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X-band CubeSat Communication System Demonstration

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ABSTRACT

Today’s CubeSats mostly operate their communications at UHF- and S-band frequencies. UHF band is presently crowded, thus downlink communications are at lower data rates due to bandwidth limitations and are unreliable due to interference. This research presents an end-to-end robust, innovative, compact, efficient and low cost S-band uplink and X-band downlink CubeSat communication system demonstration between a balloon and a Near Earth Network (NEN) ground system. Since communication systems serve as umbilical cords for space missions, demonstration of this X-band communication system is critical for successfully supporting current and future CubeSat communication needs.

This research has three main objectives. The first objective is to design, simulate, and test a CubeSat S- and X-band communication system. Satellite Tool Kit (STK) dynamic link budget calculations and HFSS Simulations and modeling results have been used to trade the merit of various designs for small satellite applications. S- and X-band antennas have been tested in the compact antenna test range at Goddard Space Flight Center (GSFC) to gather radiation pattern data. The second objective is simulate and test a CubeSat compatible X-band communication system at 12.5Mbps including S-band antennas, X-band antennas, Laboratory for Atmospheric and Space Physics (LASP) /GSFC transmitter and an S-band receiver from TRL-5 to TRL-8 by the end of this effort. Different X-band communication system components (antennas, diplexers, etc.) from GSFC, other NASA centers, universities, and private companies have been investigated and traded, and a complete component list for the communication system baseline has been developed by performing analytical and numerical analysis. This objective also includes running simulations and performing trades between different X-band antenna systems to optimize communication system performance. The final objective is to perform an end-to-end X-band CubeSat communication system demonstration between a balloon and/or a sounding rocket and a Near Earth Network (NEN) ground system.

This paper presents CubeSat communication systems simulation results, analysis of X-band and S-band antennas and RF front-end components, transceiver design, analysis and optimization of space-to-ground communication performance, subsystem development, as well as the test results for an end-to-end X-band CubeSat communication system demonstration. The outcome of this work will be used to pave the way for next generation NEN-compatible X-band CubeSat communication systems to support higher data rates with more advanced modulation and forward error correction (FEC) coding schemes, and to support and attract new science missions at lower cost. It also includes an abbreviated concept of operations for CubeSat users to utilize the NEN, starting from first contact with NASA’s communication network and continuing through on-orbit operations.

INTRODUCTION

This paper discusses SmallSat/CubeSat S- and X-band communication system simulations and analysis, transceiver development, testing, and demonstration. The analysis covers transceiver requirements, space-to-ground communication system specifications/performance, and systems demonstration utilizing a balloon platform. The LASP S- and X-band transceiver development section will address the functional components, design specifications, waveform description/parameters, and applications, as well as compliance with NASA's NEN waveform-specific performance requirements. The transceiver system level test results are presented addressing: S-Band receiver, S-Band transmitter and X-Band receiver. Also, the antennas that will be used with the LASP S- and X-band transceiver have been characterized.

The SmallSat/CubeSat S- and X-band communication system is a very promising technology that will increase science data downlink performance for future missions. Other aspects of this paper include radiation tolerance, and technology infusion plan.

CUBESAT RADIO REQUIREMENTS

The proposed CubeSat transceiver is designed to be compatible with NASA's NEN and comply with waveform-specific performance requirements. High level requirements include: compatibility with a 6U CubeSat, operation for 12 months in LEO, Tx to transmit up to 12.5 Mbps, Tx to support OQPSK modulation, Tx to support forward error correction coding, Tx to have sufficient power to close the link between LEO and NEN, Rx capable of closing the link between LEO and NEN, and operating temperature between -20C and +50C.

SIMULATIONS AND ANALYSIS

Space -to-Ground System Analysis and Simulations

Systems Tool Kit (STK) simulations were performed to evaluate space-to-ground communication

performance for a system utilizing the LASP S- and X-band transceiver. The orbital/link parameters used in this analysis are shown in Table 1. In order to achieve the desired science data downlink of 12.5 Mbps in X-band, the communication link will need a Carrier to Noise (C/N0) power level of at least 83.4dB with the standard 3dB link margin. Due to bandwidth limitations, a 5Mbps rate is desired in S-band, which will require a C/N0 power level of 79.4dB.

Table 1: Space to Ground Link Parameters

Orbit	LEO (sun-synchronous)
Altitude	705 km
S-band Frequency	2310 MHz
X-band Frequency	8210MHz
S-band Antenna Gain	0 dBi
X-band Antenna Gain	9 dBi
S- and X-band Transmit Power	1 watt
Reed Solomon Encoding	6.4 dB required Eb/No

Three of NASA's Near Earth Network (NEN) ground stations were baselined in this analysis: Wallops Ground Station (MGS) in Virginia, Alaska's Station at Fairbanks (ASF), and the McMurdo Ground Station (MGS) in Antarctica shown in Figure 1.

STK's Communications module provides the dynamic link analysis (path loss, atmospheric effects, etc.). The STK link results were also verified by an internal link analysis. Table 2 gives a summary of the minimum data rates achievable at the three NEN sites. Figure S-3 shows the dynamic C/N0 power levels provided by the S- and X-band payloads on orbit to the multiple ground stations.

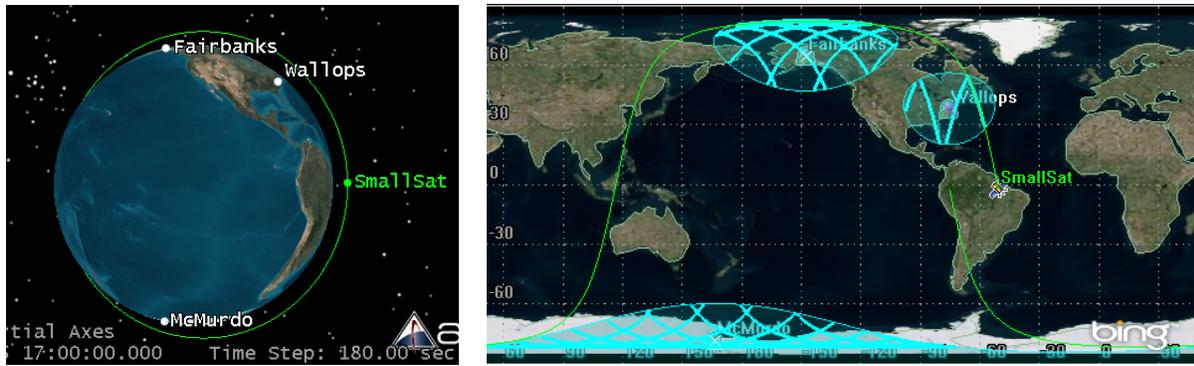


Figure 1: Space-to-Ground System Simulations

Table 2: Achievable data rates at three selected NEN sites

Ground Station	Wallops (WGS)		Fairbanks (ASF)		McMurdo (MGS)		
	WGS 11.3M		ASF 11M		MGS (10m)		
Frequency	S-band	X-band	S-band	X-band	S-band	X-band	
Elevation Angle (deg)	5	10	5	10	5	10	
Min Data Rate (Mbps) (from 705km Alt.)	4.3	42.3	4	93	2.6	33.5	
Contact Time Per Day (hrs)	0.71	0.494	1.674	1.136	2.253	1.546	
Latency (hrs)	Average	4.556	2.032	1.983	4.599	1.416	1.829
	Maximum	11.843	10.032	8.374	11.879	1.6	6.094

Results in Table 2 were generated using the assumptions for the S- and X-band communications payload systems given in Table 1.

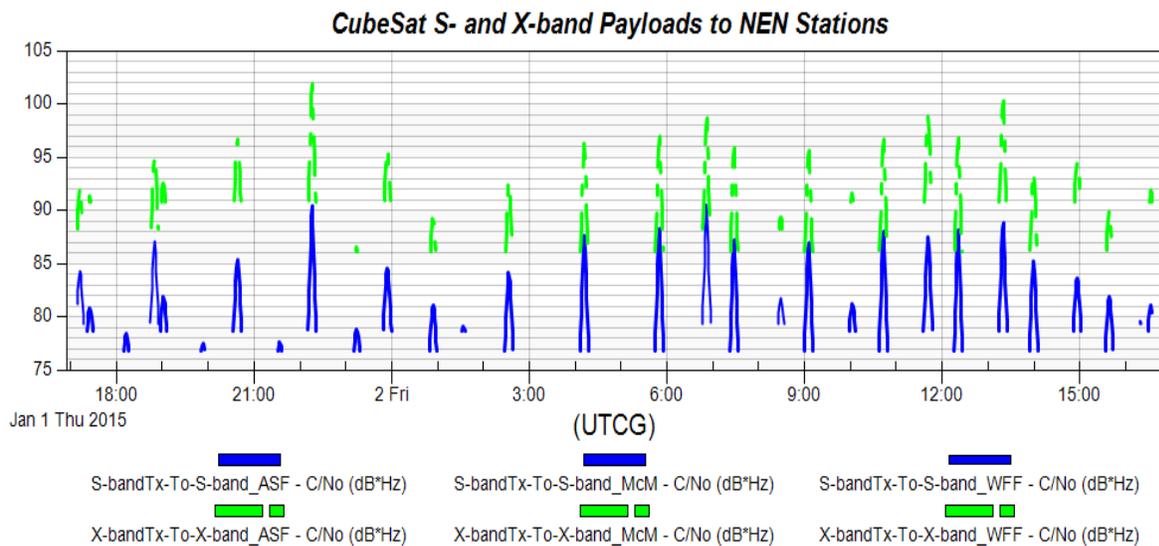


Figure 2: SmallSat S- and X-band Payloads to NEN Stations

For the S-band payload communications link to Wallops Ground Station (WGS) 11.3m antenna at a 5 degree elevation angle, the S-band payload does not close the 5 Mbps link with 3dB margin. There is about 0.6dB needed in the link. In order to close the link, the S-band payload would need a slight increase in transmit power or antenna gain or the payload would need to be operated solely above 7 degrees elevation angles. For the link to McMurdo Ground Station's (MGS) 10m antenna at 5 degree elevation, there is about 2.8dB needed to close the link with 3dB margin. This would require a 2-watt power amplifier, or operation of the 1-watt payload above 15 degree elevations to close the 5 Mbps link with the standard 3dB link margin.

For the X-band payload, utilizing a 9dBi antenna gain, there is 7.3dB margin on the link to the 10m antenna at MGS at 10 degree elevation, and 8.3dB on the link to WGS's 11.3 antenna. Figure 2 shows that there is at least 4 additional dB, over the required 3dB margin on any of the X-band links to the NEN ground stations. The links will also close with about 5dB margin if at a 5 degree of elevation with an ACS system.

For the S-band payload, the data rate of 5Mbps is not achievable without some improvements over the assumed payload performance. These could be achieved with additional antenna gain, transmitter power, or with a more advanced forward error correction (FEC) scheme. The S-band payload could also be operated only at higher ground-to-space elevation angles to achieve the desired 5Mbps the NEN sites. The X-band payload as defined is sufficient to close the 12.5 Mbps link to the multiple NEN stations from a 705km orbit.

Balloon Simulation

A balloon was simulated in STK by assuming a constant rise rate to a float altitude of 37km. A direct eastward bound drift rate of 5km/hr was used. Wallops Flight Facility (WFF) was chosen as the launch facility for the balloon flight analysis (see Figure 3).

As can be seen in Figure 4, at 24 hours of simulation, the balloon reaches a slant range of 580km from the facility at Wallops Island. As can be seen in Figure 4, the elevation at this time and distance is about 1 degree. Dynamic link margins from the simulation are shown in Figure 5 for both the S-band and X-band links to the Wallops Ground Station (WGS) 11.3m antenna.

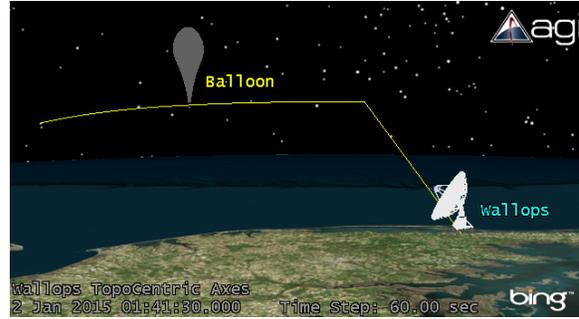


Figure 3: System Demo Using Balloon Simulation

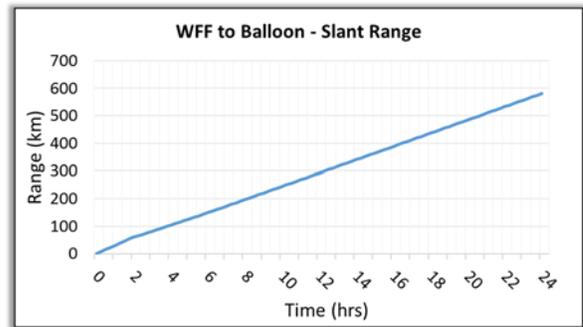


Figure 4: WFF to Balloon Slant Range

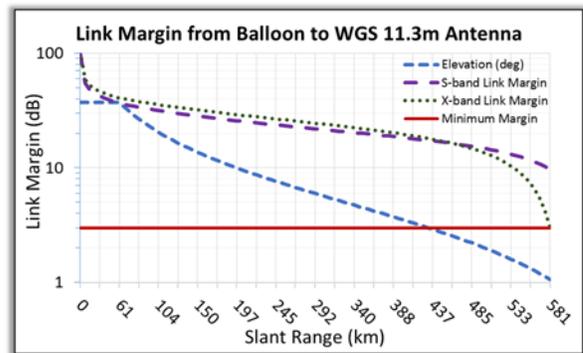


Figure 5: Balloon to WGS 11.3m Antenna Simulation

For this balloon trajectory, the simulation shows significant margin on the links. For both the S- and X-band payloads, the simulations show nearly 24 hours with achievable data rate goals of 5Mbps and 12.5Mbps, respectively. At 5 degree elevation, there is approximately 21dB and 23dB margin on the S- and X-band links, respectively. For the X-band link, the 3dB margin threshold on a 12.5Mbps link is only crossed when the elevation angle decreases to about 1 degree, which is when the multipath/scintillation effects have significantly degraded the link. In

practice, communications would not be performed below 3-5 degree elevation. Thus, the SmallSat/Balloon payload radiated power performance assumed in this analysis will not be an issue for the proposed S- and X-band communication links from a balloon trajectory. Instead, the links will likely be bandwidth limited when above very low elevation angles (<2 degrees). The X-band payload will provide more link margin than the S-band link for elevation angles above 2.5 degrees. The S-band link is more efficient through the atmosphere and at very low elevation angles, but with the greater antenna gain, the X-band payload would provide better performance (more link margin) at 12.5 Mbps than the S-band payload at 5Mbps for elevation angles above 2 degrees. Ultimately, both the S- and X-band payloads are expected to provide adequate performance margin on their respective 5Mbps and 12.5Mbps communication links for a balloon test flight.

TRANSCIEVER DEVELOPMENT

The University of Colorado, Boulder, is continuing advancement of a transceiver consisting of an X-Band transmitter and S-Band receiver under a SmallSat Technology Partnership award (NNX13AR01A). Now in year two, the X-Band transmitter design has achieved the goal of TRL5, and the team, including NASA GSFC engineers and management, continues to work on moving the receiver to this technology readiness level.

The receiver design is based on the Analog Devices AD9364 integrated RF agile transceiver IC. As shown in Figure 6, the AD9364 baseband and down-shifted subcarrier will be fed to an FPGA. The digital circuits in the FPGA implement a Costas loop, which accommodates the Doppler shift in frequencies experienced by the receiver during a pass over a ground station. The Costas loop consists of a numerically controlled oscillator (NCO), raised cosine filters matched to that used in filtering the transmitted uplink data (F1 and F2 in Figure 6), as well as multipliers to act as frequency and phase detectors, and to combine the two filtered paths to generate a

control signal feeding the NCO input. There is an additional finite impulse response loop filter, F3, to remove unwanted frequency components that are not fully attenuated by filters F1 and F2.

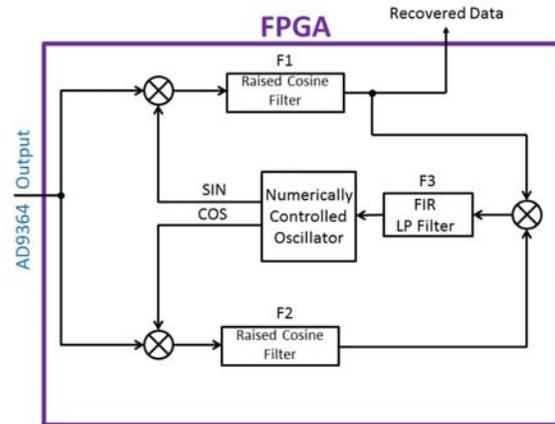


Figure 6: Block diagram of AD9364 and FPGA based digital Costas Loop for BPSK reception

As with the transmitter design process, we have implemented a model of the system using Simulink. The model is shown in Figure 7. As of this time, the model has shown that the loop achieves lock at frequencies within 2% of the NCO start up frequency. The loop then maintains lock as the carrier frequency is swept on the transmitter side (not shown in Figure 7). The entire range of Doppler-shifted frequencies has not been simulated; however, a drift of 1 MHz / second showed lock over a 100 KHz capture range once lock was achieved. This drift rate far exceeds the approximately 83 Hz / second expected drift rate, showing that the Costas loop can maintain lock with a much more challenging frequency shift/drift rate than expected in flight by four orders of magnitude. Simulation times make verification of the expected, slower drift frequency rate too slow, but loop performance will only increase with the decreased frequency drift rates. The slower drift rate will be tested in the final hardware implementation modeled in Figure 7.

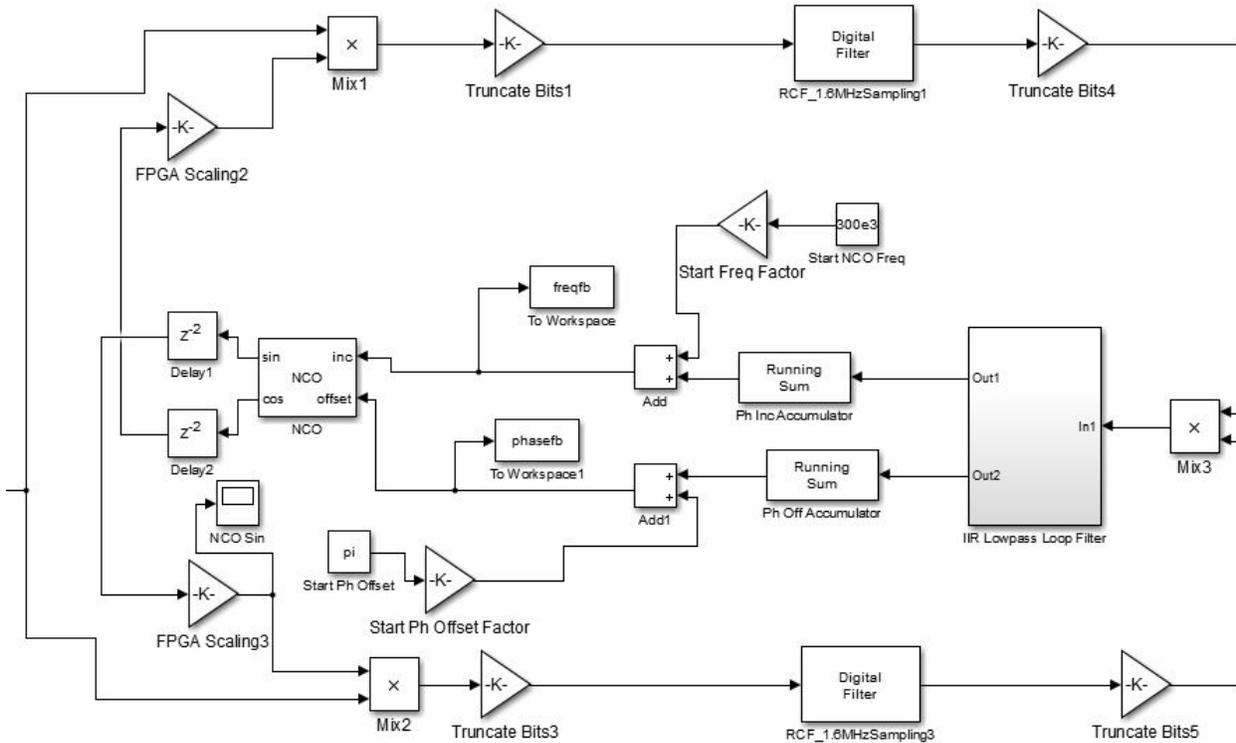


Figure 7: Simulink diagram of Costas loop implemented for verification of performance

Figure 7 shows the Simulink diagram of Costas loop implemented for verification of performance. Figure 8 shows the digital data (blue) sent to the BPSK modeled transmitter in the Simulink system, and the received data (green) resulting from the Costas loop BPSK demodulation. While the effects of filtering through RCF filters in the modulation and demodulation path have eliminated higher frequency components in the received signal, the received signal has enough information to reproduce the original data time series.

The 12 layer board design is now nearly complete and will go out for manufacture while the FPGA implementation is completed. Also during the interim, the configuration parameters for the AD9364 will be determined from Analog Devices' Linux based test platform for the chip. While using such an integrated device has simplified much of the RF development than would have been required designing with lower level components of a receiver, such as was done with the X-Band transmitter, understanding the configuration of the device and its performance remain not-insignificant tasks with this device. Because the AD9364 also contains a transmitter chain, future possibilities include the design of an S-Band transmitter and receiver on a single CubeSat form factor board. In fact, we plan to use

the transmitter output from the AD9364 to test the receiver during the receiver characterization.

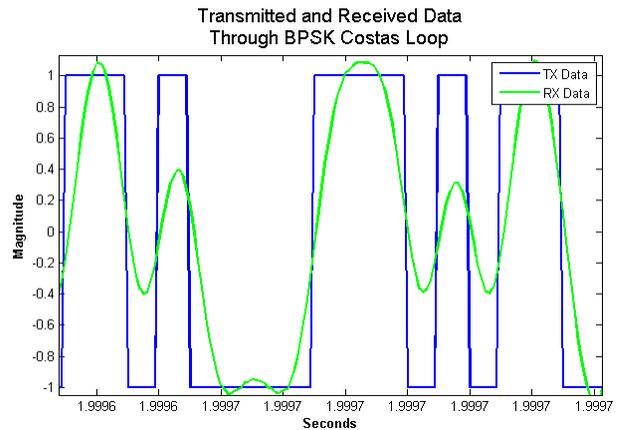


Figure 8: Transmitted (blue) and received (green) data from the Simulink model shown in Figure 7

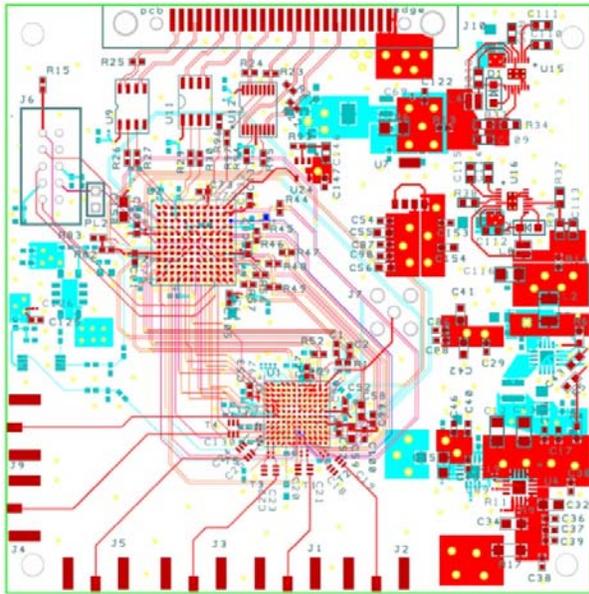


Figure 9: S-Band Receiver PCB Layout

SYSTEM LEVEL TESTS AND RESULTS

Both the I and Q FPGA LVDS outputs were verified with a pseudo random pattern defined by $PRBS7 = x^7 + x^6 + 1$. In this test mode, the Actel Proasic FPGA generates this pattern which is then sent outside the PCB through a test port with LVDS.

A loopback test was performed with cabling such that the output of this test port was put back into the PCB/FPGA input to represent user data.

Internally to the FPGA, the user data is split into separate I,Q data paths then optionally differential and convolutional encoded.

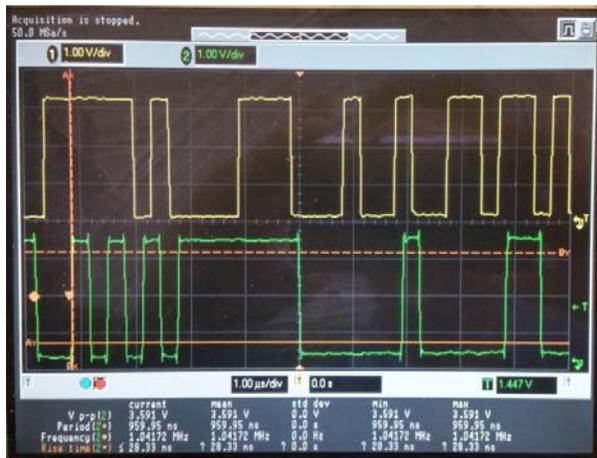


Figure 10: Receiver I and Q FPGA outputs

Figure 10 shows the I,Q FPGA outputs with the repeating 127 bit, PRBS7 pattern. The convolution and differential encoding were turned off for these measurements to make it easier to visually see the pattern which starts with 7 consecutive ones. This test produced data at 12.5 Mbits/s that is split 50/50 on the I and Q data paths.

Additional Bit Error Rate (BER) testing is planned using a Cortex XXL receiver in the lab, and also with the Wallops 11 meter antenna. Shown in Figure 11 is the BER test block diagram.

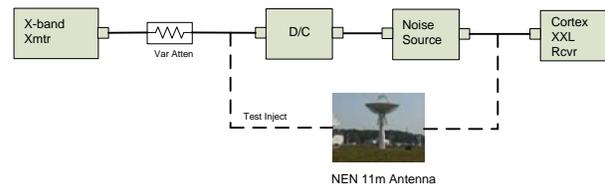


Figure 11: Transmitter BER Test Setup

ANTENNA TEST AND CHARACTERIZATION

Antenna pattern testing is being conducted at the Wallops dual mode far-field/compact antenna test range. Antennas will be mounted on a Cubesat model for pattern measurements. Figure 13 shows the 4 element patch antenna array which was designed and built by Ant Dev Corporation. It is compact, effective, low cost, and efficient with stable high gain characteristics.

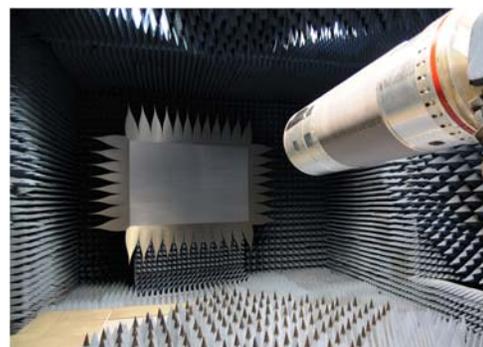


Figure 12: WFF Far-Field Compact pattern measurement range

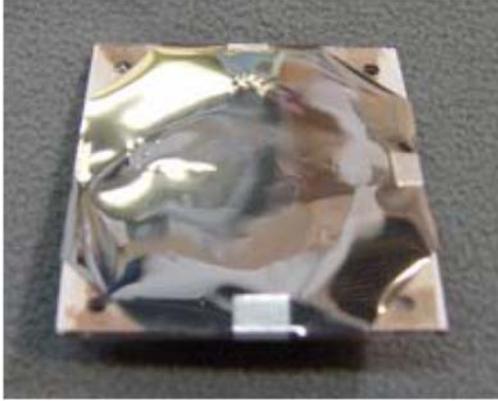


Figure 13: X-Band 4-Patch Array Antenna (AntDevCo), fc 8080 MHz, 9 dB gain

Figure 14 and 15 presents X-Band 4-Patch Array Antenna Gain Linear, Theta Cut (0 to 360 deg) at theta phi = 0 degrees and theta phi = 90 degrees respectively. Figure 16 presents X-Band 4-Patch Array Antenna VSWR.

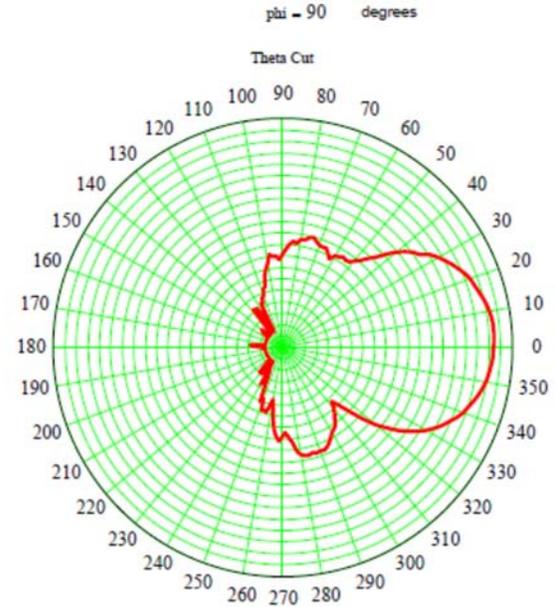


Figure 15: X-Band 4-Patch Array Antenna Gain Plot - Etheta Linear, Theta Cut (0 to 360 deg) at theta phi = 90 degrees. Plot Max 12 dBi with 2 dB per division.

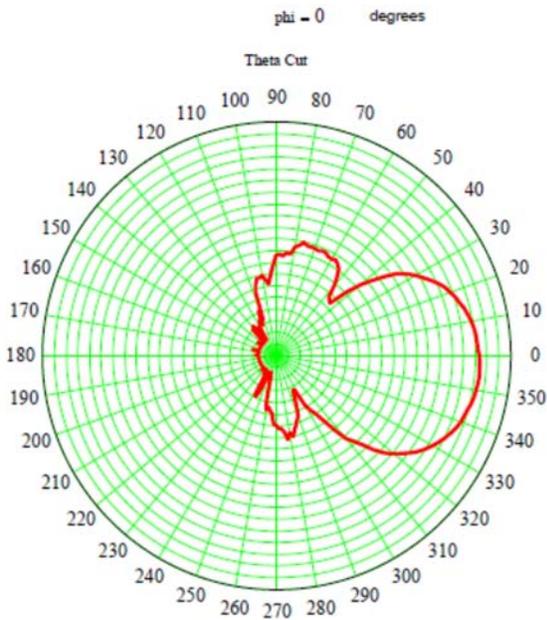


Figure 14: X-Band 4-Patch Array Antenna Gain Plot - Etheta Linear, Theta Cut (0 to 360 deg) at theta phi = 0 degrees. Plot Max 12 dBi with 2 dB per division.

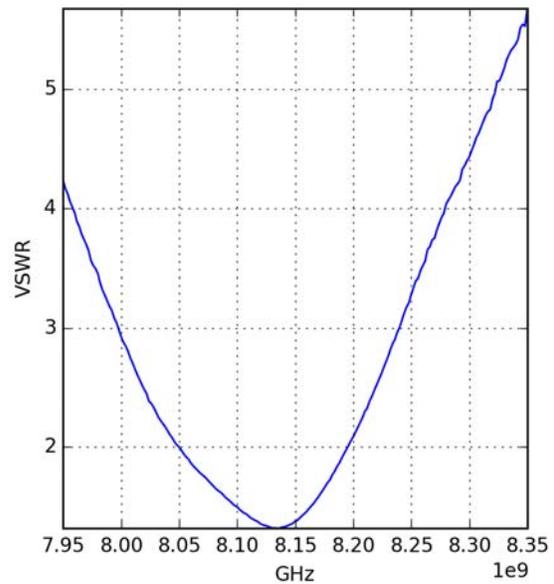


Figure 16: X-Band 4-Patch Array Antenna VSWR Plot

TRANSCEIVER NEN COMPATIBILITY

The transceiver was designed to be compatible with the NASA NEN frequency allocations in S- and X-band.

The transceiver will be tested for compatibility with the Wallops Ground Station (WGS) 11.3-meter antenna. NEN S-band command characteristics of the WGS include: NEN S-band uplink band, RHC or LHC polarization, options of PM, FM, BPSK or QPSK / OQPSK and FSK carrier modulations, and options of NRZ-L, and M, or S; or Bif-L, M, or S data formats. X-band telemetry characteristics of the WGS include: NASA NEN X-band downlink, RHC or LHC polarization, options of QPSK, UQPSK, SQPSK, AQPSK modulations, NRZ-L or M data formats, and ability to support data rates of 6 – 150 Mbps.

Also, the transceiver's baseband data format will be compatible with the NEN. WGS is compatible with baseband data in any of the following formats: IP, serial clock and data, and 4800-bit blocks encapsulated in IP packets.

FUTURE WORK AND TECHNOLOGY INFUSION PLAN

This S-band uplink and X-band downlink CubeSat communication system development and demonstration will provide a framework to build and launch a small technology demonstration satellite in response to the NASA's HEOMD CubeSat Launch Initiative. Also, X-band will be more attractive for high data rate CubeSat science missions. In the near term, CubeSats are more likely to move into X-band for higher data rates, and will utilize higher order modulation and encoding schemes that will enhance link quality and overall system capability.

Radiation Tolerance

The transceiver uses an Actel ProASIC FPGA. The components in the design were carefully selected to operate in LEO or GEO radiation environments.

Radiation tests can be performed on our current S-band and X-band hardware. Radiation testing will help to provide part selection insights. All components shall be designed to avoid or tolerate errors due to non-destructive Single Event Upsets (SEUs). No permanent loss of function shall result due to non-destructive SEUs. Degradation of individual components shall be included in appropriate worst case analyses.

Several of the parts may be susceptible to destructive/catastrophic Single Event Effects.

Technology infusion plan

The results of this demonstration will be shared with scientists throughout NASA and industry, for potential use on their future missions. This enabling capability will increase CubeSat/SmallSat development and test capabilities. Also, this S- and X-band communication system will provide a test bed for new technology demonstration missions that will enable new mission classes or reduce the cost, schedules and risk of current NASA's mission design methodologies. This system serves as a viable communications framework that can be leveraged as part of a small technology demonstration satellite.

CONCLUSION

This S- and X-band communication system will be NEN compatible and will be used as a potential standard baseline for CubeSats throughout NASA. The outcome of this development and demonstration will pave the way of a next generation NEN compatible X-band CubeSat communication system which supports higher data rates with more advanced modulation and forward error correction (FEC) coding schemes as well as to support and attract new science missions at lower cost.

Acknowledgments

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