used by ground-based sensors. The ground operations to control the sensor have been highly automated. The success of the SBV sensor in demonstrating space-based space surveillance has led to its transition to be a contributing sensor to the U.S. Space Surveillance Network. It is expected that any future space-based space surveillance sensors will find it advantageous to draw upon this heritage.

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