COMPUTER SYSTEMS AND ALGORITHMS FOR SPACE SITUATIONAL AWARENESS: HISTORY AND FUTURE DEVELOPMENT

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There is a growing international need for Space Situational Awareness (SSA), defined as knowledge of objects in Earth orbit and the space environment. Up until recently, the majority of SSA has primarily been done by the United States and Russia, which currently operate significant space surveillance tracking networks and maintain catalogs of space objects. These efforts are largely done for military and national security purposes. More recently, the European Space Agency (ESA) has initiated an SSA Program which will build upon existing European ground-based radar and optical sensors to develop a European SSA system. Emerging space States, particularly in South Asia, are also looking to develop SSA capabilities to support increased military use of space and to protect civil and commercial space assets. This paper outlines the history of mathematical algorithms and computer systems development used for space surveillance and space object catalog work primarily in the United States and to a lesser degree in Russia. It also analyses the advantages and disadvantages of various techniques and approaches and how the accuracy and development of SSA data products has been impacted by events. Based on the analysis of the traditional SSA software shortcomings and these new possibilities, the paper outlines a new initiative to develop an open source software package that combines a variety of features and algorithms in a package that is open to use and development by all.

INTRODUCTION

At the beginning of the space era, the U.S. government initiated development of a space surveillance program that detects, tracks, catalog, and identifies human-made objects orbiting Earth. This includes active and inactive satellites, spent rocket bodies, fragmentation debris, and any other mission-related materials that achieve orbit but does not include natural objects such as micrometeorites.[1] The program called for a "cradle to grave" approach to tracking these objects with the goal of providing the following: [1]

- Predict when and where a decaying space object will re-enter the Earth's atmosphere;
- Prevent a returning space object, which to radar looks like a missile, from triggering a false alarm in missile-attack warning sensors of the US and other countries;

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- Determines the present position of space objects and predicts their future orbital paths;
- Detects new man-made objects in space;
- Detects spacecraft maneuvers;
- Produce a running catalog of man-made space objects;
- Determine which country owns a re-entering space object;
- Inform responsible authorities whether or not space objects may interfere with the US space shuttle, the International Space Station (ISS), or other manned space vehicles

All of these space surveillance requirements require space object ephemeris data; the ephemeris is a table of predicted position and velocity at equal time intervals. The ephemeris data is generated by fitting mathematical models to observations of space objects collected by tracking sensors. The Space Surveillance Network (SSN) which is used by the U.S. military is comprised of phased array radars, dish radars, radar fences, and optical telescopes. These sensors collect metric observations on space objects which measure the position of the object at a specific time relative to the sensor location. The orbit fitting process makes use of the residuals between the actual measurements at time t and the computed measurements[*] at time $t+\delta t$ where δt is the timing bias. The results is an element set which can be used to predict the position of the object in the future, and is continuously updated and refined by subsequent tracking and orbit fitting.

The ephemeris by itself cannot be used to reliably predict collisions or detect maneuvers or associate observations. Uncertainty information or rather, probability distributions, are increasingly desirable in order to do these tasks. Calculating this uncertainty requires intimate knowledge about the accuracy and calibration of the sensors used to collect the metric observations as well as a detailed understanding of the force models and algorithms used and their inherent uncertainties. The uncertainty in an orbital position is commonly expressed by a covariance matrix, from which a probability distribution function can be calculated.

Within the last few years, this concept of space surveillance has been subsumed by the broader mission of space situational awareness (SSA). SSA is defined by current U.S. Air Force doctrine as "the result of sufficient knowledge about space-related conditions, constraints, capabilities, and activities in, from, toward, or through space."[2] SSA includes intelligence on capabilities and intent, space surveillance, reconnaissance, environmental monitoring (including space weather), and satellite command and control.[2]

Since the February 2009 collision between the Iridium 33 and Cosmos 2251 satellites[3], the requirement to detect and warn of potential physical interference with manned space vehicles has been expanded to include detection and warning of a potential collision threat to any operational satellite regardless of owner. This process, called Conjunction Assessment (CA), is part of an expanding role that SSA is playing in civil and commercial spaceflight safety in addition to its traditional military role.

This paper is part of a larger strategy to address the SSA problem via an Open Source Software paradigm (OSS). This paper addresses the current astrodynamics algorithms and computer systems in use by the U.S. and Russian governments. Cefola, Weeden, and Levit propose an alternative approach to the traditional software development in "Open Source Software Suite for Space Situational Awareness and Space Object Catalog Work".[4] Weeden, Cefola, and Sankaran address the sensor network part of the issue in “Global Space Situational Awareness Sensors”.[5]

[*] The computed measurements require an a priori estimate of the state vector.

HISTORY OF U.S. GOVERNMENT SSA SYSTEMS AND PROGRAMS

Over the last 50 years, the US Government has implemented several programs and computer systems to address space surveillance requirements. The development of these systems was primarily a response to the changing mission from space surveillance to SSA, as well as the explosion in the number of human-generated objects in orbit. Although over this same period of time the computing world as a whole has experienced massive increases in processing power performance and decreases in cost, the operational SSA world has been much slower to change, and as of yet has not been able to take advantage of many of those benefits. Additionally, while it was once on the cutting edge of astrodynamics theory and algorithm development, the USG systems now lag significantly behind the academic and commercial world.

NAVY Space Surveillance System

The first USG space surveillance system was developed by the US Navy. The Navy Space Surveillance (SPASUR) System consists of three (3) transmitters and six (6) receivers deployed in 1958 along a great-circle arc across the southern US. The system is a continuous–wave fully multi-static Very High Frequency (VHF) radar interferometer: any receiver station can receive signals reflected from a satellite illuminated by any transmitter, subject only to horizon and signal-strength constraints.[6] Data from these sensors flowed to a command and control center located in Dahlgren, Virginia, where it was used to maintain a catalog of space objects. In 2007, the coverage of the system was such that, on average, a satellite having reflected signal strength above the detection threshold was simultaneously visible to four (4) receivers and two (2) transmitters.[6] More details of SPASUR are given by Easton and Fleming, Mengel, and Thomas.[7,8,9]

All detections of satellites are made at one or more of the six receiver sites without any a-priori knowledge of the satellite catalog, a process also known as un-cued tracking. The raw signals are sampled at high rate and the discrete data are forwarded in real time to the Operations Center at Dahlgren, VA, where they are processed by interferometric algorithms into the basic observable quantities: a pair of direction cosines of the line of sight from receiver to satellite, reckoned at time of maximum signal strength during the pass. The direction cosines are then associated with cataloged objects and used to update the orbits of those objects. The SPASUR system makes use of the Brouwer satellite theory.[10,11]

INSSCC

The Interim National Space Surveillance Control Center (INSSCC) was located at Bedford, Massachusetts and was the first Air Force SSA center to combine radar and optical data.[12] The INSSCC was collocated with the Air Force Cambridge Research Laboratory which sponsored Brouwer's work. The algorithms employed in the INSSCC were described by Wahl, Fitzpatrick and Findley.[13,14,15] Eberhard W. Wahl was the technical director of the INSSCC. It seems likely that the orbit propagator was based on the Brouwer drag-free theory and the orbit determination was based on weighted least squares.[10] The computer is unknown but is likely to have been an IBM 704 or 709. Brouwer continued to be a consultant for the Air Force during this time and was concerned with the extension of his satellite theory to include atmospheric drag.[16] Additionally, H. Beat Wackernagel contributed an important scientific role in reducing the optical data in deriving an Earth geopotential model (STEM) which was long used as the standard for classified military satellite tracking. The fact that space surveillance adheres to the metric system is directly attributable to Dr. Wackernagel. Dr. Wackernagel had been recruited by the Air Force in 1958 specifically to assist in the development of a space surveillance capability, after he obtained his Ph.D. from the University of Basel in Switzerland that year.[17]

496L SPACETRACK

In 1959, the Air Force decided to split the US space surveillance system into a development organization based at Hanscom Field (the 496L System Program Office, also known as the SpaceTrack Research and Development Facility), and an operational organization to be based at Ent AFB in Colorado Springs, CO, and eventually in the Cheyenne Mountain Complex. The 496L would develop and unify the space surveillance hardware and software into a system called the Space Detection and Tracking System (SPADATS). Initially, the software component of SPADATS operated in the 496L Building of the Electronic Systems Command at Hanscom Field, and the new Air Force analysts were trained there, but by 1963 the operational SPADATS had already been transferred to Ent AFB and the 496L facilities served only as a backup (and a test-bed for new software, as well as managing contracts for new hardware and software).

The SPADATS software was the first operational space surveillance system in Colorado Springs. SPADATS used the Simplified General Perturbations Theory (SGP) based on the work of Kozai[18] and Brouwer[10] to generate the Two-Line-Element (TLE) orbit element sets. SGP includes the main problem for the long period motion and the J_2 short-periodic terms. Detailed analysis by C. Geoffrey Hilton[19] demonstrated that the SPADATS formulas for the gravitational terms included in SGP agree with the papers of Kozai[18] and Brouwer[10] except in notation. The drag solve-for parameter is the time derivative of the mean motion. The form of this empirical model is motivated by the work of Findley.[20] There is no explicit atmosphere density model in SGP.

SPADATS operated on the Philco 2000/Model 212 large scale transistorized computer[21] at both the 496L (Massachusetts) and the Ent AFB locations, and eventually (1966) in Cheyenne Mountain. It was coded in assembly language. SPADATS also included a Special Perturbation Program called Spiral Decay to model the motion of re-entering space objects, as well as a second Special Perturbations Program called ESPOD, for use in Project 437. The SPADATS software remained an operational program in Cheyenne Mountain up to about 1980, although some legacy terminology still carries over to today in the SPADOC follow-on systems.

Two aspects of the SPADATS operation deserve further comment. One is the move from Hanscom AFB, MA to Colorado Springs. Another such move would not happen for 45 years. The second was the switch from the Brouwer-based astrodynamic algorithms to the Kozai-based SGP theory.[22] SGP was the simplified version of the Aeronutronic-Ford General Perturbation (AFGP) theory.[23] The comparison study described in Ref. 24 supported the switch from the Brouwer theory to SGP.

427M Program

In the 1970s, the Space Computation Center (SCC) was implemented on the Honeywell 6080 computer (427M program). This Honeywell 6000-series machine was part of the Worldwide Military Command and Control System (WWMCCS) program. Overall, approximately 83 Honeywell 6000-series machines were installed at 26 sites under the WWMCCS program.[25]

The 427M SCC was a replacement for the Space Defense Center implemented in the NORAD Cheyenne Mountain Complex under 496L. The SCC computer program system was designed to provide the real-time data processing support required for the detection and tracking of all satellites in space, and for support to the NORAD/ADCOM space/missile defense functions. As a replacement for the Space Defense Center, the SCC was to provide the essential operational capabilities of the 496L. Significant improvements included a man-machine interface using graphic interactive display terminals. The SCC was to provide the capacity to process data on as many as 5,000 space objects under normal conditions.[26]

The introduction of the high-level programming language FORTRAN to the SCC was an important innovation in the 427M program. A benefit of standardized high-level languages is that they allow the generation of portable code.

From an astrodynamics point of view, the introduction of the SGP4 satellite theory into the 427M was an important event.[22] The SGP4 theory couples a power law model of atmospheric density[27] with the canonical formalism developed by Brouwer and Hori.[28,29] Brouwer and Hori had originally modeled the atmospheric density with an exponential model but the amount of formulas required was excessive.[16] Otherwise, SGP4 retained a gravity model similar to SGP (low degree zonal harmonics in the secular and long periodic motion and J_2-only in the short periodic model). Figure 1 illustrates the development flow from the Brouwer drag-free theory to SGP4.

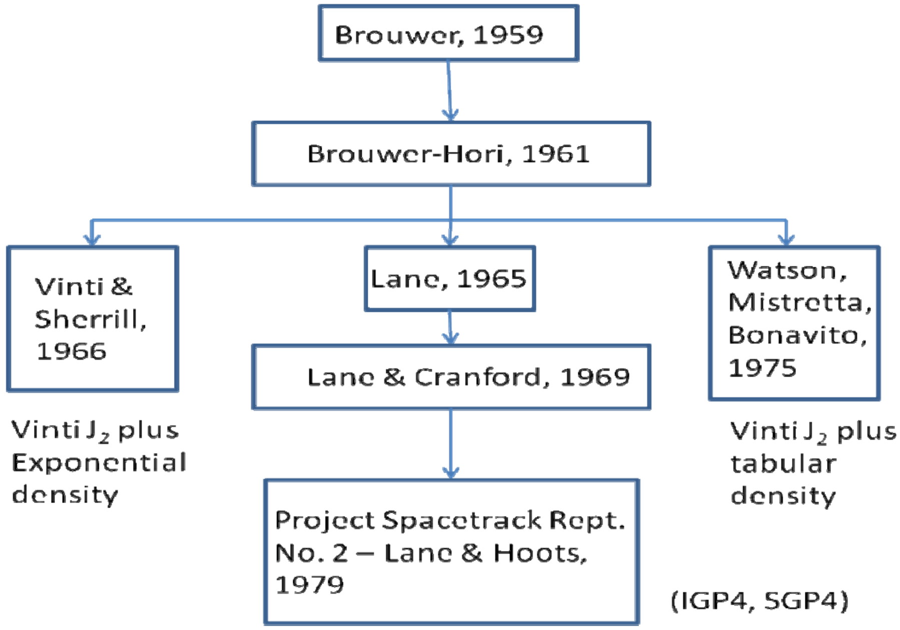

Figure 1: SGP4 Developmental History

In the second half of the 70s, the SDP4 modification was introduced for geosynchronous and Molniya high eccentricity orbits.[30] The orbit determination process continued to rely on the batch weighted least squares method. The 427M SCC did include a Special Perturbations capability which was used to support a small list of special satellites. One such special satellite was the US-operated DMSP polar meteorological satellite system where economic considerations precluded the inclusion of a cooperative, on-board SGLS transponder.

The 1980's

In the 1980s, several USAF space control facilities adopted IBM mainframe computers. Examples include the Air Force Satellite Control Facility (AFSCF) Data System Modernization (DSM)[31] and the GPS Master Control Station (MCS).[32] IBM mainframes made sense at this time as IBM was licensing its MVS operating system to manufacturers such as Amdahl and Fujitsu to produce clones of the IBM mainframe. This meant there was an evolving market for mainframes, and it was generally possible to upgrade software running on a specific IBM mainframe to a newer, higher capacity IBM mainframe.

Additionally, use of IBM mainframes by the USAF enhanced the USAF's ability to access existing space software computer programs especially those at the NASA Johnson Spaceflight Center in Houston TX, the NASA Goddard Spaceflight Center in Greenbelt MD, and the Draper Laboratory in Cambridge, MA which were IBM-mainframe 'houses' in the 1980s. NASA JSC and NASA GSFC were key centers in the US for civil manned and unmanned spaceflight, respectively. The Draper Laboratory is a not-for-profit research and development laboratory with a strong interest and tradition in manned space systems. The Draper Laboratory was originally part of the Aeronautics and Astronautics Department at MIT. In the 1980s and 90s, the Draper Laboratory supported a strong joint educational program with MIT; in this program, graduate students did their course work on campus and their research at the Draper Laboratory.

In the mid-80s, Air Force Space Command undertook the development of a Space Computation Center (SCC) to run on the IBM mainframe.[33] The development was done by Ford Aerospace Corporation personnel using the IBM 3083 as the development platform with the IBM 3090 being the eventual target. This project was known as SPADOC 4. Various phases of the project were known as SPADOC 4A, 4B, and 4C. The operational SPADOC 4B was located at the Cheyenne Mountain Air Force Station

(CMAFS) outside Colorado Springs. It has as its primary processors two IBM 3090-200J mainframes, one prime and one backup.[34] The backup was also used for exercise and training.

Given the continuing increase in the number of space objects that needs to be tracked, it was natural to require improved computational performance of each new system. Data suggests that a several-fold improvement in computer performance should have been obtained with the SPADOC 4 IBM mainframe system over the Honeywell 6080.[35]

From the point of view of astrodynamic algorithms, SPADOC 4 significantly expanded the available orbit propagator options. The SGP and SGP4 theories were retained from the 427M system. However, new GP theory HANDE[36, 37] and the Semi-analytical Satellite Theory SALT[38] were added to the SPADOC 4 system.

Both HANDE and SALT adopted aspects of the comprehensive Semi-analytical Satellite Theory whose development started at the Computer Sciences Corporation in Silver Springs, MD and continued at the Draper Laboratory.[39, 40] The HANDE model was developed by Felix Hoots, then at the Directorate of Astrodynamics, Space Command, Colorado Springs, Colorado. The gravitational model in HANDE is the same low degree zonal harmonic model employed in SGP and SGP4. The primary enhancement in HANDE is that it is able to include dynamic atmosphere density models. In general, modern dynamic atmosphere density models[41] include altitude dependency, lower boundary conditions, diurnal variation, annual and semi-annual variations, solar activity variations, and geomagnetic index variations. The Jacchia '70 is an early dynamic atmosphere density model.[42]

Hoots replaced the integrals that lead to the very long mathematical expressions in References 16 and 28 with numerical quadratures of the form

$$I = \frac{1}{2\pi}\int_{-\pi}^{+\pi} g(f)\,df \qquad (1)$$

where f is the true anomaly. The integrals in the right-hand-sides of Eq.(1) follow from the Gaussian form of the equations of motion; that is, they start as products of the partial derivatives of the orbital elements with respect to velocities (a six by three matrix) with the perturbing acceleration vector. In HANDE, the classical Keplerian orbital elements are employed. The Gauss-Legendre quadrature evaluation numerical technique is used.

Hoots claimed several advantages for the HANDE formulation, including the flexibility to choose the density model at execution time:[37] Hoots provided several test cases;[37] in these, he assumes a constant solar flux and geomagnetic index over the time interval of interest. In the tables of results, comparisons of Special Perturbations (SP), SGP, and HANDE are provided.

The SALT theory[38] is a Semi-analytical Satellite Theory also employing the classical Keplerian elements. The gravitational model in SALT is the same low degree zonal harmonic model employed in SGP, SGP4, and HANDE. The SALT atmospheric density model is Jacchia '70.[42] In the SALT test cases, constant solar and geomagnetic index are assumed.[38]

Neither HANDE nor SALT became preferred operational options in Colorado Springs. In the case of HANDE, replacement of the TLE with a more complicated transmission format (17 parameters for HANDE) and the implications for end users were key issues that prevented its acceptance and operational use.

One unanticipated aspect of the SPADOC 4 well-structured code was that the Astrodynamic CPC's[*] could be integrated easily with an external orbit determination system. References 43 and 44 describe the integration of the SGP, SGP4, SDP4, HANDE, and SALT theories with the modified form of the

[*] Computer Program Component

GTDS orbit determination system employed in the MIT community. This GTDS/NORAD GP capability allowed for independent test of the NORAD GP theories. While the GTDS/NORAD GP capability was originally developed on the Draper IBM mainframe, the software was subsequently ported to the SGI workstation by Draper and employed by the contractor Kaman Sciences in Colorado Springs.

SPADOC 4 continued to focus on batch least squares orbit determination processes although Kalman Filters were suggested for the sensor calibration in an independent study by Jim Wright.[45] The Navy SPASUR system (including both the fence transmitters and receivers and the operations center in Dahlgren VA) continued to function as the Alternate Space Control Center (ASCC) to provide backup command and control of the SSN and maintain the satellite catalog. Due to its legacy status, Dahlgren maintains its own separate catalog which is synchronized with the main catalog maintained by the SCC (and now the JSpOC).

As noted previously, an object penetrating the fence will result in several pairs of direction cosines from receiver to the space object. These direction cosines are processed to generate an equivalent range, azimuth, and elevation and observation time that are referenced to a central NAVSPASUR location. These equivalent range, azimuth, and elevation data have the same format as the conventional radar data coming to Colorado Springs.

Navy Workstation System

NAVSPASUR went through computer upgrades comparable to 427M and SPADOC 4. In the early 1990s, the NAVSPASUR astrodynamics code was executing on a CDC Cyber-174 computer and had been converted to Fortran. The CDC Cyber range of mainframe-class supercomputers were the primary products of Control Data Corporation (CDC) during the 1970s and 1980s. In their day, they were the computer architecture of choice for scientific and mathematically intensive computing. By 1995, the NAVSPASUR Operation Center in Dahlgren, VA employed IBM RISC System/6000 (7xxx-250) workstations.[46, 47]

NAVSPASUR benefited from the interest of the space systems technical staff at the Naval Research Laboratory (NRL) in Washington DC and at the Navy Postgraduate School (NPGS) in Monterey CA. NRL contributions included:

- Calibration of the NAVSPASUR Fence using Satellite Laser Ranging Data [48, 49]
- Demonstrating the feasibility of space object catalog processing using Special Perturbations [47, 50, 51,]

The Special Perturbations catalog demonstration[47,50,51] involved the addition of significant SGI server and workstation capabilities resulting in the hardware configuration shown in Figure 2.

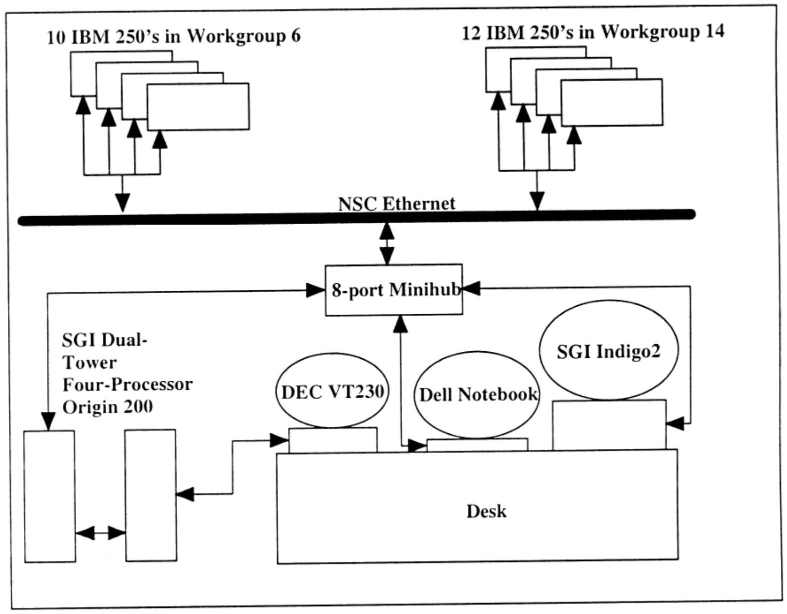

Figure 2: Hardware Configuration used in the SP catalog maintenance experiment at Dahlgren, VA, circa 1998 [47]

The NAVSPASUR PPT2 General Perturbation Theory[11] also was implemented in the GTDS/NORAD GP orbit determination test-bed at the Draper Laboratory and in a Linux PC installation.[52]

With the proliferation of satellite theories, a significant investigation was made into the conversion of element sets.[53] This was necessary to insure compatibility between the Astrodynamics calculations performed in Dahlgren with PPT2 and the calculations done in Colorado Springs. Reference 54 provides a more recent review of the analytical orbit modeling by the USAF and US Navy space surveillance organizations.

In 1999 and 2000, Dahlgren further transitioned to the IBM SP2 using multiple mainframes (SP2 towers and RS600 980s) for the computation and database/file servers with IBM workstations as the user front end.[*] The SP2 is a RS/6000 mainframe system which can host dozens to hundreds of RISC processor nodes facilitating parallel processing capability.[55] The SP2 tower runs the same operating system (AIX) as the RISC System/6000 workstations and this facilitated the port of the mission software to the SP2.

In 2003 and 2004, the NAVSPASUR system and mission were transitioned to the Air Force and the system was renamed the Air Force Space Surveillance System (AFSSS), although the system is still controlled from Dahlgren, VA.[6] Since then, effort has focused on the replacement/upgrade of the system.[6] A new radar fence system, notionally called the S-Band Fence, consisting of as many as three geographically distributed S-band receiver-transmitter pairs is being considered. This system is projected to be able to observe objects as small as 5 cm across (Ref. 6). Tracking objects down to five cm in size would push the total catalog size to more than 100,000 objects, beyond the current hard-coded limit of 69,000 using the SPADOC system.

CAVENet

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[*] Paul Cefola, ***Conversation with Paul Schumacher***, 19 October 2009 and ***e-mail from Edward Lydick***, 20 October 2009

The growth in satellite catalog and increasing demand for more SSA data products continued to outpace the ability of the formal military acquisition system to keep pace. To take advantage of the rapid progress in computer hardware and software, the operational SSA community in Colorado Springs was interested in the application of low-cost commercial technology workstations to the Space Situational Awareness problem. CAVENet was the unofficial system developed by the U.S. Air Force to augment the capabilities provided by SPADOC 4C.

In 1993, Draper Laboratory delivered a Silicon Graphic Workstation version of its GTDS R&D program to Kaman Sciences Corporation. Kaman Sciences used this capability on its SGI workstation (model IRIS 4D/310GTX) for the Ephemeris Theory Accuracy Study (ETAS).[56] Subsequently, Kaman Sciences built the SPECTR software to operate on the Silicon Graphics and IBM RS/6000 workstations.[57] SPECTR was first used in the Earth Gravitational Error Budget Study. SPECTR included:

- SP and GP (SGP4) orbit propagators
- Batch weighted least-squares Differential Correction (DC) orbit determination
- SP force models: geopotential (4 models, up to 70x70), drag (4 models), solar radiation pressure, lunar/solar gravity, and solid Earth tides
- Observation residual analysis, rejection, etc.
- Processing of observation data in B3 (internal) format and Satellite Laser Ranging (SLR) observation data format.
- Complete control over the integrator, solution parameters, and force models, etc. in expert mode
- Optional numerical partial derivatives for difficult to maintain satellites
- Determination of prediction errors (error ellipsoids) accurately for satellites when drag error is minimal
- Specially tailored for reentry assessment processing using SP vectors

Subsequently, the SPECTR software was included in the Astrodynamics Support Workstation (ASW) software which ran on the CAVENet workstations. CAVENet's original role was to provide a suite of analytical tools to perform in-depth analysis of historical element sets and observations.[58] CAVENet was considered to be an "off-line system" and was connected to SPADOC through a one-way filter, as illustrated in Figure 3, to protect the ITW/AA certification of the SPADOC system and data.

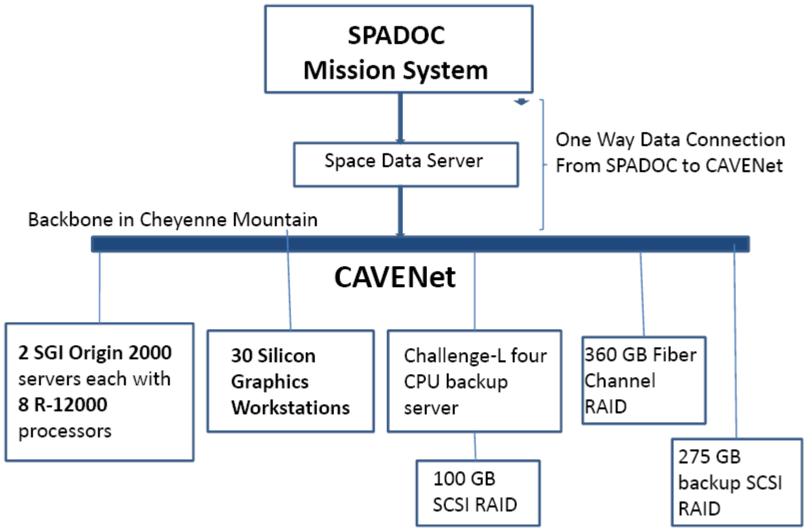

Figure 3: CAVENet Hardware Configuration at Cheyenne Mountain, circa 2000

As the space surveillance mission developed, SPADOC was increasingly unable to adapt and incorporate new models, algorithms, and analytical tools needed to support the space surveillance and SSA missions. Primary among these shortcomings was the limited number of SP element sets that SPADOC could store, which were needed for accurate conjunction assessment and to protect human spaceflight. The ASW software suite on CAVENet thus began to keep a separate satellite catalog based entirely on SP state vectors as well as covariance information. In recent years, additional tasks such as creation of the daily tasking plan for the SSN have also been moved to CAVENet.[59]

CCIC2S

In 2000, the U.S. Department of Defense initiated the Combatant Commander's Integrated Command and Control System (CCIC2S) program to upgrade all of the mission systems within Cheyenne Mountain, which included the space surveillance systems with a projected capabilities delivery date of 2006.

CCIC2S was expected to address the looming issues with the legacy SPADOC 4C system. At the time, SPADOC was processing about 400,000 sensor observations per day, 167% more than what it was designed to handle.[60] Official reports documented that an increasing number of tasks were being done on CAVEnet to compensate for SPADOC's shortcomings, but that the "off-line" nature of CAVNet was proving cumbersome.[60]

In a July 2006 report to Congress, the General Accounting Office (GAO) warned that the program was significantly over budget and behind schedule and that "none of the work on CCIC2S's critical space mission capabilities has been completed, and estimated completion dates for this work have yet to be determined." [60] Although CCIC2S work for the air and missile warning portions of Cheyenne Mountain operations is proceeding and delivering capabilities, the space portion was soon to be overcome by events.

JSpOC Mission System

On 19 July 2006, Commander USSTRATCOM signed the Establishing Directive for the Joint Functional Component Command for Space (JFCC Space).[61] The Commander JFCC Space serves as the single point of contact for all military space matters to plan, task, direct, and execute space operations.[61] This Directive also created the Joint Space Operations Center (JSpOC) located at Vandenberg Air Force Base, California. The JSpOC would serve as the primary SSA and Space command and control (C2) entity for the U.S. military, incorporating the functions previously performed by the SCC in Cheyenne

Mountain. In the fall of 2007, the JSpOC took operational control of the space surveillance mission from the SCC.

After CCIC2S and with the move of space operations out of Cheyenne Mountain, the U.S. Air Force initiated three separate programs to upgrade the capabilities of SPAODC and CAVENet to fit the new requirements of the JSpOC mission. The Space C2 program was created to provide the ability for the JSpOC to exert command and control over assigned space systems, while the Integrated Space Situational Awareness (ISSA) program was designed to handle the space surveillance catalog maintenance function. The Rapid Attack Identification Reporting System (RAIDRS) Block 20 system was designed to deliver a set of Defensive Counterspace (DCS) capabilities, primarily for detecting and geolocating radiofrequency interference.

Currently, Air Force Space Command is procuring the JSpOC Mission System (JMS), which is slated to eventually replace the legacy SPADOC and CAVENet systems. JMS is being designed to provide Commander JFCC Space with "agile and responsive command and control (C2) capabilities to conduct 24/7 world-class space operations", including Space Command and Control, Integrated Space Situational Awareness (ISSA), and System Threat Assessment and Characterization (STACS).[62] It combines the capabilities of Space C2, ISSA, and RAIDRS Block 20 into a single program.[63]

RUSSIAN SSA SYSTEMS

Software and Algorithms

As in the United States, development of the Russian Space Surveillance System (RSSS or RS^3) is intertwined with the development of the Russian Ballistic Missile Defense (BMD) and BM Early Warning systems; development of these systems commenced in the late 50s.[64]

The RSSS is influenced by the Russia's geography: Russia extends from longitudes of 30 degrees E to 190 degrees E. Most of Russia is north of 45 degrees N. The general structure and characteristics of the RSSS for LEO satellites including the network of sensors and software tools for processing the acquired data were first reported in February 1992 in Moscow at a conference on space debris and were published in 1993.[65]

There have been two developments that promote understanding of the analytical considerations supporting the RSSS:

- The U.S. and Russia organized in a series of joint space surveillance workshops in 1994, 1996, 1998, 2000, 2003, 2005, 2007 for which several Proceedings have been published [66-71]
- Russian scientists have published a series of detailed technical papers in the AIAA Journal of Guidance, Control, and Dynamics (JGCD) describing the methodology and the orbit propagators for both the LEO and GEO space objects [72-75]

One of the recurring topics in the U.S./Russia joint workshops is the comparison between the U.S. and Russian space catalogs. Russian space scientists also use the NORAD TLE element sets for scientific studies of the atmosphere density.[76]

Khutorovsky, Boikov, and Pylaev organize the LEO orbit determination methodology discussion as follows: [72]

- Observations and Their Errors
- Satellite Motion
- General Composition of the Algorithm
- Preliminary Correlation of Measurements and Objects
- Updating of Orbits

A. Minimized Function

B. Prediction of Motion

C. Minimization Technique

D. Selection of Abnormal and Alien Observations

E. Unpredictable Variation of Parameters

F. Adaptation for the Errors of Observations and Prediction

- Detection Process

A. Complete Groups of Observations

B. General Structure of the Algorithm

C. Preliminary Selection of Triplets

D. Primary Determination of Orbit

E. Calculation of Updated Orbits

F. Orbital Identification

G. Working in Complicated Situations

Of particular note is the approximation of the errors in the atmosphere density by a Gaussian process with the mean equal to zero and the matrix correlation function:[77]

$$Q(\tau_1, \tau_2) = E[V(a, \tau_1)V'(a, \tau_2)] \quad (2)$$

Boikov, Makhonin, Testov, Khutorovsky, and Shogin expand the discussion of the 'Prediction of Motion' for LEO space cataloging.[73] Five satellite theories are described:

- A: Analytical Prediction
- AP: Analytical Prediction with Enhanced Accuracy
- NA: Numerical Analytical Method
- N: Numerical Method with 6 x 2 geopotential
- NP: Numerical Prediction with Enhanced Accuracy (14th order geopotential)

Theory A is based on Brouwer. Nonsingular coordinates are employed to address the small eccentricity singularity. The geopotential includes the zonal geopotential harmonics J_2 through J_6. The periodic effects due to the $(C, S)_{2,2}$ are included. The atmosphere drag employs a simplification of the GOST-84 atmosphere density model.[78] Theory A is used for the tasks of correlation and detection.

Theory AP is also based on Brouwer. The periodic tesseral effects through $(C, S)_{8,8}$ are included resulting in significant accuracy improvement. Theory AP is used in the updating of the orbits. The value of adding tesseral periodic terms to an analytical theory was demonstrated independently.[79]

Theory NA is a semi-analytical theory based on the Brouwer canonical construct. The secular equations of motion for the triply-primed nonsingular elements are integrated numerically with a step size on the order of one to five days. An interpolator is used to obtain the triply-primed elements off the integration grid. The NA includes more of the GOST-84 atmosphere density model than theories A and AP. The NA includes the same tesseral periodic terms that are included in AP.

Theory N is based on numerical integration and employs a 6 x 2 geopotential. Theory NP employs geopotential harmonics up to 14th order and lunar-solar perturbations. The N and NP algorithms are used for propagating the orbit during the days just prior to re-entry. The numerical integration employs the variation of parameter formulation with the small eccentricity nonsingular elements. References 74 and 75 describe the analogous Russian algorithms for the geostationary case.

Clearly, the algorithms and satellite theories described in References 72 through 75 bring additional considerations to the catalog maintenance problem, in comparison with the U.S. algorithms and theories.[80] The necessity for these additional considerations may depend on the commensurability between the amount of tracking data and the number of objects in the space catalog.

Computer Systems

The Former Soviet Union (FSU) established the necessity of a monitoring system for space objects around 1960. The primary customer for the FSU space monitoring system was the Ministry of Defense.[81] Work on the space monitoring system began in 1962.82 This system had two remote nodes, one in Sary-Shagan and the other near Irkutsk in Siberia, and a command-and-control center near Moscow. The computer at the command-and-control center was a dual-machine computer system based on the M-50 machine.[81, 82] The M-50 is among the several high performance machines developed by S. A. Lebedev.[83] Initially, the system supported 12 foreign space objects. At one point, the command-and-control center was supported by a twin computing complex including both the M-50 and M-40 machines (both due to Lebedev).

By 1969, the space monitoring complex had been hosted on the 5E92 computer. The 5E92 was a special modification of the M-50 intended for use as a data processing complex.[84] The element base for this machine included vacuum tubes, ferrite cores, transistors, and semiconductor diodes. The design of this machine was due to Lebedev and V. S. Burtsev. The Main catalogue around this time included more than 500 space objects. Several Dnestr radars were contributing observations at this time.

By 1972, the space monitoring complex was hosted on a 5E51 computer which was a special modification of the 5E92. Lebedev and Burtsev were again the designers. This machine included floating point representation of numbers, a basing mechanism, protection for RAM and communication channels, and a multi-program operation mode for several users.[84, 85]

In 1972, there were 3000 space objects in space; the quantity of space debris outside the sensitivity of the sensors was estimated to be 10-12 thousand additional space objects. Lebedev also created the universal computer BESM-6 using the same semiconductor electronic components as in the 5E51 (see Figure 4).

Figure 4: BESM-6, created in the FSU in 1966, possessed the then speed record — about one million operations a second [80]

Production of the BESM-6 started in 1968 and continued until 1987. Approximately 400 BESM-6 computers were manufactured.[86] The AS-6 systems were deployed in three different centers of space information control.[85]

Burtsev proposed the El'brus computer family in 1970 based on symmetric multi-processor stack-based CPU architecture instead of vector-pipelining.[85] El'brus-1 was completed in 1980 and ran at up to 15 million operations per second. In 1985, El'brus-2 clocked a processing rate of 125 million operations per second. The Elbrus-2 computer was deployed in the space control center in the early 90s. At that time, there were approximately 5500 space objects.

Both technical and non-technical events influenced the evolution of the Russian SSS. Under technical events, we include the failures of the nuclear power installations onboard the Cosmos-954 and Cosmos-1402. Under non-technical events, we include the events of the 1990s (the transition of the FSU to the Russian Federation, economic stagnation, inflation). Such events sharply decreased the financing of works of scientific and industrial potential. The 90s also brought increased opportunities for communication among the scientists and engineers of various countries.

LIMITATIONS OFCURRENT USG SSA ALGORITHMS AND SOFTWARE

Although all the currently existing SSA systems have algorithmic and computer systems limitations, the systems used by the USG have the most acute, and documented, issues. The following list capabilities and shortcomings are not addressed in the current USG operational systems:

- Observation compression concepts are not available for either radar or optical sensors
- Fast and accurate orbit propagator concepts are not available
- Fast and accurate state transition matrix concepts are not available
- Kalman Filter-based orbit estimation concepts are not available

- Kalman Filter-based sensor calibration processes for are not available
- Realistic process noise and measurement error models are not employed
- The orbit uncertainty as represented by and propagated by the orbit determination systems is not well understood
- The processes developed by the AF Space Command for real time tracking of the atmospheric density variations are limited and narrow in scope
- There is no process for re-acquiring a significant portion of the catalog, as would be required in the event of a major geo-magnetic storm (such as 1989)
- There is no mathematically 'strong' theory for the general concept of observation association
- There is no concept for taking advantage of frameworks that can be massively parallelized on distributed computing clusters.
- There is no web services-based architecture for SSA
- There is no capability for organizing the very large databases that will result from large catalogs and improved sensors[*]
- There is only a limited cooperative, positive relationship between the U.S. military SSA community and the broader international astrodynamics research community
- The strict acquisition and operational requirements resulting from the NORAD ITW/AA certification process

While there are efforts underway to correct some of these limitations and issues, in particular with the JMS acquisition program, some of these limitations are not being addressed. And it is unknown at this time whether the JMS program will fall victim to the same programmatic issues seen in CCIC2S and the other programs which were supposed to replace and upgrade SPADOC 4C

POTENTIAL FOR AN OPEN SOURCE SOFTWARE SYSTEM FOR SSA

The goal of the authors is to develop a new software framework for SSA analysis and applications that is international and open in nature and allows users to access their own 'data' anywhere in the world through Web-based architecture and services. In this context, 'data' might be a nominal orbit for which the user was trying to understand the longer term motion. Or it could be processing raw observations (consisting of range, azimuth, elevation, range-rate, right ascension, and declination) collecting at multiple times to create an element set. The user would be able to operator on their data with algorithms and software that were transparent to them.

To develop this new SSA capability, the authors intend to develop an open source software (OSS) project following the insight of Karl Fogel.[87] The authors have three major technical goals for our project:

- To create a Web 2.0 architecture for SSA data products and services based on the human-provided services (HPS) paradigm[88]
- To adapt key astrodynamic algorithms to a modern, distributed computing environment by re-writing the applications in an object-orientated language platform and component technologies such as C++/CORBA[89]
- To extend non-invasive encapsulation techniques[90] to significant SSA applications which cannot be re-written

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[*] We assume that the SSN will be improved both qualitatively and quantitatively.

To clarify the issues in this project, the authors are undertaking three demonstration tasks:

- Migration of the Standalone Draper Semianalytical Satellite Theory (DSST)[91] from Fortran 77 to C++
- Non-invasive encapsulation of the Linux GTDS R&D orbit determination system using XML and LEGEND [92, 93]
- Initial design of Web services-based architecture for SSA

CONCLUSION

As the number of space actors and the usage of space grows, the need for SSA in both traditional national security and new civil safety roles is increasing. Historically, there has generally been a "closed" approach to creating the computer systems and software that implement astrodynamics algorithms, and only a small amount of international dialog and collaboration on algorithms and theory. The end result were systems with serious legacy restrictions that are slow to implement new techniques and fail to take full advantage of the hardware and software capabilities.

The authors propose that an open source software approach can mitigate some of these shortcomings, by increasing the opportunities to collaborate and developing common software libraries and modules where possible. This would increase the interoperability between systems and allow each end user to focus their resources on developing specific modules and libraries to meet their unique requirements.

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