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A Flight-Proven 2.4GHz ISM Band COTS Communications System for Small Satellites

Ignacio A. Mas
Robotics Systems Laboratory, Santa Clara University
500 El Camino Real, Santa Clara, CA 95053; 408-551-6047
iamas@scu.edu

Christopher A. Kitts
Robotics Systems Laboratory, Santa Clara University
500 El Camino Real, Santa Clara, CA 95053; 408-554-4382
ckitts@scu.edu

ABSTRACT

A communications system operating in the 2.4GHz ISM unlicensed band was developed for GeneSat-1, an innovative technology demonstration mission intended to validate the use of research quality instrumentation for *in situ* biological research and processing. As a key underlying mission-enabling technology, and responding to a low-cost, quick turn-around philosophy, this communications system is based on commercial-of-the-shelf components not originally intended for space flight. The system utilizes a frequency hopping spread spectrum technique widely used in wireless phones, Internet hubs and other devices. This approach provided exceptional benefits relevant to small satellite missions: low cost, highly integrated hardware resulting in small volume, ready commercial availability, plug and play integration, and simple licensing requirements. As a comparison with typical amateur band systems widely used in spacecraft of this class, besides avoiding the restrictions on the nature of the mission, it has the potential for higher throughput and includes security features such as addressing and encryption. Challenges in using this component included the accommodation of Doppler frequency shift, coordinating propagation delays with a time-division multiplexing architecture, and establishing suitable interface requirements for the Earth communication station. GeneSat-1 is a “triple-CubeSat” vehicle launched into LEO in December 2006. Its main mission objectives were successfully achieved during the first few weeks of operation This paper presents a description of the comprehensive analysis and testing produced to attain space qualification and measures of on-orbit performance collected during spacecraft operations, including link availability, effective telemetry throughput and link margin.

INTRODUCTION

The mission of the GeneSat-1 technology demonstration spacecraft was to validate the use of research quality instrumentation for *in situ* biological research and processing. GeneSat-1 is a “triple-CubeSat” vehicle that was launched as a secondary payload on a Minotaur launch vehicle in December 2006. Spacecraft and mission development was led by the NASA Ames Research Center Astrobionics group[1]. However, university participation was a crucial element of the program with significant contributions being made from a number of academic groups throughout the Silicon Valley region. Stanford University developed the first prototype of the satellite bus to include the selection of the communication system[2], California Polytechnic State University provided a "P-POD" satellite deployer for adaptation, and Santa Clara University developed the Internet-based ground segment and conducted all on-orbit mission operations tasks.

The spacecraft communication subsystem was conceived having in mind two primary objectives: rapid development -within one year- and low cost. These objectives were approached by relying on non-flight-qualified, commercial-off-the-shelf (COTS) products and by putting the stress on analysis and testing.

COMMUNICATIONS SYSTEM DESCRIPTION

Rationale and Requirements

A key point in the project was deciding the frequency band the system would operate on. Due to the aggressive schedule, any attempt to obtain a regular NASA frequency would have imposed at least a two-year delay, which was unacceptable for the mission timeline. On the other hand, the nature of the project would not have complied with the basic requirements needed for the use of an amateur frequency. These reasons, together with the huge development of unlicensed-band wireless technology in the last few years gave us a chance to adopt this new paradigm in space applications. An immense variety of devices in the Industrial-Scientific-Medical Band (ISM) are found nowadays in the market, some of which show an excellent performance, high integration and low cost.

In this particular mission, the satellite would operate in a low Earth orbit, at 410 km of altitude, with an inclination of 40 degrees. Downlink data volume was not particularly demanding given that critical science data was generated at a rate of 75 Kbytes per day only during the 96 hours of biological activity. Low rate vehicle health and status data was generated throughout the mission lifetime to meet secondary mission objectives. Telemetry and science data are downlinked to the ground upon operator request.

Transceiver

A trade study among several ISM band Frequency Hopping Spread Spectrum radios was conducted and the OEM MHX-2400 transceiver from Microhard Systems Inc.[3] was chosen for being the best match for the application. Major advantages over other options were its 1-watt RF output power, its comparatively good sensitivity, a relatively slow frequency hop time interval, its compact size, and its operational flexibility. Built-in features of this module include addressing, retransmission protocols, encryption and forward error correction.

Figure 1: Microhard MHX-2400

The over-the-air data rate is fixed at 172 kbps providing a theoretical maximum throughput of 83kbps. The signal is Gaussian Frequency Shift Keying (GFSK) modulated. It has 20 pseudo-random, user selectable frequency hopping patterns. The transceiver is a full radio-modem that performs packetization, modulation and demodulation.

The MHX-2400 electrical interface is particularly simple, which promotes rapid integration. It accepts regulated 5 Volts from the electrical power subsystem and communicates with the Command and Data Handling (C&DH) processor through a serial port with selectable data rates of up to 115.2 kbaud. Hardware flow control is used to manage data flow.

Table 1 depicts the main specifications of the transceiver.

Table 1: MHX-2400 Specifications

Parameter	Value
Band	2.4GHz ISM
Transmission Method	Freq. Hopping Spread Spectrum
Serial Data Rate	up to 115kbps
RF Output Power	up to 1W, selectable
Power Consumption (Rx/Tx)	1.15W / 4.38 W
Sensitivity (@25ºC)	-105 dBm
Max. Throughput	83kbps (no delay)
Weight	75 grams
Size	90 mm x 53 mm x 25 mm

Because of limitations on the satellite C&DH software, the serial data rate used for this mission was 9600 baud. This fact limited the effective throughput of the system.

The RF input/output to the antenna is a single MCX type connector. The electrical connections are depicted in Figure 2.

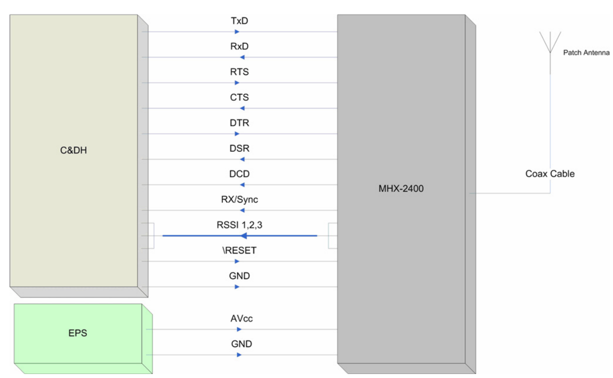

Figure 2: MHX-2400 Electrical Interface

Antenna

A microstrip or patch type of antenna was selected as the best candidate for the mission. This conformal antenna does not need to be deployed, which makes the mechanical design and integration with the P-POD deployer much simpler. Also, a patch antenna at

2.4GHz fits conveniently in one of the 10x10mm faces of the satellite structure. Additionally, circular polarization is easily achieved by design.

Because this antenna is directional, it sets pointing requirements on the spacecraft attitude. A simple passive attitude control system was developed using permanent magnets, which were aligned with the long axis of the spacecraft and hysteresis rods, placed perpendicular to the magnets.

Antenna Design

Given the relative simplicity of microstrip antenna design, a custom microstrip patch antenna was considered for this mission. RT/duroid 6002 Teflon based ceramic laminate from Rogers Corporation was selected as the substrate[4]. This microwave laminate is a ceramic-PTFE composite designed for microwave circuit applications requiring a high dielectric constant. Its extremely low loss at high frequencies and tight specification control make it a suitable material for this application.

Considering a dielectric constant $\varepsilon_r = 2.94$, a thickness h = 3.048mm and a center frequency of 2.45GHz, using the transmission line model[5], the derived patch resonant length is 32.7 mm.

To achieve circular polarization, a slot was introduced in the patch together with a 45-degree offset of the feed point[6]. The slot dimensions are 16mm x 0.5mm. The feed point is located at 12.6 mm from both edges.

The antenna was bonded to the spacecraft structure using electrically conductive silver epoxy to assure good grounding to the spacecraft.

Antenna Simulations and Prototype

Simulations were performed using the HFSS software package from AnSoft Corporation starting with the dimensions given by the transmission line model equations and tuning the values in order to get the desired results. Convergence was tested for each case separately in terms of evaluating the S11 parameter at a single frequency for a number of times. Once convergence was obtained, simulations were conducted in order to obtain swept frequency response extending from 2 to 3 GHz. The swept response gave the S11 parameter, which was used to calculate the VSWR referred to a 50Ω transmission line. After that, the radiation pattern was computed.

Antenna return loss is shown in Figure 3. The antenna bandwidth extends from 2.4 to 2.486GHz or 3.51 % within 1.5:1 VSWR. VSWR is less than 1.5:1 throughout the entire ISM band.

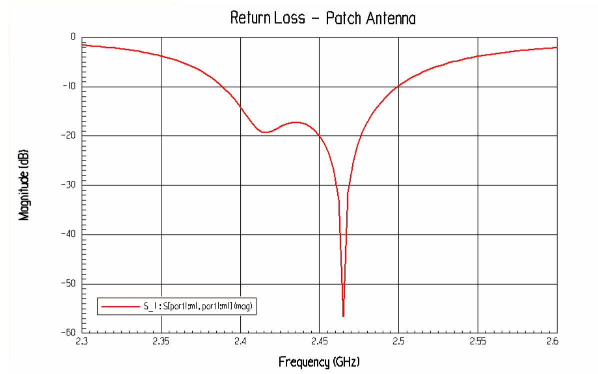

Figure 3: Microstrip Antenna Return Loss

Figure 4 shows the simulated radiation pattern of the patch antenna. The antenna gain is approximately 8 dBi and the -6dB beam width is ±60 degrees. The slot inserted in the patch creates a 90-degree shift in the signals propagating in the two dimensions of the patch, creating a right hand circular polarization (RHCP).

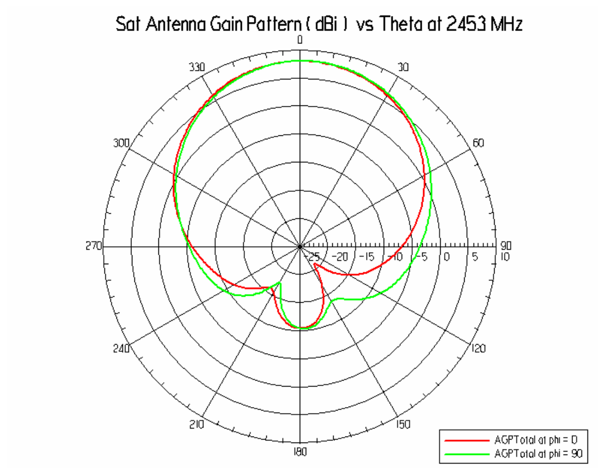

Figure 4: Microstrip Antenna Radiation Pattern

Figure 5 shows the flight antenna before integration, and Figure 6 illustrates the position of the microstrip antenna in the satellite. Table 2 summarizes the antenna specifications.

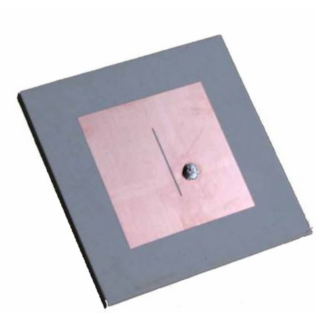

Figure 5: Microstrip Antenna

Table 2: Microstrip Antenna Specifications

Parameter	Value
Frequency Band	2.4GHz ISM (2.40~2.48GHz)
Max. Gain	8 dBi
Beam Width (@ -6 dB)	±60 degrees
Polarization	Right Hand Circular Polarization
VSWR	Better than 1.5:1
Operating Temperature	-55 to 125 degrees C
Weight	22 grams
Dimensions (incl. substrate)	50 mm x 50 mm x 3 mm

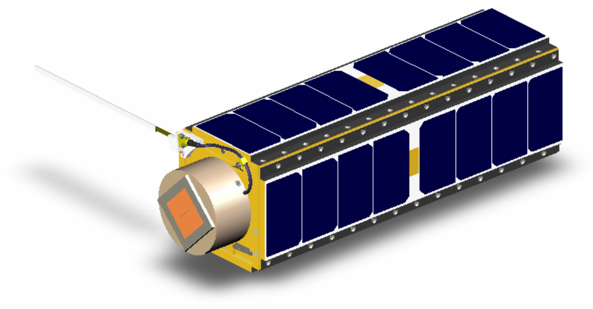

Figure 6: GeneSat-1 Showing Microstrip Antenna

Earth Station

The Communication Station used for the mission is a facility owned and operated by SRI International and located on land leased from Stanford University. The facility consists of a 60-foot parabolic antenna driven by a programmed track antenna pointing system.

The surface mesh was conditioned to operate at 2.4GHz. The gain at such frequency is approximately 50 dBi and the -3dB beam width is approximately 0.5 degrees. The antenna is only operated at elevations higher than 10 degrees in order to minimize harmful interference in the local region.

The parabolic reflector diameter is significantly larger than what is required to close the link with the spacecraft. This large diameter implies a narrow beam width, which was a concern given the expected antenna pointing errors.

For these reasons, the parabolic antenna is only illuminated over a 10-meter diameter area using a feed horn with a higher F/d ratio than appropriate for a 60-foot (18 meter) diameter antenna thereby creating a slightly less directive, wider beam. The resulting effect is a 10-meter dish antenna with a gain of 45 dBi and a beam width of approximately 1 degree. In this situation, the beam width is 5 times greater than the satellite position determination accuracy[7], therefore facilitating the communication with the spacecraft. Also, illuminating a smaller area of the dish reduces the spillover effect, increasing the total efficiency of the antenna.

A feed for the 2.4 GHz command and telemetry communication channel was mounted on the antenna tripod at the focal point. The feed horn is excited by two probes at 90 degrees from each other through a 3dB Hybrid Coupler to provide the appropriate right hand circular polarization.

A Microhard MHX-2400 transceiver, identical to the one onboard the GeneSat-1 spacecraft, is used for command transmission and data reception at the Earth station. The ground transceiver is set in *Master Mode*. In this role, it is in charge of sending synchronization data to the spacecraft transceiver in order to establish a communication.

Figure 7: SRI Earth Station 60-foot Dish Antenna

The transceiver is installed in a weatherproof box and placed next to the feed horn on the antenna tripod, using an RF coax cable length shorter than 3 feet to minimize attenuations. The box contains the MHX-2400 module, a Microhard Evaluation Board, which converts the transceiver's TTL interface to RS232 levels and which also provides power regulation, and an RS232/RS485 converter. The Box is powered with 12V @1.2A and 9V @300mA for the transceiver and the converter respectively. The RS485 signal runs from the weatherproof box to the Earth station electronics room where it is converted back to RS232 and then connected to the communication station data handling workstation. The system does not include any additional low noise amplifier or filtering.

DESIGN ANALYSIS

Link Budget

The link budget was calculated considering the Microhard MHX-2400 transceiver at its mission operating power of 1Watt. The spacecraft antenna pointing error is assumed to be 45 degrees, by taking the worst case of the attitude control accuracy (around 15 degrees) and a inherent magnetic lines to nadir offset of 30 degrees at the Earth station latitude. An effective 10-meter parabolic dish reflector was considered as a Earth station antenna. The receiver's noise figure is 4.5dB as specified by the manufacturer. Table 3 shows the downlink budget for different spacecraft elevations. Results provide a link margin of 10dB at the minimum operating elevation and 22dB at maximum elevation. Uplink margins are obtained in a similar fashion with minimal variations.

Access Time and Throughput

Access time simulations were run using STK from Analytical Graphics Inc. For the given orbit, and considering contacts only at elevations above 10 degrees, the average pass time is 3 minutes and 48 seconds and the maximum pass time is 6 minutes.

In terms of throughput, the transceiver allows a maximum theoretical throughput of around 83kbps, making use of a fixed over-the-air data rate of 172kbps. For this mission, the spacecraft data flow bottleneck is given by the Command and Data Handling processor, which transfers data to and from the communications system at a rate of 9600bps. Also, the single thread flight software needs some idle time between consecutive command processing limiting the uplink command capability to one command every 5 to 10 seconds. These limitations do not permit the system to take full advantage of the transceiver capabilities, but the component's performance was still sufficient to satisfy the not-so-demanding payload mission data and bus health and status telemetry volume requirements.

Power Budget

During the mission, the spacecraft transceiver is used in *Slave Mode* to reduce power consumption at the maximum RF output power of 1 Watt. The Hopping Interval is set to 100 msec. and the Maximum Packet Size to 255 bytes in order to reduce the impact of path delay due to distance between transceivers, as detailed in following sections. The transceiver power consumption was measured in the laboratory in this configuration. The results are shown in Table 4.

Table 3: Downlink Budget

Item	Units	DL	DL	DL
Orbit Altitude	km	410	410	410
Spacecraft Elevation Angle	deg	10	45	90
Frequency	GHz	2.4	2.4	2.4
Transmitter Power	Watts	1	1	1
Transmitter Power	dBW	0	0	0
Transmitter Line Loss	dBW	-1	-1	-1
Transmit Antenna Gain	dBi	1	1	1
Eq. Isotropic Radiated Power	dBW	0	0	0
Propagation Path Length	km	1466.32	563.29	410.00
Space Loss	dB	-163.38	-155.07	-152.31
Polarization Loss	dB	-3	-3	-3
Receive Antenna Diameter	m	10	10	10
Receive Antenna Eff		0.55	0.55	0.55
Peak Receive Antenna Gain	dBi	45.42	45.42	45.42
RX Antenna Line Loss	dB	-0.5	-0.5	-0.5
RX Antenna Beam width	deg	0.88	0.88	0.88
RX Antenna Pointing Error	deg	0.33	0.33	0.33
RX Ant. Pointing Error Loss	dB	-1.68	-1.68	-1.68
RX Ant Gain w/pointing error	dB	43.24	43.24	43.24
System Noise Temperature	K	585	585	585
Data Rate	bps	172000	172000	172000
Eb/No	dB	25.44	33.75	36.51
Bit Error Rate		10-5	10-5	10-5
Required Eb/No	dB-Hz	13.5	13.5	13.5
Implementation Loss	dB	-1	-1	-1
Margin	**dB**	**10.94**	**19.25**	**22.01**

In orbit, when the transceiver is not in contact with the ground, it is continuously listening for a synchronization signal to start communications. Considering a 410 km orbit, the transmission duty cycle is approximately 2%, with a maximum transmission time of 6 minutes and a minimum time between accesses of 85 minutes.

Table 4: MHX-2400 Power Consumption

Mode	Mean Power (W)	Peak Power (W)
Standby/Receiving	1.15	1.15
Receiving (w/ACK)	1.45	5.51
Transmitting	4.38	5.51

Pointing Budget

The link requires an Earth station antenna with high gain. In consequence, the beam width of the antenna is narrow, and the pointing requirement is important. The GeneSat-1 link margin as a function of the Earth station antenna pointing error is shown in Figure 8.

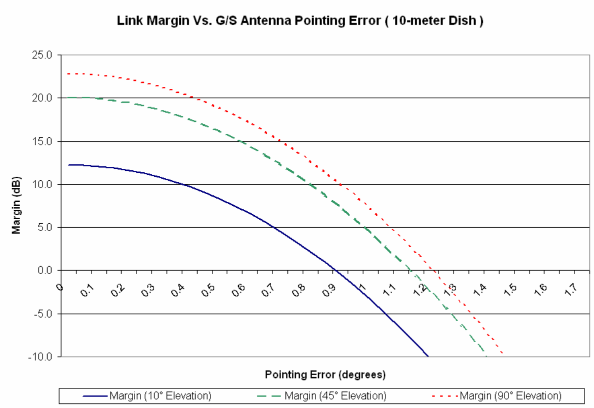

Figure 8: Link Margin as a Function of Earth Station Pointing Error

It can be seen that for a satellite at 10 degrees elevation in a 410km orbit, when using a 10-meter dish as an Earth station, the pointing accuracy must be better than 0.9 degrees in order to close the link. The desired pointing accuracy, in order to get a sustained low BER connection, is 0.5 degrees or better.

Ephemeris information provided by NORAD has an estimated accuracy of 1km[7]. For a 410km orbit, that means an uncertainty of approximately 0.1 degrees. The SRI Earth station tracking system has an accuracy of approximately 0.16 degrees. The complete pointing error budget is shown in Table 5 resulting in a total error of 0.327 degrees.

Mass Budget and Mounting Scheme

The communications system components and mass details are shown in Table 6. The GeneSat-1 spacecraft total mass is 3.5kg and the total mass of the communications system is 190 grams or 5.4% of the satellite mass.

The transceiver module is physically comprised of an exposed bottom side containing low frequency logic electronics and the top side containing the RF circuitry. The top part is contained in a metal box for electromagnetic interference protection. The metal box has holes that allow for air evacuation. The bottom side of the module was conformal coated for flight while the top side was not modified.

Table 5: Earth Station Pointing Error Budget

Source of Error	Magnitude	Pointing Error (deg)
Earth Station Location uncertainty	5 m	0.002
Antenna Misalignment	0.01 deg	0.01
Tracking Software	0.02 deg	0.02
Reflector Mech. Sag	0.05 deg	0.05
Orbital Elements	1 km	0.07
Time Uncertainty	0.01 sec	0.005
Antenna Encoders Resolution	0.01 deg	0.01
Thermal Effects	0.01 deg	0.01
Slew-induced Vibrations	0.05 deg	0.05
Margin	0.1 deg	0.1
TOTAL ERROR		0.327

Table 6: Mass Budget

Component	Mass (Grams)
MHX-2400	70
Heat Sink Plate	35
Screws and Bolts	4
Thermal Pad	20
Microstrip Antenna	22
Coax Cable Assembly	9
TOTAL	160

The MHX-2400 is plugged into the C&DH card and the top case is in contact through a thermal-conductive pad with a heat sink that allows for thermal conduction to the spacecraft structure as shown in the bus assembly diagram of Figure 9.

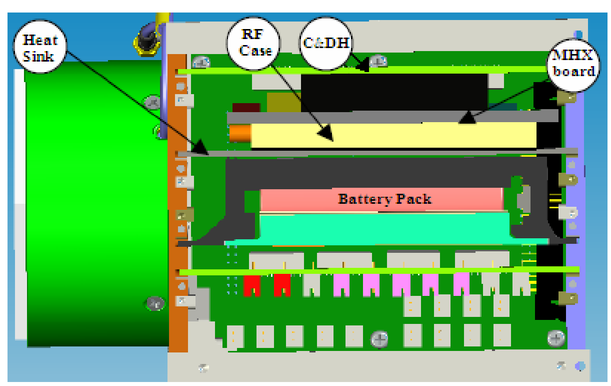

Figure 9: GeneSat-1 Bus Assembly

Security

The MHX-2400 transceiver encrypts its data by utilizing an encryption key selected by the user and stored in the module's configuration registers. The possibility of contacting the spacecraft radio from a non-authorized Earth station is minimized by the broad set of configuration parameters that need to be equally set in both transceivers. There are approximately 10^{17} possible configuration combinations that make for a sufficient level of security through configuration obscurity.

SPACE QUALIFICATION

The purpose of the space qualification process is to define and execute a method for inserting a Commercial-Off-The-Shelf (COTS) transceiver into a space flight system.

Doppler Shift

Doppler shift is a consequence of the relative velocity between a transmitter and receiver. Doppler shift cannot be compensated in the MHX-2400 transceiver. For that reason, the radio has to be able to handle the frequency shift for the mission orbit.

The MHX-2400 transmitted signal is approximately 200 kHz wide. The receiver bandwidth is about 400kHz. While this can be considered an inefficient feature of the receiver, due to the unnecessary increase in noise entering the unit, it also allows for signal shifts to fall within the receiver bandwidth. This is the case when the signal is shifted due to Doppler effect.

The MHX-2400 was tested using the configuration shown in Figure 10. The transmitted signal was mixed twice with CW signals in the same band, making appropriate use of attenuators and filters, effectively shifting the transmitted signal from F_{tx}=2.4GHz to F_{rx}=2.4GHz+(F_2-F_1). Results showed that the receiving unit successfully demodulated signals with shifts of up to 55 KHz, which is the maximum Doppler shift at 2.4GHz for a 410km orbit.

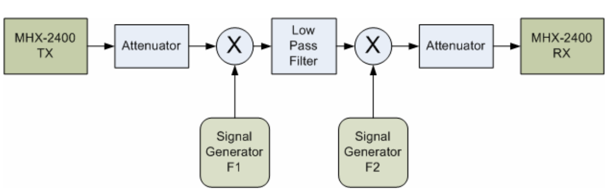

Figure 10: Doppler Shift Test : F_{rx}= 2.4GHz+(F_2-F_1)

Path Delay

When radio waves travel long distances between transmitter and receiver, such as in a satellite application, the propagation delay could be significant and could affect the data protocol in the modem.

Tests were conducted in the lab as well as at Microhard Corporation[3] using only the digital stage of two radios, bypassing the RF circuitry, and connecting the TX and RX digital outputs and inputs through a digital delay circuit. The test setup is shown in Figure 11. The waveforms on probes 1-6 of the test setup are shown in Figure 12.

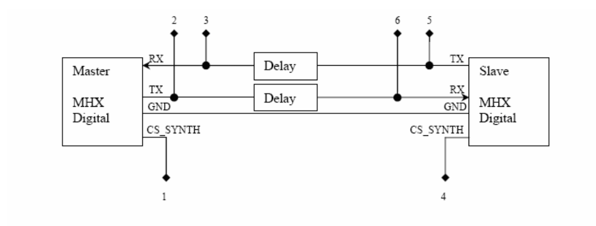

Figure 11: Propagation Delay Test Setup

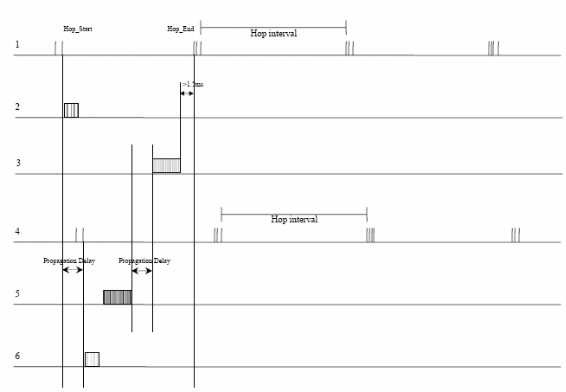

Figure 12: Propagation Delay Test Waveforms

The maximum delay expected for the 410 km orbit is around 10msec. Any data exchange should be completed 1.5msec before *Hop_End* happens in order for the protocol to correctly decode the information.

Setting the Hop Interval (register S109) to 100msec and the maximum packet size to 255Bytes (register S122) allows sending any packet in both directions, finishing the data exchange within the same Hop Interval. As a result, the effective throughput of the transceiver is decreased around 20% in order to accommodate for the propagation delay.

Thermal Cycling

The MHX-2400 transceiver was tested in a thermal-vacuum chamber using the setup depicted qualitatively in Figure 13. The chamber was brought down to 10^{-5} Torr and temperature was cycled five times from 50 to

–40 degrees Celsius holding the temperature for 30 minutes in each state while the transceiver was operated.

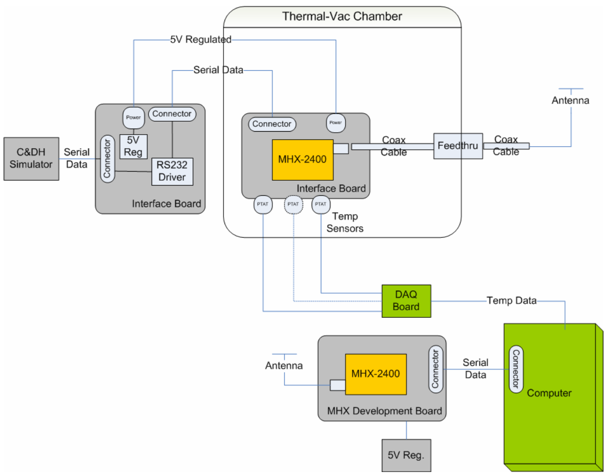

Figure 13: Thermal-Vacuum Test Setup

Results showed an excellent performance in this simulated space environment. Figure 14 illustrates a portion of the thermal cycle with temperatures measured on different parts of the transceiver as well as in the chamber cooling/heating plate.

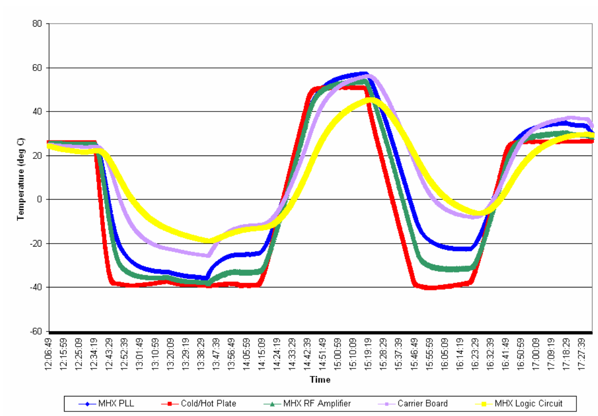

Figure 14: Thermal-Vacuum Results

Space Radiation

Given the low altitude of the LEO orbit where the satellite was intended to operate, the radiation effects were considered negligible and no further steps were taken to radiation harden the unit. Nonetheless, latch-up protection circuitry was put in place in the Electronics Power Subsystem (EPS) to monitor the transceiver current draw and to shut down power supply momentarily if an anomaly was detected.

Environmental RF Noise

Many concerns were raised in the community regarding the environmental man-made noise existing in the band due to the wide proliferation of ISM band devices in the recent years.

Noise surveys were conducted in the Earth station area and compared with previous measurements taken in other sites. Results showed that although some background noise levels were clearly noticed –averaging a 10dB noise increase–, these levels were particularly lower –20 to 30 dB lower– than those found in highly populated areas. The geographical location of the Earth station antenna, in the Stanford foothills a few miles away from residences, played a critical role in this attenuation.

FLIGHT RESULTS

On December 16th 2006, GeneSat-1 was successfully launched as a secondary payload in a Minotaur-1 rocket and inserted into a 412x410km, 40.5 degrees inclination orbit.

Satellite Access

During the first day of operations satellite ephemeris was obtained through propagation of pre-launch state vectors and no contact with the satellite was achieved due to the lack of accuracy of such calculations. On the second day NORAD published the first set of TLEs, which allowed the Ground Operations team to establish a radio link with the spacecraft.

From that point on, access to the satellite was achieved on every attempted pass except a few times where mechanical issues associated with the Earth station dish tracking system caused the loss of link. Some improvement on link performance was noted as the first two or three weeks of operations went by, most certainly due to the improved accuracy of the NORAD TLEs.

Table 7 shows predicted and measured access time statistics over 4 months of operations. The in-flight measured average pass time is approximate 20% below the expected value derived from simulations. As will be discussed in following sections, this is probably due to an unsteady pointing of the spacecrafts antenna.

Table 7: Access Time Statistics

Parameter	Predicted	In-Flight Measured
Average Pass Time	3'48''	3'04''
Maximum Pass Time	6'00''	5'10''

It was noted that link performance was noticeably better when the satellite was in the southern part of the sky with respect to the Earth station than when it was on the northern half of the sky. This is probably due to the alignment of the satellite with the Earth's magnetic lines that provides a north-pointing attitude during the passes. No measurable signal degradation was noticed due to man-made noise when pointing the Earth station antenna towards the known sources of interference. Furthermore, no variations due to time of day were perceived, a characteristic that was monitored given the assumed increase in use of the 2.4 GHz frequency band during the daytime hours.

During the period of operations approximately 500kBytes of data containing payload science information and bus telemetry was transmitted to the ground.

Thermal Profile and Space Environment

Telemetry from the spacecraft showed the transceiver as the hottest component of the spacecraft, with a recorded maximum temperature of 33.4 degrees C and a minimum of 8.6 degrees C. The average temperature value was approximately 23 degrees C, and the swing from sunlight to eclipse was typically around 14 degrees C.

Figure 15 shows telemetry data with a typical transceiver temperature trend together with external solar panels temperatures throughout three orbits.

No latch-ups, software resets or single event upsets were detected during the first four months of operations.

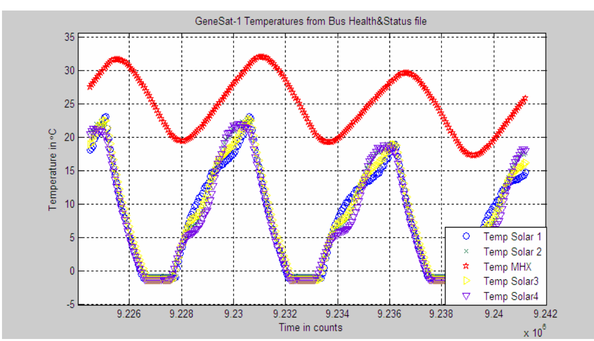

Figure 15: Microhard Temperature in Space

Satellite Attitude

Solar panel current measurements were taken at high data rates to observe satellite attitude as a means of verifying the effectiveness of the passive attitude control system. Figure 16 shows a short fraction of the measured solar current trends for two solar panels. From this information satellite attitude was estimated. The spacecraft is spinning around its long axis with a period of approximately 40 seconds. This happens together with an axis misalignment of approximately 25 degrees with a precession period of 275 seconds.

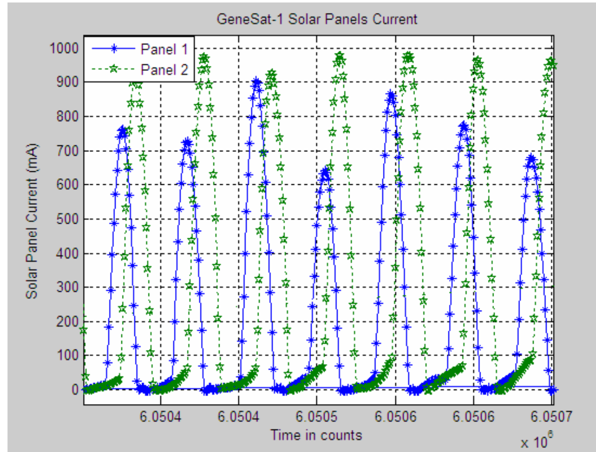

Figure 16: Measured Solar Panels Current

Link Margin Measurements

One of the key design parameters to be verified in flight was the link margin, given its criticality and the significant level of estimation involved in its derivation. Signal strength measurements were taken along the satellite pass over the Earth station on multiple occasions using one of the built-in features of the transceiver. Figure 17 depicts some of those readings locating them at the corresponding satellite elevation and azimuth position with respect to the Earth station.

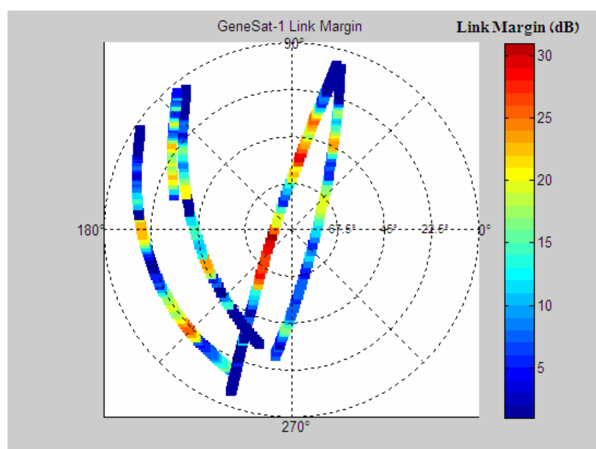

Figure 17: On-orbit Link Margin Measurements

Figure 18 contains link margin values and satellite elevations for one single pass. The oscillatory nature of the link's quality due to the changing spacecraft attitude can be seen. Both precession and spinning affect the on-board antenna footprint on the ground, causing variation in the performance of the link. This behavior even prevents the link to be closed during some instants of the pass.

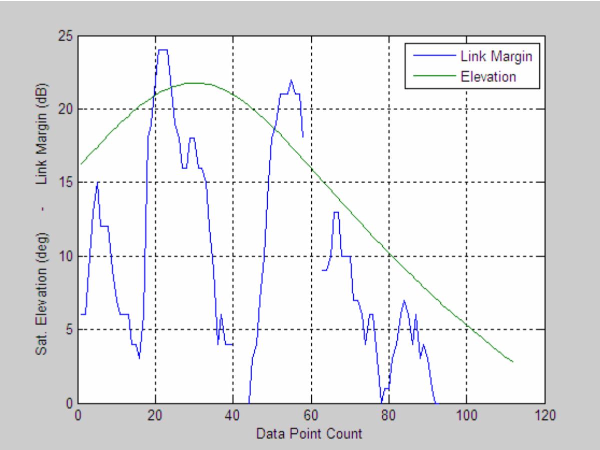

Figure 18: Typical Pass and its Link Margin

CONCLUSIONS

The GeneSat-1 mission successfully demonstrated that the Microhard MHX-2400 commercial off-the-shelf 2.4GHz ISM band transceiver can operate onboard a low Earth orbit spacecraft. With only partial conformal coating, this component was used as purchased from the manufacturer without any further modifications. A comprehensive phase of space qualification and testing allowed for the reduction of risk in using this low cost terrestrial device with no space heritage.

Development of the communications system was done over the 3 years of spacecraft development, and it was accomplished by students with strong mentoring support from professors, professionals and members of the amateur radio community.

Regarding future improvements to the system, the data rate of the transceiver should be utilized in a more efficient way to unleash the real potential of the system. In order to do this, the onboard processor and flight software should be designed to optimize data transmission. Further automation of ground-based command and telemetry operations can also increase data throughput.

Although the link margin was strong on average, large variation in this parameter indicated the effects of antenna pointing losses caused by the limited performance of the satellite's passive attitude control system; a more accurate attitude control system would certainly allow for a more sustained RF link throughout the pass. A less directional type of antenna would also improve the performance but at the expense of a lower average link margin.

At the time of writing the paper, at least 6 universities are considering using the Microhard 2.4GHz ISM band system in their spacecraft, and a company is including it as a part of its COTS CubeSat Kit.

NASA Ames Research Center is planning on launching two additional satellites in 2008 containing different biological payloads, making use of the GeneSat-1 spacecraft bus, including the 2.4GHz ISM band system as the main communications link.

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