

# United States Air Force Scientific Advisory Board



Report on

## Space Surveillance, Asteroids and Comets, and Space Debris

Volume I: Space Surveillance

SAB-TR-96-04

June 1997

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14. ABSTRACT This Study was produced by the Air Force Scientific Advisory Board. It was requested by the Commander Air Force Space Command and approved by the Secretary and Chief of Staff of the Air Force. It covers three topics, each of sufficient depth to be study of its own: Space Surveillance, Asteroid and Comet Impact Warning for Earth, and Space Debris. Space Surveillance is the unifying theme. Space Surveillance is a secondary mission to that of Missile Warning and has long been neglected. Almost all sensors were deployed for missile warning and used for Space Surveillance on a non-interference basis. Attempts to improve data processing, though expensive, were upgraded to the mainframe environment, keeping most old algorithms in place. Fortunately, improving the accuracy and timeliness of the sensors and data processing is now relatively inexpensive because most techniques are commercially available. Ultimately, Space Surveillance should be conducted from spaceborne sensors. They are discussed and recommended here.	

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## Executive Summary

This study of *Space Surveillance* is the first part of a threefold study on *Space Surveillance, Asteroids and Comets, and Space Debris* that was requested by Commander, Air Force Space Command, and approved by the Secretary of the Air Force and Chief of Staff of the Air Force.

In future hostilities, it is essential that the Air Force control not only the access to space by adversaries, but also their access to information management resources in space. A fundamental requirement to achieve this posture is timely and accurate information regarding the orbital characteristics, physical configuration, and mission of every object in space. Space Surveillance can support this Space Control requirement with available technology.

For measuring low earth orbit (LEO) satellite parameters, the Space Surveillance Network (SSN) is dependent on radars built for the Ballistic Missile Early Warning System (BMEWS) of the 1950s, some solid state radars of more recent vintage, and C-band trackers. Fortunately, utility of these radar instruments can be optimized by a serious on-line calibration effort. The overall calibration effort would be partitioned — sensors will continue to provide local calibration information and correct their observations for factors that are local in nature, while the overall accountability for definition of the system calibration model used to drive the orbit estimation processes will remain with the Space Control Center.

Accurate measurements from a calibrated worldwide radar sensor network of the SSN have been demonstrated to produce orbital element accuracies capable of 12-hour predictions of 100 meters provided the satellite does not maneuver and the atmospheric fluctuations are properly characterized by improved modeling or an on-line drag-measurement process. In a more controlled environment, trajectory accuracies of 10 meters have been demonstrated with National systems using filter techniques, with data-rich cooperative tracking.

A network of optical sensors is required for measuring geosynchronous earth orbit (GEO) satellite parameters because current and deep-space radar resources are incapable of search at deep-space distances. The improved Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) is in a major upgrade in which obsolete cameras and computers were to be replaced by state-of-the-art, high-sensitivity, large format, visible spectrum charged coupled device (CCD) cameras with appropriate computers to handle the data. With these improvements, GEODSS will be able to do an adequate job at both GEO and medium earth orbit (MEO).

For LEO, Space Control, and reentry processing, tracking by all of the existing radar installations is needed. However, even with them, there is negligible southern hemisphere coverage and a large longitudinal gap in coverage. As a consequence, great care must be exercised in closing installations, particularly overseas where coverage is sparse. If, for example, Pirinlik were to be closed\* it should be replaced perhaps with HAVE STARE at Diego Garcia.

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\* Radar operations at Pirinlik were terminated in March 1997, after this study was completed and briefed at Hq USAF and Air Force Space Command.

All of these coverage issues would be solved by a space-based surveillance system of appropriate design. The first opportunity to gain some experience will occur when the already launched Space Based Visible (SBV) camera on the midcourse space experiment (MSX) spacecraft, designed for ICBM midcourse experiments, can be made available and considered for Air Force Space Surveillance. In addition, in a few years, the Space Missile Tracking System (SMTS) of the Space Based Infrared System (SBIRS), designed for midcourse ICBM tracking after hand-off from a boost phase detection and tracking system, could be tested for its support to Space Surveillance. Unlike the SBV camera, the SBIRS was designed for tracking rather than surveillance and has a limited field of view and restricted search capability.

Spacetrack has cataloged some 24,000 objects since the dawn of the space age in 1957. Of these, some 15,000 have decayed, leaving some 9,000 objects in the catalog. Of these about 5 percent are active spacecraft, with the remainder being debris, i.e., spent operational spacecraft, boosters, intermediate boost phase stages, and fragments. For Space Control, it is important to know in what missions the operational spacecraft are engaged. Mission and payload assessment must remain an essential part of the Spacetrack function and is best carried out by the collection and reduction of all sources of signature and imaging data.

In summary, the SSN radars and atmospheric models should be calibrated, up-to-date processing algorithms should be employed, gravitational models should be upgraded, the GEODSS upgrade program should be completed (including CCD cameras), an accurate assessment should be completed when considering closure of sites, and a transition to spaceborne space surveillance should be considered. The Committee's recommendations follow.

## Summary of Recommendations

***Low Earth Orbit.*** For surveillance of objects in low earth orbit, the Committee recommends that the Air Force

- Introduce on-line sensor calibration capabilities using earth satellites with known, high-precision ephemeris products to exploit fully the capabilities of a shrinking sensor base
- Implement an experimental test site in partnership with a Center of Excellence at Falcon AFB for space surveillance technology to evaluate emerging hardware and software technologies in the military and commercial worlds
  - To demonstrate state-of-the-art techniques for data and ephemeris management, in anticipation of needs imposed by emerging Space Control requirements
  - To demonstrate improved methods for atmospheric density representation
  - To demonstrate methods of achieving greater autonomy in operations
  - To provide support capabilities for manned and high-value payloads not routinely programmed in the Space Defense Operations Center (SPADOC) system
  - To demonstrate utility of spaceborne sensors by processing SBV data
- Expand nucleus of Falcon AFB expertise (50 percent scientists, 50 percent operations personnel) to include filter technologies, space debris surveillance and processing technology, and mission assessment and planning
- Consider employing the FPS-85 radar connected by data lines to Falcon AFB as the primary radar sensor, using others as necessary

- Support dual use of the Ballistic Missile Defense Organization X-band radar for Space Control and debris monitoring.

***Geosynchronous Orbit.*** For surveillance of objects in geosynchronous orbit, the Committee recommends that the Air Force should complete its upgrade of GEODSS while ensuring that the gaps in eastern Atlantic and western Pacific longitudes are filled.

***Data Processing.*** In the area of data processing, for the Space Surveillance catalog to be more useful and militarily significant in the near term, the Committee recommends that the Air Force

- Employ low-cost commercial technology currently available in the marketplace (“special perturbations” algorithms and workstations)
- Establish routine use of “trusted covariance matrix” to ensure interoperability.

***Spaceborne Sensor Systems.*** For spaceborne sensor systems to replace ground-based systems, the Committee recommends that the Air Force pursue surveillance of space from space with search capability. Specifically, the Air Force should

- Integrate the Space Based Visible camera on Midcourse Sensor Experiment into SSN
- Establish search and track requirements for the Space and Missile Tracking System of Space Based Infrared Systems and pursue appropriate redesign.



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## Acknowledgments

The United States Air Force Scientific Advisory Board and the Ad Hoc Committee on Space Surveillance, Debris, and Asteroids and Comets acknowledge the participation of and express thanks and appreciation to Air Force and NASA organizations for their outstanding support throughout this study. Their genuine interest, encouragement, and cooperation made this study possible. We are especially thankful for the participation in the study by representatives of U.S. Air Force Space Command, the Space and Missile Systems Center, and Phillips Laboratory, and the National Reconnaissance Office.

Special thanks are also due to the staff of the Air Force Space Command, who facilitated all phases of this study. Thanks also to the staffs of the Air Force Scientific Advisory Board and to ANSER (Analytic Services, Inc.), who assisted in the final outbriefings and preparation of the report. Their dedication and untiring support of our study did not go unnoticed.

For the Committee,  
F. Robert Naka, Chairman  
1 November 1996

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# Introduction

This study of *Space Surveillance, Asteroids and Comets, and Space Debris* is a study that is separable into three parts, each of which is sufficiently complex to be a study of its own. It was requested by Commander, Air Force Space Command, and approved by the Secretary and Chief of Staff of the Air Force. Because increased knowledge of asteroids and comets as well as debris depends on an enhanced space surveillance system, the unifying subject is that of space surveillance. This document reports the Committee's findings on Space Surveillance.

Space Control is an important element of future Air Force activity. Space Surveillance that can provide accurate and timely information on every object in space is a fundamental need of Space Control.

This study describes today's Satellite Surveillance Network, which mainly consists of sensors deployed for missile attack warning and makes use of technology now several decades old. The present radars, with some modest upgrades and proper calibration, could perform superior earth satellite surveillance, if the processing capability were updated to realize the inherent detection and orbit determination accuracies of the sensors. Deep-space surveillance is dependent on optical sensors deployed in locations around the world that could provide a timely search capability for new or maneuvering objects.

This study provides recommendations that can vastly improve Air Force surveillance capabilities at modest cost.

Ultimately, Space Surveillance should be conducted from space to obtain worldwide coverage and to ensure timely data without the need for surveillance and tracking stations on foreign soil. This study recommends steps to be taken immediately.

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# Space Surveillance

F. Robert Naka, Louis G. Walters  
Antonio F. Pensa, Samuel M. Tennant, O'Dean P. Judd

**Space Control.** It is becoming more important to military success that the Air Force control not only the access to space by adversaries, but also their access to information management resources in space. A fundamental requirement for achieving this posture is timely and accurate information regarding the orbital characteristics, physical configuration, and mission of every object in space. With the technology available in today's marketplace, Space Surveillance can support this Space Control requirement.

**Global Awareness and Space Surveillance.** As we move into the 21st century, the threat has changed from primarily that of a single military power, the Soviet Union, to a multitude of military powers throughout the world, with access to high-technology commercial products. Accompanying this changing threat is the explosion in information technology, which makes information dominance key to winning future wars.

Global and theater awareness and the ability to acquire and disseminate data to support the warfighters, to disrupt, deny, corrupt, and destroy enemy information flow and data bases, and to provide disinformation through deception will depend highly on space assets. Space assets have the advantage over airborne or ground assets in their ability to overfly denied or hostile territory. Therefore, the control of space to protect friendly assets and to deny the enemy the advantage of information warfare opportunities will be paramount in determining the outcome of future conflicts.

A fundamental element in achieving Space Control is having accurate and timely Space Surveillance. Space Surveillance must support Space Control by cataloging space objects, detecting, tracking, and identifying new, maneuvering, and hostile objects, and supporting information warfare tactics.

This study describes today's Space Surveillance Network (SSN), which mainly consists of sensors deployed for missile attack warning, utilizing the technology of several decades ago. The present radars, with some modest upgrades and proper calibration, could perform superior earth satellite surveillance if the processing capability were updated to realize the inherent detection and metric accuracies of the sensors. Deep-space surveillance depends mostly on optical sensors deployed in locations around the world and, because of lighting and weather limitations, does not yet provide a timely search capability for new or maneuvering objects.

**Background.** The original (U.S.) military mission in space—as assigned by the Chief of Staff, USAF, to the 1st Aerospace Control Squadron in June, 1961—was to “... detect, track, identify, and catalog every man-made object in space.” Since 1961 the capabilities of what is now the Air Force SSN and Space Control Center (SCC) have expanded and evolved. Major mission responsibilities that have been added include (among others)



- Operation of the first USAF antisatellite system (Program 437)
- Space collision avoidance
- Satellite maneuver detection
- Precise reentry prediction
- Space and laser clearinghouse functions
- Satellite launch and anomaly support
- A variety of Space Control-related functions.

At this time the SSN/SCC represents a space surveillance capability unequaled in the world. Nevertheless, the SSN/SCC is not fully adequate for present or anticipated tasks. A major hindrance is that the 1961 mission statement has not been expanded to reflect actual mission responsibilities. Simply put, there presently are no validated and funded requirements reflecting the current and future needs of space surveillance which provide the resources necessary even to sustain the SSN/SCC capabilities at the current (sometimes less than adequate) levels, let alone to improve them.

A high-integrity capability to detect, track, identify, and catalog *noncooperating* earth satellites is absolutely essential to support Space Control (including mission identification and threat assessment), collision avoidance, and the other important missions of national interest. Today's technologies can provide this capability, but there are serious shortcomings in application. In particular, there are

- Large geographical gaps in SSN sensor coverage
- Shortfalls in sensor detection sensitivity
- Inadequate atmospheric drag models for the processing of lower-altitude satellites
- Poor SSN sensor calibration procedures.

The net results are

- An incomplete catalog
- Slow SSN responsiveness when satellites intentionally maneuver, change orbits because of high solar activity, or break up into multiple pieces
- Limited accuracy and timeliness in routine satellite position predictions
- Delays in mission identification and threat assessment for some newly launched satellites.

The anticipated increase in active space payload population during the next decade will intensify the impacts of these deficiencies. Architectural considerations for maintaining space catalog(s) to address this population, with the requisite accuracies to meet Space Control needs, are discussed in Appendix 6, "SCC System Architecture."



Figure 1. A Snapshot of the Locations of All Cataloged Space Objects

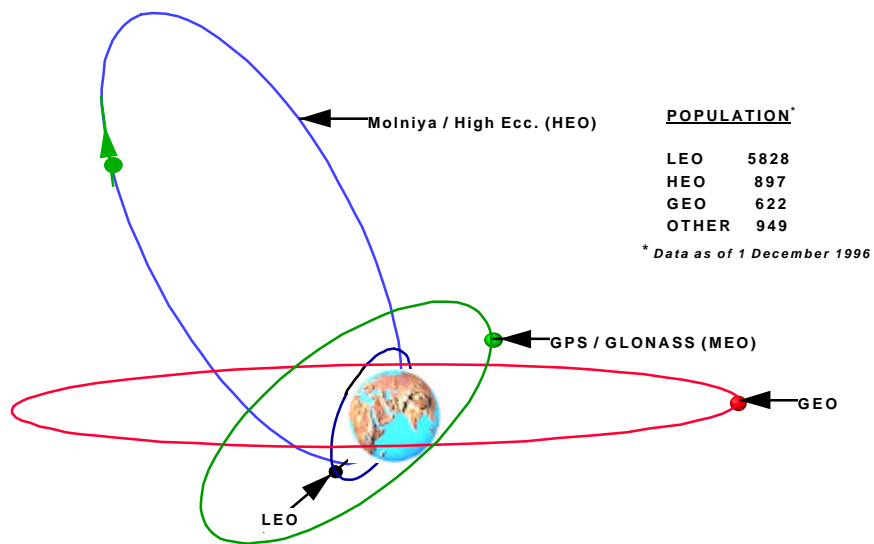


Figure 2. Satellite Orbits

An early criterion for space catalog accuracy was 12 km. This general standard minimized the system effort required to maintain the orbits of more than 8,000 satellites. It allows the use of quick, analytical programs (simplified general perturbations programs) and—under normal conditions—prevents the loss or misassociation of satellites.

From time to time it has been suggested that only a few sensor sites should be necessary to maintain the catalog. Theoretically, during quiet solar conditions—and assuming no new massive space breakups—two to three sites could maintain *most* of the catalog *most* of the time. Satellites that would not be included are those at high altitude (e.g., in 12- to 24-hour orbits and beyond), those in high-drag or low-inclination orbits, and those that have small cross-sections or are maneuvering. Decaying satellites, particularly those that may harbor hazardous or intelligence payloads, have special tracking requirements as discussed in Appendix 5, “Spiral Decay.” It should be noted that such a network of a few sensors would not assure the accomplishment of critical DoD missions.

Today the SSN provides special support for a variety of missions that require high-accuracy predictions. Assuming the use of

- All the present worldwide SSN sensors
- Properly calibrated data
- Existing special perturbations programs for orbit estimation and prediction

and provided high atmospheric drag and satellite maneuvers are not factors, the SCC should be able to provide 12-hour satellite position predictions within 100 meters (1 sigma). In many cases important to Space Control and other missions, these assumptions will not hold, and the predictions may not be sufficiently accurate to permit mission accomplishment.

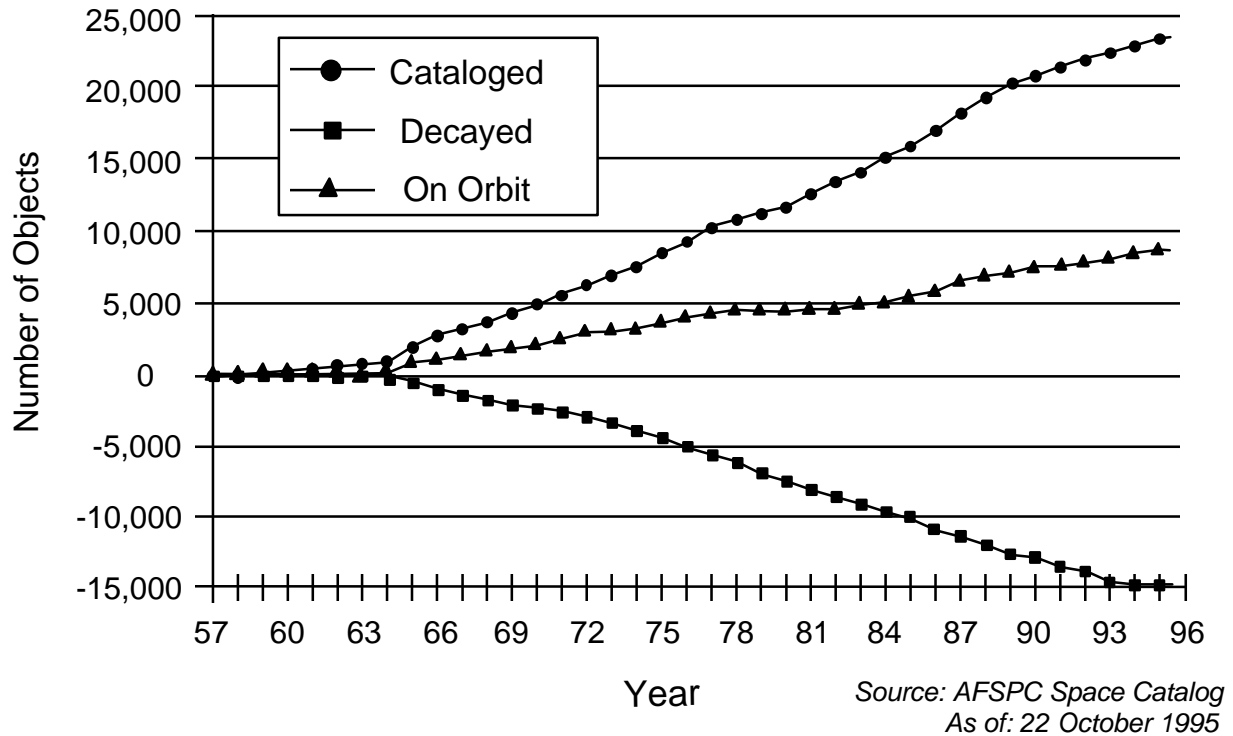
In comparison, National, military, NASA, and commercial satellite systems all rely on *cooperative* (transponder link) tracking of their satellites, and—in contrast to the SSN—are data-rich with regard to the computation of accurate orbits. They have few if any gaps in contacts with their satellites and recompute orbits to meet their internal requirements. Their prediction accuracies run from 10s of meters for satellites not greatly affected by atmospheric drag or other perturbations to 100-300 meters for geosynchronous satellites and high-drag satellites. Whenever better accuracies are needed, the satellite operators simply increase the frequency of orbit recomputation. (Historically, whenever cooperatively tracked satellites are “misplaced,” or the operators have difficulties with communications, the SSN is called upon to provide tracking and help determine orbits.)

***Earth Satellite Space Environment.*** Finding and identifying objects in space is especially challenging in the context of the environment in which we attempt to perform these functions. Figure 1 depicts the space population (manmade objects in earth orbit) as it appeared in an instantaneous snapshot circa 1995. It is evident that the space environment is rich with targets, and new targets can only be found if the existing population is completely accounted for.

Fortunately, in spite of the instantaneous situation, objects in earth orbit tend to be clustered in a few orbital categories, and the distinction between them is such that they can be completely and uniquely maintained.

The satellite population is represented by the altitude regime in which the satellite orbit exists. Figure 2 shows the satellite orbital categories as well as an estimate of their populations. The situation is somewhat simplified by the existence of orbits and the fact that the instantaneous position of any satellite in space can be determined by knowing the “orbital elements” that describe the satellite orbit and the position of the satellite in the orbit as a function of time. Therefore, the entire population of objects in space can be maintained by a “catalog” of orbital elements. A new object launched into space is detected and tracked and its position is compared with the existing catalog. That comparison ensures that the data represent a new object rather than one already in the catalog.

Orbital elements and the space catalog provide the means of knowing where all of the space objects are. The sensors that comprise the SSN provide the data that sustain the space catalog. Principally, two types of sensors observe and measure objects in space from ground-based instruments: radar and visible band optics.



*Figure 3. Space Object Population History*

In summary, the two types of data are very different yet complementary. Radar affords the greatest availability. Range data are extremely valuable in determining the orbital elements of the target. On the other hand, the sensitivity and field of view available in the visible optics are very valuable in searching and tracking satellites at very long ranges, such as those associated with the geosynchronous earth orbit (GEO) shown in Figure 2.

Spacetrack has cataloged some 24,000 objects since the dawn of the space age in 1957. Of these, as indicated in Figure 3, some 15,000 have decayed, leaving some 9,000 objects in the

catalog. Of these about 5 percent are active spacecraft, with the remainder being debris — spent operational spacecraft, boosters, intermediate boost phase stages, and fragments. For Space Control, it is important to know understand the missions in which the operational spacecraft are engaged.

**Measurement Systems.** The SSN has sensors concentrated in the CONUS but also distributed worldwide. In order to meet a realistic projection of mission requirements, the SSN will need

- Sensors located to fill critical gaps in coverage
- Improved sensor sensitivities to permit detection and tracking of high-altitude (e.g., geosynchronous) satellites and small payloads and debris.

With the exception of data received from the Ground Based Electro-Optical Deep Space Surveillance System (GEODSS) and the Eglin phased-array radar, the SSN radar sensor data mainly have been obtained from missile warning and intelligence sensors. Recently, the southeast and southwest PAVE PAWS radars were closed, and the operational functions of the Cobra Dane radar were discontinued. This degraded the existing sensor coverage in the northern hemisphere. Compounding the problem, there is very little orbital coverage from Europe and Asia and essentially no southern hemisphere coverage at all. See Figure 4.

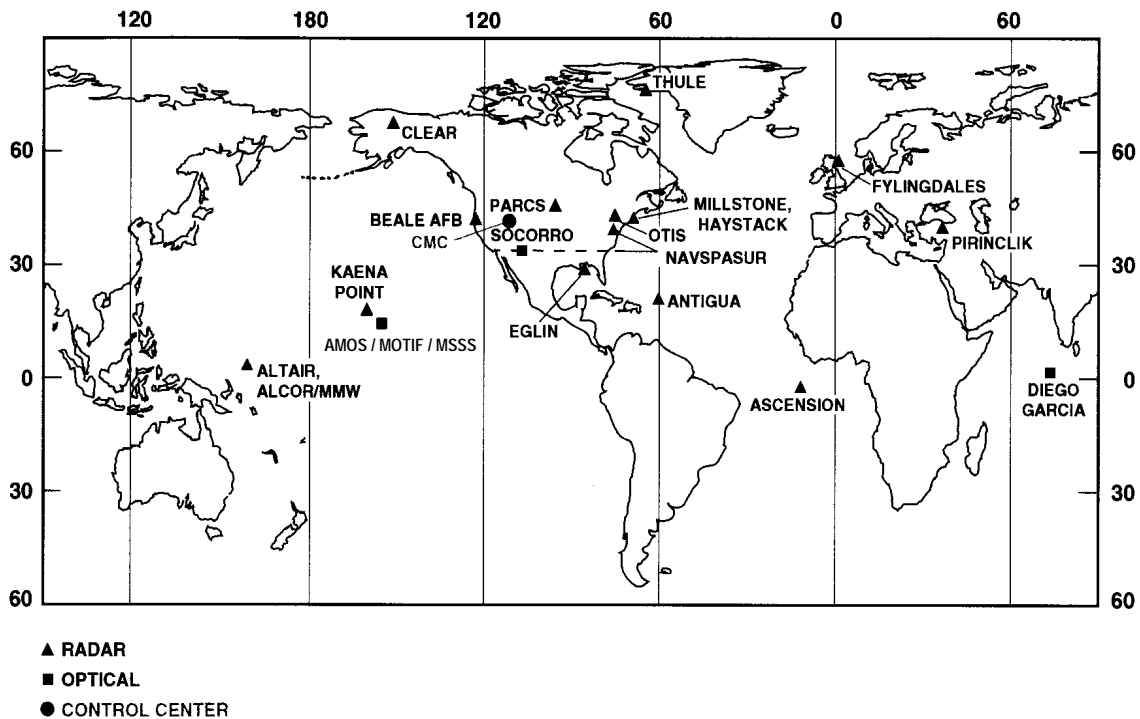


Figure 4. The United States Space Surveillance Network

These new and existing sensor coverage gaps seriously compromise today's capabilities

- To keep up with high-drag satellites and satellites that maneuver
- To provide orbital support for new launches
- To handle satellite breakups and space debris
- To provide accurate predictions and assessments in support of critical DoD missions.

In sum, the SSN cannot be expected to maintain space catalog integrity and to provide highly accurate predictions and assessments for Space Control and other missions unless sensor coverage capabilities are retained and gaps are filled. Updated, compelling, formal requirements obviously are needed.

**Ground-Based Radar Systems.** Electronically scanned radars that inherently have a large field of regard produce most of the data to maintain the low earth orbit (LEO) portion of the catalog. The principal sensors are the following.

The FPS-85 radar, located at Eglin AFB, FL, is a UHF phased array radar originally built as a space surveillance sensor and later modified to act as a submarine-launched ballistic missile (SLBM) warning instrument. Approximately 5 years ago, it was returned to a full-time space surveillance mission. At the present time, it lays a search fan beam fence to the south  $180^\circ \pm 40^\circ$  at an elevation of  $35^\circ$  to detect LEO satellites. It spends some of the time searching deep space. It is the most sensitive radar available for routine space surveillance operations.

The PAVE PAWS radars are UHF phased-array radars built in the late 1970s and early 1980s primarily for the SLBM warning mission. However, they are also capable of providing data on resident space objects (RSOs), and hence their primary utility has been in space surveillance. Four such radars have been built. Only two are operational now—at Cape Cod AFS (MA), and at Beale AFB (CA). In addition, two copies of these radars have been installed for ICBM warning at Fylingdales (UK) and Thule (Greenland). These radars are 5 to 10 dB less sensitive than the FPS-85 radar.

The NAVSPASUR interferometric fence, operating at 216 kHz, is one of the first dedicated surveillance systems ever built. It is essentially a zenith fence extending across CONUS (and slightly beyond) at about  $30^\circ$  N latitude. It detects RSOs as they penetrate the fence.

Several conventional narrow field-of-view radars with steerable parabolic antennas on pedestals complement the low-altitude surveillance system. Examples are the radars at Kaena Point (HI), Ascension Island, and Pirinçlik<sup>1</sup> in Turkey. These are steerable dish radar systems that can track only one RSO at a time in the main beam.

The deep-space catalog is maintained mostly by optical sensors with assistance from certain radars. Optical sensors will be covered in the next section.

The distinguishing difference between near-earth and deep-space radars lies in their mode of signal processing the backscattered return from RSOs. All the radars in the surveillance system (except for NAVSPASUR) operate in a pulsed mode; that is, the radar transmits a series of short high-power pulses of electromagnetic energy. The receiver is turned on between the pulses to

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<sup>1</sup> Radar operations at Pirinçlik were terminated in March 1997, after this study was completed and briefed at Hq USAF and Air Force Space Command.

detect the returned signal. Near-earth radars detect a target based on the returned energy from a single pulse and hence are limited in the range at which an RSO can be detected. For example, the FPS-85 radar can detect a 0 dBsm ( $1 \text{ m}^2$  radar cross section) target at a range of 7,500 km on a single pulse. The signal processing algorithms in deep space radars, on the other hand, process the returns from many pulses (typically as many as 1,024) together to enhance the signal-to-noise ratio for detection over single-pulse radars. By using such techniques (called coherent integration), the FPS-85 radar can detect a 0 dBsm RSO at a range of 36,000 km in GEO.

Coherent processing for satellite tracking was first accomplished at the Millstone Hill radar located in Westfield, Massachusetts. This radar is a narrowbeam ( $0.44^\circ$ ), high-power (3 MW peak), L-band (1,295 MHz) system with an 84-foot parabolic antenna. It is capable of detecting and tracking a 0 dBsm ( $1 \text{ m}^2$ ) target in GEO. Many of the currently accepted calibration and modeling techniques were developed at the Millstone Hill radar. Consequently, it is also the most accurate tracking radar routinely available for space surveillance.

The deep-space tracking technology was transferred from Millstone to ALTAIR on the Kwajalein Atoll in the Pacific and to the FPS-79 radar in Pirinlik, Turkey. These two radars complete the coverage of the geosynchronous belt. ALTAIR is nearly as sensitive as Millstone Hill radar, and Pirinlik is approximately 10 dB less sensitive.

Lately, the capability has also been transferred to the FPS-85 radar albeit at the expense of energy available for near-earth search and tracking. While this radar partially overlaps the coverage of the Millstone, it has some unique features, such as an electronic fence scan that can be exploited in deep-space tracking. Further, this radar is able to detect and track a large percentage of deep-space RSOs in high eccentricity orbits because their perigee altitudes are low, and hence they can be tracked using the near-earth mode of the radar.

Radars are important to the space surveillance system for the following reasons:

- They can operate 24 hours/day, unlike optical sensors, which are limited by cloud cover and sunlight (see discussion below).
- Radars provide data in three or four dimensions (i.e., azimuth, elevation, range, and range rate), unlike optical sensors, which do not measure range or range rate. This enables more rapid orbit determination with fewer data points.
- In general, the data accuracy of the radars exceeds that of the optical systems significantly, enabling more accurate orbit determination.

A potential complementary capability could come from dual use of the proposed BMDO X-band phased array radar at Kwajalein. This radar, designed to provide RDT&E support for Army Theater Ballistic Missile Defense, also could provide high metric accuracy satellite tracking data for Space Control and other applications and for debris environment monitoring. (If future requirements—such as collision avoidance support for the Space Station—evolve, this debris information could be used to maintain a special debris catalog that would support accurate hand-off to other sensors for follow-on tracking.) In addition, this X-band system could provide wideband imaging to support satellite payload mission identification and threat assessment.

***Ground-Based Optical Systems.*** Visible optics systems provide one of the significant sources of space surveillance data, especially on satellites in deep space. Optical sensors take advantage of the fact that the source of illumination is the Sun and that the solar power density is uniform to the first order in the earth's orbit around the sun. Transmission loss suffered by an

optical sensor will be proportional to the square of the range between the sensor and the target (as contrasted with the fourth power of range loss that the radar suffers).

Optical sensors can measure the position (angular) of a target with respect to the known star background. These sensors do not provide any measurement of the range or velocity of the target. Nevertheless, because the positions of stars are very well known, the angular measurements can be very precise.

The use of optical systems for space surveillance began shortly after the launch of the Soviet Sputnik satellite. At that time, a film plate exposure system known as Baker-Nunn was used to detect satellites against the star background. With wide field-of-view optics, a long exposure in a sidereal tracking mode was used. In this mode, the star field would remain fixed as a system of spots, and an illuminated satellite would appear as a streak across the star field. The detection medium was film, and the detection process involved manually measuring the location of the streak with respect to known stars in the exposure. This process was slow and labor intensive, yet it served as the principal means of detecting and tracking deep-space satellites well into the early 1970s.

By the early 1970s, it became clear that the military use of deep space, particularly GEO, was growing rapidly, and a more responsive system was needed. The GEODSS system was designed to constitute a clear weather satellite surveillance network for deep space. It is designed to be especially effective in monitoring satellites that are small and/or maneuverable.

The GEODSS baseline sensitivity is such that it is capable of detecting an object about the size of a white soccer ball at ranges that are consistent with geosynchronous altitudes of 22,000 nmi. Unlike the Baker-Nunn system, which used film, the GEODSS system uses the digitized output from a video camera, allowing operators of the system to see the satellites detected by the system in near real time. Both the GEODSS and the Baker-Nunn systems use sidereal drive telescopes to eliminate the apparent movement of stars across the night sky caused by the rotation of the Earth. As a result of this movement, satellites appear as streaks of light against the background of point light sources. In GEODSS, the star field, which is not moving, can be eliminated by subtracting successive frames of video in the camera processor. The resulting output will be the satellite without the star field. This greatly enhances the detectability of faint targets in dense star backgrounds.

The present system consists of three GEODSS sites, located at Socorro, NM, Maui, HI, and Diego Garcia in the Indian Ocean. Each of these sites consists of two 40-inch telescopes with 86-inch focal lengths and a  $2.1^\circ$  field of view.

These large or main telescopes are used primarily to search for and track the faint, relatively slow-moving satellites in deep space. In addition to the main telescopes, each GEODSS site has a 15-inch auxiliary telescope with a 30-inch focal length and a  $6^\circ$  field of view. The auxiliary telescope is particularly well suited to search for satellites in lower altitude orbits that are moving at relatively faster angular speeds.

***Space-Based Sensor Systems.*** It was stated in the previous section that all but the most stringent tactical requirements or needs can be met in the LEO case with ground-based radars. The situation is somewhat different in high earth orbit (HEO) and GEO. HEO and GEO space surveillance requires distributing sensors worldwide to see all objects. The ground-based optical



sensors currently used for this mission suffer from poor availability resulting from the need for clear dark skies and solar illuminated targets.

Utilizing sensors on space platforms eliminates the need for foreign basing and provides multiple aspect viewing of the target. In addition, communication connectivity and a high degree of survivability through availability of multiple sensing platforms are provided. The ideal system is a distributed low-altitude system of many relatively small satellites with optical sensors capable of search and track to the extent of providing the necessary data for establishing ephemerides.

As early as 1968, a serious study<sup>2</sup> of Space Surveillance recommended that the surveillance of space be conducted from space platforms. Two opportunities exist in the near term to explore the use of space-based sensors in LEO for surveillance: MSX and SBIR/SMTS.

The Midcourse Space Experiment (MSX) satellite was launched on 24 April 1996. The purpose of this satellite experiment is to detect and track missile plumes very near to the earth's limb. The satellite has a large suite of sensors spanning a wavelength range from 0.1 to 26 microns. The satellite is expected to be in full operation for 12 to 15 months on the primary mission, depending on the depletion rate of cryogen for the infrared sensors.

A dedicated sensor, the Space Based Visible (SBV) camera, is intended to be used to perform space surveillance demonstrations such as surveillance of RSOs. The SBV sensor is well suited for the space search and track mission. The 15 cm aperture provides a 1.4-inch  $\times$  6.6-inch field of view over a spectral range of 0.3 to 0.9 microns. The instantaneous field of view is 60 microradians or 12.2 arc seconds. The focal plane array consists of four charge coupled devices (CCDs), which provide an array size of 420  $\times$  1680 pixels. The camera has multiple frame times: 0.4, 0.5, 0.625, 1.0, 1.6, and 3.125 seconds. The pixel size is 27 microns. The sensor is cooled to -40 °C and is expected to exhibit 28 percent quantum efficiency and six noise electrons per sample. The sensitivity is sufficient to detect a 14th magnitude object.

The signal processor suppresses background clutter, detects moving targets, and generates target reports. It can operate in sidereal track mode, where it rejects stars and detects moving targets or, in a target track mode, where it rejects the moving background stars. The experiment controller may be commanded to execute a closed-loop tracking sequence using data from the SBV focal plane, sent through the SBV signal processor, to determine the future position of an observed target in the focal-plane coordinates. The sensor can scan objects from LEO to GEO. Data can be downlinked at 2.5 Mbps or stored on 54 gigabit on-board recorders.

Currently, the satellite is operated as part of a consortium involving the AFSPC and Ballistic Missile Defense Office (BMDO). At the end of life of the experiment, the SBV will continue to function for an unspecified time. Discussions are in progress to transfer the operation and use of the satellite to the Space Operations Center at Air Force Space Command (AFSPC).

The Space-Based Infrared System (SBIRS) has an LEO component designated as the Space Missile Tracking System (SMTS). This system has the objective of tracking objects during midcourse to support ballistic missile defense. It is advocated by BMDO but is currently in the Air Force Total Obligational Authority (TOA). The SMTS is a phased effort that has a flight

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<sup>2</sup> F. R. Naka et al., "Surveillance of Objects in Space in the 1970s," Air Force Systems Command, August 1968 (2 volumes), SECRET

demonstration system (FDS) program to demonstrate critical space vehicle capabilities in a real-world setting using known threat-representative targets.

The SMTS concept is optimized for tracking missiles and reentry objects and uses two sensors per satellite: an acquisition scan sensor that looks down and has full horizon-to-horizon shortwave infrared (SWIR) scanning and processing capability with short revisit time and a track sensor. The track sensor has a small field of view with detectors in the SWIR, medium wave infrared (MWIR), medium long wave infrared (MLWIR), and long wave infrared (LWIR) (if this option is funded) ranges. It also includes a visible wavelength capability of a  $128 \times 128$  CCD with a  $0.4^\circ$  instantaneous field of view.

The FDS program consists of building two satellites and launching them on a Delta launch vehicle into the same orbit but separated in epoch. A 2-year flight demonstration program is baselined, although only the first year of on-orbit operation is currently funded.

Space surveillance is to be accomplished using the track sensor looking above the earth's limb. All LEO RSOs of 10 cm or greater are detectable as well as large targets ( $3 \text{ m}^2$  or greater) in HEO and GEO. Smaller targets at high altitudes are detectable with both the LWIR and visible light sensors using the "target follow" mode of operation. The radiometric data in both the infrared (IR) and visible bands provide useful signature variation. With available multiple viewing geometry, it may be possible to determine if a given satellite's solar panels are deployed, if the satellite is tumbling, and if the payload is active.

Studies to date indicate that 4 percent of constellation track sensor assets perform the space surveillance mission in one day. Because of the Sun-earth geometry, deep-space objects in the geosynchronous belt are unviewable up to 4 hours per day. Another consideration is the number of satellites, which varies with the chosen constellation's orbital altitude. This selection is driven in part by the radiation environment, which substantially increases above 700 km and varies with inclination.

There is a legacy issue in that the final choice of the SMTS configuration is going to be largely driven by cost. A major tradeoff will be the use of existing commercial parts as contrasted with the use of specially qualified hardened parts required at the higher deployment altitudes. The number of satellites required declines as the altitude elevates, but the radiation increases very rapidly. The impact on space surveillance is that as the number of satellites increases in the constellation, so does the potential search and tracking capability for more objects.

The SMTS also appears to have a substantial capability for surveillance of asteroids and comets. The track sensor in both the visible and LWIR is capable of detecting potentially threatening near-earth objects (NEOs), asteroids, and comets. The Air Force could initiate a credible capability integrated with ground sensors for NEO space surveillance.<sup>3</sup>

The FDS program is already being overrun by the contractor. The System Program Office's expectation is that the space surveillance requirements will be removed from the contract to save money on ground testing. Also, while the FDS program is being designed for a 2-year on-

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<sup>3</sup> R. Wright and C. Hault, "The Space and Missile Tracking System Contribution to Planetary Defense: Detection of Asteroids and Comets with Earth-crossing Orbits," The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009, 19 December 1993.

orbit life, only the first year of test operations is funded. This is a serious problem if space surveillance is to be conducted from these platforms.

The expectation for the 21st century is rapid expansion of commercial space providing direct broadcast, personal communications, and data transfer as well as hyperspectral imaging. These commercial systems will also be used by the military to support the warfighters with information dominance along with specialized military systems providing secure communications, precision navigation, and timing. Protecting these space assets and denying and disrupting the enemy's access to space assets will make Space Control imperative in winning future conflicts.<sup>4</sup>

Space Surveillance is a fundamental requirement for effective Space Control; therefore, it is important that plans be laid to achieve a superior capability for the 21st century. The 30 or so satellites that would make up an operational SMTS represent an ideal low-altitude, distributed system and are likely to be the only space system available for carrying out the Space Surveillance function. The SMTS track sensor and the multitude of satellites provide a significant capability to track NEOs and offer the surveillance necessary for Planetary Defense if the Air Force wishes to pursue this mission.

**Catalog Processing.** The catalog is the most visible product of the Space Surveillance system (at times called SPADOC or Spacetrack). It identifies (with limitations imposed by security concerns) all space objects capable of being tracked by the SSN, generally larger than 10 cm in LEO, and provides a state vector ("element set") for each. The catalog is primarily used for sensor tasking and acquisition and for object identification when observations are collected.

The catalog format has been virtually unchanged over the 4-decade existence of the SSN. The processing algorithms represent a compromise between computational assets available to the system and user community and accuracy, resulting in extensive use of closed form or general perturbation methods for propagation of ephemerides. A large and international base of legacy users must be served irrespective of the future evolution of the SSN.

While the catalog processing algorithms have changed little over the last several decades, there are now compelling reasons to reexamine this architecture. Consider the following:

- Computer technology has expanded to erase any global requirements for optimization in the processes and processing; a single desktop PC now has the processing power of the entire SSN when the current SPADOC system was conceived.
- The Space Control issue will impose a new dimension on the satellite position predictions of the SSN, i.e., a highly reliable estimate of prediction accuracy. This property is a product of modern filter technologies exploited by the National Programs, TALON SHIELD, and NASA, and inevitably will become an essential element of future space surveillance capabilities (Appendices 3 and 4). In order to provide benefits in the current SSN environment, application of a modern filter technology must be accompanied by accurate, timely calibration of satellite sensors, as outlined in Appendix 1, "Sensor Calibration."
- While the techniques of sensor calibration have been exploited in the past, the availability of outside reference orbits (third-party ephemerides of submeter quality) will permit the definition of radar sensor performance down to the thermal RF design limits (3 meters in range for PAVE PAWS-type radars, for example). The overall calibration function would be partitioned—sensors themselves will continue to provide local calibration information, and

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<sup>4</sup> G. McCall et al., "New World Vistas, Air and Space Power for the 21st Century," USAF/SB 1995.

correct their observational data for factors that are truly local in nature (e.g., angle biases, refraction in angle and range), and the overall accountability for definition of the system calibration model used to drive the orbit estimation process will remain with the centralized Space Control Center.

- Global high-speed communications will permit the SSN mission to be distributed and dispersed.
- The environment, particularly atmospheric drag, may be better defined by on-line measurements of satellite decay rates made possible by the higher precision measurements currently available.
- High-value missions will be concerned with collision with any crossing orbits, so the risk assessment will require trusted error estimates for these objects to define the need for evasion, if taken.

But, more critical to the future configuration and capabilities of the SSN, effective Space Control will require greater accuracy and responsiveness in SSN catalog products, and accuracy must be quantified for each element set in terms of covariance products conveying realistic estimates of both tracking data and environmental definition effects. The future system must support the acquisition requirements of the smallest aperture device fielded for tracking, illumination, and negation of foreign space assets—for the laser *a reasonable requirement would be 100 m or better for a 12-hour prediction at all operational altitudes.*

**Data Processing Impact on Requirements.** To measure the impact of these requirements on the architecture of a future SSN, consider the data flow, shown in Figure 5, for a conceptual Spacetrack 2000, which is described in Appendix 6. While it resembles the current system in the Cheyenne Mountain Complex, several important changes stand out:

*Two satellite catalogs will be produced.* The first, the familiar general perturbations version in use over the past 4 decades, will support the legacy users for an indefinite time. The second, a special perturbations catalog, will convey all the accuracy potential available from the tracking data and environmental knowledge and will describe its accuracy in terms of trusted covariance products. A proven orbit estimation technology is capable of generating this product—a technology based upon modified Kalman filter technology, which has been qualified for use in the National Program family. This special perturbations capability is sized to maintain up to the entire satellite inventory if needed.

## Spacetrack/2000 Concept

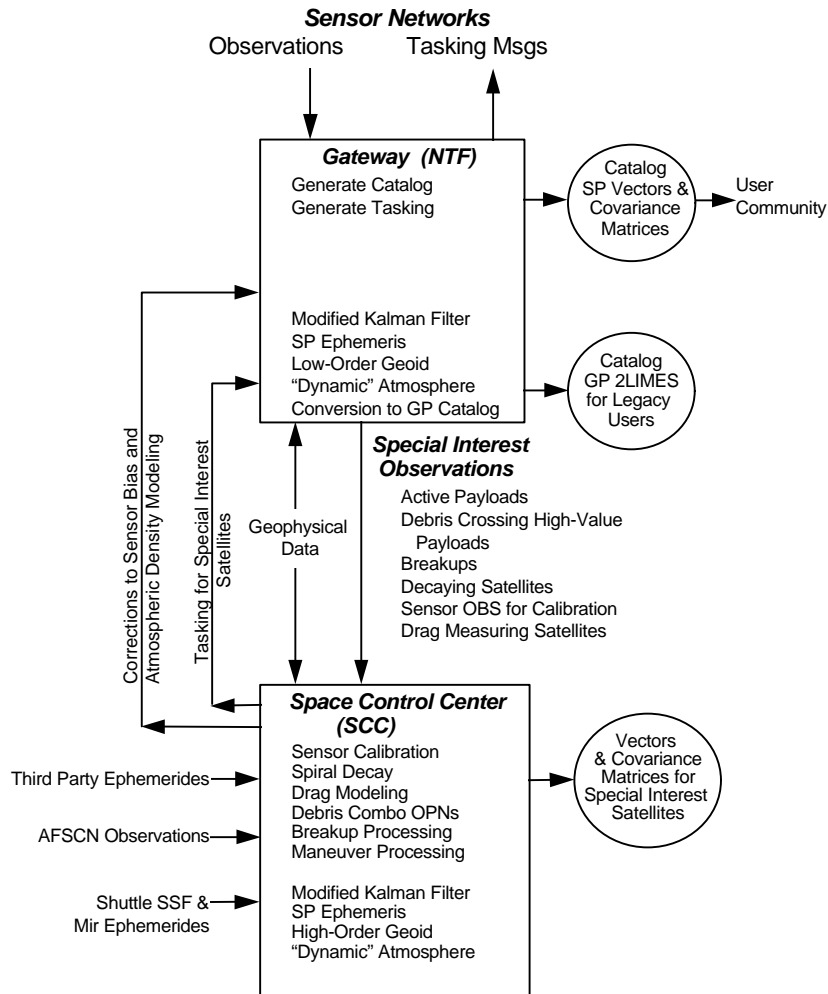


Figure 5. Spacetrack/2000 Concept

Poor understanding of the lower atmosphere densities (primarily between 80 km and 600 km) together with critical gaps in sensor coverage represent the major contributions to satellite prediction error. Recent advances in atmospheric modeling by the Air Force Geophysics Laboratory may lead to near-term improvements, and development of a real-time atmosphere model based upon sampling of SSN catalog satellite accelerations may represent the beginnings of a longer-term solution, as outlined in Appendix 2, “Direct Measurement of Drag Properties.” (Note: the latter approach has been used successfully by the Russian tracking network—RSSS—since 1982, and the Russians claim a factor of 3 to 4 improvement in position prediction accuracy for 2- to 3-day predictions, and a 30 to 40 percent improvement for 6-day predictions.)

With the emergence of the Space Control mission, in which the Spacetrack System is embedded as an element, a new definition of accuracy emerges. *Force application by Space Control operations will be outcome-oriented, in which decisions will be based on well understood measures of success.* Judgments regarding the projected effectiveness of complex operations will rely on each contributing element's ability to describe its error in mathematically concise form, so that a system measure of success can be defined. The National Program community has briefed the committee on its successful application of a new (to Spacetrack) estimation filter technology that incorporates correlated error modeling of the environmental errors (gravity, drag, etc.) into a state vector covariance product with the necessary high-confidence properties. This filter technology has been adopted by the Shield program to support theater missile defense, and its early evaluation for an inevitable role in Space Control and other applications requiring highly accurate, well understood predictions should be considered.

The covariance products generated by the modified Kalman filter are powerful tools in the observation association and tasking logic and will provide early clues as to maneuvers executed by adversaries for mission or evasion purposes. *By defining how well the system is entitled to know a satellite's orbit, these covariance products will contribute to autonomy and automation in many routine operations.*

*By adopting the principles of open architecture, many of the routine software functions can be drawn from commercial inventories of these products, with dramatic savings in cost and development time.* The latter is important to avoid the early obsolescence of prior procurement practices, and the unforgiving nature of users of these commercial off-the-shelf (COTS) products will reduce testing time and latent errors. Commercial information management products have a reliability seldom achieved over the lifetime of stovepipe development practices, in which the "maintenance" costs over the system life cycle commonly exceed the original development costs. These commercial products must survive an unforgiving marketplace, and their qualifications are far more extensive than that affordable to the custom system developer. With alternative sources available for many of the information management products, such as operating systems, software development products, database management systems, and communications software, and for products that make these alternatives interchangeable, the system developer can devote a shrinking software development and qualification resource to the central military application. This luxury will take years off the development process for new and improved systems and will substantially reduce the life-cycle costs as well. All COTS products must be subjected to a stringent suite of tests to qualify them for their intended use; consider, for example, the meaning and usage of time in astrodynamics calculations.

*The Spiral Decay requirement remains one of the more demanding on the tracking assets.* During terminal decay, the orbital environment is changing substantially, and to the extent that these changes are not accurately modeled, additional tracking contacts are needed to maintain integrity in the orbit estimation. This process is intrinsically international in scope, for the debris corridor can contaminate any country. In the past, international cooperation has been solicited when the decaying object has posed a physical or health hazard, and this need should be formalized with interoperability agreements and joint sensor calibration. In the future, the Spiral Decay problem will also be complicated by dependence upon high-energy orbits, which will decay from elliptic orbits, complicating the global need for better modeling of the atmosphere.

Not shown, but under consideration, is a catalog of asteroids and comets, derived from observations collected by the electro-optical (EO) sensors organic to the SSN. This process is clearly not real time, nor does it present a threat requiring immediate action to defend military assets. It should be based upon the integrated observational assets of the SSN and of observatories and amateur observers international in scope. The process is competently supported by the university astronomy community at the present time, and this effort should be supported by connectivity to the SSN EO telescope data source and the ability to task that resource.

***Recommended Technology Initiatives.*** The past practice of committing new systems development to a protracted (often 10-year) development cycle has denied each new generation of Spacetrack the benefits of dynamic research into improved astrodynamics and estimation algorithms. This problem is best illustrated by presentations made to the Committee by the National Program sponsors that show dramatic improvements in accuracy and computational efficiency achieved in operations by sponsoring concurrent prototype development of these new technologies within the operational environment. To assure that the next and following generations of Spacetrack system(s) benefit from algorithm improvements, the Committee *recommends that a dynamic technology prototype effort be undertaken. Coupled with a commitment to open architecture* in future systems, the benefits of technology can be rapidly assimilated into the operational system. Candidates for such a prototype effort can include the following:

- ***Modified Kalman Filter Orbit Estimation Technology.*** Over the past 2 decades, two system upgrades have been installed in the Cheyenne Mountain Complex for the Spacetrack function: the 427M and SPADOC systems. In each upgrade, computer platforms were replaced with then-current models, and more sophisticated user interfaces were developed to facilitate analyst intervention in the processing functions. Each upgrade inherited the astrodynamics design and algorithms of its predecessor, however, with marginal improvements in the ephemeris processing routines. Consequently, a wide gulf exists between techniques, particularly orbit estimation, used in Spacetrack and those that have evolved in the National Program community. Through several briefings sponsored by that community, the AFSAB Space Surveillance Panel has been apprised of substantial improvements in the efficiency and accuracy of orbit estimation methodologies based upon the modified Kalman filter.

The objective of prototyping the modified Kalman filter in the SSN data environment is to demonstrate robustness and a realistic covariance matrix property for every element set and to provide a consistent suite of integrated applications, such as collision avoidance, that can exploit that covariance.

- ***On-Line Drag Measurement Techniques.*** The large population of satellites tracked by the SSN afford a laboratory for the evaluation of contemporary atmospheric density models and for the real-time global adjustment of these models to improve the predictions of satellite ephemerides. Some work in this direction has been attempted at Los Alamos National Laboratory (LANL) with catalog mean elements, with limited success.

To provide utility in a catalog environment based upon special perturbation techniques, as contemplated in the future, the process must directly address the drag interaction with satellite area-to-mass ratio, rather than the mean period decay rate, expressed as either  $B^*$  or  $n\text{-dot}/2$  but without physical connection to this interaction.

Through selection of a subset of the catalog with stable orbits (no maneuvers), with known area-to-mass ratios, with known or (preferably) spherical configurations, and orbiting over a range of altitudes under 1,000 km, actual errors in the density modeling can be determined at a

single altitude if the satellite orbit is circular or if it is averaged over a range of altitudes if the satellite is eccentric. These data can be used concurrently to adjust the derived drag coefficients for the satellite population under 1,000 km.

***Mission and Payload Assessment.*** Air Force Space Command uses a variety of information sources to perform mission and payload assessment (MPA). These sources include information about the launch site, launch vehicle, type of orbit, intercepted satellite communications, optical signatures, optical images, radar signatures, and radar images.

The Committee did not review this area in depth. However, it notes that the data are collected and analyzed as technical intelligence to support strategic intelligence. Time is not considered to be a critical factor. In the future, the needs of Space Control will shorten the time lines so that MPA will move toward tactical intelligence. Further, in the future, there will be many spacefaring nations in place of the single one the United States has faced to date. The Air Force should, therefore, reevaluate the future MPA evolution and consider ways to reduce the timelines.<sup>5,6,7,8,9,10,11,12</sup>

***Findings: Measurement Systems.*** The current space surveillance system has evolved in response to the threat that existed from the space capability of the Former Soviet Union. Satellite attack warning and new foreign launch detection were the principal missions that needed to be supported by the space surveillance system. The sensor suite that evolved over the years was, however, more the result of the availability of the sensors to support other missions, such as missile warning. The principal reason why the United States was able to take existing sensors and force them into a system that successfully addressed the Soviet space threat is that Soviet space operations were predictable and repeatable. In the world today, several countries are capable of significant military operations in space. Thus the schemes for new launch detection that were built upon the “railroad tracks” to orbit from a few fixed launch locations will not work.

Ground systems that are capable of providing tactically responsive surveillance information will need to be distributed more or less uniformly around the globe. Without a single spacefaring enemy, the United States will have to be prepared for the threat that may come from any one of several launch sites. The cost of operating and maintaining such a geographically

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<sup>5</sup> N. Johnson, “The Soviet Year in Space - 1990,” Teledyne Brown Engineering, UNCLASSIFIED.

<sup>6</sup> T. Wallace, “Techniques for Monitoring Satellite Status Using Narrowband Radar Signatures,” MIT Lincoln Laboratory, Project Report PSI-174, 16 January 1992, UNCLASSIFIED.

<sup>7</sup> T. Wallace, “Monitoring Satellite Status Using Partial Narrowband Radar Signature Comparison,” MIT Lincoln Laboratory, Project Report SPI-175, 22 December 1992, SECRET.

<sup>8</sup> S.B. Bowling, C.K. Chan, H.M. Jones, J. Rheinstein, “Radar Imaging of Objects in Space and Reentry,” J. Defense Research, Volume 16, No. 4, Page 375, 1984, SECRET.

<sup>9</sup> C. Burt, private communication.

<sup>10</sup> B. Francis, “Special Data and Features Analysis for COSMOS 516 (Object 6154),” MIT Lincoln Laboratory, Project Report PSI-22, 19 February 1974, SECRET.

<sup>11</sup> Space Systems Handbook-CIS, DIA, DST-1400H-252-93, SECRET.

<sup>12</sup> C. Solodyna, “Final Report: Survivability Technology Program FY 92: A Survey of Satellite Multi-Spectral Data,” MIT Lincoln Laboratory, Project Report PSI-178, Volume 1, SECRET



distributed system will continue to rise in the future. Furthermore, with the changing world political climate, it will become increasingly difficult to maintain sensor systems on foreign soil.

Space-based space surveillance sensors offer the promise of eliminating many of the problems associated with foreign basing. The low component of SBIRS, SMTS, could provide Air Force Space Command with the space surveillance capability that it needs to carry out all of the tactical components of the Space Control mission, except search. AFSPC needs to define the space surveillance requirements in terms of using space-based sensors and to evaluate the FDS test program to determine if its legacy is adequate to support specification of an operational SMTS that has the desired space surveillance capability. Furthermore, if space surveillance were added to the FDS, AFSPC should support the funding of testing for the 2-year expected lifetime of the FDS in order to build confidence in the definition of operational requirements.

***Findings: Data Processing.*** In the area of data processing, several significant findings are noteworthy.

- The catalog data processing of today is committed to the filter and computer technologies that were available 40 years ago. The more accurate and efficient methods used in the commercial world and elsewhere in the National Programs community have not been exploited in the current space surveillance system.
- Data products coming from the sensors are not generally well calibrated except in off-line processing. The processes, employing third-party ephemerides of known accuracy, should be introduced as routine on-line functions.
- There is no way to develop or communicate the accuracy of catalog products to the Space Control community to support applications for negation, denial, or maneuver to avoid collision.
- The present space surveillance data processing system is tied to the missile warning data processing system in a manner that prohibits innovative solutions to the evolving space surveillance data processing problem.

## Recommendations

The current SSN dilemma is characterized by a downsized budget in conflict with an evolving and expanding set of missions. Complicating the situation is the lack of a clear set of definitive requirements, uncertain standards, stovepiped systems, and merging/downsizing of existing space-related operational units (e.g., re-allocation of AFSCN units under 14th AF). In view of this situation, the following recommendations represent the Committee's best judgments regarding resource decisions for effective mission accomplishment against a reasonable projection of requirements.

***Low Earth Orbit.*** For surveillance of objects in low earth orbit, the Committee recommends that the Air Force pursue the following initiatives in the areas of sensor calibration and modernization:

- ***Sensor Calibration.*** Sensor calibration is relatively inexpensive and should provide a higher cost payoff. The correct way to do sensor calibration has been successfully demonstrated and implemented. *Air Force Space Command should actively pursue implementation of that calibration methodology at the sensor sites, with accountability centralized in the SCC.*

- *Modernization.* Air Force Space Command should begin a process to modernize both the hardware and the software that are used for space surveillance data processing. The first step would be to establish a Center of Excellence with an off-line prototype test bed using modern engineering workstations and low-cost commercial software. This facility should be located within the Space Command complex (at Falcon AFB, for example), where both knowledgeable personnel (50 percent scientists and 50 percent operations personnel), and sensor data are available. This facility would be used to determine the operational impact of new processing techniques on the space catalog. Possible areas for investigation are:
  - *Orbit Estimation.* Determine whether improved propagators and filter technologies can reduce the personnel required to maintain the Spacetrack catalog during normal atmospheric changes and during maneuvers while providing greater track prediction accuracy and useful, trusted covariance estimates.
  - *Atmospheric Drag Estimation.* Determine whether orbits can be maintained during high and variable drag conditions by using self-consistent calculations of drag for a subset of reference satellites to establish useful estimates of air density for calculating drag for the remaining. Determine whether this technique will maintain good tracks using real (archived) sensor data taken during the onset of solar storms.
  - *Standards.* Establish standards for astrodynamics, telemetry, software, launch processing, and payloads (platforms, services, monitoring, data processing, etc.) in order to reduce stovepiping and to facilitate data exchange between military space systems.
  - *Sensor Coverage.* Support dual use of the proposed BMDO X-band radar at Kwajalein in order to supplement our Space Control and debris monitoring capabilities.

***Geosynchronous Earth Orbit.*** For surveillance of objects in geosynchronous orbit, the Committee recommends that *the Air Force should*

- Complete its upgrade of GEODSS while ensuring that the gaps in eastern Atlantic and western Pacific longitudes are filled.

***Spaceborne Sensor Systems.*** For spaceborne sensor systems to replace ground-based systems, the Committee recommends that the Air Force pursue surveillance of space from space with search capability.

- *MSX Satellite.* The Committee urges the Air Force to utilize the MSX satellite to the maximum extent possible in order to gain experience in performing the mission of space surveillance from a space platform.
- *Space Surveillance Requirements.* In addition, the Air Force should define the space surveillance requirements in terms of using space-based sensors and to evaluate the FDS test program to determine if its legacy is adequate to support specification of an operational SMTS that has the desired space surveillance capability. Furthermore, if the FDS includes a space surveillance capability, the Air Force should support the funding of testing for the 2 years of expected lifetime of the FDS to build confidence in the definition of operational requirements.

The Air Force can advocate actionable changes to Spacetrack by aiming toward a prototype operation in which experiments are carried out at relatively low levels primarily using the personnel and tools currently available with modest guidance and support from the outside. System changes will only be accomplished in response to demonstrated results with realistic inputs. The Air Force should emphasize using real-world data rather than synthetically generated sensor observations for which consistency must be demonstrated. It should proceed by considering the FPS-85 as its given fundamental sensor and adding observations from others, while monitoring track and prediction quality through the use of trusted covariance matrices.

Finally, Air Force Space Command, with its key and expanding national role in space operations, should be the location for an international center of excellence for space-related activities. Since 1980, the space-oriented analytical capability in AFSPC has been pared to the bone, and the R&D community has no operational space experience. Technical progress essentially has ground to a halt. This center would provide operational planning and technology depth for critical improvements to the SSN/SCC to meet the tough future challenges. It would work in concert with established AFSPC planning and requirements activities and AFMC technical support efforts.

# Appendix 1

## Sensor Calibration

Louis G. Walters

The earliest efforts for calibrating the inhomogeneous network of tracking instruments available to the SSN, and comprising 21 different sensor types, employed joint tracking efforts with the AFSCN. They used shared data collected on stable beacon-tracked satellites to establish the integrity of the geolocation and of the on-site processing for each participating sensor. These early efforts provided some impressive results (relocation of the Hawaiian datum, survey errors at the New Hampshire radar site, data processing errors at the Diyarbakir radar site) and continued with contractor support through 1965. For the following three decades, the SSN has depended upon self-calibration, content with the knowledge that errors that could seriously contaminate the reference orbit(s), such as geolocation, had been resolved. This effort was also driven by the fact that the processing algorithms used in SPADOC were not as accurate as the demonstrated quality of the sensors themselves, and the sensor data had to be deweighted to prevent the editing of good data.

In an environment driven by Space Control requirements, this sensor calibration process will need radical changes to incorporate the filter technologies that can provide the requisite prediction accuracies and the trusted covariance products describing those accuracies. A properly constructed orbit estimation filter will need accurate descriptions of the errors in data and environmental modeling to properly evaluate the contribution of tracking data to the derived orbit state, particularly in the era of a declining tracking resource.

The following table is cited from a dramatic demonstration<sup>13</sup> of the calibration potential of the SSN. In the referenced effort, the contractor endeavored to determine the thermal noise limits of the participating radars, and every factor that needed to be considered to achieve data accuracy at the thermal noise threshold, as confirmed by Gaussian histograms of the ranging residuals. By employing modified Kalman filter technology in the calibration effort, the product was a self-calibration process that does not permit the aliasing of errors into the calibration process and is real time. (In actual practice, it will be desirable to include third-party tracking data and/or ephemerides of certifiable accuracy in this processing).

Specific conclusions of this effort are that the tracking performance of the SSN ranging radars is far superior to that currently modeled in SPADOC. For PAVE PAWS and COBRA DANE, the calibration results are in good agreement with design data provided by the radar contractor (Raytheon), and the thermal noise limits, which were used in a predicted range residual

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<sup>13</sup> Wright, James R., "A New Method for Real-Time Calibration of the AFSPACECOM Tracking Network," ATA report TR SC-0001, 23 October 1987.

consistency test, were readily achieved. In this effort, an insidious problem contributing errors up to 600 meters at Eglin was also identified with operational errors in the periodic setting of the site's clock.

### RADAR RANGE

Sensor Number	Location	Thermal Noise Root Variance (meters)	Mean Bias Value (meters)	Bias Root Variance (meters)	Bias Half life (minutes)
354	Ascension Island	20	0	48	5
363	Antigua Island	18	0	26	5
386	Otis AFB, MA	3	0	3	5
387	Otis AFB, MA	3	0	8	5
388	Beale AFB, CA	6	-13	25	5
389	Beale AFB, CA	7	0	15	5
393	Cobra Dane AK	3	-18	15	5
396	PARCS, ND	6	5	45	5

The probable transition to modern filter technologies in routine orbit estimation demands highly competent sensor calibration data to reinforce the trustworthiness of the error modeling by covariance properties of the estimation process. A careful calibration process will also partially immunize the network products from the effects of reductions in the sensor inventory. The correction of metric observations takes two forms:

- The adjustment of each observable for errors that are local in nature, such as tropospheric and ionospheric refraction and offsets in the local clock determined from a global standard
- The adjustment for each observable for errors best determined by a global process for the entire network or for which key data, such as slant range needed to make a "light time" correction, are not acquired at an optical sensor.

Local corrections require local measurements, such as relative humidity and solar heating of the antenna pedestal, which would vastly complicate the transmission of data to a centralized facility for processing but which can be accurately modeled at the sensor site as functions of elevation angle and environmental measurements. In addition, refraction of radar rays by the ionosphere and troposphere introduce range errors that should be corrected.

The need for accountability in the sensor calibration process demands that monitoring adjustments for geolocation and sensor biases, and for latent errors in on-site smoothing, be determined at a centralized facility where third-party ephemerides and tracking data and the characteristics of the "calibration satellites" can be electronically collocated. Where the appropriate technical skill levels in radar engineering and estimation theory have been assembled, it has been demonstrated that truly impressive calibration results can be derived from orbital calibration. The limiting factor is the thermal limit of the radar instrument itself, and for radars currently organic to the network, this limit can be of the order of a few meters.

Third party sources of tracking data and ephemerides to support the sensor calibration process include satellites designed and tracked for this purpose, such as LAGEOS, and tracking data (not ephemerides) for stable satellites organic to the AFSCN. The latter contribute importantly to the low altitude measurement of sensor quality and to the quality of the on-site refraction modeling.

Sensor calibration, carefully done, affords the most cost effective means of improving SCC accuracy performance and, coupled with improved filter technologies, may partially immunize the network from site closures, since fewer observations per satellite may be needed to achieve the required accuracy of catalog products.

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## Appendix 2

### Direct Measurement of Drag Properties

Louis G. Walters

For cataloging applications, the average decay rate is included in the satellite state, and ephemeris propagation propagates this modeling with an isothermal approximation for the variation of density with perigee altitude. For precision special-perturbations applications, the density variation with satellite position is modeled by highly structured models that relate spatial density to parameters that have demonstrated a relationship to density, such as subsolar position, as well as geophysical parameters, such as decimetric solar flux and geomagnetic indices. These latter parameters are empirically related to a global modification of the atmospheric temperature profile, which in turn defines the density over an atmospheric column, including the spatial position of the satellite.

Of the family of satellite perturbations, the density is the more uncertain, as is the interaction of the satellite body with the atmosphere, the so-called drag coefficient. This density uncertainty is greatest at higher altitude, where the density falls off approximately exponentially with height; above 1,000 km, the drag effects of the atmosphere are generally negligible. For lower altitudes, errors of 15 percent are common, due in large part to the nonconcurrency of geomagnetic measurements as well as the empirical approximations relating them to exospheric temperature.

Concurrent direct measurements of the average density variations from installed models can be determined from the observed global variation in drag coefficients for a constellation of satellites of known or, preferably, spherical configuration. These variations can then be used to modify the density modeling or drag interaction coefficients of all satellites then modeled by the installed atmospheric model. This technique has been used by the Russians since the mid-1980s, and recently published<sup>14</sup> results indicated good success for the short-term predictions. A more ambitious program would continuously adjust the empirical relationship between geomagnetic data and the exospheric temperature, affording some predictive capability for atmospheric density modeling. The latter approach remains to be demonstrated.

For either approach, the data are readily available in the Spacetrack system, and the algorithms are readily understood. The benefit-cost ratio is believed to be high for inclusion of some form of drag monitoring in the Spacetrack system, since improvements in the direct modeling of the atmospheric density have been elusive over the past two decades. Atmospheric drag remains the more challenging modeling problem for satellites in low earth orbit and in the terminal phases of decay from orbit.

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<sup>14</sup> Nazarenko, A. I., "Technology of Evaluation of Atmospheric Density Variation," Center for Program Studies, Russian Academy of Sciences (paper presented at International Astrodynamics Meeting, Poznan, Poland, 5 July 1996).



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## Appendix 3

### Modified Kalman Estimation Filter

Louis G. Walters

Kalman developed the filter concept based upon the assumption that the “plant” noise was white. Under these conditions, an optimal estimate was derived subject to the conditions that the errors in the unestimated parameters were unbiased and white and that the data sources were properly modeled (or calibrated). In recent years, Kalman has published several works (in econometric journals) stating that the white noise hypothesis was incorrect and extolling the need to restate the filter theorem in the context of the problem. Unfortunately, most engineers use the Kalman filter and its derivatives without first verifying that the white noise hypothesis is satisfied. When the white noise hypothesis is satisfied *or* when the data overwhelm the problem, the filter works satisfactorily, but when the forcing function is nonwhite *and* the data are sparse, the filter can behave poorly. The Spacetrack orbit estimation is such a problem, where tracking data availability is variable and the forcing functions are time correlated. Some earlier studies of Kalman filter applications to the sparse data situations encountered in Spacetrack were based upon improper application of the filter concept and should be considered in that light.

The forcing functions in orbit determination are a set of force models (gravity, drag, thrusting, etc.). The state of the art in these models is imperfect. In Spacetrack, these models are further truncated and amplified. The resulting force model errors incurred are not white but are highly correlated spatially and temporally. A few orbit estimation specialists have recognized this fact and have developed and tested a modified Kalman filter designed specifically for this problem. (See, for example, J. Wright, “Sequential Orbit Determination with Auto-Correlated Gravity Model Errors,” *Journal of Guidance and Control*, 1981.) These filters, which derive the process noise function from physical principles, do work well in sparse data orbit estimation problems.

By properly incorporating physically derived relationships, these filters yield optimal orbit estimates and realistic covariance properties of the derived state. A trusted covariance matrix is useful in further automating orbit analyst functions (and reducing manpower requirements). Examples include editing poor tracking data, correlating tracking data to known objects, computing probability of collision, rapid post-maneuver recovery of orbit accuracy, allowing tasking to be based upon achieved accuracy, and providing an accuracy assessment for each ephemeris prediction for each user.

To exploit this autonomous property in driving editing and tasking, the tracking system must be adequately characterized by an ongoing calibration procedure. The expression “tuning” is often associated with the Kalman filter. With the modified Kalman filter, the process noise is

“tuned” by direct calculation from physically connected expressions, while the sensor “tuning” is accomplished by sensor calibration, preferably with third-party ephemerides of known accuracy.

Impressive demonstrations of the accuracy and processing efficiency of the modified Kalman filter have been reported in the literature, particularly by the Goddard Space Flight Center, and have been briefed to the AFSAB Space Surveillance Committee by the National Program sponsor. Efforts to extend these demonstrations to the sparse data situations encountered in Spacetrack should be considered to exploit these properties in any designs of Spacetrack systems in the 21<sup>st</sup> century.

# Appendix 4

## Physically Realistic Modifications to the Extended Kalman Filter

**Richard Hujsak**

### Abstract

A successful modification of the Extended Kalman Filter for orbit determination purposes gives improved orbit determination accuracy and can provide a trusted covariance. In the orbit determination problem the data are sparse, and for space surveillance they are very sparse, with long periods between periods of tracking. In a sparse data application it is critical to characterize force model errors and tracking system model errors realistically, especially the autocorrelation properties. Realistic stochastic processes for physical systems can be derived from the physical models themselves.

The following discussion provides some insight into the use of physical models in deriving stochastic models for orbit determination. It is apparent that this is a challenging science, requiring computationally efficient solutions to interdisciplinary problems in orbit mechanics, estimation, spacecraft operations, environment modeling, and tracking system models.

### 1.0 The System Equation

Application of a filter to the orbit determination problem begins with the system equation:

$$\frac{dX(t)}{dt} = A(t)X(t) + B(t)u(t). \quad (1.1)$$

If the orbit problem can be linearized and stated in the form of Eq. (1.1), then the integral is known and it defines the state time update process:

$$X(t_{k+1}) = \Phi_{k+1,k} X(t_k) + \int_{t_k}^{t_{k+1}} \Phi_{k+1,t} B(t)u(t)dt$$

where:  $X(t) \equiv$  state at time  $t$ ,  $u(t) \equiv$  error process at  $t$ ,  $A(t)$ ,  $B(t) \equiv$  continuous, integrable functions of  $t$ , and  $\Phi_{k+1,k} \equiv$  state transition from  $t_k$  to  $t_{k+1,k}$ . The covariance prediction becomes:

$$P_{k+1} = \Phi_{k+1,k} P_k \Phi_{k+1,k}^T + Q_{k+1,k}$$

where  $Q$  is the process noise. However  $Q$  is a function of  $u(t)$ ,

$$\begin{aligned}
Q_{k+1,k} &= \int_{t_k}^{t_{k+1}} \int_{t_k}^{t_{k+1}} \Phi_{k+1,t} B(t) E\{u(t)u(h)^T\} B^T(h) \Phi_{k+1,h}^T dt dh \\
&+ \left[ \int_{t_k}^{t_{k+1}} \Phi_{k+1,t} B(t) E\{u(t)X^T(t_k)\} dt \right] \Phi_{k+1,k}^T \\
&+ \Phi_{k+1,k} \int_{t_k}^{t_{k+1}} E\{X(t_k)u^T(t)\} B^T(t) \Phi_{k+1,t}^T dt
\end{aligned}$$

and is determined by the linearization process. If the filter is to be physically meaningful, the statistical character of  $u(t)$  must be derived and *not* assumed.

## 2.0 Physical Modeling of Acceleration Errors

The System Equation Eq. (1.1) is a system of first-order linear differential equations, written in matrix form. The orbit problem can be expressed as a system of first-order differential equations through the Lagrange Planetary Equations:

$$\begin{aligned}
\dot{a} &= f_a(a, e, i, \Omega, \mathbf{w}, M, \ddot{R}, \ddot{I}, \ddot{C}) \\
\dot{e} &= f_e(a, e, i, \Omega, \mathbf{w}, M, \ddot{R}, \ddot{I}, \ddot{C}) \\
&\vdots \\
\dot{M} &= f_M(a, e, i, \Omega, \mathbf{w}, M, \ddot{R}, \ddot{I}, \ddot{C})
\end{aligned} \tag{2.1}$$

where  $\ddot{R}, \ddot{I}, \ddot{C}$  are radial, intrack, and crosstrack accelerations,  $a, e, \dots, M$  are classical orbit elements. Define the state ( $X$ ) as the orbit elements and linearize the system of equations by expanding about the current estimates at the current epoch. Let:

$\ddot{R} = \ddot{R}_m + \Delta\ddot{R}$ ,  $\ddot{I} = \ddot{I}_m + \Delta\ddot{I}$ , and  $\ddot{C} = \ddot{C}_m + \Delta\ddot{C}$ , denoting the acceleration model by  $m$  and model error by  $\Delta$ . Then the System Equation (1.1) has been derived from the Lagrange Planetary Equations and the forcing function ( $u(t)$ ) can be defined by:

$$u(t) = \begin{bmatrix} \Delta\ddot{R} \\ \Delta\ddot{I} \\ \Delta\ddot{C} \end{bmatrix}. \tag{2.2}$$

At this point the stochastic properties of acceleration errors are not defined. In a textbook Kalman filter application each component of  $u(t)$  would be assigned a white noise variance, and  $Q$  would be a diagonal matrix. While most orbit determination experts recognize that acceleration errors are not characterizable as white noise, most authors fall into the trap of assigning a generic Gauss Markov process to each component of  $u(t)$ . In any case the noise model is usually *assumed* and *not derived*. Filter performance depends critically on that assumption. Filter performance is also critically dependent upon the analyst's ability to set "knobs" for the Gauss Markov model, that is, to "guess" how the physical behavior of the error can be characterized by a generic Gauss Markov model.

In contrast, it is possible to derive a stochastic model to represent acceleration errors. Such a derivation considers the acceleration equations and identifies the source of error in those equations. When such a derivation is made, the resultant process noise often has properties that

are quite distinct from a Gauss Markov process. In the case of acceleration errors due to gravity, the process noise model is completely defined by physical constants, and the analyst has no “knobs” to set.

A high-level discussion of two forces (gravity and drag) follows, illustrating these claims.

## 2.1 Gravity Errors

Gravity accelerations are usually computed from functions of latitude ( $\phi$ ), longitude ( $\lambda$ ), and height ( $h$ ), which are computed from the satellite position and hence are functions of orbit elements (states). Acceleration components can be computed in the up ( $U$ ), east ( $E$ ), and north ( $N$ ) coordinate system by:

$$\begin{aligned}
 g_U &= -\frac{\mathbf{m}}{r^2} \left\{ 1 + \sum_{n=2}^{n_{\max}} (n+1) \left( \frac{a_e}{r} \right)^n \sum_{m=0}^n P_n^m(\sin \mathbf{f}) [C_{nm} \cos m\mathbf{l} + S_{nm} \sin m\mathbf{l}] \right\} \\
 g_E &= -\frac{\mathbf{m}}{r^2 \cos \mathbf{f}} \left\{ \sum_{n=2}^{n_{\max}} \left( \frac{a_e}{r} \right)^n \sum_{m=0}^n m P_n^m(\sin \mathbf{f}) [C_{nm} \sin m\mathbf{l} - S_{nm} \cos m\mathbf{l}] \right\} \\
 g_N &= \frac{\mathbf{m}}{r^2} \left\{ \sum_{n=2}^{n_{\max}} \left( \frac{a_e}{r} \right)^n \sum_{m=0}^n \cos \mathbf{f} P_n^{m'}(\sin \mathbf{f}) [C_{nm} \cos m\mathbf{l} + S_{nm} \sin m\mathbf{l}] \right\}
 \end{aligned} \tag{2.3}$$

where prime ( $'$ ) indicates the derivative with respect to ( $\sin \phi$ ). The model coefficients  $C_{nm}$  and  $S_{nm}$  are defined by the gravity modeler (e.g., DMA), as are fundamental constants  $\mu$  and  $a_e$ , and  $n_{\max}$  is the maximum degree of the model.

There are two sources of gravity acceleration error. The first source of error is the gravity model itself, errors of commission, where each coefficient ( $C_{nm}$ ,  $S_{nm}$ ) in the model has some error associated with it. A second error arises in the application of a gravity model, when it is truncated for computational efficiency (as in Space Surveillance Center applications). Truncating the model generates errors of omission. Regardless of whether the error is due to omission or commission, the error in gravity accelerations can be written as:

$$\begin{aligned}
 \Delta g_U &= -\frac{\mathbf{m}}{r^2} \left\{ \sum_{n=2}^{n_{\max}} (n+1) \left( \frac{a_e}{r} \right)^n \sum_{m=0}^n P_n^m(\sin \mathbf{f}) [\Delta C_{nm} \cos m\mathbf{l} + \Delta S_{nm} \sin m\mathbf{l}] \right\} \\
 \Delta g_E &= -\frac{\mathbf{m}}{r^2 \cos \mathbf{f}} \left\{ \sum_{n=2}^{n_{\max}} \left( \frac{a_e}{r} \right)^n \sum_{m=0}^n m P_n^m(\sin \mathbf{f}) [\Delta C_{nm} \sin m\mathbf{l} - \Delta S_{nm} \cos m\mathbf{l}] \right\} \\
 \Delta g_N &= \frac{\mathbf{m}}{r^2} \left\{ \sum_{n=2}^{n_{\max}} \left( \frac{a_e}{r} \right)^n \sum_{m=0}^n \cos \mathbf{f} P_n^{m'}(\sin \mathbf{f}) [\Delta C_{nm} \cos m\mathbf{l} + \Delta S_{nm} \sin m\mathbf{l}] \right\}
 \end{aligned}$$

where  $\Delta$  is either the error in the coefficient retained or the size of the coefficient omitted. Therefore a physically realistic plant noise for the gravity problem is derived to be:

$$u(t) = \begin{bmatrix} \Delta C_{2,0} \\ \Delta C_{2,1} \\ \Delta S_{2,1} \\ \vdots \\ \Delta C_{70,70} \\ \Delta S_{70,70} \end{bmatrix},$$

a matrix of random constants. Alternative formulations provide for computational efficiency (see Wright [1]), but all physically derived plant models for gravity errors are driven by random constants. Use of white noise or a Gauss Markov process (which is driven by white noise) to characterize gravity model errors is obviously a risky proposition.

## 2.2 Drag Errors

Drag acceleration errors require a stochastic representation that is completely different. Drag acceleration is usually simplified and written in vector form as:

$$\ddot{\mathbf{r}}_D = -\frac{1}{2} B \rho v_a \dot{\mathbf{r}}_a$$

where  $B$  is a function of area, mass, and drag coefficient,  $\rho$  is a density computed from an atmospheric density model (e.g., Jachia '71),  $\dot{\mathbf{r}}_a$  is satellite velocity with respect to the rotating atmosphere, and  $v_a = |\dot{\mathbf{r}}_a|$ .

In the space surveillance problem drag acceleration error is dominated by the errors in  $B$  and the errors in  $\rho$ . One might wish to assign  $B$  as a state and write plant noise as an error in density:

$$u(t) = [\Delta\rho(t)].$$

But the state  $B$  requires an a priori variance and a stochastic characterization. One could assign Gauss Markov processes, but consider that  $\Delta B$  is a function of the uncertainty in size, shape, orientation, and mass of an object.  $B$  can be a constant (though rare), periodic (operational satellites with solar panels), or vary randomly depending on the satellite type and the attitude stability. The variability in  $B$  is constrained by the size of the object itself. (Note that least squares treats  $B$  as a constant when  $B$  is actually time-varying.) How can physically realistic characterizations of the variability in  $B$  be achieved? The Space Surveillance system has long collected data which can be exploited to bound and quantify the variability in  $B$ . The Space Surveillance Center data base includes radar cross section and vehicle type (payload, rocket body, etc.), that can be exploited. For much of the catalog the characterization as fragments of debris bounds the problem.

Density varies exponentially with altitude. Density errors ( $\Delta\rho$ ) also vary exponentially with altitude. To simplify the stochastic models for eccentric satellites it is convenient to scale density error by density ( $u(t) = \mathbf{D}\mathbf{r}(t)/\mathbf{r}(t)$ ). If atmospheric density models have low percentage error (20 percent) at low altitude and higher percentage error (100 percent) at higher altitudes,

then the stochastic model will have a variance that is altitude dependent. Density errors decorrelate rapidly with latitude and sun hour-angle but are highly correlated on consecutive revs through the same latitude and same sun hour-angle. These properties all contribute to the stochastic model for density errors, and it is apparent that a single Gauss Markov stochastic function will not accurately represent the physical processes at work.

### **3.0 Realistic Covariance**

The Kalman filter is derived from statistical hypotheses, assuming that the statistics of the problem are known. A covariance is formed by the filter, not as a byproduct but as an integral part of the mathematical machine. Filter performance is tied to the statistical integrity of the statistical characterization of the system errors, both in the models and in the inputs to the models. In estimation theory a filter is “optimal” if the statistical characterization of the system errors is correct; otherwise it is suboptimal. In engineering parlance the axiom is “garbage in = garbage out.” Modification of the Kalman filter is an attempt to correctly characterize system errors, especially force model errors, by deriving the actual statistical properties from physics expressions. If the physically derived process noise improves filter performance, it is because it also improves the realism of the covariance.

### **References**

Wright, J. R., “Sequential Orbit Determination with Auto-correlated Gravity Modeling Errors,” *Journal of Guidance and Control*, Vol. 4, No. 2, May-June 1981, page 304.



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## Appendix 5

# Spiral Decay

Louis G. Walters

Spiral decay imposes demanding requirements on surveillance support. During the terminal phase, as each perigee passage lowers the apogee altitude and the satellite engages the denser atmosphere around the entire orbit, the satellite, with a spherical earth and isothermal atmosphere, would execute a logarithmic spiral until terminal impact (hence the name Spiral Decay). This convenient theoretical model is compromised by several physical processes:

- The atmosphere above 90 km, the altitude at which terminal decay is certain, is not isothermal and, while it is carefully modeled, is subjected to changes due to geophysical phenomena with only approximate (and empirical) modeling to temperature and density.
- During the terminal phase, the attitude will be subjected to large and unpredictable aerodynamic torques, unless the object is spherical. The aerodynamic properties of the satellite may also change due to the surgical effect of high localized heating on heat-sensitive surfaces and components. The best that can be expected is that the object will tumble, permitting the derivation of an average drag coefficient consistent with the modeled density.

These factors contribute to the rapid transition during terminal decay and to the need for frequent radar contacts to monitor these transitions. Where a real impact hazard exists, such as that from a 3,000-pound lead safe (Skylab) or an active nuclear source (Cosmos 954), international surveillance assets have been recruited to provide as much as one contact/rev. To prepare for future high-risk decay events, the interoperability of these assets should be improved by joint calibration exercises.

A new dimension has been added with interest in the decay phenomenology from high-energy orbits. As demonstrated by Molniya experience, these orbits will decay in 4 to 8 years yet may not circularize prior to decay due to lunar and solar gravity perturbations. These satellites also have perigees in southern latitudes, where few surveillance assets exist, making their observation difficult.

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# Appendix 6

## SCC System Architecture

Louis G. Walters

### Catalog Processing Architecture

The catalog is the most visible product of the space surveillance system (at times called SPADOC or Spacetrack). It identifies (with limitations imposed by security concerns) all space objects capable of being tracked by the SSN, generally larger than 10 cm in LEO, and provides a state vector (“element set”) for each. The catalog is primarily used for sensor tasking and acquisition and for object identification when observations are collected.

The catalog format has been virtually unchanged over the 4 decade existence of the SSN. The processing algorithms represent a compromise between computational assets available to the system and user community and accuracy, resulting in extensive use of closed form or general perturbation methods for propagation of ephemerides. A large and international base of legacy users must be served irrespective of the future evolution of the SSN.

While the catalog processing algorithms have changed little over the last several decades, there are now compelling reasons to reexamine this architecture. Consider the following:

- Computer technology has expanded to erase any global requirements for optimization in the processes and processing; a single desktop PC now has the processing power of the entire SSN when the current SPADOC system was conceived.
- Physical hardening, which during the cold war depended upon thousands of feet of granite cover, can now be achieved by redundancy and physical dispersal of the modest computer platforms now available.
- Global high-speed communications will permit the SSN mission to be distributed and dispersed.
- The environment, particularly atmospheric drag, may be better defined by on-line measurements of satellite decay rates made possible by the higher precision measurements currently available.
- High-value missions will be concerned with collision with any crossing orbits, so the risk assessment will require trusted error estimates for these objects to define the need for evasion, if taken.

But, more critical to the future configuration and capabilities of the SSN, effective space control will require greater accuracy and responsiveness in SSN catalog products, and accuracy must be quantified for each element set in terms of covariance products conveying realistic estimates of both tracking data and environmental definition efforts. The future system must support the acquisition requirements of the smallest aperture device fielded for tracking,

illumination, and negation of foreign space assets—for the laser *a reasonable requirement would be 100 m or better for a 12-hour prediction at all operational altitudes*. To measure the impact of these requirements on the architecture of a future SSN, consider the data flow in the accompanying figure. While it resembles the current system in the Cheyenne Mountain Complex, several important changes stand out:

- Two satellite catalogs will be produced. One, the familiar general perturbations version in use over the past 4 decades, will support the legacy users for an indefinite time. The second, a special perturbations catalog, will convey all the accuracy potential available from the tracking data and environmental knowledge and will describe its accuracy in terms of trusted covariance products. The proven orbit estimation technology capable of generating this product—a technology based upon modified Kalman filter technology, which has been qualified for use in the National Program (NP) family—is described in Appendix 3, “Modified Kalman Estimation Filter.” This special perturbations capability is sized to maintain up to the entire satellite inventory if needed.
- An on-line sensor calibration system will be embedded in the process to define and monitor sensor performance, utilizing third-party ephemerides and/or tracking data. Accurate definition of sensor characteristics is required to properly allocate sensor and environmental errors in the modified Kalman filter technology. Independent sources of ephemerides for sensor calibration will be drawn from satellite programs such as LAGEOS and from the beacon-tracked satellite inventory supported by the AFSCN.
- By tracking passive satellites whose exact configuration (shape, attitude, on-orbit mass) is known, changes from the modeled atmospheric density can be monitored (in addition to those due to and modeled by the solar and geomagnetic indices). To the extent that it can be demonstrated that these changes are global, they can be applied to the population as a whole, as discussed in Appendix 4, “Physically Realistic Modifications to the Extended Kalman Filter.”
- The covariance products generated by the modified Kalman filter are powerful tools in the observation association and tasking logic and will provide early clues as to maneuvers executed by adversaries for mission or evasion purposes. By defining how well the system is entitled to know a satellite’s orbit, these products will contribute to autonomy and automation in many routine operations. intended use; consider, for example, the meaning and usage of time in astrodynamic calculations.
- By adopting the principles of open architecture, many of the routine software functions can be drawn from commercial inventories of these products, with dramatic savings in cost and development time. The latter is important to avoid the early obsolescence of prior procurement practices, and the unforgiving nature of users of these commercial off-the-shelf (COTS) products will reduce testing time and latent errors. Commercial information management products have a reliability seldom achieved over the lifetime of stovepipe development practices, in which the “maintenance” costs over the system life cycle commonly exceed the original development costs. Commercial products must survive in an unforgiving marketplace, and their qualifications are far more extensive than that affordable to the custom system developer. With alternative sources available for many of the information management products, such as operating systems, software development products, database management systems, and communications software, and for products that make these alternatives interchangeable, the system developer can devote a shrinking software development and qualification resource to the central military application. This luxury will take years off the development process for new and improved systems and will substantially reduce the life-cycle costs as well. All COTS products must be subjected to a stringent suite of tests to qualify them for their intended use; consider, for example, the meaning and usage of time in astrodynamic calculations.

# Spacetrack/2000 Concept

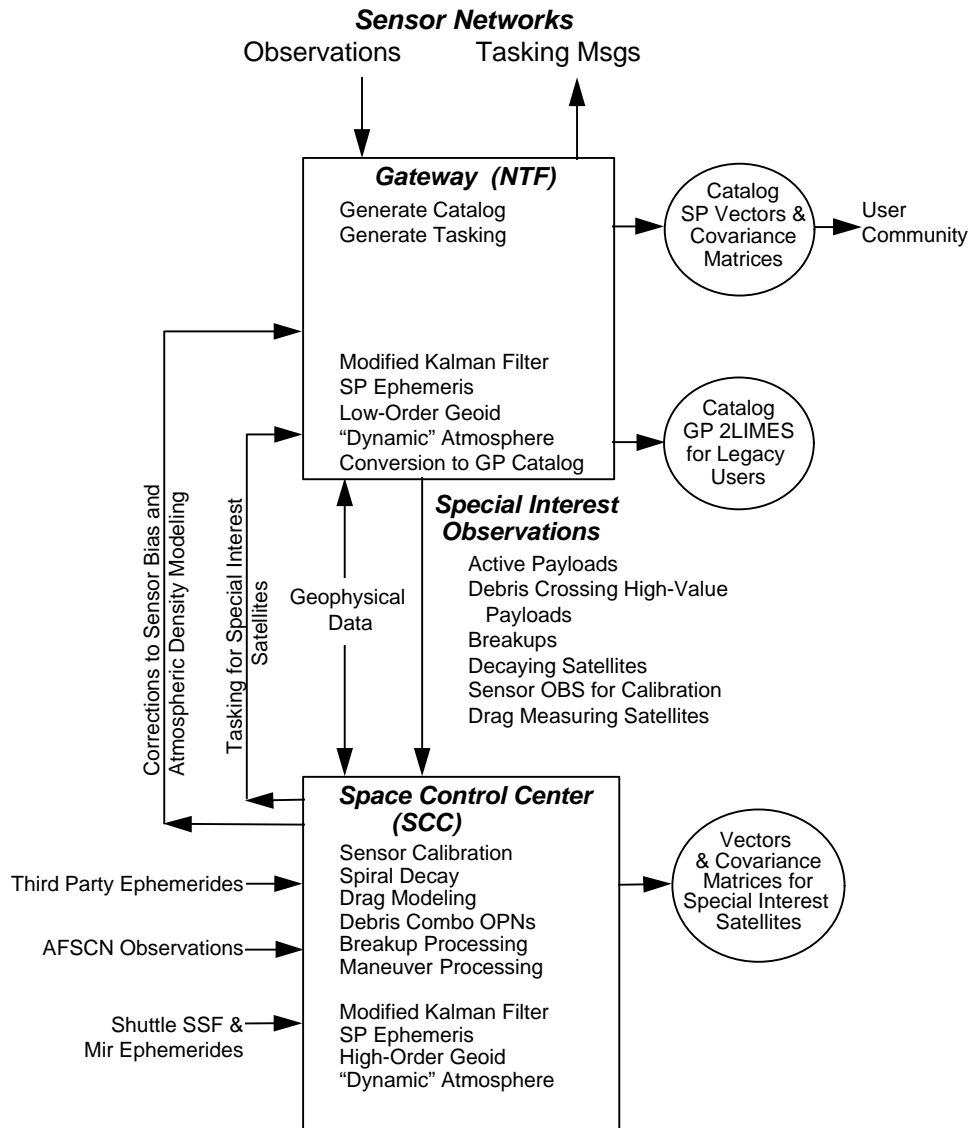


Figure 3

- The spiral decay requirement remains one of the more demanding on the tracking assets. During terminal decay, the orbital environment changes substantially, and to the extent that these changes are not accurately modeled, additional tracking contacts are needed to maintain integrity in the orbit estimation. This process is intrinsically international in scope, for the debris corridor can contaminate any country. In the past, international cooperation has been solicited when the decaying object has posed a physical or health hazard, and this need should be formalized with interoperability agreements and joint sensor calibration. In the future, the spiral decay problem will also be complicated by dependence upon high-energy orbits, which

will decay from elliptic orbits, complicating the global need for better modeling of the atmosphere.

- Not shown, but under consideration, is a catalog of asteroids and comets, derived from observations collected by the electro-optical sensors organic to the SSN. This process is clearly not real time, nor does it present a threat requiring immediate action to defend military assets. It should be based upon the integrated observational assets of the SSN and of observatories and amateur observers international in scope. The process is competently supported by the university astronomy community at the present time, and this effort should be supported by connectivity to the SSN electro-optical telescope data source and the ability to task that resource.

**Appendix A**  
**Task Statement**  
**Space Surveillance,**  
**Asteroid and Comet Impact Warning for Earth,**  
**and Space Debris**

*March 1995*

**Space Surveillance**

*Background.* The Space Surveillance mission has been handled by the Air Force since 1957 when the first Sputniks were launched. The initial facility was at Hanscom AFB and was later moved to the Cheyenne Mountain Complex in Colorado Springs. The mission requirements were largely driven by the Soviet threat for all these years. In fact, the missile warning mission has dominated the space surveillance mission to such an extent that the evolution of capability in the latter has been painfully slow and has lagged the state of the art substantially.

The space surveillance mission area remains an essential part of the Air Force function to support the warfighter with space assets. The threat to space assets and their supporting capability is evolving with the need to monitor an increasingly crowded environment. Operational spacecraft have in general been large objects easily tracked by the space surveillance network.

The most serious problem with the current system is that the theory, software, and hardware used for orbit determination at Space Control Center (SCC) have evolved only slowly over the last 20 years, while the state of knowledge of orbit determination, the state of software and hardware technology, the sensitivity of sensors, and the accuracy of the data have advanced immensely. This has precluded the system from taking advantage of the accuracy of the data to reduce the overall tasking load of the sensors, which at the same time would enable them to contribute more in other areas of space surveillance, such as debris monitoring, and consequently address more areas for the same total cost.

The sensitivity of several sensors has increased significantly in the last 20 years. This has substantially enhanced the number of objects detected. However, processing limitations at SCC have precluded the maintainable catalog from absorbing all these new objects into the data base.

In future applications of surveillance data, improved accuracy and the ability to define that accuracy in meaningful terms to the warfighter will be a primary objective. The accuracy of sensors has increased substantially over the last two decades, but the capability to calibrate these instruments on-line to their inherent noise level is only now becoming available with laser instrumentation. The remaining impediment to achieving higher accuracy is the drag environment for satellites operating below 1,000 km, and this will only be resolved when on-line procedures



for calibration of the density models are implemented. Finally, as increasing demands on accuracy are made by the user community, alternative filter technologies that can produce covariance products incorporating both the sensor and environmental error models should be considered.

**Task Description.** The Committee should

- Assess the capability of the current Space Surveillance Networks (SSN) with respect to search for new or lost earth satellites or objects, accuracy of measurements, timeliness, and transmission of sensor data to a central catalog station for all altitudes from 150 km to 35,000 km. Include considerations of reducing errors.
- Determine what and how improvements to the SSN should be accomplished.
- Assess the capability of the current earth satellite catalog production with respect to accuracy, timeliness, and dissemination of data products. Include analyses of environmental factors that introduce errors into catalog products and of technologies that define the propagation of these errors into catalog products with high confidence.
- Determine what and how improvements in producing the catalog(s) can be accomplished. Consider the exploitation of computer performance as an opportunity to transition the catalog to a format based upon special perturbations technology with trusted covariance properties embedded into it.
- Assess the benefits of improved accuracy and of the ability to define that accuracy in meaningful terms to Air Force, interagency, and international operations as orbits with desirable properties (e.g., sun synchronous) are exploited by an increasing number of spacefaring nations.
- Recommend appropriate Air Force actions.

## **Asteroid and Comet Impact Warning for Earth**

**Background.** The growing concerns about the asteroid and comet threat to earth may result in a new mission for the space surveillance system. The capability to integrate and perform this potential mission needs to be assessed as part of the future architecture of space surveillance.

Asteroids and comets have struck the earth over its history in Russia, Yucatan, and the United States (Arizona). It is now believed that an asteroid impact caused the cataclysmic extinction of the dinosaurs. Although impacts are rare, they could have devastating effects. At a minimum the Air Force should consider Deep Space Surveillance as a new mission area.

**Task Description.** The Committee should

- Review and assess the Asteroid and Comet environment and earth impact rate
- Assess detection and tracking requirements and Air Force capabilities
- Determine and describe appropriate capabilities and missions for the Air Force
- Recommend Air Force actions for these new missions

## **Space Debris**

**Background.** There is a proliferation of smaller-size satellites on one hand and a large, uncontrolled growth of debris, consisting of dead satellites and fragments from breakups of a variety of sizes, on the other. As a result, there is a significant overlap of the two. Further, there is a growing national concern, driven by the National Aeronautics and Space Administration's

(NASA's) requirements for keeping track of debris down to 1 cm characteristic size for safety of manned spacecraft. Hence, the space surveillance system must maintain an orderly and accurate catalog of all objects in space to ensure that the mission is accomplished despite its evolving nature.

The only organized collection and analysis of small Space Debris has been by NASA/JSC, employing modeling and estimates because of the sparse data that have so far been collected. Further, the numbers of objects in the Air Force catalog and NASA's debris curves do not agree where they overlap in the 10- to 100-cm object size range. The Air Force should consider a more active role.

**Task Description.** The Committee should

- Independently assess the seriousness of space debris as it may affect Air Force assets and space operations.
- Evaluate the dynamics and factors that produce and/or reduce space debris.
- Independently review the models and assumptions for the evolution of the historical space debris calculations and predictions, particularly for the condition of unstable growth known as collisional cascading.
- Review and compare Air Force studies measurements, assumptions models and assessments of space debris with those produced by other government agencies. Determine the reasons for any differences.
- Recommend appropriate Air Force actions.

## Potential Impact of the Study

The major result of the study would be to identify means to enhance overall mission capabilities of the Air Force in the three subjects addressed substantially while reducing operational costs of the system

The reduction of the manpower and the reduced number of sensor sites required for Space Surveillance, the reduction of the maintenance of the software by using more commercial packages, and minimizing the use of one-of-a-kind software/hardware packages in application will be clarified.

The actions required by the Air Force in the new mission area of Planetary Defense will be identified.

The seriousness of Space Debris and its effects on Air Force space operations will be clarified and any additional efforts required will be identified.

## Study Organization

Chairman	Dr. F. Robert Naka
General Officer Participant	Brig Gen Thomas J. Scanlan, Jr., SAF/ST
Senior Civilian Participant	Mr. John H. Darrah, HQ AFSPC/CN
Executive Officer	Lt Col Donald Jewell, HQ AFSPC

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## Appendix B

### Members and Affiliations\*

Dr. F. Robert Naka, Chair  
President and CEO  
CERA, Inc.  
Vice President, Engineering (Ret)  
GTE Government Systems Corporation

Dr. Gregory H. Canavan  
Senior Scientific Advisor  
Los Alamos National Laboratory

Dr. Rankin A. Clinton  
Director (Ret)  
Army Intelligence Agency

Mr. Theodore Jarvis  
Director of Strategic Studies (Ret)  
The MITRE Corporation

Dr. O'Dean P. Judd  
Laboratory Fellow  
Los Alamos National Laboratory

Dr. Antonio F. Pensa  
Associate Division Head  
AeroSpace Division  
MIT Lincoln Laboratory

Maj Gen Robert A. Rosenberg, USAF (Ret)  
Executive Vice President and  
General Manager  
Washington Operations  
Science Applications International  
Corporation

Dr. Edward Teller  
Director Emeritus  
Lawrence Livermore National Laboratory

Mr. Samuel M. Tennant  
President Emeritus  
The Aerospace Corporation

Dr. Louis G. Walters  
Astrodynamics Consultant

Col Simon P. Worden, USAF  
Commander  
50<sup>th</sup> SAF Space Wing

Mr. John H. Darrah  
Chief Scientist  
HQ Air Force Space Command

Brig Gen Thomas J. Scanlan, Jr., USAF  
Director, Space Systems  
SAF/ST

Lt Col Donald L. Jewell, USAF  
Executive Officer  
HQ Air Force Space Command

*\* Affiliations as of 1 March 1995*

## Panel Organization

### **Surveillance Panel**

Dr. Bob Naka, Chair

Dr. Greg Canavan

Mr. Ted Jarvis

Dr. Dean Judd

Dr. Tony Pensa

Mr. Sam Tennant

Dr. Lou Walters

### **Space Debris Panel**

Dr. Bob Naka, Chair

Dr. Greg Canavan

Dr. Dean Judd

### **Asteroids and Comets Panel**

Dr. Greg Canavan, Chair

Mr. John Darrah

Dr. Dean Judd

Dr. Bob Naka

Dr. Edward Teller

### **At-Large Members**

Dr. Randy Clinton

Maj Gen Rosie Rosenberg, USAF (Ret)

Col Pete Worden, USAF

## **Appendix C**

### **Committee Meetings**

#### ***Full Committee Meetings***

- MIT Lincoln Laboratory, Lexington, MA 8-10 May 1995
- MITRE Corporation, McLean, VA 30 May - 2 June 1995
- HQ AFSPC, Colorado Springs, CO 19-21 June 1995
- MITRE Corporation, Colorado Springs, CO 18-20 September 1995
- MIT Lincoln Laboratory, Lexington, MA 20-23 February 1996

#### ***Surveillance Panel Meetings***

- MITRE Corporation, Colorado Springs, CO 28-29 November 1995
- Phillips Laboratory, Albuquerque, NM 9-11 January 1996
- Space and Missile Systems Center, Los Angeles, CA 14 March 1996
- Cape Cod AFS, MA 19 March 1996

#### ***Asteroids and Comets Panel Meetings***

- Lawrence Livermore National Laboratory, Livermore, CA 22-26 May 1995
- Many installations, Maui, Hawaii, Oahu, HI \* 8-12 April 1996

#### ***Debris Panel Meetings***

- Loral Aeronutronic, Santa Margarita, CA \* 17-19 July 1995
- Phillips & Sandia Laboratories, Albuquerque, NM 11 August 1995
- NASA Johnson Space Center, Houston, TX 16-17 August 1995
- NASA Johnson Space Center, Houston, TX 17 October 1995

\* *Joint meetings with Surveillance Panel*

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## Appendix D

### Acronyms and Abbreviations

AFSCN	Air Force Satellite Control Network
AFSPC	Air Force Space Command
AMOS	Air Force Maui Optical Station
AMTA	Advanced Multicolor Tracker for AMOS
ASAT	Antisatellite
AU	Astronomical Unit
BMDO	Ballistic Missile Defense Office
BW	Bandwidth
CCD	Charge-Coupled Device
CINC	Commander-in-Chief
CIS	Compensated Imaging System
CMC	Cheyenne Mountain Complex
COE	Center of Excellence
COMINT	Communications Intelligence
COPOUS	UN Commission On The Peaceful Uses Of Outer Space
COTS	Commercial Off the Shelf
dB	Decibel
dBsm	Decibels Above One Square Meter
DMSP	Defense Meteorological Support Program
DOSE	Dynamics of Solid Earth
ELINT	Electronic Intelligence
EO	Electro-Optical
FDS	Flight Demonstration System
FISINT	Foreign Instrumentation Signals Intelligence
FOBS	Fractional Orbit Bombardment System
FSU	Former Soviet Union
GEO	Geosynchronous Earth Orbit
GEODSS	Ground-Based Electro-Optical Deep Space Surveillance
GPS	Global Positioning System
GSO	Geostationary Orbit
HAX	Haystack (radar)



HEO	Highly Inclined Earth Orbit
IR	Infrared
JSC	Johnson Space Center
kg	kilogram
km	kilometer
LANL	Los Alamos National Laboratory
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
LPC	Long Period Comet
LWIR	Longwave Infrared
MOTIF	Maui Optical Tracking and Identification Facility
MLWIR	Medium Longwave Infrared
MPA	Mission and Payload Assessment
MSSS	Maui Space Surveillance Site
MWIR	Mediumwave Infrared
NASA	National Aeronautics and Space Administration
NB	Narrowband
NCMC	NORAD Cheyenne Mountain Complex
NEO	Near-Earth Object
NP	National Programs
NSA	National Security Agency
O&M	Operations and Maintenance
RSO	Resident Space Object
RTODS	Real Time Orbit Determination System
SBIRS	Space-Based Infrared System
SBV	Space-Based Visible
SCC	Space Control Center
SIGINT	Signals Intelligence
SLBM	Sea-Launched Ballistic Missile
SMTS	Space Missile and Tracking System
SPADOC	Space Defense Operations Center
SSN	Satellite Surveillance Network
SWIR	Shortwave Infrared
TOA	Total Obligational Authority
UHF	Ultrahigh Frequency
USSPC	United States Space Command
WB	Wideband

# Appendix E

## Report Distribution

### Headquarters Air Force

SAF/OS	Secretary of the Air Force
AF/CC	Air Force Chief of Staff
AF/CV	Vice Chief of Staff
AF/CVA	Assistant Vice Chief of Staff
SAF/AQ	Assistant Secretary for Acquisition
SAF/AQ	Military Director, USAF Scientific Advisory Board
SAF/SX	Deputy Assistant Secretary for Space Plans and Policy (2 copies)
AF/IL	Deputy Chief of Staff, Installations and Logistics
AF/ST	Air Force Chief Scientist
AF/XO	Deputy Chief of Staff, Air and Space Operations
AF/XP	Deputy Chief of Staff, Plans and Programs
AF/HO	Air Force Historian
AFCIC/CC	Commander, Air Force Communications and Information Center

### Air Force Space Command

AFSPC/CC	Commander
AFSPC/ST	Chief Scientist (4 copies)

### Air Force Materiel Command

AFMC/CC	Commander
AFRL/CC	Commander, Air Force Research Laboratory
AFRL	Space Vehicles (Geophysics) Directorate

### National Reconnaissance Office

Director  
SIGINT Acquisition and Operations Directorate

### Other

AF SAB Co-Chairs  
Study Committee  
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<b>13. ABSTRACT (Maximum 200 Words)</b> This Study was produced by the Air Force Scientific Advisory Board. It was requested by the Commander Air Force Space Command and approved by the Secretary and Chief of Staff of the Air Force. It covers three topics, each of sufficient depth to be study of its own: Space Surveillance, Asteroid and Comet Impact Warning for Earth, and Space Debris. Space Surveillance is the unifying theme.  Space Surveillance is a secondary mission to that of Missile Warning and has long been neglected. Almost all sensors were deployed for missile warning and used for Space Surveillance on a non-interference basis. Attempts to improve data processing, though expensive, were upgraded to the mainframe environment, keeping most old algorithms in place. Fortunately, improving the accuracy and timeliness of the sensors and data processing is now relatively inexpensive because most techniques are commercially available. Ultimately, Space Surveillance should be conducted from spaceborne sensors. They are discussed and recommended here.			
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