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O/OREOS Nanosatellite: A Multi-Payload Technology Demonstration

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ABSTRACT

The Organism/Organic Exposure to Orbital Stresses (O/OREOS) nanosatellite follows in the footsteps of the successful GeneSat-1 and PharmaSat missions to validate key technologies developed to conduct compelling science experiments in space for a small price tag. Developed by the Small Spacecraft Division at NASA Ames Research Center, the 5.5-kg 3U satellite contains two completely independent payloads and a novel drag-enhancing device which shortens the spacecraft's orbital lifetime, thereby mitigating orbital debris. This paper provides an overview of the mission as well as an in-depth discussion of each payload and the de-orbit mechanism (DOM) while highlighting lessons learned from the spacecraft's development.

INTRODUCTION

The O/OREOS nanosatellite is the first technology demonstration spacecraft and flight mission of the NASA Astrobiology Small-Payloads Program (Figure 1). The spacecraft is NASA's first nanosatellite to incorporate two completely independent and interchangeable payloads. Each payload will conduct a distinct demonstration experiment that investigates (i) how microorganisms survive and adapt to the stresses of space (Space Environment Survivability of Living Organisms, SESLO) and (ii) the stability of organic molecules in space (Space Environment Viability of Organics, SEVO). At the time of writing, the spacecraft is scheduled to launch in September of 2010 aboard a US Air Force Minotaur IV rocket from Kodiak, AK as a secondary payload. The high-inclination (72°), 650-km Earth orbit will provide the spacecraft and its payloads with exposure to the inner Van Allen belts, which contain trapped particle radiation, and a higher exposure to galactic cosmic rays relative to the orbital realms of the International Space Station and Space Shuttle due to decreased shielding by the Earth's magnetosphere, as well as the unshielded ultraviolet radiation environment available in spaceflight. Exposing live organisms and complex organic molecules to this environment is of great interest not only to astrobiological research and planetary science, but to planetary protection research as well, since proving whether or not organisms are viable in space for extended periods of time with little protection can affect how payloads are handled and sterilized prior to interplanetary trips.

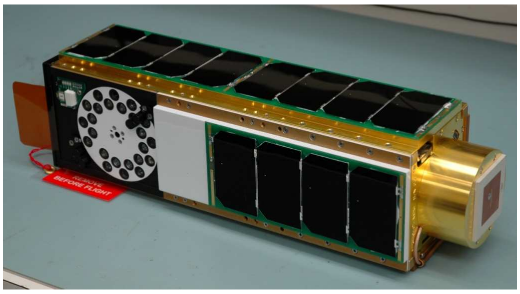

Figure 1: The O/OREOS Nanosatellite

The Mission

The O/OREOS mission represents a number of firsts for the NASA Ames Nanosatellite Missions Office. Building on the successes and lessons learned from the Genesat-1 [1] and PharmaSat [2, 5, 6, 7] missions, this technology demonstration requires that the 3U spacecraft fly at a higher altitude in an inclination that will subject the nanosatellite to a greater radiation dose (approximately 11-15 times that of an ISS orbit), and support a much longer experiment duration than the two previous missions. The total duration of the mission is six months, with extended operations lasting another six. Previous missions developed by this group had primary operations nominally lasting just a few weeks.

The increased mission duration and harsher space radiation environment led to a number of design considerations to reduce risk, including added fault recovery measures, more controllability, and an increase in radiation shielding, attributes that are traditionally difficult to implement in small satellite missions. The higher altitude also means that if left unchecked, the spacecraft's orbital lifetime would exceed NASA and UN orbital debris-minimization guidelines to re-enter Earth's atmosphere within 25 years of mission completion. To address this, the team developed a passive De-Orbit Mechanism (DOM) which roughly doubles the spacecraft's surface area upon deployment and is expected to bring the satellite down within 23 years of orbital deployment.

The experiments flown on the O/OREOS spacecraft generate a significantly larger data volume than its predecessors, which also means a significant change to the mission operations approach. Conducted by students at the Robotic Systems Laboratory of Santa Clara University, the primary operations will be performed using newly installed 3-m dishes at the university. The requirement for consistent data download due to a combination of limited onboard storage space and comparatively high generation rates mean that the operations crew will be required to be on console routinely during the primary operations phase of the mission. Allotting an additional 6 months of ground operations after nominal experiment completion enables the team to comfortably download experimental data during business hours as opposed to operating at all hours of the day and night.

Lastly, this mission must support two completely independent and interchangeable payloads within a 2U volume, allowing for use of a heritage 1U bus (Figure 2). Previous 3U missions flown by NASA have all contained one experiment in this volume; thus, the additional payload necessitated a significant miniaturization effort. Integrating the work of two completely separate science teams onto the same nanosatellite mission also presented new challenges.

Figure 2: O/OREOS Prototype Showing Payloads

SPACECRAFT PAYLOADS

The ability to carry two independent and interchangeable payloads in a 3U volume is the defining characteristic of the O/OREOS technology demonstration. Each payload includes the electronics, microcontroller, and data storage in an autonomous stand-alone package requiring only a standard power-and-data interface. Using a heritage bus that has flown on GeneSat-1 and PharmaSat missions (with an upcoming launch on the NanoSail-D [3] mission), the team's development effort rested primarily with the two payloads.

The SESLO Payload

O/OREOS's SESLO payload (Figure 3) contains two strains of each of two biological species: *Halorubrum chaoviatoris* and *Bacillus subtilis* spores. These specimens are dried and sealed at one atmosphere of internal pressure and laboratory-ambient relative humidity; at multiple times after deployment, organisms are provided with the appropriate temperature and growth medium to initiate and maintain growth. The payload uses time-resolved optical density and absorbance measurements to track growth and metabolism of the organisms. The growth data are stored in memory and downlinked by the operations team.

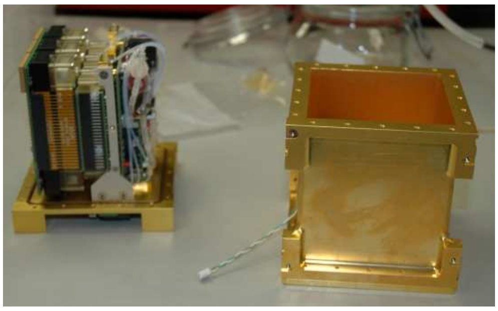

Figure 3: The SESLO Payload

The experiment contains three modules, each of which includes six 75-µL microfluidic wells of each species (Figure 4). The biology is loaded into the modules, air dried to impart a condition of stasis, and rehydrated on orbit with growth media, which cause viable cells to resume growth and reproduction. The modules are rehydrated at three timepoints during the mission to measure to effects of microgravity and cumulative radiation dose. The first module is rehydrated immediately after launch, the second module is rehydrated after three months of exposure, and the final module is activated after six months. Relative to a companion ground control experiment, differences in growth patterns among the three flight modules should be attributable to the different radiation doses.

Each module (Figure 5) contains a combination of reservoirs, microfluidic channels, sensors, and valves that control the flow of growth media to the biological specimens in the microwells. Six temperature sensors and a heater are installed on each module. Pressure and relative humidity are also measured inside the payload container. A diaphragm air pump maintains pressure, via elastomeric membranes, on the fluid reservoirs housed within the biomodules whenever one of the modules is in organism-growth mode. Gas-permeable membranes covering the microwells allow exchange of oxygen and CO_2 with the atmosphere inside the payload container during growth. Embedding fluidic reservoirs within the modules and flying dry biology, with survival of more than eight months demonstrated in ground testing prior to integration and launch, were two major developments for the NASA team. These advances make a more volume-efficient fluidic system, reduce the number of plumbing connections, and enable storage of specimens in stasis for longer durations than "wet stasis."

The growth of the biological specimens is measured via optical absorbance and density, a technique with heritage from the PharmaSat mission. A dedicated tri-color LED illuminates along the axis of each well and a detector at the opposite end of the well reads the intensity for each color in turn. In the case of *B. subtilis*, the redox metabolism indicator dye Alamar Blue provides a blue-to-pink color change as a consequence of cellular metabolism. Microbial growth is quantified in real time for both organisms in three wavelength bands: 470, 525, and 615 nm, for up to 17 days from growth initiation. For *B. subtilis*, the 470-nm band primarily tracks optical density, while the 525-nm band detects increases in the reduced form of Alamar Blue (pink), and the 615-nm band registers decreases in the oxidized form (blue). For *Hrr. chaoviatoris*, all 3 wavelengths track optical density, but there is slightly larger (and quantifiable) absorbance at 470 nm than the

Figure 4: Sample Modules

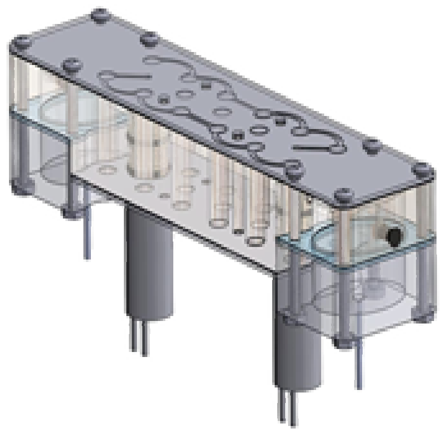

Figure 5: SESLO Biology Module

other 2 wavelengths due to the carotene produced by this halophile, providing growth information complementary to the optical density.

To better expose the biology to space radiation, the aluminum pressure vessel necessary to keep air in the payload was thinned on the side nearest to the samples. This required additional shielding internally for the payload electronics. To adequately shield the detector without blocking transmitted light, a sapphire window (similar radiation attenuation to aluminum metal) was placed between it and the radiation path through the well. Radiation doses are measured with radiation-sensitive field-effect transistors (radFETs); their output will be included with all growth telemetry. Figure 6 shows a cross section of a biological sample well.

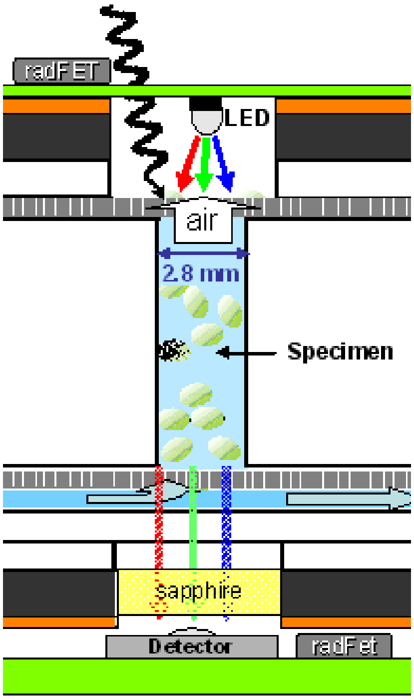

Figure 6: Sample Well Cross Section

The SEVO Payload

The experiment flown on the SEVO payload (Figure 7) will investigate the stability, modification, and degradation of organic molecules in thin-film form—in model environments including interplanetary/ interstellar space, the lunar surface, wet/salty environments, and the Martian atmosphere—by providing four experimental "microenvironments" within miniature reaction cells. Thin films of each of four astrobiologically significant organic molecules are housed in the four different microenvironments and the chemical consequences of their exposure to solar UV, visible light, and space ionizing radiation will be monitored periodically by UV-visible spectroscopy over the 6-month mission time span.

The payload includes a highly capable UV-visible-NIR spectrometer, a 24-sample carousel, and integral optics enabling use of the Sun as light source for spectroscopy. The spectrometer was designed and built by Aurora Design and Technology and shares heritage from the NASA missions LCROSS and LADEE. The thermally stable instrument provides 1–2 nm spectral resolution, < 0.1 nm spectral band-shift-measurement capability, 0.03 absorbance-unit resolution, and covers the 200 – 1000 nm wavelength range. The CCD acquires a single spectrum in 100 ms or less; multiple spectral acquisitions (e.g., 16 full spectra acquired in 1.6 s) can be averaged to improve signal-to-noise ratios.

Figure 7: The SEVO Payload

To use the Sun as the light source for UV-visible spectroscopy, a pair of baffled diffuser assemblies is included to ensure that the organic sample film under interrogation by the spectrometer is uniformly illuminated over a 3-mm diameter spot with light intensity that varies by no more than ±25% for sun angles between –35° and +35° from normal. Integral solar intensity sensors provide synchronous light intensity measurements with each spectral acquisition.

The hermetically sealed reaction cells (Figure 8) are similar to those used for the EXPOSE experiment currently in orbit on the ISS [4], with the important difference that the SEVO cells use room-temperature indium cold-weld sealing of the optical windows following organic film deposition on windows. Each of the four organic materials is vacuum sublimed onto several MgF_2 windows, which allow UV-visible irradiation of the samples at wavelengths as short as 124 nm; some of the windows have either SiO_2 or Al_2O_3 thin coating layers between the organic and the MgF_2 to tune the optical bandpass and/or provide a chemically relevant substrate pertinent to the defined microenvironment. A sapphire window (with high optical transparency across the spectrometer's 200 – 1000 nm range) is used on the far side, where light enters the collection optic and is routed via optical fiber to the spectrometer. Both windows are cold welded to a stainless-steel spacer, using indium gasket seals, inside a glovebox, thus creating a hermetically sealed microenvironment with the desired simulated atmosphere. The sealed cells are then assembled in 11-mm diameter housings and installed into the rotatable payload carousel. The housing and carousel protect the fragile windows from damage in the launch environment.

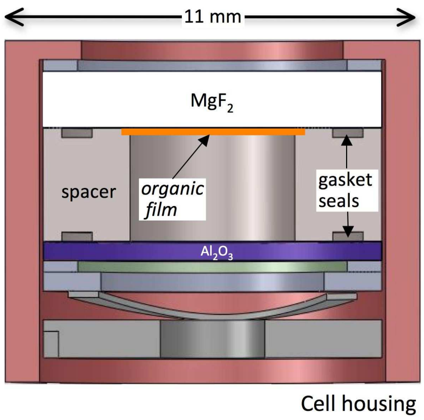

Figure 8: Reaction Cell Cross Section

To maximize the number of cells in the carousel, the samples were staggered and divided into two concentric rings. Two optical fibers are located under the carousel; however, only one fiber at a time is illuminated owing to the cell spacing. The fiber outputs are combined for input to the spectrometer.

When in orbit, the magnetically-stabilized satellite is expected to rotate about its long axis at a rate of 1-2 RPM. Given the absence of active attitude control, SEVO requires that baffled solar intensity sensors be located on the front of the payload to provide simple sun-pointing information. As the exposed face of the SEVO instrument rotates through an angle at which an adequate level of solar intensity for measuring a UV-visible spectrum is detected (Figure 9), the spectrometer is turned on and returns 16 averaged spectra for the current cell collected near the peak intensity for that rotation of the satellite.

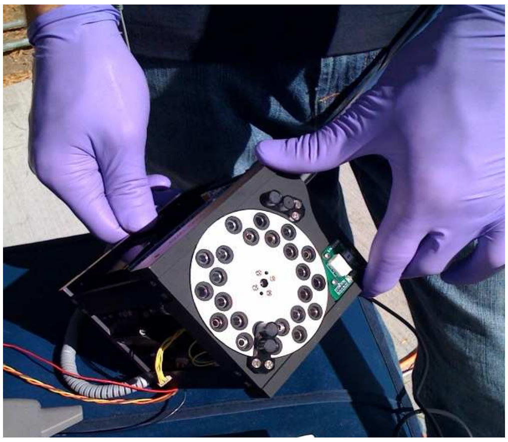

Figure 9: SEVO Undergoing Solar Intensity Testing

Acquiring 16 consecutive spectra during peak solar intensity and averaging them provides a comparatively high signal-to-noise ratio. A combination of adequate baffling and high acquisition thresholds mitigate false positives from Earth/Moon shine.

The De-Orbit Mechanism (DOM)

The ever-increasing number of man-made objects in low Earth orbit (LEO) has made tracking them more difficult, and has even led to a satellite collision. As the barrier of delivering multiple small satellites to orbit is driven ever lower, the space debris problem will only worsen unless defunct hardware is efficiently disposed. NASA STD-8719.14 states that spacecraft in LEO must de-orbit within 30 years after launch or 25 years after the end of the mission. Since small satellites typically do not carry large quantities of propellant, their lifetimes in orbit are largely passively determined. Carrying large drag chutes or sails is also difficult because of the limited space available on the spacecraft. For most high altitude missions, therefore, the hardware can easily remain in orbit for more than 30 years before burning up in the atmosphere.

The O/OREOS mission would fall in this category without a DOM, and early in the planning process the team found that increasing the spacecraft's surface area by 60% would shorten the orbital lifetime from 60 to approximately 22 years. Surplus space inside the PPOD (the poly-picosat orbital deployer, which will deploy the O/OREOS nanosatellite in LEO) was nonexistent given the two 2 U's of dedicated payload space and 1 U allocated for the bus; therefore, any external attachments to the satellite of significant size would have required a modification of the PPOD. By modifying the backplate of the PPOD, space for an extra 1 cm of spacecraft length was provided, sufficient to attach a passively deployed device to the front of the spacecraft without sacrificing valuable payload volume.

The final design of the DOM was a lightweight, fully enclosed assembly that does not affect spacecraft pointing or solar panel operation. Less than 7.6 mm thick before deployment, the DOM will extend to 28 cm as the PPOD door is opened and the satellite is released to orbit (Figure 10).

Figure 10: O/OREOS with Deployed DOM

The DOM is built using two aluminum plates with a coiled spring attached between them. Four germanium-coated kapton sheets make up the outer walls of the device. These sheets along with the spring fold into a small form factor, and are fully enclosed by the aluminum plates. Figure 11 shows both configurations of the DOM.

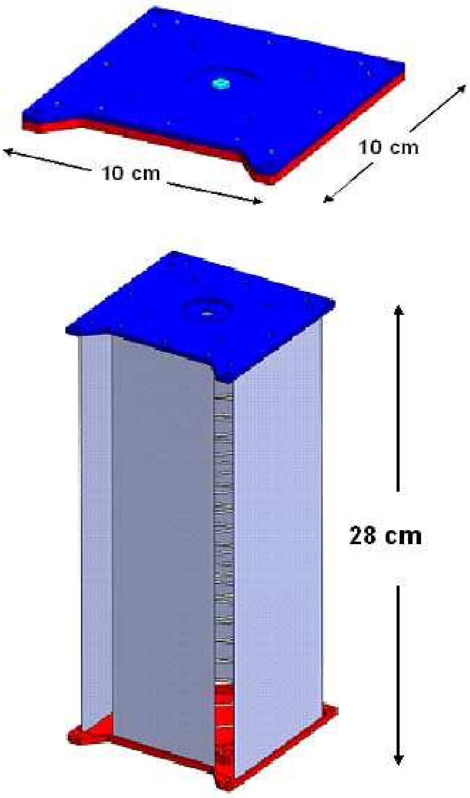

Figure 11: The O/OREOS DOM

MISSION OPERATIONS

The O/OREOS mission operations subsystem consists of the distributed Ground Segment facilities, components, and functionalities that have been designed and selected for meeting the needs of the GeneSat-1 O/OREOS PharmaSat mission. Significant portions of this system are currently in use to support on-orbit mission operations for the GeneSat-1 and PharmaSat satellites. The O/OREOS spacecraft has communications parameters, command and data handling characteristics, and operational strategies that are very similar to GeneSat-1 and PharmaSat; this results in high re-use of fully-verified and mission-proven systems, thus promoting confidence in the capabilities of the system.

The system consists of human operators at a Control Node from/to which commands and telemetry are relayed to the PharmaSat spacecraft via a remote Communication Station. The Control Node and Communication Station are connected via a secure, public internet connection which includes both wired and wireless links. Figure 12 provides an overview of ground segment facilities and connectivity. For contact operations, human operators at one or more Control Node locations connect to the mission database and to the appropriate communication stations via a secure internet connection. Commands are selected at operator workstations at the Control Node(s), with the equivalent validated command bit pulled from the mission database. When commands are sent, they travel from the Control Node to the operational communication station via secure internet, are converted to S-Band radio commands, and broadcast to the spacecraft by the communication station antennae. Satellite telemetry travels in a similar manner in the reverse direction.

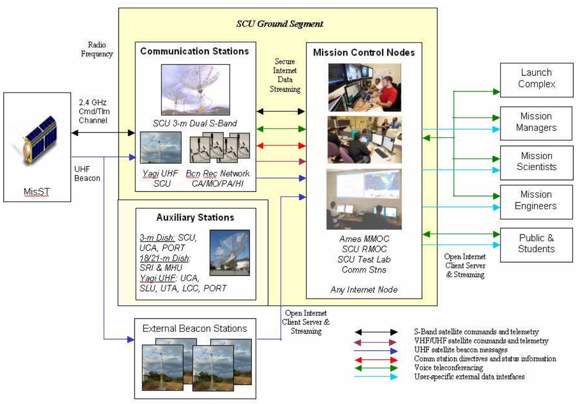

Figure 12: O/OREOS Ground Segment Overview

The satellite also broadcasts a simple, periodic UHF beacon signal, which is received by UHF stations within the ground segment as well as by public operators. Beacon messages received by external users (in the educational and ham radio community) may be forwarded to the Mission Operations team via a public web page; messages are archived and available for public perusal, and an automated QSL card is returned to the external user submitting the packets as per tradition in the amateur radio community.

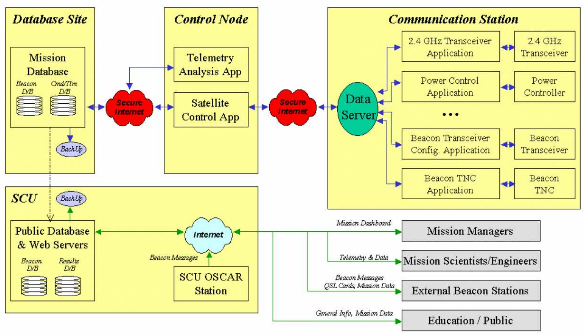

Figure 13: Distributed Software Architecture

Figure 13 depicts the notional command and data handling architecture across the Ground Segment. Using a channel subscription model, a streaming data server allows distributed software applications to be easily interfaced. Contact operations software at the Control Node connects to communication station equipment control applications as well as the mission database in order to allow an operator to remotely configure the communication station, select pre-approved spacecraft commands, transmit commands to the satellite, receive satellite telemetry that is subsequently archived in the mission database, etc. This contact operations software infrastructure is distinct from the servers and software that support data dissemination with managers, scientists, engineers, and the public.

Control Nodes

Control Nodes are located in the NASA/ARC MMOC, the CREST operations center in the NASA Research Park, the SCU Satellite Operations Lab on the SCU campus, and within all communication stations configured for use. Additional Control Node locations may be easily added to the network. The underlying technical design makes this very simple to do; however, limits are placed on doing this in practice for security and configuration control reasons.

A variety of functional processing is performed by the mission operations team in order to support the O/OREOS mission. Functions include command planning and formatting, telemetry processing and analysis, data archiving, orbit analysis, health analysis and anomaly management, and mission planning. Figure 14 shows student operators at the SCU Control Node.

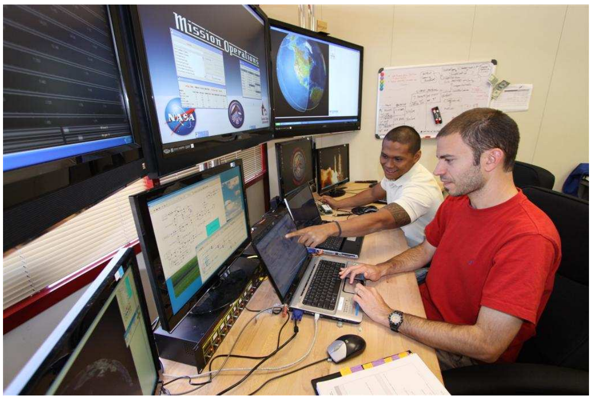

Figure 14: SCU Mission Control Node

Communication Stations

The command and data handling architecture of the mission operations system allows for the operation of numerous communication stations in support of the O/OREOS mission. The primary stations will include SCU Dual S-Band station and the SCU UHF Yagi station, both located on the SCU campus (Figure 15).

Figure 15: SCU Communication Antennae

The S-Band stations are used for conducting standard command and telemetry operations for the O/OREOS spacecraft. Both of the S-Band stations consist of a 603-meter-foot parabolic antenna driven by a programmed track antenna pointing system. The antennae have a 35 dB gain, a beamwidth of 2.9 degrees, and an azimuth speed of 6 degrees/sec. A left hand circular polarization feed is used. For licensing purposes, the antenna is only active at elevations above 10 degrees. A Microhard MHX-2420 transceiver, identical to the O/OREOS transceiver, is used for command transmission and data reception. The ground transceiver operates at 1 watt of RF power and is set in Master Mode thereby causing it to send synchronization data to the spacecraft transceiver.

The UHF/VHF station is used to verify operation of the amateur radio beacon; the beacon has been included on O/OREOS to support participatory mission operations as part of the program's education and outreach efforts. The UHF/VHF station is an OSCAR-class station typical of those used by amateur radio operators. It consists of dual-Yagi antenna driven by a programmed track antenna pointing system. Additional equipment includes transceivers, a terminal node controller (packet modem), and data processing components/workstations for the command/telemetry channel.

Automated Beacon Receiving System

SCU operates an automated beacon monitoring system that extends SCU's access to beacon messages as part of its education and outreach program and which provides automated anomaly detection and notification services [8]. The architecture of this system is shown in Figure 16.

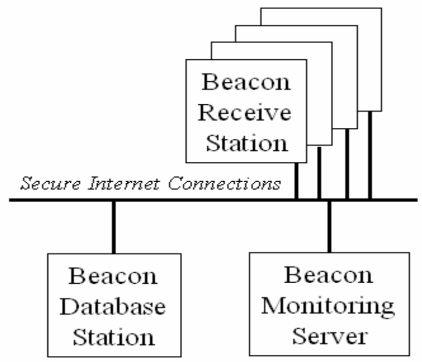

Figure 16: Beacon Monitoring Architecture

Several receive-only beacon stations exist across the United States, currently located in Pennsylvania, Missouri, California and Hawaii. Receive equipment (an omni antenna, a UHF transceiver, a terminal node controller, and a data computer) receive beacon messages (at high elevations due to low signal strength) during satellite overflights. The messages are forwarded via the internet to a central server at SCU, which archives the messages for public access. As part of a student research effort, anomaly detection software filters messages (or the lack thereof) and is capable of automatically notifying on-call operators in the event of an anomaly.

Given station locations and the expected O/OREOS orbit, it is expected that several beacon packets will be received by each station on a daily basis.

CONCLUSION

The O/OREOS mission demonstrates that small satellites can play a key role in astrobiology and astrochemistry programs in the space environment. The demonstration that single-cube stand-alone payloads can produce valuable scientific return paves the way for the technology developed in this mission to be applied to a piggyback mission to the lunar or Martian surface. For example, systems like the compact UV-visible spectrometer or the independent biology growth-and-analysis modules with long shelf lives can be readily adapted for missions beyond Earth orbit.

The growing problem of space debris is particularly relevant to the small satellite community, which is seeking ways to reduce the cost and increase the frequency of launches to orbit. One such mitigation is demonstrated in the O/OREOS mission by use of a passively deployed mechanism that increases the surface area of the satellite by 60% and reduces orbital lifetime by about 60%. Given that the mechanism fits the 1U form factor and is only 1 cm thick, the NASA team is optimistic that variants of this device will be employed in future small satellite missions.

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