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Foley, April J.

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THESIS

NANOSAT EMPLOYMENT: A THEORETICAL CONOPS FOR SPACE OBJECT IDENTIFICATION

by

April J. Foley

June 2014

Thesis Advisor:	Stephen Tackett
Second Reader:	William J. Welch

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NANOSAT EMPLOYMENT: A THEORETICAL CONOPS FOR SPACE OBJECT IDENTIFICATION

April J. Foley
Captain, United States Air Force
B.A., University of Maryland, 2004

Submitted in partial fulfillment of the
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June 2014

Author: April J. Foley

Approved by: Stephen Tackett
Thesis Advisor

William J. Welch
Second Reader

Rudolf Panholzer
Chair, Space Systems Academic Group

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ABSTRACT

Space Situational Awareness and Space Object Identification are vital to discovering and assessing space-based threats. The current ground-based mission architecture and operational concept do not provide enough detailed information on space objects to give planners and strategists a true picture of the space order of battle. This thesis looks at the possibility of using space-based assets, based on the CubeSat standard, to perform these missions to a higher level of quality. How this system would be folded into the current space systems operational concept is analyzed, as well as some recommendations for further study.

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LIST OF ACRONYMS AND ABBREVIATIONS

1U – One Unit CubeSat

2U – Two Unit CubeSat

3U – Three Unit CubeSat

6U – Six Unit CubeSat

ADACS – Attitude, Determination, and Control Subsystem

AEOS – Advanced Electro-optical System

AEOS−L – Advanced Electro-optical System – Long Wave Infrared

AFB – Air Force Base

AFS – Air Force Station

AFSCN – Air Force Space Control Network

AFSPC – Air Force Space Command

AIS – Automatic Identification System

ALCOR – Advanced Research Project Agency Lincoln C-Band Observables Radar

BMEWS – Ballistic Missile Early Warning System

C2 – Command and Control

CCD – Charged Coupled Devices

C&DH – Command and Data Handling

CDR JFCC Space – Commander Joint Forces Component Command for Space

CMOS – Complementary Metal-Oxide-Semiconductor

COD – JspOC Combat Operations Division

CONOPS – Concept of Operations

CONUS – Continental United States

COTS – Commercial Off The Shelf

CPD – JSpOC Combat Plans Division

DARPA – Defense Advanced Research Projects Agency

DIACAP – Defense Information Assurance Certification and Accreditation Process

DOD – Department of Defense

DOD EA for Space – Department of Defense Executive Agent for Space

ELaNa – Educational Launch of Satellites Program

FY – Fiscal Year

GEO – Geosynchronous Earth Orbit

GEODSS – Ground-Based Electro-optical Deep Space Surveillance System

GPS – Global Positioning System

GSCA – Global Space Coordinating Authority

HISPICO – Highly Integrated S-Band Transmitter for Pico and Nano Satellites

IAA – International Academy of Astronautics

IC – Intelligence Community

ICBM – Intercontinental Ballistic Missile

ISRD – JSpOC Intelligence, Surveillance and Reconnaissance Division

IT – Information Technology

ITAR – International Traffic in Arms Regulations

JFCC – SPACE – Joint Functional Component Command – Space

JHU/APL – Johns Hopkins University/Applied Physics Lab

JNWIC – Joint Navigation Warfare Center

JSpOC – Joint Space Operations Center

JWS – Joint Warfighting Space

LEO – Low Earth Orbit

LIDAR – Light Detection and Ranging

LLNL – Lawrence Livermore National Labs

LWIR – Long Wave Infrared

MDA – Missile Defense Agency

MEMS – Microelectomechanical

MIT/LL – Massachusetts Institute of Technology/Lincoln Laboratories

MISC – Miniature Imaging Spacecraft

MSX/SBV – Mid-course Space Experiment/Space Based Vehicle

MVS – Machine Vision System

MW – Mega Watt

MWC – Missile Warning Center

NASA – National Aeronautical and Space Administration

NASIC – National Air and Space Intelligence Center

NGA – National Geo-spatial Intelligence Agency

NMS – Nanosatellite Propulsion System

NRO – National Reconnaissance Office

NSA – National Security Agency

ORS – Operationally Responsive Space

OSD – JSpOC Operations Support Division

OPCON – Operational Control

PARCS – Perimeter Acquisition Radar Attack Characterization System

PAVE PAWS – Perimeter Acquisition Vehicle Entry Phased-Array Weapons System

P-Pod – Poly-picosatellite Orbital Dispenser

R&D – Research and Development

SAE – Space Avionics Experiment

SATS – Small Agile Tactical Spacecraft

SBSS – Space Based Surveillance System

SCP – Satellite Communications Package

S&IS – Space and Intelligence System

SLBM – Sea Launched Ballistic Missile

SMDC−ONE – Space and Missile Defense Command – Operational Nanosatellite Effect

SNAP – Surry Nanosatellite Applications Program

SOI – Space Object Identification

SOPS – Space Operations Squadron

SPINSat – Single Purpose Inexpensive Satellite

SPOCC – Space Based Vehicle Processing and Operations Control Center

SRD – JSpOC Strategy Division

SSA – Space Situational Awareness

SSN – Space Surveillance Network

SSPAR – Solid State Phased Array Radars

SSTL – Surrey Satellite Technology Ltd

STARE – Space-based Telescopes for Actionable Refinement of Ephemeris

STK – Systems Took Kit

TACSAT – Tactical Satellites

TCS – Thermal Control System

TT&C – Telemetry, Tracking, and Command

UNP – University Nanosat Program

USASMDC/ARSTRAT – U.S. Army Space and Missile Defense Command/Army Forces Strategic Command

USSTRATCOM – United States Strategic Command

USV – JSpOC United Space Vault

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The completion of this thesis would not have been possible without the patience and encouragement of my wonderful husband, Joseph Foley. His constant encouragement, even though the toughest times, was instrumental to the completion of the project. Equally vital to the completion of this project was my fantastic advisor, Professor Steve Tackett, without whose patience, advice, and assistance this would not have been possible. I would also like to thank my boss, Lieutenant Colonel Robert Light, and all of my co-workers whose intellectual discussion inspired the later stages of my research. Lastly, I would like to thank my mother, Linda Squires, for always having faith in me.

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I. INTRODUCTION

A. BACKGROUND

The vulnerability of U.S. space systems to disruption and attack by potential adversaries was assessed during the January 2001 Space Commission on the Organization and Management of United States Space Activities (hereafter referred to as The Space Commission). The dependence of the U.S. military on space systems continues to increase as more sophisticated targeting, communications and imaging systems that rely on space assets, such as communications satellites and Global Positioning System (GPS), become available. The growing reliance of the warfighter on these systems has the potential to lead to grave consequences should they be denied. The Space Commission Report stated, "The U.S. needs to strengthen its ability to collect information about the activities, capabilities and intentions of potential adversaries and to overcome their efforts to deny the U.S. [critical] information." One of the areas of improvement needed was that of space situational awareness (SSA).[1]

SSA is the "current and predictive knowledge of space events, threats, conditions, and space system status, capabilities, constraints, and employment—current or future, friendly and hostile—to enable commanders, decision makers, planners, and operators to gain and maintain space superiority across the spectrum of conflict."[2] Space surveillance deals with the "detecting, tracking, cataloging, and identifying man-made objects orbiting Earth." This allows, among other things, for the cataloguing and identification of man-made objects in space.[3] The discipline is comprised of four core functions (illustrated in Figure 1): characterization, detect/track/identify, threat warning assessment, and data integration and exploitation. Joint Publication 3-14 (Space Operations) states that SSA is

1. Commission to Assess United States National Security Space Management and Organization, *Report of the Commission to Assess United States National Security Space Management and Organization*, Rep. (2001), Washington, D.C.

2. *Space Surveillance Network (SSN) Site Information Handbook* (Peterson AFB, CO: HQ Air Force Space Command/A3CD, 2007), 16.

fundamental to conducting all space operations and is the key component for space control as the enabler of all other control tasks.[4]

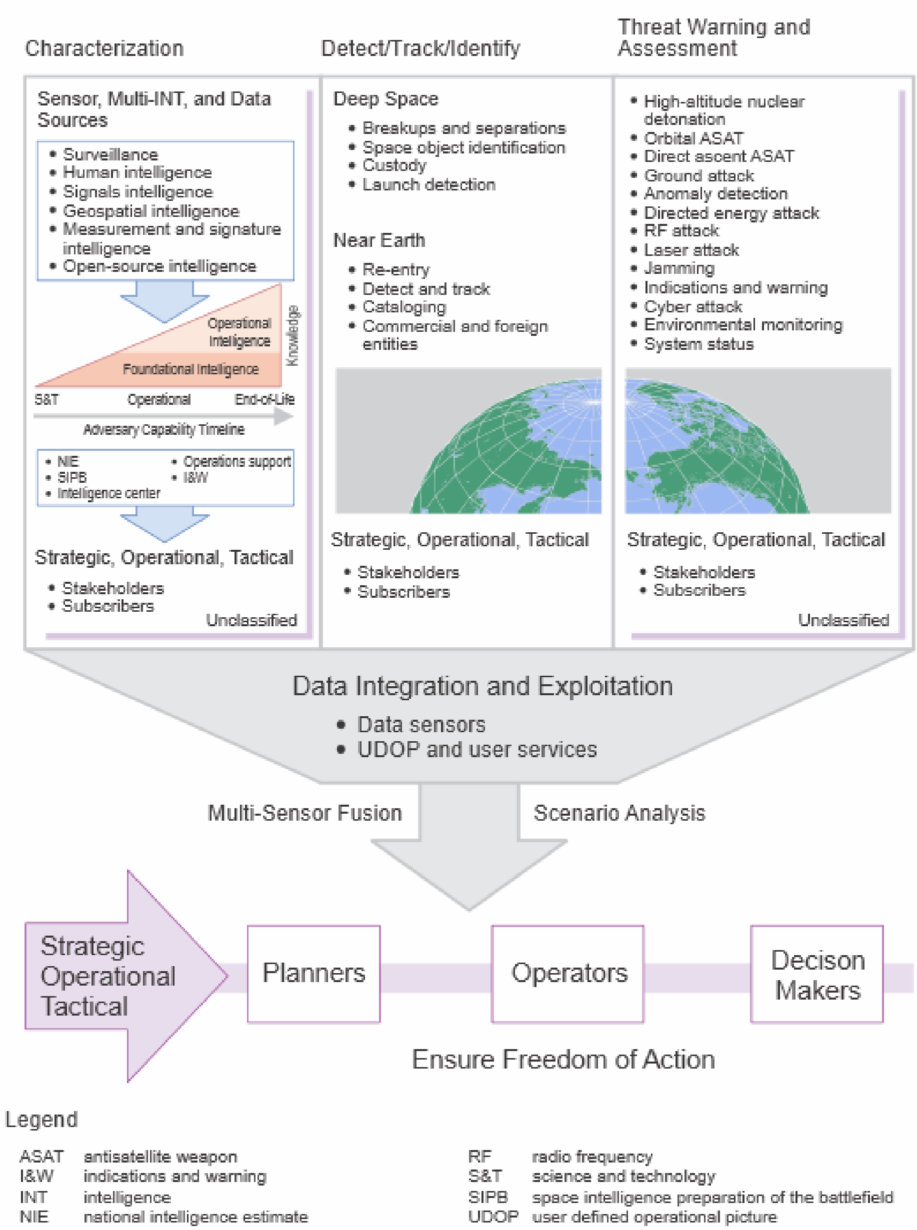

Figure 1. Space Situational Awareness Core Functions[5]

4. *Joint Publication 3−14: Space Operations* (n.p., 2013), II−1.

5. Ibid., II−3.

A critical part of the SSA process is Space Object Identification (SOI). SOI is a sub-discipline within SSA in which characterization of individual space objects enables planners to determine their use and capabilities. A number of systems within the Space Surveillance Network (SSN), such as the Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) and the Space Based Surveillance System (SBSS), currently accomplish the SOI mission in addition to object tracking.[6]

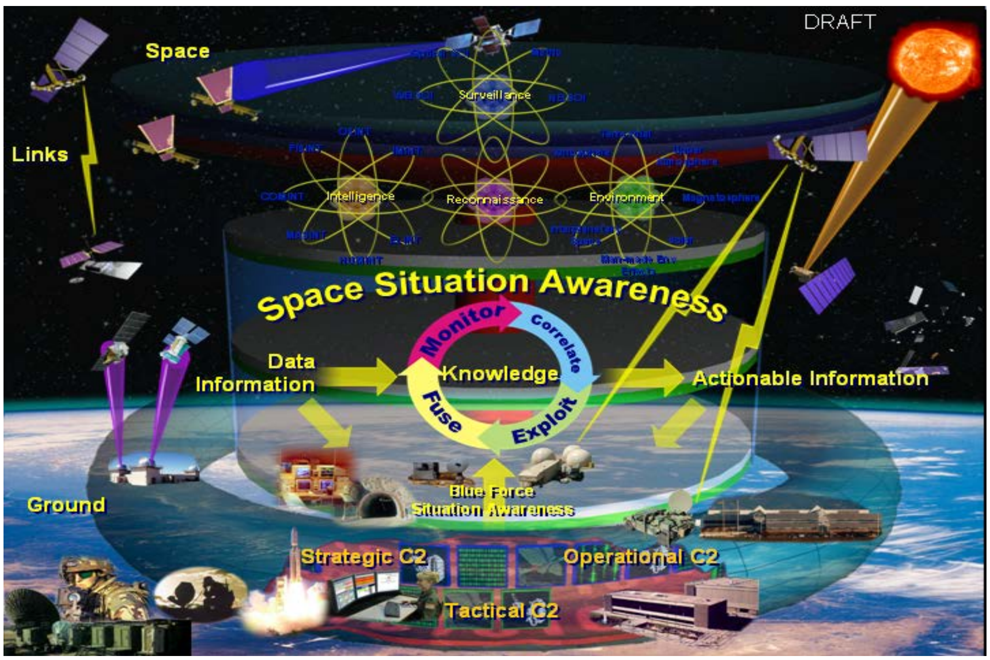

Figure 2. Space Situational Awareness OV−1 Diagram[7]

Figure 2 illustrates the current structure of SSA through ground and space assets. The addition of more sensors into the current architecture enables a more accurate database. It might also provide the flexibility within the operations environment to allow agencies within the Intelligence Community (IC) the ability to track movements and changes in the status of those systems, changes that may be indicators of other actions on the owner nation’s part.

6. *Space Surveillance Network (SSN).*

7. Ibid., 15.

The Space Commission's finding that better intelligence capabilities were needed on space assets, the widespread fear of a possible "Space Pearl Harbor" and the concern about how other nations exploit space, mean that new and innovative ways to ascertain space activities are required. The reality of tighter fiscal constraints dictate that the utmost care must be given to system value for the whole Department of Defense (DOD). Space systems have traditionally been large and expensive acquisitions. The National Aeronautical and Space Administration's (NASA) response to these fiscal constraints has been the employment of the "faster, better, cheaper" initiative. This approach, advocated by NASA Administrator Daniel Goldin in 1992, proposed instituting a philosophy of cost-cutting measures while still delivering the same number (or more) missions.[8] "Faster, better, cheaper" has helped to spark the research into using miniature electronics for smaller, less expensive space systems that can be operationally deployed quickly, to meet the emergent needs of the warfighter.[9]

The Operationally Responsive Space (ORS) framework was the DOD response to fiscal constraints as well as a change in the nature of U.S. military conflicts. The ORS approach to employing space systems is to provide on-demand capabilities that are "good enough" to meet mission requirements.

ORS uses a three-tier system to define the responsiveness of an asset. Tier 1 describes a system that uses existing assets or assets already on station. No engineering solution is required, and the user has access to the desired capability within minutes to hours. Tier 2 systems are pre-existing, field-ready capabilities that must be deployed before the user has access to the capability. As with Tier 1 assets, Tier 2 does not require an engineering solution. The targeted timeframe for employment of a Tier 2 assets is days to weeks. Tier 3 describes an asset that is still in development. Once development is complete, Tier 3 assets are employed using the Tier 2 model. Targeted timeframe for Tier 3 assets is months to years.[10]

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8. "Daniel Saul Goldin," National Air and Space Administration, accessed December 27, 2013, http://history.nasa.gov/dan_goldin.html.

9. R. F. Turner, "Small Spacecraft Missions − The U.S. Scene," Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 213, no. 4 (1999).

10. "Operationally Responsive Space," accessed December 27, 2013, http://ors.csd.disa.mil.

B. PURPOSE

The purpose of this study is to investigate one possible application of emerging technologies with the intention of developing and influencing future requirements for nanosatellite systems. Current development of nanosatellite systems are taking place primarily at the university level with incentives given by way of research funding and cash prizes in competitions.[11] As the capabilities of nanosatellite systems progress it is important for there to be a vision of potential applications, to ensure the proper investment of funds and to ensure capabilities advancement. This study looks at the use of nanosatellite technology and the ORS construct of rapid asset deployment as applied to SOI.

C. BENEFIT OF THE STUDY

The result of this study will be a theoretical concept of operations (CONOPS) for a nanosatellite system as applied to the SOI mission. This will enable a more focused development of nanosatellite capability that traces directly to operational needs identified in the 2001 Space Commission. Encouraging a more focused development relatively early in systems development will allow smarter investment of time and resources, and ensure system capabilities are in line with national objectives.

There are gaps in today's SSA and SOI capabilities and few platforms dedicated to these mission areas. The reality of the current fiscal situation means that many of these sensors are facing an austere environment where needed upgrades and routine maintenance are set aside in order to achieve cost savings. Future capabilities are at risk. The exploration of assets that are low cost and responsive to emergent needs anywhere in the world is the direction the military is taking for new acquisitions.

Developing a potential CONOPS for the use of emerging technologies will enable military commanders and members of the IC to influence and provide feedback on methods of utilization of an emerging system. This CONOPS will provide a sight picture of one potential capability and spark discussion for modification of not only the

11. Air Force Research Laboratory, "University Nanosat Program," accessed January 19, 2012, http://www.kirtland.af.mil/shared/media/document/AFD-111103-034.pdf.

employment of nanosatellite systems for this purpose, but also for others. This study may also provide a framework for organizations involved in the employment of satellite systems to think about necessary changes to force development and structure.

D. SCOPE AND METHODOLOGY

This study establishes a theoretical CONOPS for the employment of nanosatellite systems to shadow space objects and provide information on those objects in support of SOI. This study covers the current structure of the SSA mission architecture and SOI's place in it. A survey of available nanosatellite technology and systems provides a foundation of current nanosatellite capabilities and their employment possibilities within the SSA and SOI framework.

The results of the review of relevant literature was then analyzed by the researcher and a new CONOPS developed with reference to the suggestions of the 2001 Space Commission, the policies of the Air Force Space Command (AFSPC), and requirements of the individual agencies currently conducting the SSA mission.

II. A SURVEY OF SPACE OBJECT IDENTIFICATION METHODS

The launch of the first artificial satellite, Russian spacecraft Sputnik, in 1957 was the catalyst for the United States' interest in SOI and SSA. There are two disciplines of collection for SOI: imagery and signatures. Imagery methods consist of those systems that collect optical signals while signatures collection deals with the collection of data using radar systems.[12]

A. CURRENT METHODS OF SSA AND SOI

Today's approach to SOI is two-pronged and includes both terrestrial-based and space-based assets. The Space Surveillance Network (SSN) system of systems utilizes a combination of phased array radars, mechanical radars, multistatic radar, optical systems and a space-based system to detect and identify objects in support of the DOD space situational awareness and space order of battle missions.[13] There are three sensor categories based on their availability to support the SSN's mission. Figure 3 shows SSN asset location and category.

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12. John Lambert and Kenneth Kissell, "Historical Overview of Optical," 159–163.

13. *Space Surveillance Network (SSN)*, 23.

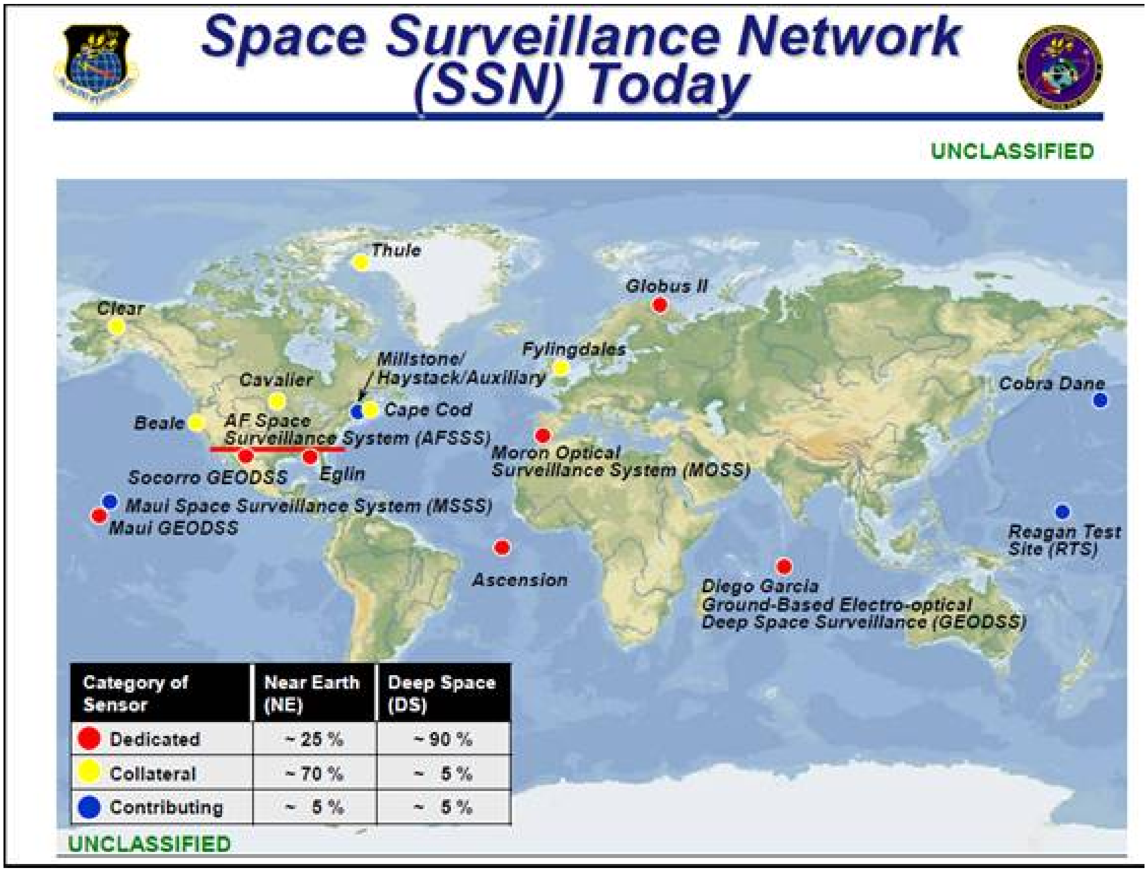

Figure 3. The Space Surveillance Network[14]

Dedicated sensors are those that are subordinate to USSTRATCOM and have a primary mission of SSN support. These sensors include the Ground-Based Electro-optical Deep Space Surveillance (GEODSS) sites located at Diego Garcia, Maui, HI and Soccoro, NM; the Globus II sensor in Vardo, Norway; Eglin's single face phased array radar at Eglin AFB, FL.[15]

Collateral sensors are sensors that are also subordinate to USSTRATCOM, but have a primary mission other than SOI and contribute as a secondary or tertiary mission on a non-interference basis. These systems include the PAVE PAWS (located at Cape Cod AFS, Beale AFB, and Clear AFS), PARCS (Cavalier AFS), and BMEWS (Thule

14. "Issue Brief Details Space Situational Awareness Sharing Program," Newswise, last modified November 22, 2010, http://www.newswise.com/articles/issue-brief-details-space-situational-awareness-sharing-program.

15. *Space Surveillance Network (SSN)*, 67–69.

AB, Clear AFS, and RAF Fylingdales, UK) systems whose primary mission is missile defense.[16]

Contributing sensors are those systems that provide data through contract or agreement. Massachusetts Institute of Technology Lincoln Lab's Haystack systems fall into this category, as does COBRA DANE located in Shemya, Alaska and Kwajalein's Reagan Test Range sensors (ALCOR, ALTAIR, MMW, and TRADEX).[17]

SOI collection systems fall into two broad categories: electro-optical and radar. The electro-optical systems use photometric and optical methods. The photometric method involves using optical telescopes augmented with advanced Electro-optical System (AEOS) Long-Wave Infrared (LWIR) (AEOS−L) and AEOS adaptive optics sensors. Optical methods consist of SOI analysis of the intensity; luminance, the intensity of light per unit area; and illuminance, the measure of brightness of an object, from GEODSS.

Radar techniques include Wideband and Narrowband collection. Narrowband collection provides a two-dimensional depiction of the object as a graph showing amplitude/time. These sensors are located at Ascension, Beal, Cavalier, Clear, Cape Cod, Shemya, Eglin, Fylingdales and Milstone. Wideband collection provides a more detailed radar picture. Sites providing this data are located at Haystack and ALCOR.[18]

B. COMMAND AND CONTROL (C2)

Command and Control (C2) for all SSA operations passes through USSTRATCOM in support of the Commander, Joint Functional Component Command Space (CDR JFCC Space). The Joint Space Operations Center (JSpOC) is the primary node for coordinating all these diverse efforts and is the conduit for CDR JFCC SPAC's execution of space coordination activities. JSpOC provides SSA products and integrates space operations for all DOD space capabilities.[19]

The Figure 4 shows the space operations command relationships.

16. Ibid., 23.

17. *Space Surveillance Network (SSN),* 23, 67–69.

18. *AU−18: Space Primer* (Maxwell AFB, AL: Air University Press, 2009), 251.

19. *Space Surveillance Network (SSN),* 27.

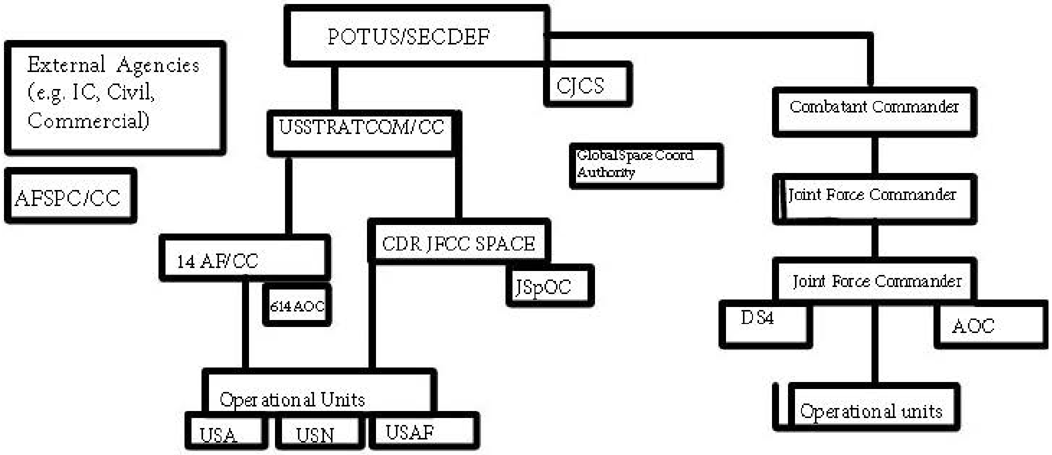

Figure 4. Command Relationships

1. United States Strategic Command (USSTRATCOM)

The USSTRATCOM is the command and control center for U.S. strategic forces and controls U.S. military space operations. Part of USSTRATCOM's mission is to provide coordinated space and information operations capabilities consistent with U.S. national security objectives. Joint Functional Component Command (JFCC) Space, located at Vandenberg AFB, and the subordinate JSpOC group fall under the USSTRATCOM chain of command.[20]

2. Joint Functional Component Command (JFCC) Space

JFCC Space consists of three operations centers in addition to the headquarters staff. These are the Missile Warning Center (MWC) at Cheyenne Mountain AFS, CO, the Joint Navigation Warfare Center (JNWC) at Kirtland AFB, NM, and the JSpOC, collocated with JFCC Space at Vandenberg AFB, CA. The commander (CDR JFCC Space) is dual hatted as the 14th Air Force Commander and designated as the Global Space Coordinating Authority (GSCA). JFCC Space is responsible for planning and

20. *Space Surveillance Network (SSN)*, 24.

conducting space operations and, as directed, planning and executing space control and force application missions.[21]

JFCC Space conducts space operations, exercises Operational Control (OPCON) of designated space and missile warning forces for USSTRATCOM and submits prioritized space operational requirements to USSTRATCOM.[22]

3. Joint Space Operations Center (JSpOC)

JSpOC is comprised of core elements of the 614 Air & Space Operations Center augmented with multi-service capabilities to form USSTRATCOM's command and control center for space operations. JSpOC continuously plans, integrates, commands, controls, executes, and assesses operations of forces supporting the Unified Combatant Commands and global space operations. JSpOC is composed of six core divisions.[23]

The Strategy Division (SRD) develops comprehensive space strategy that supports JFCC Space and combatant commanders by integrating space effects, timing, and tempo into the commander's campaign objectives. This division ensures the integration of space capabilities to campaign planning and provides support to planners during that process.[24]

The Combat Plans Division (CPD) supports space operations by providing products used to plan, direct, and execute JFCC Space forces. CPD ensures that application of space assets will produce optimal effects in support of CDR JFCC Space's intent, priorities, and objectives.[25]

Combat Operations Division (COD) conducts command and control over operations executed by JFCC Space forces. This includes serving as a conduit of

21. "Joint Functional Component Command for Space (JFCC Space)," accessed January 17, 2012, http://www.stratcom.mil/factsheets/JFCC_-_Space/.

22. "Joint Functional Component Command for Space (JFCC Space)."

23. "USSTRATCOM Space Control and Space Surveillance," accessed January 17 2012, www.stratcom.mil/factsheets/USSTRATCOM_Space_Control_and_Space_Surveillance.

24 Ibid.

25 Ibid.

information on mission results and tasking responses to the CDR JFCC Space and other JSpOC divisions, higher command, and theater space personnel for their situational awareness.[26]

The Unified Space Vault (USV) conducts various classified and unclassified Defensive Space Control, Offensive Space Control. The USV is responsible for consolidating the SSA inputs.[27]

Intelligence, Surveillance and Reconnaissance Division (ISRD) integrates into all phases of the operational cycle. They provide pertinent space intelligence information to the other divisions in support of strategy, planning, and operations monitoring efforts.[28]

The Operations Support Division (OSD) provides training, standardization, evaluation, and system integration support to the operations center.[29]

C. THE USE OF SATELLITES FOR SPACE OBJECT IDENTIFICATION

There are two major advantages to using space-based SOI assets. They are above the atmosphere, and are therefore not subject to the effects of atmospheric distortion or weather. Also, systems operating in the visible spectrum do not need to consider time of day (day vs. night) or limitations due to moonlight.

The Space Based Surveillance System (SBSS) (developed for USSTRATCOM and JFCC Space by Boeing, in conjunction with Ball Aerospace.[30]) is the only on-orbit system providing some SOI capability. SBSS was developed as a follow-on to a previous space surveillance experiments, the Mid-course Space Experiment/Space Based Vehicle MSX/SBV). MIT/LL and Johns Hopkins University/Applied Physics Laboratory

26 Ibid.

27 “USSTRATCOM Space Control and Space Surveillance.”

28 Ibid.

29 Ibid.

30. “Defense, Space, and Security: Space Based Space Surveillance (SBSS) System,” Boeing, accessed September 26, 2012, http://www.boeing.com/defense_space/space/satellite/sbss.html.

(JHU/APL) developed MSX/SBV on a Ballistic Missile Defense Organization (now the Missile Defense Agency) initiative.[31]

1. Mid-course Space Experiment/Space-Based Vehicle (MSX/SBV)

The Mid-course Space Experiment was a visible wavelength optical-based sensor mounted on a space platform. The MSX/SBV system's development provided a proof of concept demonstrating the feasibility of above the horizon, space-based surveillance platform observing missile events and resident space objects using the visible band. MSX/SBX integrated into the SSN to detect and track deep space objects, primarily those in geosynchronous orbits, within its coverage. The system launched on 24 April 1996, and though there were initial problems with gyro degradation, the system test was a significant success and has had a major impact on the overall performance of the SSN.[32]

Operations were conducted by MIT/LL, JHU/APL, and 1 SOPS at Schriever Air Force Base. MIT/LL operated the SBV Processing and Operations Control Center (SPOCC). SPOCC provided sensor scheduling and data processing functions. The Mission Operations Center, at JHU/APL in Maryland, was responsible for command uploads and provided availability for some mission data download. The 1 SOPS provided back-up satellite command and control, satellite commanding, data recovery, and satellite ranging support. The data, once processed, provided data back to the JspOC SSA Cell (ASCC). Due to system limitations, MSX/SBV was not ever responsible for quick reaction events.[33]

The MSX/SBV became available for use to the SSN in 1998, and incorporated as a contributing sensor. The system consisted of a 15.2 cm aperture off-axis telescope with stray-light rejection characteristics. The Charge-coupled Device (CCD) camera system used four three-sided abuttable-frame transfer CCDs in the focal plane. CCDs use a light-sensitive integrated circuit to store and display data for an image by matching each

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31. "Air Force Space Command Celebrates MSX 10th Anniversary," Space Daily, accessed October 5, 2012, http://www.spacedaily.com/reports/Air_Force_Space_Command_Celebrates_MSX_10th_Anniversary.html.

32. *Space Surveillance Network (SSN)*, 138–140.

33. Ibid.

pixel's intensity to a color in the visible spectrum. MSX/SBV utilized two different methods for tracking objects. The first was Sidereal Tracking. This method used the movement of the system's telescope sensor across the sky, keeping the sweep at the same rate as the stars appear to move. As the sensor moved across the sky, it would take rapid pictures of the field of view. Analysts compared the images with those from previous passes and were able to track the apparent movement of satellites across the sky. The second method, Rate Tracking, worked in a similar way, but exactly opposite. The sensor maintained track on the satellite of interest so that the stars appear as streaks and the satellites appear motionless.[34] MSX/SBV was retired 2 June 2008.[35]

2. Space Based Space Surveillance (SBSS) System

The SBSS system plan calls for a constellation of satellites, plus supporting ground infrastructure, with the aim to improve tracking and classification of earth orbiting objects. Like the MSX/SBV before it, the SBSS is currently the only space-based sensor in the SSN with the ability to detect and track objects without interference due to weather or time of day. The project builds on the success of the MSX/SBV proof-of-concept testing.[36] The primary contractor for the SBSS program is the Boeing Company, with Ball Aerospace and Technologies Corporation developing the satellite and sensor.[37]

SBSS aims to provide an 80% improvement on the performance of the MSX sensors. SBSS Block 10, the test bed case for the system, became operational in August of 2012 after initial deployment and testing in September of 2010. This positive progress is remarkable after early issues plagued the program. In 2005, an independent review panel declared the program's baseline to be "not executable." In 2006 Boeing restructured the SBSS program, streamlining assembly, integration, and the test plan, as

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34. *Space Surveillance Network (SSN)*, 138–140.

35. Don Branum, "MSX Retires," Air Force Magaizine: Online Journal of the Air Force Association, June 2, 2008, accessed December 27, 2013, http://www.airforcemag.com/DRArchive/Pages/2008/June%202008/June%2002%202008/MSXSatelliteRetires.aspx.

36. "Space Based Surveillance Makes Headway [SBSS]," *Defense Industry Daily*, last modified August 21, 2012, accessed October 6, 2012, http://www.defenseindustrydaily.com/preventing-a-space-pearl-harbor-sbss-program-to-monitor-the-heavens=06106.

37. "Defense, Space, and Security," Boeing.

well as relaxing the original requirements. Full operational capability for the complete Block 20 constellation, consisting of four satellites only one of which is deployed, has no definite date established for full capability at this time.[38]

The spacecraft segment of the SBSS program consists of a 1031 kg 3-axis stabilized platform. The sensor payload consists of a visible sensor with a large aperture with wide field of view lens on a two-axis gimbal. This two-axis gimbal allows ground controllers the ability to move between multiple targets of interest without expending fuel. The system runs off very low noise payload electronics with a reprogrammable on-board processor at the back end. SBSS improves sensitivity and threat detection by a factor of two, provides three times improvement in threat detection probability, and an amazing improvement by a factor of ten in capacity. SBSS operates in a sun-synchronous orbit with an altitude of 630 km. Expected mission life is five and a half years, with a system design life of seven years.[39]

The ground segment consists of the Satellite Operations Center, located at Schriever AFB, located near the SBSS depot at Boeing Colorado Springs, Colorado. The SBSS operations team consists of the Boeing Company, Ball Aerospace and Technologies Corporation, Harris IT services, and MIT/LL. Each of these team members has clearly defined program roles. Boeing's program support locations are Space & Intelligence System (S&IS), El Segundo and Seal Beach, California and Mission System Operations in Colorado Springs, Colorado and Chandler, Arizona. Boeing is the prime contractor and provides program management and mission assurance functions. Boeing is also responsible for system engineering and integration, space vehicle mission data processing hardware and software, mission engineering, modeling and simulation as well as launch engineering and integration, ground segment hardware and software development integration, user interface, TT&C, infrastructure software, mission operations and maintenance, on-orbit initialization and checkout and security and transition to military operators. Ball Aerospace, with locations at Broomfield and Boulder, Colorado, is responsible for the spacecraft bus and payload, on-orbit

38. "Space Based Surveillance Makes," *Defense Industry Daily*.

39. "Defense, Space, and Security," Boeing.

initialization and checkout as well as operations support. Harris IT services, Melbourne, Florida, provides satellite command and control software (OS/COMET). MIT/LL, located in Boston, Massachusetts, supports the program by providing mission planning software and ground-based mission data processing software.[40]

D. LIMITATIONS TO THE SSA/SOI ARCHITECTURE

There are four main limitations to the Space Surveillance Network's architecture. These are the number of sensors, the geographic distribution of those sensors, the sensor capability, and the availability of the systems. The two most important limitations are the availability of the sensors and the geographic locations of the network sensors.

The issue of availability will always be a factor where there is a large number of sensors included in a system not dedicated to that mission. In the case of the SSN, only seven of the nineteen sensors are dedicated. The other twelve are either collateral or contributing and are subject to the demands of other primary missions or the terms of agreements or contracts with the Air Force. This does not mean that these sensors are not important contributors to SSA/SOI.

The most important limiting factor for a more complete SSA/SOI is the geographic locations of the SSN sensors. The most glaring issue is that there are two sensors in the southern hemisphere, located on Ascension Island, UK and Diego Garcia. These sensors are still quite close to the equator and only provide limited viewing angles of anything to the south.

Increasing the number of sensors dedicated to the SSA and SOI missions can help ease the burden on existing systems. Cheaper, smaller, dedicated, and responsive sensors enable the ability for global coverage. Creating a support structure and operating concept where these small satellites with the ability to deploy when and where needed will improve the ability to characterize and assess space objects.

40. "Defense, Space, and Security," Boeing.

III. A REVIEW OF NANO AND SMALL SATELLITE SYSTEMS

As the miniaturization of electronics continues, it is natural that the same trend would extend to satellite technology. The concept of ORS and cheaper, smaller, disposable satellite technology is tempting for a number of defense industry applications. ORS satellites include classes developed entirely within a year (ORS tier three) at low cost.[41] The use of this technology in space object identification and space situational awareness is key to ensuring we can accurately characterize possible space threats.[42] This chapter presents a discussion of some nano- and small-satellite systems that have been developed and their uses. The trend towards ever smaller, more capable systems can be seen readily in this brief survey.

A. DEFINITIONS – CLASSES OF SMALL SATELLITES

The terminology used for the various classes of small satellites has been non-standard. LightSats, Single Purpose Inexpensive Satellite (SPINSat) systems, Tactical Satellites (TACSats), SmallSat, CheapSat, MicroSat, MiniSat, and NanoSat are all common terms used in conjunction with the smaller and cheaper systems now being developed. There does not seem to be a formal standardized term; some classes are defined by convention.[43]

"Small" satellite systems have a "wet mass," that is weight including fuel, of less than 500 kg. In addition to the weight restrictions, there are also some common characteristics on kick-off to launch schedule, commonly pegged at a range from six to thirty-six months and the utilization of either leading edge technology or commercial off-the-shelf (COTS) techniques.[44]

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41. John R. London, III, A. Brent Marley, and David J. Weeks, "Army Nanosatellite Technology Demonstrations for the Tactical Land Warfighter," U.S.ASMDC/ARSTRAT, 2010, 2.

42. "Small Is Beautiful: U.S. Military Explores Use of Micro Satellites," *Defense Industry Daily*, last modified June 30, 2011, accessed October 7, 2012, http://www.defenseindustrydaily.com/Small-Is-Beautiful-US-Military-Explores-Use-of-Microsatellites-067201.html.

43. "Satellite Classification," accessed August 12, 2012, http://centaur.sstl.co.uk/sshp_classify.html.

44. Ibid.

The International Academy of Astronautics (IAA) has suggested three further criteria, but these have not been widely accepted. These are the requirement that the program must have an unusual or unconventional approach, the mission must fill a clear gap, and the program must have a short lead-time. At this time, there are five classes of satellite within the SmallSat definition. These are the Mini Satellite (MiniSat) with a wet mass of 100 – 500 kg, the Micro Satellite (MicroSat) with a wet mass of 10 – 100 kg, the Nano Satellite (NanoSat) with a wet mass of 1−10 kg, the Pico Satellite (PicoSat) with a wet mass of 0.1 – 1 kg, and the Femto Satellite (FemtoSat) with a wet mass of less than 100 g.[45]

B. A REVIEW OF OPERATIONAL SMALL SATELLITE PROGRAMS

The small satellite initiative grew out of the need to curb the ever-expanding cost and size of spacecraft and the increasing difficulty in getting these large and expensive systems into orbit.

1. Clementine

The Clementine program was the first satellite developed with a mandate for a smaller system as part of NASA's "faster, better, cheaper" initiative for long duration space missions. Clementine, shown in Figure 5, was a landmark system in that it showed the potential of making a highly capable system built and launched for under $100 million. Today, this system, at 1690 kg wet mass, would not classify as a small satellite, but it was an important first step in the trend of ever-smaller systems.[46]

45. "Satellite Classification."

46. Michael J. Shannon, "The Clementine Satellite," Energy and Technology Review, June 1994.

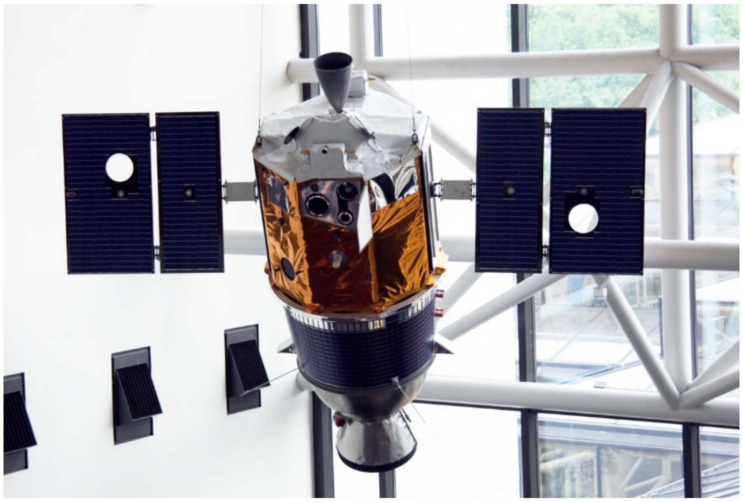

Figure 5. Clementine Display in the National Air and Space Museum.

Clementine's mission was to perform a scientific two-month lunar survey and demonstrate advanced, lightweight technology for detecting and tracking ballistic missiles. The Clementine spacecraft was a joint design and manufacture effort between the Naval Research Laboratory and NASA's Goddard Space Flight Center and Jet Propulsion Laboratory. Design, fabrication, integrations, and operations were the primary responsibility of the Naval Research Laboratory, but NASA provided design assistance and support. The Lawrence Livermore National Laboratory designed, developed, and calibrated the system's sensor package.[47]

The sensor suite consisted of six cameras: two star trackers, an ultraviolet/visible camera, a high-resolution camera, a near infrared camera, and a long-wave infrared camera. These sensors mapped the lunar surface successfully in 14 discrete spectral bands from near ultraviolet to far infrared. Clementine also made use of a Light Detection and Ranging (LIDAR) system to map relative heights on the lunar surface.[48]

The spacecraft itself was equipped with new lightweight reactor wheels, inertial measurement units, batteries, computer, and solid-state recorder. Two star tracker stellar compasses provide inertial reference using star field comparison.[49]

47. Shannon, "The Clementine Satellite."

48. Ibid.

49. Ibid.

2. Surrey Nanosatellite Applications Program (SNAP)

The Surrey Nanosatellite Applications Program (SNAP−1) nanosatellite program began as a series of design projects at the graduate and undergraduate level by Surrey Satellite Technology Ltd (SSTL), associated with the University of Surrey, UK. This program was the first British move into the smallsat field. The program's goal was to demonstrate the feasibility of a low cost, COTS-based, modular nanosat platform.[50]

The spacecraft itself, pictured in Figure 6, uses the standard module-box mechanical format with 'Eurocard' printed circuit board, which provides the ability for the mechanics, avionics, and payload to operate in parallel. All modules, with the exception of the on-board computer and the Machine Vision System (MVS) (payload) contained a standard 8-bit Controller Area Network (CAN)-micro-controller (Siemens C515) communications chip. The spacecraft's computer and MVS systems operated via StrongARM's Small Peripheral Interface. The communications system consisted of a VHF uplink and 100 mW S-Band downlink. A pitch-axis momentum wheel and orbit position detected via GPS receiver provides attitude control. The power subsystem consisted of six high-energy-density 'A' sized NiCd rechargeable cells and four GaAs solar panels which provided 5 Watts average power.[51]

50. Craig I. Underwood, Guy Richardson, and Jerome Savingol, "In-Orbit Results from the SNAP−1 Nanosatellite and Its Future Potential," Philosophical Transactions: Mathematical, Physical, and Engineering Sciences 361, no. 1802 (2003): 199–203.

51. Underwood, Richardson, and Savingol, "In-Orbit Results from the SNAP−1."

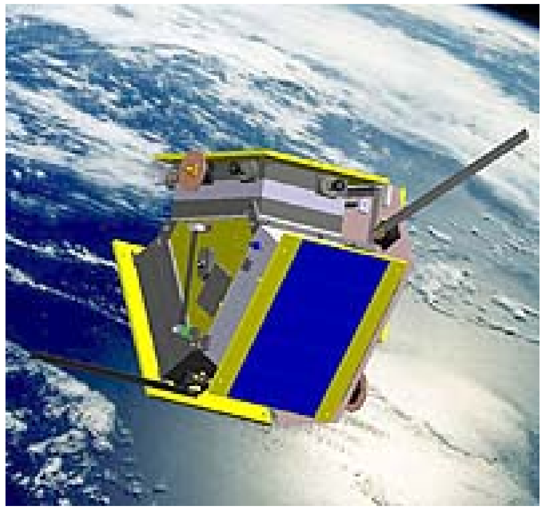

Figure 6. SNAP−1 Nanosatellite

SNAP−1 launched in 2000 from Plesetsk Cosmodrome, Russia sharing the rocket with a Russian satellite and a Chinese satellite, Tsinghua−1. The platform was operations tested with three different types of payloads. The first was a communications application, testing VHF communications capabilities. The second test was an ultra-high frequency inter-satellite communications link for use in rendezvous assistance. The final application was the MVS payload, which consisted of four ultra-miniature COTS CMOS video cameras: three with wide-angle lenses (90 degrees) and one with a narrow angle lens (20 degrees). All of the lenses were standard CTV style lenses, and the three wide-angle lenses designed for low-light operations. These imaged the Tsinghua−1 microsat, which launched concurrently, for an on-orbit inspection.[52]

The test orbit was a 700 km sun-synchronous orbit. The MVS test was successful, and MVS returned several images of the Tsinghua−1 deployment. Unfortunately, the system ran out of fuel during rendezvous procedures. Overall, the test was highly successful and SSTL has provided several nano- and microsat systems to other countries including Portugal and South Korea.[53]

52. Ibid.

53. Ibid.

3. CubeSat

Jordi Puig–Suari of California Polytechnic University and Robert Twiggs of Stanford University first proposed the CubeSat nanosatellite standard in 2003. The development of the idea, and the standard, was in response to the lack of opportunity for engineering and science students, and aerospace engineering students in particular, to participate in conventional satellite systems.[54]

Figure 7. Standard 1U CubeSat

The CubeSat system can be defined as a discrete, scalable, 1.33 kg 10x10x10 cm cuboid spacecraft unit, known as 1U(nit) CubeSat (see Figure 7). As mentioned, these systems are scalable, so they can combine to produce larger mass and/or volume systems, depending on use. Systems using up to three units (3U systems) have been demonstrated on-orbit, and systems of up to six cubes (6U) are possible. Additionally, the CubeSat program advocates a standardization of the interfaces between the launch vehicles and the spacecraft. The point of this is to allow developers to pool together and reduce cost, as well as increase the number of launch opportunities.[55]

CubeSat developers have advocated many cost saving measures in the systems. These include reduction in project management and quality assurance roles; use of

54. K. Wollert et al., "CubeSats: Cost Effective Science and Technology Platforms for Emerging and Developing Nations," Science Direct. Advances in Space Research, 47.

55. "Some Useful Information about CubeSats: History." Clyde Space, accessed October 14, 2012, http://www.clyde-space.com/cubesat/som_useful_info_about_cubesats.

student labor with expert oversight to design, build, and test key systems; reliance on non-space rated COTS components; limited or no built in redundancy; access to launch opportunities through standard launch interfaces; use of amateur communications frequencies and support from amateur ground stations; and simplicity in design, architecture, and objectives.[56]

CalPoly's CubeSat international collaboration includes over 40 universities, high schools, and private firms. All participants in the CalPoly program benefit from a streamlined launch program where CalPoly coordinates with the State Department and other launch authorities for launch. CalPoly obtains the required documentation, ensures conformance to ITAR regulations, and organizes the final delivery of the integrated Poly−Picosatellite Orbital Dispenser (P−Pod) delivery systems, shown in Figure 8 and developed at CalPoly, to the launch site. Currently, CubeSat systems are launching on decommissioned Russian rockets through Eurokot and Kosmotras, with launch costs running at about $40,000 per cube. American launch service is also available for non-defense related launches. These are coordinated through NASA and the Launch Services Program.[57]

Figure 8. Poly-Picosatellite Orbital Dispenser (P−Pod) CubeSat Launcher

56. Ibid.

57. "About Us." Cube Sat, accessed October 14, 2012, http://www.cubesat.org/index.php/about-us.

4. Space and Missile Defense Command–Operational Nanosatellite Effect (SMDC−ONE)

Space and Missile Defense Command–Operational Nanosatellite Effect (SMDC−ONE) was envisioned as a feasibility test for fielding a beyond line-of-sight (BLOS) communications nanosat constellation for the U.S. Army.[58] The time requirements for rapid delivery and deployment was that eight nanosat technology demonstrators be delivered within 12 months and at a cost of less than $350K per unit. The units were required to have a 12-month life on-orbit in LEO.[59]

The communications focus of the mission held an emphasis on data exfiltration from ground stations beyond the spacecraft's line-of-sight. This program was the first U.S. Army Space & Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT) indigenous satellite program to explore the use of the nanosat-class of satellites and they complied with CubeSat standards. The systems deployed from the standard P−Pod. SMDC−ONE's mission equipment included a custom VHF/UHF transceiver and eight antennas, four VHF and four UHF, placed on either side of the systems body.

The SMDC−ONE concept of operations starts with the satellite systems receiving a tasking order from one of the Army's Forward Operating Bases (FOB) or a command and control (C2) station. There are two C2 stations planned for the system's potential operational use. The first is located at USASMDC/ARSTRAT headquarters in Huntsville, Alabama and the second is located at USASMDC/ARSTRAT Battle Lab in Colorado Springs, Colorado. Original testing of the concept started with a text message issued from the first station in ground track, then downloaded to the second station, a 1200-mile separation.[60] Though the initial test satellites only maintained orbit for 35 days, initial testing was highly successful.[61]

58. London, Marley, and Weeks, "Army Nanosatellite Technology Demonstrations."

59. "SMDC−One: Nanosatellite Technology Demonstration," U.S. Army Space & Missile Defense Command/Army Forces Strategic Command, accessed October 8, 2012, http://www.smdc.army.mil/FactSheets/SMDC-One.pdf.

60. London, Marley, and Weeks, "Army Nanosatellite Technology Demonstrations."

61. "SMDC−One: Nanosatellite Technology Demonstration," U.S. Army Space & Missile Defense Command/Army Forces Strategic Command.

5. Kestrel Eye

The Kestrel Eye program, another USASMDC/ARSTRAT initiative, was a visible imagery nanosatellite technology demonstration. The demonstration's goal was to show the feasibility of an electro-optical near-nanosat class imagery satellite, pictured in Figure 9, with the ability to complete tasking orders by the tactical level ground component Warfighter.[62] The original requirements for the system were a mass of 10 kg, cost of $1 million per production unit, an operational life of more than 12 months in LEO, and the capability for ground imaging resolution of 1.5 m.[63] The final demonstration model ended up slightly over mass, at 14 kg, but still maintaining a "near-nanosat" size.[64]

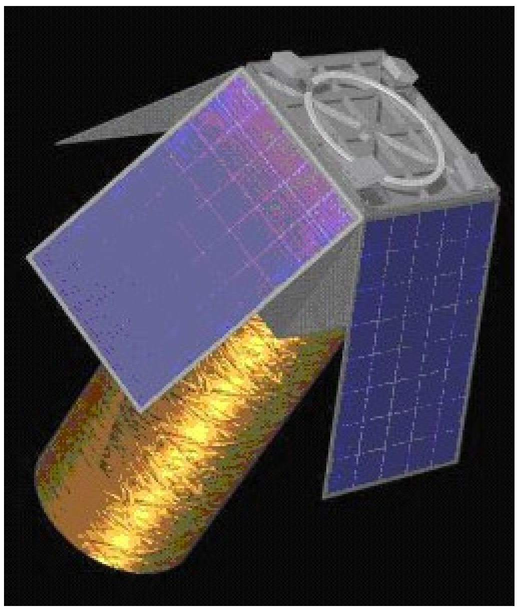

Figure 9. Kestrel Eye

52. "Kestrel Eye: Kestrel Eye Visible Imagery Nanosatellite Technology Demonstration." U.S. Army Space & Missile Defense Command/Army Forces Strategic Command, accessed October 8, 2012, http://www.smdc.army.mil/FactSheets/KestrelEye.pdf.

63. London, Marley, and Weeks, "Army Nanosatellite Technology Demonstrations."

64. "Kestrel Eye: Kestrel Eye Visible Imagery Nanosatellite Technology Demonstration," U.S. Army Space & Missile Defense Command/Army Forces Strategic Command.

The system objective of tactically responsive operations consists of the ability to task and receive the collected imagery data within the same ten-minute satellite pass. The operational concept for the system emphasizes simplicity, for the warfighter at the FOB. The only equipment required for testing were the satellite systems themselves, a laptop, and an S–band receive communications antennae. The operator, located on the ground at the FOB, simply used mouse clicks to identify the area of interest for the imagery, the software being set up in such a way as to allow easy identification of systems passing overhead and their imaging capabilities (field-of-view). Once the operator designated his area or object of interest, he then sent the command to the tasked system. The system then executed the order at the designated times. On completion of the tasking Kestrel Eye then immediately sent the data back to the operator. The data was then accessible directly to the operator, independent of any intelligence review. An additional copy in a central database provides for others who may need that same data for further analysis.[65] The first Kestrel Eye system launched in November 2013.[66]

6. NanoEye

The NanoEye system (pictured in Figure 10), like the Kestrel Eye, was a technology demonstration to provide a low-cost microsatellite-class system on orbit to provide responsive, tactical imaging from LEO to the ground component warfighter. NanoEye's requirements were to provide sub-meter resolution imagery from a small, low cost, electro-optical imagery satellite.[67] Program development fell under the Department of Defense's Small Business Innovative Research (SNIR) program with a cost per unit of approximately $1.4 million.[68]

65. "Kestrel Eye: Kestrel Eye Visible Imagery Nanosatellite Technology Demonstration," U.S. Army Space & Missile Defense Command/Army Forces Strategic Command.

66. Chris Bergin, "USAF Kestrel Eye 1 Spacecraft to Ride on Falcon 9 in 2013," NASA Spaceflight, accessed October 8, 2012, http://www.nasaspaceflight.com/2012/08/usaf-kestrel-eye-1-spacecraft-falcon-9-2013.

67. "NanoEye." U.S. Army Space & Missile Defense Command/Army Forces Strategic Command, accessed October 8, 2012, http://www.smdc.army.mil/FactSheets/NanoEye.pdf.

68. London, Marley, and Weeks, "Army Nanosatellite Technology Demonstrations."

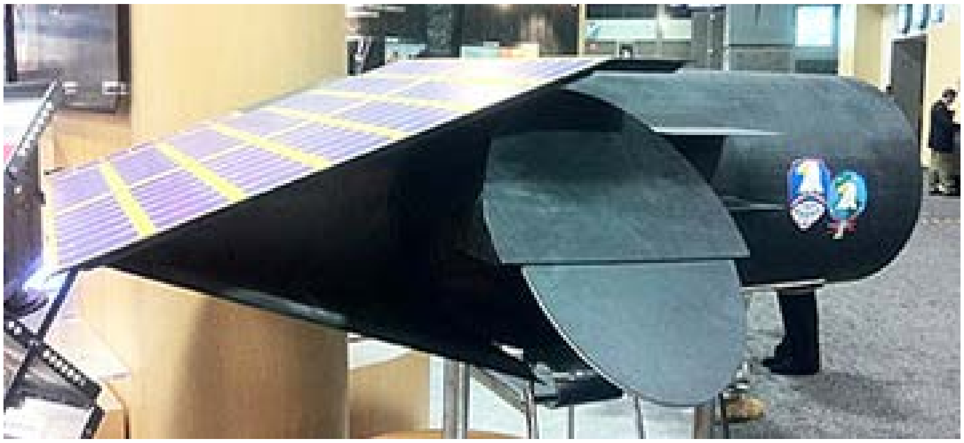

Figure 10. Mockup of the NanoEye system on display

Microcosm provided the spacecraft's design, and it consisted of a unibody design that contained the fuel tank as the primary satellite structure. The system also took advantage of COTS components used in CubeSat designs, and the new lighter weight, lower cost telescope was designed to decrease the vulnerability and consequences of anti-satellite weapons when compared with traditional imaging systems.[69]

The anticipated concept of operations for an operational NanoEye system would be identical to that of Kestrel Eye, in that the system will be tasked by a ground component Warfighter at a FOB, with the expectation that imagery will be taken and delivered on the same ten-minute pass. With a dry mass of 20 kg and a wet mass several times that number, the NanoEye did not classify as a nanosat, but the system did have an ample fuel supply and a significant capability for delta−v burns for maneuvering and station keeping.[70]

7. Small Agile Tactical Spacecraft (SATS)

The Small Agile Tactical Spacecraft (SATS) program was, like Kestrel Eye and NanoEye, focused on providing electro-optical imagery to the ground component warfighter. These systems (pictured in Figure 11) were a bit larger and a bit more expensive at 32 kg and approximately $3 million per unit, but designed with a 36-month

69. Ibid.

70. "NanoEye," U.S. Army Space & Missile Defense Command/Army Forces Strategic Command.

on-orbit lifetime in mind. The resolution requirements for the SATS systems was 1.5–2 meters. SATS had three modes of operation: a point and shoot option, similar to what was tested on Kestrel Eye and NanoEye; a scene mode, giving the ability to capture video and still images of specific coordinates; and a real time video mode that had the capability to track user specified targets of interest. The SATS primary sensors were comprised of five megapixel cameras capable of taking video at four frames per second.[71]

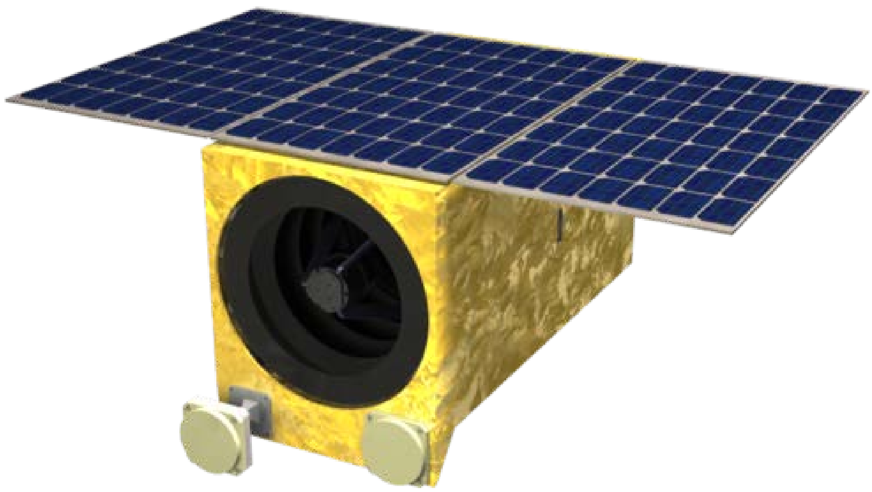

Figure 11. Small Agile Tactical Spacecraft (SATS)

8. Experimental Satellite System (XSS) 10

The Experimental Satellite System (XSS) 10, shown in Figure 12, was a technology demonstration by the Air Force Research Laboratory (AFRL) to demonstrate microsat maneuvering capability. This 30 kg, low cost system was the first in a series of two U.S. Air Force microsatellite tests. Capabilities envisioned by this system, or similar systems, were inspection, rendezvous and docking and close-up orbiting other space objects.[72]

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71. London, Marley, and Weeks, "Army Nanosatellite Technology Demonstrations."

72. "XSS−10 Micro Satellite," Air Force Research Laboratory, accessed January 18, 2012, http://www.kirtland.af.mil/shared/media/document/AFD-070404-107.pdf.

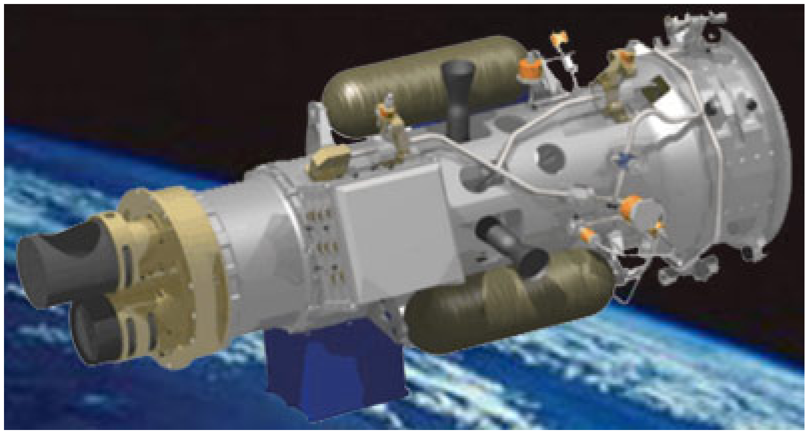

Figure 12. Experimental Satellite System 10

Key technologies tested on XSS−10 were lightweight propulsion and guidance, navigation, and control systems as well as a miniaturized communications system and smaller lithium polymer batteries for primary power storage. The testing sequence consisted of launch as a secondary payload aboard a Delta II launch vehicle. Once the system deployed, it commenced a complicated inspection circuit around the spent second stage of the Delta II. The demonstration mission lasted for approximately 24-hours and was very successful.[73] The integrated visual camera, lightweight propulsion system, and guidance control software performed exceptionally well during the testing phase.[74]

9. Experimental Satellite System (XSS) 11

The XSS−11 system, tested in 2005 by AFRL, was a follow-on project to the XSS−10 system. The XSS−11, shown in Figure 13, system was significantly larger, with a mass of 100 kg and was equipped with a more complex LIDAR imaging system. The goal of testing was to explore the feasibility and develop technology for use in rendezvous and proximity operations, autonomous mission planning for military applications in space servicing, diagnostics, maintenance, and space support. The mission

73. Ibid.

74. "XSS (Experimental Satellite System) Series," IHS, Jane's, last modified January 17, 2013, accessed December 28, 2013,https://janes.ihs.com.libproxy.nps.edu/CustomPages/Janes/DisplayPage.aspx?DocType=Reference&ItemId=+++1384691#XSS-10.

focus was on increasing the level of autonomy and mission complexity that microsatellite systems can safely execute.[75]

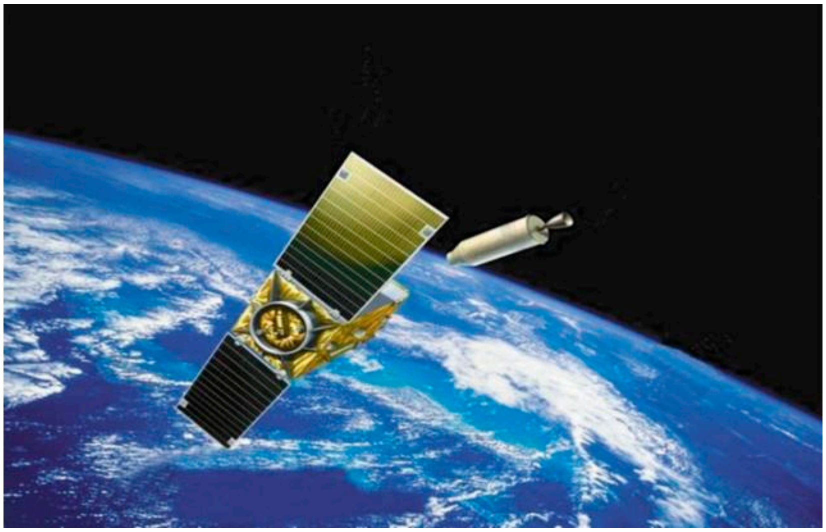

Figure 13. Experimental Satellite System 11

The primary contractor and mission partner was Lockheed−Martin Astronautics of Waterton, Colorado, who were responsible for the structure, propulsion, and systems. The 18-month testing sequence began after launch in April 2005, and consisted of deployment, then rendezvous with the spent second stage of that launch vehicle. After rendezvous, the XSS−11 system would move into an orbit around the tank, all while capturing images of the object. By the fall of 2005, XSS−11 totaled over 75 circumnavigations, providing a successful test.[76]

10. Tactical Microsatellite Experiment (TacSat−1)

The Tactical Microsatellite Experiment (TacSat−1), pictured in Figure 14, was an effort between DOD's Office of Force Transformation (OFT) and the Naval Research Laboratory. The program was conceived in 2002, while the NRL was studying tactical applications for space systems. The study concluded that due to technology

75. "XSS−11 Micro Satellite," Air Force Research Laboratory, accessed January 18, 2012, http://www.kirtland.af.mil/shared/media/document/AFD-070404-108.pdf.

76. Ibid.

advancements and miniaturization for smaller satellites, as well as the availability of cheaper quick response launch systems coupled with wider availability of classified SIPRNET, it might be possible to use a class of tactically responsive satellite systems. OFT agreed with the assessment made by the study, and instituted the Operationally Responsive Space (ORS) Initiative, the first test bed of which would be TacSat−1.[77]

Figure 14. Tactical Microsatellite Experiment 1

The overarching goal of the ORS program was to provide a quick response, Joint Task Force (JTF) organic platform for which multiple payloads could be applied that would provide coverage for various military conflicts and opportunities for data collection at any point on Earth. The cost per unit should be comparable to the cost per unit for unmanned aerial vehicles (UAV).[78]

The TacSat−1 program's mission was to provide and launch an operationally relevant micro-satellite with the ability to task and disseminate data through existing operational networks (primarily SIPRNET) in less than one year. The program requirements stipulated that cost could be no more than $15 million, including launch costs. The ORS program as a whole was tasked with making space assets and their capabilities available to operational users and to help generate policies where the

77. M. Hurley, "'Tactical Microsatellite Experiment (TacSat−1)," Naval Research Laboratory, accessed October 14, 2012, http://www.nrl.navy.mil/research/nrl-review/2004/space-research-and-satellite-technology/hurley/.

78. Ibid.

operational concepts and the technology co-evolves, making for a more organic and logical approach.[79]

NRL completed TacSat−1 spacecraft development in less than one year; from project go-ahead to system-level testing. Actual system cost came in at under $10 million. The design of a commercial MicroStar system provided the basis of spacecraft design, and the final system carried three payloads. The two imaging payloads were IR and color optical systems. The Army Night Vision Laboratory developed the IR system, the infraSPOT Indigo Omega infrared camera. The system was able to harness new methods and technology that removed the need for cryogenic cooling. This enabled a significant simplification of the spacecraft. The IR system was designed to collect in the 7.5 – 12 micron range and provides imaging at 850 m resolution. The visible system, the HanVision HVDUO−F7 Industrial Camera, was a commercial system modified for environmental conditions met in space operations. This system provided 70 meter resolution imaging. The third payload was the Copperfield−2 system, designed by the NRL. This system was a prototype to detect, track, and identify pulsed radio frequency signals.[80]

Unfortunately, due to continued launch related delays, the system originally scheduled for launch in 2005 became redundant after the successful TacSat−2 mission. The program was canceled in 2007.[81]

11. Tactical Satellite (TacSat) 2 Micro Satellite

The advanced technology demonstration, TacSat−2 micro satellite (pictured in Figure 15), was a joint collaboration between the AFTL, the DOD Space Test Program, the Naval Research Laboratory, the Army Space Program Office, Air Force Space Command, and the Space Warfare Center. This platform built on the success of the TacSat−1 acquisition timeline, and focused on demonstrating objectives of the joint warfighting space (JWS) initiative. The three main objectives for the system were first to

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79. M. Hurley, "'Tactical Microsatellite Experiment (TacSat−1)."

80. "TacSat/Joint Warfighting Space (JWS)," Global Security, accessed October 14, 2012, http://www.globalsecurity.org/space/systems/tacsat-1.htm.

81. Ibid.

rapidly design, build and test, and to have a launch-ready spacecraft in 15 months. The second objective was to provide responsive launch, checkout, and operations including launch within a week from call out of storage. The final objective for the program was to show that the platform could provide a significant military capability, in this case, providing images with resolution to a level that would be tactically useful. The spacecraft systems themselves consisted of a number of experimental subsystems, including an experimental solar array, a target indicator experiment and the RoadRunner On-board Processing Experiment (ROPE).[82]

Figure 15. Tactical Satellite 2

TacSat−2 launched in December 2006 from Wallops Island Flight Facility, Wallops Island, Virginia. The successful year long mission, ceasing operations December 2007, demonstrated all three of their objectives and was the first satellite to be successfully tasked by ground operations, collect, then transmit that data back to ground stations within 90 minutes. The test also performed real-time signal geolocation and identification using a satellite based platform, including a test that showed the capability to detect ship-borne identification broadcasts (Automatic Identification Systems (AIS)) from space.[83]

82. ”TacSat−2 Micro Satellite,” Air Force Research Laboratory, accessed January 18, 2012, http://www.kirtland.af.mil/shared/media/document/AFD-070404-105.pdf.

83. “TacSat−2’s Milestone Mission Advanced Responsive Space Concept.” SpaceRef, accessed October 14, 2012, http://www.spaceref.com/news/viewpr.html?pid=24531.

12. Tactical Satellite (TacSat) 3

TacSat−3, pictured in Figure 16, is the third system in the TacSat line. Launched in May of 2009, TacSat−3 features an on-board processor that provided real-time data within ten minutes of its collection to commanders in the field. Project partners were Army Space and Missile Defense Command, Air Force Space Command, DOD's ORS office, Office of Naval Research, National Air and Space Intelligence Center, National Geospatial–Intelligence Agency, and Air Force Research Laboratory's Sensor Directorate.[84]

Figure 16. Tactical Satellite 3

TacSat−3 was the first smallsat program to participate in a realistic payload selection process where recommendations solicited from the Combatant Commanders and reviewed by a flag officer panel defined the objectives. The final system incorporated three different payloads. They consisted of a hyperspectral imager, the Office of Naval Research's Satellite Communications Package (SCP) and the Space Avionics Experiment (SAE). Raytheon developed the system's primary experiment, the ARTEMIS HSI hyperspectral imager. The design rapidly supply target detection and identification data and battlefield preparation and combat damage assessment. The mission of the SCP trial was to collect data from sea-based buoys and then transmit that information back to ground stations to test new methods of faster communications. The AFRL designed SAE

84. "Tactical Satellite−3." Air Force Research Laboratory, accessed January 18, 2012, www.kirtland.af.mil/shared/media/document/AFD-0704-106.pdf.

payload validated plug-and-play avionics packages. This system design allowed a standard, reprogrammable package, reconfigurable based on mission needs.[85]

The complete system had a wet mass of just less than 400 kg and utilized the first generation TacSat modular bus. The program cost was $55 Million. TacSat–3 launched from NASA's Wallops Flight Facility at Wallops Island, Virginia in 2009. The total test mission time lasted a year, during which all payloads completed all milestones. TacSat–3's ARTEMIS sensor took over 2,200 data collects during the initial testing phase. The program transferred to Air Force Space Command in June 2010 for operational use.[86]

13. Small Satellite Initiatives

The popularity and results that have been achieved by the CubeSat standard, as well as all the technology demonstrations described in this chapter have inspired a number of other U.S. Government initiatives to encourage the development of student satellite systems. Chief among these are the University Nanosat Program and the Educational Launch of Satellites program.

a. University Nanosat Program

The University Nanosat Program (UNP) is an Air Force Research Laboratory funded initiative to encourage U.S. University students to competitively design, build, launch, and track a small-satellite or nanosat. AFRL's Space Vehicles Directorate at Kirtland Air Force Base, New Mexico is the program's headquarters.[87]

Participating universities propose a mission, then design and fabricate a flight quality satellite. Throughout the competition, there are workshops and reviews, culminating in a final competition to choose a spacecraft for sponsorship by AFRL to the Space Experiment Review Board in order to fly under the Space Test Program. As of September 2012, five winning projects developed for launch came from the University of

85. "Tactical Satellite–3." Air Force Research Laboratory.

86. Ibid.

87. "University Nanosat Program."

Texas, Austin; Cornell University; University of Colorado, Boulder; Michigan Technical University; and one developed by a collaboration between University of Colorado, New Mexico State University, and Arizona State University.[88]

b. NASA Educational Launch of NanoSatellites Program (ELaNa)

The NASA Educational Launch of NanoSatellites Program (ELaNa) is part of NASA's CubeSat Launch initiative. This contest offers the opportunity for a system to receive launch services. The competition's requirements state that the experiment must be consistent with NASA's Strategic Plan and the Education Strategic Coordination Framework and that the research should address aspects of science, exploration, technology development, education, or operations.[89]

Participating systems must also adhere to the CubeSat standard of 1.33 kg per unit and dimensions of 10x10x10 cm. The systems, however, may be 1U, 2U, 3U, or 6U in size. The systems meet a series of board reviews throughout the competition, and selected for mission and readiness at those reviews.[90]

The program originated to assist building the national STEM fields by helping to attract and retain students. Additionally, NASA envisions the program as promoting and developing innovative technology partnerships with U.S. industry and other sectors to assist in future NASA projects.[91]

C. THE ADVANTAGE OF SATELLITE SYSTEMS FOR SOI AND SSA

1. Space as the Ultimate High Ground

The concept of using orbital regimes to obtain a better vantage point for observation and communication transmissions is a concept well explored in any professional space program. The concept of gaining and maintaining control of the high ground in battle is not new, though the application to SSA/SOI operations is. The number

88. "University Nanosat Program."

89. "CubeSat Launch Initiative." National Aeronautics and Space Administration, accessed October 14, 2012, http://www.nasa.gov/directorates/heo/home/CubeSats_initiative.html.

90. Ibid.

91. Ibid.

of systems in use is growing, and as nations of interest begin to acquire and operate more complex and robust space systems, the more the United States will be interested in the operational status and purpose of those spacecraft.

2. Proximity and Clarity of View

Keeping the concept of the ultimate high ground in mind, there are a number of disadvantages to observing space objects from the ground. Weather and atmospheric effects can leave large gaps in observations of particular systems. The fact that ground sites are stationary means that they cannot maintain track on a passing system throughout its entire orbit. This gap allows time for a hostile object of interest to perform certain maneuvers unobserved.

By observing and tracking a space object from space, it is possible to eliminate or greatly reduce these problems, as well as adding some additional benefits. A spacecraft which matches the orbital regime of a target object closely by performing proximity operations will not only be able to be in position to observe the maneuvers and day-to-day changes in the operations patterns, but will be able to do so with a much smaller system.

The constant observation, with analysts observing the maneuvers will enable planners to establish a base-line operations picture and to extrapolate from that whether current operations are non-routine. More opportunity to take observations will be available. By placing the observation platform closer to the object of interest, the size and power required for comparable optical images is much lower. The possibility of using a common cell phone camera, that provides excellent quality images with low cost and low weight and space requirements, is currently being explored and should the system prove effective will provide a level of detail that is cost prohibitive of a terrestrial based system.

There are some downsides to using space systems for SSA and SOI, however. The operational complexity increases with the use of satellite systems and the need for precise orbital maneuvering for proximity operations. These, however, are not prohibitive, but should be considered when determining how and when to use a space-based SOI/SSA system.

Despite the initial complexity of designing missions using close proximity, using on-orbit assets to perform SSA/SOI missions has enormous potential. By using smaller and cheaper platforms, like those embodied in the CubeSat standard and ORS operational concept, it is possible to perform higher quality, responsive space-based SSA and SOI missions. The next chapter describes what such a system might look and how that system can be embedded in today’s operational construct.

IV. SSA NANOVIEW CONOPS

A. CURRENT SYSTEM OR SITUATION

1. Background, Objectives, and Scope

The importance of the space situational awareness (SSA) mission to the national security of the United States is one that becomes more evident as the number of space capable nations increase, and the abilities of those space-faring nations increases in scope and capability. The SSA mission consists of characterizing the space capabilities deployed in both the space segment as well as the ground segment of operations. By knowing the capabilities of other actors in space operations, it is possible to acquire the battlespace awareness required for planning, executing, and assessing protection of friendly assets, the prevention of hostile action, and the removal of hostile resources in the battlespace.[92]

A Nanosat system provides the capability to obtain and disseminate data on space objects of both known and unknown origin. The operational phases of the program consist of responsive launch from theater or from CONUS, autonomous close proximity operations on the object of interest, commanded or automatic begin of optical data collection, commanded or automatic download of collected information via currently existing support networks, commanded or automatic end of collection and operational disposal of the spacecraft into the atmosphere.

2. Identification

A representative Nanosat system is the NanoView, a 3U spacecraft bus equipped with an electro-optical imager to be used in imaging space systems. The 3U bus is comprised of three standard CubeSat systems, each by convention 10cm by 10cm by

92. Daniel P. Lewandowski, “Space Intelligence: Imperative for Space Situational Awareness,” AIAA SPACE 2009 Conference & Exposition, 4−5.

10cm. Total spacecraft size is therefore 10cm by 10cm by 30cm with a mass of 3kg.[93] The linear configuration of the spacecraft is shown below with the imager at one end.

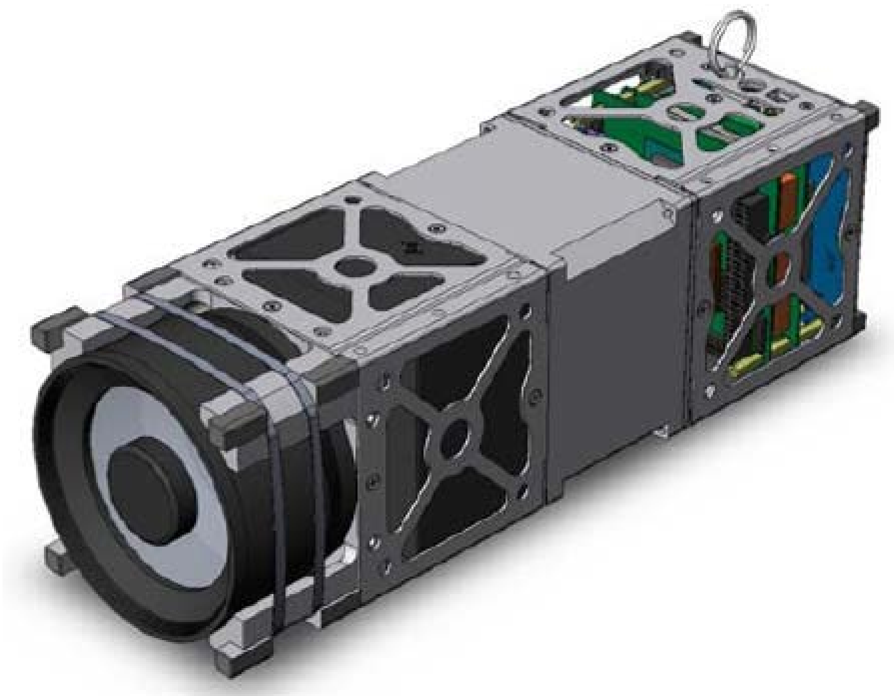

Figure 17. NanoView Representative Design, Miniature Imaging Spacecraft (MISC) from Pumpkin, Inc.[94]

NanoView, a representative design of which is shown in Figure 17, is deployed into low earth orbit as operationally required. Responsive launch of the spacecraft is accomplished as necessary utilizing small sat deployment launchers (still to be developed). Launch can occur from in theater or from CONUS as mission need and availability dictates.

Orbital requirements for each system are determined as needed, on a case-by-case basis. These should be low earth orbits (below 2,000km).

93. Kirk Woellert et al., "CubeSats: Cost−Effective Science and Technology Platorms for Emerging and Developing Nations," Advances in Space Research 47:665.

94. Pumpkin, Inc., accessed March 10, 2013, http://www.cubesatkit.com.

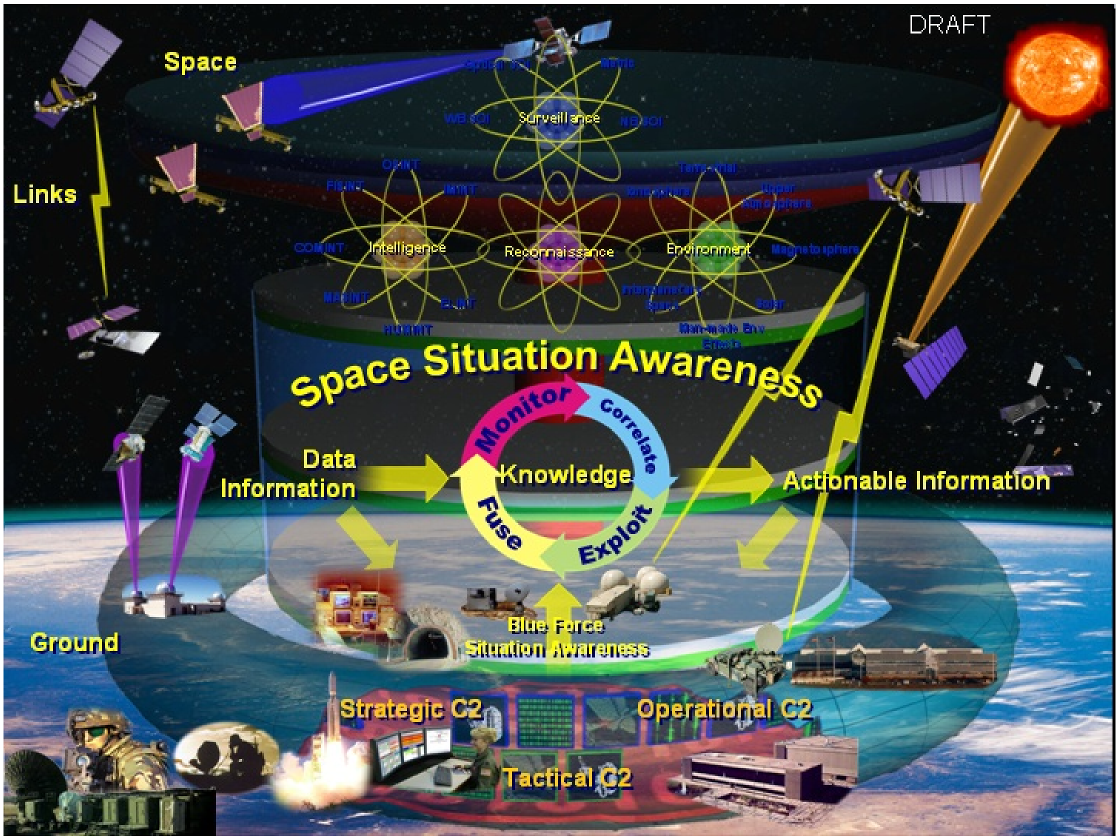

Figure 18. Space Situational Construct (OV−1)[95]

3. Organization

The broad nature of the mission set involved requires the cooperation of a wide variety of mission partnerships with a formal reporting process established and clear lines of responsibility. The service components, the Intelligence Community (IC), and JFCC−Space must establish reporting requirements as well as methods of data analysis and distribution of those products. These organizations must also refine and determine a system of mission assignment and mission prioritization.

The Department of Defense Executive Agent for Space (DOD EA for Space) serves as the senior executive for space operations and acquisition. The program director will report directly to the DOD EA for Space for programmatic issues. Operational

95. *Space Surveillance Network (SSN)*, 15.

control will be granted through USSTRATCOM's Joint Space Operations Center (JSpOC) located at Vandenberg AFB, California.[96]

The NanoView program office will be a joint organization, tasked with the development and deployment of the NanoView system. Representatives from this office will conduct acquisition, testing, and evaluation of the spacecraft. The NanoView Operations unit will support operationally deployed units. This support includes spacecraft health and status reporting, back-up spacecraft command and control, and programmatic resource management. The NanoView office will also be responsible for applying and developing further capabilities required by Joint Functional Commands and other users.

The IC and Information Assurance Communities consist of the National Reconnaissance Office (NRO), National Security Agency (NSA), Defense Intelligence Agency (DIA), and the National Geo-spatial Intelligence Agency (NGA). These agencies will be involved in the prioritization of asset deployment. Establishment of working relationships is required to enhance capability and operating philosophy.

All entities within the acquisitions community that are part of the National Security Space (NSS) enterprise are the natural mission partners of the NanoView program. The acquisitions community must assist in developing not only the spacecraft systems, but also to improving the infrastructure and information dissemination architecture associated with NanoView, including the integration of products into future net-centric architectures.

Other government agencies may also benefit from partnerships and acquisition of NanoView capabilities and technologies. Some of the government entities that have such a stake are DARPA, NASA, the service laboratories, as well as the national laboratories.

Other mission partners must include the commercial and industry contacts capable of system development. Further possible mission partners may come from allied counties, collaborating as needed.

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96. *DHS Acquisition Instruction/Guidebook #102-01-001*: Appendix F. Interim Version 1.9 ed. 2008.

B. OPERATIONAL CHAIN OF COMMAND

NanoView satellite systems will fit into the existing AFSPC and Joint operations structure. Figure 19 illustrates a typical space asset management organization. USSTRATCOM manages all operations. Operational control for the NanoView program will utilize the same process. Requirements will be established or requested through coordination with the JSpOC, who will then operationally task the unit operating the NanoView systems.

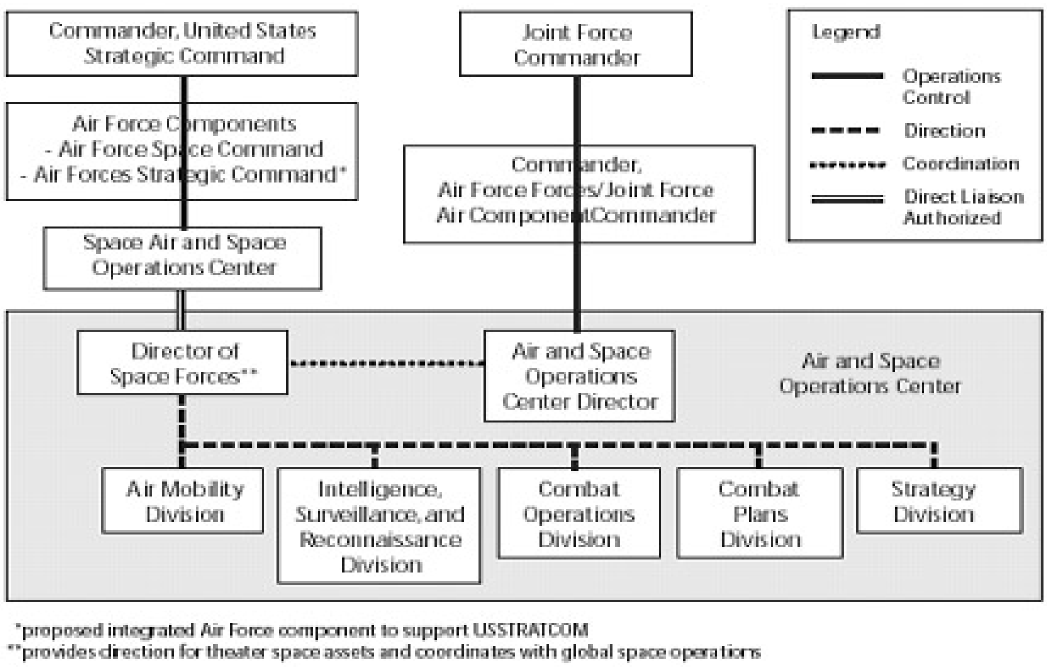

Figure 19. Space Forces Command Structure[97]

Another unit involved in SSA who will be involved in this mission include 14th Air Force. The 14th Air Force is the numbered Air Force tasked with C2 of space forces and provides planning, tasking, directing and synchronizing all space operations. Space warning, surveillance, and battlefield characterization also fall under their purview. [98]

97.Unified Command Plan (n.p.: n.p., 2011).

98. *Space Surveillance Network (SSN)*, 30.

1. Crew Makeup

Each crew should consist of at least four individuals filling the following roles:

- Crew Commander: This individual has the overall responsibility for the mission and mission equipment. The Commander is more a supervisory role and should be an experienced system operator.
- Satellite Operations Officer – The Satellite Operations Officer is responsible for all upload and download operations pertaining to mission data including receiving and responding to payload performance feedback. He or she operates the mission payload and responds to mission payload faults and status. The operations officer is also responsible for ensuring the delivery of mission data to the analysts.
- Satellite Systems Engineer – Maintains spacecraft health and status. The systems engineer is responsible for satellite bus and subsystem commands, faults, and status. The engineer also maintains communications links and analyzes data, correcting as necessary.
- Lead Engineer – The lead engineer does not fall under the direct crew construct. This position is responsible for providing system expertise. The Lead Engineer is responsible for responding to anomalies or unforeseen events and is the technical expert. The Lead Engineer is also responsible for maintaining the lessons learned database.

2. Training

The training of operations qualified personnel is vital to the success of the NanoView mission. Four phases of training are standard across space operations:

Initial Training – Initial training is the first formal instruction in the system. The 381 Training Group at Vandenberg AFB, California, currently accomplishes initial training for all space operators. The scope of initial training is to instill knowledge of the fundamentals of basic satellite operations. The course also covers a broader operational view, teaching operators where their system fits into the larger structure of operation.

Positional Qualification Training – This phase of training narrows the scope of instruction to the specific tasks and requirements the individual is responsible for while serving on the operations crew. Specific activities taught in the classroom and in simulation environments allow the crewmember to learn his or her specific responsibilities.

Mission Crew Training – This final phase of instruction brings all the crew positions together to perform in a more mission-oriented and realistic environment. This phase of training primarily consists of simulation scenarios with training equipment. It is at this phase of training that crew and team coordination are developed.

Recurring Training – Recurring training helps maintain operational sharpness and exposure to events not often seen in day-to-day operations. This can include periodic calibrations, responses to short notice or routine tasking, and response to contingency events. A robust recurring training program is vital to maintain skills and pass on the fruits of lessons learned.

C. TASKING PROCESS

Joint Space Operations Center, Combat Operations Division (JSpOC/COD) will issue implementation of NanoView collections by Space Tasking order. Joint SSA collection priorities will be established by JFCC Space in conjunction with NASIC's SOI office and JFCC ISR. This will ensure that a complete listing for items of interest is available to mission planners. Periodic reviews will be done at least monthly to ensure the accuracy of priority listings, and the community will conduct additional reviews as needed. JSpOC will determine view and collection opportunities for target objects. An example of the data flow from space assets is shown in Figure 20.

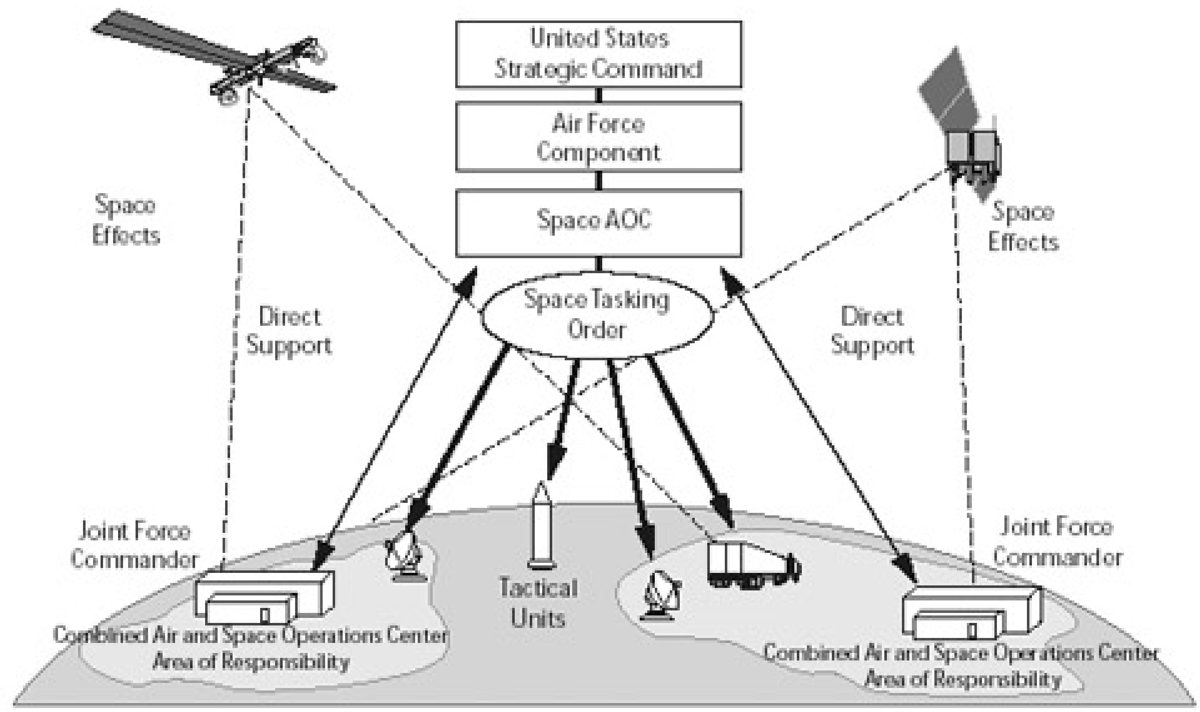

Figure 20. Space Asset Data Flow.

JFCC ISR is the joint component of USSTRATCOM dedicated to coordination of global intelligence collection. It fulfills requirements for both DOD worldwide operations and ensures national level intelligence requirements are filled. JFCC ISR is the focal point for all planning, execution and assessment for military ISR operations.[99]

NASIC is DOD's primary producer of foreign aerospace intelligence. They determine the performance characteristics, capabilities, vulnerabilities and intentions for those systems. NASIC's assessments are used as key factor for shaping national security and defense policies.[100]

Involving these two agencies will ensure that all DOD and national level requirements are met and will minimize the possibility of missed objectives. The focal point for all task planning will remain with JFCC Space. Inputs to the tasking process are submitted on a periodic basis to JSpOC/ISRD, JSpOC's intelligence requirements

99.*Space Surveillance Network (SSN)*, 27.

100. "National Air and Space Intelligence Center," Air Force ISR Agency – NASIC, http://www.afisr.af.mil/units/nasic/.

section, for coordination. Once deconflicted, ISRD presents the final prioritization list to the mission planning division, CPD, to formulate the operational strategy.

Mission planning should include orbital analysis of the item of interest, including a launch trajectory solution for the NanoView chase spacecraft, and specific target operations of interest, if any.

D. MISSION PLANNING

Each mission will require careful and dedicated planning products. A single team will be responsible for assessing the object of interest, specific functions of note, and activities to observe. These can be determined through a number of sources, and the process must remain flexible to ensure response as required. The planning phase should encompass the development of the orbital regime needed for proximity operations, launch insertion point, and time of launch. The mission planning document should include priorities of times and activities to be observed. This document should, again, be flexible, to ensure adequate response to changes in target behavior.

The planning process will begin with the establishment of the need to observe a certain object. This requires that other systems in the SSA architecture detect the launch and/or be capable of determining the orbital parameters of the object. The JSpOC SSA Cell is responsible for managing the database of space objects. The SSA Cell will coordinate with JFCC−ISR and NASIC to determine a priority order for object observation by NanoView systems. This is to ensure the best use of limited resources. JFCC−ISR, NASIC, and JSpOC will jointly maintain and provide regular updates to the list. This ensures that the list remains in keeping with national level objectives and other requirements. Updates to the prioritized listing should occur at least quarterly, or as needed to respond to emerging developments. Coordination with stakeholders and members of the IC is recommended to ensure the broadest possible usefulness of data.

Once requirements are established, the responsible mission-planning agency will formulate a mission-planning document with the objectives clearly stated in the background section. Other sections of the mission planning documentation will include desired orbital parameters for the NanoView system and detailed imagery requirements.

Close coordination between the planning, analysis, and systems operations teams is necessary to ensure the best operation of the system. The operations team, as the entity with direct responsibility for the health and status of the system, is the lead agency for coordination.

E. PRE-LAUNCH AND LAUNCH ACTIVITIES

(1) Storage. ORS Tier 2 requires field-ready units be ready to deploy within days or weeks. To ensure that timeline is met, pre-positioned NanoView systems housed in central storage locations will be available for short-timeline deployments. A specified number of forward deployed units at Vandenberg AFB, California and Patrick AFB, Florida and kept in a cold stand-by will further ensure short-notice availability. These stand-by systems should be ready for integration with the rocket in two days or less and operational in seven days. Forward deployed spacecraft units, controlled by the theater commander, are housed in environmentally controlled containers and placed near the operationally feasible launch site further decreasing the time to operations. This is a very demanding timeline for space launch operations, but the off the shelf nature of the systems and launch on demand concept will allow for ease of use.

Systems in storage will be status checked every 48 hours, to ensure environmental controls are still operational. The deployed operations team will ensure all subsystems are operating nominally by conducting weekly function checks.

(2) Launch–Prep Testing and System Mating. When the operations team receives notification from the directing authority (JFCC−Space) to deploy NanoView, preparations for launch operations will begin. The launch cycle will begin with running a function test on the payload. If there are issues with the payload selected, the team will use another available unit and the defective one returned to the central storage depot for repair as needed. Final system checkout and mating will occur onsite.

These preparations include running collision avoidance simulations with the assistance of JFCC−Space, calculating desired launch windows, and performing crew training and rehearsal in preparation for the launch.

(3) Launch. Pre-designated launch units at Vandenberg or Patrick AFB or deployed units in the theater of operations will deploy the spacecraft. The launch unit's

responsibility for the payload lasts until the satellite has reached its initial orbit. The satellite operations squadron, to be located at Schriever AFB, Colorado, will conduct on-orbit check out of the spacecraft and transfer of the spacecraft from its insertion orbit to proximity operations orbit.

F. ON-ORBIT OPERATIONS

1. Post Launch Activities

Once the Spacecraft has achieved transfer orbit, a series of system and subsystem checkout actions must take place to ensure the proper functionality. Individual checkout will be performed on each subsystem and the payload, following procedures in operational checklists. Once batteries have been charged and communication with the AFSCN tested, operators will command images be taken and sent back to complete the payload calibrations.

Routine operational activities include monitoring the health and status of the spacecraft systems and payload operations.

a. Health and Status Operations

Health and status operations include those tasks scheduled by the operations team to ensure proper maintenance of the spacecraft and payload. These include monitoring health and operational status via routine uplink/downlink communications with the satellite. Analysis of this information will determine what sort of operations will be necessary to maintain optimal performance. Some items of interest could include:

- Status of communications links
- Temperature of subsystems
- Functional status of subsystems
- Functional status of payload
- Processor status and temperature
- Storage space available
- Periodic system calibrations of subsystems and payload

b. Payload Operations

Payload Operations tasks are those tasks required for the employment of the imaging system payload aboard the NanoView systems. The mission set for each individual satellite determines the number and scope of payload operations, and may vary with time and operations tempo. These include:

- Establishing sensor pointing requirements
- Deconflicting pointing requirements with status and health functions
- Setting time delay imager start/stop
- Maintaining onboard mission processing regimes
- Scheduling download of mission data

The first step in establishing day-to-day sensor operations is to determine the pointing requirements. Careful pre-planning is required to determine what orbital regime is of interest for general SSA operations or what opportunities are available to investigate a single object for SOI missions. This requires the NanoView mission planners to work closely with JSpOC Combat Plans Division (CPD) and Intelligence, Surveillance and the Reconnaissance Division (ISRD) in order to get match priorities determined by the SSA Cell and the National Air and Space Intelligence Center (NASIC) with collection opportunities.

The next step is to then deconflict those opportunities (pointing requirements) with the scheduling of status and health functions. As a cheaper, ORS concept design it may not be as necessary to ensure that all health and status functions are performed as often as those platforms with a longer expected life. These considerations need to be taken into account. JSpOC's CPD section should be involved in determining the health and status philosophy for each mission based on expected length of mission and individual collection requirements.

Once pointing requirements have been coordinated with the necessary health and status functions, the time delay for the imager start/stop time needs to be established. JSpOC CPD and United Space Vault (USV) divisions should be involved in this process. CPD to determine a check for intent, priority and objective consistency and USV as a coordinator for any elements of the mission that fall under Space Control or SSA mission sets.

For NanoView systems there is little processing that will be accomplished aboard the space vehicle. Despite the simplicity of the system, there will be a need for payload operations, data management, and data compression. Operations squadron line crews manage and maintain these activities.

Getting the post-mission data back to the analyst team is the final step to close the NanoView collection operations. Scheduled downlinks over the AFSCN will allow data to flow from spacecraft to central data collection points in a consistent and reliable data flow.[101]

c. Contingency Operations

The need to develop and continuously evaluate methods of recovering systems from contingencies is vital to the success of any system. It is difficult to determine all such issues that a system might encounter in its lifetime or throughout the course of the program. It is vital, however, for detailed reports and lessons learned be developed and maintained whenever such issues arise. These should be maintained, available, and discussed through a robust recurring operations training program.

2. Example Missions Using Systems Tool Kit (STK)

As a proof of concept, two sample missions were run on STK. In both cases a generic target satellite (TargetSat) was used as the object of interest. In the first scenario, launch occurs from CONUS. In the second scenario launch takes place from in theater. Details for both examples follow. Table 1 lists TargetSat's orbital elements.

101.”Joint Functional Component Command for Space (JFCC Space).”

Table 1. TargetSat orbital elements.

TargetSat Orbital Element	**Value**
Semi-major Axis (*a*)	7000 km
Eccentricity (*e*)	0
Inclination (*i*)	66°
Right Ascension of the Ascending Node (*Ω*)	86.664°
Argument of Perigee (*ω*)	0°
True Anomaly (*v*)	0.000112652 °

The first test run of the CONOPS consisted of a launch from Vandenberg AFB, CA. TargetSat's orbit was designed to simulate a standard earth-sensing system in a 66° orbit. The simulation depicts NanoView's launch and adjustment into an orbit trailing the TargetSat system. The sample sensor beam associated with NanoView shows a continuous viewing opportunity of the TargetSat system and a sensor aperture of 1.67 degrees.

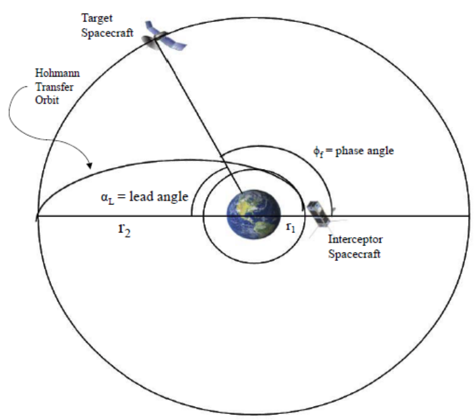

Figure 21. Geometry Depicting Rendezvous between Two Circular, Coplanar Orbits.[102]

102. Daryl G. Boden, "Introduction to Astrodynamics," in *Space Mission Analysis and Design*, ed. James R. Wertz and Wiley J. Larson, 3rd ed. (El Segundo, CA: Microcosm Press, 1999), 152.

Each of these scenarios deployed NanoView in the same orbit as the target object with a slightly different phase angle. Once NanoView was inserted into proximity orbit, the sensor maintained track of the target throughout the NanoSat's operational life. Figure 22 shows a representative NanoView sensor swath with the TargetSat system within the detection field.

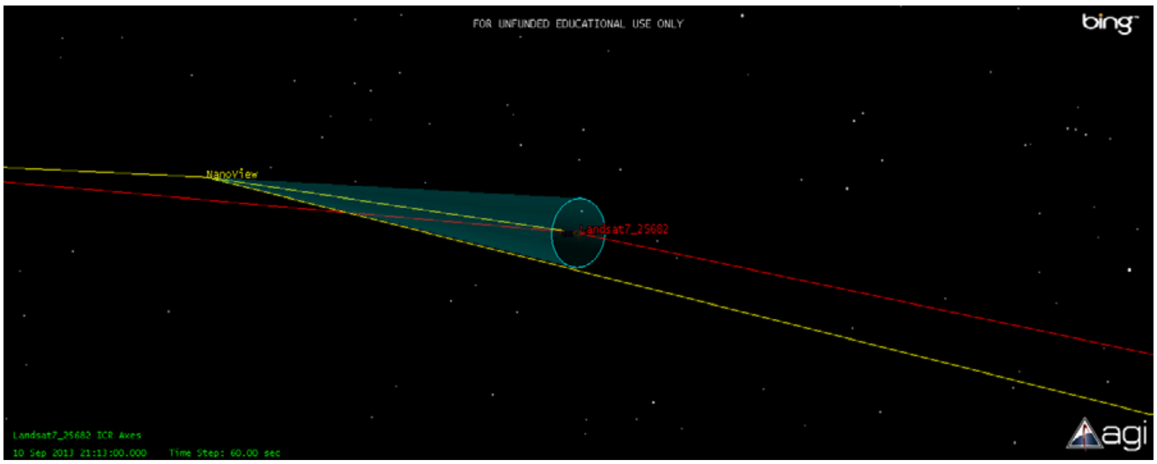

Figure 22. NanoView Sensor Application Picture for Proximity Operations.

a. *STK Scenario 1: Launch from Vandenberg AFB*

As stated previously, the first scenario depicts a sample launch from Vandenberg AFB into a 66° inclined orbit. The situation opens with the detection of a previously unknown satellite system deployed by a recent space launch from Asia.

The new system, TargetSat, was detected by the Haystack radar at MIT during an assigned track of the newly launched payload. JSpOC, NASIC, and JFCC–Space are suspicious of the purpose of this deployed system and desire more information

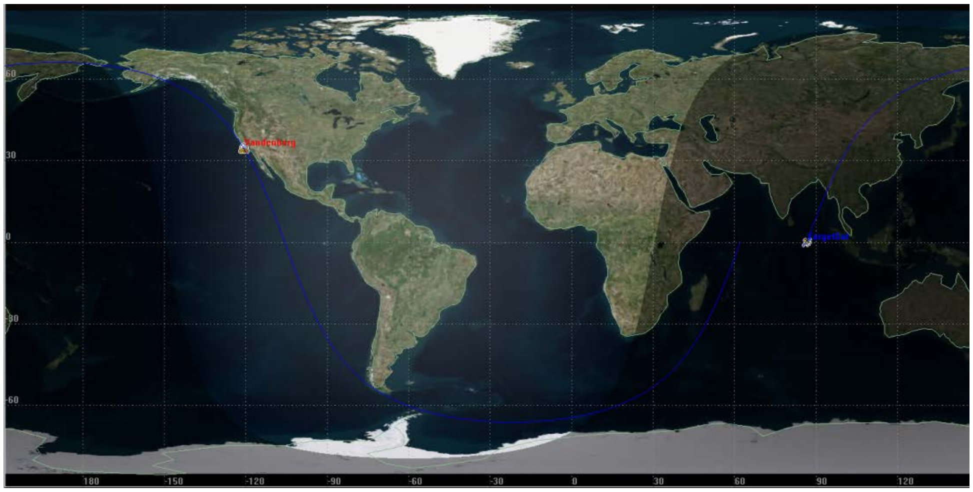

Figure 23. Initial Scenario State; Showing Position of TargetSat and Vandenberg Launch Site.

JFCC–Space captures the requirement from JSpOC for further information and produces a tasking order to deploy the NanoView system and collect data on the new system.

Operational planning for mission is the responsibility of the NASIC SOI office, with input and coordination from JSpOC and the 856th Space Operations Squadron (the notional launch unit). The mission planning phase is where the launch trajectory, orbit, launch window, and collection parameters are assigned. The development of the NanoView sensor will be the primary factor in what the system will be able to capture, and the fidelity of data. For this scenario, a 1.67-degree sensor is used to illustrate coverage.

A real-world launch window must be determined based on variety of factors; including space weather conditions and the timing of other space objects passing through the desired orbit. In this simplified version, the determination of a launch window was based solely on optimal rendezvous conditions. In this case, launch occurred 2,280 seconds (38 minutes) after the initial scenario start.

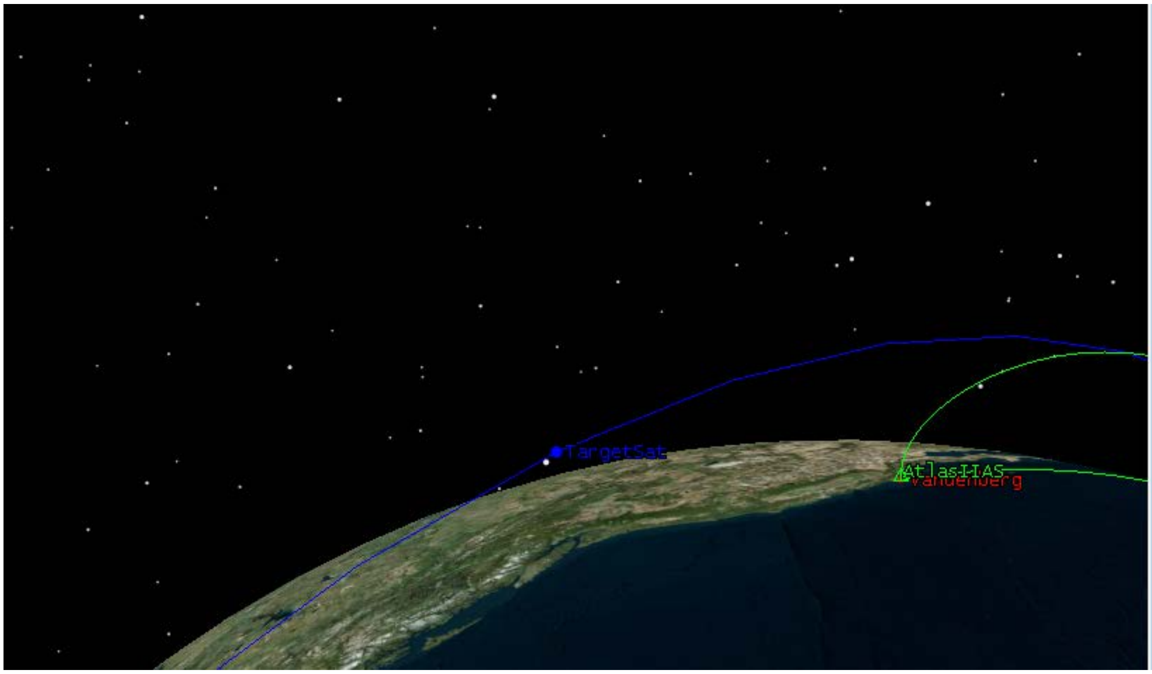

Figure 24. Position of the Atlas launch vehicle and TargetSat at launch.

Proximity operations begin 6,240 seconds after launch (1 hour 49 minutes), and place NanoView in a trailing orbit to TargetSat, roughly one km distant from the TargetSat system. Closer proximity is achievable using more sophisticated STK programing techniques.

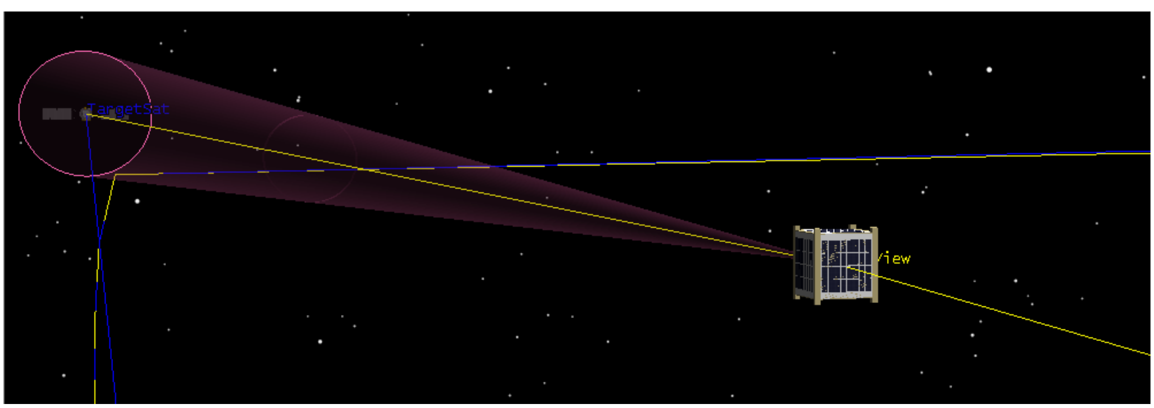

Figure 25. NanoView to TargetSat sensor view.

NanoView and launch vehicle checkout runs concurrent with this planning phase. As mentioned previously, a certain number of systems are held in reserve at the launch points in a ready reserve status. The crew selected NanoView system is tested for deployment and mated to the Atlas launch vehicle used in this scenario within 48 hours.

Once mission guidance has been received, the operations crew will begin mission-specific training to ensure the mission guidance is understood and all crew members are aware of any special action that might be necessary. In this simple scenario, no additional maneuvers or looks were required, but the option for more complicated, multi-system missions might require additional sensor pointing or even orbital adjustments.

After launch, the crew maintains station keeping of the NanoView system, monitoring health and status and ensuring data collection and transmission via AFSCN to the analysis centers.

In this scenario there is no immediate tactical need for the information, so the data will be delivered electronically via secure network to NASIC for data analysis. This analysis will then be shared with JSpOC, the 856th Space Operations Squadron, and the wider community for SSA purposes.

Upon completion of the mission, the NanoView operations crew will perform after action reports on the process to record lessons learned.

b. STK Scenario 2: Launch from Bahrain

The second scenario is a situation where a land-based army unit requires SSA information prior to performing an operation in west Asia. In this notional operation the 78^{th} Brigade, operating in Afghanistan, has received intelligence that a recent space launch from the CENTCOM theater might pose issues for maneuvers they are planning. There is some question as to the purpose of the satellite, communications has been the official line, but no one is quite sure.

At this point the Brigade commander has the option of calling for support through JSpOC to coordinate SSA support. Since JSpOC has no information on the purpose of the space vehicle, and the 78th Brigade needs a full battlespace picture quickly to support operations, JSpOC issues an order to the 856th Space Operations Squadron to prepare for launch and contacts the mission planning team at NASIC to prepare short-order mission guidance to respond to the situation.

Just as in the first scenario, mission planning and preparation for launch occur simultaneously and the NanoView system will be ready for launch within 48 hours. Mission planning for this scenario shows that the optimal launch position to achieve positive SSA fastest is determined to be from the deployed location. For this scenario, we assume that deployed location is in Bahrain.

The scenario as programed shows an Atlas launch vehicle delivering the NanoView to orbit. The use of such a large and cumbersome launch vehicle at a deployed location is impractical, as a launch vehicle of that size and complexity requires the presence of a significant support facility and network. The development of a simple deployable launch vehicle that does not require much by way of support facilities and is easily transportable must be developed for real world operations of this nature.

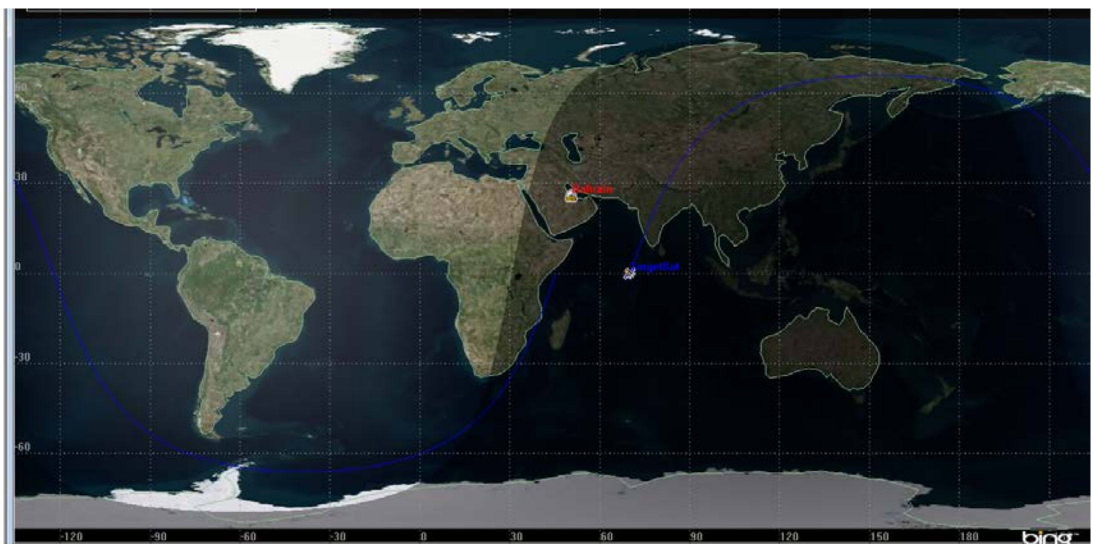

Figure 26: TargetSat Position at Scenario Start.

Upon receipt of launch instructions and the launch window, the 856th Space Operations Squadron briefs the launch and operations crews and prepares for system deployment. The launch window in this scenario does not open until 12,180 seconds (3 hours 23 minutes) after scenario start. Convergence was calculated using STK Astrogator and occurs at 18,420 seconds (5 hours 7 minutes) after scenario start time, a 1 hour 44 minute time from launch to proximity operations with the object of interest, TargetSat.

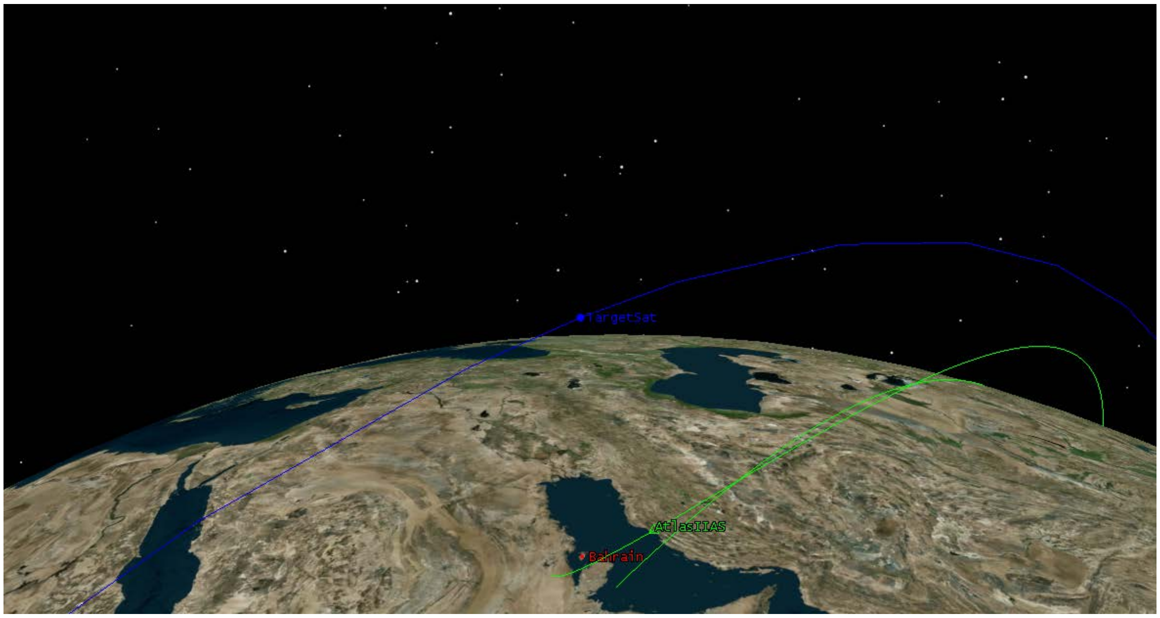

Figure 27: Launch Conditions for NanoView.

Once on-station NanoView begins collection on the target system (TargetSat) in accordance with the mission guidance developed by NASIC. As in the previous Vandenberg scenario, this data is sent back to NASIC for analysis. Since this data was requested to support an active operational mission with tactical implications, the priority on processing the solution is higher than a routine SOI mission.

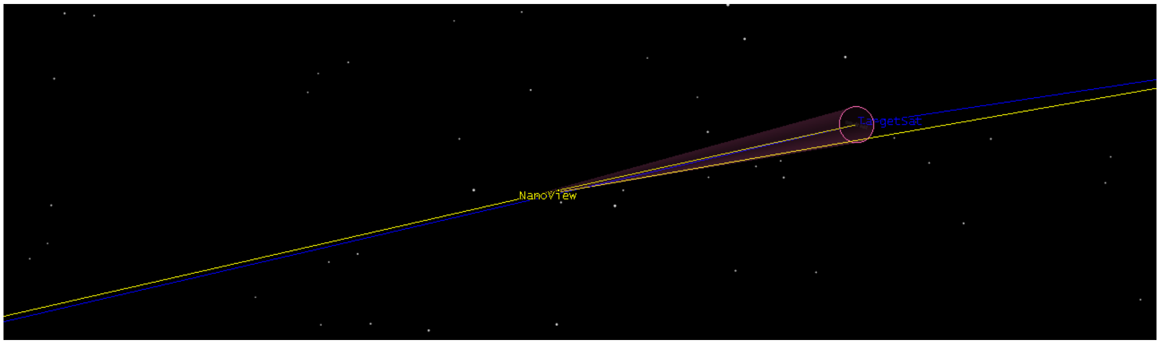

Figure 28: NanoView with TargetSat in View.

Once NASIC has developed an initial analysis of the object, they coordinate with the 78th Brigade's intelligence and planning divisions to deliver products indicating the purpose of the satellite system and impacts the system might have on the up-coming operation.

Once the tactical need has been satisfied the IC might continue to process the data and develop a more sophisticated space order of battle. The Intelligence Community determines these requirements. NASIC then shares he fully analyzed results and implications with JSpOC and JFCC–Space to integrate with the larger SSA picture.

3. Operational NanoView System

This chapter has described the details of the concept of operations for deploying a responsive space asset, NanoView, collecting and transferring data to the analysts and users, and has described two scenarios in which this system was used. While these two scenarios are not an exhaustive list of possible applications, they do show some different ways in which the NanoView system might be deployed, and how it might be used. The next chapter describes some currently available COTS components for a prototype NanoView system.

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V. THE NANOVIEW SYSTEM

A. BUS OPTIONS

The model for NanoView Bus is the Pumpkin, Inc. MISC system design. This system is a 3U design constant with the CubeSat standard. Each of the three segments is 10x10x10cm and 1 kg. A spacecraft bus developed by Pumpkin, Inc. serves as a model. These COTS-style systems come with a pre-fabricated spacecraft bus constructed of lightweight aluminum. The structure should be fully alodined, the application of chemical a protective chromate conversion coating on aluminum, for electrical conductivity and protection from the environment. The three cubes are stacked linearly with the sensor at one end.[103]

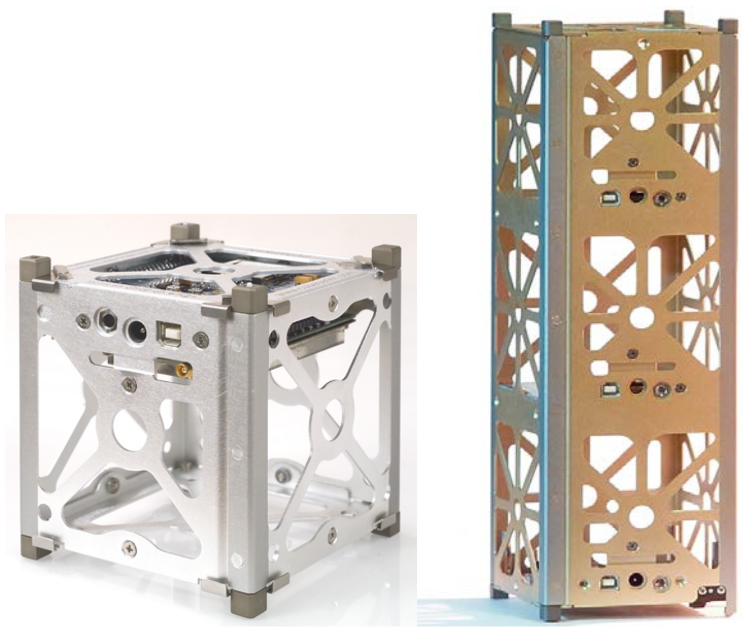

Figure 29. 1U and 3U Structures.

B. SUBSYSTEMS

1. Attitude, Determination, and Control Subsystem (ADACS)

The Attitude Determination and Control Subsystem (ADACS) is responsible for stabilizing the vehicle and maintaining the proper orientation throughout the spacecraft's

103.Pumpkin, Inc.

life.[104] Multiple methods of achieving this are available for space systems, but few are yet to the point of miniaturization and power for use on CubeSat systems.

Pumpkin Inc. offers two types of ADACS with their CubeSat kits. The first is the MAI−100, a miniature 3−axis reaction wheel ADACS system. This system orients the spacecraft in any direction (Sun, nadir, offset-nadir, ram, anti-ram, etc). Pointing accuracy is a minimum of one degree. It is possible to achieve better results, depending on the sensor. The system boasts fully autonomous operation with miniature reaction wheels, and three torque coils for momentum dumping. MAI−100 also includes an external 3−axis magnometer. The system is low mass, low power, hermetically sealed, and has hard-anodized contact surfaces. The MAI−200's characteristics are essentially the same. The MAI−200 has a higher momentum storage capacity for each wheel (10.8 mNms momentum storage vice 1.1 mNms per wheel) and slightly higher power consumption values (3.5W typical with 6W maximum compared to 1.5W typical with 4.5W maximum). Both of these systems provide pointing accuracy of better than 1 degree and either would be sufficient for the NanoView mission.[105]

Additional options are available, including systems such as the Nanosatellite Micropropulsion System (NMS). MicroSpace microelectromechanical (MEMS) technology enables such minimized components. This allows the scaling of the system to meet the needs of a 1kg 1U system up to a small microsat at 100kg. Like the previous choices, the NMS provides 3−axis stabilization with variable thrust control from 1 – 100% thrust and impulses of 2ms to unlimited. Power usage is lower with 2W maximum power required. The NMS system also advertises considerably more pointing accuracy (0.1 arcsec vice 1 degree), but at a much higher price at $108,200 compared to $38,000 for the MAI−100 (prices taken from cubesatshop.com).[106]

104.John S. Ernesto, "Attitude Determination and Control," in *Space Mission Analysis and Design*, ed. James R. Wertz and Wiley J. Larson, 3rd ed. (El Segundo, CA: Microcosm Press, 1999), 354.

105.Pumpkin, Inc.

106.Cubesatshop. Accessed March 10, 2013, www.cubesatshop.com.

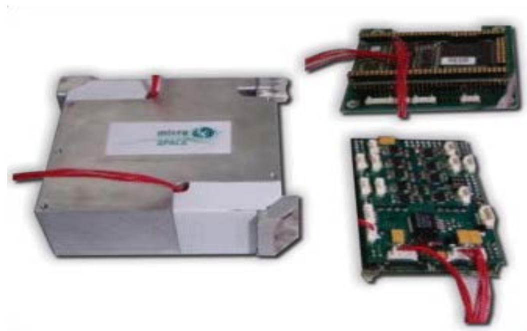

Figure 30. Nanosatellite Micropropulsion System.[107]

Fitting a GPS receiver into the system may provide more accurate spacecraft positioning information. This can be useful for a number of SSA applications. The first is precise positioning of an object of interest. The second application is establishing an awareness of the configuration or activities taking place with regard to the object of interest as relates to position and time. A representative unit of this type is the SSBV GPS receiver. Since the unit is also a software receiver, it has the added benefit of reducing some of the required processing needed in the on-board data-handling system, and thus saving some weight associated with the capability. Availability of position accuracy commercially is at less than 10m, but these systems use only the L1 band. A military grade receiver with access to the L2 band will increase accuracy.[108]

Figure 31. Representative GPS Receiver for Nanosat Systems.

107.Ibid.

108.Cubesatshop.

2. Telemetry, Tracking, and Command

The Telemetry, Tracking and Command (TT&C), or Communications subsystem, is the interface between the spacecraft and the ground. TT&C transmit spacecraft commands as well as data, telemetry, ranging, and status of health information using this equipment.[109] Compatibility with existing ground equipment must be instrumental in the selection process to ensure that use of the AFSCN is possible. There are a few S-band modules commercially available.

The ISIS TXS S-Band Transmitter is one such low power, S-Band, option, and can transmit data at rates of up to 100kbps. Though this rate is perfectly adequate for transmitting simple commands, the mission of the NanoView system is optical data collection and transmission. The mission will require higher data rates to be viable. Another S-Band system available is the Highly Integrated S-Band Transmitter for Pico and Nano Satellites (HISPICO) system. The design goal of this system optimizes Pico and Nano satellite use; it is very small and very low power. This system is capable of providing a broadband data rate of up to 1 Mbps, a substantial improvement over the ISS system. Never the less, this data rate is still quite low and is a limiting factor on the capabilities of the system until an improved transmitter can be developed and deployed.[110]

3. Command and Data Handling (C&DH)

Command and data handling (C&DH) systems receive and distribute commands to the other subsystems and prepare housekeeping data for downlink.[111] Many CubeSat kits come with these systems included. The Pumpkin Inc. CubeSat kit comes with several motherboards that integrate TT&C and C&DH functions along with mass storage capacity.[112] Serious consideration should be given to these systems for space and

109.Douglas Kirkpatrick, "Telemetry, Tracking, and Command," in *Space Mission Analysis and Design*, ed. James R. Wertz and Wiley J. Larson, 3rd ed. (El Segundo, CA: Microcosm Press, 1999), 381.

110.Cubesatshop.

111.Richard T. Berget, "Command and Data Handling," in *Space Mission Analysis and Design*, ed. James R. Wertz and Wiley J. Larson, 3rd ed. (El Segundo, CA: Microcosm, 1999), 395.

112.Pumpkin, Inc.

compatibility efficiency. While these systems would not, in an ideal scenario, provide the processing power on-orbit of the more sophisticated imaging systems, they do provide an adequate amount of processing and storage capacity for data collection and transmission to a central processing ground station. This method of data transmission requires a more robust downlink system, in order to handle larger data streams. The system size constraints makes tradeoffs of this sort necessary.

4. Power

The power subsystem provides, stores, and distributes power for all spacecraft functions. For anything under a very short duration mission (of perhaps hours to days), a power generation source is necessary. Solar cells attached to the spacecraft bus usually supply power. Excess power is stored in a battery until such time (like an eclipse) it is needed.[113]

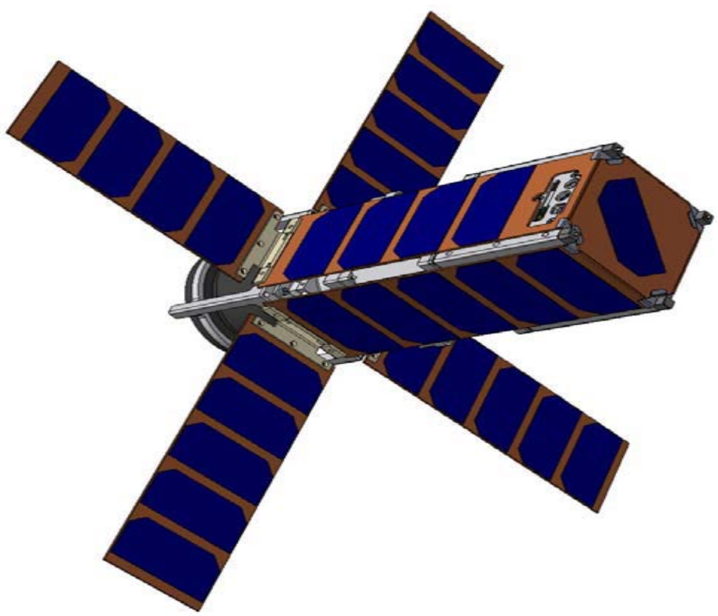

Figure 32. Sample Solar Array Deployment on a 3U satellite system.[114]

113.Joseph K. McDermott, "Power," in *Space Mission Analysis and Design*, ed. James R. Wertz and Wiley J. Larson, 3rd ed. (El Segundo, CA: Microcosm Press, 1999.), 407.

114.Pumpkin, Inc.

Silicon and Gallium Arsenide solar arrays are typical materials used in spacecraft power sources. With efficiencies of only 14.8% and 18.5% respectively, they may not be the best choice for a size and weight constrained nanosat system.[115] Developers are increasingly using various laminate materials for CubeSat missions where the consequences are lower and innovation is more acceptable.[116] The NanoPower Solar 100 solar panel from AzurSpace is one such system and use an Fr4 Tg180 laminate. These panels, with a mass of 59 grams, provide 28% efficiency and when two cells are reflow soldered and connected in series they provide a 4.6 output voltage and provide between 2.270 and 2400 mW of power. The NanoPower Solar 100 arrays also have an option to include an integrated magnetorquer, coarse sun sensor, temperature sensor, and gyroscope included.[117] The total number of panels depends on final sensor selection, though 8 Watts is a representative requirement for a representative optical sensor (discussed below). To achieve the power requirement, a six solar panel system will be needed and periods of dedicated charging will need to be scheduled.

5. Thermal Control Subsystem (TCS)

This subsystem maintains appropriate operating temperatures for the spacecraft and payload. Actual thermal controls will depend on final determination of equipment. Some considerations for LEO missions (between 400 and 800km) are the length of the eclipse periods. At this altitude, these are consistent with time spent in eclipse. These missions also typically have one side of the spacecraft never exposed to the sun (called the "cool side").[118]

There are two types of thermal control used on spacecraft, active and passive. Active methods consist of actuators and cooling/heating systems.[119] Passive systems are

115 McDermott, "Power," in *Space Mission Analysis and Design*, 414.

116. Ibid.

117 Pumpkin, Inc.

118.David G. Gilmore et al., "Thermal," in *Space Mission Analysis and Design*, ed. James R. Wertz and Wiley J. Larson, 3rd ed. (El Segundo, CA: Microcosm Press, 1999), 428.

119.Ibid.

far more appropriate to the CubeSat mission. Radiators and coatings are the recommended method of thermal control.

6. Payload

Currently no operationally active sensor would satisfy the imaging and size requirements for the NanoView mission. The design of a small, lightweight sensor, with high resolution is an area where further research and design activity should focus. This sensor would not be required to capture distances at any great distance. A sensor with the same rough characteristics as the standard cell phone camera could gather useful information about target spacecraft.

Research is currently being conducted by NASA to use cell phone technology on CubeSats, with the goal of creating cheaper satellite systems. The PhoneSat program's goal is to test a cell phone (the HTC Nexus One with Android in the first test) on-orbit to determine what functions are operational on-orbit and for how long. The smart phone is expected to remain operational in orbit for approximately six weeks.[120] Results for the camera function test would provide an excellent starting point for nanosat sensor development.

Further research and development could also be done with other types of commercial cameras. The quality and capabilities of consumer camera technology has increased dramatically, and a relatively inexpensive consumer model could be capable of delivering high-quality digital photos for analysis. Further testing and analysis would need to be done on these systems to establish feasibility of use.

Whatever the solution is, the system should be able to fit in a single CubeSat unit. It is important to balance the sensor's capabilities with the weight and size. Limiting the payload to 1 unit of a 3U spacecraft should provide that balance.

120. John Breeden, II, "NASA's Smart Phone Satellites Launch New Era in Space Communications," GCN: Technology, Tools, and Tactics for Public Sector IT, accessed March 24, 2014, http://gcn.com/articles/2013/04/24/nasa-smart-phone-satellites.aspx.

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VI. CONCLUSIONS AND FURTHER RESEARCH SUGGESTIONS

A. FURTHER RESEARCH SUGGESTIONS

The first item for further research to ensure success of a project following the NanoView model is the development of an adequate sensor. As discussed in Chapter IV, there is currently no operational sensor capable of capturing short-range, high quality images of space objects for SSA/SOI. In order for this, or any similar project, to be successful an appropriate sensor must be developed.

Another area of further research is the propulsion system. Current propulsion systems that would allow for multiple changes in orbital regime are expensive in weight, and therefore cost of deployment. Further study in the development of a small and efficient way to allow a system like the NanoView to perform multiple burns and perhaps collect information on multiple targets would provide a vastly increased functionality.

An additional deployment concept where multiple NanoView-like systems are deployed into space and can be detached from a central orbital storage station may help decrease response time to objects of interest and should be explored.

Limitations in the rate of data transmission back to Earth may have an adverse effect on the timely analysis of an object's behavior. As transmission systems become more efficient it may be worthwhile to re-examine the data handling systems employed by on-orbit imaging satellites as a whole to determine if upgrades would be better using a cost-benefit model.

B. CONCLUSIONS

The increase in space activity by other countries and the desire to prevent being taken by surprise from space means that the U.S. needs to be better aware of what is happening on orbit. There is certainly room for improvement and expansion in the SSA architecture and the SOI process. This research looks at the insertion of a CubeSat style nanosatellite system into that architecture and exploring how it might be used, tasked, and manned.

While the architecture for command and control already exists for this project, there is still a significant amount of research and development that will need to be accomplished before such a project is feasible. The need for an appropriate sensor, as mentioned in the further research section is vital to producing a low cost option on this model. The development of an improved launch vehicle is equally important to ensure the maximum responsiveness at a minimum cost.

There are several projects in the works now looking at cheaper ways to use pre-existing technology for space applications. The most promising for SSA/SOI application may be NASA's PhoneSat experiment to put a cell phone in orbit and test its functionality. Being able to use that sophisticated level of technology with minimal preparations for making the system "space worthy" can significantly increase the capabilities for monitoring objects on orbit.

The budgetary challenges that the defense community continues to face have a stark reality for large, complex, and expensive space systems. The way forward is to develop systems leveraging existing commercial technology to maintain the level of space awareness that will prevent our nation or our allies being surprised in the Space arena.

LIST OF REFERENCES

Air Force ISR Agency. "National Air and Space Intelligence Center." Air Force ISR Agency – NASIC. Accessed October 14, 2012, http://www.afisr.af.mil/units/nasic/.

Audit Report − Faster, Better, Cheaper: Policy, Strategic Planning, and Human Resource Alignment, Report Number IG−01−009. Washington, DC. NASA Office of the Inspector General, 2001.

AU−18: Space Primer. Maxwell AFB, AL: Air University Press, 2009.

Balan, Mugurel, M. Piso, M. Trusculescu, C. Dragasanu, and Pandele. "CubeSat Formation Flying: A Suitable Platform for Space Situational Awareness Applications." Paper presented at International Astronautical Federation, IAF, Prague, The Czech Republic, September 27, 2010−October 1, 2010.

Berget, Richard T. "Command and Data Handling." In *Space Mission Analysis and Design*, edited by James R. Wertz and Wiley J. Larson, 395−407. 3rd ed. El Segundo, CA: Microcosm, 1999.

Bille, M., P. Kolodziejski, and T. Hunsaker. "Distant Horizons: SmallSat Evolution in the Mid-to-Far-Term." Paper presented at 25th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 8−11, 2011.

Boden, Daryl G. "Introduction to Astrodynamics." In *Space Mission Analysis and Design*, edited by James R. Wertz and Wiley J. Larson, 131−58. 3rd ed. El Segundo, CA: Microcosm Press, 1999.

Commission to Assess United States National Security Space Management and Organization, *Report of the Commission to Assess United States National Security Space Management and Organization*, Rep. (2001).

"CubeSat Launch Initiative." National Aeronautics and Space Administration. Accessed October 14, 2012. http://www.nasa.gov/directorates/heo/home /CubeSats_initiative.html.

"Cubesatshop." Accessed March 10, 2013. www.cubesatshop.com.

Erdner, Matthew T. "Smaller Satellite Operations Near Geostationary Orbit." Master of Science in Space Systems Operations, Naval Postgraduate School, 2007.

Ernesto, John S. "Attitude Determination and Control." In *Space Mission Analysis and Design*, edited by James R. Wertz and Wiley J. Larson, 354−80. 3rd ed. El Segundo, CA: Microcosm Press, 1999.

Fairley, Richard E., Richard H. Thayer, and P. Bjorke. “The Concept of Operations: The Bridge from Operational Requirements to Technical Specifications.” (1994): January 16, 2012.

Flanagan, Jason A. “Enhancing Space Situational Awareness using a 3U Cubesat with Optical Imager.” Masters of Science in Astronautical Engineering, Naval Postgraduate School, 2010.

Garvey, John M. and Eric Besnard. “Progress Towards the Development of a Dedicated Launch System for Nanosat Payloads.” Paper presented at American Institute of Aeronautics and Astronautics, San Diego, CA, September 28, 2004−September 30, 2004.

Gilmore, David G., Robert C. Prager, Eric W. Grob, and Wess Ousley. “Thermal.” In *Space Mission Analysis and Design*, edited by James R. Wertz and Wiley J. Larson, 428−58. 3rd ed. El Segundo, CA: Microcosm Press, 1999.

Global Research White Papers: Spacecraft 2020. “Space Modular Systems.” Air University. Accessed January 19, 2012. http://www.au.af.mil/au/awc/csat/2020/papers/app-k.pdf.

———. “Space Traffic Control: The Culmination of Improved Space Operations.” Air University. Accessed January 19, 2012. http://wwwau.af.mil/au/awc/csat/2020/papers/app-d.pdf.

Hurley, M. “‘Tactical Microsatellite Experiment (TacSat−1).” Naval Research Laboratory. Accessed October 14, 2012. http://www.nrl.navy.mil/research/nrl-review/2004/ space-research-and-satellite-technology/hurley/.

IHS. “XSS (Experimental Satellite System) Series.” IHS, Jane’s. Last modified January 17, 2013. Accessed December 28, 2013. https://janes.ihs.com.libproxy.nps.edu/CustomPages/Janes/DisplayPage.aspx?DocType=Reference&ItemId=+++1384691#XSS-10.

Joint Chiefs of Staff. Joint Publication 3−14: Space Operations, Washington, DC, 29 March 2013.

“Joint Functional Component Command for Space (JFCC Space).” Accessed January 17, 2012. http://www.stratcom.mil/factsheets/7/JFCC_Space/.

Kirkpatrick, Douglas. “Telemetry, Tracking, and Command.” In *Space Mission Analysis and Design*, edited by James R. Wertz and Wiley J. Larson, 381−94. 3rd ed. El Segundo, CA: Microcosm Press, 1999.

Lambert, John V., and Kenneth E. Kissell. “Historical Overview of Optical Space Object Identification.” *SPIE Proceedings* 4091:159−63.

Lee, E. T. “Space Object Surveillance and Identification.” *Policy Analysis and Information Systems* 3, no. 1 (1979): 171−185.

Lewandowski, Daniel P. “Space Intelligence: Imperative for Space Situational Awareness.” Paper presented at AIAA SPACE 2009 Conference & Exposition, Pasadena, CA, September 14, 2009−September 17, 2009, 1−9.

Li, Ju−Feng and Dan Xne. “Review of Relative Motion Description Methods for Satellite Formation Flying.” *Xuhand Xuebao/Journal of Astronautics* 29, no. 6 (2008): 1689−1694.

Liu, Yanmei, Yibo Li, and Jianhui Xi. “Design and Simulation of Satellite Formation Flying Position-Keeping Control Method.” Paper presented at IEEE Computer Society, Mexico City, Mexico, August 25, 2010−August 27, 2010.

London III, John R., A. Brent Marley, and David J. Weeks. *Army Nanosatellite Technology Demonstrations for the Tactical Land Warfighter*: USASMDC/ARSTRAT, 2010.

Marshall, Joseph R., Richard W. Berger, Jeffrey E. Robertson, and Suzanne Miller. “Reconfigurable and Processing Building Blocks in Responsive Space.” Paper presented at American Institute of Aeronautics and Astronautics Inc., Rohnert Park, CA, May 7. 2007−May 10, 2007.

McDermott, Joseph K. “Power.” In *Space Mission Analysis and Design*, edited by James R. Wertz and Wiley J. Larson, 407−27. 3rd ed. El Segundo, CA: Microcosm Press, 1999.

Michels, Jennifer L. “Focusing on the Future: Deployment and Intelligent Nanosatellite Operations.” Paper presented at American Institute of Aeronautics and Astronautics Inc., San Diego, CA, September 28, 2004−September 30, 2004.

O’Brien, Tolulope E. “Space Situational Awareness CubeSat Concept of Operations.” Master’s thesis, Naval Postgraduate School, 2011.

Pearson, Jerome, Eugene M. Levin, and John C. Oldson. “LEO Mobility Vehicle for Space Situational Awareness.” Paper presented at American Institute of Aeronautics and Astronautics, San Diego, CA, September 9, 2008−September 11, 2008.

Pongvthithum, R., S. M. Veres, S. B. Gabriel, and Rogers. "Universal Adaptive Control of Satellite Formation Flying." *International Journal of Control* 78, no. 1 (2005): 45−52.

Sandhoo, Gurpartap, Aaron Q. Rogers, Patrick A. Stadter, Eric Finnegan, Michael Aurley, Mark Johnson, William Raynor, Paul D. Schwartz, and James Griswold. "Standards for Responsive Small Satellites." Rhodes, Greece, European Space Agency, 2008.

Secure World Foundation. "Issue Brief Details Space Situational Awareness Sharing Program." Newswise. Last modified November 22, 2010. Accessed December 30, 2013. http://www.newswise.com/articles/issue-brief-details-space-situational-awareness-sharing-program.

Space Surveillance Network (SSN) Site Information Handbook. Peterson AFB, CO: HQ Air Force Space Command/A3CD, 2007.

"STARE (Space-based Telescopes for the Actionable Refinement of Ephemeris)." eoPortal Directory. Accessed September 27, 2012. https://directory.eoportal.org/web/eoportal/satellite-missions/s/stare.

"Tactical Satellite−3." The Air Force Research Laboratory. Accessed January 18, 2012, www.kirtland.af.mil/shared/media/document/AFD-0704-106.pdf.

Teehan, Russell. *Responsive Space Situational Awareness in 2020*: Air War College, Center for Strategy and Technology, 2007.

Turner, R. F. "Small Spacecraft Missions − the U.S. Scene." *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 213, no. 4 (1999): 213−221.

United States Strategic Command. Operationally Responsive Space (ORS): Initial Concept of Operations. United States Strategic Command, Offutt AFB, NE, 2007.

Vanwijck, Xavier and Tim Floher. "Possible Contribution of Space-Based Assets for Space Situational Awareness." Paper presented at International Astronautical Federation, IAF, Glasgow, Scotland, September 29, 2008−October 3, 2008.

Wertz, James R. and Wiley J. Larson, eds. *Space Mission Analysis and Design*. 3rd ed. El Segundo, CA: Microcosm Press, 1999.

Woellert, Kirk, Pascale Ehrenfreund, Antonio J. Ricco, and Henry Hertzfeld. "Cubesats: Cost-Effective Science and Technology Platforms for Emerging and Developing Nations." *Advances in Space Research* 47:663−84.

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