SENSE: The USAF SMC/XR NanoSatellite Program for Space Environmental Monitoring

Capt George Sondecker IV, Capt Paul La Tour
Space and Missile Systems Center
483 N. Aviation Blvd. El Segundo, CA 90245; 310-653-9991
george.sondecker.1@us.af.mil

Lyle Abramowitz
The Aerospace Corporation
2310 El Segundo Blvd. El Segundo, CA 90245; 310-336-2657
lyle.abramowitz@aero.org

ABSTRACT

The Development Planning Directorate at the Air Force Space and Missile Systems Center (SMC/XR) is assessing the utility of NanoSatellites for performing operational space weather missions. The directorate is leading a demonstration called the Space Environmental NanoSatellite Experiment (SENSE) that will enhance the field of Space Environmental Monitoring (SEM) and provide data to populate the Global Assimilation of Ionospheric Measurements (GAIM) model. Scheduled for launch in 2013, the SENSE architecture consists of two 3U CubeSats and supporting ground segment. The space vehicles carry a combined suite of three SEM payloads designed to characterize total electron content (TEC) and ionospheric scintillation, ion and neutral winds composition, and ionospheric UV nightglow. This paper outlines how the SENSE CubeSat mission contributes to enhanced global awareness for the warfighter and space weather community.

INTRODUCTION

Since the CubeSat Design Specification (CDS) was established nearly a decade ago, CubeSat technologies have emerged as a highly cost-effective approach to delivering space capabilities. While most CubeSat programs to date have featured scientific experiments led by NASA or university researchers, the achievements of the CubeSat community have not gone unnoticed by the U.S. Department of Defense (DoD). For select mission classes, the CubeSat standard offers a new paradigm for DoD space acquisitions to rapidly procure and deploy highly capable satellite systems at substantially reduced cost.

The Developmental Planning Directorate at the Space and Missile Systems Center is leading the Space Environment NanoSatellite Experiment (SENSE) to assess the utility of CubeSat architectures to perform or augment operational space missions. The SENSE architecture consists of two, three-unit (3U) CubeSats and supporting ground segment. These assets will contribute to the field of Space Environmental Monitoring (SEM) by advancing sensor miniaturization and by distributing sensors to provide expanded coverage. The requirements driving the SENSE mission are derived from the National Polar Integrated Operational Requirements Document (IORD-II) [1] and work toward addressing potential capability gaps identified in the Defense Meteorological and Oceanographic Collection (METOC) Initial Capabilities Document (ICD)[2]. The data collected by the SENSE sensor suite will be used to populate the Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) model with near real-time measurements of Earth's ionosphere.

Beyond SENSE's scientific objectives, the program serves to establish a streamlined acquisitions process for procuring future Air Force small satellite systems. Many lessons have been learned throughout the SENSE acquisition process. The SENSE CubeSats rely heavily on modular designs utilizing Commercial-off-the-Shelf (COTS) components. This approach to spacecraft design enables the Air Force to procure space assets faster and at substantially reduced cost. Further, SENSE is a pathfinder for exploring the mission capabilities achievable using a 3U form factor while still addressing uniquely military aspects of spacecraft design. Such aspects include data encryption, radiation tolerance, and mission assurance.

SENSE ARCHITECTURE

The SENSE architecture is comprised of two space vehicles and a supporting global ground system. Roles and responsibilities for the acquisition and operation of the space and ground segments are shared among several organizations across the Space and Missile Systems Center (SMC) and the Air Force Research Laboratory (AFRL). The Weather Directorate (SMC/WM) is the primary sponsor of the SENSE mission. Acquisition of the SENSE ground and space assets is led by the Development Planning Directorate (SMC/XR). The Space Development and Test Directorate (SMC/SD) is the owner-operator of the SENSE ground system, and the Space Vehicles Directorate at AFRL (AFRL/RV) is responsible for data processing, analysis, and distribution.

capability that can be readily leveraged by future space programs.

The two SENSE space vehicles are 3U CubeSats designed in accordance with the *CubeSat Design Specification* Rev. 12[3]. The Boeing Company is the prime contractor for the SENSE space segment. The SENSE space vehicles leverage heritage from Boeing's Colony II CubeSat bus. The SENSE bus is highly modular and relies heavily on COTS components. This approach to spacecraft design is intended to minimize development time and cost.

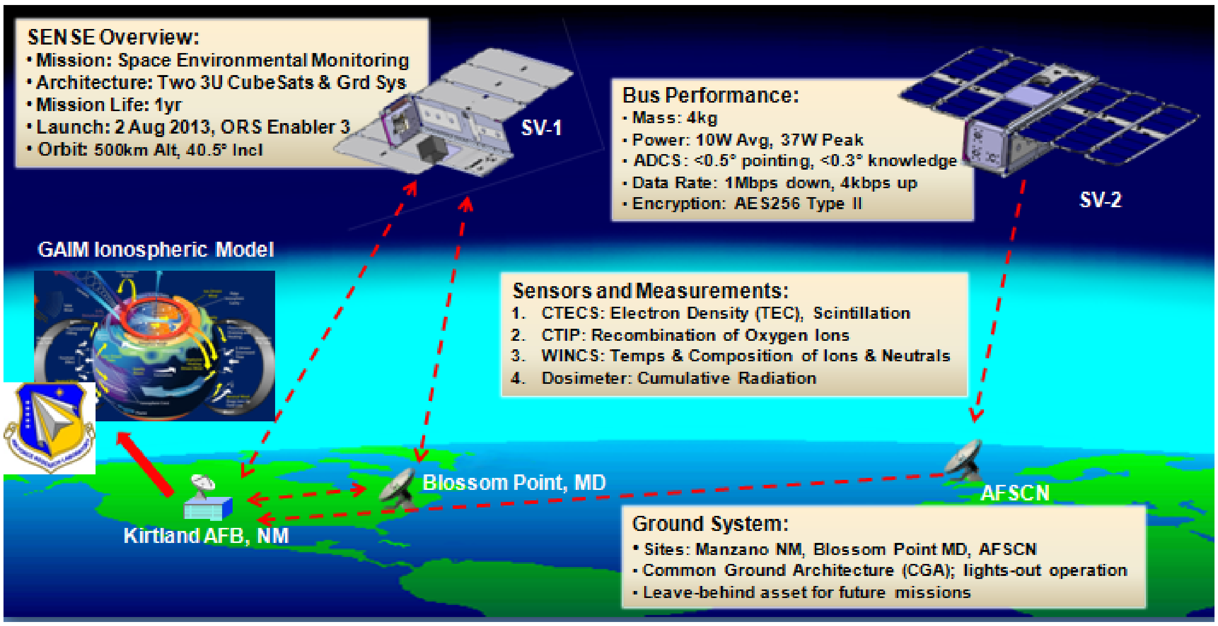

Figure 1: SENSE Mission Overview

The SENSE ground system consists of several antenna sites around the globe controlled from the Research, Development, Test and Evaluation (RDT&E) Support Complex (RSC) at Kirtland AFB, NM. As shown in Figure 1, SENSE will utilize antennas located at Kirtland AFB, NM. To link these sites together, the SENSE ground system relies on the Common Ground Architecture (CGA) developed by the Naval Research Laboratory. CGA is a command and control software tool that enables highly autonomous operation of the SENSE satellite system. CGA allows operators to manage simultaneous space vehicle passes and schedule "lights-out" operations for times when no operators are present. Further, CGA is a key enabler of SENSE's requirement to achieve data latencies of 90 min or less during high-tempo operations "Data latency" is the duration of time between taking measurements on orbit to delivering processed data to space weather models for use by the space weather community. Lastly, CGA and the SENSE ground assets provide a leave-behind

The spacecraft are powered using one bi-fold, one tri-fold, and one body-mounted solar array with ultra-triple junction solar cells on each panel. This arrangement provides a maximum power production capacity of 37W. Power is stored in six lithium-ion cells capable of providing the vehicle with 10W average power.

For communication, the SENSE vehicles are equipped with a Unified S-Band transceiver designed to operate at 4kbps uplink and 1Mbps downlink. SENSE carries a miniaturized encryption module in its full-duplex transceiver that enables 256-bit Type II encryption.

The SENSE Attitude Determination and Control Subsystem (ADCS) employs a diverse collection of sensors and actuators to provide inertial three-axis control to 0.5° (3σ) or better. Attitude and position knowledge are measured using star cameras, inertial measurement units (IMUs), magnetometers, and GPS. For control, SENSE has four reaction wheels and three torque coils.

The two SENSE space vehicles are identical with the exception of two of their payloads. Space Vehicle 1 (SV-1) carries the Compact Tiny Ionospheric Photometer (CTIP), while Space Vehicle 2 (SV-2) is equipped with the Winds-Ion-Neutral Composition Suite (WINCS). The CTIP instrument was developed by the Stanford Research Institute. CTIP measures electron density profiles, Total Electron Content (TEC), and identifies features of the E and F2 regions of Earth's ionosphere[4]. The WINCS instrument was developed by the Naval Research Laboratory. WINCS is designed to acquire densities, velocities, and temperatures of ions and neutral particles in Earth's ionosphere[5].

Each vehicle is also equipped with a Compact Total Electron Content Sensor (CTECS) and a micro dosimeter. The CTECS payload measures ionospheric Total Electron Content (TEC) and scintillation using GPS Radio Occultation[6]. The CTECS payload is designed to satisfy the Key Performance Parameters (KPPs) for TEC and scintillation measurements specified in the NPOESS IORD-II[1]. This payload was developed by The Aerospace Corporation and also provides GPS position and velocity inputs for the ADCS subsystem. The micro dosimeter is a COTS component sourced from Teledyne, which was developed by The Aerospace Corporation. The SENSE program included the dosimeter in the design of the space vehicles in an effort to quantitatively assess the resilience of CubeSat electronics throughout prolonged exposure to the radiation environment in Low-Earth Orbit.

As of December 2012, the SENSE program office has taken delivery of both space vehicles, and the SENSE ground system is complete. A picture of the SENSE CubeSats entering thermal vacuum testing is shown in Figure 2. At present, the SENSE space vehicles are in storage at AFRL in Albuquerque, NM. The space vehicles will be shipped to the Wallops Space Launch Complex in Virginia where they will be processed for launch on the ORS Enabler 3 mission. The vehicles are scheduled for launch in the late fall of 2013.

ACQUISITIONS APPROACH

A key challenge of the SENSE acquisition is to obtain a balance between two competing interests: (1) the desire to execute an agile acquisition strategy to demonstrate that CubeSats are viable, low-cost solutions for future space architectures and (2) the necessity to meet important requirements and regulations governing an operational SMC system, which inherently brings overhead to programs and can become unwieldy in a minimally-staffed rapid acquisition effort.

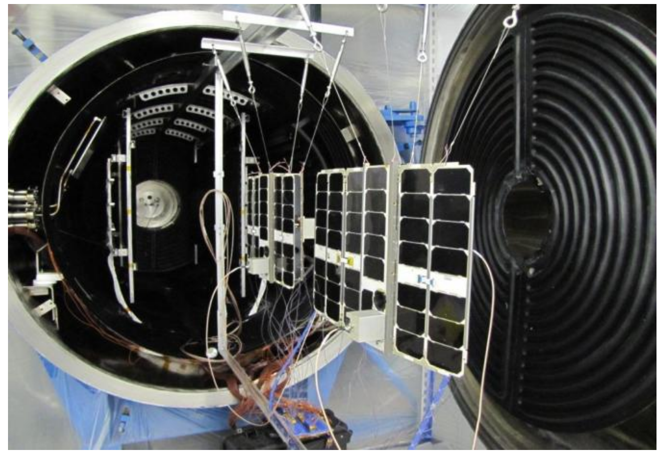

Figure 2: SENSE Thermal Vacuum Test

A fundamental objective of SENSE is to present DoD decision makers with an understanding of the benefits and costs of integrating CubeSats into an operational architecture. SENSE is a pathfinder demonstration that will help to establish how this class of vehicle—one radically different in scale from what SMC typically procures—can be acquired, launched and operated to support future SMC missions. Early on it was decided that the SENSE ground architecture would be based upon assets organic to the Space Development and Test Directorate (SMC/SD). The intent of this decision was to create a ground segment capability that will remain in place to support subsequent national security space CubeSat and NanoSat missions. The principal objective of the SENSE ionospheric science payloads is to provide data that can be usefully ingested by prototypes of the ionospheric prediction models (e.g. GAIM) employed by the Air Force Space Weather Agency. To demonstrate this objective, the SENSE system is required to provide SEM data to the Air Force Research Laboratory at Kirtland Air Force Base in a format that can be directly ingested by GAIM and also be capable of performing frequent downlink contacts to demonstrate that operational SEM data latency requirements are satisfied.

To achieve these goals, it was necessary to structure SENSE to be compatible with SMC processes. This first required that a full and open competitive acquisition process be followed in accordance with Federal Acquisition Regulation (FAR) Part 15. The SENSE Request for Proposal[7] (RFP) called for a thorough—though somewhat streamlined—set of program reviews, technical interchanges, and documentation. As a SMC program, SENSE requires a higher standard of mission assurance than that which is often provided for CubeSat experiments. To that end, engineering models of the vehicles and payloads were developed and an extensive series of environmental qualification, acceptance and ground segment compatibility tests were performed. All operational SMC systems need to comply with Information Assurance (IA) requirements. Thus for SENSE to demonstrate operational suitability, it too must satisfy these IA requirements. The ground and processing segments, which for SENSE are provided by the government, are also required to meet IA standards.

While significant acquisition processes exist in SENSE, substantial effort has been made to employ these processes selectively to minimize administrative burdens and their associated costs without sacrificing quality and mission assurance. For one, the number of program reviews and deliverable documents was reduced. The traditional System Requirements Review and Preliminary Design Review were consolidated into a single Initial Design Review. Communication between the SENSE program office and the contractor is frequent and often informal. Further, the particular instruments for the SENSE payload and many spacecraft performance parameters were not specified in the RFP[7]. Instead, Key Performance Parameters from the IORD-II standards were provided as requirements, along with requirements to operate with specified reference ground terminals in Unified S-Band and to meet the CubeSat Design Specification[2]. Bidders were allowed to choose their payload suites and integrate them into vehicles designed to support their selected payloads. Characteristics such as spacecraft power, pointing accuracy, downlink data rates and waveform were not specified and left as design trades for the SENSE bidders.

LESSONS LEARNED

Throughout the SENSE acquisition, a number of lessons have been learned that should be applied to the future Government acquisition of small satellite architectures. This section outlines four key lessons from the SENSE program.

"Small" Satellite ≠ Low Complexity

Given the CubeSats' small size, it is often difficult to appreciate the complexity of the SENSE mission--significant engineering effort was required to design and integrate the various subsystems. SENSE required the use of CAD and thermal models to ensure the physical fit and thermal balance of the space vehicles. As SENSE is a mostly single string failure design, reliability modeling was also performed to gauge the most likely failure modes. As a pathfinder for exploring the role of CubeSats in operational military space, SENSE is striving to stretch the bounds and assess the capabilities achievable using a 3U form factor. With this goal in mind, SENSE has departed from the realm of the "simple" satellite. As such, disciplined engineering practices are as important for SENSE as for larger space systems. Rigorous documentation standards, test practices, and operator training are critical for mission success and meeting key performance parameters.

Do Not Over-estimate the Potential for Savings by Using COTS Components and Designs with Flight Heritage

The CubeSat community takes great pride in its use of COTS components to execute missions at low cost. The SENSE CubeSats have also achieved efficiencies in both development time and cost by leveraging heritage from the Boeing Colony II bus. That said, SENSE overestimated the potential for savings from using these proven components. Flight software reuse from the predecessor Colony II program was originally estimated to be ~90%-95%; ~75% reuse was ultimately obtained. Software development and test as well as interface management between COTS hardware components required substantial engineering effort. Each space vehicle faced its own unique set of development challenges, and this level of effort should not be underestimated when planning future small satellite missions. From inception to completion, the cost of COTS hardware grew by approximately 40% and accounted for 15% of the overall hardware cost growth.

Future DoD CubeSat Contracts Should Blend Cost Plus and Fixed Price for Various Aspects of Development

Because SENSE is a first-of-kind pathfinder mission, the Air Force chose to develop the vehicles using a cost plus contract. This approach was taken given SENSE's technical uncertainties, but future CubeSat missions should tailor contracts to be a blend of cost plus and fixed price. Certain aspects of satellite subsystem development are of inherently greater risk than others. For SENSE, the payloads and S-Band transceiver were the most difficult and risky components to develop. Acquiring high-risk components under cost plus contracts and with substantial schedule margin is advisable. Alternatively, for vehicle integration and test efforts, SENSE advocates a fixed-price contract. Repeated contract modifications for additional funding and period of performance extensions were a substantial burden on the program that detracted from the program's ability to focus on efficiently resolving routine technical problems. Such minor problems ranged from manufacturing defects to minor electrical component failures during burn-in. By tailoring the contract with cost plus and fixed price constructs, SENSE believes future CubeSat acquisitions will be better optimized to achieve lower program cost and shorter development time.

Scope Space-Ground Activities as Sequential Development Efforts

Parallel acquisition of both the space and ground segments added challenge and complexity to the SENSE program. Converging on performance requirements between the vehicles and ground segment as well as resolving communications protocol issues proved quite difficult. Ideally, the SENSE ground system would have been a defined entity of known performance prior to space vehicle development. This would have enabled the space vehicle developer to lock down the communications trade space and converge on a final design much faster. The fact that SENSE is one of the first Air Force satellite systems to operate in Unified S-Band (USB) introduced challenges since the existing ground infrastructure did not support USB at the start of the SENSE development. Furthermore, inefficiency was introduced as the space vehicle integrator had to develop unique ground support software to test the space vehicle radios. If the ground system were mature, the space vehicles could have been tested using a ground system simulator providing assurance early in the program that the ground system and space vehicles were compatible. Fortunately, future small satellite missions will benefit from SENSE leave-behind ground assets like the Common Ground Architecture.

Understand CubeSat Launch Opportunities from the Beginning and Design Accordingly

Ride-share missions usually do not receive the gentlest ride to orbit. The original SENSE Statement of Work specified a highly conservative vibration requirement for the space vehicles intended to enable SENSE to survive launch loads induced by nearly any launch vehicle. This imposed a substantial engineering burden. While many CubeSats in the past have been relatively simple with few if any moving parts, future generations will likely be more susceptible to damage from vibration. Possible rides and the environments associated with each launch vehicle must be considered to avoid costly expenses for over, or worse, under-engineering a CubeSat structure.

CONCLUSION

The SENSE program is establishing an important precedent for future air force space acquisitions. By implementing an agile acquisitions strategy using the CubeSat form factor, SENSE is a pathfinder to future low-cost space architectures for operational military applications. Several key lessons have been learned throughout the sense acquisition process. By heeding these lessons and continuing to push the threshold of capability with future generations of CubeSat missions, the SENSE program office is confident CubeSats can play a significant role in augmenting or performing operational military missions. Stay tuned for updates at IEEE Aerospace 2014, at which SENSE looks forward to presenting the results of early on-orbit operations following launch of the SENSE CubeSats in fall 2013.

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