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SENSE: The USAF SMC/XR Space Environmental NanoSatellite Experiment

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ABSTRACT

The Space Environmental NanoSatellite Experiment (SENSE) is a demonstration mission for assessing the utility of NanoSatellites for performing operational space weather missions for the United States Air Force. The SENSE space architecture consists of two three-unit (3U) CubeSats that launched on 19 Nov 2013. The space vehicles carry a combined suite of three payloads for space environmental monitoring. This paper outlines how the SENSE CubeSat mission is contributing to enhanced global awareness for the space weather community and summarizes the lessons learned throughout acquisition and on-orbit checkout.

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 (Exhibit 1) 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. SMC/SD is also contributing a core team of four Lieutenants with engineering backgrounds to operate the vehicles on orbit. Lastly, the Space Vehicles Directorate at AFRL (AFRL/RV) is responsible for data processing, analysis, and distribution.

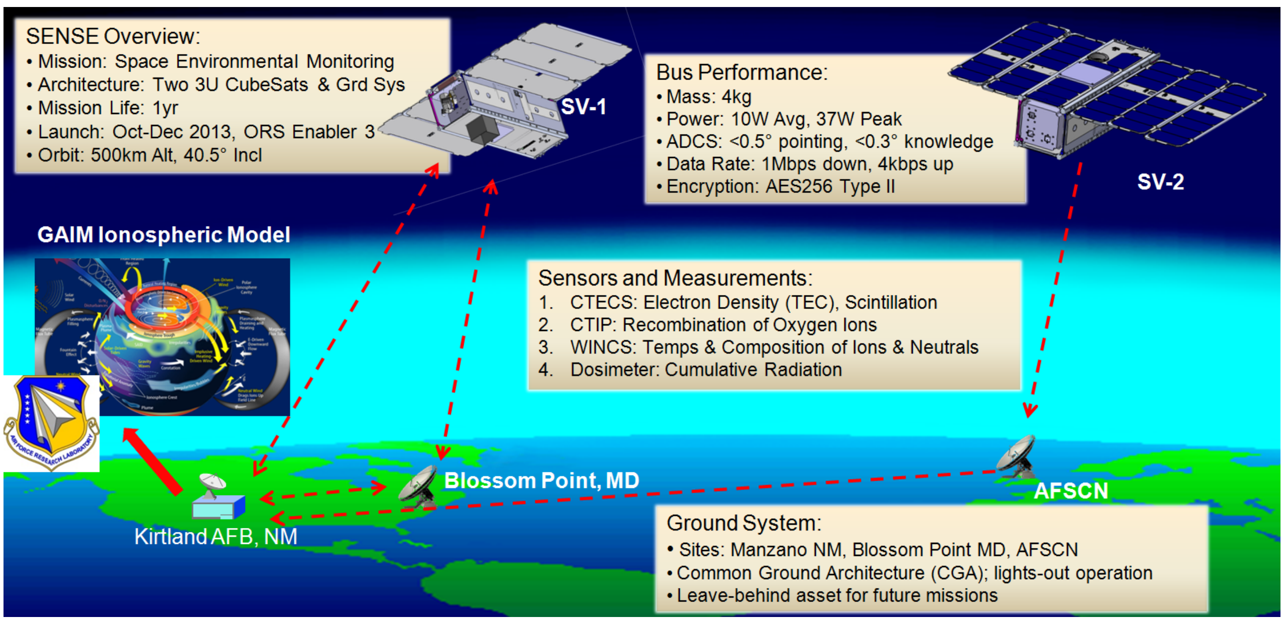

Exhibit 1: SENSE Mission Overview

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. SENSE utilizes antennas located at Kirtland AFB, NM (Exhibit 2). 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 capability that can be readily leveraged by future space programs.

Exhibit 2: SENSE Ground Terminal at Kirtland Air Force Base, New Mexico

The two SENSE space vehicles (Exhibit 3) 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, which is highly modular and relies heavily on COTS components. This approach to spacecraft design is intended to minimize development time and cost.

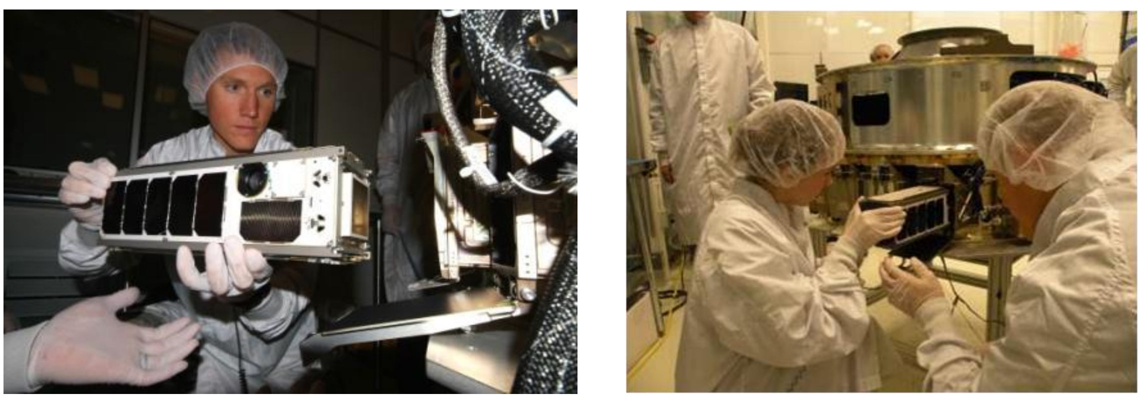

Exhibit 3: SENSE Space Vehicle Integration

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, 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.

SUMMARY OF ON-ORBIT PERFORMANCE

The two SENSE CubeSats were launched on 19 November 2013 from Wallops Island, Virginia on the Operationally Responsive Space (ORS) 3 Enabler mission. This mission deployed a record setting twenty-eight CubeSats. The SENSE mission experienced a number of challenges following launch. First, SENSE operators were unable to obtain an accurate element set for tracking the vehicles for sixteen days following launch. An element set is a standardized method for reporting a space vehicle's orbital parameters and is needed for communications to estimate when and where a satellite will pass over ground antennas. The SENSE program was reliant upon the Air Force's Joint Space Operations Center (JSpOC) for generating element sets. Due to an international launch and a national security space launch that occurred near the same time as the ORS 3 launch, high quality element sets were delayed as Air Force space tracking assets were allocated to higher priorities than the CubeSats on the Enabler mission.

An additional contributing factor that delayed initial contact was that both vehicles experienced solar array deployment failures. Nominally, the vehicles were designed to autonomously deploy their solar arrays thirty minutes following launch and autonomously point the arrays toward the sun. In reality, SV-1's bi-fold array and SV-2's bi-fold and tri-fold arrays failed to deploy as designed. Both vehicles attempted to orient the arrays toward the sun after launch, but the ADCS was not designed to operate in an off-nominal configuration. The vehicles were essentially crippled with no control and limited capacity to produce power.

To further compound the vehicle acquisition problem, both vehicles were programmed to activate a beacon if contact was not established within twenty-four hours following launch. The vehicle's beacon was not long enough in duration to enable the SENSE mission's ground antennas to lock on to each vehicle using the antenna's auto track feature. Under nominal conditions, the beacon transmits for ten seconds of every minute. In a low power situation, the beacon transmits for a couple seconds or not at all. These intermittent beacons were the only means of distinguishing the SENSE vehicles from the other twenty-six CubeSats during the first two weeks on-orbit. The sparse beacons combined with the high uncertainty of the element sets made tracking the vehicles extremely challenging.

Once operators finally obtained an accurate element set for each CubeSat, the real work began of assessing the vehicles' state of health. While the few, brief observations of the beacons were encouraging to operators, the beacons' frequent transmissions were a significant draw on the vehicles' batteries. The first step was to disable the beacons and allow the batteries to recharge. Once enough charge was stored, telemetry was downloaded allowing the team to diagnose the solar array deployment anomaly that occurred following launch. The team also conducted an extensive root cause and corrective action plan to assess why the solar arrays failed to deploy. SV-2, the vehicle with neither array deployed, could not sustain prolonged communications. The team transitioned SV-2 to a low power state for approximately one month in attempt to recharge the vehicle's batteries. During this time, operators pressed ahead with diagnosing problems with SV-1's control algorithms.

On SV-1, the team's highest priority was to detumble the vehicle and transition it into a two-axis stabilized sun-pointing orientation called sun safe mode. This is the default mode the vehicle was supposed to default to after launch. In reality, it took the team three months on-orbit test to calibrate the sun sensors and magnetometers and integrate these measurements into control outputs that enable the vehicle to maintain sun pointing. As of the writing of this paper, SV-1 remains stable in sun safe mode and is days away from completing testing to transition to its operational attitude. Progress has been made with SV-2, but power limitations with the vehicle have resulted in intermittent losses of communications and slower progress.

Once SV-1 reaches its operational attitude, bus checkout will be nearly complete. Completing bus checkout signifies the end of the launch and early orbit period and the beginning of nominal operations. Bus checkout is complete when the functionality of all subsystems and sensors has been verified and the bus has been transitioned to its operational attitude. In the case of SV-1, Local Vertical Local Horizontal (LVLH) is the operational attitude. LVLH keeps the CTIP sensor nadir pointing with high precision. If a positive power balance cannot be maintained indefinitely in LVLH, it may be necessary to temporarily slew toward the sun and/or duty cycle the CTIP/CTECS payloads to maintain positive power. For SV-2, sun safe is the operational attitude the vehicle will spend the majority of its life in. Excursions from sun safe to LVLH will be conducted with SV-2 to characterize WINCS performance, but these excursions are not considered nominal operations at this time.

Going forward, the completion of bus checkout marks the beginning of the sensor verification and validation study. AFRL/RV is the lead organization for conducting this study. The study is scheduled to last for approximately six months. Pending the quality of the on-obit data, the SENSE mission is working to incorporate mission data into space weather models such as GAIM. In December 2014, the SENSE mission will conclude its thirteen month on-orbit assessment.

LESSONS LEARNED

Given the small size of the SENSE CubeSats, it is easy to overlook the complexity of the SENSE system. The SENSE vehicles do not appear to be "small" to the ground segment; they can transmit over 1300 telemetry items and the ground terminal hardware (modems, antennas) is the same as that used on larger missions. In addition, a part of the SENSE experiment is to demonstrate that CubeSats can be acquired and operated within Air Force Space processes and integrated into existing architectures as a system. The SENSE team learned that many of the current processes and interfaces do not scale downward "linearly" as the size of the space vehicles decrease. For example, the time spent on spacecraft source selection ended up being a significant fraction that for the spacecraft development itself: roughly seven months of source selection were followed by nineteen months of hardware development. A source selection effort of such scope clearly does not fit into the small satellite paradigm and tailored processes need to be implemented to promote more efficient acquisition of small space systems. Development of the SENSE ground architecture required an extensive system integration effort including, mission unique software development, RF engineering and testing, control of multiple interfaces, and compliance with launch safety, information assurance and frequency regulatory requirements. The lesson there is that when planning small satellites for operational purposes, one must consider development of the end-to-end integrated system.

The initial delay and difficulty in establishing ground contact with the SENSE vehicles highlights the need for improvements which will make tracking and determination of orbital elements faster and more efficient. Some of these difficulties were SENSE-specific resulting from the solar array deployment failures but others stemmed from the release of twenty-eight CubeSats into a relatively tight formation. Tracking this cluster of space objects led to cross- tagging errors so that the two-line elements used by the SENSE spacecraft ground stations did not result in contacts until more objects were correctly cataloged. Going forward, more multiple CubeSat deployments are likely and early orbit operations need to anticipate a significant delay in achieving initial contacts. This problem can also be mitigated by the development of additional mechanisms, such as optical tags or compact broad-beam beacons, to aid initial vehicle acquisition by the ground antennas.

The SENSE early orbit operations concept was designed such that if deployment anomalies occurred, the vehicles would step through a sequence of operating states each with decreasing bus functionality and power consumption. The SENSE on-orbit experience indicates that this approach was too optimistic: the nature of the vehicle anomalies was such that the intended intermediate operating states could not be properly achieved. Performance in deployment and early operation would have been improved if the vehicles began operation in their free drift mode.

In hindsight, the solar array deployment failure was due to a design weakness which could have been discovered during vehicle development if that mechanism had either been screened more thoroughly for workmanship or tested under vacuum. Part of the CubeSat concept is to accept higher risk in return for lower cost and faster development. It has been difficult to establish where that balance should be. That balance will vary in accord with the needs and cultures of different CubeSat developers and sponsoring organizations. The SENSE program adopted a more aggressive risk posture than would be required for an operational SMC acquisition. SENSE tailored traditional SMC processes as appropriate for a demonstration mission. The experience with SENSE confirms additional mission assurance testing under space environmental conditions must be performed on components whose failure can have a catastrophic mission impact, at least for vehicles which have not flown successfully prior.

RF compatibility testing between the spacecraft and the ground terminals has been long been recognized as a best practice. The SENSE program employed this practice with great success. Clearly, the small size of the space vehicles simplified the logistics of such tests—the SENSE engineering models were transported easily to the SENSE ground terminals. SENSE also was able to establish connectivity between the vehicles in the factory, ground software developers, flight operators in training and ground terminals while development was ongoing. With this setup, the various ground system developers could command the vehicles directory and see the response in the return telemetry in real time, all the time. The result was that the ground segment integration proceeded smoothly and its performance with the vehicles on-orbit has been excellent, more than justifying the expense of establishing the supporting communication network.

Additionally, the SENSE program acquired an engineering model of each space vehicle. The engineering models have proven highly valuable to the SENSE program during both development and on-orbit operations. The engineering models served as a test bed for the contractor to troubleshoot hardware-software functionality issues and test the vehicles to more rigorous qualification levels. The engineering models also allowed the contractor to practice integration procedures prior to implementation on the flight hardware. This approach enabled the team to reduce integration and test risk and ensured the flight space vehicles remained in pristine condition prior to launch. After the flight vehicles were on orbit, the engineering models were used to develop and verify procedures to resolve solar array deployment and ADCS anomalies.

A robust antenna configuration on both the vehicles and on the ground proved invaluable for anomaly resolution. The SENSE vehicles have transmit / receive antennas mounted on both the zenith and nadir faces. Both vehicles went into a tumble prior to successful contact and also were transmitting at a very low duty cycle because of their limited power. The two antenna configuration facilitated successful contacts during long intervals where the vehicles were not stabilized. The SENSE ground configuration provided contact opportunities from multiple antenna locations and the Blossom Point antenna was often operated remotely on nights and weekends from Kirtland. The availability of frequent contact opportunities provided to be invaluable as SENSE proceeded with anomaly resolution.

As an early DoD user of Unified S-Band frequencies, SENSE needed to obtain frequency licensing from the National Telecommunications and Information Agency (NTIA). As part of this process, SENSE needed to coordinate operation with the civil user (electronic news gathering) that has co-primary status in that band. NTIA approval for RF operation of SENSE was obtained prior to launch, albeit with much difficulty. The importance of starting the frequency licensing process early cannot be overstated, as the frequency approval process may very well take longer than the time required to develop the space vehicle.

CONCLUSION

The SENSE program has established 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. While the SENSE spacecraft have suffered performance degradation due to solar panel deployment failures on orbit, SENSE still will be able to provide ionospheric measurements for analysis and assessment. Moreover, SENSE has successfully demonstrated advances in streamlined, automated spacecraft operation using CGA and this architecture is available to support future CubeSat missions. The work done on SENSE to address Air Force space weather capability gaps provides a foundation for subsequent small satellite acquisitions. 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 the 7th Space Symposium in 2015, at which SENSE looks forward to presenting the results of early on-orbit operations following one year on orbit.

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