The GeneSat-1 Biological Nanosatellite Mission

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ABSTRACT

During its three and a half year mission, the GeneSat-1 spacecraft has established several spacecraft industry precedents. The mission's primary outcome was the validation of research-quality instrumentation for conducting *in situ* biological research in a sub-5-kg spacecraft. The satellite payload's complexity, miniaturization, and automation set a benchmark for spacecraft of this class. The mission also demonstrated the highly streamlined application of management practices, a unique government-industry-academia teaming arrangement, and a highly participatory education and outreach program. This paper reviews the development of the mission, the design of the spacecraft, on-orbit results, and contributions made by the mission.

KEY WORDS

Satellite technology, space vehicle electronics, space environment testing, biological instrumentation.

INTRODUCTION

The GeneSat-1 mission evolved from a combination of the challenges facing space-based biological research and the opportunities presented by a nascent but promising nanosatellite industry.

Space-based Biological Research

Experimental studies of how biological systems are effected by the space environment directly supports several critical NASA interests, such as fundamental astrobiological research and the development of long-duration human space flight capability [1, 2]. NASA has historically conducted space environment experiments through the use of terrestrial simulators (such as centrifuges, drop towers, and parabolic aircraft flights, radiation chambers, and so on), unmanned spacecraft that de-orbit for subsequent analysis, and manned facilities such as the Space Shuttle and the International Space Station [3-5]. However, terrestrial simulators lack fidelity, re-entry loads during a mission's de-orbit phase can result in corrupted results and the loss of experimental control, and the drawbacks of manned space flight experiments include the high cost of crew involvement, the lack of routine access, the constraints on equipment and processes, the cost of ensuring safety for a manned space flight system, and the vibrational disturbances caused by crew and support system operations [3, 6].

Several highly integrated bioreactors using strategies similar to some of the solutions ultimately incorporated into GeneSat-1 have previously flown on manned space vehicles to study biological phenomena [7-9]; however, these systems required a human operator to initiate the experiment, record data, collects samples for analysis, and/or prepare (freeze/fix) samples for return to Earth [9]. In contrast, once initiated by ground command, the objective for GeneSat-1 was to have its payload automatically execute the experimental protocol, to include establishing a temperature-controlled environment, activating the specimens through the supply of nutrients, tracking cell growth and gene expression via the optical measurement of light scattering and fluorescence, and storing collected data for eventual telemetering to the ground.

The Evolution of Nanospacecraft

Since the start of the Space Age 50 years ago, spacecraft have generally grown in size and mass due to the capability of launch vehicles and the advantages that large spacecraft have in supporting high-power and large-aperture applications. Small satellites, however, have played a vital role during this time, and more than 80 active nanosatellites, defined as spacecraft with a mass in the range of 1-10 kg, have been launched during this time [10]. In 1958, the U.S. Navy's Vanguard 1 was the first nanosatellite ever launched into space [11], and the 1959 NASA Pioneer 4 lunar mission was the first nanosatellite, and the first U.S. probe, to escape Earth's gravity [12]. In the 1960's, additional nanosatellite missions included the AMSAT OSCAR I and II amateur radio spacecraft [13], several inflatable spheres used to conduct atmospheric density studies as part of the NASA Explorer program [14], and a number of U.S. Air Force Environmental Research Satellite spacecraft used to characterize the space environment [15].

From the early 1970's until 2000, launches of active nanosatellites dropped dramatically, with no launches for more than a decade starting in the mid-1970's. Although not nanosatellites, the 1990 launch of the four 12-16 kg AMSAT MicroSats laid a foundation for future nanospacecraft by exploiting digital technologies, secondary launch capabilities, and significant involvement of universities [10]. Over the next 15 years, hallmark missions of this type included the 1998 TUBSAT-N and –N1 communication spacecraft missions [16], the 2000 SNAP-1 photo-inspection spacecraft mission, which set a variety of impressive technical benchmarks such as three-axis attitude control and orbit control using both GPS and active propulsion [17], and the 2003 initial launch of the first six CubeSat spacecraft [18].

The CubeSat initiative has played a critical role in expanding nanosatellite activity [19]. In addition to leading to a major expansion of university-class educational missions, both government agencies (NASA, NSF, NRO) and companies (Boeing, Tethers Unlimited Inc) are now developing or sponsoring CubeSat-class missions for science and technology validation

objectives [20, 21]. It is interesting to note that the critical innovation is not in the satellite standard but in the use of an ejector given that this plays an enormous role in decoupling the nanosatellite from the launch vehicle, its primary spacecraft, and the launch manifest process [19]. Indeed, several "standard" ejectors have been developed for nanosatellite-sized spacecraft: the California Polytechnic State University's (CalPoly) Poly Picosatellite Orbital Developers (P-POD) [22], the Aerospace Corporation Picosatellite Orbital Deployer (A-POD), the University of Tokyo's Tokyo Picosatellite Orbital Deployer (T-POD) which was used for the first launch of CubeSats in 2003, the University of Toronto's experimental Push Out Deployer (X-POD), and the Ecliptic RocketPod™.

The Impetus for GeneSat-1

In the early 2000's, the combination of promising low-cost small satellite options and the desire to conduct high-fidelity space biological research motivated a team of NASA Ames scientists and engineers to launch a program to develop small bioreactors using standard bioanalytical techniques and to fly them in space on free-flying small spacecraft. Affiliation with several local universities with experience in the development, launch and operation of micro- and nano-satellites ultimately resulted in Ames inviting these universities to become a part of the mission team.

After developing a science and technology roadmap and prototyping several bus and payload capabilities, in 2004, the team ultimately decided to develop the GeneSat-1 spacecraft mission as a technology demonstration for verifying several critical technologies and components required for enabling their long-term vision. The mission was also intended to serve as a pathfinder for learning how to operate within the NASA systems engineering framework for missions that, by NASA standards, would be very low cost, rapidly developed, and high risk. The intent of the mission was for it to serve as the first step in the development of a high-performance space platform and mission team capable of executing future missions that would employ far more

advanced life support, sensing, and analytic techniques for studying complex specimens, fully imaging their behavior, and conducting robust *in situ* research.

THE GENESAT-1 MISSION

The programmatic objective for GeneSat-1 was to develop an autonomous technology demonstration payload with sensors capable of characterizing the behavior of cellular and microscopic organisms in space, and to accommodate this payload as part of a free-flying small spacecraft [23]. Upon review of resources, team capabilities, and launch opportunities, the team decided to develop GeneSat-1 with a "triple CubeSat" form factor. This constrained the mass to sub-5 kg and the volume to approximately 10 cm x 10 cm x 30 cm. It also implied significant challenges relating to the availability of power during on-orbit operations, the demand for life support services, the need for miniaturization of instruments and components, and the strategy by which biological samples would be stored, fed, cultured, and analyzed. If successful, GeneSat-1 would be the first ever *in situ* bioanalytical system ever flown and arguably one of the most technically sophisticated nanosatellites developed to date.

Because the purpose of GeneSat-1 was to verify critical technologies for performing *in situ* space biological studies, the team selected a well-understood science objective that could serve as a baseline for allowing evaluation of the payload and bus technologies. This science objective was to monitor the metabolism of E. coli as a function of the microgravity environment using a green fluorescent protein (GFP) imaging technique and its associated, standard experimental protocols.

Driving Requirements and Challenges

The needs of the GeneSat-1 biological test payload levied a number of requirements on the space system; several of these were new challenges, even to those on the team with previous experience developing small spacecraft.

First, the use of the triple-CubeSat class form factor, required due to programmatic and cost constraints, drove a significant engineering effort to miniaturize and tightly integrate the elements of the payload system. This was particularly true for the instrumentation-grade optical sensing system. Second, the biological specimens required continuous thermal regulation to within +/- 0.5° C during their nominal 96-hour growth phase in order to properly characterize metabolic rate as a function of microgravity effects alone; this was a challenging requirement given the small thermal mass of the payload, the space environment, and the small amounts of available power.

Third, numerous challenges arose relating to the design and engineering of the microfluidics system, such that it would operate properly in a microgravity environment; this system was used to feed the biological specimens in the same sample wells used for storage and analysis. Finally, the limited shelf life of the E. coli samples motivated changes to typical launch preparation and ground handling processes and mandated a launch vehicle integration date no more than 30 days prior to launch, which is often a challenge for secondary launch payloads.

Mission Team

Development of the GeneSat-1 mission was led by NASA Ames Research Center's Small Satellite Division, with several of its critical personnel having significant experience with previous space biological tests through the Shuttle, Space Station and BION programs. Because Ames had never developed a low-cost nanosatellite mission, Ames invited several local universities to participate in various aspects of the mission. The faculty, staff and students of these schools had significant expertise in small satellite development, albeit without the background in science-grade biological instrumentation or NASA-level systems engineering and project development processes.

Stanford University's Space Systems Development Laboratory was a bus prototyping partner early in development, prior to the mission's Critical Design Review, with a role of exploring various CubeSat satellite architectures and bus components with the Ames team [24]. CalPoly provided a standard P-POD ejection system, which was modified by the Ames team to support several

adaptations motivated by the final GeneSat-1 form factor and the team's risk management policies. Santa Clara University's (SCU) Robotic Systems Laboratory developed the ground communications and control segment and provided all on-orbit mission operations services; SCU personnel also played primary roles in the bus mechanical design, bus communications analysis and test, and payload design. As the GeneSat-1 development effort became formalized as a full Class D NASA flight project, Santa Clara University students, staff and faculty were fully integrated into the GeneSat-1 mission team, interacting with NASA personnel on a daily basis, providing critical deliverables, and serving in primary mission management team positions.

Mission Development

Development of GeneSat-1 served a pathfinding function to identify ways to appropriately streamline standard NASA project management and systems engineering practices in order to develop follow-on biological nanosatellites on a one-year timeline and for a budget in the range of $2-3 million. This initiative went far beyond simply classifying the program as a Class D mission, a designation for high-risk, low-cost and inexpensive missions that is used to set expectations for programmatic risk [25]. Instead, the project team collaborated with program managers to develop what the project termed "7120-lite," a highly tailored, minimal implementation of NASA Procedural Requirement (NPR) 7120.5D. This process-oriented NPR governs the management of all NASA space flight programs [26] and permits tailoring given appropriate approvals. Program managers also required a very minimal implementation of program-level reviews, which in some cases were handled simply as requests for information.

Another enabling development strategy related to testing, which was reduced to what the team considered to be a bare minimum while still ensuring Class D-level confidence among the project team. The project test plan emphasized the use of integrated system level tests to verify survivability of launch environments and subsequent functional reliability. Some tests were eliminated altogether. An example of this was the EMI/EMC testing; with the exception of functional tests demonstrating self-compatibility, no EMI or EMC tests were required. This was made possible by the fact that the satellite was powered off during launch and enclosed in the P-POD, which acted a grounded Faraday cage.

Surprisingly, the team found that attempts to dramatically reduce documentation was not a useful strategy, learning over time that most documentation content was still a requirement for a well-controlled project. That said, in many cases, documents were combined. In addition, documents for board-level procedures were often created as "white sheets" in which procedures are created and documented as they are executed. The team found that could be effectively implemented given a strong engineering team and the use of complete assembly-level procedural documentation.

A final lesson of note pertains to the engineering team itself. Over time, the make-up of the team necessarily shifted such that it consisted of personnel with multiple engineering talents and developmental skills. This allowed the small team to cover the wide range of required capabilities and to also to provide continuity with particular team members were unavailable. Furthermore, it became clear that a single flight project of this type could not completely support the number of personnel required on a full time basis. This led to a program-level strategy of conducting multiple flight projects, with engineers serving on more than one team at any given time.

GENESAT SPACE SYSTEM

The GeneSat-1 space system consisted of the GeneSat-1 spacecraft, the P-POD launch ejector enabling the satellite to be deployed as a secondary payload from a Minotaur I launch vehicle,

several communication stations for primary command and telemetry operations and beacon reception, and several mission control nodes. A simplified diagram of the mission architecture is depicted in Fig 1.

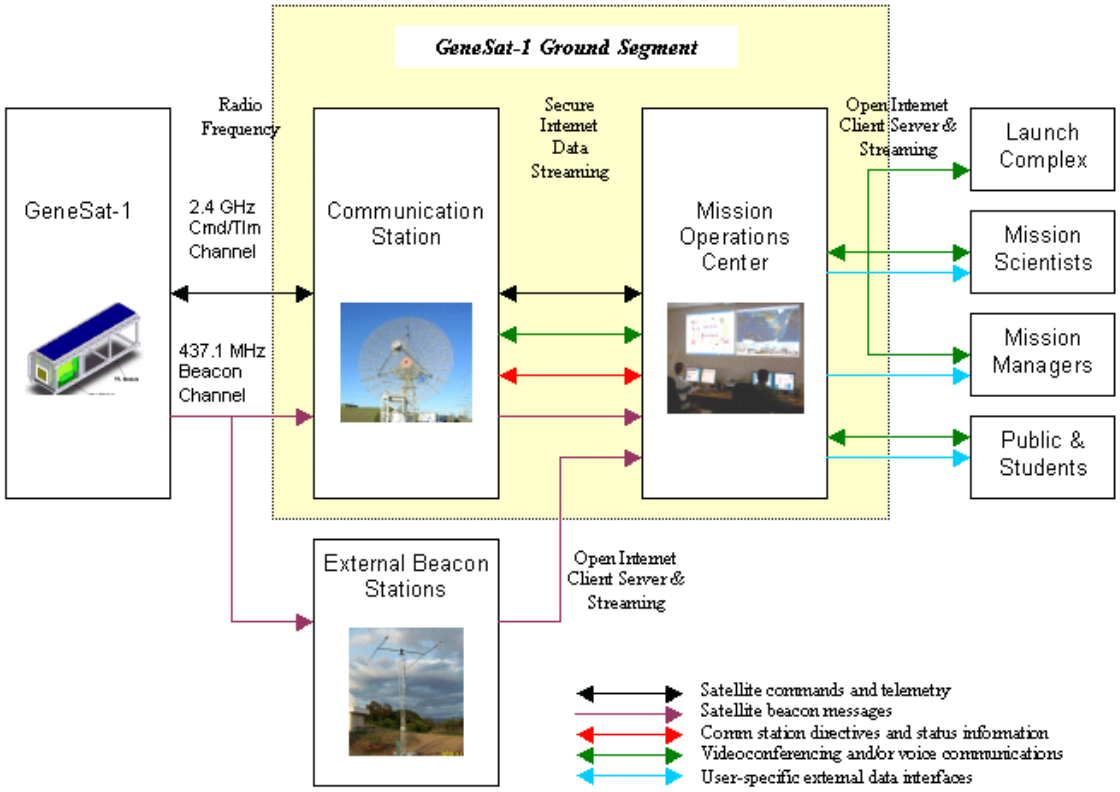

Fig 1: GeneSat-1 Mission Architecture. The program's mission operations center linked to the primary communication station via the internet. This station supported two-way S-band communication with the satellite and also received one-way beacon transmissions. Operators of external beacon stations were able to submit and share their collected data via a program web site.

Spacecraft

The satellite, shown in Fig 2, was approximately 100mm x 100mm x 340mm in size and had a mass of approximately 3.5 kg. This form-factor was an adaptation of the CubeSat size standard [27], consisting of a "triple-Cube" configuration with an additional 40mm tall cylindar added to one end in order to provide expanded volume for satellite components. Satellite bus components

were contained within a one 10 cm^3 Cube, within the cylindrical extension, and on the external faces of the spacecraft. The bus included body-mounted solar panels, a single NiCad battery, a PIC-based command and data handling board, a passive magnet/hysteresis rod orientation control suite, a 2.4 GHz communications transceiver, and an amateur radio beacon.

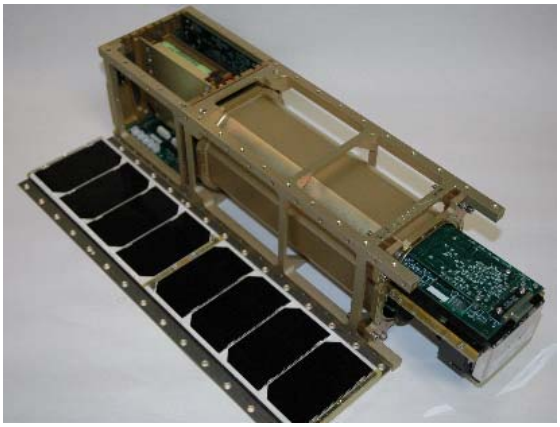

Fig 2: GeneSat-1 Spacecraft. The biological laboratory was contained in a pressure vessel that required two 10 cm cubes. Bus components were housed in the third cube. Body mounted solar panels covered the four largest sides of the spacecraft.

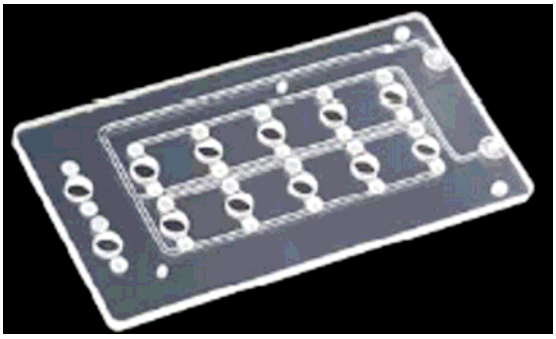

Fig 3: GeneSat Biological Wellplate. Ten wells housed biological samples and two held calibration samples. Microfluidic channels embedded within the plate were used to pump nutrients to the biological samples.

The miniature biological laboratory that served as the spacecraft's payload was housed in a pressurized, sealed container that fit within two 10 cm^3 Cubes. This container housed a biological wellplate with an integrated fluidics system, optical sensors, and support equipment [28]. The

internal volume provided humidified air for gas exchange with the fluidic card's microwells via a gas-permeable membrane. Shown in Fig 3, the wellplate housed ten 110-µL culture wells and two solid-state references. The card contained fluidic channels that filled all 10 wells evenly from the single inlet channel by restricting flow through individual wells. The fluidic card was manufactured from multiple laser-cut acrylic layers using pressure-sensitive-adhesive interlayers. The reservoir/pump unit was a 15 mL medical-grade polymer bag with a helical spring. Off-the-shelf sensors tracked key parameters throughout the mission; these parameters included pressure, humidity, radiation dose, 3-axis accelerations, and the temperature at six locations across the wellplate.

To exploit the GFP measurement strategy, the GFP protein had been fused to the E. coli gene associated with metabolism, thereby establishing a correlation between the bacteria's metabolic state and its level of green fluorescent response. During measurements throughout the E. coli growth cycle, each specimen was excited through illumination with a blue LED. Due to its GFP preparation, the bacteria would fluoresce green in response to this excitation. This visual response was observed via optics by a detection circuit in order to quantify the light level, which served as the observable proxy for metabolic rate of the bacteria. In order to normalize readings by the size of the bacteria population, which grew throughout the growth cycle, each measurement of fluorescent response was paired with a measurement of the specimen's optical density. For this measurement, a green LED was shone through the sample and the resulting light intensity was recorded by the same optical detection system used to measure fluorescence. These experimental measurements and other payload telemetry were made periodically throughout the 96-hour growth cycle of the E. coli. A diagram of one of the optical instruments is shown in Fig 4.

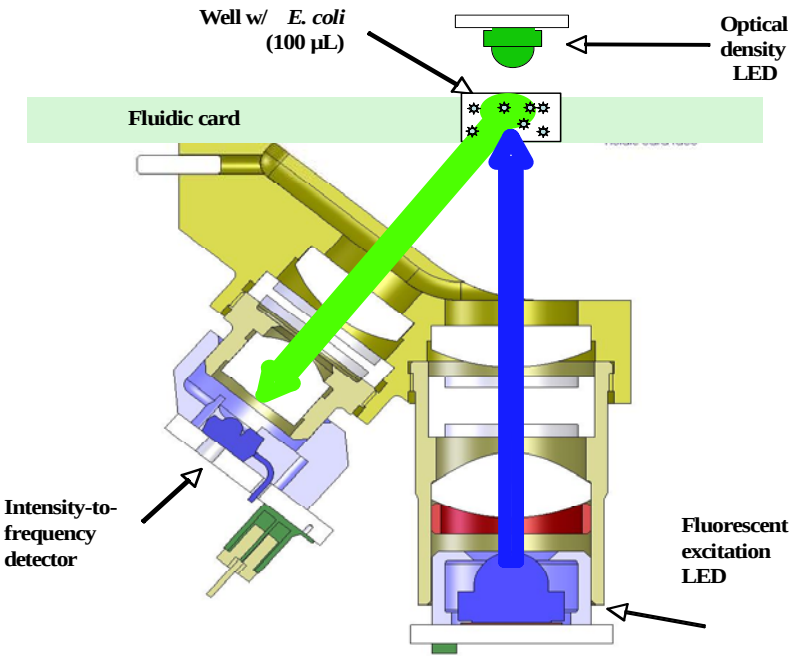

Fig 4: Optical instrument. To measure fluorescence, a blue LED was used to excite the biological samples. As the samples fluoresce, a detector sensitive to the GFP frequency records intensity. To measure growth, a green LED was shone through the sample, allowing the same detector to be used for this second measurement.

Launch Segment

For launch, the Genesat-1 spacecraft was enclosed within the P-POD ejection system. The P-POD is a simple device that mounts to the launch vehicle in a secondary launch location, encapsulates the spacecraft during launch in order to protect primary payloads, and ejects the spacecraft upon receipt of a simple trigger signal. When this signal is received, a release mechanism allows the P-POD's door to open, and a spring-loaded pusher plate pushes the spacecraft out of the ejector.

To accommodate the needs of the GeneSat-1 mission, the Ames team modified the standard P-POD in two significant ways. The first modification was made to account for the cylindrical extension that was added to the standard triple-Cube form factor. The cylindrical module was sized to fit inside the helical ejection spring, but the pusher plate required modification to allow the cylinder to fit through it. The resulting mechanical configuration is shown in Fig. 5.

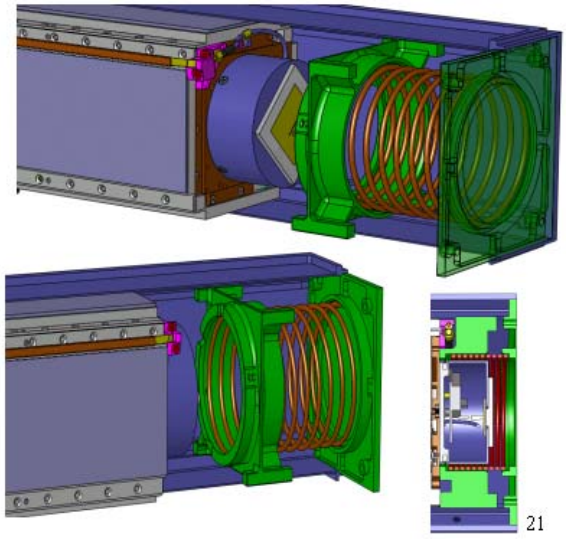

Fig 5: Modified P-POD Assembly. The satellite's cylindrical extension fit within the ejector's spring. Modifications to the "pusher plate" that physically contacted the spacecraft were made to allow the cylindrical extension to fit.

The second P-POD modification consisted of using an NEA-brand split spool device as the door release mechanism. This change was motivated by concerns over the effect that the launch environment's thermal stresses would place on the standard release mechanism; the split spool device is now a standard option on P-POD models [22].

Ground Communication and Control Segment

GeneSat-1 was operated through the use of a distributed, internet-based satellite control network developed and operated by Santa Clara University (SCU) [29]. This infrastructure linked several communication stations with a variety of control nodes in order to conduct contact operations.

Control nodes (the location of command and telemetry operators during contact operations) could be configured at any internet-accessible location, but during primary experimental operations they were confined to pre-determined locations due to security and configuration control policies. These locations included the NASA Ames Multi-Mission Operations Center (MMOC), the SCU

operations rooms on campus and in the NASA Research Park at Moffett Field, California, and at the physical location of each communication station. In addition to remotely linking to the selected communication station, the operational control node also remotely linked to the mission's command and telemetry database, which was located in the NASA MMOC. All on-orbit contact operations were run by SCU students, staff and faculty, with operators undergoing a formal training and certification program and using formal, verified command and telemetry procedures.

Mission-critical command and telemetry operations were supported via a 2.4GHz S-Band link using a frequency-hopping COTS transceiver identical to the on-board unit. An 18-meter station leased from SRI International in Palo Alto, California was refurbished and used for primary communications during the experimental part of the mission. Two 3-meter stations at SCU in Santa Clara, California were also used and ultimately became the primary communication stations for the post-experiment phase of the mission. An additional SCU-owned and operated 3-meter station in El Salvador was also used for occasional mission support.

As part of the mission's education and public outreach program, students and amateur radio operators could use UHF radio equipment to receive the GeneSat-1 amateur radio beacon signal. This signal broadcast a limited set of bus telemetry at five second intervals. SCU maintained a public beacon message database and web site service, originally developed in conjunction with students at Ohlone College in Freemont California, which allowed amateur radio operators throughout the world to share their data. SCU also operated its own UHF stations in order to support this effort; this included manually controlled stations as well as a network of automated stations deployed across the country.

FLIGHT RESULTS

On December 16, 2006, Genesat-1 was successfully launched from Wallops Flight Facility as a secondary payload on a Minotaur I launch vehicle. The launch placed the satellite into its nominal 410 km altitude, 40° inclined circular orbit. The on-orbit mission timeline consisted of two major

phases: the NASA-specific science phase and the post-experiment phase during which SCU continued to operate the spacecraft for experimental and education purposes until its end of life. The science phase included an initial period of early orbit checkout operations, then the 96-hour biological growth period, then up to 10 weeks of additional time to download science data and to characterize bus performance.

Flight Operations

Early orbit operations during the first two days in orbit were outstanding, with communications link, stabilization speed and satellite health all exceeding expected performance. Because of this, the biological experiment was initiated by ground command at the end of day two, five days earlier than nominally planned. Over the course of the next four days, the experiment was automatically executed by flight computer. This process included warming and maintaining the E. coli within each well at a growth temperature of 34 °C and then activating the E. coli by pumping a sugar-based growth medium into the wells via the microfluidic system, displacing a saline "stasis buffer" that was used to preserve the bacteria during loading and launch [30].

Measurements of biological activity and payload/bus state were logged throughout the four-day growth cycle, with the operations team checking system health and downloading experimental data during this time. By the conclusion of the 96-hour experiment, a complete baseline profile of science data had been retrieved and delivered to the science team for initial analysis. This baseline profile provided data at a sample period of approximately 2 hours, a resolution finer than standard ground-based acquisition for this type of experiment. As a matter of routine, science data products were automatically calibrated and delivered via internet to the science team within an hour of download by the operations team.

Over the course of the following three weeks, additional science data was retrieved and more thorough analysis of spacecraft health and performance was accomplished. After approximately one month of on-orbit operations, all primary mission procedures had been executed, and all

associated flight data had been retrieved, thereby constituting mission success. During the second month of operations, auxiliary analyses were conducted, additional technical experiments were performed, and new student mission operations crew members were trained and certified. On February 21, 2007, after approximately two months of on-orbit operations and several weeks ahead of the nominal schedule, NASA transferred control authority of the mission to SCU such that the satellite could be operated for the purposes of supporting student education and engineering research experiments.

Biological Results

The GeneSat-1 biological experiment involved the assessment of E. coli. metabolism as a function of microgravity through the use of GFP experimental protocols. During development, the 30 day or more delay between biological load to launch and experiment initiation motivated extensive testing in order to ensure the selection of a viable E. coli strain, biocompatible materials, and stable reagents. Two strains, MM294 (pGREEN plasmid) and DH5α cells (plasmid AcGFP), were selected for flight given their characteristics and the desire to reduce risk.

During the on-orbit experiment, fluorescence and growth measurements for each well were taken every 12 minutes. All biowells exhibited growth after 10 hours, and all biowells eventually expressed GFP signals. Flight growth and GFP data was compared with that from an identical ground unit run in a delayed synchronous manner in order to assess the impact of the microgravity environment. The flight data showed a decreased growth rate and a higher final growth plateau [31], the later of which was consistent with previously published results [32-35] and which was not found to be statistically significant. This was as expected since, as previously discussed, the E. coli. experiment itself was selected in order to serve as a known baseline that would challenge engineering development but which would not introduce unknown scientific variables into attempts to verify and validate the performance of the engineering system.

Engineering Results

As the first-ever fully autonomous *in situ* outer space gene-expression analytical system, the primary purpose of the GeneSat-1 mission was to validate the capabilities of the instrumentation system and to characterize the ability of the space system to support the biological payload, process the scientific data products, and maintain its own health over the duration of the mission. From this perspective, the engineering results were outstanding.

Within the payload module, biological growth and fluorescence were observed in all biowells, the fluidic system functioned properly, and the optical detectors performed as required. From a life support perspective, nominal pressure and humidity levels were maintained within the payload canister, and the wellplate temperature was successfully controlled to a set-point of 34°C [36, 37].

In terms of bus performance, sub-milli-gravity-level accelerations were achieved, power was successfully managed for all loads, and all data was successfully stored and relayed to the ground. Furthermore, performance of the S-Band transceiver was sufficient for mission needs as evidenced by the ability of the operations team to download all baseline science data during the realtime experiment; this unit had been considered a high-risk item given its criticality and lack of flight heritage [38]. Finally, during experimental operations during its second phase of flight, GeneSat-1 was used for numerous research studies involving the use of model-based anomaly management techniques [39, 40] and the demonstration of automated beacon-based health monitoring [41, 42].

Education and Training Results

The educational achievements relating to the GeneSat-1 mission were significant. The direct result was the involvement of more than 30 undergraduate and graduate students at Stanford, CalPoly, and SCU during the development phase of the mission; this involvement was incorporated into the academic programs of the individual students through project-based courses, capstone projects, thesis research and internships. During the past three and a half years of flight operations, more than 70 additional undergraduate and graduate students have been trained and certified to operate GeneSat-1 and its ground control segment as part of a formal SCU course in

satellite operations, and more than a dozen students have operated the on-orbit system as part of novel student experiments involving topics such as wireless communications, fault diagnosis, and software engineering.

Apart from educating conventional students, involvement in this mission provided critical flight project engineering and management training for more than a dozen young aerospace professionals on the Ames team. Many of these scientists and engineers have become subsystem leads and management team members on follow-on nanosatellite flights, and a number have joined other NASA Ames teams working on larger, more sophisticated spacecraft.

With respect to broader education and outreach efforts, the public accessibility of the amateur radio beacon was a highlight of the mission and one of the first known examples of a "participatory space mission" in which the public is able to have direct access to data, conduct their own analyses, and interact with the mission team. During the first two months of operations, more than 40,000 packets of beacon telemetry were collected and submitted to the GeneSat-1 operations team by more than 50 operators in more than a dozen countries throughout the world. This publicly available data has been used by hobbyists to perform their own satellite analyses, by K-12 educators to demonstrate principles of math and physics, and by university professors in courses about spacecraft design and operation. Additional K-12 education and public outreach efforts included a large number of classroom visits, facility tours and public exhibits.

MISSION IMPACT AND CONTRIBUTIONS

As NASA's first modern, active nanosatellite mission, GeneSat-1 serves as a benchmark, supporting an unprecedented level of design sophistication and functionality given its size, mass, and power limitations. At the time of its launch, it was the smallest space biology spacecraft to have ever been launched, and it provided life support and highly-integrated bio-processing capabilities for the first-ever automated, spaceborne, *in situ* bio-laboratory. GeneSat-1's extreme

cost and schedule constraints led to the highly streamlined application of NASA-standard management and systems engineering practices.

One testament to the success of GeneSat-1 is the series of follow-on nanosatellite missions that continue to be pursued by the NASA Ames team and which have capitalized on GeneSat-1 technology and development practices. The first were PreSat and NanoSail-D, both of which unfortunately failed to reach orbit during the August 2008 launch of a SpaceX Falcon 3 rocket. PharmaSat, a triple-Cube mission launched in May 2009, successfully conducted a biological test of antifungal drug efficacy in the space environment [43]. O/OREOS, another triple-Cube mission to be launched in September 2010, will conduct dual biological tests, one characterizing the stability of organic molecules in space and another testing how microorganisms adapt to living in space [44]. NanoSail-D, a triple-Cube mission also manifested for launch in September 2010, will use an evolved GeneSat bus and test a solar/drag sail mechanism developed by NASA Marshall Space Flight Center [45]. MisST, a "six-pack" CubeSat bus carrying several biological science and technology demonstration missions, is currently in development for launch in mid-2011.

GeneSat-1 technology and development practices are also being applied to the development of a new NASA Ames nanosatellite launch adapter system, several university flight programs; and NASA's new Stand Alone Missions of Opportunity (SALMON) program. The team's Continuous Risk Management process was also adopted for use by the NASA Ames LCROSS program. Furthermore, lessons learned from the GeneSat team's design and test methodology have been used to significantly influence NASA Ames' Procedural Requirements 8070.2 for Class D Spacecraft Design and Environmental Test, thereby impacting a wide range of future low-cost, high-risk missions developed at Ames.

The NASA-university teaming arrangement was also unique from two perspectives. First, NASA invited the universities to participate on the GeneSat-1 team not only as a way to promote student education but to also acquire critical nanosatellite mission experience. Second, the partnership

with SCU became so strong that, over time, four of ten critical mission management team positions ultimately became filled by SCU faculty and staff.

The operations phase of the mission also resulted in several innovative achievements. First, this was the first NASA mission run by a student-centered ground segment and mission operations team; other professional-class missions have certainly incorporated students, but this is generally as part of a professional staff. Second, this was the first NASA mission completely operated via use of the public internet; this is common for university-class missions, and SCU upgraded its distributed satellite control network to incorporate NASA-approved security and configuration control technologies and policies. Third, as previously discussed, the use of the amateur radio beacon provided a popular, participatory experience for the public throughout the duration of the mission, establishing a model for new participatory mission initiatives within NASA.

CONCLUSIONS

Launched in December 2006 and operating for more than three and a half years, the GeneSat-1 mission successfully met all of its mission objectives, providing an important contribution to the development of research-quality instrumentation for *in situ* biological research and processing. As the first such free-flying satellite-based genetic analysis experiment, its design provided significant insight into the appropriate application of small satellite technology for enabling high-performance space-borne laboratories. Furthermore, as NASA's first modern, active nanosatellite, its development served as a pathfinder for managing high-risk missions with cost and schedule constraints that are extreme by NASA standards. In addition to providing these unique benefits, NASA's partnership with regional academic institutions allowed a critical flow of expertise relating to small satellite design and operation, and it provided significant education and workforce training experiences for the participating students and engineers.

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REFERENCES

[1] Des Marais, D.J., Nuth, J.A., Allamandola, L.J., Boss, A.P., and Farmer, J.D., T.M.Hoehler, et al. "The NASA Astrobiology Roadmap," *Astrobiology*, Vol. 8, No. 4, 2008, pp. 715-730.

[2] White, R.J., and Averner, M., "Humans in space," *Nature*, Vol. 409, Feb 2001, pp. 1115-1118. doi: 10.1038/35059243

[3] Lynch S. V. and Matin A., "Travails of microgravity: man and microbes in space," *Biologist*, Vol. 52, No. 2, 2005, pp. 80-87.

[4] Ballard, R.W. and Connolly, J.P., "U.S./U.S.S.R. joint research in space biology and medicine on Cosmos biosatellites," *FASEB Journal*, Vol. 4, No. 1, Jan 1990, pp. 5-9.

[5] Wilson, J.W., Ott, C.M., Honer zu Bentrup, K., Ramamurthy, R., Quick, L., et al., "Space flight alters bacterial gene expression and virulence and reveals a role for global regulator Hfq," *PNAS*, Vol. 104, No. 41, Oct 2007, pp 16299-16304. doi: 10.1073/pnas.0707155104

[6] Rogers, M., Hrovat, K., and Moskowitz, M.E., "Effects of exercise equipment on the microgravity environment," *Advances in Space Research*, Vol. 24, No. 10, 1999, pp 1283-1287. doi: 10.1016/S0273-1177(99)00734-6

[7] J.J. Cefai, D.A. Barrow, P. Woias, and E. Muller, "Integrated Chemical Analysis Microsystems in Space Life Sciences Research," *J. Micromech. Microeng.*, Vol. 4, No. 4, 1994, pp 172-185. doi: 10.1088/0960-1317/4/4/002

[8] Walther, I., Vanderschoot, B.H., Jeanneret, S., Arquint, P., Derooij, N.F., et al., "Development of a Miniature Bioreactor for Continuous Culture in a Space Laboratory," *J. Biotechnology*, Vol. 38, No. 1, 1994, pp. 21-32.

[9] Hammond, T.G., Lewis, F.C., Goodwin, T.J., Linnehan, R.M., Wold, D.A., et al., "Gene Expression in Space," *Nature Medicine*, Vol. 5, No. 4, 1999, p. 359. doi: 10.1038/7331.

[10] Janson, S.W., "The History of Small Satellites," *Small Satellites: Past, Present, and Future*, edited by H. Helvajian and S.W. Janson, The Aerospace Press, El Segundo, CA, 2008, pp. 47-94.

[11] Binning, P.W., "Defining moments in the naval research laboratory's project vanguard," *Advances in the Astronautical Sciences*, Vol. 130, No. 2, 2008, pp. 1791-1804.

[12] Curtis, H., and Schneiderman, D., "Pioneer III and IV space probes," *IRI Transactions on Military Electronics*, Vol, MIL-4, No. 2-3, Apr-Jul 1960, pp. 123-129.

[13] Pronko, J.G., "OSCAR: your own communication satellite," *Proceedings of the ITC/USA/'80 International Telemetering Conference*, San Diego, CA, Oct 1980, pp. 393-398.

[14] Mullins, J.A., Keating, G.M., McDougal, D.S., and Prior, E.J., "Determination of Mean Atmospheric Densities During Minimum Solar Activity by Means of the Explorer XIX Satellite," NASA Technical Note D-3432, 1962.

[15] Peterson, L.E., Gruber, D. Lewis, S.J., Stone, M.R., and Vette, J.I., *Environmental Research Satellite-18 Data Reduction and Analysis. Volume 1 Satellite Description and Operations.* University of California San Diego, La Jolla, CA, 1968.

[16] Schulte, R., "TUBSAT-N, an ultra low cost global communication nanosatellite system," *Air & Space Europe*, Vol. 2, No. 5, Sep 2000, pp. 80-83.

[17] Steyn, W.H., and Hashida, Y., "In-Orbit Attitude Performance of the 3-Axis Stabilised SNAP-1 Nanosatellite," SSC01-V-1b, *Proceedings of the 15th AIAA/USU Conference on Small Satellites*, Logan UT, August 2000.

[18] Lee, S., Toorian, A., Clemens, N. Puig-Suari, J., "Cal Poly Coordination of Multiple CubeSats on the DNEPR Launch Vehicle," SSC04-IX-06, *Proceedings of the 18th AIAA/USU Conference on Small Satellites*, Logan UT, August 2004.

[19] Swartwout, M., "The Promise of Innovation from University Space Systems: Are We Meeting It?" SSC09-XII-03, *Proceedings of the 23rd AIAA/USU Conference on Small Satellites*, Logan UT, 13 August 2009, pp 1-13.

[20] Taraba, M., Rayburn, C., Tsuda, A., and MacGillivray, S., "Boeing's CubeSat Testbed 1 Attitude Determination Design and On-Orbit Experience," SSC09-X-06, *Proceedings of the 23rd AIAA/USU Conference on Small Satellites*, Logan UT, August 2009.

[21] Hoyt, R., Voronka, N., Newton, T., Barnes, I., Shepard, J., et al., "Early Results of the Multi-Application Survivable Tether (MAST) Space Tether Experiment." SSC07-VII-04, *Proceedings of the 21st Annual AIAA/USU Conference on Small Satellites*, Logan Utah, August 2007.

[22] "Poly Picosatellite Orbital Deployer Mk III ICD", California Polytechnic State University, San Luis Obispo, CA, August 2007.

[23] Kitts, C., Hines, J., Agasid, E., Ricco, A., Yost, B., et al., "The GeneSat-1 Microsatellite Mission: A Challenge in Small Satellite Design," SSC06-IV-08, *Proceedings of the 20th Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2006.

[24] Lee, E., Jaroux, B., Spremo, S., D'Ortenzio, M., Mas, I., et al., "The *.Sat CubeSat Bus: When Three Cubes Meet," SSC05-VI-04, *Proceedings of the 19th AIAA/USU Conference on Small Satellites*, Logan UT, August 2005

[25] "NASA Procedural Requirement 8705.4: Risk Classification for NASA Payloads," NASA, Washington, D.C., July 2008.

[26] "NASA Procedural Requirement 7120.5D: NASA Space Flight Program and Project Management Requirements," NASA, Washington, D.C., March 2007.

[27] "CubeSat Design Specification Rev 8", California Polytechnic State University, San Luis Obispo, CA, May 2006.

[28] Ricco, A.J., Agasid, E., Barker, V., Fahlen, T., Hines, J.W., et al., "Integrated System to Analyze the Genetic Effects of the Space Environment on Living Cells in Culture: GeneSat," *Proceedings of the 8th European Conference on Optical Chemical and Biosensors*, Tubingen, Germany, April 2006, pp. 527-529.

[29] C. Kitts, M. Rasay, I. Mas, P. Mahacek, G. Minelli, et al., "Responsive Small Satellite Mission Operations Using An Enterprise- Class Internet-based Command and Control Network," AIAA 2008-7830, *Proceedings of AIAA SPACE 2008 Conference & Exposition*, San Diego CA, Sep 2008.

[30] Ricco, A.J., Hines, J.W., Piccini, M., Parra, M., Timucin, L., et al., "Autonomous Genetic Analysis System to Study Space Effects on Microorganisms: Results from Orbit," *Proceedings of Transducers'07: The 14th International Conference on Solid-State Sensors, Actuators and Microsystems*, Lyon France, June 2007, pp. 33-37.

[31] Parra, M.P., Ricco, A.J., Yost, B., McGinnis, M.R., and Hines, J.W., "Studying Space Effects on Microorganisms Autonomously: GeneSat, Pharmasat, and the Future of Bio-Nanosatellites," *Gravitational and Space Biology*, Vol. 21, No. 2, June 2008, pp. 9-18.

[32] Benoit, M.R. and Klaus, D.M., "Bacteria, and the Influence of Motility. Advances in Space Research," *Microgravity*, Vol. 39, 2007, pp. 1225-1232.

[33] Bouloc, P. and D'Ari, R., "Escherichia coli Metabolism in Space," *Journal of General Microbiology*, Vol. 137, No. 12, Dec 1991, pp. 2839-43.

[34] Gasset, G., Tixador, R., Eche, B., Lapchine, L., Moatti, N., et al., "Growth and Division of Escherichia coli Under Microgravity Conditions," *Research in Microbiology*, Vol. 145, No. 2, Feb 1994, pp. 111-20.

[35] Kacena, M.A., Merrell, G.A., Manfredi, B., Smith, E.E., Klaus, D.M., and Todd, P., "Bacterial Growth in Space Flight: Logistic Growth Curve Parameters for Escherichia coli and Bacillus subtilis," *Applied Microbiology and Biotechnology*, Vol. 51, No. 2, Feb 1999, pp. 229-34.

[36] Kitts, C., Ronzano, K., Rasay, R., Mas, I., Williams, P., et al., "Flight Results from the GeneSat-1 Biological Microsatellite Mission", SSC07-XI-01, *Proceedings of the 21st Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2007.

[37] Minelli, G., Kitts, C., Ronzano, K., Beasley, C., Rasay, R., et al., "Extended Life Flight Results from the GeneSat-1 Biological Microsatellite Mission," SSC08-II-04, *Proceedings of the 22nd Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2008.

[38] Mas, I., and Kitts, C., "A Flight-Proven 2.4 GHz ISM Band COTS Communications System for Small Satellites," SSC07-XI-11, *Proceedings of the 21st Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2007.

[39] Kitts, C., "Managing space system anomalies using first principles reasoning," *IEEE Robotics and Automation Magazine*, Special Issue on Automation Science, Vol. 13, No. 4, December 2006, pp. 39-50.

[40] Kitts, C., Rasay, R., Mas, I., Mall, P.J., and Van Buskirk, R., "Model-based anomaly management for spacecraft mission operations at the NASA Ames Space Technology Center," *Proceedings of SMC-IT 2006: 2nd IEEE International Conference on Space Mission Challenges for Information Technology*, 2006, pp. 241-242.

[41] Kitts, C., and Swartwout, M., "Beacon Monitoring: Reducing the Cost of Nominal Spacecraft Operations," *Journal of Reducing Space Mission Cost*, Vol. 1, No. 4, 2002, pp. 305-338.

[42] Young, A., Kitts, C., Neumann, M., Mas, I., and Rasay, R., "Initial Flight Results for an Automated Satellite Beacon Health Monitoring Network," SSC10-XII-1, *Proceedings of the 24th Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2010.

[43] Kitts, C., Ronzano, K., Rasay, R., Mas, I., Acain, J., et al., "Initial Flight Results from the PharmaSat Biological Microsatellite Mission," SSC09-IV-10, *Proceedings of the 23rd Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2009.

[44] Minelli, G., Ricco, A., Squires, D., Beasley, C., Hines, J., et al., "O/OREOS: A Multi-Payload Technology Demonstration," Accepted *Proceedings of the 24th Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2010.

[45] Whorton, M., Heaton, A., Pinson, R., Laue, G., and Adams, C., "NanoSail-D: The First Flight Demonstration of Solar Sails for Nanosatellites," SSC08-X-01, *Proceedings of the 22nd Annual AIAA/USU Conf on Small Satellites*, Logan UT, 2008.