From Satellite Tracking to Sp
The USAF and Space Surve

pace Situational Awareness:
eillance, 1957-2007

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(Overleaf) NAVSPASUR transmitter site, Lake Kickapoo, Texas, 1993. *(Photo by T. Kneisel) (Unless otherwise credited, all photos courtesy of the author.)*

In 2007, discussions about the need to improve space situational awareness (SSA) abounded among senior leaders in the United States Air Force (USAF), elected officials, corporate executives, and a host of others worldwide who relied on satellite systems. As one expert explained, SSA—“the ability to ‘see’ and understand what is going on in space”—provided the “foundation stone” for all operations in that domain. It ensured that working satellites did not interfere with one another, that collisions with detectable debris could be avoided, and that reasons—natural, nefarious, or other—for satellite ailments could be accurately diagnosed.[1] From a military perspective, Gen. Kevin P. Chilton, commander of Air Force Space Command (AFSPC), focused first and foremost on SSA, because he needed “to not only catalog but also understand what is up there, to understand when a satellite maneuvers, to understand when something is deployed off a satellite or a bus, and ultimately to be able to determine the capabilities of the satellite and the intent of the operator.”[2] Fundamental to meeting demand for improved SSA in 2007 was the U.S. Space Surveillance Network (SSN) that had evolved over a half century for detecting, tracking, identifying, and cataloging all man-made objects in outer space.

“THE ABILITY TO ‘SEE’ AND UNDERSTAND WHAT IS GOING ON IN SPACE”—PROVIDED THE “FOUNDATION STONE” FOR ALL OPERATIONS IN THAT DOMAIN

Evolution of the SSN occurred in several phases. The first phase, which lasted seven years (1957-1964), focused on the fundamental requirement for detection, tracking, and identification of a small but growing number of artificial earth-orbiting satellites and assorted pieces of space debris. Efforts to establish a Space Defense Center deep underground in Cheyenne Mountain and to meet more demanding requirements for computational precision, better network communications, improved tracking capacity, accurate decay predictions, and anti-satellite (ASAT) support marked a second phase (1964-1971). More foreign satellites in higher-altitude orbits, greater need for timely warning and verification of attacks on U.S. space assets and, somewhat later, preparations for an experimental, air-launched U.S. ASAT system, along with creation of a Space Defense Operations Center to replace the Space Defense Center, constituted a third phase (1971-1998). Pursuit of SSA as an essential first step toward achieving and maintaining space control signaled the emergence of a fourth phase (1998-present).

A nagging concern among U.S. Presidents and their national security advisers underlay all these phases. From Dwight D. Eisenhower to George H.W. Bush, Presidents confronted a nuclear-armed, openly confrontational Soviet Union in a Cold War—one where, after 1957, the arsenals included intercontinental ballistic missiles and earth-orbiting satellites. Mindful of the surprising blow Japan struck against the United States on December 7, 1941, U.S. political and military leaders remained acutely sensitive to avoiding another “Pearl Harbor,” regardless of whether the attack came from land, sea, air, or space. As the role of space-based platforms in reconnaissance, surveillance, early warning, and communications became increasingly vital to national security, especially to guarding against surprise attack on North America, safeguarding those platforms became increasingly important. The collapse of the Soviet Union and the end of the Cold War did little to dampen that sensitivity among later Presidents, because the number of nations with nuclear weapons, long-range rockets, and a potentially hostile presence in space was on the rise. The world of the early twenty-first century appeared just as dangerous, perhaps more dangerous, than the Cold War era. Therein lay the most compelling reason for the maturation of satellite tracking into space situational awareness.

Phase One: 1957-1964

Plans for satellite tracking began in early 1955, preparatory to launching the first U.S. earth satellite for the International Geophysical Year (IGY), scheduled from July 1957 through December 1958. Convinced that an object in orbit could be acquired optically by observers with binoculars or Askania-type cameras, Harvard University’s Dr. Fred L. Whipple, director of the Smithsonian Astrophysical Observatory (SAO), arranged for Ohio State University’s Dr. J. Allen Hynek to head a program sometimes referred to as SPOT (Smithsonian Precision Optical Tracking). Whipple and Hynek arranged for renowned optician Dr. James G. Baker and mechanical specialist Joseph Nunn to collaborate on designing a high-precision, satellite-tracking camera based on the Super-Schmidt camera developed for the Harvard Meteor Project in the 1940s. Meanwhile, recognizing the need to detect the satellite visually and obtain sufficiently precise, preliminary orbital data for the twelve SAO Baker-Nunn stations to know where to point their cameras, Whipple prevailed upon

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(Top) Moonwatch telescope operators, ca. 1958.

(Above) Moonwatch analysts, ca. 1958.

"Operation Moonwatch" teams of volunteer, amateur astronomers worldwide to report their visual observations.[3]

Several Moonwatch teams and individual participants in the western United States would become interested in precision satellite spotting as early as 1959. With financial support from North American Aviation's Space and Information Systems Division and the U.S. Air Force's Air Defense Command (ADC), those teams formed the Western Satellite Research Network (WSRN). One volunteer in particular, Professor Arthur S. Leonard of Davis, California, proved so adept at detection and precise observation of small, faint objects that ADC officers concluded Moonwatch could provide better identification of space objects than mechanical radars. Intended originally to last only for the duration of the IGY and to track at most a handful of U.S. satellites, Whipple's SAO optical network would continue its operations into the 1970s.[4]

Despite most upper-air research scientists' confidence in optical methods for tracking the first U.S. satellite, Milton Rosen, who was technical director for the Vanguard project, had doubts. Consequently, he asked John T. Mengel's Tracking and Guidance Branch at the Naval Research Laboratory (NRL) to develop an electronic detection and tracking system for use in conjunction with the optical one. Using radio interferometry to triangulate signals transmitted from a satellite, Mengel's assistant Roger L. Easton designed the Minitrack system. Ultimately, Minitrack included fourteen ground installations situated mostly on a north-south "fence" or "picket" line that stretched along the east coast of North America and the west coast of South America to maximize chances of intercepting every pass of a Vanguard IGY satellite launched from Cape Canaveral and orbiting higher than 300 miles. Like Moonwatch on the optical side, Minitrack had its amateur complement—Project Moonbeam—that enabled amateur radio operators to build simplified tracking stations for about $5,000 using a "Mark II" system also devised by Easton. The Minitrack network itself operated only into the early 1960s.[5]

The Soviet Union's launch of *Sputnik* on October 4, 1957, surprised nearly all American civilian and military space observers, causing them to scramble in the quest for satellite-tracking capabilities. Moonwatch volunteers provided much of the initial orbital information on *Sputnik*, because Baker-Nunn cameras were only then being deployed and Minitrack, which had become minimally operational only a few days earlier, was designed to detect radio signals transmitted by U.S. Vanguard satellites not Soviet Sputniks.[6] By *Sputnik*'s third orbit, however, fewer than five hours after launch, the NRL's radio array at Hybla Valley, Virginia, had begun compiling data on the satellite's orbital track.[7] Within a couple days, sufficient data poured into the Vanguard Computing Center from U.S. Army Signal Research and Development Laboratory receiver equipment at Fort Monmouth, New Jersey, and its experimental sites worldwide to enable determination and prediction of *Sputnik*'s present and future orbits.[8] Meanwhile, the Massachusetts Institute of Technology (MIT) Lincoln Laboratory's Millstone Hill long-range tracking radar, under development as a prototype for the USAF Ballistic Missile Early Warning System (BMEWS), became the first radar to detect signals reflected by *Sputnik* and to track the satellite in range, azimuth, and elevation angle.[9] The Army hastily expanded the Microlock radio-tracking system by moving portable ground stations to San Diego, Cape Canaveral, Singapore, and Nigeria to track Explorer satellites.[10] All this effort made the United States acutely aware of its severely limited, relatively disorganized ability to detect, track, or identify man-made objects in space.

The first organized, full-time attempt at space surveillance originated from Air Force Cambridge Research Center (CRC) efforts in early October


Aerial view of a portion of the Naval Space Surveillance (NAVSPASUR) radar fence.

THE COLD WAR ENVIRONMENT CREATED A SENSE OF URGENCY IN RESOLVING DIFFERENCES OF OPINION WITHIN THE U.S. DEFENSE COMMUNITY; ON THE OTHER HAND, EXTREMELY BITTER INTER-SERVICE RIVALRIES ONLY INTENSIFIED

1957 to track *Sputnik* using four interferometers together with Doppler radar. Led by Milton Greenberg, head of Air Research and Development Command (ARDC) Geophysics Research Directorate, the CRC opened a primitive filter center at Hanscom AFB, Massachusetts, on November 6, 1957. Following a November 18-19 conference at ARDC headquarters, where participants discussed consolidating all ARDC center capabilities for space surveillance, Project Harvest Moon (subsequently called SPACETRACK) became operational at the CRC on November 30. Bringing together electronics, geophysics, computer, communications, astronomical, and mathematical experts in a unified program to predict satellite behavior, the Harvest Moon filter center received satellite-related radar, optical, radio, and other data from various civil and military sources. At the time, only two artificial satellites—*Sputnik* and *Sputnik 2*—orbited Earth.[11]

On January 18, 1958, William M. Holaday, Director of Guided Missiles in the Office of the Secretary of Defense, instructed the Secretary of the Navy to survey existing resources applicable to space tracking and data collection and to draft a plan for coordinated application of all national capabilities to perform the tracking, data collection, and computing required for maximizing knowledge about satellites in the future. Five months later, under Advanced Research Projects Agency (ARPA) sponsorship, a team headed by the NRL's Roger Easton undertook construction of an electronic "fence" composed of transmitters and receivers across the United States from coast to coast. When radio signals transmitted into space bounced off an orbiting satellite, the receivers detected the returning signal. Repeated crossings by the satellite enabled analysts to predict its orbital path with reasonable accuracy, but the more immediate benefit of the system lay in the ability of its operators to notify other surveillance sensors that an object had passed through the fence. The first two stations of that Naval Space Surveillance (NAVSPASUR) system became operational in early August 1958; when fully operational in February 1959, the system included three transmitters and six receivers spread across the southern United States along the 33rd parallel, with control and computation at Dahlgren, Virginia.[12]

Meanwhile, the Air Force dissented in July 1958 when it became clear that a majority of the Satellite Tracking Review Committee, created pursuant to Holaday's instructions earlier that year and chaired by Navy Captain E. M. Gentry, favored operation of the Interim Satellite Detection and Tracking System by an Armed Forces Special Weapons Project-type organization. Richard E. Horner, Air Force Assistant Secretary for Research and Development, informed the ARPA director that both the interim system and its ultimate successor ought to be controlled operationally by the recently established North American Air Defense Command (NORAD). From Horner's Air Force perspective, "detection and identification of the nature of all satellites" was an operational consideration far more important than the research and development (R&D) aspects on which the committee had focused.[13]

Several factors, in addition to the issue of the balance between R&D and operational considerations, affected how long it would take to officially designate a lead organization for space surveillance and which entity that ultimately would be. On one hand, the Cold War environment created a sense of urgency in resolving differences of opinion within the U.S. defense community; on the other hand, extremely bitter inter-service rivalries, only intensified by arguments over who should have what responsibilities for missiles and space systems, predisposed senior officers and civilians in one military department to steadfastly resist, if not outspokenly oppose, the turnover of anything to another department. Since the Air Force and NORAD had responsibility for early warning against a Soviet ICBM attack, however, logic dictated those entities should have primary responsibility when it came to space surveillance. Whether carrying a nuclear warhead or a satellite as its payload, a long-range rocket transited outer space; radar systems designed for early warning also were capable of performing space surveillance, and some space surveillance equipment could provide early warning data. Furthermore, in June 1958, the Air Force issued General Operational Requirement

Ballistic Missile Early Warning System (BMEWS) detection radar, Thule AB, Greenland, early 1960s.

NOT UNTIL MID-AUGUST 1960, HOWEVER, DID THE DECISION-MAKING PROCESS BEGIN TO ACCELERATE, UNDOUBTEDLY PROMPTED BY THE FIRST FULLY SUCCESSFUL, HIGHLY CLASSIFIED CORONA PHOTORECONNAISSANCE SATELLITE MISSION

170 for a satellite defense system, its first phase being space tracking and control and its second anti-satellite weapons. This practically paralleled General Operational Requirement 96, generated three years earlier, for a ballistic missile detection radar system. When it came to defense against attack, however, traditional Army and Navy roles came into play, and those services sought to extend their prerogatives into the new medium of space. Logic and inter-service rivalry came toe to toe.[14]

While ARPA, ARDC, and NRL sought to define military and NASA requirements for the satellite detection and tracking system, and to develop it, the question of an organization to manage it remained unsettled for more than two years. On November 26, 1958, NORAD Commander in Chief General Earle E. Partridge, pursuant to a letter of encouragement from Lieutenant General Roy H. Lynn, USAF vice chief of staff, had asked the Joint Chiefs of Staff (JCS) to give NORAD that responsibility. He cited several operational considerations, foremost among them being to reduce the number of false alarms that satellites generated in the new Ballistic Missile Early Warning System (BMEWS). This required the systematic use of satellite detection and tracking data to continually update files in the planned BMEWS "Satellite Prediction Computer" at the NORAD Combat Operations Center in Colorado Springs. At the end of May 1959, two days after Secretary of Defense Neil H. McElroy asked the JCS to consult with ARPA on assigning operational responsibility for an interim satellite detection system, General Partridge advised the JCS to urge the Secretary of Defense to designate NORAD as operator of the National Space Surveillance Control Center (NSSCC), because that would facilitate positive planning for the rapidly evolving system. Still, decisions about operational responsibilities proceeded glacially, even as actual operations gained momentum.[15]

In March 1960, ARDC voiced concern to HQ USAF that steadily increasing operational aspects of the NSSCC threatened the research and development program and recommended assigning responsibility for the center to NORAD, with ADC as the operating agency beginning in June 1961. Since HQ USAF agreed but said the Secretary of Defense had to decide, ARDC opted to unburden itself of interim operational responsibility by directing its 496L (SPACETRACK) System Program Office to build up within NORAD, as soon as possible, an operational detection and tracking capability. On April 20, Gen. Laurence S. Kuter, who had succeeded General Partridge as CINCNORAD, repeated his predecessor's desire that NORAD receive the space surveillance mission.[16]

Not until mid-August 1960, however, did the decision-making process begin to accelerate, undoubtedly prompted by the first fully successful, highly classified Corona photoreconnaissance satellite mission. Three days after an ad hoc committee of the Air Force Scientific Advisory Board recommended that NORAD gain responsibility for the entire national space surveillance system, Under Secretary of the Air Force Joseph Charyk expressed to Secretary of Defense Thomas S. Gates lingering concern over the lack of a decision in that regard. Charyk believed that establishment of the NSSCC and integration, under USAF management, of all three services' sensors afforded the best path toward initial system capability. One day later, on August 19, although Gates informed the JCS that responsibility for SPACETRACK and NAVSPASUR soon would transfer from ARPA to the appropriate military departments, he requested a recommendation on which existing organization should have overall control of the operational Space Detection and Tracking System (SPADATS). When the service chiefs failed to agree on a recommendation, Gates directed the JCS to assign operational command of SPADATS to Continental Air Command (CONAD) and operational control to

USAF Baker-Nunn space surveillance camera, Edwards AFB, California, September 1968.

IN MARCH 1959, NORAD OFFICIALS ADVOCATED CREATION OF A SPACE ORDER OF BATTLE, ESSENTIALLY A CATALOG OF ALL OBJECTS IN SPACE, AS A FIRST STEP TOWARD AN ACTIVE DEFENSE AGAINST SUCH THREATS

NORAD, which occurred officially on November 7, 1960. Meanwhile, SPACETRACK operations went to ADC, which also functioned as the conduit for collection and transmittal to HQ USAF of all NORAD and CONAD requirements for SPACETRACK and the NSSCC. Finally, on February 9, 1961, USAF Chief of Staff General Thomas D. White directed ADC to assume full technical responsibility for NSSCC operation of SPADATS by July 1.[17]

Although inter-service rivalries and resulting indecisiveness slowed assignment of SPADATS operational responsibilities, development and acquisition of operational capabilities continued to advance. The ARPA-sponsored NRL surveillance program that evolved into NAVSPASUR had begun in June 1958, and ARPA directed ARDC to proceed with the SPACETRACK project, which absorbed Projects Harvest Moon and Shepherd, the latter an alternative to NAVSPASUR for detecting "dark" or passive satellites as they passed over the United States, in December 1958. Sharing the cost, ARPA and ARDC worked to establish requirements, methods, and capabilities for a Space Detection and Surveillance System with an interim NSSCC at Hanscom Field to collect and process data from all tracking sources, maintain an up-to-date catalog of the current space population, research and develop (R&D) analysis and display techniques, and distribute information to various users. During the first two months of 1959, SPACETRACK was designated System 496L, and the Cambridge Research Center purchased five Baker-Nunn cameras to support R&D projects and tracking operations. Around the same time, the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA), which would assume sponsorship of the SAO camera network a few months later, reached a support agreement on global tracking, data acquisition, and communications networking that also acknowledged the importance of a free exchange of information between the Cambridge filter center and the NASA data center.[18]

Locating, tracking, and identifying potentially hostile types of space vehicles concerned NORAD, because someone might use such platforms for reconnaissance or to deliver nuclear warheads.[19] Consequently, in March 1959, NORAD officials advocated creation of a Space Order of Battle, essentially a catalog of all objects in space, as a first step toward an active defense against such threats. Those same officials expressed deep concern about tracking "dark" or non-radiating satellites launched by other countries, because that required different equipment from what was used to track "cooperative" or radiating IGY satellites. Furthermore, detection and tracking of potentially hostile, dark satellites necessitated special communications and computing facilities for rapid processing of raw surveillance data and for quick dissemination of analyses. Such a system demanded maintenance of a catalog to enable both differentiation of

SPADATS-SPACETRACK Operations Center, Ent AFB, Colorado Springs, early 1960s.

"known" objects from newly launched vehicles (not to mention artificial objects from meteors) and rapid prediction of orbits for new vehicles.[20]

When the new NSSCC began operations at Hanscom Field on January 1, 1960, the latest bimonthly satellite situation bulletin reported two dozen objects launched since *Sputnik*, with half of them still in orbit. The computation relied on approximately 800 observations monthly by a "heterogeneous collection of electronic and optical sensors that fed data into a computing facility." That hodgepodge of sensors included NAVSPASUR; various USAF detection and tracking radars, like the AN/FPS-17 at Laredo, Texas, the AN/FPS-49 at Moorestown, New Jersey, and the AN/FPS-43 and 44 on the island of Trinidad; General Electric's Radio-Optical Observatory near Schenectady, New York; the SAO camera network; and Moonwatch teams. Most of the data handling at the sensors and at the computing center was performed manually. Even when the first USAF Baker-Nunn camera, situated near Harestua, Norway, became operational in August 1960 and when the first contingent of USAF personnel arrived at the NSSCC in November to train as space trackers, operations remained rather primitive. Finally, in mid-January 1961, DoD and NASA agreed their general and special-purpose tracking networks would provide trajectory and ephemeris information on U.S. military and scientific satellites, along with whatever was available on foreign spacecraft, to a centralized data collection and cataloging center in the NORAD Combat Operations Center (COC).[21]

NO ORGANIZATION, INCLUDING NORAD, HAD AUTHORITY TO MARSHAL ALL THE SPACE SURVEILLANCE RESOURCES INTO AN INTEGRATED OPERATIONAL SYSTEM

The January 1961 DoD-NASA agreement, which provided for DoD disseminating catalog data to NASA, came after the Joint Chiefs of Staff reneged somewhat on the original 1959 support agreement by deciding to no longer share SPACETRACK data with NASA. That decision came in the immediate wake of the first successful Corona reconnaissance satellite missions and a perception on the part of DoD officials that precise orbital information about those satellites should be protected. Henceforth, a DoD-NASA Aeronautics and Astronautics Coordinating Board (AACB), created on September 13, 1960, provided a channel for military screening of catalog data for sensitive information that NASA otherwise might pass inadvertently. The formal DoD-NASA agreement stated, "In some instances, security considerations may dictate the withholding of specific items for limited time periods." When NASA issued its first "Satellite Situation Report" under the restrictive agreement on February 17, 1961, complaints arose almost immediately and drew congressional criticism.[22]

As previously directed by General White, ADC at Ent AFB in Colorado Springs assumed full technical responsibility for NSSCC operation of SPADATS by July 1961. The command procured the computer industry's first transistorized model, a high-speed Philco 2000, plus some IBM peripheral equipment. Organizationally, ADC activated the 1st Aerospace Surveillance and Control Squadron to operate both the SPADATS Center (i.e., a name change, with NORAD concurrence, from NSSCC) and the BMEWS Central Computer and Display Facility in the NORAD COC, which featured a computer system—the Display Information Processor—custom built by Radio Corporation of America (RCA). Lieutenant General Robert M. Lee, ADC commander, explained, "SPADATS, with developed improvements, will be the key to control of space." Even before June 12, 1961, when the SPADATS Center at Ent assumed operational functions previously conducted by the NSSCC at Hanscom, ADC pressed for improvements that would better satisfy military requirements: direct input from radars in Turkey; transfer of the mechanical tracker and detection fan on Shemya to ADC; integration of BMEWS and SPADATS; and design and fabrication of a phased-array radar specifically dedicated to space surveillance (i.e., the AN/FPS-85 at Eglin AFB, Florida).[23]

By late summer 1961, SPADATS operation remained dependent on participation from many different sensors operated by various military and civilian organizations, principally for purposes other than space surveillance. No single element could perform the total mission, and most relied on beacon tracking with little detection capability. No organization, including NORAD, had authority to marshal all the space surveillance resources into an integrated operational system. Informal agreements, personal cooperation, and outright bootlegging characterized the methodology behind what had been accomplished thus far. High cost projections and long lead times for developing and deploying the "SPADATS-Improved" envisioned by CINCNORAD left future capabilities uncertain, even as the number of satellites in orbit continued to grow.[24]

With forty-six active satellites and a total of 225 man-made objects in the space catalog in early December 1962, plus an official task from DoD Director for Defense Research and Engineering

Space Defense Center inside the Cheyenne Mountain Complex near Colorado Springs, Colorado, 1973.

BY YEAR'S END, AN AGGRESSIVE PROGRAM TO COLLECT SIGNATURE DATA ON VARIOUS KINDS OF SOVIET SPACECRAFT WAS UNDERWAY AT THE SPADATS CENTER

(DDR&E) Dr. Harold Brown to survey the first-orbit detection capability of existing sensors, the USAF pointed out that SPADATS needed considerable improvement. The existing system, still heavily dependent on development equipment never intended for operational use, could not predict a satellite's location with sufficient accuracy to satisfy anticipated requirements. Radars lacked the desired range and resolution, and deployed sensors could not detect or track objects in all orbits or inclinations. Precise geodetic locations for individual sensors remained a mystery, and Earth's gravitational effects on orbiting objects were unknown, although persistent on-site improvements by Dr. Louis G. Walters of Ford Aerospace Corporation gradually would produce much higher accuracy. At the same time, no programmatic plans existed for overcoming deficiencies in the system.[25]

By this time, the SPADATS Center functioned according to an established routine. It collected positional data from participating sensors at 100 words per minute via a teletype network. That information went into a computer programmed with sophisticated computational routines for near-earth and interplanetary orbits to initially define the new object's orbital elements. Further observations helped refine those orbital elements, which then entered the NORAD master catalog of all man-made space objects. Those element sets, usually maintained with sufficient accuracy to permit reliable positional predictions on average up to thirty days, enabled system sensors to reacquire each object periodically throughout that object's on-orbit lifespan.[26]

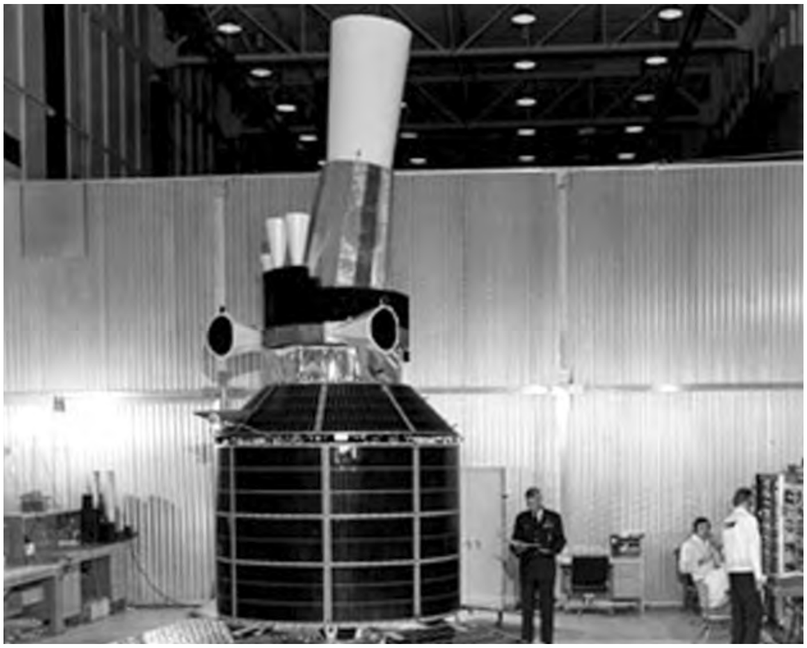
During 1963, the challenge of identifying the type or purpose of man-made space objects received heightened attention. In April, the USAF sent the first personnel to Space Object Identification (SOI) courses conducted by RCA at Cherry Hill, New Jersey. By year's end, an aggressive program to collect signature data on various kinds of Soviet spacecraft was underway at the SPADATS Center. This effort, combined with new techniques that included computer-assisted interpretation and reduction of data from various kinds of sensors positioned around the globe, improved analysts' ability to estimate the operational mission of any particular object the Soviet Union launched.[27]

Phase Two (1964-1971)

If the half dozen years after the launch of *Sputnik* constituted an initial phase in the development of a national space surveillance system, a second phase occurred during 1964-1971. Further upgrades to computational capabilities and to existing ground-based sensors occurred to meet more demanding requirements. In May 1964, for example, the USAF deployed an operational anti-satellite (ASAT) system—Program 437—pursuant to DoD direction. Consequently, the service needed quicker, more accurate orbital determination and identification of potentially threatening objects—e.g., reconnaissance satellites or multiple orbital bombardment satellites (MOBS)—launched from the Soviet Union.[28] Another requirement that placed significant demands on the surveillance network involved accurate prediction of impact points for reentering space objects. This was required initially for owners of U.S. spacecraft but, subsequently, was formalized in the 1967 Outer Space Treaty, which made countries responsible for damages resulting from anything they launched into space that reentered and impacted another country.[29]

In addition to those more demanding requirements, the second phase involved moving the entire NORAD Combat Operations Center, including the manually operated SPACETRACK/ SPADATS Center, from Ent AFB into a new, hardened facility deep inside Cheyenne Mountain southwest of Colorado Springs. The Cheyenne Mountain Task Force, appointed by Secretary of Defense Robert McNamara, recommended in March 1964 that all space-defense activities—i.e., System 496L—be separated from command-and-control (C2) tasks—i.e., System 425L—and performed in a new semi-automatic computer-operated facility called the Space Defense Center (SDC). When the SDC became operational in the Cheyenne Mountain Complex (CMC) on February 6, 1967, ADC and NORAD gained a faster flow of information on the more than 1,000 orbiting objects then in the space catalog. An upgrade of command, control, and communications from the SDC to various sensor sites also occurred.[30]

More powerful software took into account additional variables, such as atmospheric drag and gravitational forces as functions of latitude and longitude. A Spiral Decay computer program, designed by Aeronutronic Systems, Inc. cofounder Louis G. Walters' team and introduced in 1964 for reentry processing, assigned weights and biases to data from SSN sensors and performed a differential correction to more accurately predict the position and



First Defense Support Program (DSP) satellite in assembly facility, 1970.

FROM 1967 THROUGH THE REMAINDER OF THE DECADE,… THE NUMBER OF MAN-MADE OBJECTS IN SPACE… GREW EXPONENTIALLY FROM AROUND 1,200 TO MORE THAN 2,400

velocity of objects affected by high atmospheric drag. The new "Delta" computer system in the SDC also provided capabilities for real-time interrupts for new foreign launches and for automatic sequencing routines. Despite these improvements, senior military officials perceived the continued inability of SPADATS to detect all Soviet space objects on the first orbit as posing a grave risk.[31]

From 1967 through the remainder of the decade, despite a decrease in the total number of space launches worldwide, the number of man-made objects in space that required identification and cataloging grew exponentially from around 1,200 to more than 2,400. Although primarily due to improved sensing and computing capabilities, the numerical increase in cataloged objects also reflected the military desire for a more complete understanding of potential space-related threats. If the need for greater accuracy to support ASAT and impact-prediction responsibilities was not sufficiently demanding, emergence of the Sentinel and Safeguard anti-ballistic missile (ABM) systems created a further need for SPADATS information to purge the ABM tracking system of known satellites and to prevent the possibility of a false attack warning.[32]

The SPADATS network sensors evolved and expanded during 1964-1971. Relocation of two Baker-Nunn cameras, one from Chile to Mt. John Observatory near Christchurch, New Zealand, and the other from Norway to San Vito, Italy, improved optical tracking. Furthermore, the entire Baker-Nunn system underwent a technical enhancement that reduced from twenty-four hours to twelve the time to search, find, compile an accurate observation, and report it to the SDC for more timely orbital analysis.[33] Despite a major setback in January 1965, when fire destroyed the transmitter and receiver antenna faces during acceptance testing of the AN/FPS-85 phased-array radar at Eglin AFB, Florida, the network eventually gained its first radar designed expressly for space surveillance. After extensive rebuilding, the FPS-85 radar began SPACETRACK operations on January 29, 1969, and almost immediately, it autonomously discovered many new, small objects (usually debris related to launches from years past) for addition to the catalog. Because of its relatively lower latitude, the FPS-85 radar allowed the network to pick up low-inclination satellites and greatly increased the overall capacity of the surveillance system. It could track simultaneously 200 known objects or twenty "unknowns" compared to earlier sensors that tracked a single object. Its computational capability earned the Eglin radar site designation as the alternate SDC.[34] The USAF also began experimenting with RCA's AN/FSR-2 "optical radar" at Cloudcroft, New Mexico, and an improved system atop Mount Haleakala on Maui, Hawaii, to obtain a satellite's "optical signature" instead of its photographic image.[35]

Phase Three (1971-1998)

A third phase in SPADATS network evolution became apparent in 1971, largely due to launch of U.S. Defense Support Program (DSP) infrared-detecting satellites and in response to a perceived Soviet ASAT threat. Timely warning and verification of an attack against U.S. or other friendly satellites became imperative, because the Soviet Union had conducted its first successful test of a complete co-orbital ASAT in October 1967 and performed a series of successful tests against a hardened target satellite in 1971.[36] At the same time, the United States had begun phasing out Program 437 nuclear ASAT capability, thereby relinquishing its ability to respond in kind to a Soviet attack on a low-orbiting satellite and, in the eyes of some defense specialists, inviting the Russians to become more aggressive.[37] In the mid-1980s, developmental testing of a U.S. air-launched ASAT system demanded extremely accurate tracking data to ensure successful interception of target satellites. Although deployed to provide early warning of a Soviet nuclear missile attack against North America by detecting missiles in their boost phase, it soon became obvious that DSP also supplied more timely data to SPACETRACK. Instead of the twenty to thirty minutes previously required to determine the purpose of a launch—i.e., long-range missile test or space lift—DSP satellites orbiting at geosynchronous altitude permitted such a determination in as little as one-tenth the time.[38]

As for ground-based sensors, a number of upgrades and additions significantly enhanced the space surveillance network during the 1970s. The Perimeter Acquisition and Attack Characterization System (PARCS), originally built at Concrete, North Dakota, for the Safeguard ABM system and designed for precise tracking of small objects reentering the atmosphere, joined the SPADATS network in 1974. Three years later, the AN/FPS-108 Cobra Dane phased-array radar replaced the

(Above) Diego Garcia GEODSS site in the Indian Ocean, ca. 1990.

(Right) Ground-based Electro-Optical Deep Space Surveillance (GEODSS) camera.

mechanical tracker and detection fan on Shemya, which greatly increased the number of objects it could track simultaneously and, furthermore, extended the range for detection and tracking of Soviet launches. In 1978, addition of the Maui Optical Tracking and Identification Facility (MOTIF) advanced the network's optical capability over Baker-Nunn by providing near-real-time observations on satellites in deep space—those with an orbital period greater than or equal to 225 minutes. Finally, in 1980, the AN/FPS-115 PAVE PAWS radars at Cape Cod AFS in Massachusetts and Beale AFB in California, although employed primarily for detection of submarine-launched ballistic missile launches, began furnishing highly precise detection and tracking of satellites.[39]

THE USAF BEGAN OPERATING ITS GROUND-BASED ELECTRO-OPTICAL DEEP SPACE SURVEILLANCE SYSTEM (GEODSS) TO SUPPLEMENT AND, ULTIMATELY, TO REPLACE BAKER-NUNN CAMERAS

The 1980s witnessed further expansion and improvement of network sensors. To better cover the increasing number of objects in deep space, the USAF began operating its Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) to supplement and, ultimately, to replace Baker-Nunn cameras. To improve early detection of Soviet space launches and determine orbital elements more accurately, the service deployed a series of mechanical tracking radars across the South Pacific in what became known as the Pacific Barrier (PACBAR) system. Using data from the Navy's Transit satellites to recalibrate various existing radars, the Improved Radar Calibration Sensor Program resulted in more accurate positioning data on new launches. Upgrades to contributing mechanical radars on Kwajalein and at Diyarbakir in Turkey enabled geosynchronous satellite tracking. At the very end of the decade, Air Force Space Command began deploying passive radio-frequency (RF) sensor systems—the Deep Space Tracking System (DSTS) and the Low-Altitude Space Surveillance System (LASS). Altogether, those initiatives significantly increased the amount of data available to analysts at the central processing facility, where assessing potential threats and maintaining the space catalog were increasingly crucial.[40]

Meanwhile, to improve command and control (C2) of space surveillance operations, the Space Defense Operations Center (SPADOC) replaced the SDC in Cheyenne Mountain during October 1979. The establishment of SPADOC came with recognition of USAF responsibilities for satellite protection—i.e., the need for advisory warning to U.S. and other friendly satellite owners or operators of any hostile threat to their systems and to supply collision-avoidance information. In the mid-1980s, SPADOC also played a key C2 role in the air-launched ASAT test program. A merger of the Space Surveillance Center and SPADOC in 1994 resulted in a Space Control Center (SCC). Through most of the 1990s, a major effort known as SPADOC-4 reduced many functions still being performed manually; it automated the correlation of large quantities of intelligence and operational data to meet short timelines for supplying orbital information. The SPADOC incorporated Special Perturbations (SP) ephemeris, which led to an Omitron Corporation team headed by William N. Barker introducing SPECTR software for more accurate orbit determination and prediction. This software ran on the Astrodynamics Support Workstation (ASW) that became operational in 1998. It supported NASA International Space Station (ISS) operations by maintaining a subset of the space catalog—about 700 satellites that posed a collision threat to the ISS.[41]

As the end of the twentieth century approached, a host of factors on earth and in outer space reconditioned how military, civil, and commercial owners or operators of satellite systems perceived, even defined, space surveillance. Increasingly, people worldwide understood how much they depended daily on space-based services. Proliferation of commercial satellite systems, mostly for communications and remote sensing, sparked discussions about their need for the same kinds of protection that nations accorded their commercial vessels at sea. The number of countries and other entities owning operational satellites began to grow markedly, especially with the advent of relatively inexpensive micro-satellites, many with dual-use capabilities that could satisfy both civil and military requirements.[42] Perhaps the best known dual-use system became the U.S. military's

Global Positioning System (GPS), which officially achieved full operational status in April 1995 and became widely acknowledged as an essential global utility for highly accurate positioning, navigation, and timing. Another factor, certainly one of the most worrisome, was the accumulation of orbital debris—rocket bodies, dead spacecraft, fragments from explosions or collisions, and other so-called "space junk"—that posed a threat to the growing number of active satellites, piloted spacecraft like the Shuttle, and platforms like the Russian *Mir* and the *International Space Station*.[43]

MILITARY STRATEGISTS REVITALIZED THE CONCEPTS OF "SPACE CONTROL" AND "SPACE SUPERIORITY" THAT SOME VISIONARIES HAD EXPRESSED EVEN BEFORE THE LAUNCH OF THE WORLD'S FIRST ARTIFICIAL SATELLITE

Naturally occurring objects also posed a threat, both to active satellites and to the earth itself. Consequently, a cooperative effort between the Jet Propulsion Laboratory/NASA and AFSPC began in December 1995 to study earth-crossing asteroids and comets. This Near-Earth Asteroid Tracking (NEAT) project aimed to detect, track, and catalog natural objects that potentially could collide with the earth or interfere with satellite operations. The team relied first on the Maui 1-meter GEODSS telescope, which continued making NEAT observations until mid-February 1999. NEAT operations at Maui recommenced in January 2000 using the AMOS 1.2-meter telescope and, in April 2001, the 1.2-meter Samuel Oschin telescope at Palomar Observatory joined the endeavor.[44]

Meanwhile, the Air Force Research Laboratory began developing a 16-inch Raven telescope system, which used commercially available components to lower acquisition, operation, and maintenance costs. The Raven program evolved from an investigation of using small-diameter (i.e., less than 0.5 m) telescopes for automated follow-up observations of asteroids discovered by the NEAT or other search projects. Although these instruments proved unsatisfactory for seeing very dim NEAT objects, they were ideal for routine, very low-cost, high-quality surveillance of cataloged satellites in deep space, thereby reducing the load on more capable telescopes and freeing the latter to perform more demanding observations. One expert suggested that placing about thirty Raven scopes atop U.S. embassies or consulates around the globe would cost roughly $10 million in the near term compared to several billion dollars for a space-based space surveillance system.[45]

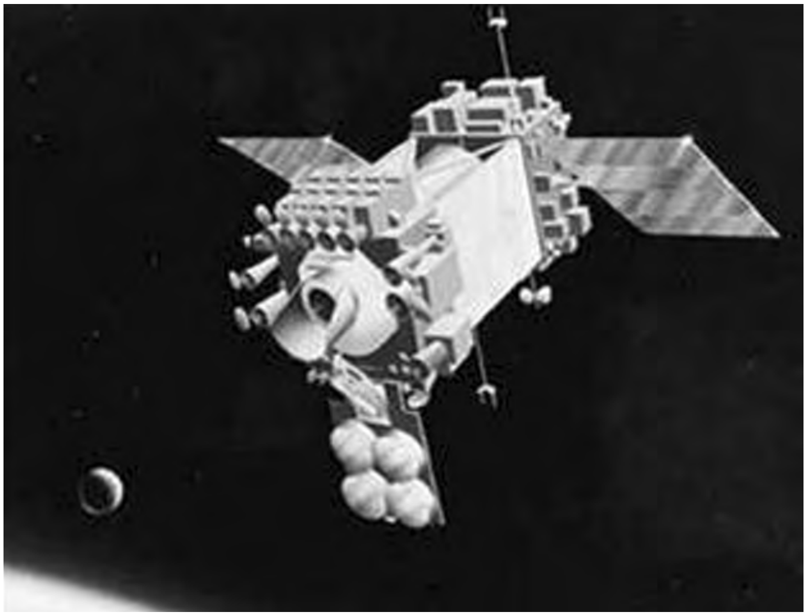
Political and defense-related considerations further complicated the need for understanding what was occurring to, or around, U.S. and other on-orbit spacecraft. In Operation Desert Storm during early 1991, a coalition of forces led by the United States drove Saddam Hussein's Iraqi military out of Kuwait and, in the process, used satellite systems so extensively as to earn the sobriquet "the first space war." Later that same year, the Soviet Union collapsed, bringing an end to the decades-old Cold War. A new nemesis began to emerge in the form of global terrorism, even as the Chinese caused consternation by expanding their space-related activities. As the United States attempted to resolve conflicts, even to end genocide, by intervening militarily in places like Bosnia and Kosovo, the reliance of all its forces on satellite communications and the demonstrated effectiveness of GPS-guided munitions caused military strategists to ponder with heightened concern the consequences of interference with U.S. space systems. This became a critical issue as satellites designed primarily for strategic purposes became increasingly integral to successful theater or tactical war fighting and increasingly vulnerable, at least potentially, to enemy attacks.

Anticipated changes in requirements also affected planning for a fourth phase of surveillance network development. In the early 1980s, USAF experts already had perceived the current system, designed for peacetime operations and dependent on overseas sensors, would not "remain viable through an attack, after the attack, through another attack, for some unspecified length of time" without extraordinary alterations. Although they cautioned against automatically assuming that space-based systems could be made more survivable than terrestrial systems, they extolled that possibility. Furthermore, surveillance specialists worried that the existing network was designed for detection and periodic tracking of satellites in relatively predictable orbits affected only by such natural forces as gravitational variance, atmospheric drag, and solar radiation pressure. They argued that existing capabilities made it extremely difficult, if not impossible, to keep track of satellites capable of orbital maneuvering, particularly those moving from one plane to another. Since space-based space surveillance (SBSS) offered the prospect of nearly continuous, comprehensive observation, it seemed to be the best way to keep track of maneuvering satellites over their orbital lifetime. The rapidly increasing number of man-made objects, whether in "natural" orbits or unpredictable ones, also heightened the need for the "reliable and enduring worldwide coverage of space objects at all altitudes" that SBSS offered.[46]

Phase Four: 1998-Present

With all these factors or conditions in mind, military strategists revitalized the concepts of "space control" and "space superiority" that some visionaries had expressed even before the launch of the world's first artificial satellite.[47] Space surveillance became widely acknowledged as the fundamental key to achievement of space control and, as such, theorists began to reconstruct its meaning in a broader sense. A report from the USAF Scientific Advisory Board (SAB) in June 1997, anticipating the emergence of space-control requirements, recommended improvements to the accuracy and responsiveness of space surveillance.[48] The *Long Range Plan* presented by General Howell M. Estes III, United States Space Command commander in chief, in March 1998 not only touted space surveillance as "the foundation for space superiority" but added, "Near real-time space situational awareness, enabled by Surveillance of Space is the key contributor to the Control of Space and enabling rithms and covariance matrices recommended in the SAB report, the HAC or special catalog became fully operational in Cheyenne Mountain in September 1999. Both catalogs contained data on all objects being tracked by the surveillance network, but the special catalog provided sharper awareness of foreign satellites that at any particular time might have high national-security interest.

Furthermore, it allowed more accurate orbital predictions for potentially hazardous debris at the lower altitudes of human spaceflight. The general catalog remained available to users of the Integrated Tactical Warning and Attack Assessment (ITW&AA) system and to others via NASA's Orbital Information Group (OIG) website; information from the special catalog went only to selected users on a case-by-case basis. Several times more accurate than the general catalog, the HAC represented the most significant advancement in space cataloging since the late 1950s.[54]



MSX satellite with Space Based Visible (SBV) sensor provided space-based space surveillance data, 1998-2008.

freedom of operations within it."[49] A new term—"space situational awareness" or SSA—had entered the lexicon.[50]

Essentially, SSA amounted to sufficient current and predictive knowledge—gained through space surveillance, space-related intelligence and reconnaissance, and space environmental monitoring—about "conditions, constraints, capabilities, and activities…in, from, toward, or through space" to enable, first, discernment of an adversary's intentions and, second, development of effective counterspace courses of action, either defensive or offensive.[51] The January 2001 report of the congressionally mandated Commission to Assess United States National Security Space Management and Organization, chaired by soon-to-be Secretary of Defense Donald Rumsfeld, called for improving SSA to avoid a "Space Pearl Harbor." Nine months later, the *Quadrennial Defense Review Report* noted the United States would "pursue modernization of the aging space surveillance infrastructure, enhance the command and control structure, and evolve the system from a cataloging and tracking capability to a system providing space situational awareness."[52] To promote coordinated, cost-effective evolution toward SSA, the Secretary of the Air Force directed the AFSPC commander to create a Space Situational Awareness Integration Office in early 2002.[53]

SECRETARY OF DEFENSE DONALD RUMSFELD, CALLED FOR IMPROVING SSA TO AVOID A "SPACE PEARL HARBOR"

By then, pursuant to the 1997 SAB recommendations and to satisfy specific NASA and NRO requirements, an effort led during 1998-1999 by Wilbert F. "Bill" Craig III, a mathematician whose intimate association with satellite tracking began when he joined the Air Force SPACETRACK team in 1961 and who oversaw many of the significant system improvements during the next 35 years, used the ASW and its SPECTR software to test the High Accuracy Catalog (HAC) concept. Using only data from sensors tasked by the Space Control Center to maintain the general or standard catalog, but employing Special Perturbation (SP) algo-

To enable even better orbital predictions, work also commenced in the late 1990s to improve modeling of atmospheric density. This effort focused on using the observed drag effects on low-perigee, inactive payloads and debris for calculation of atmospheric-density variations in near-real time. An Omitron team headed by Stephen J. Casali, and working through the AFSPC Space Battlelab, developed a Dynamic Calibration Atmosphere (DCA) algorithm to account for diurnal and semidiurnal variations in density of the upper atmosphere. Aided by Bruce R. Bowman's team from the AFSPC Space Analysis Center (HQ AFSPC/A9AC), this effort evolved into the High Accuracy Satellite Density Model (HASDM) project. After undergoing peer review and operational testing in 2002-2003, the first phase of HASDM/DCA—essentially HAC's atmosphere—became operational in Cheyenne Mountain in 2004, thereby enabling extremely accurate predictions for satellites orbiting at or below 800 kilometers. From that initial phase, which relied on eighty satellites for calibration, HASDM entered a second phase—Sapphire Dragon—that used 140 satellites for calibration. Sapphire Dragon yielded highly accurate orbital predictions for three-day periods. In June 2007, a third HASDM phase—Fiery Dragon—sought to use even more satellites and to extend highly accurate predictions outward to seven days. The HASDM/DCA amounted to an evolutionary replacement for the comparatively static atmospheric-density model used by the SPADOC system.[55]

From a sensor perspective, space-based space surveillance (SBSS) offered one avenue toward realization of improved SSA. The SBSS program originated from conceptual studies begun during the early 1970s, when it became obvious that the number of man-made objects in deep space would increase dramatically over the next twenty years. Formal initiation of an SBSS program occurred in Fiscal Year 1976. As the Air Force neared completion of an SBSS Request for Proposal (RFP), however, a critical Air Force Audit Agency report in November 1983 and establishment of the Strategic Defense Initiative (SDI) program in January 1984 resulted in a March 28, 1984, decision to defer acquisition of the SBSS system. Despite this setback, the need remained for an SBSS capability to enhance deep-space tracking. Admittedly, an SBSS system could complement ground-based radars and optical sensors by providing an alternative phenomenology for detection of objects against the cold background of space. The existing network of ground-based sensors performed near-space surveillance well, but it inadequately addressed deep-space surveillance in general and, in particular, left a serious gap in coverage of the geosynchronous belt over the eastern hemisphere. An SBSS system could improve deep-space surveillance overall, and could cover the eastern-hemisphere gap in particular.[56]

ESTABLISHMENT OF THE STRATEGIC DEFENSE INITIATIVE (SDI) PROGRAM IN JANUARY 1984 RESULTED IN A MARCH 28, 1984, DECISION TO DEFER ACQUISITION OF THE SBSS SYSTEM

Launch from Vandenberg AFB, California, of the Ballistic Missile Defense Organization (BMDO) *Midcourse Space Experiment* (MSX) satellite, with its Space-Based Visible (SBV) optical sensor, on April 24, 1996, resurrected AFSPC's prospects for a near-term SBSS capability. The SBV flight sensor project had begun at MIT's Lincoln Laboratory in 1989 and, during the first eighteen months on orbit, a variety of experiments conducted by the BMDO Space Surveillance Principle Investigator team demonstrated the possibility that MSX/SBV might serve as a highly productive asset in the Space Surveillance Network (SSN). Consequently, efforts commenced in October 1997 to transition the SBV sensor from its experimental status into an SSN contributing sensor. The transition occurred as part of AFSPC's first OSD-approved Advanced Concept Technology Demonstration (ACTD)—SBSS Operations (SBSSO). On May 13, 1998, the SBV sensor completed its trial period and attained fully operational status as an SSN contributing sensor. By then, it provided an average of 100 tracks daily on deep-space objects.[57]

Per DoD direction, BMDO transferred control authority over the MSX satellite to AFSPC on October 1, 2000. This allowed the command to transition MSX/SBV further into AFSPC operations as a dedicated SSN sensor. By then, the satellite was contributing over 1,500 observations daily to the SSN, which enabled AFSPC "to locate objects in key deep-space orbits every 2.5 days, compared with five days when using only ground-based systems." This helped reduce the list of "lost" satellites by eighty percent. Consequently, in September 2002, the USAF decided to acquire a full-fledged SBSS system and contracted, in March 2004, with a Boeing-Ball Aerospace team to develop and initially operate it. The industry team bore responsibility for delivering a single "pathfinder" satellite and ground segment that would pave the way toward a full on-orbit constellation. Although AFSPC did not plan to launch the SBSS pathfinder satellite until early 2009, it decommissioned the MSX on June 2, 2008, because the SBV sensor had degraded to the point of being unreliable.[58]

A new X-band, mechanical radar for tracking and imaging objects in deep space also became operational at a test site on Vandenberg AFB, California, in 1996. The AN/FPS-129 radar, sporting a 27-meter dish and using specialized waveforms, delivered sensitivity and metric accuracy that exceeded the capabilities of all previously existing U.S. Air Force surveillance radars. Built by Raytheon Electronic Systems and dubbed HAVE STARE, the AN/FPS-129 could detect objects in the 1 to 10-centimeter range out to a distance of 40,000 to 45,000 kilometers. Moved from Vandenberg AFB to its final operating location near Vardø, Norway, during October 1998-May 1999 and renamed Globus II, the AN/FPS-129 underwent a lengthy trial period before rejoining the SSN as a dedicated sensor.[59]

Several other SSA-related initiatives, some with more longevity than others, emerged during the first decade of the twenty-first century. Originating from a 1995 "Geosynchronous Imaging Experiment" analytical study and a 1999 "Space-Based Deep Space Imager" idea, the concept of an Orbital Deep-Space Imager (ODSI) emerged in 2004. Unlike the low-earth-orbiting SBSS, ODSI would enter a high-altitude orbit and be allowed to "drift," approach deep-space satellites without maneuvering, and obtain high-resolution images of them. Funding priorities, however, forced cancellation of ODSI only a few months after the February 2005 contract award for a concept study.[60]

The Air Force Research Laboratory, in April 2004, awarded Trex Enterprises Corporation of San Diego, California, a contract for development of a Satellite Active Imaging National Testbed (SAINT). Using Fourier telescopy as the basis for a new ground-based surveillance system, the USAF planned to demonstrate within five years that SAINT could image objects in low-earth orbit, then improve its capabilities to achieve geosynchronous observations within fifteen years. Like ODSI, however, SAINT became the victim of higher funding priorities in the Fiscal Year 2008 budget request.[61]

In August 2007, Defense Advanced Research Projects Agency (DARPA) program manager Roger Hall reported progress on development and demonstration of two new, ground-based systems—Space Surveillance Telescope (SST) and Deep View—for detecting, tracking, and identifying small, dimly lit objects in deep-space orbits. The SST, a 3.5-meter optical device with a large, curved focal-plane array, combined "high detection sensitivity, short focal length, wide field of view, and rapid step-and-settle to provide orders of magnitude improvements in…detection of un-cued objects in deep space for purposes such as asteroid detection and space defense missions." To help identify faint objects (e.g., microsatellites) and determine their status, the Deep View program upgraded MIT Lincoln Laboratory's Haystack Radar facility in Tyngsborough, Massachusetts, from X-band (9.5-10.5 GHz) to W-band (92-100 GHz) for order-of-magnitude improvement in imaging resolution.[62]

In addition to pursuing new space-based and

NAVSPASUR receiving site, San Diego, California, 1993. *(Photo by T. Kneisel)*

ground-based sensors, the USAF sought to improve existing systems. Eglin's AN/FPS-85 system received a new radar-control computer in 1994 and a new software package in 1999. These changes allowed it to detect smaller-size debris objects at human-spaceflight altitudes.[63] The GEODSS Modification Program, which included new mission-critical computer resources and reconfiguration of the entire system to permit dynamic scheduling in near-real time, became operational on August 3, 1999. The following year, replacement of GEODSS outdated Ebsicon analog video cameras with state-of-the-art, highly sensitive digital cameras using Charge-Coupled Device (CCD) arrays commenced under the five-year DEEP STARE program. Those upgrades significantly improved the metric accuracy, throughput, and sensitivity of the system.[64]

"ADVANCING SURVEILLANCE" … REQUIRED NEW GROUND- AND SPACE-BASED OPERATIONAL CAPABILITIES THAT BRIDGED BETWEEN SURVEILLANCE AND DEFENSIVE COUNTER SPACE

Meanwhile, in 2003, the Navy began transitioning operational control of its aging AN/FPS-133 NAVSPASUR interferometric detection fence—three transmitters and six receivers located across the United States along the 33rd parallel—and the Alternate Space Control Center at Dahlgren, Virginia, to AFSPC. After the official transfer ceremony on October 1, 2004, the NAVSPASUR fence became known as the Air Force Space Surveillance System (AFSSS), which AFSPC planned to convert from a very high frequency (VHF) system to S-band. That conversion, scheduled for completion sometime after 2013 depending on funds, would improve measurably the AFSSS detection threshold. From finding basketball-size objects at 15,000 nautical miles, AFSSS detection capability would improve to finding golf ball-size objects at a similar range.[65]

All these upgrades, nonetheless, remained in the traditional realm of detecting, tracking, identifying, and cataloging man-made objects in outer space. Advancing surveillance to a truly different level, one where warfighters could become more aware of environmental or emerging man-made threats to critical U.S. space assets, required new ground- and space-based operational capabilities that bridged between surveillance and Defensive Counter Space. By 2007, the USAF had already prototyped a Rapid Attack Identification, Detection and Response System (RAIDRS) and envisioned an incremental approach to its full implementation, which would employ on-orbit sensors to differentiate among man-made threats, intentional attacks, unintended encounters, and natural events that affected DoD satellites.[66]

Military planners contemplated several different concepts for on-orbit sensing to support RAIDRS. One harkened back to the Satellite Interceptor (SAINT) for which the USAF had issued a requirement in June 1958. It involved orbital maneuvering to rendezvous with a target, examine the suspicious craft up close to determine whether it posed a threat, and take defensive measures as necessary to protect U.S. satellites. In the late 1990s, AFRL revived this idea with an Experimental Spacecraft System (XSS) Microsatellite Demonstration Project and, in 2003, successfully used the XSS-10 satellite to approach an orbiting Delta II second stage, maneuver around it, and transmit video imagery live to analysts on the ground. The XSS-11 in 2004 and Orbital Express in 2007 further demonstrated the potential for microsatellites to perform inspection and other functions in close proximity to another on-orbit object.[67]

Building on the XSS experience, AFRL began seeking information in 2005 for a program called Autonomous Nanosatellite Guardian for Evaluating Local Space (ANGELS). This program aimed for launching a very small satellite into geosynchronous orbit to escort a larger satellite, monitoring the space around that host satellite, and warning of intruders or threats.[68] Under a different program dubbed Self-Aware Space Situational Awareness (SASSA), which Under Secretary of the Air Force Ronald M. Sega vigorously advocated, the USAF would develop "a suite of sensors in the visible through the RF spectrum" that would reside on a satellite's bus to detect, locate, and report threats to the satellite's health.[69]

If SSA was necessary to protect America's military and national security assets in space, distribution of basic information from the space catalog to a wide variety of commercial and foreign entities (CFE) also became increasingly critical. Interference, intentional or otherwise, by one party with another's satellite could cause degradation in service, destruction of an on-orbit asset, or international conflict. Although the U.S. Space Surveillance Network originated for essentially military purposes, other government, commercial, and foreign entities had relied almost exclusively since the early 1960s on information it released to reduce the risk of their spacecraft colliding with other objects orbiting Earth. At the end of the twentieth century, the U.S. military, in accordance with the January 1961 DoD-NASA support agreement, sent an unclassified portion of its processed surveillance data to NASA, which made the information available to other non-military users. On January 10, 2000, however, a DoD memorandum directed the USAF to study, in coordination with the other military services and space agencies, alternatives for providing space-surveillance support to CFE.[70]

THE CFE PILOT PROGRAM, SCHEDULED TO RUN FROM MAY 22, 2004, TO MAY 21, 2007, INVOLVED A THREE-PHASE TRANSITION OF RESPONSIBILITIES FROM NASA TO AFSPC

By June 2002, AFSPC was proposing a pilot study to replace the existing NASA arrangement with one using a Federally Funded Research and Development Center (FFRDC). Approval to proceed with the study depended on resolution of data-control issues, DoD approval, and enactment of authorizing legislation to make dissemination of space-surveillance data to CFE part of the AFSPC mission. Section 913 of Public Law 108-136 (The National Defense Authorization Act for Fiscal Year 2004), signed on November 24, 2003, stipulated the AFSPC pilot program should commence "not later than 180 days" from that date or by May 22, 2004. Lt. Col. David M. Maloney, HQ AFSPC chief of space situational awareness (XOCS), noted in a public announcement that implementation of the pilot program involved receiving delegation of authority from the Secretary of Defense and transferring as many as 1,115 currently active user accounts from the NASA Orbital Information Group (OIG) website to the new CFE Space-Track website. Furthermore, Maloney explained it would take several months to provide "the same latency" or "functionality" that the OIG website had provided for many years.[71]

The CFE pilot program, scheduled to run from May 22, 2004, to May 21, 2007, involved a three-phase transition of responsibilities from NASA to AFSPC. In phase one, the CFE Support Office (CSO), operated by The Aerospace Corporation under oversight from the HQ AFSPC operations directorate, would begin developing the Space-Track website that, ultimately, would replace the NASA OIG website. Plans called for a ninety-day transition period during which the CSO would continue adding functionality to fully replicate OIG capabilities, while NASA would advertise termination of its website and encourage its OIG customers to register and activate accounts on the new Space-Track website. Although the CSO had implemented on Space-Track more than half the OIG capabilities by early September 2004, AFSPC Commander General Lance W. Lord still waited for delegation of authority from the Secretary of Defense to conduct the pilot program. This delegation and assignment of responsibility finally occurred on November 8, 2004, but the CFE Space-Track website remained inoperative until January 3, 2005. Meanwhile, on December 30, 2004, NASA's OIG website posted a notice that it no longer would accept new users.[72]

Closure of the OIG website and provision of all its former capabilities, free of charge, to users via the Space-Track website would characterize the CFE pilot program's second phase of operations. Ultimately, the provision of more advanced services and products on a fee-for-service basis would constitute a final, third phase. On January 10, 2005, a notice posted on the OIG website said it would shut down on March 31, 2005. After the OIG website experienced severe technical difficulties—i.e., hardware and software failures—in early February, however, NASA decided as of February 14, 2005, to abandon all further attempts to recover the system. The new Space-Track website finally achieved the full functionality of the old OIG website in May 2005. By year's end, more than 16,000 users had established Space-Track accounts, and legislation the following year extended the CFE pilot program through September 30, 2009.[73]

Over the course of a half century, the focus of U.S. space surveillance activities and services had grown and shifted from merely tracking a single U.S. IGY satellite during its limited on-orbit lifetime to cataloging all man-made objects in space and to determining threats, human or natural, to operational satellites. At the end of July 2007, the space catalog listed 31,925 objects recorded since the launch of *Sputnik* in 1957, including 3,195 payloads and 9,064 pieces of debris still on orbit and being tracked by AFSPC.[74] To meet SSA requirements, NORAD and AFSPC decided in 2006 to move Cheyenne Mountain's Space Control Center to the Joint Space Operations Center at Vandenberg AFB, California, thereby consolidating it with other day-to-day space operations in support of warfighters around the globe.[75]

After a Chinese ASAT test on January 11, 2007, created thousands of additional debris fragments that stressed the capacity of the existing surveillance network, AFSPC undertook a comprehensive “clean sheet” review of its space-monitoring capabilities to plan beyond simply sustaining the Cold War architecture.[76] Working through the spring and summer, a “tiger team” laid the groundwork for the review by asking what, where, when, and why capabilities were needed for present and future space surveillance. By September 2007, the Space and Missile Systems Center at Los Angeles AFB, California, and the Electronic Systems Center at Hanscom AFB, Massachusetts, were using that team’s data to complete a cost-and-performance analysis of candidate ground- and space-based surveillance systems to determine an overall “best value” for network performance. This meant, within funding constraints, that some existing systems might be scrapped, others improved, and new ones added to satisfy changing requirements.[77] It seemed another chapter in the development of space surveillance was about to begin. ■

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14. David N. Spires, *Beyond Horizons: A History of the Air Force in Space, 1947-2007*, 2d ed. (Peterson AFB, Colo.: Air Force Space Command, 2007), pp. 56-76 (hereafter cites as Spires, *Beyond Horizons*); Temple, pp. 64 and 105.

15. “Chronology,” pp. 5-13.

16. *Ibid.,* pp. 13-15; Ltr., Col Edgar B. Gravette, Director of Advanced Systems, ADC C2 Systems Office, to CCO, “Interim Space Track Control Center,” May 16, 1960.

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20. “Chronology,” pp. 10-11.

21. *Ibid.,* pp. 13-19; Roy E. Anderson, “General Electric Early Space-Age Adventures,” *Quest* 15:3 (2008):53-58; E-

Mail, Thomas W. McCarthy to Rick W. Sturdevant *et al*., "Sort of Final Draft: Spacetrack on the Eastern Test Range, Fifty Years Ago," Mar. 18, 2007; Agreement, Herbert F. York, DDR&E, Department of Defense, and High L. Dryden, Deputy Administrator, NASA, "Functions Involved in Space Surveillance of U.S. and Foreign Satellites and Space Vehicles," Jan. 16, 1961. For an earlier agreement see, Neil H. McElroy, Secretary of Defense, and T. Keith Glennan, NASA Administrator, "Agreement between National Aeronautics and Space Administration and Department of Defense on Global Tracking, Data Acquisition, Communications, and Data Centers for Space Flight," Jan. 10, 1959.

22. Temple, pp. 324-25.

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29. Strub and Moorman, 1982. One of the better known incidents concerning accurate reentry prediction and associated liability was the Soviet Union's *Cosmos 954*, which contaminated the wilderness of the Canadian Northwest with radioactive material in January 1978. See Leo Heaps, *Operation Morning Light: Terror in Our Skies—The True Story of Cosmos 954* (New York: Paddington Press, 1978).

30. "Chronology," pp. 49-60; Strub and Moorman, 1982.

31. Louis G. Walters *et al*., Philco Newport Beach, California, Aeronutronic Division, *Spiral Decay and Sensor Calibration Differential Correction Programs, Volume III, Programmer's Manual*, February 1965; "Chronology," pp. 49-60; Strub and Moorman, Jr., 1982. Spiral Decay was a special perturbations (SP) program aimed at predicting time and location for an uncontrolled satellite reentry. To achieve even greater predictive accuracy, one needed to know atmospheric density through time, something difficult to determine even with abundant measurements. By the 1990s, advances in computing technology and modeling techniques led to more sophisticated SP programs. See Remarks by Col Wilbert Craig, USAF (Ret), "2007 Space & Missile Pioneers Roundtable," Aug. 8, 2007; Craig, Sep 5, 07.

32. "Chronology," pp. 61-64.

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34. *Ibid.,* 1982; John Pike, "AN/FPS-85 Spacetrack Radar," Global Security Website, Sep. 20, 2006, www.globalsecurity.org/space/systems/an-fps-85.htm (accessed August 2, 2007); E-Mail, Robert F. Morris, HQ AFSPC/A9AC, to author, Sep. 5, 2007 (hereafter cited as Morris, Sep 5, 2007).

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46. Strub and Moorman, 1982. Under Col Strub's leadership, a comprehensive USAF "Space Surveillance

Architecture Study" was begun in Jan. 1982 to address ways of correcting deficiencies in the existing network and how best to satisfy evolving requirements through the year 2000. See HQ USAF/CV, "Space Surveillance Architecture Study—Final Report," 2 Vols., Jun. 10, 1983; E-Mail, Col James Strub, USAF (Ret), to author, September 4, 2007 (hereafter cited as Strub, Sep. 4 2007).

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48. USAF SAB, *Report on Space Surveillance, Asteroids and Comets, and Space Debris, Volume I: Space Surveillance*, SAB-TR-96-04, Jun. 1997 (hereafter cited as SAB, *Report on Space Surveillance*).

49. *Long Range Plan*, p. 28. The *Long Range Plan* (pp. 107-109) included "roadmaps" for commercial and international partnerships to develop and provide services for the SSN, but an ESA study in 2006 seemed to favor creation of an independent European Space Surveillance System. See Briefing, Gerhard Brauer, ESA, "European Approaches to Space Security Capability," May 2006.

50. The precise origin of the term "space situational awareness" remains an open question. An official report on space surveillance from Jun. 1997 failed to use the term, despite coming close to defining it. That report stated in a section titled "Global Awareness and Space Surveillance" that "A fundamental requirement for achieving this posture [i.e., space control] is timely and accurate information regarding the orbital characteristics, physical configuration, and mission of every object in space. …A fundamental element in achieving Space Control is having accurate and timely Space Surveillance." See SAB, *Report on Space Surveillance*, p. 3. One person began using the term "space situational awareness" in the early 1990s at Air University's Squadron Officer School "to explain to pilots what 'space surveillance' and 'space control' are. I was aware then that an SSA would require knowledge of weather and intel as well but not sure that I really explored it to the depth we are using the term today." See E-Mail, Lt Col Derek S. Ho, AFSPC/A5CC, to author, Sep. 4, 2007.

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52. *Report of the Commission to Assess United states National Security Space Management and Organization, Executive Summary*, Jan. 11, 2001, p. 16; DoD, *Quadrennial Defense Review Report* (30 September 2001), p. 45.

53. Fact Sheet, AFSPC/PA, "Space Situational Awareness Integration Office," Nov. 2006.

54. SAB, *Report on Space Surveillance*, pp. iv-v; Briefing, Bill Craig, NRO, "Satellite Catalog Status," Jun. 17, 2003; Craig, Sep. 5, 2007.

55. Mark F. Storz *et al*., "High Accuracy Satellite Drag Model (HASDM)," AIAA 2002-4886, *AIAA/AAS Astrodynamics Specialist Conference* (Monterey, Calif.), Aug. 2002; Briefing, Bill Craig, NRO, "Satellite Catalog Status," Jun. 17, 2003; Hoots, 2007; Craig, Sep. 5, 2007. It was crucial, as HASDM/DCA evolved within the context of SSA, to consider space-weather challenges. Scientists developed a new empirical thermospheric density model—Jacchia-Bowman 2006 (JB2006)—as part of HASDM. Significant features of JB2006 included "solar indices based on satellite EUV and FUV (i.e., extreme and far ultraviolet solar emissions) sensors and an improved semiannual variation." See W. Kent Tobiska *et al*., "The Development of New Solar Indices for Use in Thermospheric Density Modeling," AIAA-2006-6165, *AIAA/AAS Astrodymics Specialist Conference* (Keystone, Colo.), Aug. 2006; Bruce R. Bowman *et al*., "A New Empirical Thermospheric Density Model JB2006 Using New Solar Indices," AIAA-2006-6166, *AIAA/AAS Astrodymics Specialist Conference* (Keystone, Colorado), August 2006; Frank A. Marcos *et al*., "Accuracy of Earth's Thermospheric Neutral Density Models," AIAA-2006-6167, *AIAA/AAS Astrodymics Specialist Conference* (Keystone, Colo.), Aug. 2006.

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Hotel, Anaheim, California, pp.208-11; Amy Butler, "DOD Looks to Speed Up Haystack Effort," *Aviation Week*, Jul. 28, 2008.

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