The GeneSat-1 Test Demonstration Project: A Unique Use of Smallsats

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ABSTRACT: The GeneSat-1 technology demonstration project, planned for flight in late 2005, will demonstrate the value of utilizing biological surrogates and advanced analytical techniques as remote, autonomous monitors of relevant space exploration environments. GeneSat-1 is based on a triple-Cubesat architecture and integrates the power of genetic, biological probes with a standardized smallsat platform to provide a robust, repeatable, low-cost technology validation platform for Exploration research.

INTRODUCTION

The emergence of cubesats as a technology platform has generated a number of ideas and opportunities for space-based experiments. In addition, the small size, relatively low cost, and universal availability of cubesats and cubesat subsystems has allowed space technologists to envision, construct and flight test key technologies for application in complex systems. The end result is reduced risk and valuable flight heritage for these systems. Use of cubesats can, therefore, be a critical component of many technology development programs. The GeneSat-1 spacecraft and mission plays such a role in NASA's Astrobionics Technology Program. GeneSat-1 marries the cubesat architecture with novel biological life support systems and advanced molecular sensors to demonstrate the feasibility and applicability of autonomous biological investigations in the space environment, as required for the NASA Exploration Vision[1].

Key features and applications of this combination of biological genetic probes and small spacecraft include:

- Generation of large data sets from relatively small biological sensors
- Ability to evaluate techniques and approaches

in space for molecular medicine applications as potential countermeasures for human Exploration crews.

- Multiple replicates as part of a robust measurement strategy.
- A reduction of the reliance on human-tended architectures resulting in enhanced reliability and accuracy.
- Addition of sophisticated microanalytical methods and small-platform computational power to reduce Exploration risk elements
- Reduction of costly sample return requirements

Small satellites, such as the GeneSat-1 cubesat can provide ready access to a range of space environments. Multiple flights are possible and probable, enabling a test/learn/redesign iterative approach and allowing multi-replicate evaluations. Similarly, autonomous small spacecraft technologies are becoming quite capable, with advanced and robust command and control, communications, and power management subsystems. In addition, the secondary (or even tertiary) payload accommodations approach for space access is relatively low in cost and also provides ideal partnering and collaborative opportunities.

The objectives of the GeneSat-1 technology demonstration mission are to:

1) Develop, design, assemble, and test a flight-ready autonomous technology demonstration platform, which will lead to advanced sensors that exploit cellular or microscopic organisms in a small form factor. This implies a heavy reliance on miniaturized optical systems, microelectronics, microfluidic systems, and computer-based technologies.

2) GeneSat-1 must be capable of accommodating multiple technologies including fluorescent imaging of single proteins using green fluorescent protein (GFP) techniques. Future GeneSat missions may investigate other sensor types such as imaging and polymerase chain reaction (PCR) DNA amplification techniques.

3) Support specific investigations and assessments of technologies used in ground applications, which are directly targeted at human Exploration risks. The initial GeneSat-1 mission will focus on quantitatively detecting levels of GFP expressed in living cultures (*E. coli*). This first step will provide the basis for further development of biologically-based sensors for human exploration, including biosentinels for use on the surface of other planets as occupational health sensors.

4) The final objective for GeneSat-1 is to exploit and investigate the advantages of small satellites to accelerate the migration of key technologies and platform(s) to broader applications such as autonomous spacecraft operations, man-tended space vehicles, and novel ground-based research applications.

REQUIREMENTS SUMMARY

Other than the unique nature of the payload systems, the requirements for GeneSat-1 as a spacecraft demonstrator are relatively straightforward. The spacecraft must generate and provide power to the payload, and provide reliable communications and data management services. Another key requirement is contained in the area of thermal performance. Unlike inanimate systems which can tolerate temperature excursions and thermal cycles to a greater extent, the GeneSat-1 payload must regulate internal temperatures to $\pm$ 0.5°C. This requirement is quite challenging even for ground-based systems, which have the luxury of large masses and virtually unlimited power sources. In addition, some knowledge about the space environment must be sensed and provided by GeneSat-1. In addition to temperatures, of interest are the space radiation and the microgravity environments.

A final challenge is driven by the perishable nature of the on-board biological specimens (bacteria). These cultures have a limited viable shelf life, which is strongly affected by temperature and handling. Therefore, final loading and preparation of the biological specimens must be done as late as possible at the launch site.

SPACECRAFT DESCRIPTION

The GeneSat-1 spacecraft, which is equivalent to a triple cubesat, consists of a bus module (1 cubesat volume) and a payload module (2 cubesat volumes). The entire satellite is about 100mm X 100mm X 340mm and weighs approximately 3 kg.

The GeneSat-1 spacecraft is housed during launch in a Poly Picosat orbital Deployer (PPOD) developed and provided by CalPoly San

Lius Obispo. The PPOD provides for structural containment, attachment to the launch vehicle (LV), and a deployer/release mechanism for satellite ejection. Upon receipt of the deploy signal from the LV, a Starsys Qwiknut 3k is activated, releasing the spring-loaded PPOD door. A spring-loaded pusher plate at the rear of the PPOD then ejects GeneSat-1.

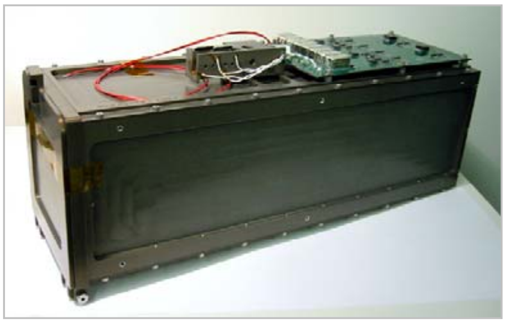

Figure 1 PPOD (CalPoly)

Satellite services are provided by a modular, compact system developed primarily by Stanford University. The *.Sat Bus is a full-service, stand-alone spacecraft intended to accommodate a large number of payloads and functions. The *.Sat bus is self-contained in a $100mm^3$ volume and integrates the following subsystems:

- Command and Data Handling (C&DH)
- Secondary batteries
- Electrical power system (EPS)
- Interface to payload systems
- Communications (radio and monopole antenna)
- Solar cells for power generation
- Attitude control elements, (hysteresis rods, magnets, accelerometers, gyros)

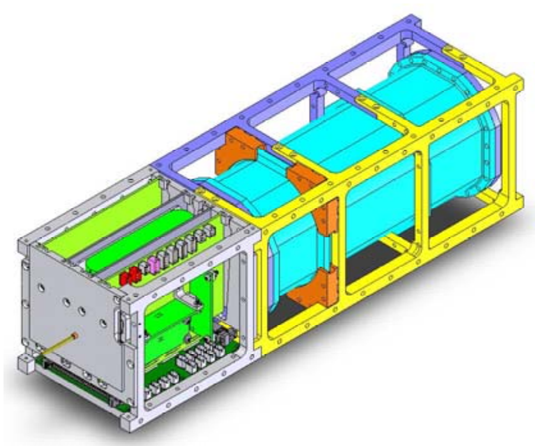

Figure 2 GeneSat-1 Spacecraft (solar cells/outer panels removed)

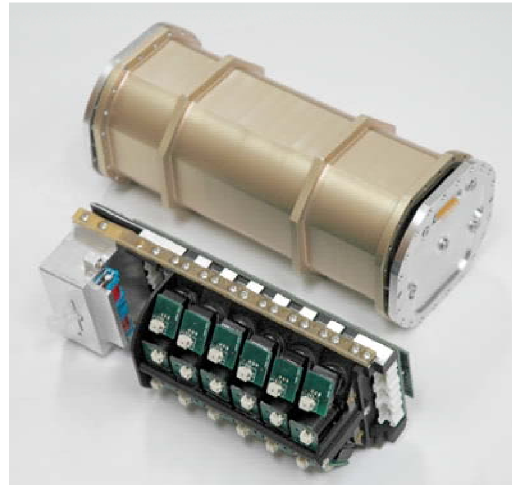

Figure 3 GeneSat-1 payload pressurized volume showing optical bench

The GeneSat-1 payload is a 2 cubesat equivalent size containing a pressurized, sealed volume. The pressure vessel (cylinder) contains the integrated fluidics, optical sensors, and electrical/mechanical subsystems, internal heaters and controllers. The internal volume also provides humidified air to exchange with the microwells via a gas-permeable membrane. Light sources (LEDs) and detectors for the fluorescent optical assay are located outside the humidified headspace.

At the core of the GeneSat-1 demonstration platform is an integrated analytical fluidics card assembly.

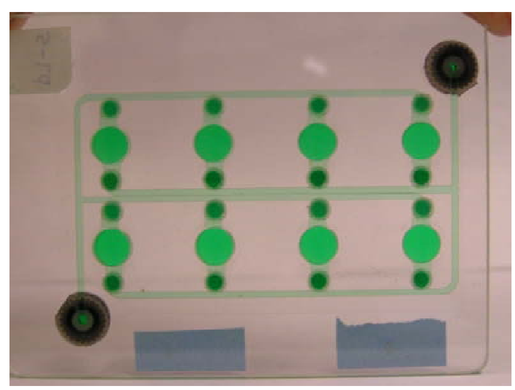

Figure 4 Fluidics card

It includes a media pump, valves, microchannels, filters, membranes, and wells to maintain the biological viability of various microorganisms. Inside the pressurized volume, off-the-shelf sensors for pressure, humidity, temperature at 6 locations, radiation dose, and a 3-axis accelerometer track environmental parameters throughout the mission. Once in stable orbit, the system warms the *E. coli* to growth temperature (~32°C) using custom-patterned metal/Kapton heater films under closed-loop control, then "resuscitates" the *E. coli* by pumping a sugar solution to displace the stasis buffer, which is used to preserve the bacteria during loading and launch activities.

A dedicated blue-LED-excited fluorescent detection system probes gene expression levels by quantifying levels of light emitted by green fluorescent protein (GFP) which has been fused to a bacterial gene associated with metabolism. Concurrent light scattering measurements are made in order to normalize the fluorescence results to culture population as it grows. Results are then transmitted to Earth.

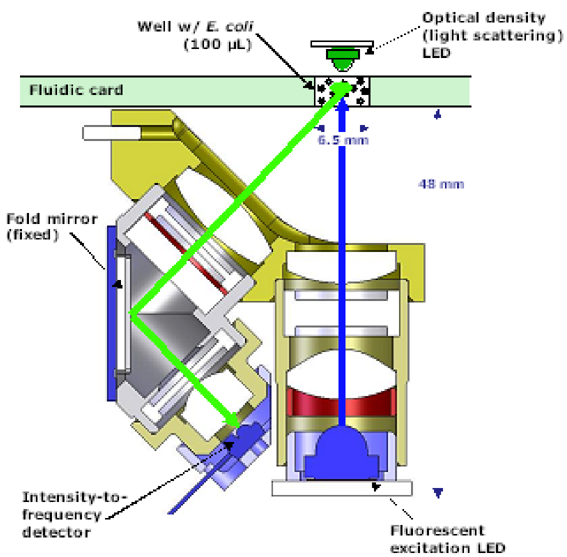

Figure 5 Fluorescent/visible optical detector schematic

GROUND SEGMENT DESCRIPTION

Development of the Genesat-1 ground segment and its use during on-orbit operations is the responsibility of Santa Clara University's Robotic Systems Laboratory (RSL). In providing this portion of the Genesat-1 mission system, RSL is exploiting more than a decade of experience in using internet-enabled communication stations for conducting satellite operations.

Command and telemetry data is broadcast between the spacecraft and a ground communication station located in the Stanford foothills in Palo Alto, California. The station relays this information between the satellite and the Mission Operations Center (MOC) via a secure internet link. The MOC is located in the Space Technology Center, which is located in NASA Research Park at Moffett Field, California. Command and telemetry operations are conducted within the MOC, and external interfaces to mission managers, payload scientists and the public are provided via web-based public internet access. Figure 6 shows the key facilities within the ground segment.

Figure 6 GeneSat-1 Mission Operations Center and Communication Station.

Ground Communication Station

Command and telemetry data is transmitted between the spacecraft and the ground communication station through the use of a commercially available 2.4 GHz Microhard spread spectrum wireless radiomodem. Because of limited satellite power and the characteristics of the on-board communication system, a ground communication station with significant antenna gain was required. Accordingly, an 18-meter radio-telescope antenna operated by SRI International and located on the Stanford University campus is being refurbished for mission support.

Specific upgrades to this station include the resurfacing of the antenna, the installation of a new antenna feed, and an upgrade to the antenna pointing control system. A Microhard radiomodem (configured to serve as the synchronization master unit for communication with the satellite) is being added for RF operations. In addition, a videoconferencing system is being installed to support communications among the operations team and to provide visual antenna monitoring.

Operation during launch and early orbit check-out will be supported by SRI International staff given the challenges in acquiring the satellite and the sophisticated nature of the facility. However, the mission team plans to quickly transfer communication station operations to a team of trained and certified SCU students; student participation in this activity will be conducted as the hands-on component of a formal undergraduate course in the engineering principles that underlie satellite operations. As the yearlong GeneSat-1 mission progresses, the team plans to conduct a portion of its contact operations in an unattended mode with station configuration managed via remote control from the MOC.

Internet-Based Ground Segment Link

The MOC communicates with the ground station via a network bus using TCP/IP as the underlying communication protocol. Data is communicated between these nodes through the use of a real time data server that routes data between applications with sub-second delays[2]. This architecture has a significant heritage within RSL both for the operation of university-class spacecraft as well as for the real time piloting of robotic systems ranging from underwater robots to aerial vehicles. Information transmitted through the network bus is secured through the use of hardware virtual private networking components located at both facilities.

Mission Operations Center (MOC)

The MOC has been developed by RSL as part of its field robotics program in order to centrally manage operations for a wide range of robotic systems to include orbiting spacecraft, UAVs, multi-rover clusters, and underwater robots.

MOC hardware includes a suite of high performance computer workstations equipped with dual displays. Additional large-format projection and plasma displays promote visualization of mission critical data during operations.

MOC software includes a wide variety of industry-class commercial software tools and RSL-developed research-class operations and analysis packages. Industry standard software includes Satellite Toolkit, Braxton Technologies' ControlPoint command and telemetry processing software, and MATLAB for advanced analysis. RSL software includes the following:

- Mission Control – This enterprise-class software suite supports real time command and telemetry operations with the satellite[3]. The suite supports multiple simultaneous operator workstations, runs on multiple platforms, and interfaces with the network bus, MATLAB, and other external programs. The suite is mission independent and accesses a mySQL database for mission-specific databases supporting command validation, telemetry processing, and model-based estimation. The suite includes a power GUI for the creation of dynamic data displays and the creation/execution of task-specific procedures.
- RACE – This software package supports remote communication station operation[4]. It has been used extensively to control OSCAR station-class facilities and is being extended with device drivers to support the Microhard transceiver and the SRI station tracking system.
- MATLAB Toolboxes – The mission control software is built to stream satellite telemetry into the MATLAB environment for real time analysis. As part of its research program, RSL has created several MATLAB toolboxes for supporting advanced operational capabilities. For example, anomaly management will be conducted through the use of both an Expert System Toolbox[5] and a Model-Based Reasoning Toolbox[6].

Standardization in the GeneSat-1 Ground Segment

The GeneSat-1 mission relies on standardization even within the ground segment in order to constrain cost and streamline development.

One of the most obvious uses of standardization is in the reliance on internet-based real time communication between the MOC and the communication station as well as in the external post-contact data dissemination architecture. The inexpensive and ubiquitous nature of internet connectivity allows the GeneSat-1 team to leverage a significant installed infrastructure and a generation of commercially funded hardware development.

Perhaps more instrumental, key mission control software systems have been developed such that their processing algorithms and services are independent of mission design and operations data. For example, the RSL command and telemetry software performs command validation and telemetry processing based on parameters stored in a database of mission-specific data. As another example, RSL's MATLAB-based anomaly management toolboxes separate the computational algorithms for detecting, diagnosing and resolving anomalies from the system models and real time data used by these algorithms in order to manage system state of health.

By using software systems that separate standardized operational processing algorithms from mission-specific data, the GeneSat-1 mission is able to leverage a rich history of algorithm development and verification. In addition to reducing development costs, it also streamlines operational preparation since the algorithms and software exists already and only the mission-unique data needs to be formalized.

MISSION DESIGN

Pre-Launch Phase

Since the GeneSat-1 test contains perishable materials (bacteria), loading and final preparations will be performed as late as possible at the launch site. Assuming that GeneSat-1 can be launched on a Kosmotras Dnepr using the cluster deck for secondary payloads, pre-launch activities will begin at the launch site around 2 weeks prior to launch. Hardware systems will be checked out, bacteria cultures installed, and limited testing to verify interfaces and satellite readiness will be performed. At L-7 days, GeneSat-1 and PPOD hardware systems will be integrated onto the Dnepr space head module (SHM). After encapsulation, the SHM is transported to the launch vehicle and integrated vertically in the Dnepr launch silo.

Launch and Insertion Operations

The Dnepr typically employs 3 staging events. At the completion of the third event, the SHM rotates 180° and ejects its gas dynamic shield. Primary spacecraft separation will be followed by the GeneSat-1 spacecraft ejection from its PPOD in a retrograde manner behind the SHM.

On Orbit Operations

After deployment, GeneSat-1 will begin to detumble using its attitude control system. Identification and orbital location of GeneSat-1 will be acquired through the Space Command orbital tracking service over the next 1-3 mission days. Once link is established with the satellite, health status and other housekeeping functions will be performed and downlinked.

Primary Payload Operations

GeneSat-1 will be commanded to begin payload operations once all of the "Go" criteria have been achieved or completed. These criteria are centered around the thermal condition and stability of the payload systems. The bacterial cultures are brought up to growth temperature and a valve is opened to flow nutrient media to the cultures. The *E. coli* cultures then grow for approximately 48 to 96 hours, depending on payload temperatures. During this phase, fluorescent and visible wavelength LEDs are cycled in a pre-programmed sequence to collect data on the growth and physiology of the bacterial cultures. This data, along with relevant housekeeping and environmental data are buffered and downlinked to the MOC for further processing.

Secondary Payload Operations

After the completion of the primary test objectives discussed above, the GeneSat-1 mission management authority will be transferred to the STC. Santa Clara University, along with other participants will then exercise the GeneSat-1 spacecraft and ground systems as part of ongoing engineering and operations training curricula. The total orbital life for GeneSat-1 is estimated to be around 4 years. Assuming key systems are able to continue functional past the end of the primary test objectives, GeneSat-1 is expected to contribute to a number of research and educational projects.

ORGANIZATIONS

Development of the GeneSat-1 mission and systems was the product of a diverse team of government, academia and industry personnel.

The NASA Astrobionics Integrated Program/Project Team at Ames Research Center led the development and testing of the GeneSat-1 payload elements. The National Center for Biological Technologies at Stanford University also contributed significantly to the development and maturation of key GeneSat-1 payload technologies, especially the optical and fluidics systems.

The Space Technology Center, comprised of Stanford University, Santa Clara University, California Polytechnic University San Luis Obispo, and Utah State University, and managed by San Jose State University led the design effort for the *.Sat bus which is the spacecraft portion of the GeneSat-1 satellite. Students at Stanford, CalPoly, and Santa Clara University made significant contributions to the design, development and operational plans for GeneSat-1, including the GeneSat-1 ground segment systems, launch operations, and mission operations functions.

The Inland Northwest Space Alliance (INSA) through its Free Flyer Research Consortium (FFRC) will provide the flight accommodations and missions operations support functions for the GenSat-1 test demonstration. INSA is comprised of a number of partners to help it fulfill its charter to provide advocacy for space exploration and to encourage space and aerospace development in the inland Northwest. INSA partners include NASA, Naval Research Laboratory (NRL), U.S. Customs Service, Bigelow Aerospace, Inc. and Infotrek, as well as many regionally based organizations, including the Space Dynamics Laboratory at Utah State University, University of Montana (UM), Salish Kootenai College, St. Patrick Hospital, Rocky Mountain Eye Surgery Center, Dinny Stranahan Research Institute, Montana Aerospace Development Association (MADA), Northern Rockies Educational Services (NRES), Northern Rockies Consortium for Space Privatization (NRCSP), and other private companies.

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REFERENCES

1. President G. W. Bush, *A Renewed Spirit of Discovery*, January 2004.

2. O. Petrovic, C. A. Kitts, R. Rasay, and M. MacKinnon, "NETROL: An Internet-Based Control Architecture for Robotic Teleoperation," *IEEE Transactions on Industrial Electronics (submitted).*

3. T. Van Buskirk and K. Weiler, An Enterprise-Class Mission Control Software Suite, Santa Clara University Undergraduate Thesis, Advisor: C. Kitts, Santa Clara, CA, June 2005.

4. P. Salas and C. Chen, Remote Automated Communications Environment IV, Santa Clara University Undergraduate Thesis, Advisor: C. Kitts and N. Quinn, Santa Clara, CA, June 2004.

5. C. Anderson and C. Kitts, “A MATLAB Expert System for Ground Based Satellite Automation,” Proc. IEEE Aerospace Conference, Big Sky, MT, March 2005.

6. D. Schuet and C. Kitts, “A Distributed Satellite Operations Testbed for Anomaly Management Experimentation," Proc. 3rd AIAA "Unmanned Unlimited" Systems, Technologies and Operations Conference, Chicago, IL, September 2004.