

Initial On-Orbit Engineering Results from the O/OREOS Nanosatellite

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ABSTRACT

The Organism/Organics Exposure to Orbital Stresses (O/OREOS) nanosatellite mission successfully launched on November 19, 2010 from Kodiak, AK aboard a Minotaur IV launch vehicle. The principal goals for this 5.5 kg spacecraft include conducting astrobiologically-relevant experiments in two separate payloads within the 3U cubesat form factor and demonstrating *in-situ* measurement technology in a small satellite. Developed by the Small Spacecraft Payloads and Technology Team at NASA Ames Research Center, O/OREOS builds upon heritage gained from its two predecessors, GeneSat-1 and PharmaSat. Mission operations are conducted by students at Santa Clara University using several 3-meter S-Band antennas and supporting stations, an OSCAR-class dual-Yagi UHF station, and an automated network of receive-only UHF stations located throughout the United States. This paper presents an overview of the O/OREOS mission objectives, a description of the system design, and initial results for the on-orbit performance of the spacecraft and its ground segment.

INTRODUCTION

The O/OREOS nanosatellite (Figure 1) is the first technology demonstration spacecraft and flight mission of the NASA Astrobiology Small Payloads Program. The spacecraft is NASA's first 3U nanosatellite to incorporate two completely independent and interchangeable payloads. These two payloads contain experiments which assess the viability of microorganisms in the space environment (Space Environment Survivability of Living Organisms, SESLO) and the stability of organic molecules in space (Space Environment Viability of Organics, SEVO) [1].

The spacecraft was successfully inserted into a high-inclination (72°), 650-km Earth orbit, which provides decreased shielding by the magnetosphere leading to increased exposure to trapped charged particles in the inner Van Allen belts when compared to the orbital environments of the International Space Station (ISS) and Space Shuttle. In addition, the spacecraft is immersed in solar ultraviolet radiation and galactic cosmic rays. Exposing live microorganisms and complex organic molecules to this environment is of

particular interest not only to researchers in the fields of astrobiology and planetary science, but to those involved in planetary protection as well. Proving whether or not organisms are viable in the space environment for extended periods of time can affect how payloads are sterilized and handled prior to interplanetary trips.

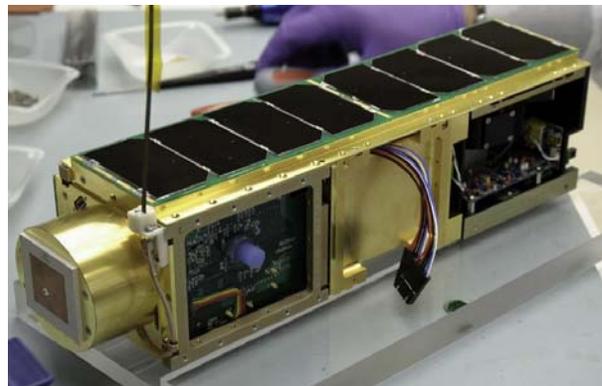


Figure 1: O/OREOS with Solar Panel Removed Showing Payloads and Bus

THE O/OREOS SPACECRAFT

Building on the successes and lessons learned from the GeneSat-1 [2] and PharmaSat [3, 4] missions, the O/OREOS technology demonstration provided a number of firsts for the NASA Ames Small Spacecraft Payloads and Technology (SSPT) Team. This is the first time the group has developed a spacecraft whose baseline payload systems' operational lifetime was six months. Previous missions only required a few weeks to carry out their biology experiments; therefore it was particularly necessary for the O/OREOS team to improve fault tolerance, manage larger data volumes, and increase radiation testing and shielding. The higher altitude also meant that, if left unchecked, the satellite's lifetime in orbit would greatly exceed the NASA and UN orbital-debris minimization guidelines to re-enter Earth's atmosphere within 25 years of mission completion. The addition of a passively deployed deorbit mechanism, which roughly doubled the surface area of the spacecraft, reduced the projected orbital lifetime of the spacecraft from over 60 years to fewer than 25.

To shorten the development life cycle, the bus that had been successfully used on GeneSat-1 and PharmaSat was adapted to accommodate two independent payloads. Occupying only 1U (a unit of 10 cm³ commonly used in describing cubesats), this heritage bus allowed the team to focus its efforts and budget on development of the two payloads that filled the remaining 2U volume. Each payload includes its own electronics, microcontroller, and data storage to autonomously execute its respective experiment, requiring only a standard power and data interface to the bus. This payload architecture is particularly useful for future applications outside of the nanosatellite free-flyer domain, where experiments can be integrated onto other spacecraft, landers, or the ISS.

The heritage bus employed a PIC-based microcontroller that communicated with payload microcontrollers via an I²C data protocol. Primary command and telemetry communications with the ground was supported through the use of a Microhard MHX-2420 transceiver, and an amateur radio beacon transmitter was used to support outreach and educational activities through the periodic broadcast of selected bus telemetry. Antennae were mounted to the ends of the spacecraft body, which was made from machined aluminum. Body-mounted solar cells and lithium ion batteries were used for power generation and storage. Passive attitude control was achieved through a combination of magnets and hysteresis rods, and a passive thermal design was employed for bus components (active thermal control was used for the payloads).

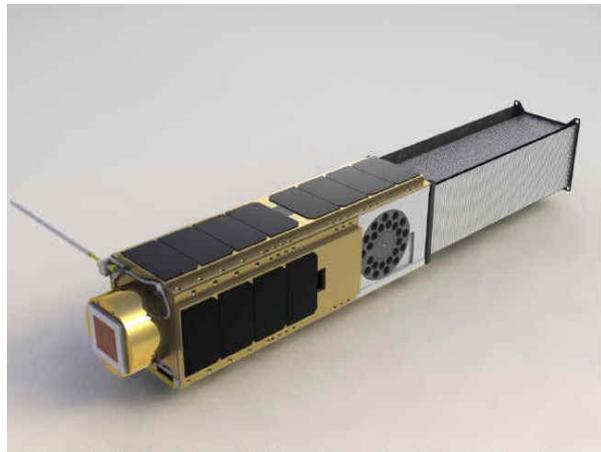


Figure 2: The O/OREOS spacecraft with the deorbit mechanism deployed

The SESLO and SEVO payloads were developed to assess the viability of microorganisms in the space environment and the stability of organic molecules in space. The design of these payloads is reviewed in [1, 6, 16], and scientific findings are pending publication in [5, 7].

Of particular interest to the small satellite community is the design of the deorbit mechanism. Shown in Figure 2, the deorbit mechanism aboard O/OREOS is a first-of-its-kind passive aerodynamic drag device which changes the satellite's ballistic coefficient, causing it to reenter Earth's atmosphere sooner than it otherwise would in order to reduce space debris hazards. The mechanism was developed to comply with NASA-STD 8719.14, a standard that requires all earth-orbiting NASA spacecraft to reenter the atmosphere (or otherwise leave orbit) within 25 years of the end of their mission or 30 years from launch, whichever comes first. Normally, drag from the outer edges of Earth's atmosphere causes low-Earth-orbiting satellites to reenter and burn up naturally within the specified time of the NASA standard, but because of O/OREOS' high orbit, density, and cross section, its natural decay time would exceed the requirement by decades. It was determined that by increasing the satellites surface area by 60%, O/OREOS' orbital lifetime could be reduced from over 60 years to fewer than 25.

Larger spacecraft that require supplemental influence to deorbit in a timely manner traditionally use a propulsion system to leave their orbit at the end of a mission. Small spacecraft such as O/OREOS generally cannot afford the mass, volume, risk, and cost of such a system, so a more simple passive mechanism must be used. The O/OREOS deorbit mechanism consists of

two square aluminum plates mounted on the end of the spacecraft which (when held apart by a spring) support four rectangular sheets of Kapton film. The deployed mechanism takes on a square prism shape that extends along the length of the satellite. Before deployment, the two aluminum plates are held together by the P-POD door, and the sheets are folded inside cavities within one of the plates. An hourglass-shaped spring pushes the two plates apart when the P-POD door opens. In its stowed position, the deorbit mechanism is only 0.3” thick, but after deployment it is nearly a foot long. Once the P-POD door opens, the outer plate is free to be pushed away by the spring, and the deorbit mechanism is deployed instantly.

After launch, the deorbit mechanism’s effects on the tumble of O/OREOS were observed. For ridged bodies, rotation in free space can take place around either the body’s minor or major moment of inertia, however when energy dissipation takes place (i.e. from a non-ridged deorbit mechanism) rotation on the object’s minor moment of inertia becomes unstable. Accordingly, it was noticed that O/OREOS did not maintain a stable rotation on its minor moment of inertia as GeneSat-1 and PharmaSat did, but often nutated close to its major moment of inertia.

THE MISSION OPERATIONS SYSTEM

Mission operations for O/OREOS were conducted using an internet-based, geographically-distributed command and control network that is owned and operated by Santa Clara University (SCU) and which has been used over the past decade to support numerous satellite and robotic missions [8]. The ground segment architecture, depicted in Figure 3, includes a centralized mission control center on the Santa Clara campus in northern California, shown in Figure 4, with back-up control nodes at NASA Ames Research Center. During command and telemetry operations, the operational control node is connected via a secure internet link to one of the available S-Band stations, which use a 3-meter diameter parabolic dish and a radio compatible with the on-board spacecraft transceiver. The two S-Band stations on the Santa Clara campus shown in Figure 5 were the primary stations for the missions, with back-up stations in El Salvador and in the form of a portable equipment suite that could be geographically deployed as necessary. Beacon telemetry operations were supported through OSCAR-class amateur radio stations as well as through a network of automated receive stations located in California, Missouri, and Pennsylvania. It is worth noting that all ground segment designs and mission operation protocols conform to NASA space flight, configuration control, and security requirements.

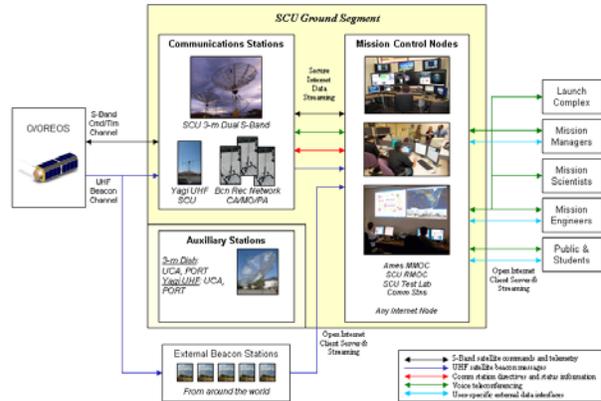


Figure 3: O/OREOS Mission Operations Architecture consisting of internet-based mission control nodes and communication stations.



Figure 4: The Primary Mission Control Node at SCU, supporting contact operations, ground segment configuration control, contact planning tasks, and health operations.



Figure 5: Two S-Band Communication Stations installed at SCU, using 3-meter parabolic dishes. A dual-Yagi amateur radio station, used for high-gain beacon reception operations is seen in the background.

The mission operations team consists primarily of SCU students. A core team of students manage experimental and health operations as well as ground segment operations and maintenance. A broader group of graduate and undergraduate students supplement this core team by assisting with contact operations. All student operators go through a formal training program in ground segment engineering and mission operations as part of a routinely offered SCU engineering class; they are then formally certified to be a member of the operations team, often receiving additional on-the-job-training in order to support more complex activities.

Human-in-the-loop contact operations are often used given the educational integration of students into the program. However, the mission control system has been engineered to support routine, automated data download contacts. In general, this is done by scheduling the download of a predefined set of data for passes, which have a maximum elevation above a specified threshold, and which occur over an arbitrary length of time. This capability was originally verified during a number of supervised passes and has been successfully used to download a significant amount of data during the mission. Subsequent experiments have proven that the system is capable of routine lights-out operation. Scheduling automated passes does not completely remove the necessity for human operators, as the software does not react to anomalies or perform verifications needed during sensitive commanding; however, it will be invaluable in future missions as it enables the productive use of routine passes that would not be run due to operator unavailability.

PRELIMINARY ON-ORBIT RESULTS

Shortly after launch and orbital insertion, the spacecraft activated its primary S-band radio and an amateur frequency beacon that broadcasts basic health and status telemetry. In the first week on orbit, Keplerian elements were still being refined, leading to an inconsistent position estimate and consequently poor S-band radio linking (this performance is typical for such cubesat missions and was anticipated by mission management). Given the lack of directionality and wider beam-width of the amateur beacon, its signal was successfully received by ham radio operators around the world within a day of launch. The SCU mission operations team made available a website (www.ooreos.org) where "hams" could submit packets that were successfully decoded. Mission management team members were able to access these data.

The 72° orbital inclination provides mission operators in California 1- 2 passes per day where science as well as detailed health-and-status data can be downloaded

and commands can be uplinked. Unless there exists a particular need, after the first few weeks mission operations are typically limited to business hours to reduce costs and avoid staffing burnout. Though the mission lifetime is six months, extended operations are expected to last up to another two months beyond end-of-mission to complete the data download. At the completion of the full mission and any NASA-authorized mission extension, the spacecraft will be handed over to SCU where it will be used as a laboratory asset for space systems engineering and satellite operations classes.

From an engineering perspective, there are several specific aspects of the system where on-orbit performance is of general interest to the small spacecraft community. Here, we review the preliminary results for several of these: radiation profile, thermal control given the power-limited vehicle design, S-Band link performance, and the use of the automated beacon monitoring system for anomaly detection.

Radiation Profile

Each of the two payloads contains two radFET sensors that change their threshold voltages based on accumulated radiation dose. The high-inclination orbit takes O/OREOS through comparatively weak regions of the magnetosphere and the inner Van Allen belt, where it is exposed to higher levels of trapped particle (electrons, protons) radiation and galactic cosmic radiation (GCR) than a similar orbit of lower inclination. Before launch, it was estimated that the dose could be as high as 14 Gy/day on the spacecraft's outer surface including approximately 0.5 mGy/day of GCR, which is some 15 times higher than the GCR dose just outside the ISS.¹ Figure 6 shows the radiation measured by a radFET located on the exterior of the SEVO payload after approximately 200 days of operation in orbit. The total measured dose on one face of the spacecraft shows nearly 12 Gy of total exposure after 6 months (183 days) in orbit, which is about 50% less than originally predicted. The team's preliminary estimate was approximately 25 Gy based on shielding and geometric factors. The sensor located within the SEVO payload shows about 1.5 Gy of total dose at 6 months; our calculations indicate this dose would be expected if the equivalent of 6.5 mm of aluminum were interposed between outer space and this radFET. The

¹ Radiation dose calculations were made using the SPENVIS, ESA's Space Environment Information System. SPENVIS is a web interface to models of the space environment and its effects, including the natural radiation belts, solar energetic particles, cosmic rays, plasmas, gases, and "micro-particles" (see <http://www.spervis.oma.be/>).

payload contains an equivalent of about 5 mm shielding so this result is fairly consistent. Though both sensors produced reasonable values, the overall dosage was lower than originally predicted.

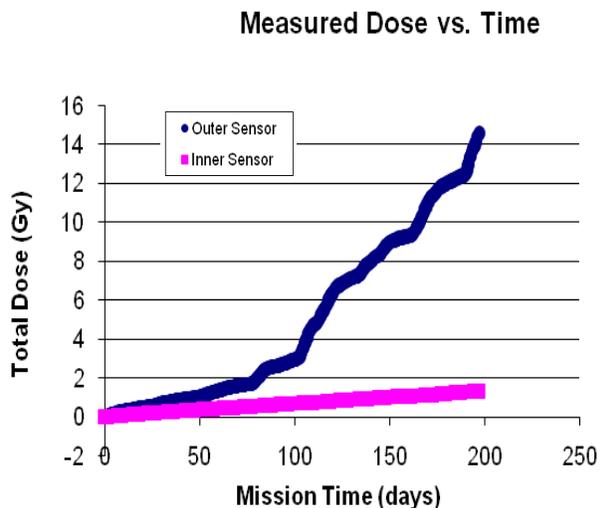


Figure 6: RadFET Sensor Data. Accumulated radiation dose as a function of time. The “Outer Sensor” is not shielded at all on one side, and the “Inner Sensor” is shielded by the equivalent of ~ 5 mm of aluminum.

Externally, the lower dose can be explained at least in part by shielding that the spacecraft effectively provides for the sensor, as it was exposed on only one side and the calculation assumed hemispherical (2π steradian) exposure. Using the radFET-measured dose and the SPENVIS calculations to establish a most probable range of dose, the organic compounds received a total dose of 6 - 30 Gy over 6 months after accounting for the 1.5-mm-thick MgF2 window behind which each film resides.

The extended mission lifetime and advanced onboard instrumentation provided a number of unique challenges for the SSPT Team at NASA ARC. The increased radiation dose relative to previous missions meant that the satellite electronics needed additional shielding and enhanced fault tolerance to possible single-event upsets (SEUs). The spacecraft’s electronics boards (from the bus and both payloads) underwent radiation testing at NASA ARC up to an accumulated dose of 50 Gy of gamma radiation. Additional aluminum shielding was added in strategic locations to help reduce the total dose received by the electronics, along with the sapphire windows mentioned above. After six months, some radiation effects have already been visible. The CCD detector in the SEVO spectrometer exhibited significant number of

“hot” pixels (pixels for which the dark level abruptly becomes much higher than most of the other pixels; this affected as much as 10% of the 2436 total pixels). These pixels are easy to identify and account for and so have not materially affected the quality of the data gathered. Approximately six weeks into the mission, the spacecraft apparently suffered an SEU, resulting in temporary interruption of communications. After the lack of activity exceeded an onboard watchdog timer limit, the command and data handling system was automatically reset as designed and communications resumed. This was NASA ARC’s first demonstrated apparent SEU recovery in a nanosatellite.

Payload Thermal Control

Given finite power resources, active thermal control onboard the spacecraft was limited to the SESLO payload, whose fluidic system must be kept above freezing levels. Additionally, SESLO’s biology experiments require precise thermal control during the germination and growth phase, which lasts approximately 24 hours per module for the *B. subtilis* organism. The only other significant source of heat within the spacecraft is the MHX-2420 radio (Microhard, Inc.), which is operated on a duty-cycle scheme to limit power consumption and avoid overheating in the spacecraft bus. Figure 7 shows the thermal profile of the SESLO payload’s three biological modules shortly before and during the first experimental phase when microorganisms were given growth media, incubated, and measured using time-based colorimetry. The programmed growth temperature was 37 °C for Module 1, the only actively controlled module for this first growth time point. The three thermal profiles show heating of Modules 2 and 3, which occur primarily by conduction from Module 1, since the 3 modules reside in close proximity (see Figure 2).

The SEVO payload was designed to acquire a solar spectrum automatically when onboard sensing determined that its sample wheel and collection optics were pointed at the sun (within a few degrees off-normal). Though the spacecraft’s attitude is not actively controlled, each 98-min orbit has between 50 and 98 min of sun exposure, presenting several such opportunities for sampling given a passive rotation rate of about 1 RPM about the satellite’s long axis. The integration time of the payload’s CCD detector is fixed unless altered by ground command, which means that the overall intensity of the acquired spectrum is directly proportional to the angular velocity of the spacecraft over a particular angular range. More rapid rotation therefore offers the collection optics and detector less time to integrate photon exposure, resulting in a lower

average signal-minus-dark value. Conversely, a slower rotation rate provides more integrated intensity.

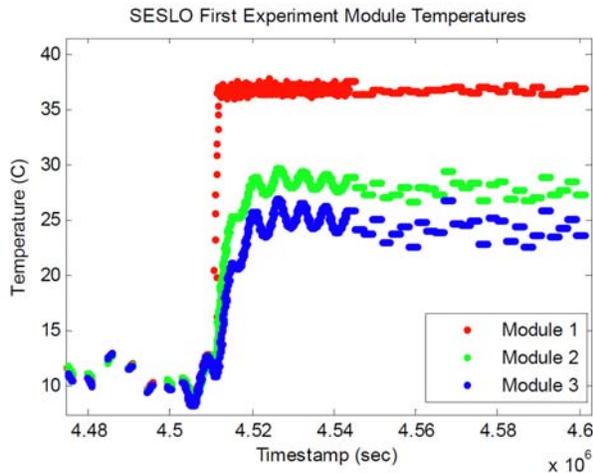


Figure 7: SESLO Thermal Profile for all three biomodules during the first biological growth experiment; only Module 1 was actively heated and controlled.

The payload was optimized for collecting data at a nominal rotation rate of 1 - 2 RPM. After orbital deployment, it was found that the spacecraft was rotating at more than 6 RPM, likely due to the extra angular momentum imparted to the system by the spacecraft's P-POD spring-loaded deployment system and the process of exiting the P-POD itself. This led to spectral acquisitions which were usable, albeit of sub-optimal-average intensity. These data provide a noisy but useable set of baseline spectra for the organic films in the first week of the experiment.

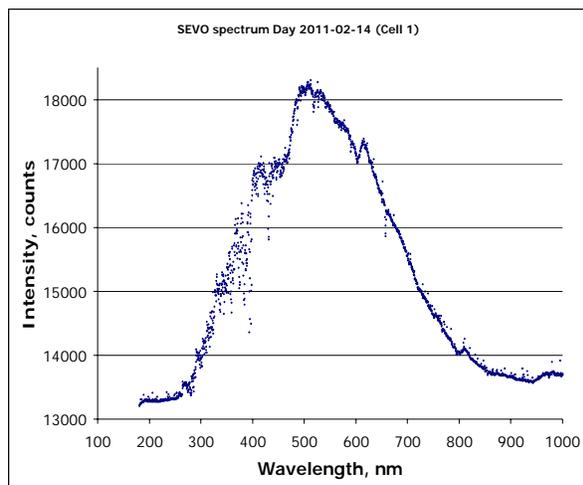


Figure 8: Solar Spectrum obtained at 650 km by the SEVO payload UV-visible spectrometer.

Within several weeks into the mission, the rotation rate stabilized near 1 RPM as expected, where it has remained, with minor variations, ever since, leading to acquired UV-visible spectra with much better signal-minus-background values. An example of a solar spectrum, obtained through one of the two open holes in the SEVO carousel that contain no sample cell, is given in Figure 8. The solar reference spectra are necessary to calculate the absorbance of the organic films and are obtained along with each complete set of sample spectra.

S-Band Communication Performance

The communication stations used for primary S-Band command and telemetry operations employ 3-meter parabolic dishes that have a pointing accuracy of 0.5° and a maximum azimuth rate of approximately 6°/sec. A Microhard MHX-2420 transceiver is used; this model is the successor to the transceiver that has been characterized by the mission operations team [9] and proven during the GeneSat-1 and PharmaSat missions [2, 4]. The MHX-2420 is a commercially available, off-the-shelf transceiver that provides a cost-effective and reliable 2.4 GHz S-band connection for point-to-point terrestrial applications.

Licensing restrictions prevent operations at elevations lower than 10 degrees. However, this is a minor constraint given that successful commanding typically requires a higher elevation. Figure 9 shows the azimuth and elevation of successfully received S-Band packets over the first six months of operation. Figure 10 shows the success rate of commanding as a function of azimuth and elevation. As can be seen, a 50% success rate for command is typically not achieved unless the elevation is above 40-50°. It is worth noting the particularly good performance when the antenna is oriented in the South West direction, which is consistent with the operations team's understanding of the spacecraft's passively controlled orientation. Given the O/OREOS orbit and the communication station location, link availability averages only about 3 minutes/day for elevations above 40°.

An additional challenge is the passively controlled spacecraft attitude, which affects the pointing of the slightly directional S-Band antenna mounted to one end of the spacecraft. O/OREOS uses a combination of magnets and hysteresis rods in order to attempt to align the vehicle's long axis with the magnetic field. It also has a deorbit mechanism which serves to lower the system's energy and which can also induce aerodynamic drag torques. It is difficult to explicitly determine the satellite's attitude profile given the lack of dedicated sensors for this purpose as well as due to

sampling limits of other affected sensors, such as solar panel current sensors.

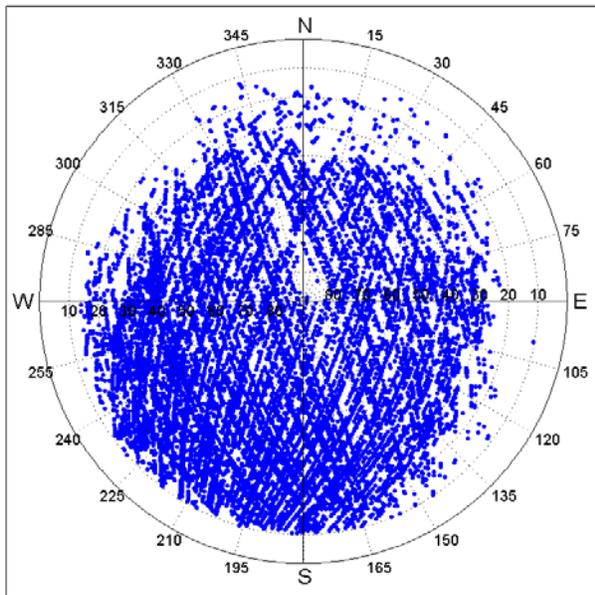


Figure 9: Successful S-Band Data Packet Reception as a function of antenna azimuth and elevation.

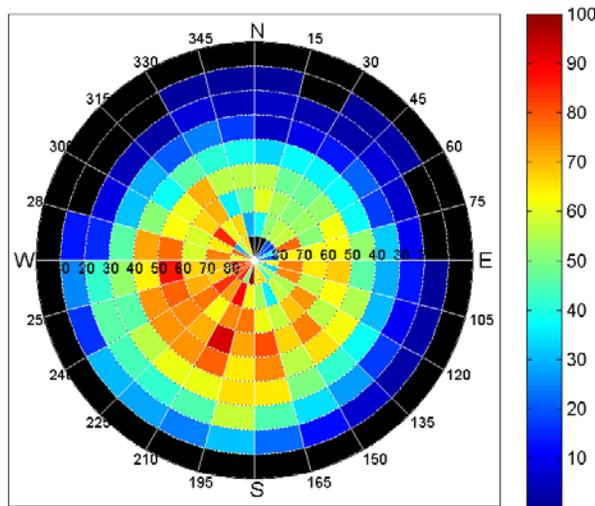


Figure 10: Success Rates (% of commands successfully received) for S-Band Data Packet Reception as a function of antenna azimuth and elevation.

That said, solar panel current monitoring has shown that the attitude profile has improved as the mission has progressed. Figure 11 shows typical panel currents

during the first week of the mission, implying a minor axis spin rate of about 6 RPM and significant nutation about this axis; during this phase of the mission, approximately 11.5 kB of data could be downloaded on a daily basis. After several weeks, rotation behavior improved and average daily downloads increased to about 27.1 kB. After about 4 months on orbit the spin about the main axis had reduced to about 0.9 RPM with far less nutation, as can be seen in Figure 12, and the daily data download increased to about 40.4 kB. Over the first six months of the mission, approximately 6.9 MB of data was collected.

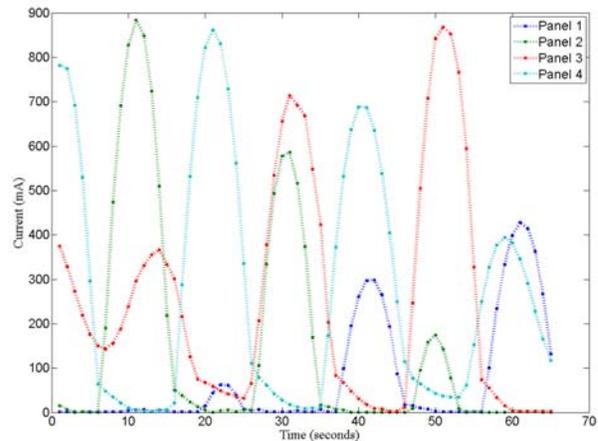


Figure 11: Typical Solar Panel Current Data During the First Week of the Mission, showing rapid spin and significant nutation.

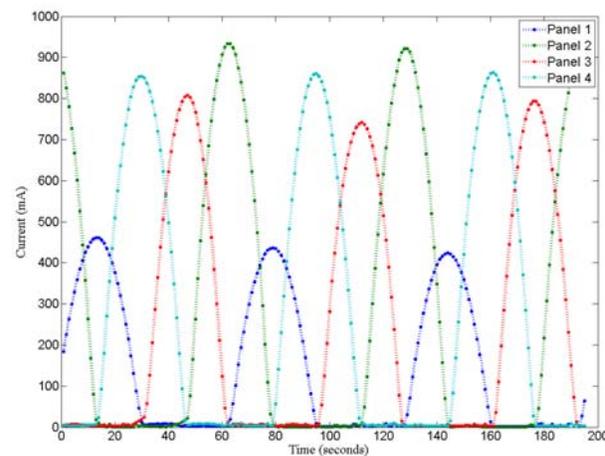


Figure 12: Typical Solar Panel Current Data After Three Months of On-Orbit Operation, showing a dramatically improved passive attitude profile with a slower spin and less nutation, compared to the early-orbit profile.

Automated Beacon Network for Anomaly Detection

Beacon monitoring is a spacecraft mission operations architecture that, for certain mission classes, can provide cost-effective anomaly detection and notification capabilities [10]. A health message is periodically broadcast by the spacecraft and received by a network of geographically distributed low-cost automated receiving stations. The message is forwarded to a central monitoring workstation, which can perform additional telemetry filtering and which then notifies on-call operators and initiates response actions as necessary. Beacon monitoring has been explored for a wide variety of spacecraft missions, to include spacecraft constellations such as the Global Positioning System and the Defense Satellite Communications System [11], NASA/JPL's Deep Space 1 [12], and Stanford's Space Systems Development Laboratory's Sapphire microsatellite [13]. However, these missions either did not adopt the beacon monitoring concept or only implemented beacon monitoring in the form of prototype operations or in ground test scenarios. To the authors' knowledge, Santa Clara University's automated beacon network is the first example of an operational satellite beacon-based health monitoring network, having obtained flight results during end-of-life operations for the GeneSat-1 mission [14] and during standard operations for the O/OREOS mission.

The SCU beacon network system consists of the O/OREOS satellite, networked and automated receive-only beacon stations, and a central monitoring station, as shown in Figure 13. Stations receive the packets opportunistically as the spacecraft orbits the Earth, periodically broadcasting its signal. O/OREOS is particularly well suited for support by a beacon monitoring network, as the beacon transmitter broadcasts packets (health messages) every five seconds containing critical telemetry information such as solar panel electrical currents, payload temperatures, and battery voltage, which are sufficient for health analysis.

Current stations are located in Pennsylvania, at St. Louis University in St. Louis, Missouri, and on the SCU campus in Santa Clara, California; an additional station is located at the University of Hawaii in Manoa Hawaii, but is not operational for the O/OREOS mission. The geographical distribution of the beacon stations, shown in Figure 14, provides the capability of receiving beacon packets over consecutive passes, resulting in enhanced timeliness of state-of-health updates. The stations use a vertically pointed, directional, 7-element Yagi antenna and simple amateur radio reception equipment, connected to a networked computer. The antenna provides enhanced gain for

high elevation passes, while limiting the station's ability to receive packets at lower elevations. Figure 15 shows a typical antenna installation.

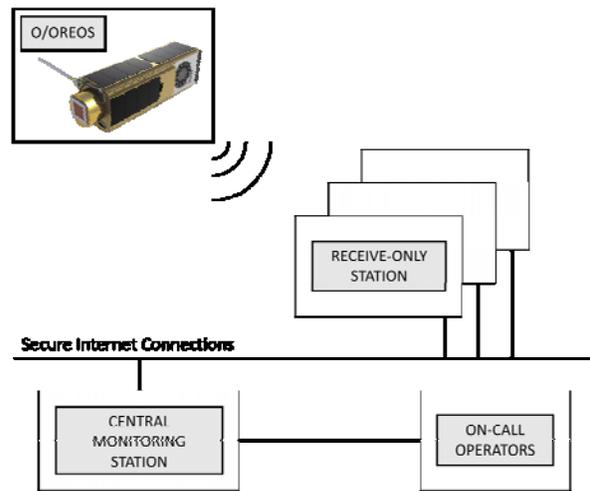


Figure 13: The Automated Beacon Receive Network Architecture, with geographically distributed receive-only stations opportunistically receiving spacecraft beacon packets and forwarding them via the internet to a central monitoring workstation.



Figure 14: Beacon Receive Station Locations, showing the 0 degree and 40 degree elevation masks.

Packets received by the stations are forwarded to the central monitoring station via secure Internet connections. At the central monitoring station, health monitoring tasks such as data handling, anomaly detection, and operator notification are implemented using MATLAB, Satellite Tool Kit (STK), and MySQL database. Anomaly detection is accomplished by implementing a set of rules to check the health of the satellite as well as the functionality of the beacon network. Upon receiving a beacon packet, the rules are used to perform basic telemetry limit checks to ensure nominal operating conditions. In addition to "packet" rules, another set of rules is checked daily to ensure that

the receive-only stations are receiving packets if the satellite has passed over the station with a high enough elevation. In the event that any rule is violated, on-call operators are notified via email or text message (SMS), whereby appropriate actions are taken, such as performing full state-of-health contact operations via the two-way S-Band communications link and/or reconfiguring systems as necessary to restore the satellite and the beacon network to nominal functionality.



Figure 15: A Beacon Station Antenna, using a vertically aligned 7-element Yagi antenna.

As of June 2011, the automated beacon network has received over 2,100 O/OREOS beacon packets, resulting in an average of nearly 11 packets/day; as reviewed in [10], this is enough to satisfy operator confidence in the satellite's nominal state of health during periods when standard operations are not being conducted. Packets are received over 75% of the time (e.g., on 3 out of 4 days), with an average time of roughly 9 hours between passes where a beacon packet was received. Beacon packets are typically received during passes with a maximum elevation greater than 50°, which occur at one or more of the three receive-only stations each day. The azimuth-elevation distribution of beacon packets received by each receive-

only station over a 3-month period is shown in Figure 16. Note that the beacon packets received at lower elevations by the STL station are the result of experimenting with an antenna setup which is oriented in a direction other than straight up.

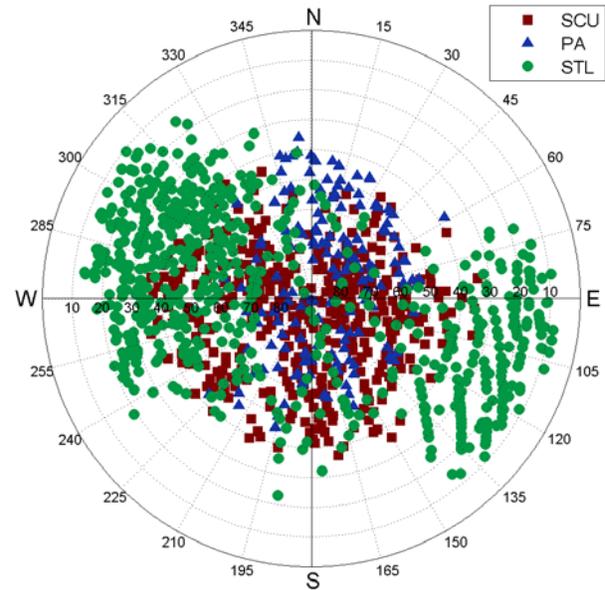


Figure 16: Beacon Station Packet Reception Performance, showing the azimuth and elevation of successfully decoded beacon packets for all three stations over a three-month period.

Various satellite anomalies have been detected using the automated beacon health monitoring network, to include low battery voltage, unexpected system resets, and off-nominal temperature conditions. In addition, a number of receive-only station anomalies have been detected, which are typically attributed to dropped Internet connections, but events such as facility reconfigurations and power outages have also been detected. Overall, the use of the automated satellite beacon health monitoring network has resulted in a significant reduction of required on-console time by human operators, and the beacon network has become a standard part of Santa Clara University's satellite operations environment. The beacon network also provides an operational testbed for maturing SCU's expertise in model-based reasoning for anomaly management [15]. Model-based reasoning algorithms have been incorporated into the system and favorable results have been obtained with the use of an integrated model-based reasoning system for anomaly detection and diagnosis in the O/OREOS operational space

system. Future work includes refined integration of model-based reasoning systems for more precise and focused anomaly detection and diagnosis, as well as the support of anomaly resolution activities within the ground segment.

EDUCATION AND OUTREACH

The O/OREOS program has a strong student education and public outreach element. The most significant element of this is the teaming with SCU in order to provide mission operations, ground segment engineering, and functional test services. This is formally addressed through unique undergraduate and graduate level classes in satellite operations through which students can become certified to be members of the mission control team. Satellite data is also routinely used in SCU's graduate space systems courses which are cooperatively taught with Lockheed Martin as part of their Engineering Leadership Development Program.

With respect to public outreach, the amateur radio beacon system plays a critical role in engaging amateur radio enthusiasts and small satellite experimenters/students throughout the world. Beacon packet decoding and calibration instructions are publicly available, and external members of these communities are encouraged to collect and process data for their own purposes. These external operators have the option to submit collected beacon packets to the operations team through a website. Submission of valid packets yields a QSL "proof of radio contact" card, which is traditional in the amateur radio community. The web site also allows the public to access previously submitted beacon data. During the first six months of the mission, over 39,000 external radio packets had been submitted by operators in 19 countries around the world. This "participatory" element of the mission has been used previously by the team as part of the GeneSat-1, PharmaSat, and NanoSail-D missions.

CONCLUSIONS

The O/OREOS mission demonstrates that single-cube payloads can be effective at producing answers to real and compelling questions in space science. This and future experiments in similar form factors can be easily adapted to a variety of host spacecraft, including nearly any lander or orbiter with as little as 1 kg, 1 L, and 1 W of mass, volume, and power availability (depending on the environment and science goals), respectively. Efforts are already underway to streamline a process for adapting such payloads for use on the ISS for frequent and quick-turnaround experiments that require minimal crew time and down mass. Technology developments for this mission, including the UV-visible spectrometer and long-term dry biological sample storage and

rehydration, can be readily adapted to missions in and beyond Earth orbit.

The long-term need to address space debris mitigation, even for very small spacecraft, was shown to be feasible with the spacecraft's deorbit mechanism. This passively-deployed, lightweight, and unobtrusive means of increasing a spacecraft's surface area was the first step in future efforts to safely bring down orbiting hardware that at the end of its mission lifetime.

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References

1. Minelli, G. et al., "O/OREOS Nanosatellite: A Multi-Payload Demonstration", Proc. 24th Annual AIAA/USU Conf on Small Satellites, Logan UT, 2010
2. Kitts, C., et al., "Flight Results from the GeneSat-1 Biological Microsatellite Mission", Proc. 21st Annual AIAA/USU Conf on Small Satellites, Logan UT, 2007
3. M. Parra, D. Ly, A.J. Ricco, M.R. McGinnis and D. Niesel, "The PharmaSat Nanosatellite Platform for Life Science Experimentation: Effects of Space Flight on Antifungal Activity Against *Saccharomyces cerevisiae*," *Gravitational and Space Biology*, 23, 30 (2009).
4. Kitts, C., et al., "Initial Flight Results of the PharmaSat Biological Microsatellite Mission", Proc. 23rd Annual AIAA/USU Conf on Small Satellites, Logan UT, 2009

5. W. Nicholson, R. Mancinelli, O. Santos, A.J. Ricco, P. Ehrenfreund, D. Squires, C. Kitts, R. Rasay, A. Young and the O/OREOS-Sat Engineering Team at NASA Ames, "The O/OREOS Mission: First Science Data from the Space Environment Survivability of Living Organisms (SESLO) Payload", *Astrobiology*, submitted
6. N. Bramall, R. Quinn, A. Mattioda, K. Bryson, J. Chittenden, A. Cook, P. Ehrenfreund, A.J. Ricco, D. Squires, O. Santos, G. Minelli, G. Defouw, C. Friedericks, D. Landis, N. C. Jones, S.V. Hoffmann (2011) "*The Development of the Space Environment Viability of Organics (SEVO) Experiment aboard the Organism/Organics Exposure to Orbital Stresses (O/OREOS) Satellite*", *Planetary and Space Sciences*, accepted for publication.
7. P. Ehrenfreund, A.J. Ricco, R. Quinn, Bramall, K. Bryson, J. Chittenden, A. Cook, R. Mancinelli, A. Mattioda, G. Minelli, W. Nicholson, O. Santos, D. Squires, C. Kitts, R. Rasay, A. Young and the O/OREOS-Sat Engineering Team at NASA Ames. "The O/OREOS Mission: First Science Data from the Space Environment Viability of Organics (SEVO) Payload", *Astrobiology*, submitted
8. C. A. Kitts, R. M. Rasay, I. Mas, P. Mahacek, G. Minelli, J. Shepard, and J. Acain, "Responsive Small Satellite Mission Operations Using an Enterprise-Class Internet-Based Command and Control Network," in *Proceedings of the AIAA SPACE 2008 Conference and Exposition*, San Diego, California, AIAA Technical Paper Number AIAA-2008-7830, September 2008, pp. 1–10.
9. I. Mas and C. A. Kitts, "A Flight-Proven 2.4 GHz ISM-Band COTS Communications System for Small Satellites," in *Proceedings of the Twenty-First Annual AIAA/USU Conference on Small Satellites*, Logan, Utah, August 2007.
10. C. A. Kitts and M. A. Swartwout, "Beacon Monitoring: Reducing the Cost of Nominal Spacecraft Operations," *Journal of Reducing Space Mission Cost*, vol. 1, no. 4, pp. 305–338, 2002.
11. S. Hovanessian, S. Raghavan, and D. Frostman, "LIFELINE: A Concept for Automated Satellite Supervision," *Aerospace Report No. TOR-93(3516)-1*, 1993.
12. R. Sherwood, A. Schlutsmeier, M. K. Sue, and E. J. Wyatt, "Lessons from Implementation of Beacon Spacecraft Operations on Deep Space One," in *Proceedings of the 2000 IEEE Aerospace Conference*, Big Sky, Montana, March 2000.
13. C. G. Niederstrasser, C. A. Kitts, and M. A. Swartwout, "Design and Performance Testing of a Satellite Health Beacon Receiving Station," in *Proceedings of the 1999 IEEE Aerospace Conference*, Snowmass, Colorado, March 1999.
14. A. Young, C. Kitts, M. Neumann, I. Mas, and R. M. Rasay, "Initial Flight Results for an Automated Satellite Beacon Health Monitoring Network," in *Proceedings of the Twenty-Fourth Annual AIAA/USU Conference on Small Satellites*, Logan, Utah, August 2010.
15. C. A. Kitts, "Managing Space System Anomalies Using First Principles Reasoning," *IEEE Robotics and Automation Magazine*, Special Issue on Automation Science, vol. 13, no. 4, pp. 39–50, December 2006.
16. P. Ehrenfreund, A. J. Ricco, D. Squires, C. Kitts, E. Agasid, N. Bramall, K. Bryson, J. Chittenden, C. Conley, A. Cook, R. Mancinelli, A. Mattioda, W. Nicholson, R. Quinn, O. Santos, G. Tahu, M. Voytek, C. Beasley, L. Bica, M. Diaz-Aguado, C. Friedericks, M. Henschke, J.W. Hines, D. Landis, E. Luzzi, D. Ly, N. Mai, G. Minelli, M. McIntyre, M. Neumann, M. Parra, M. Piccini, R. Rasay, R. Ricks, A. Schooley, E. Stackpole, L. Timucin, B. Yost, A. Young, "The O/OREOS Mission – Astrobiology in Low Earth Orbit", *Proceedings 9th IAA Low-Cost Planetary Missions Conference*, Laurel, MD, June 2011, p. 1-8.