SSC19-WKVII-02

Neutron-1 Mission: Low Earth Orbit Neutron Flux Detection and COSMOS Mission Operations Technology Demonstration

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ABSTRACT

The Neutron-1 mission is scheduled to launch on ELaNa 25 during the Fall of 2019. The 3U CubeSat will measure low energy neutron flux in Low Earth Orbit (LEO). The CubeSat was developed by the Hawaii Space Flight Laboratory (HSFL) at the University of Hawaii at Manoa (UHM). The science payload, a small neutron detector developed by Arizona State University (ASU) for the LunaH-Map, will focus on measurements of low energy secondary neutrons, one of the components of the LEO neutron environment. In addition, this mission presents an excellent opportunity to establish flight heritage and demonstrate the technological capabilities of the NASA EPSCoR funded Comprehensive Open-architecture Solution for Mission Operations Systems (COSMOS, http://cosmos-project.org). COSMOS is an open source set of tools that is being developed at HSFL as an integrated operations solution (including flight software, ground station operations, and mission operations center) for Small Satellite missions. It is intended to enable/facilitate SmallSat mission operations at universities with limited budgets and short schedules.

INTRODUCTION

The Neutron-1 mission is a 3U CubeSat being developed by the Hawaii Space Flight Laboratory (HSFL) at the University of Hawaii at Manoa (UHM). A rendering of the Neutron-1 CubeSat is shown in Figure 1. The satellite will study low energy neutron flux in Low Earth Orbit (LEO) as a function of time and location. The spacecraft bus was integrated and tested at HSFL. The science payload, developed by Arizona State University (ASU), uses a novel elpasolite sensor[1,2] developed for the Lunar Polar Hydrogen Mapper, or LunaH-Map Mission[3,4,5]. Neutron-1 is expected to launch in the Fall 2019 while the LunaH-Map is expected to launch in 2020. This will allow the LunaH-Map team to test the instrument operations in Low Earth Orbit (LEO) prior to launching the instrument to Lunar orbit. The satellite will be delivered to NanoRacks in August 2019 and launched in October 2019 on the NASA sponsored ELaNa 25 mission carrying 18 other CubeSat missions to the ISS. The cubesat will be launched to the ISS via the Antares II rocket vehicle launched from Wallops Flight Facility, VA. Once aboard the ISS, the satellite is expected to be deployed in early 2020 from the NanoRacks CubeSat Deployer (NRCSD). Since Neutron-1 is deployed from the ISS, the orbit will be approximately circular at ~400km at 51.6 degrees inclination.

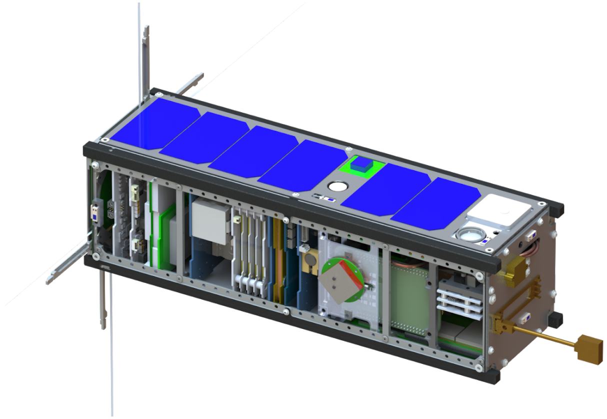


Figure 1: Rending of the Neutron-1 3U CubeSat

The project involved more than 30 students of varying levels, mostly from undergraduate and high school, during all phases of development. Through the extensive involvement of the students developing Neutron-1, HSFL is providing valuable training for the next generation of space engineers.

SCIENCE MISSION OVERVIEW

Neutrons in LEO have three major sources: production in the atmosphere via Galactic Cosmic Radiation (GCR) and Earth's radiation belt, production in the spacecraft by the same ionizing radiation interacting with spacecraft materials, and direct emission from the Sun during large Solar Particle Events (SPE). These neutrons are slowed by components of the atmosphere. One fraction is absorbed by nuclear reactions, another fraction decays, and the significant remainder leaves the atmosphere forming the Earth albedo neutron flux. The flux and energy spectrum of these neutrons are variable in time and space, as their production depends on variable high-energy charged particle fluxes and properties of the upper atmosphere.

The overall science goal of the Neutron-1 mission is to measure the time dynamics of low energy Earth albedo neutrons as a function of solar activity level, time, and space coordinates of the CubeSat. To achieve this goal, we use the small neutron detector developed by ASU for the upcoming LunaH-Map mission[3,4,5,6]. The measurements will focus on low energy secondary neutrons, one of the components of the LEO neutron environment. Maps of secondary low energy neutron abundances will be derived from the data as a function of latitude, longitude, and time.

Data gathered by the neutron detectors will contribute to understanding the complex relationship between the Earth and the Sun through mapping neutron abundances in LEO. We will also evaluate our neutron data for potential application in space weather characterization and radiation safety.

The LunaH-Map mission is seeking to make neutron observations around the Moon to evaluate the abundance of water ice on the lunar surface. Neutron-1 will provide the LunaH-Map instrument on-orbit flight experience. The experiment will evaluate detector sensitivity, particle count accuracy, data processing capability, Single Event Upset (SEU) effects, and in-space operability in an environment similar to lunar orbit; moreover, Neutron-1 will allow ASU to evaluate instrument spaceflight performance and gain flight heritage. The performance information collected will allow ASU to make required improvements to the LunaH-Map instrument prior to its lunar mission. Flight heritage is important for the LunaH-Map mission to ensure instrumentation is tested and reliable prior to flight. The Neutron-1 launch date aligns with the ASU requirements and facilitates ample time to make adjustments and modifications to the instrument before the LunaH-Map launch.

Science Payload

The mission's primary payload is designed to use the scintillator material Cs_2LiYCl_6 or "CLYC" to measure count rates of epithermal neutrons. The instrument is contributed to the Neutron-1 program by Arizona State University as part of the Lunar Polar Hydrogen Mapper (LunaH-Map) mission[2,7]. The payload consists of a single flight spare neutron detector module from the LunaH-Map Miniature Neutron Spectrometer (Mini-NS). LunaH-Map will enter lunar orbit and measure the epithermal neutron count rates above south pole's permanently shadowed regions to place constraints on the abundance and distribution of water ice that may be trapped within those regions. The Mini-NS is an eight module detector array where each module, pictured in Figure 2 on the left, within the arrays are controlled by an electronics board assembly pictured in Figure 2 on right[2,3,7].

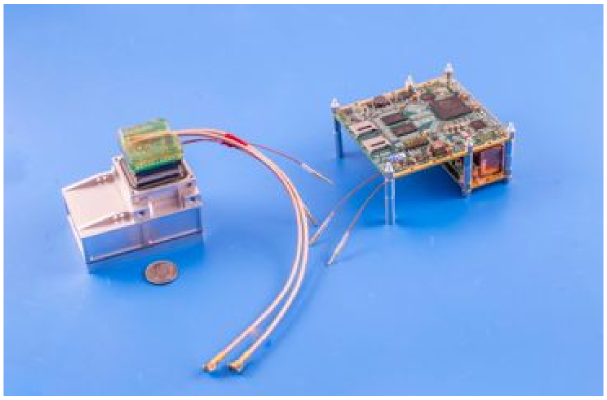


Figure 2: Neutron module (left) consists of a single CLYC scintillator hermetically sealed in an aluminum enclosure with a photomultiplier for light readout. The electronics board assembly (right) consists of a high voltage power supply, as well as an analog and digital board.

For Neutron-1, the module and electronics board assembly functionality and performance will be evaluated in the space environment, in preparation for the LunaH-Map mission which will launch on the Space Launch System (SLS) Exploration Mission 1 (EM-1) in 2020 or later. Instrument telemetry, health and safety information, neutron data products, and pulse shape discrimination parameter data will be downlinked from the payload for evaluation of the detector performance. Data collection with the detector operating in the positive and negative spacecraft velocity directions as well as pointing nadir and zenith will enable a qualitative assessment of detector performance throughout the operational temperature ranges.

The detector is covered with a gadolinium shield, which has a high thermal neutron cross section, on the nadir face, as shown in Figure 3, which makes the instrument sensitive to epithermal neutrons from 0.4 eV to 10keV in energy (the neutron energy region primarily sensitive to hydrogen abundance). This will enable the detector to measure the upward and downward epithermal neutron flux in LEO by reorienting the spacecraft. Assessment of data collected in these orientations may help place useful constraints on the detector performance, as well as demonstrate the feasibility of future neutron payloads that may measure the directionality of the LEO low energy neutron environment, or for considerations with respect to experiments for measuring the neutron lifetime.

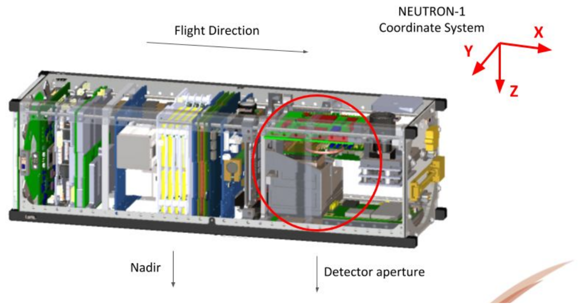


Figure 3: Neutron 1 Coordinate System and instrument aperture direction.

SYSTEMS ENGINEERING

Mission Design

Neutron-1 is designed to the 3U CubeSat standard, the NASA CubeSat Launch Initiative (CSLI) Launch Services Program (LSP)[8] requirements, and the NanoRacks CubeSat Deployer (NRCSD)[9] requirements. Besides the program level, launch, and deployment requirements, the main mission requirements were as follows:

1. The CubeSat shall be 3-axis stabilized and be capable of orienting the instrument aperture in four different directions: the flight direction, opposite to the flight direction, nadir and zenith. The Science mission requires that data will be taken for 10 orbits in each direction.
2. The Attitude Determination and Control System (ADCS) shall provide a pointing accuracy of ± 5° or better for the science mode and the antenna pointing.
3. The On-Board Computer (OBC) shall store and forward the instrument data to the ground and include a redundant data channel.
4. The instrument requires ~1MB of data per orbit, this includes science data volume and state of health data. Each science data collection orbit the instrument is on during 7.5 min.

Overall System Architecture

To support the science instrument the Neutron-1 bus system includes the primary OBC that serves to control the instrument data collection and to store and forward the data to the ground. The Electronic Power System (EPS) provides switchable power to the various systems in the bus and it is charged with four body mounted solar panels. The ADCS provides the 3-axis system stabilization to perform science experiments. Finally the RF Communication system uses three different radios to transfer information. The science data is transferred via an S-band channel while the command and control of the spacecraft is executed via the globalstar radio. Figure 4 shows the overall system diagram.

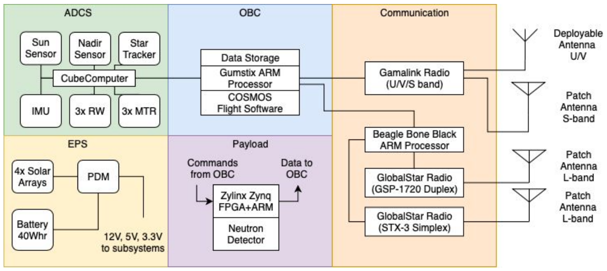
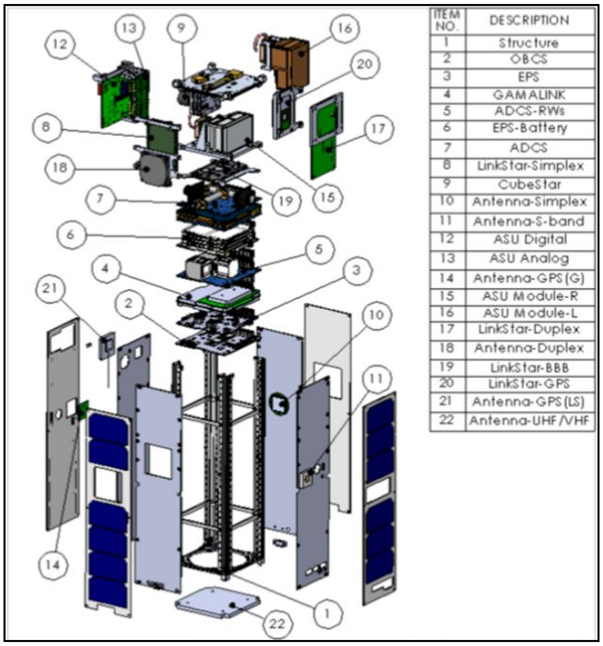


Figure 4: Neutron-1 System Level Block Diagram

SPACECRAFT BUS

The Neutron-1 spacecraft bus provides a complete system, including a 3U CubeSat structure, an Electrical Power System (EPS) with 4 body mounted solar panels and a battery, On-Board Computer System (OBCS) (sometimes referred to C&DH), thermal management, a 3-axis stabilized Attitude Determination and Control System (ADCS), and RF Communications (COMM). The RF system has two radios suites 1) A Software Defined Radio (SDR) for UHF/VHF/S-band comms and 2) GlobalStar Simplex and Duplex radios. The GlobalStar radio system provides near real time communication with the satellite when the radio is in contact with the GlobalStar network. An exploded view of the spacecraft with the main functional components is detailed in Figure 5.



ITEM NO.	DESCRIPTION
1	Structure
2	OBCS
3	EPS
4	GAMALINK
5	ADCS-RWs
6	EPS-Battery
7	ADCS
8	LinkStar-Simplex
9	CubeStar
10	Antenna-Simplex
11	Antenna-S-band
12	ASU Digital
13	ASU Analog
14	Antenna-GPS(G)
15	ASU Module-R
16	ASU Module-L
17	LinkStar-Duplex
18	Antenna-Duplex
19	LinkStar-BBB
20	LinkStar-GPS
21	Antenna-GPS(LS)
22	Antenna-UHF/VHF

Figure 5: Neutron-1 exploded view detailing main components

Structures and Mechanisms

Several off-the-shelf structures were evaluated for use as the primary structure for Neutron-1. A principal evaluation criterion in selecting a structure from Clyde Space AAC was the compatibility of the structure with predetermined flight hardware such as the CubeADCS. Several modifications were made to the structure to accommodate the various bus and payload components as they matured. The shear panels were also customized.

Most subsystems utilize the CubeSat Kit (CSK) form factor with the exception of the instrument payload and GlobalStar communications package. To accommodate these components, custom brackets and mounts were designed and fabricated. FEA analysis was performed in these cases to levels compliant with the NanoRacks CubeSat Deployer Interface Definition Document[9]. Acceptable factors of safety were greater than 1.25 for tensile yield strength and greater than 1.4 with respect to ultimate tensile strength.

Thermal

The spacecraft is in LEO where principal sources of heat are the Sun, Earth, and powered components depending upon operational modes. The only heat rejection sink is deep space. The Neutron-1 spacecraft bus is a very small and tightly packaged platform. Such a cubesat configuration could create hot components on the boards because the boards are mounted on rods in the boards' corners. Rail mounted boards do not effectively conduct heat away from the board, thus heat generating components can exceed requirement temperatures. The thermal operational range requirements for avionic components are -5°C to +55°C. The assessed internal heat sources are computers (2-2.5W), radios (1-2W), and the detector payload (4.2W). An infrared camera was used to identify which chips heated up the most as candidates for thermal management, an example of which is pictured in Figure 6.

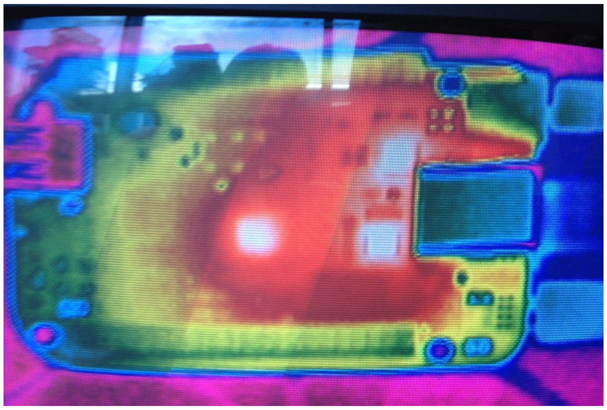


Figure 6: Thermal image of the BeagleBone Board showing +60C to +80C.

The Neutron-1 spacecraft mainly uses passive thermal control methods. Primary methods include conducting heat through copper strapping from hot components to the frame rails and using the external spacecraft surfaces, connected to the frame rails, as thermal radiators to reject heat to deep space. Secondary thermal management methods include turning off subsystem hardware that is not needed where possible. Temperature sensors are on the avionics boards including the payload. The battery has its own active internal thermal regulating system with a sensor, heater, and controller. The detector's performance is temperature dependent and is susceptible to damage from significant thermal gradients. The detector module has its own temperature sensor and during ground testing, temperature rate changes are limited to 0.5°C/min. A Thermal Desktop model was created to evaluate spacecraft transient temperature behavior in orbit as shown in Figure 7.

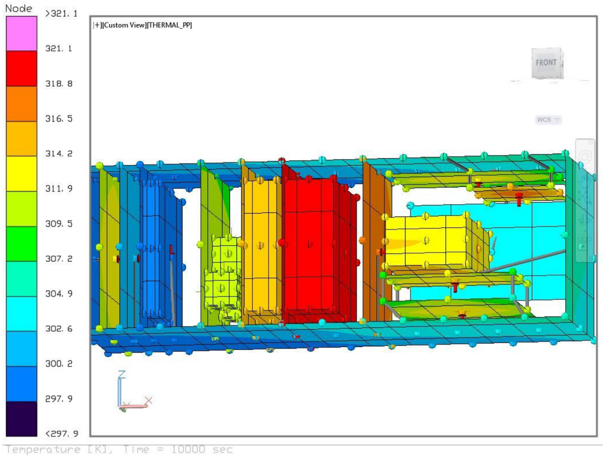


Figure 7: Thermal Desktop model of Neutron-1 avionics.

Electrical Power Subsystem (EPS)

The Neutron-1 bus electrical power system receives power input from the HSFL solar panels. The four solar panels are installed in the +Z (nominal facing nadir), -Z (nominal facing zenith), +Y (nominal facing the normal of the orbit) shown in Figure 8, -Y (nominal facing the negative normal of the orbit).

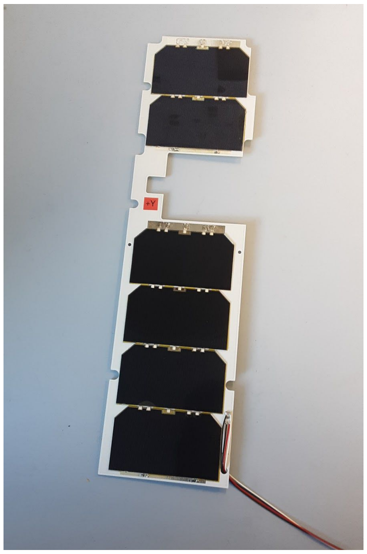
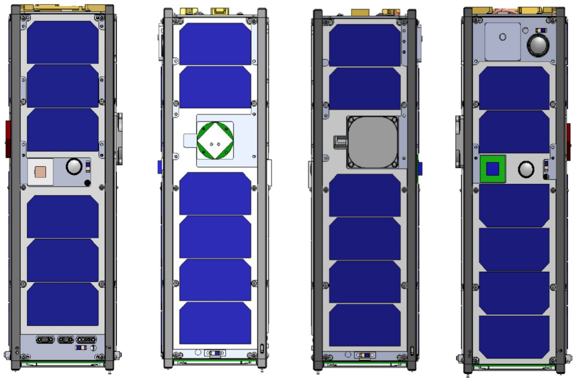


Figure 8: Y+ solar panel before sheer panel integration

Each individual solar panel has 6 cells producing a total ~6W solar output if directly exposed to the sun. The configuration of the four cells are shown in Figure 9 and shown mounted to the scraftcraft in Figures 10 and 11.



+Z (6 cells) +Y (6 cells) -Y (6 cells) -Z (6 cells)

Figure 9: Body mounted solar panel arrangement

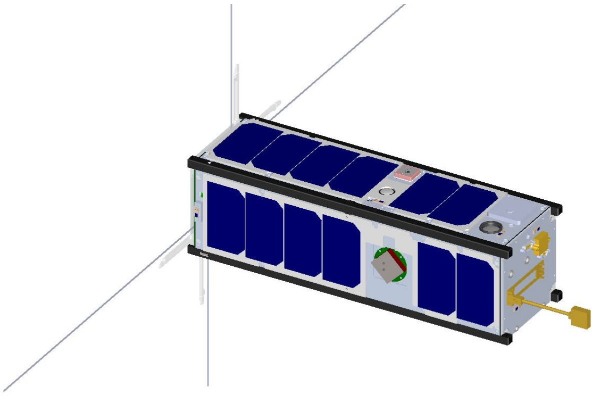


Figure 10: Body mounted solar panel arrangement
(top -Z, left side +Y)

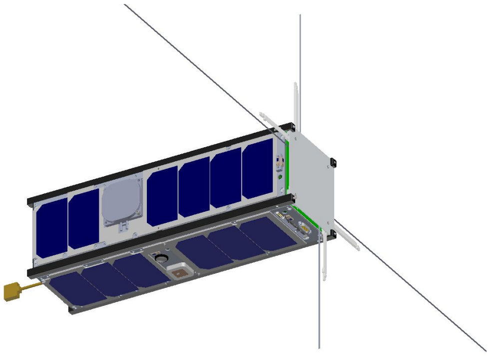


Figure 11: Body mounted solar panel arrangement
(left side -Y, bottom)

The expected tumbling rate coming out of the deployer is 1 to 2 deg / sec. For the power simulation we used 1.5 deg/sec. The average power generated in nominal mode is ~5W. The average power consumption is 4.5W over the 90 min orbit. The average power generated tumbling at 1.5 deg/sec is slightly lower at ~4.8W. This produces a positive net power so that the battery can be slightly charged over time. Figure 12 shows the overall battery capacity increase over a period of two days while the spacecraft is taking science data and transmitting it to the ground. The duplex radio is on every 3 hours during 10 minutes.

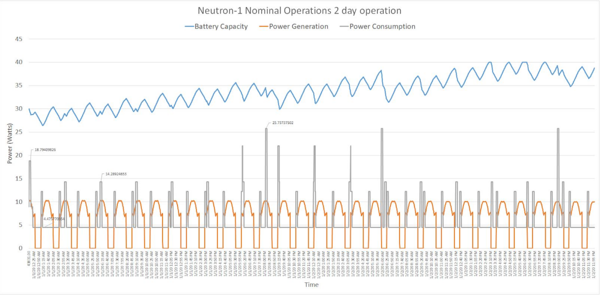


Figure 12: power simulation for battery power capacity, in nominal mode and science data taking mode the battery capacity increased over the two days of operations.

The solar power is stored in a 40 Whr lithium polymer battery pack and distributed via an EPS unit, both made by ClydeSpace. The 40Whr battery consists of two lithium polymer pouch cells in a 2s4p arrangement with a typical capacity of 5200mAhr at a nominal 7.6V. To comply with manned flight launch requirements, the battery features multiple high-side and low-side solid-state inhibits as well as voltage, current and temperature telemetries to monitor battery operation[10].

The EPS performs all the main functionalities of power generation and protection. It provides power conditioning modules which provide three regulated output buses (3.3V, 5V and 12V) and an unregulated battery bus with up to 90% efficiency for the regulated buses, while providing battery over-current and under-voltage protections[11].

Attitude Determination and Control Subsystem (ADCS)

The ADCS used for this mission is a CubeADCS 3-Axis integrated bundle from CubeSpace shown in Figure 13. Attitude determination is conducted via sensor measurements from ten coarse sun sensor diodes, two CMOS cameras as fine sun and earth sensors, three MEMS gyro rate sensors, a three-axis magnetometer, and a low-power star tracker. These sensor measurements are combined using an extended Kalman filter, and used with control algorithms for 3-Axis pointing (including Earth target tracking, Sun tracking, inertial pointing etc.). The CubeADCS enables full 3-Axis control of the satellite utilizing three reaction wheels, and three magnetorquers used for desaturation of the built up momentum in the wheels. Fine Point mode is entered when the following requirements are met: valid attitude is obtained by star tracker and propagated by the IMU, a valid time is obtained by GPS and propagated by onboard oscillator and the GPS has acquired a valid ephemeris[12].

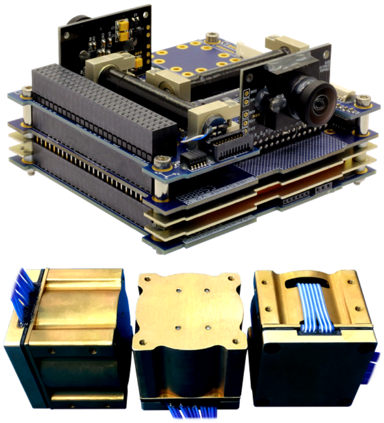


Figure 13: CubeADCS 3-Axis bundle[10]

The following simulation results, shown in Figure 14, are obtained using an ISS representative orbit (401 x 408 km) with an inclination of 51.64° and an orbital period of 92 min.

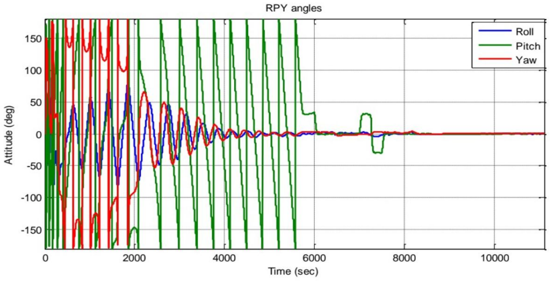


Figure 14: True RPY attitude angles during detumbling and Y-Momentum wheel control

The ADCS uses the 3-axis reaction wheel setup with the maximum momentum of 1.77 milli-Nms and a maximum torque of 0.23 milli-Nm. The torque coil and rods use a maximum magnetic moment of M(X) = 0.13 Am^2, M(Y) = 0.2 Am^2, and M(Z) 0.2 Am^2. The initial Roll is 10°, Pitch = 0°, Yaw = 5° and the initial rates are ω_{xi} = 4.0°/sec, ω_{yi} = 2.0°/sec, ω_{zi} = 0.0°/sec. This can be considered a worse case scenario because the expected tipping rate from the NanoRacks deployer is between 1 and 2 °/sec. The simulation starts with the magnetic B-dot and Y-spin controllers to bring the satellite to a Y-Thompson spin of 1°/sec, with the spin axis aligned orthogonal to the orbital plane. Afterwards the control changes the pitch attitude towards nadir. At 7000 sec a pitch reference of +30° was commanded and 250 seconds latter a -30° pitch reference then back to 0°. The satellite takes approximately 100 minutes to stabilize, or just over an orbit. The 3-axis reaction wheel control accuracy is dependent of the CubeStar availability to provide an attitude performance better than 0.2°, otherwise the attitude is expected to be in the order of 2°.

Communications

Neutron-1 uses three radios to provide a complete set of redundant communications. The Gamalink Radio is used primarily for the science operations and the GlobalStar radio is used as the primary telemetry and control link. There is also a GlobalStar simplex radio to transmit simple system level status messages. This radio configuration architecture, shown in Figure 15, enables a level of redundancy in case any of the radios fails.

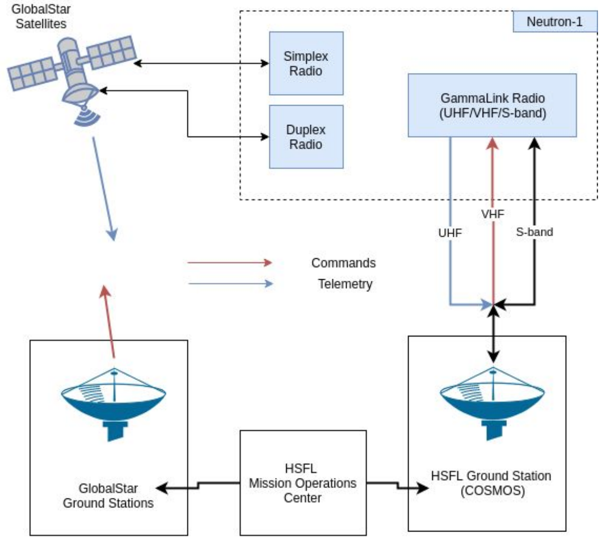


Figure 15: Neutron-1 communications architecture

The Gamalink Software Defined Radio (SDR) is developed by Tekever with the purpose to enable future satellite networks (constellations, formation flying mission, etc.)[13]. The Gamalink provides VHF uplink commands, UHF telemetry/beacon downlink, S-band downlink for science data, S-band uplink for software updates. This particular SDR also receives GPS signals and provides a GPS time and position state vector when lock is achieved. This GPS is used as a redundant GPS. The Gamalink SDR and antennas are shown in Figure 16 below.

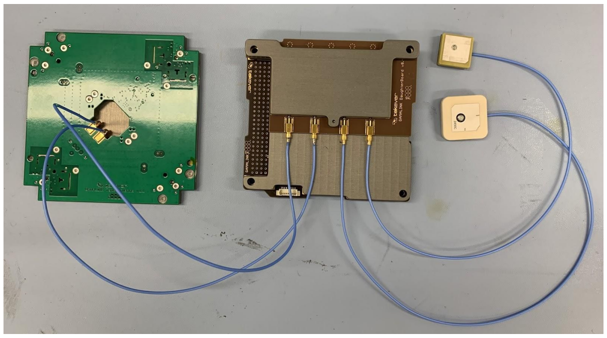


Figure 16: Gamalink SDR (center), UHF/VHF antenna collapsed (left), S-band and GPS (right)

The other communication system on board the Neutron-1 is the GlobalStar radio GSP-1720, a duplex radio system that enables a near continuum stream of data when operating under GlobalStar coverage, shown in Figure 17. Additionally there is a GlobalStar radio STX-3 for simplex messages relaying to the ground very small packets of information (144 bytes every 10 min) which allow ground operators to quickly check the overall status of the spacecraft.

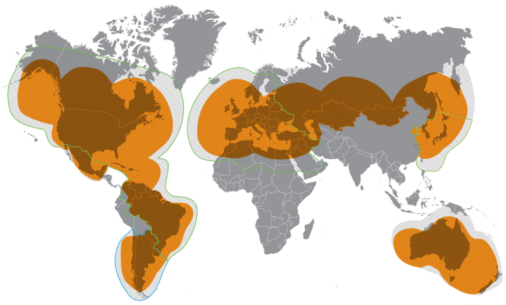


Figure 17. GlobalStar Network coverage for GSP-1720 radio (duplex). Neutron-1 will be controlled in near real time when operating within GlobalStar coverage. (https://www.globalstar.com/en-us/products/coverage-maps)

On-board Computer Subsystem

HSFL has developed the main flight computer for the Neutron-1 mission based on a COTS available ARM processor board as shown in Figure 18. The COTS board model is the Gumstix Overo IronSTORM-Y which was recently successfully flown on the NASA Mars Cube One (MarCO) CubeSats[14]. The computer is based on the Extended temperature Texas Instruments DaVinci DM3730 Applications Processor with a base clock capable of running up to 1GHz. It includes a 512 NAND Flash memory with the option to dual boot. The OBC is able to connect to CubeSat via the CSK connector bus using the standard interfaces. The main features of the HSFL OBC board are the 4 port UART device to enable more devices to be connected via serial. This device allows communications up to 921600 baud. The other main feature is the ETH device to enable Ground Support Equipment (GSE) connectivity and/or node-to-node connectivity for redundant on board computer architectures.

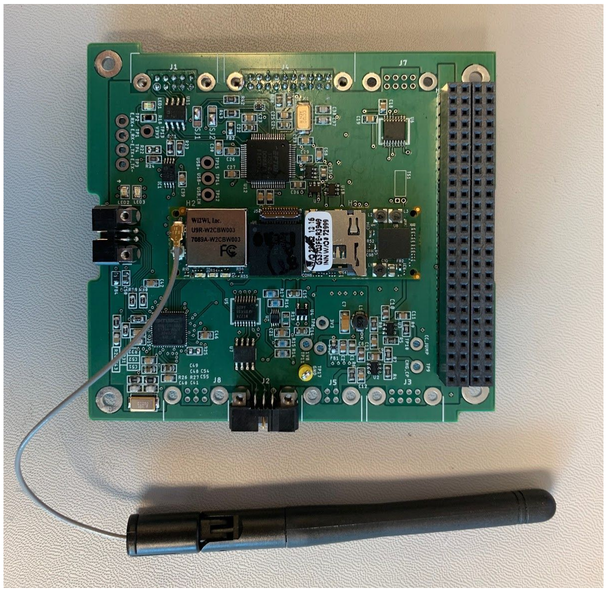


Figure 18. HSFL On Board Computer v3.3 (wifi antenna is not used in flight version)

COSMOS Software

All aspects of software; flight, ground and mission operations are implemented using the HSFL COSMOS Software Framework (http://cosmos-project.org) [15,16,17,18,19,20]. The key operational concepts of this Framework as it relates to the Neutron-1 mission are:

- Reliance on standards: User interfaces are implemented over a web framework. All information is represented in JavaScript Object Notation (JSON), both on disk and over the network. All Command and Control is implemented as Native OS programs (clients and servers). Everything is transferred as either files or network packets. All network communication is performed via IPV4 UDP packets.
- Generalization of complex devices: All devices are simplified to their most general basics and then hidden behind COSMOS "Agents" running as Native OS servers.
- Modularization: Subsystems and/or Devices are broken out as Agents. Specific functionalities are broken out as Requests to an Agent. Every possible Command is accessible from the Native OS command line.
- Reuse of components: A number of Agents are used in every aspect of operations. Other Agents are constructed so as to operate in a common way at the System level, while behaving uniquely at the device level.

The exact implementation of these concepts on Neutron-1 is detailed below, as a simple block diagram, in Figure 19.

Common Agents: These Agents are general purpose in nature and are used in more than one location.

- **Executive Agent (agent_exec)** gathers State of Health (SOH) information from all other Agents, manages a time and SOH driven queue of Native OS commands, and logs both executed commands and SOH.
- **File Transfer Agent (agent_file)** manages the upload and download of files when there is a ground station contact over UDP. This process is modeled after such protocols as the Saratoga File System and CCSDS File Delivery Protocol to be robust over intermittent connections. Files are selectively transferred to and from a set of standard Agent specific directories based on size and priority.
- **Network Tunnel Agent (agent_tunnel)** creates an IP network interface tied either directly to a serial port, or indirectly to a local network socket. Specific hardware Agents can then attach to this Agent to send and receive packet data across various radio interfaces.

Flight Agents:

- **Electrical Power System Agent (agent_eps)** controls power switches and reports power telemetry.
- **Attitude Determination and Control System Agent (agent_adcs)** commands ADCS unit and reports attitude telemetry.
- **Globalstar Agent (agent_globalstar)** manages the transmission and reception of radio packets through the GlobalStar radios.

This is tied to agent_tunnel to simulate an IP connection.

- **Gamalink Radio Agent (agent_gamalink)** manages the transmission and receiving of radio packets through the Gamalink radio. This is tied to agent_tunnel to simulate an IP connection.

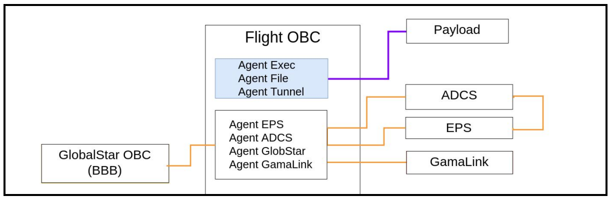


Figure 19: Flight Agents

Ground Station Agents:

- **Antenna Agents (agent_antenna)** control the pointing of antennas and tracking satellite passes.
- **Radio Agent (agent_radio)** controls the tuning and doppler shift of the radio during satellite passes. Depending on the radio model, this will either rely on agent_tnc, or directly connect to agent_tunnel to simulate an IP connection.
- **Terminal Node Controller (agent_tnc)** converts between audio signals and AX.25 packets. This is tied to agent_tunnel to simulate an IP connection.

Mission Operations Agents:

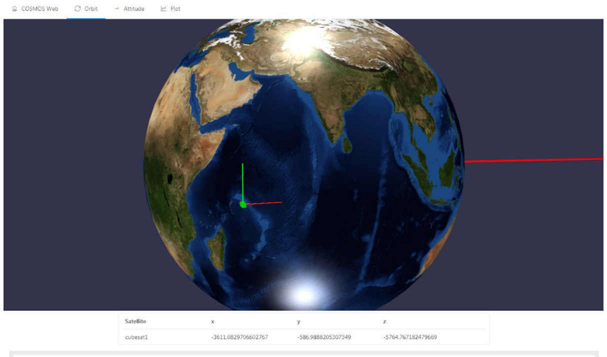
- **Mongo Database Agent (agent_mongodb)** collects telemetry from flight and ground station agents and stores the data in a Mongo Database. This process also services queries from other programs and responds with corresponding database data.
- **NodeJS Services Agent (agent_nodejs)** acts as the interface between Web based services and agent_mongodb.

Operations Testbed Agents: The HSFL satellite test facilities are also operated within COSMOS. This allows for extensive hardware in the loop testing of various mission aspects.

- **Motion Tracking Agent (agent_motion)** interfaces with our OptiTrack IR tracking system to provide real-time attitude information for anything within our attitude control testbed.
- **ACS Testbed Agent (agent_testbed)** interfaces with our Attitude Control System testbed to simulate the magnetic field, GPS satellite configuration and solar input that would be experienced by a satellite in orbit.
- **Additional Support Agents (agent_load, agent_supply, etc.)** interface to other support hardware, allowing us to simulate the power environment consistent with different payloads and solar panel configurations.

Graphical Interfaces:

COSMOSWeb is a NodeJS based web framework developed as a mission operations tool for the flight and ground station agents. The web interface utilizes the COSMOS agents generalized functionality to display real-time telemetry data and launch agent requests. COSMOSWeb is capable of live agent telemetry visualization, as shown in Figure 20, as well as historical data queries from the Mongo Database. The user interface is developed with modularity to be compatible with any COSMOS agent. It is built up from customizable widgets, each with a single function. The modularity and customizability of the interface allows COSMOSWeb to be tailored to a particular mission without the need for redesign of the software.



Satellite	x	y	z
cubesat1	-3611.0829706602767	-586.9888205307349	-5764.767182479669

Figure 20: COSMOSWeb view of a satellite orbit simulation

The COSMOS Mission Operations Support Tool (MOST), shown in Figure 21, was developed initially as a spacecraft control interface using the Qt development environment. We are currently porting this capability to COSMOSWeb for the Neutron-1 mission.

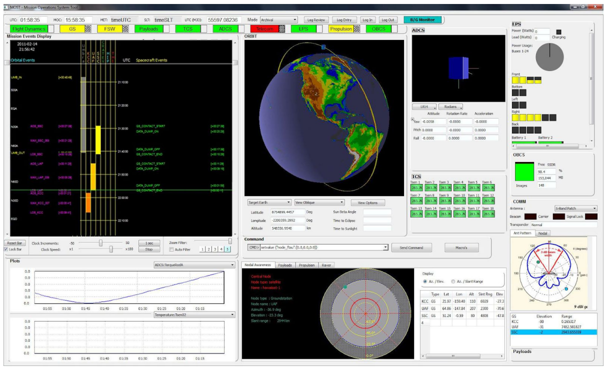


Figure 21: COSMOS Mission Operations Support Tool (MOST)

The COSMOS Executive Operator (CEO), shown in Figure 22, was developed initially as a control interface for multiple assets (spacecraft, ground stations, etc.) using the Qt development environment. Similarly we are porting this capability to COSMOSWeb.

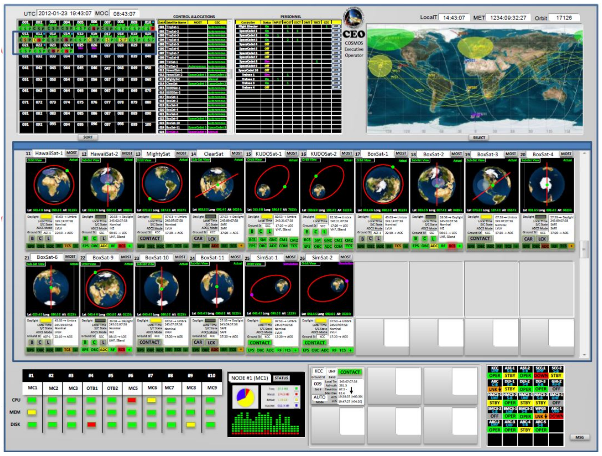


Figure 22: Command Executive Operator (CEO)

SYSTEMS INTEGRATION AND TESTING

Integration

Functional testing and flight integration activities were conducted by HSFL in its labs and cleanroom facilities, all located at the University of Hawaii at Manoa. The HSFL facilities include a machine shop, various development laboratories, a shock/vibration table, and a class 10,000 cleanroom containing a state-of-the-art ADCS testbed and a thermal vacuum chamber.

Random Vibration testing

Random vibration testing was conducted utilizing HSFL's vibration and shock table shown in Figure 23. Random Vibration Testing requirements for Neutron-1 are detailed in the NanoRacks CubeSat Deployer Interface Definition Document[9]. The minimum requirement is to perform one acceptance vibration test, but Neutron-1 was subjected to two vibration tests. The first test was performed under the "hard-mount" configuration and profile at the system level. This preliminary test served as an opportunity to validate the design and functionality of the spacecraft. The second test was performed with NanoRacks personnel as a part of the official delivery process under the "soft-stow" configuration.

Figure 23: Vibration and Shock Table. Tests objects 1.2m x 1.2m. 5-2200 Hz to 7000 kgf; 14000 kgf shock

Thermal Vacuum testing

System level Thermal Vacuum testing is not required for launch by NanoRacks, but is listed in the CSLI LSP requirements document[8]. This environmental test was used to validate design robustness and verify hardware functionality with changing orbital temperatures. The NASA LSP requirements document recommend thermal vacuum testing with varying degrees of rigor, as documented in the CubeSat environments test table[8] (for acceptance a minimum of 2 cycles with a range of -9°C to +66°C and a dwell time of 1 hour at the extremes, and a rate of temperature change of < 5°C/min). We conducted a more rigorous set of tests, closer to the suggestions for protoflight and qualification, by conducting 8 cycles with a range of -15°C to +66°C and a dwell time of 2 hours at the extremes. The temperature rate of change did not exceed 0.5°C/min, based upon thermal analysis and a constraint imposed by the payload. The detector material is susceptible to cracking due to rapid temperature changes. During these tests, the thermal-vac chamber maintained a vacuum of ≤ 1x10-4 Torr., and the spacecraft was exercised under different thermal environments including payload testing and hot/cold power on activities. Finally, thermal vacuum bakeout was performed at 70°C for over 3 hours after thermal stabilization. Thermocouples measured hot components on avionics boards and the copper strapping for heat dumping. These tests were conducted using HSFL’s thermal vacuum chamber, shown in Figure 24, located in the HSFL cleanroom.

Figure 24: Intlvac Thermal Vacuum Chamber. Dimensions 1.6 m I.D. x 2.25 m long, Vacuum spec: 10-8 Torr.

Battery Pack Flight Acceptance Testing for ISS

Additional Flight Acceptance Testing (FAT) on the battery pack was required by NanoRacks in order to launch and deploy from the ISS via the NRCSD[9]. Originally, Neutron-1 was not planned to be deployed from the ISS, so a battery pack pre-qualified for manned flight was not purchased. Once manifested for an ISS launch and deployment, all additional necessary testing was performed at HSFL for the safety review according to NanoRacks FAT requirements (NR-SRD-139 RevC) based on NASA JSC-20793[21]. The testing includes physical and electrochemical characteristics, charge cycling, vibration testing, and vacuum testing. Sample results of the testing are shown in Figures 25, 26, and 27.

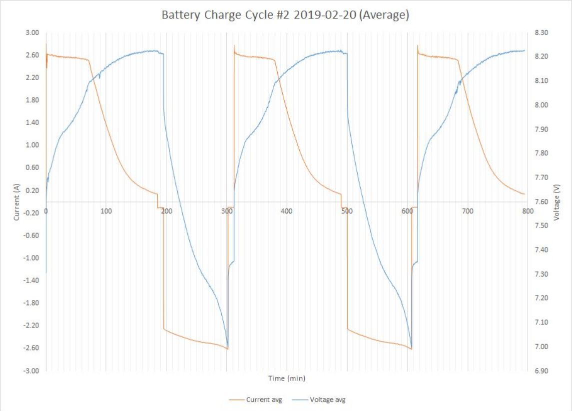
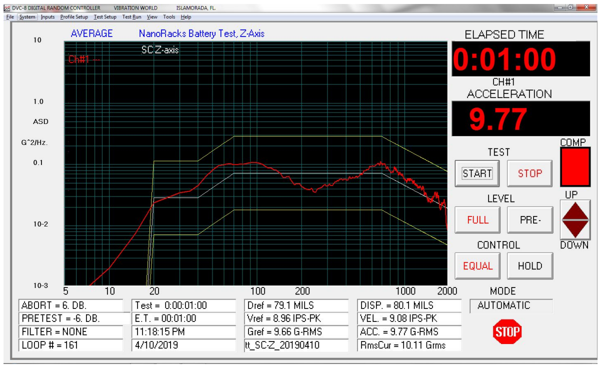


Figure 25: Sample charge cycling test results



ABORT = 6. DB.
PRETEST = -6. DB.
FILTER = NONE
LOOP # = 161
Test = 0:00:01:00
E.T. = 00:01:00
11:18:15 PM
4/10/2019
Dref = 79.1 MILS
Vref = 8.96 IPS-PK
Gref = 9.66 G-RMS
tt_SC-Z_20190410
DISP. = 80.1 MILS
VEL. = 9.08 IPS-PK
ACC. = 9.77 G-RMS
RmsCur = 10.11 Grms

Figure 26: Sample vibration testing results

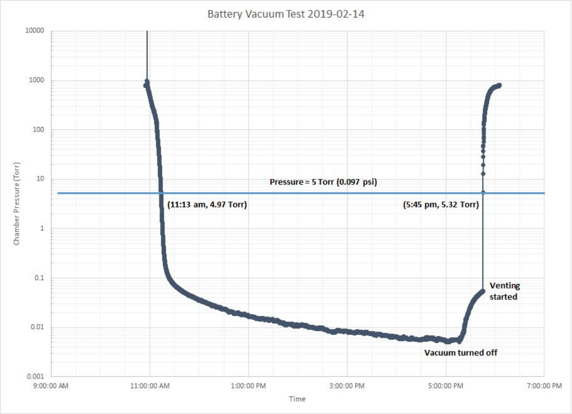


Figure 27: Sample vacuum testing results

ADCS Testing

ADCS testing was conducted using HSFL’s state-of-the-art ADCS testbed, shown in Figure 28. The ADCS tests were conducted to verify functionality of the ADCS sensors and actuators, as well as the combined functionality over a simulated orbit. A sample plot of a nadir pointing test over a full orbit is shown in Figure 29. This shows the ADCS can hold the spacecraft within 5 degrees (without a Star Tracker) meeting the original pointing requirements.

The ADCS components were integrated on a testing assembly and balanced on a hemispherical air bearing, to closely replicate the frictionless environment of space with minimal external torques. The bearing is located inside a helmholtz cage which replicates the expected magnetic field at the simulated orbit to achieve an attitude vector from the magnetometer. A sun simulator stimulates the sun sensors for a second attitude vector. The ADCS was wirelessly commanded, including setting the GPS TLE data, and different maneuvers were tested to verify the expected functionality of the system

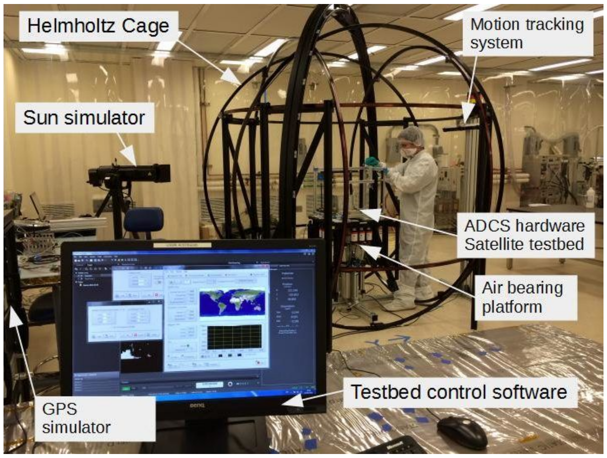


Figure 28. HSFL ADCS Testbed configured for CubeSat testing and satellites up to 100 kg. Includes Magnetic Field Stimulator, Sun Stimulator, GPS simulator.

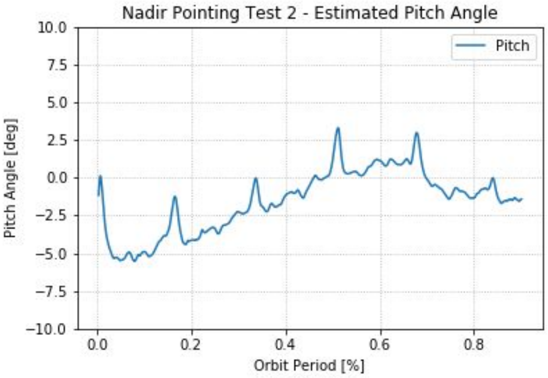


Figure 29: Nadir pointing test example over a full orbit.

GROUND SYSTEMS

HSFL operates and maintains a UHF, VHF, and L/S-Band amateur ground station for satellite operations at the Kauai Community College (KCC). This ground station is integrated with our in-house developed (and open source) COSMOS software to facilitate coordination of equipment, and tracking of satellites. Using COSMOS, this system is capable of complete automation of satellite contacts. The ground station is also manually controllable and assisted with Orbitron. HSFL also partners with the Naval Postgraduate School on the operation of the MC3 ground station at the UH Manoa Campus. The KCC ground station will be used as the primary operations station of the Neutron-1 mission. Figure 30 shows the full ground capabilities at the University of Hawaii.

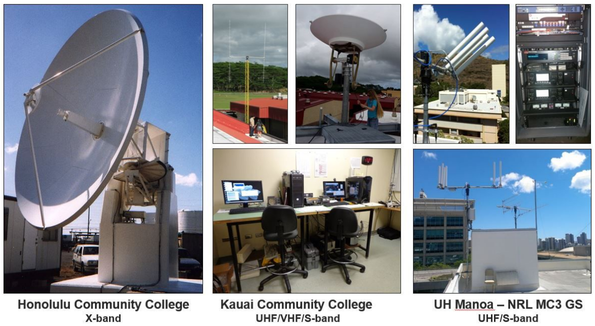


Figure 30: HSFL ground stations. The KCC ground station (center) will be used for Neutron-1 operations.

The KCC ground station uses an ICOM IC-9100 as the main radio for the VHF uplink channel to the Gamalink. This radio is connected to a M2 Antenna 2MCP22 controlled with a Yaesu G-5500 rotor. The ICOM IC-9100 is also the main radio for the downlink channel of the Gamalink. This radio is connected to a M2 Antenna 2MCP22 controlled with a Yaesu G-5500 rotor (this is a similar setup but separate system from the VHF). The radios and antennas are operated via COSMOS running in Linux.

The Gamalink Ground station radio is used for the S-band uplink/downlink channel. This radio is connected to a M2 Antenna AZEL1000 controlled with a M2 Antenna RC2800PRKX2SU rotor. The radio and antenna are operated via the Gamalink ground software and COSMOS running in Linux.

MISSION OPERATIONS

Deployment and commissioning

Separation switches are released upon ejection from the NanoRacks deployer. These switches will allow the spacecraft to power up and boot up. The process takes approximately 60 seconds. The ADCS processes are initialized and if there is sufficient power the detumble maneuver is started, followed by the nadir pointing maneuver. If the battery is in low power mode the ADCS will point the spacecraft to the sun to maximize sun exposure. The spacecraft stays in a low power mode until the batteries are fully charged. Upon full battery charge, the ADCS is re-activated, the mag boom is deployed, and the Duplex radio is powered on to enable spacecraft checkout procedures. The software then runs a series of system checks to verify the health of the avionics system. Heath and housekeeping data is transmitted via the Duplex radio. After 30 min, the spacecraft is far away from the ISS for non-interference, and the Simplex radio beacon is activated to transmit basic health data and status every ~5 min. Basic data includes: mode, battery status, computer status, payload status and temperatures.

Upon satisfactory spacecraft health and automatic functional checkouts, the UHF/VHF antennas are deployed and we can perform a ground station telemetry checkout. Telemetry is sent down to the ground station via UHF radio and commands are sent up to the spacecraft via VHF radio. After data packets are verified, the spacecraft can begin Science Mode operations using the S-band radio.

Nominal Operations

During nominal mode the S-band antenna is nadir-pointing while the two GPS antennas, the star tracker and the Sun tracker are zenith looking. During the science mode the spacecraft is collecting neutrons from 4 different orientations: Velocity direction, Wake direction, Nadir direction and Zenith. The payload will be powered on for 7.5min per orbit during the high latitude portion of the orbit.

CHALLENGES AND LESSONS LEARNED

1. *CSLI launch change.* During the project the launch vehicle changed going from a Polar Orbit to the Antares vehicle for ISS resupply mission. This created some issues with the spacecraft systems and sensor configuration but more critically the requirements for the selected battery. The HSFL team had to qualify the battery according to the NanoRacks standards for the ISS launch. This required extra testing and preparation that was not scheduled.

2. "*Test, Test, Test - EARLY*". CubeSats are well known for having short development timelines, enough time needs to be allocated to integration and testing. Ideally the team should have all the hardware in house at least 6 months prior to delivery. It is well known that hardware requires "Test, Test, Test" before delivery. Questions should be well documented for vendors in order to facilitate more efficient responses. Emails may not be sufficient, so a shared spreadsheet "issue tracker" is useful to record all activities and questions regarding a piece of equipment.

3. *COTS mods*. Many of the components used in CubeSats are Commercial off-the-shelf (COTS) and not necessarily ready for space. These parts need to be modified to fit into the volume (ex. remove connectors), conformal coated to not outgas or allow the components to arc. Critical skills are required in the team to modify off-the-shelf hardware for flight without damaging the part. For example: Removing connectors and soldering harnesses directly to the boards can be time consuming and should be tested on equivalent hardware before modifying the flight hardware - as much as possible.

4. *Start FCC/NOAA licensing ASAP*. This is also a well known concept, but starting the government applications as early as possible benefits the team and all parties involved. Fix your frequencies as soon as possible in coordination with CSLI or another authority in the small satellite industry. Learn about the current state of the regulations, talk to the launch provider (ex. NanoRacks), and apply for the licencing as early as possible. Start the professional personnel contracts as early as possible. Do not miss form submission deadlines.

SUMMARY

The Neutron-1 mission is a technology demonstration mission using a 3U CubeSat developed by the Hawaii Space Flight Laboratory (HSFL) to measure low energy neutron flux in LEO. Data gathered by the neutron detector will contribute to understanding the complex relationship between Earth and Sun through mapping neutron abundances in LEO. This will be evaluated for space weather characterization and radiation safety applications. The CubeSat carries new technologies that are being demonstrated such as the COSMOS flight software and the HSFL OBC. The CubeSat will be launched in the Fall of 2019 with the ELaNa 25 as part of the ISS resupply mission NG-12 and is expected to be deployed into orbit in early 2020.

This HSFL mission has included students from all levels (including high school), senior scientists and engineers in the continuing tradition of providing training to the next generation of space engineers and scientists, and will continue to do so during all phases of operations until decommissioned.

ACKNOWLEDGEMENTS

This mission would not have been possible without the ongoing support and continuing funding of the NASA Hawaii EPSCoR Research Infrastructure Development Program and the Hawaii Space Grant Consortium (http://www.spacegrant.hawaii.edu/). HSFL thanks the Air Force Research Lab for the provision of solar cells.

We want to offer special kudos to the fiscal team at the Hawaii Institute of Geophysics and Planetology (Willam Doi, Marcia Rei Nii, and Sharisse Nakasone) in particular as well as the Research Corporation of the University of Hawaii fiscal team for their outstanding support with rushed replacement parts and complicated orders. They help us to fly!

Various HSFL students and engineers have also given their support to this mission including, Glenn Galvizio, Christianne Izumigawa, Keane Hamamura, Aditya Kumar, Alex Noveloso, Cyrus Noveloso, Donna Noda (RPI), Spencer Young, Kenny Son, Laurence Diarra (USC), and Devan Tormey (USC).

The payload team was critical to the success of this mission by delivering the neutron detector to HSFL. The payload team led by Arizona State University includes members: Teri Crain, Erik Johnson, Graham Stoddard, Igor Lazbin, Michael Fitzgerald, Nathaniel Struebel, Patrick Hailey, among others.

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