SENSE: Lessons Learned through Acquisition and On-Orbit Operations

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ABSTRACT

This paper reports on the Space Environmental NanoSatellite Experiment (SENSE), its successes and failures, and lessons learned that can be applied to future nanosat missions. SENSE was a pathfinder mission to show that CubeSats could be designed and acquired to perform Air Force missions while satisfying the existing requirements and regulations for mission certification and launch. On November 19, 2013 the two 3U SENSE CubeSats were launched into low earth orbit as part of the ORS-3 Enabler mission. Several major problems were encountered in the initial operation and activation of the satellites. These problems were mitigated to some extent, although the intended mission capability was not fully achieved. One SENSE vehicle has exceeded its one-year design life on-orbit. SENSE developed a ground architecture that was able to successfully demonstrate autonomous operation of a ground antenna network in Unified S-Band frequencies at a data rate of 1 Mbps, operating within Air Force cybersecurity requirements. A SENSE satellite has also provided a test platform for experimentation with cloud-based and disaggregated satellite ground architectures.

INTRODUCTION

Recently the demand for smaller, more cost-effective, and resilient satellite architectures has increased in both the government and private sector. The explosion of the CubeSat form factor has symbolized this trend, and the US Air Force has begun to explore the utility of CubeSats to augment National Security Space (NSS) missions.

The Advanced Systems and Development Directorate at the Space and Missile Systems Center (SMC/AD) sponsored the Space Environmental NanoSatellite Experiment (SENSE) mission to assess the utility of CubeSat architectures in the context of operational space missions. The SENSE architecture consists of two three unit (3U) CubeSats, with a supporting ground segment consisting of the Global Space Telemetry Resource (GSTR) antenna and Neptune Common Ground Architecture (CGA) multi-mission capable ground software.

The original requirements that drove the SENSE mission design were derived from the National Polar Integrated Operational Requirements Document (IORD-II)[1] and begin to address potential capability gaps identified in the Defense Meteorological and Oceanographic Collection (METOC) Initial Capabilities Document (ICD)[2]. From this document, the specific needs for charged particle characterization and ionospheric scintillation measurement were used to derive the payload requirements for the SENSE mission.

The SENSE program also achieved a strategic objective for future Air Force CubeSat programs by establishing a streamlined (and tailored) acquisition process for procuring small satellite systems. The streamlined acquisition process was executed to balance the mission assurance needs of SMC with the cost-reduction benefit enabled by CubeSat architectures. This cost reduction was enabled by using primarily commercial off-the-shelf (COTS) components, which also allowed the Air Force to procure the space vehicles on a much shorter timeline than previous space development projects.

MISSION OVERVIEW

The SENSE mission had two basic objectives: 1) demonstrate that a CubeSat system can be acquired, integrated and operated within existing Air Force SMC processes and constraints and 2) demonstrate that the performance of miniaturized space weather payloads on a 3U CubeSat can satisfy Air Force requirements for collection and processing of ionospheric measurements in support of the Space Environmental Monitoring (SEM) mission.

A fundamental objective of SENSE was to present DoD decision makers with an understanding of the benefits and costs of integrating CubeSats into an operational architecture. SENSE helped 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 Advanced Development and Directorate (SMC/AD). 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.

Further, SENSE was a pathfinder for exploring the mission capabilities achievable using a 3U form factor while still addressing military requirements for spacecraft design. Such features include military grade data encryption, radiation tolerance, and compliance with the SMC mission assurance process. To provide a meaningful demonstration SENSE developed a complete mission architecture that could demonstrate an end-to-end flow of mission data collected by the spacecraft through a processing segment to assess the quality of its ionospheric measurements.

The SENSE architecture consists of two space vehicles and a supporting ground system as shown in Figure 1. The two SENSE space vehicles are 3U CubeSats

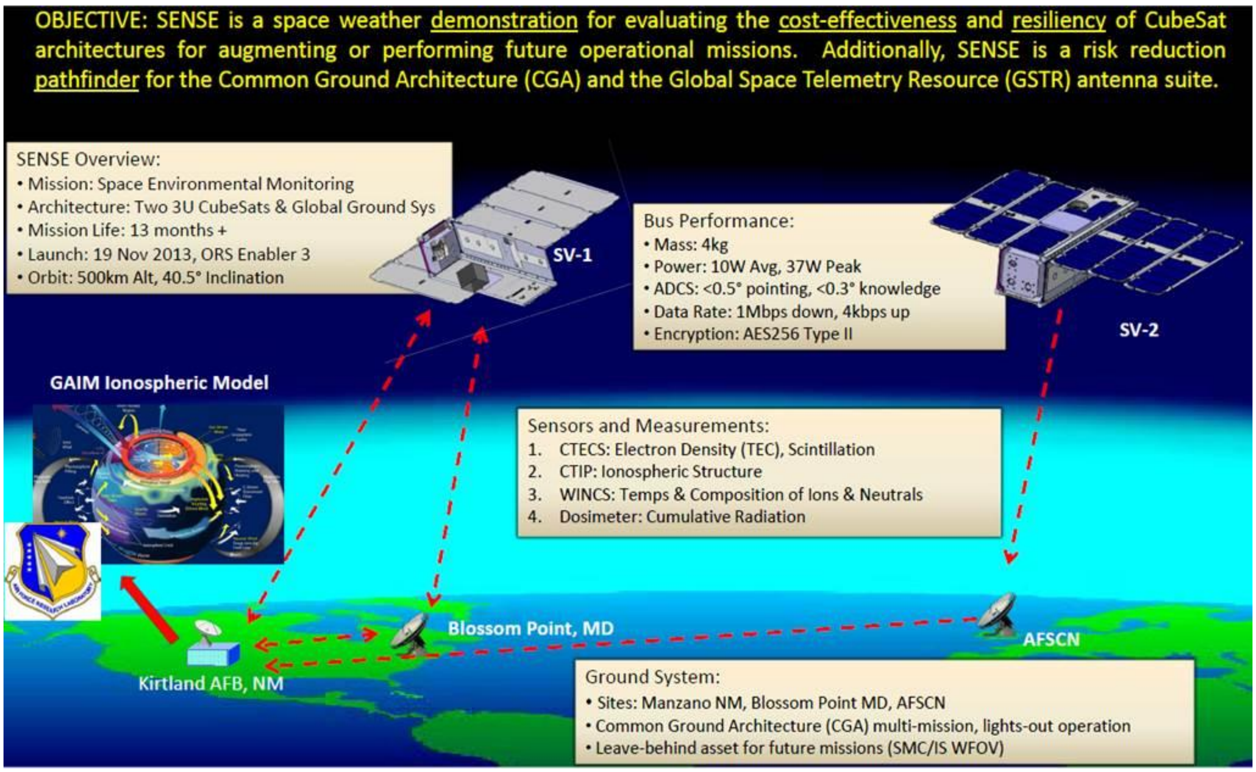

Figure 1: SENSE Mission Overview

The principal objective of the SENSE ionospheric science payloads was to provide data that could be usefully ingested by prototypes of the ionospheric prediction models, in particular, Global Assimilation of Ionospheric Measurements (GAIM), employed by the Air Force Space Weather Agency. To demonstrate this objective, the SENSE system was 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.

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 spacecraft were 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 was stored in six lithium-ion cells capable of providing the vehicle with 10W average power. The bi-fold and tri-fold arrays were deployed from their stowed configuration using a burn wire mechanism. For communication, the SENSE vehicles were equipped with a Unified S-Band transceiver designed to operate at 4kbps uplink and 1Mbps downlink. SENSE carried a miniaturized encryption module in its full-duplex transceiver that enables 256-bit Type II encryption. The SENSE Attitude Determination and Control Subsystem (ADCS) employed 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) carried the Compact Tiny Ionospheric Photometer (CTIP), while Space Vehicle 2 (SV-2) was 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 and developed by The Aerospace Corporation.

ACCOMPLISHMENTS

The two SENSE CubeSats were launched on 19 November 2013 from Wallops Island, Virginia on the Operationally Responsive Space (ORS) 3 Enabler mission. SV-1 remained operational and on-orbit for over 16 months, before re-entering earth's atmosphere on 21 March 2015. SV-2 was officially decommissioned (but remains on-orbit) on 30 April 2015. This section organizes SENSE accomplishments in terms of the ground segment and space segment.

Ground Segment

The ground segment was arguably the most successful component of the SENSE mission. The Air Force operations team, composed primarily of second and first lieutenants, performed extremely well given the complexity of the SENSE mission. A primary goal of SENSE was to provide a training test bed for space acquisition officers. The operations team was also deeply involved in development of the ground architecture and the operational procedures for SENSE.

Another successful piece of the ground segment was the GSTR antenna at Manzano, procured specifically for SENSE but intended to provide a leave behind capability upon conclusion of the SENSE mission. The auto-track feature specifically increased the contact success rate at low elevation passes. In addition to the GSTR antenna, SENSE demonstrated successful vehicle communication using the Air Force Satellite Control Network (AFSCN) for downlink, and another antenna at Blossom Point Tracking Facility with full uplink and downlink capability.

The foundation of the ground segment was the Neptune CGA ground software, which provided the backbone for all operations for SENSE. Using Neptune CGA, the operations team was able to consistently demonstrate "lights out" operation of SENSE from both Manzano and Blossom Point with data rates near 1 Mbps, paving the way for future minimally manned missions. Furthermore, the flexibility of CGA allowed the operations team to customize the graphical user interface (GUI) command screens, and prioritize the most important SENSE-specific telemetry indicators.

The SENSE ground segment, along with a spacecraft engineering model (EM) was used to successfully demonstrate the use of cloud technology for satellite operations. The SENSE satellite operators were able to conduct nominal command and control operations of the SENSE EM, through its radio interface, from a virtualized application hosted on MilCloud, a cloud service offered by the Defense Information Systems Agency (DISA) to DoD customers. For this demonstration, Neptune CGA was virtualized and hosted on MilCloud virtual data centers (VDCs) physically located Oklahoma City and Montgomery, AL. Using MilCloud, a contingency failover scenario between the two VDCs was successfully demonstrated.

Finally, SENSE was the first CubeSat to use unified S-Band frequencies with NTIA frequency assignment and coordination. Altogether, the ground segment for SENSE represents an impressive distributed ground architecture with leave-behind capability to fly the next minimally manned small satellite mission.

Space Segment

One significant, though understated, accomplishment of the SENSE mission is that SV-1 exceeded the designed mission life of 12 months using primarily COTS components. A secondary goal of the SENSE mission was to investigate the survivability of COTS components for future CubeSat missions. During 16 months on-orbit, the SENSE mission raised the Technology Readiness Level (TRL) and demonstrated the reliability of several science payloads and bus components. The CTECS sensors on both vehicles provided useful radio occultation and navigation data. SV-1 collected CTECS data for varying periods over 127 days and SV-2 collected CTECS data over eight days.

Another accomplishment with the space segment is the flight software update implemented on SV-1 during the final months of operations. After attempting (unsuccessfully) to resolve on-orbit command and data handling issues through software parameter changes, a full update of the flight software was implemented on the vehicle. This effort was a significant accomplishment in which the SENSE program demonstrated the benefits of the "fly-fix-fly" approach inherent in CubeSat development.

ON-ORBIT ANOMALIES

The SENSE mission experienced a number of challenges following launch. Difficulties identifying, acquiring and communicating with both vehicles were initially thought to be due principally to the large number of small satellites which were flying in a cluster-- the ORS 3 mission deployed twenty-eight CubeSats. While this was indeed a factor, it was later learned that many problems were caused by solar array deployment failures and design faults in the attitude control system.

Early Operations

Limited telemetry was obtained from SV-1on November 24 which indicated that its bi-fold solar array failed to deploy and that there was abnormally high use of control authority by the reaction wheels and torque coils, which were operating simultaneously, one control opposing the other. These factors caused the vehicles to remain in a low power state. 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. Accurate Two Line Elements (TLEs) were obtained on December 6, which enabled consistent communication with the vehicles.

Space Vehicle Checkout

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. Analysis and laboratory testing of the burn wire mechanism in vacuum indicated that the burn wire rapidly overheated upon activation, usually destroying itself in less than one second and before it is able to melt the nylon line holding down the solar panels. This mechanism had performed properly on-orbit on earlier vehicles where it was run off of a 5V line. There was a concern in vehicle development that the burn wire would be unable to melt the heavier nylon line now being used. For that reason, the burn wire was switched to the 12V rail. The burn wire problem was not detected because he new configuration was not tested in vacuum. 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 began to diagnose the 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 attitude control mode the vehicle was supposed to default to after launch. In reality, it took the team three months of on-orbit test to calibrate the sun sensors and magnetometers and integrate these measurements into control outputs that enabled the vehicle to maintain sun pointing.

Transition Attempts to Operational Attitude

The operational attitude for the SENSE vehicles is Local Vertical Local Horizontal (LVLH), which is required for the operation of the payloads. The control system was designed to use the two star cameras to achieve this attitude. One of the two star cameras on SV-1 was obscured completely by the un-deployed bi-fold solar panel. It was decided to try to achieve LVLH without the star camera control inputs through the use the sun sensors and rate gyros. A design limitation of the sun sensors, which were intended to provide only coarse attitude measurements made this impossible. The sun sensors were picking too much earth glow and as a result could not provide a correct sun vector to the control system. Moreover, the controls were designed such that sun sensor measurements were more heavily weighted by the ADACS than magnetometer measurements and this could only be corrected with a change to the flight software. Star camera images were extremely noisy and were not useful for attitude determination.

Flight Software Issues

To avoid a software change, efforts to obtain attitude knowledge from the unblocked star camera were intensified. Analysis of star camera images from SV-1 indicated that the camera focal plane was significantly degraded, most likely due to the sensors overexposure to the sun. At this point the program manager determined that a modification of the flight software was necessary to make any progress toward an operational attitude for SV-1. The flight software was not written in a modular form so that a refresh of the entire software image was required to implement the needed changes to the control algorithms. However, once uploaded to the flight vehicle and activated, the updated flight software fixed several on-orbit problems which significantly enhanced the final month of operations.

LESSONS LEARNED

Several lessons were learned during both the developmental and operational phases of the SENSE mission. These lessons will hopefully be applied to future Government acquisition of small satellite architectures. This section highlights six key lessons from the SENSE program.

Small Satellite ≠ Low Complexity

Given the CubeSat's small form factor, it is difficult to appreciate the complexity of the SENSE mission. Considerable engineering effort culminated in the design and integration of various subsystems. Functionally, these subsystems, including attitude and control, power management and distribution (PMAD), and command and data handling (C&DH), behaved very similar to subsystems on larger, more expensive operational military spacecraft. During the mission assurance process, reliability modeling was performed to gauge the highest probability failure modes, and a full suite of environmental tests was performed analogous to the mission assurance process for larger missions. As a pathfinder for exploring the role of CubeSats in operational military space, SENSE pushed several technical boundaries to assess the achievable capabilities using a 3U form factor.

Avoid designs where critical components cannot be repeatedly operated and tested

Another significant lesson learned from SENSE with respect to mission assurance is that use ofcritical components which cannot be operated and tested repeatedly and non-destructively should be avoided. As described above, the solar panel deployment burn wire mechanism failed on-orbit. This failure was not observed during testing, in part due to the fact that the mechanism could only be fired once and retest would have required disassembly of the burn wire mechanism and replacement with an untested burn wire heater. Such a retest would have failed to provide the intended mission assurance because the part flown is never actually tested. Future CubeSat designs should ensure testing repeatability of all critical functions.

Balancing risk management with agile space acquisition is difficult

Another major lesson learned from the SENSE mission was the delicate nature of the balance between risk management and agile space acquisition. Two obvious advantages that CubeSats provide to the Government are their relatively low cost and short development timeline. In many ways, tailoring the SENSE acquisition process to align with traditional SMC risk management and mission assurance processes was akin to fitting a square peg in a round hole, since there was no precedent for the development of rapid, affordable nanosatellite projects at SMC. Building on the SENSE acquisition framework, future Government missions should accept the fact that the CubeSat architecture represents an entirely new paradigm in space mission design, and to operate in this paradigm requires an increased tolerance for risk and a "fly-fix-fly" approach to development. Fortuitously, on-orbit experience is growing as the number of CubeSat missions continues to increase, and this will certainly reduce risk for all programs going forward.

Identification and tracking of CubeSats launched in swarms is difficult

As documented in the Mission Overview section, 29 CubeSats launched on ORS-3, and it took considerable time and effort to discriminate the two SENSE space vehicles from the swarm. Space vehicle discrimination methods in early operation require enhancement as satellites are deployed in larger numbers. This problem is exacerbated by the use of higher communications frequencies and data rates which result in smaller signal beamwidths. For SENSE, the uplink beamwidth was one degree, which required highly accurate antenna pointing to track and communicate with the vehicles. Potential solutions for the problem of discrimination are the use of inexpensive optical reflectors or spacecraft radio frequency identification (RFID) tags. The unique problems associated with CubeSat discrimination and potential solutions are explored in depth by Cousins[7] and Hall[8].

Don't try to do too much "right out of the P-POD"

As described above, multiple interrelated and cascading anomalies hampered initial spacecraft operations. These difficulties multiplied because the on-board initialization procedures were designed aggressively to autonomously transition the vehicles to their full LVLH operational attitude upon release from the Poly-PicoSat Orbital Dispenser (P-POD). To attempt this transition, the vehicles exercised control authority before ADCS performance was verified on-orbit. The solar array deployment failure and control system faults forced the vehicles into adverse configurations. The vehicles had to be transitioned back to their simpler and less power consuming free drift mode before procedures to stabilize power and attitude could be performed. Ultimately, the complex deployment sequence executed "right out of the P-POD" created more problems than it solved.

The lesson learned for future experiments is to design for simpler operations after P-POD ejection. Ideally, the vehicle should deploy into the lowest power state and the free drift ADCS mode. Methodical systems checkout should accompany incremental progress of the vehicle into increasingly complex operational modes. This approach would be an iterative procedure allowing more operator oversight and intervention throughout the checkout process.

Automated ground operations are feasible and beneficial for small satellite missions

There were several lessons learned for future CubeSat missions regarding automated ground operations. SENSE used automated contacts extensively during operations, but automation requires careful planning and advanced knowledge of mission objectives. Automated passes were especially beneficial during midnight contacts when personnel availability was limited. In order to fully realize the cost savings potential of CubeSats, especially for future government missions, the automated ground operations capability should be pursued.

An additional benefit provided by the SENSE leave behind ground infrastructure was the opportunity to execute ground demonstration experiments. Using the SENSE engineering units and the existing ground architecture, the operations team executed several experiments that investigated the feasibility of cloud based disaggregated satellite operation architectures . SENSE, as a platform for ground demonstration experiments, continues to provide lessons learned for future ground architectures.

CONCLUSIONS

Despite initial on-orbit anomalies, the SENSE mission achieved the primary mission objectives of increasing the TRL of next generation space weather sensors, increasing access to space for future Air Force CubeSat missions, and developing a state of the art ground architecture with leave behind capability for future minimally manned missions. Building upon lessons from acquisition, development, and operations, the SENSE program office is confident that CubeSats will continue to play an increasingly large role augmenting future military missions.

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