

Extended Life Flight Results from the GeneSat-1 Biological Microsatellite Mission

Giovanni Minelli, Christopher Kitts, Karolyn Ronzano, Christopher Beasley, Richard Rasay, Igancio Mas, Phelps Williams, Paul Mahacek, John Shepard, Jose Acain
 Robotic Systems Laboratory, Santa Clara University
 500 El Camino Real, Santa Clara CA 95053, 408.554.4382
 gminelli@scu.edu, ckitts@scu.edu

John Hines, Elwood Agasid, Charlie Friedericks, Matthew Piccini, Macarena Parra, Linda Timucin, Mike Henschke, Ed Luzzi, Nghia Mai, Mike McIntyre, Robert Ricks, David Squires, Chris Storment, John Tucker, Bruce Yost, Greg Defouw
 Astrobionics Program, NASA Ames Research Center
 Small Spacecraft Office, NASA Ames Research Center, Moffett Field CA 94035
 john.w.hines@nasa.gov

Antonio Ricco
 National Center for Space Biological Technologies, Stanford University
 Stanford CA 94305
 aricco@mail.arc.nasa.gov

ABSTRACT

The Genesat-1 technology demonstration mission validated the use of research quality instrumentation for *in situ* biological research and processing. After its launch from Wallops Flight Facility as a secondary payload off a Minotaur launch vehicle on December 16, 2006, all primary science and engineering test objectives were completed successfully within one month of operation. Since that time, additional trend analyses and experiments have been performed to further quantify the performance of the bus; such quantification is of particular interest for at least five heritage-based missions currently in development, three of which are set to launch in 2008 and two slated for 2009. This paper revisits the GeneSat-1 mission system and presents results from the extended mission.

INTRODUCTION

Since its launch in December of 2006, the GeneSat-1 spacecraft has been as a trailblazer for conducting advanced satellite technology demonstrations in the footprint of a triple CubeSat configuration. In particular, the novel biological processing technology successfully demonstrated by the GeneSat-1 platform has served to stimulate a sequence of missions that will soon lead to routine, peer-reviewed, autonomous *in situ* spaceborne biological studies.

The program objectives for the GeneSat-1 mission were to exploit the advantages of small spacecraft technology in order to develop an autonomous technology demonstration platform with sensors

capable of characterizing the behavior of cellular and microscopic organisms in space. To focus this effort, detecting levels of green fluorescent protein (GFP) in *E. coli* was selected as the baseline science investigation.¹

One of the most demanding mission constraints was the need to perform these objectives in a triple CubeSat form factor of 10 cm x 10 cm x 30 cm volume and under 5 kg of mass. This led to significant development efforts to miniaturize the optical sensing systems and develop microfluidic systems for nutrient delivery.

The small size of the vehicle also constrained power generation, which, in turn, led to challenges in the temperature control needs of the biological payload.

Furthermore, the need to ensure the viability of the biology given the 1-month pre-launch delivery drove design elements of the mission’s launch preparation and ground handling.

THE GENESAT-1 SPACECRAFT¹

As shown in Figure 1, the GeneSat-1 Space System consists of the GeneSat-1 satellite, a communication station for primary command and telemetry operations, and a Mission Operations Center.

The GeneSat-1 spacecraft, shown in Figure 1, was designed in a triple CubeSat configuration. The bus occupied one CubeSat volume while the payload was integrated in the other two. The satellite was approximately 100mm x 100mm x 340mm in dimension and weighed about 3.5 kg. The satellite bus included four body-mounted solar panels, a single battery, a PIC-based command and data handling board, a passive magnet/hysteresis rod orientation control suite, a 2.4 GHz Microhard communication transceiver, and an amateur radio beacon.

The GeneSat-1 payload, shown in Figure 2, was contained in a pressurized, sealed cylinder that housed the biological experiment. Within the cylinder was a fluidic card, shown in Figure 3, containing twelve samples of *E. coli* and support equipment designed to incubate and characterize the biology over the course of a 96-hour experiment. Support equipment included an integrated micro fluidics network, temperature control components, and the optical sensors. The internal volume also provided humidified air to exchange with the fluidics card’s microwells containing the biology via a gas-permeable membrane.

The integrated optical sensors, shown in Figure 4, were used to make two measurements of the biology. To measure fluorescence, a blue LED was used to stimulate the biology, which would respond by fluorescing in a green wavelength that was detected by the sensor. By tagging the gene associated with metabolism with GFP, the fluorescence measurement provided information about the metabolism of the *E. coli* samples.

A second measurement was made by shining a green LED through the sample, which was detected by the same optical detector. This provided an “optical density” measurement indicating the size of the *E. coli* population, which was used to normalize to fluorescence measurements.

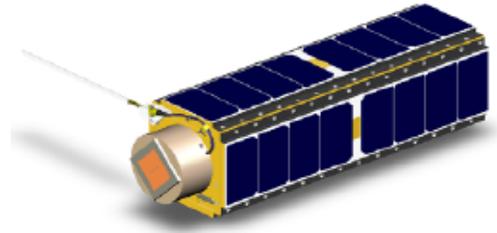


Figure 1: The GeneSat-1 Satellite



Figure 2: The GeneSat-1 Payload Module



Figure 3: The GeneSat-1 Sample Well Plate

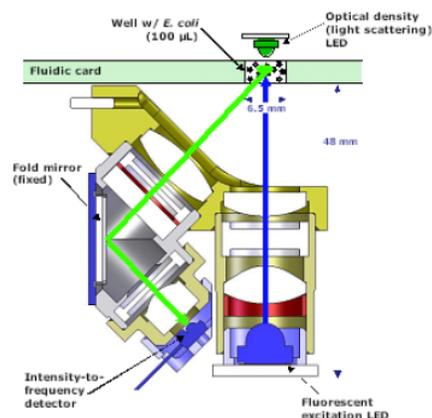


Figure 4: The GeneSat-1 Optical Detector

LONG TERM GENESAT-1 PERFORMANCE

Initial results of science and engineering operations have been previously reported.¹⁻⁴ In the year following mission success, characterizing the long-term performance of the spacecraft's various subsystems was of interest to validate the design and to investigate technologies under development which would be supporting future missions. This section presents noteworthy findings relating to the spacecraft itself.

Bus Characterization

The nominal performance of the spacecraft's bus in a year and a half of operations is a testament to the effective design employed on GeneSat-1. By collecting health and status telemetry at regular intervals over this time period several conjectures can be made on its performance.

Just after launch, solar panel telemetry, shown in Figure 5, showed that in full sunlight the panels would generate a maximum current of 1043.52 mA. After 15 months of LEO operations the highest current recorded was 1009.38 mA, as shown in Figure 6, translating to 3.28% degradation or 2.62%/year. This is an average amount of power loss and can be attributed to factors such as radiation, thermal cycling, micrometeoroid strikes, and off gassing. It is interesting to note that the voltages generated by the panels remained remarkably consistent at 10.074V in full sunlight.

Bus temperatures, shown in Figure 7, indicate that the thermal profile had not changed significantly over the lifetime of the spacecraft. The Microhard transceiver is still shown to be the hottest component on the spacecraft.

An evaluation of the register file generated by the bus PIC microprocessor indicated no CPU resets, latch-ups, or single event upsets after 18 months of operation. Additionally, experimental optics data stored in memory two weeks after launch was successfully downloaded after 15 months of storage. While experimental data is never overwritten, health and status data is overwritten every 21 days making it possible to only download recently recorded telemetry.

Lastly, it was noted that the system's clock had drifted more than 24 hours over the course of 15 months.

Payload Characterization

After mission success, the payload heater set point was changed from the experiment-required 34°C to 25°C in an effort to conserve power but to provide the spacecraft an additional source of heat. In the fall of

2007 it was noted that the payload's well plate temperature had dropped from this set point to a stable oscillating range of 5°C to 15°C despite the set point never having been changed, as indicated in Figure 8. Further analysis showed that the temperatures' fluctuations were consistent with a typical orbital period when transitioning from eclipse to sunlight and back.

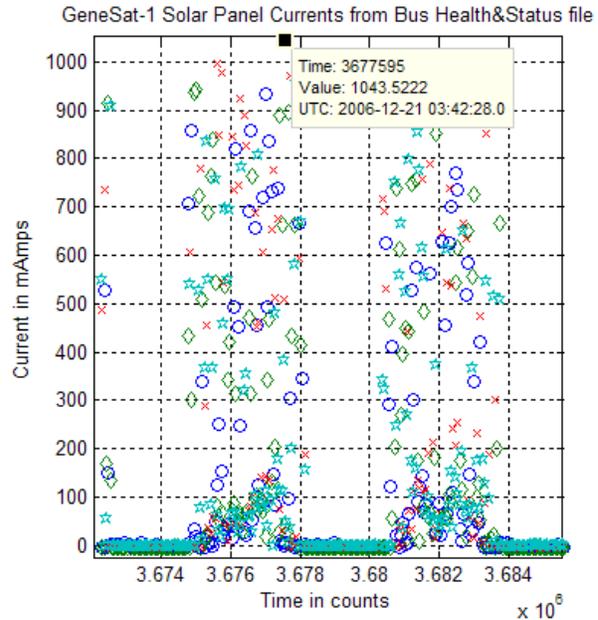


Figure 5: Solar Panel Current Telemetry

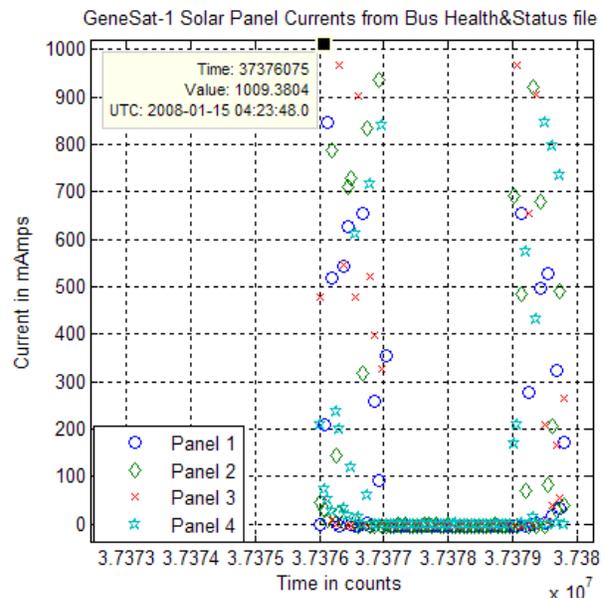


Figure 6: Solar Panel Current Telemetry

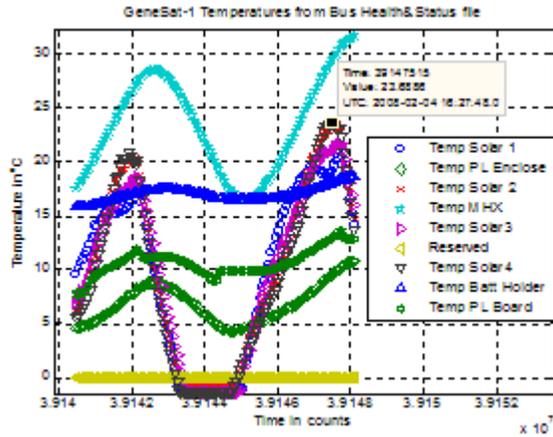


Figure 7: Satellite Temperature Profile

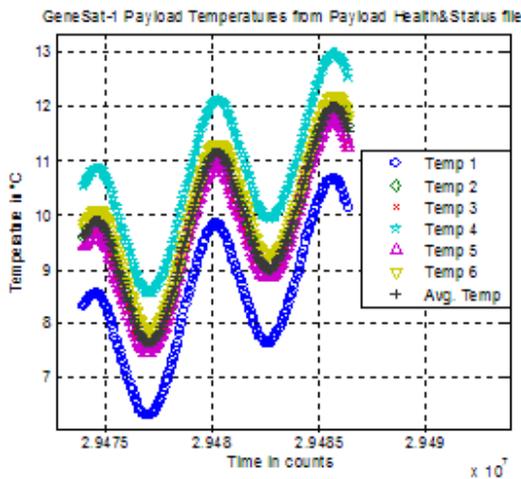


Figure 8: Payload Temperatures – Well Plate

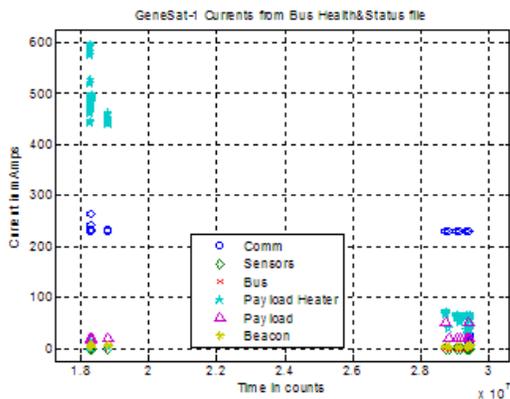


Figure 9: Spacecraft Current Draw Telemetry

When examining the spacecraft’s power telemetry it was observed that the heater’s current draw had dropped from its expected values of 500-700mA to an inconsistent 50mA, shown in Figure 9. Note the sharp drop in the heater current output depicted by the light blue data points. Changing the heater set point once more to 16°C showed no difference in results therefore justifying the conclusion of complete heater shut off.

A blown FET driving the duty-cycled heater is suspected to be the cause of the anomaly. Although the fault occurred well after the official end of the mission and does not jeopardize spacecraft health it is the most serious to date and over time has affected its thermal profile.

THE EVOLVING GROUND SEGMENT

The early success of the GeneSat-1 mission can be partially attributed to effective ground operations. This section reviews the design of the ground segment, outlines the long-term performance of GeneSat-1’s primary ground station, and reports on recent results using small 3-meter groundstations.

Ground Segment Overview

Figure 10 depicts the overall design of SCU’s distributed ground segment, which was used to support GeneSat-1 operations.⁶⁻⁸ During primary operations, which were run for the first two months of the mission, the Mission Operations Center (MOC) was the NASA Ames Research Center Multi-Mission Operations Center, pictured in Figure 11. A second mission operations center at a Santa Clara University (SCU) research building in the NASA Research Park served as the secondary MOC during this time, and became the primary MOC once extended operations began.

For contact operations, human operators at one or more locations, termed Control Node locations, would configure their workstations and contact software in order to connect via secure internet to the mission database, located in the MOC, and the communication station. The ground segment software architecture, shown in Figure 12, supports such operation from any networked location; however, for security and configuration control reasons, only pre-approved locations were used for such operations. These locations include the primary and secondary MOCs, the communication station location, and the satellite operations laboratory at SCU.

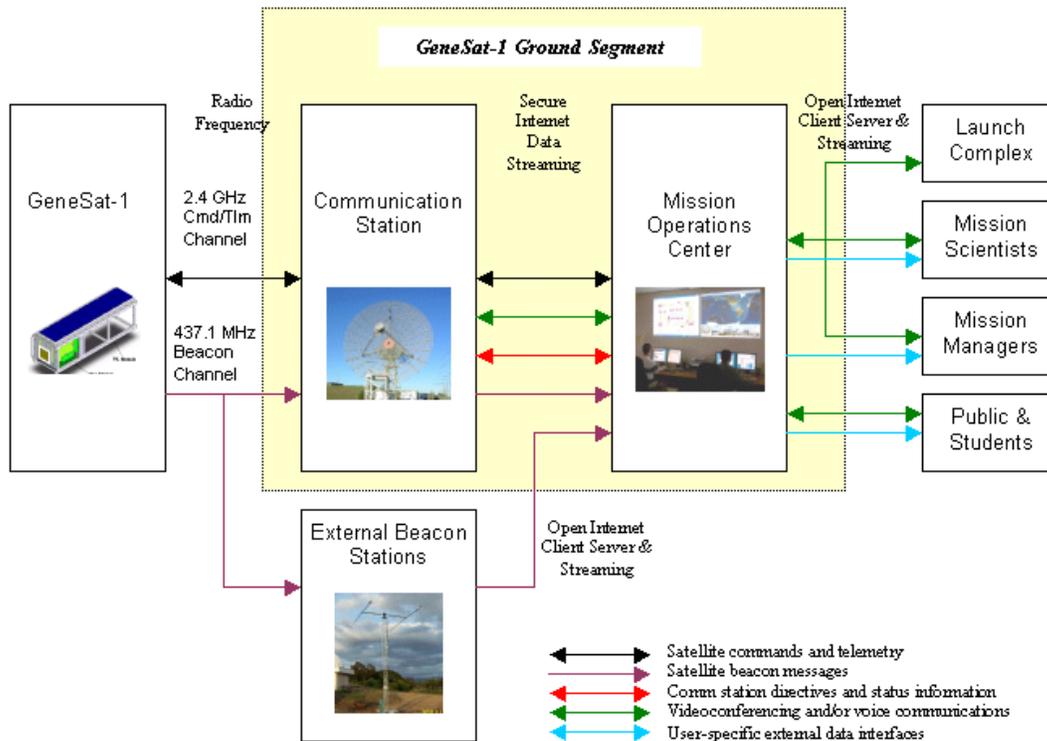


Figure 10: GeneSat-1 Ground Segment Overview



Figure 11: NASA Ames Multi-Mission Operations Center

Primary Communications Station

The primary communications station for the GeneSat-1 space system was an 18-meter parabolic antenna used for command and telemetry operations as shown in Figure 13. The antenna facility is owned by SRI International and is on land leased from Stanford University. The station was completely refurbished by

SCU students to include installing a new antenna mesh (yielding an equivalent antenna diameter of ~12 meters) and bringing in new strings of radio, data handling and computing equipment.

The driving need for an antenna of this size was due to the use of a low-cost ISM-band 2.4 GHz transceiver for the satellite command and telemetry link. This radio, the Microhard MHX-2400 which is shown in Figure 14, was not developed for space applications but had been (and continues to be) adopted by a number of low-cost small satellite missions; the GeneSat-1 flight, however, was the first flight demonstration of this unit. Indeed, one of the most requested sets of information regarding the GeneSat-1 mission is the performance of these radios and the necessary communication station requirements in order to make effective use of them.⁹

The antenna is driven by a programmed track pointing system and was recalibrated every few months by SRI personnel to maintain accuracy. The dish itself provides the 40 dBi needed to close the link with the spacecraft's transceiver. The 2.4 GHz channel radio was mounted on the tripod as well as the 437.1 MHz beacon receive antenna.

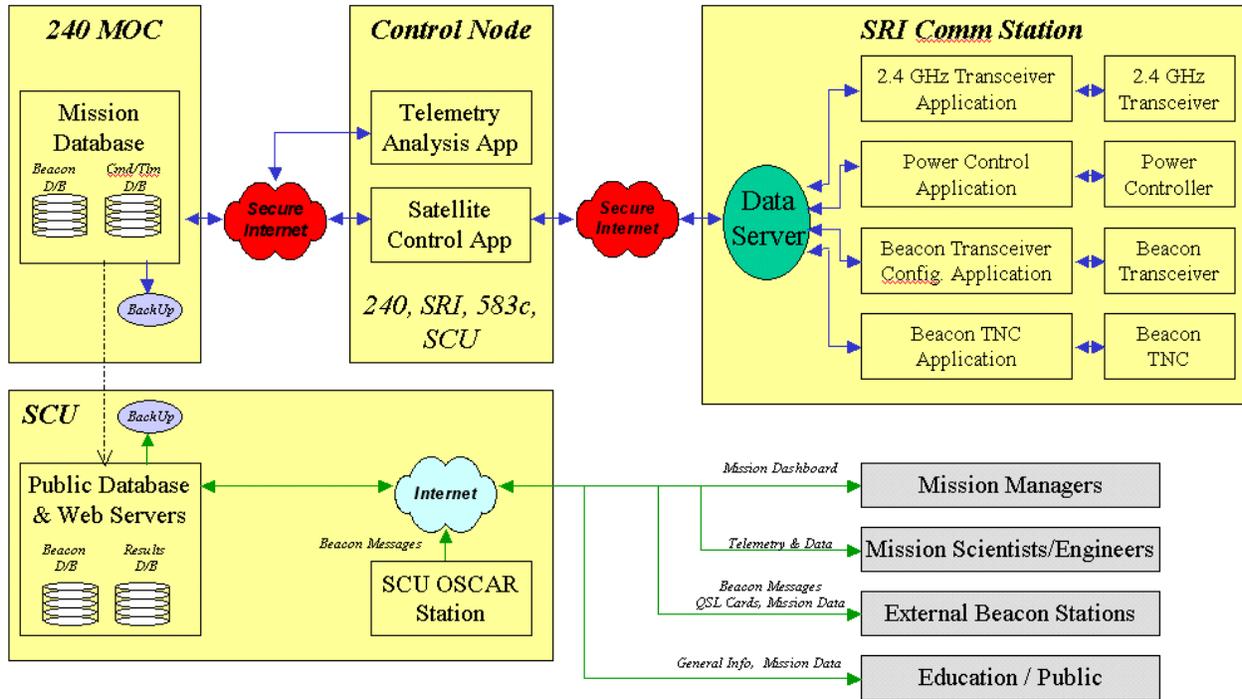


Figure 12: GeneSat-1 Distributed Ground Segment Software Architecture



Figure 13: Primary Communication Station

One year after launch, link strength between the antenna and satellite was measured to help characterize long-term transceiver operation. Figure 15 shows the signal strength from a maximum elevation of a 51° back down to loss of signal at 10° . Elevations between 50° and 70° are the most common for operations, this plot shows a maximum of 27 dB of link margin. There was no measurable degradation in link performance over the first year of operations.

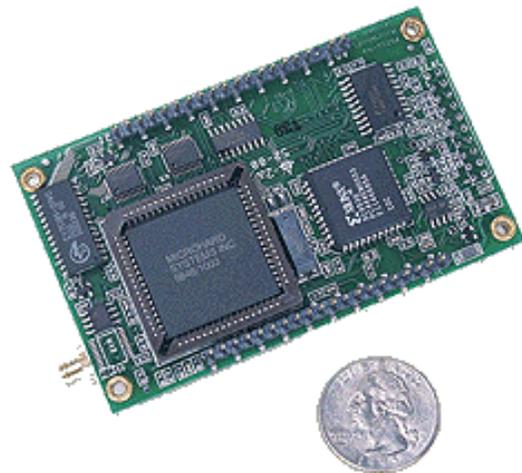


Figure 14: Microhard MHX-2400

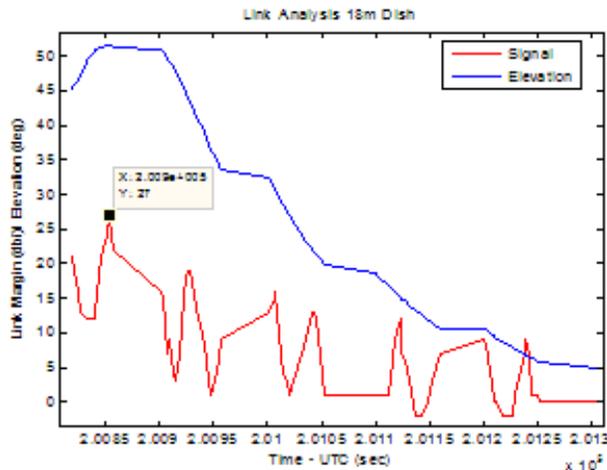


Figure 15: Link Analysis – 18m Dish

Communication performance plots such as that shown in Figure 15 also provide a means to confirm attitude characteristics such as the spacecraft's spin rate and precession. Measuring the fluctuations peak-to-peak confirms the solar panel telemetry findings of a 40-second spin rate. Precession also caused variations in signal strength on the ground as the antenna footprint onboard the satellite was continuously changing. In some cases, this behavior prevented the link to be closed.

Over time the link performance remained better when the satellite was in the southern part of the sky with respect to the ground station. It is still accepted that this is probably due to the alignment of the satellite's axis with respect to the Earth's magnetic lines, consequently pointing the antenna's footprint to the north. No measurable signal degradation was perceived due to man-made noise or time of day, though it was qualitatively noted that nighttime contacts had a slight link margin advantage.

The New Microhard MHX-2420

The transceiver vendor, Microhard, has recently discontinued the MHX-2400 product. This component has been replaced by an enhanced unit, the MHX-2420, which is claimed to support backwards compatibility with the MHX-2400 with an appropriate modification to its firmware. Given the incorporation of 2400's into a number of new spacecraft as well as the inability to get spare 2400's for ground control, this has sparked great interest in the level to which the 2420 is truly compatible with the 2400.

The GeneSat-1 operations team has verified compatibility between the units in ground-based bench testing. Performance evaluation within the GeneSat-1 ground to space link is currently planned for the Summer 2008.

Low-Cost Rapidly Deployable Ground Stations

To conduct ground operations for two new missions using the same Microhard transceiver, the SCU operations team developed several new deployable stations using a 3-meter dish to support S-Band communications. This started as a test to see if such a station could support minimal command and telemetry operations given constraints such as low daily throughput, operation only at high elevations, etc. The two missions motivating this development were to be launched from Kwajalein Atoll and inserted into a 9° inclination orbit that would not allow line-of-sight communication with the SRI dish or with any other conveniently borrowed or leased large-scale antenna.

Several analyses were performed prior to development to consider the feasibility of such smaller aperture antenna. The primary analysis was a link budget, shown in Table A. As can be seen, this analysis supported the premise that such stations could be used for limited operations.

We note a few of the considerations that make the use of this station worth considering, especially in light of the fact that such a large antenna was originally baselined for the mission. First, although a small antenna obviously has less gain (about 10 dB in this case), its beamwidth is wider, and therefore the negative effects of pointing error are less. Second, an amplifier stage was added to the system not for the purposes of amplifying the downlink (since such amplification amplifies both signal and noise) but rather in order to employ a better radio component with better noise temperature, thereby gaining an additional 1 dB. Third, in our original link analysis prior to launch of GeneSat-1, the design team was conservative with their analysis given the lack of any spaceflight experience with the transceiver.

Given this link analysis, these stations were developed using almost entirely off-the-shelf systems with some modifications for improved performance. In addition to the antenna and amplifier, a key component was a gimbal/antenna rotator with a pointing resolution of 0.5° and a maximum azimuth rate of 6°/sec. Together, these attributes allowed contact to be established with GeneSat-1 at relatively low elevations (~15°) and can support elevations as high as 70° without saturating the rotor due to azimuth rate limits.

Table A – GeneSat-1 Link Budget w/3-meter Antenna

GeneSat-1 ISM Cmd&Tlm 2.4GHz DownLink Budget			
Item	Sym	Units	DL
Orbit Altitude (km)		km	450
Elevation Angle		deg	10
Frequency	f	GHz	2.4
Transmitter Power	P	Watts	1
Transmitter Power	P	dBW	0
Transmitter Line Loss	Ll	dBW	-1
Avg Transmit Antenna Gain	Gpt	dBi	3.0
Transmit Total Gain	Gt	dB	2.0
Eq. Isotropic Radiated Power	EIRP	dBW	2.00
Propagation Path Length	S	km	1570
Space Loss	Ls	dB	-164.0
Propagation and Polarization Loss	La	dB	-3
Receive Antenna Diameter	D	M	3
Receive Antenna Eff	Eta		0.55
Peak Receive Antenna Gain	Grp	dBi	34.96
Receive Antenna Line Loss	Lr	dB	-0.5
Receive Antenna Beamwidth*	Theta	deg	2.92
Receive Antenna Pointing Error	E	deg	0.50
RX Antenna Pointing Error Loss	L _θ	dB	-0.35
Receive Antenna Gain with pointing error	Gr	dB	34.1
System Noise Temperature **	Ts	K	585
Data Rate	R	bps	86000
Eb/No (1)	Eb/No	dB	20.7
Bit Error Rate	BER		10-5
Required Eb/No (2)	Req Eb/No	dB-Hz	13.5
Implementation Loss (3)		dB	-2
Margin		dB	5.2

Upon assembly and integration, functional tests were performed with GeneSat-1 to test the capabilities, and an effective link was established. Figure 16 shows the communications performance for a typical contact. It can be seen that even at low elevations there exists a

few dBs of margin. Near maximum elevation at 57° yields 19 dB of margin. Through the maximum elevation of 78° signal is lost because the antenna could not keep up with the spacecraft. The graph indicates the next data point was recorded when the antenna had caught back up to the satellite at 19° on the tail end of the pass. While most passes are not conducted at such high elevations this was a good example of the attributes and limitations of the hardware.

Measuring the peak-to-peak time in the signal of this graph shows an average spin rate of 38 seconds. Signal degradation was more visible in the day with this antenna as well. The best contacts were conducted on cool and clear nights.

For the new missions that motivated this work, one station was installed in El Salvador and another was configured for rapid deployment to Kwajalein. Figures 17 and 18 show elements of these systems.

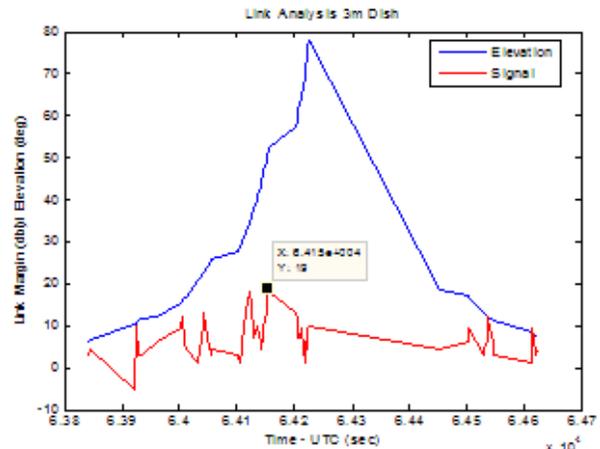


Figure 16: Link Analysis – 3m Dish



Figure 17: 3m Dish and OSCAR Antenna



Figure 18: Mission Operations Control Node

GENESAT-1 HERITAGE-BASED MISSIONS

The successful demonstration of the GeneSat-1 platform immediately spawned the use of key bus components/designs for a number of follow-on missions. Three of these missions are slated for launch in 2008 while plans are in the works for at least two for 2009.

PharmaSat

The primary follow-on mission to GeneSat-1 is the PI-science driven pharmacological experiment PharmaSat. This mission focuses on the study of the effects of microgravity on a laboratory yeast strain *Saccharomyces cerevisiae* and its resistance to antifungal agents. Photos of the PharmaSat spacecraft are shown in Figure 19.

While essentially a reflight of the GeneSat-1 bus, the payload is a complex adaptation of GeneSat-1 technologies based on the needs of the PharmaSat mission and the lessons learned from GeneSat. A larger payload canister houses a fluidics card with sixty biological sample wells and an advanced micro fluidics system capable of administering growth media to the biology as well as preparing three dilutions of pharmacological agents to dispense in later stages of the experiment. An LED-based optics system tracks the biological growth while heaters actively maintain temperature set points of both the fluidics and well plate.

The satellite's launch is currently slated for October 2008 from Wallops Flight Facility as a secondary payload. As with GeneSat-1, the SRI communication station will be used to support mission operations, although the 3-meter stations will most likely be used as well to supplement operations.

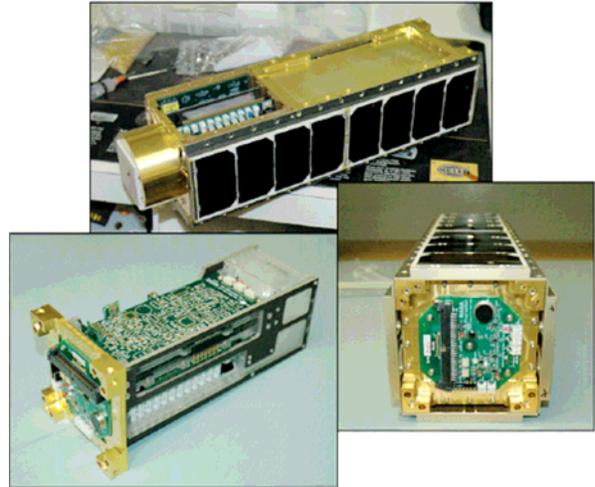


Figure 19: The PharmaSat and PreSat Satellites

PreSat

A derivative of the PharmaSat mission is the PreSat spacecraft, also shown in Figure 19, which was designed as a quick-turnaround technology validation and evaluation flight for systems used in PharmaSat, such as fluidic handling and environmental management systems. The satellite is scheduled to launch during the Summer of 2008 as a secondary payload aboard a Space-X Falcon-1 launch from the Regan Test Site in the Kwajalein Atoll.

The GeneSat-1 operations team will operate PreSat using the 3-meter stations previously described from locations in El Salvador and Kwajalein.

NanoSail-D¹⁰

The third spacecraft to fly a modified GeneSat-1 bus in 2008 is NanoSail-D, shown in Figure 20, which is slated as a secondary payload for the same launch as PreSat. This spacecraft was designed to deploy a 10 m² solar sail from its two CubeSat volume payload. The sail deployment will mark the first time this has been done with nanosat technology and will offer an opportunity to study atmospheric drag characteristics in low-earth orbit.

Additional GeneSat-1 Follow-on Missions

In 2009 and beyond, a number of additional missions may fly using extended forms of the GeneSat-1 design. As a continuation of the GeneSat-1 / PharmaSat chain of spaceborne biological laboratories, several new PI-led biological missions are being planned using GeneSat-like triple CubeSat vehicles. In addition, the

NASA Ames' COTSAT program, which is focusing on a 3-axis stabilized common bus, has baselined the use of the GeneSat-1 communications and CDH front-end for its command and control channel.¹¹ Furthermore, NASA Ames is working with a number of other partners to develop new missions capable of exploiting components and technologies demonstrated on GeneSat-1.

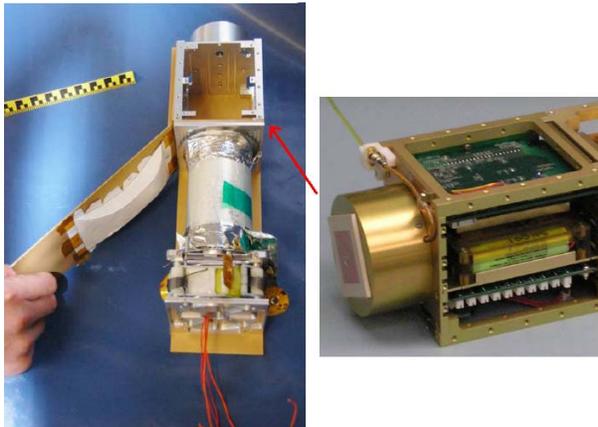


Figure 20: NanoSail-D Satellite with Bus Close-up

SUMMARY AND CONCLUSIONS

Over one year after operation and a mission success declaration, the GeneSat-1 spacecraft has proven that the designs implemented for a short-lived study can last successfully for extended periods of time. This mission continues to play an important role in the development of research-quality *in-situ* space-borne laboratories. Insights from its design as well as its prolonged operation have spawned a number of new flights carrying heritage components. This same heritage allowed for streamlined ground segment development to support new missions.

ACKNOWLEDGMENTS

Portions of the work were funded by NASA Grant No. NNA06CB13A and No. NNX07AE60A, National Science Foundation Grant No. EIA0079815, and Santa Clara University Grant No. TSC231 and No. TSC235; any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NASA Ames, the National Science Foundation, or Santa Clara University.

REFERENCES

1. 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
2. Yost, B., et al., "The GeneSat-1 Test Demonstration Project: A Unique Use of Small Satellites," Proc 19th Annual AIAA/USU Conf on Small Satellites, Logan UT, 2005.
3. Kitts, C., et al., "The GeneSat-1 Microsatellite Mission: A Challenge in Small Satellite Design," Proc 20th Annual AIAA/USU Conf on Small Satellites, Logan UT, 2006.
4. Ricco, A., et al., "Integrated System to Analyze the Genetic Effects of the Space Environment on Living Cells in Culture: GeneSat," 8th European Conference on Optical Chemical and Biosensors, Tubingen, Germany, April 2006.
5. Ricco, A.J., et al., "Autonomous Genetic Analysis System to Study Space Effects on Microorganisms: Results from Orbit," Proc. of Transducers'07: The 14th International Conference on Solid-State Sensors, Actuators and Microsystems, Lyon France, June, 2007.
6. D. Schuet and C. Kitts, "A Distributed Satellite Operations Testbed for Anomaly Management Experimentation," Collection of Technical Papers—AIAA 3rd "Unmanned-Unlimited" Technical Conference, Workshop, and Exhibit, Chicago, IL, September, 2004.
7. Kitts, C, and M. Rasay, "Responsive Small Satellite Mission Operations Using An Enterprise-Class Internet-based Command and Control Network," Accepted for Proceedings of AIAA Space 2008 Conference, San Diego CA, 2008.
8. Van Buskirk, T., and K. Weiler, Enterprise Class Mission Control Software Suite for the NASA GeneSat-1 Spacecraft. Advisor: C. Kitts. Santa Clara University Undergraduate Thesis, June 2005.
9. Mas, I., and C. Kitts, "A Flight-Proven 2.4 GHz ISM Band COTS Communications System for Small Satellites," Proc. 21st Annual AIAA/USU Conf on Small Satellites, Logan UT, 2007.
10. Whorton, M., A. Heaton, and R. Pinson, "NanoSail-D: The First Flight Demonstration of Solar Sails for Nano-Satellites," To appear in Proc. 22nd Annual AIAA/USU Conf on Small Satellites, Logan UT, 2008.
11. Spremo, S., et al, "Low-Cost Rapid Response Spacecraft, LCRRS (CheapSat) – A Research Project in Low-Cost Spacecraft Design and Fabrication While Maintaining Flight Standards in a Rapid Prototyping Environment," To appear in Proc. 22nd Annual AIAA/USU Conf on Small Satellites, Logan UT, 2008.