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NPS-SCAT communications system : design, test, and integration of NPS' first CUBESAT

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THESIS

NPS-SCAT; COMMUNICATIONS SYSTEM DESIGN, TEST, AND INTEGRATION OF NPS' FIRST CUBESAT

by

Cody K. Mortensen

September 2010

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NPS-SCAT; COMMUNICATIONS SYSTEM DESIGN, TEST, AND INTEGRATION OF NPS' FIRST CUBESAT

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The Naval Postgraduate School’s (NPS) first CubeSat, NPS Solar Cell Array Tester (NPS-SCAT), will be the foundation for future advances in CubeSats at NPS. NPS-SCAT demonstrates the capability of the CubeSat form factor as a technology test bed for a single experiment – a solar cell tester. This thesis discusses and explains the design, testing, and integration of two full TT&C sub-system for NPS-SCAT. The primary and secondary transceivers will both use the amateur frequency band through an approved AMSAT license. This thesis explains the concept of operations of NPS-SCAT, which drove the data requirements for the TT&C. This thesis also explains the testing of the primary and secondary transceivers and the design, test and integration of the antennas. Finally, this thesis will discuss the TT&C ground station construction, methodology, testing and the frequency coordination access.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

1U	One Unit CubeSat
2U	Two Unit CubeSat
3U	Three Unit CubeSat
AM	Amplitude Modulation
AMSAT	Amateur Satellite
AMSAT-NA	The Radio Amateur Satellite Corporation
ASFCR	Amateur Satellite Frequency Coordination Request
C&DH	Command and Data Handling
Cal Poly	California Polytechnic State University
CERTO	Coherent Electromagnetic Radio Tomography
CFTP	Configurable Fault Tolerant Processor
CGA	Common Ground Architecture
CONOPS	Concept of Operations
COTS	Commercial-Of-The-Shelf
CRC	Cyclic Redundancy Check
CSD	CubeSat Design Specification
EPS	Electrical Power System
FCC	Federal Communications Commission
FM	Frequency Modulation
HPA	High Power Amplifier
IARU	International Amateur Radio Union
ISM	Industrial, Scientific, and Medical
LV	Launch Vehicle

NMSC	Navy-Marine Corps Spectrum Center
NPS	Naval Postgraduate School
NPS-SCAT	Naval Postgraduate School – Solar Cell Array Tester
NPSAT1	Naval Postgraduate School Spacecraft Architecture and Technology Demonstration Satellite
NSP	NanoSatellite Protocol
P-POD	Poly-Picosatellite Orbital Deployer
PANSAT	Petite Navy Satellite
SCAT	Solar Cell Array Tester
SD	Secure Digital
SMAD	Space Mission Analysis and Design
SMS	Solar cell Measurement System
SOCEM	Sub-Orbital CubeSat Experimental Mission
SSAG	Space Systems Academic Group
SSB	Single Side Band
SSPL	Space Shuttle Payload Launcher
STK	Satellite Tool Kit
T-POD	Tokyo-Picosatellite Orbital Deployer
TAPR	Tucson Amateur Packet Radio
TINYSCOPE	Tactical Imaging Nanosatellite Yielding Small Cost Operation for Persistent Earth Coverage
TNC	Terminal Node Controller
TT&C	Telemetry, Tracking and Command
VSWR	Voltage Standing Wave Ratio
X-POD	eXperimental Push Out Deployer

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I. INTRODUCTION

A. CUBESAT – WHERE DID IT ORIGINATE? WHAT IS IT?

In 1999 two inspired men, Professor Bob Twiggs of Stanford University and Professor Jordi Puig-Suari of California Polytechnic State University (Cal Poly) developed the CubeSat form factor for incredibly small satellites also known as picosatellites. This fascinating idea came about to provide a learning atmosphere for space engineering students. The goal of the CubeSat was to provide education while keeping scheduling and cost minimal, and maintaining a standard for building a launchable spacecraft. The CubeSat standard is now defined as a 10 cm cube with a mass of no more than 1.33 kg. “Over 100 universities, high schools and private firms” have embraced the CubeSat standard because of its capability to provide an inexpensive platform for numerous payloads [1].

The growth of the CubeSat can be partially attributed to the long design, construction and testing that is associated with traditional small satellites. The lengthy timelines create difficulty for students to complete the spacecraft in the time allowed for undergraduate or graduate student curricula. CubeSats have become increasingly popular because of their ability to provide education wherein a student has the opportunity to design, construct, and test his/her spacecraft from beginning to possible launch. The small, yet capable CubeSat has also become popular in private and government organizations because of its ability to be flown in a timely manner. It also mitigates the risks associated with larger more expensive spacecraft and can be used as an experimental test bed.

There have been additional form factors added to the original CubeSat since its birth. A 1U or U, defined as the standard 10 cm cubed CubeSat, can be stacked to form larger versions of the CubeSat. The larger versions are defined by the number of CubeSats stacked on top of each other. For example, a 2U CubeSat is two 10 cm cubes stacked one on top of the other. The maximum number of CubeSats that can be stacked and still fit into the Cal Poly CubeSat launcher, the Poly-Picosatellite Orbital Deployer (P-POD), is three or 3U. If a CubeSat is designed as outlined in the CubeSat Design Specification (CSD), it can be launched using a P-Pod, seen in Figure 1. The P-POD can be secured to a Launch Vehicle (LV) and when commanded, it will launch the CubeSats with its spring loaded pusher plate [1].

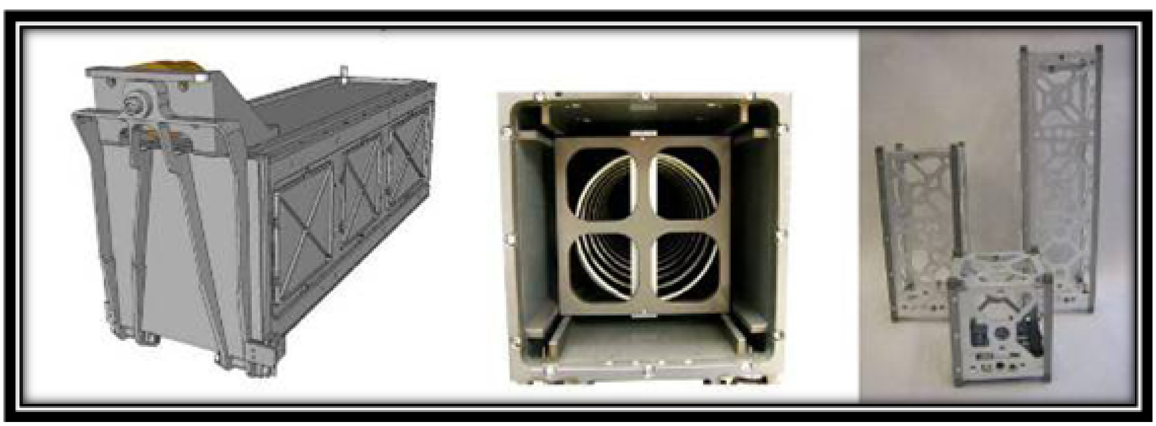

Figure 1. P-POD and CubeSat Structures: 2U, 1U, 3U (From [2])

B. A BRIEF HISTORY OF CUBESATS AND THEIR COMMUNICATION SYSTEMS

As of March 2010, there have been a few batches of CubeSats launched with some single and double launches in between the batches. The total number of CubeSats that have been integrated into a launch is 52 but only 36 have been successfully injected into a low earth orbit. At least 35 more CubeSats are either ready to launch or are in varying stages of development with hopes of launching in the near future [3]. The opportunities for launching a CubeSat are becoming increasingly available which will provide students, private businesses, and government agencies with incentive to design and build these intriguing picosatellites.

1. CubeSats Prior to 2007

The first three batches and two single launches were comprised of 25 CubeSats between June 30, 2003 and December 6, 2006. These CubeSats came from a wide variety of countries: United States of America, Japan, Canada, Denmark, Norway, Germany, and South Korea. On June 30, 2003, the first batch of six CubeSats was launched from Plesetsk, Russia on a Eurockot LV using a P-POD and a Tokyo-Picosatellite Orbital Deployer (T-POD) [3].

The second batch of three CubeSats was launched October 27, 2005, from Plesetsk, Russia on a Kosmos-3M LV using a T-POD. A single CubeSat was launched on February 22, 2006, on an M-V LV from Uchinoura, Japan using a T-POD [3].

The third batch of 14 CubeSats was supposed to launch on July 26, 2006, on a DNEPR LV from Baikonur, Kazakhstan using P-PODs. Unfortunately, the LV failed to reach orbit due to a premature separation of the first stage causing a complete loss of all payloads on board [4]. Another single CubeSat launched on December 16, 2006, on a Minotaur from MARS at NASA Wallops Flight Facility, Virginia using a P-POD [3].

A large majority of these CubeSats used UHF transceivers in the amateur frequency band from 436 to 438 MHz. They used the AX.25 Link Layer Protocol at data rates from 1200 to 9600 bps [3]. Generally, the CubeSats used Commercial Off-the-Shelf (COTS) radios, which they modified for use in Space.

2. 2007 CubeSats

The fourth batch of seven CubeSats, one being 3U, launched on April 17, 2007, on a DNEPR LV (EgyptSat) from Baikonur, Kazakhstan. All seven CubeSats were launched from P-PODs designed and built by Cal Poly. Aerospace Corp. launched their second CubeSat, AeroCube-2. Boeing, Tethers Unlimited, The University of Louisiana and The University of Sergio Arboleda (Columbia) launched their first CubeSats: CSTB-1, MAST, CAPE-2, and Libertad-1. Cal Poly also launched their first and second CubeSats, CP3 and CP4 [3].

CTSB-1, AerCube-2 and Mast all used proprietary packet protocols for their missions. These three missions were also unique because of the different frequencies chosen to operate at. CTSB-1 used 400.0375 MHz for the operating frequency, using an experimental license [5]. AeroCube-2 used a frequency between 902–928 MHz in the ISM band [6].

MAST utilized a Microhard MHX2400 transceiver, which uses the S-band and operates at 2.4 GHz [7].

CAPE-2, Liberatad-1, CP3, and CP4 all used the AX.25 Protocol as well as frequencies in the amateur band between 435-438 MHz. All of the satellites except CAPE-2 and Libertad-1 have established communications with the ground and passed data. CAPE-2 had a faulty transceiver and Libertad-1 had a non-working ground station prior to launch which repairs were not completed in time to communicate with the satellite. The other six CubeSats have all established a downlink connection and passed between hundreds of kilobytes to hundreds of megabytes [6].

3. 2008 CubeSats

The fifth batch of six CubeSats, one being a 2U and two being 3Us, launched on April 28, 2008, from Satish Dhawan Space Centre, India. All six CubeSats were launched using an eXperimental Push Out Deployer (X-POD). This was the first launch of multiple CubeSats outside Russia and consisted of satellites from Canada, Denmark, Germany, Holland, and Japan (2 spacecraft). The spacecraft names are CanX-1, DTUsat, Compass One, Delfi-C3, CUT 1.7 + APD II and SEEDS-2 respectively. This was the first CubeSat launched for Holland and second or more for the other four countries [3].

All the CubeSats launched in the fifth batch used the amateur frequency band ranging from 435-438 MHz for part of their communication subsystem. CanX-2 was unique in that it also used 2.407 GHz for a second transceiver and a modified AX.25 Protocol, which the design team referred to as the NanoSatellite Protocol (NSP). CanX-2 utilized two

S-Band patch antennas for its higher frequency transceiver [8]. CUTE 1.7 + APD II used an uplink at 1.267 GHz at 9600 bps and utilized the standard AX.25 Protocol [3]. All CubeSats in this batch were able to communicate with their ground stations and transmit data [7].

4. 2009 CubeSats

The sixth batch of four CubeSats, one being a 3U, launched May 19, 2009, on a Minotaur-1 from the Mid-Atlantic Regional Spaceport (Wallops Island). All four CubeSats were launched using P-PODs. NASA Ames Small Spacecraft Division entered the CubeSat community by launching Pharmasat-1 and Hawk Institute of Space Sciences also launched its first, Hawksat-1. Aerospace Corp. launched its third, AeroCube-3 and Cal Poly launched its fifth, CP6. Hawksat-1, Pharmasat-1, and CP6 used the amateur frequency band centered on 437 MHz; they also utilized the AX.25 Protocol [3].

Batch seven was small consisting of two nanosatellites which launched on July 30, 2009, from the space shuttle Endeavor. The University of Texas at Austin and Texas A&M University launched their first two nanosatellites, BEVO 1 and Aggiesat-2 respectively. These two spacecraft were a form of a CubeSat but slightly larger and did not conform to the CubeSat standards. The nanosatellites were launched from Endeavor using the Space Shuttle Payload Launcher (SSPL) located in the orbiter’s cargo bay [9]. Both spacecraft used the amateur frequency band between 436-438 MHz and also the AX.25 Protocol.

The third and final launch in 2009 consisted of four CubeSats, which launched on September 23 on a PSLV-C14 from the Indian Satish Dhawan Space Centre. The four CubeSats designed and deployed by four different countries: BEESAT was designed by Technical University of Berlin; ITUpSAT1 was designed by Istanbul Technical University; SwissCube was developed by the Swiss Polytechnic School of Lausanne; and UWE-2 was built by the German University of Wurzburg [2]. The communications subsystem information was not available for these four CubeSats.

5. 2010 CubeSats

The most recent CubeSat launch was on March 27, 2010. A NASA suborbital Terrier-Improved Malemute sounding rocket launching from Wallops Island carried two spacecraft. The University of Kentucky designed ADAMASat and Cal Poly developed a CubeSat determination testbed, Poly-Sat testbed. The two spacecraft together were called the Sub-Orbital CubeSat Experimental Mission (SOCEM). These two spacecraft performed their mission, transmitted the required data to their respective ground stations and re-entered the atmosphere shortly after. ADAMASat used a standard 1200-baud APRS packet stream on the North American APRS frequency, 144.390 MHz. Amateur radio operators in the Eastern United States with VHF equipment (a radio and a Terminal Node Controller (TNC)) participated and collected packets and emailed them to Kentucky Space to aid in the post processing of the data [10].

The complete list of CubeSats that have been launched as of March 27, 2010, is available in Table 1.

Table 1. List of CubeSats Launched (After [3])

2003	2005	2006	2007	2008	2009	2010
30 June	**27 October**	**22 February**	**17 April**	**28 April**	**19 May**	**27 Mar**
AAU CubeSat	NCube2	CUTE 1.7 + APD	AeroCube-2	AAUsat-2†	AeroCube-3	ADAMASat
CanX-1	UWE-1	**26 July**	CAPE-1	CanX-2	CP6	Poly-Sat testbed
CUTE-I†	XI-V†	AeroCube-1*	CP3†	Compass One†	HawkSat-I	
DTUsat-1		CP1*	CP4†	CUTE 1.7 + APD II†	PharmaSat-1	
QuakeSat-1		CP2*	CSTB 1†	Delfi-C3†	**30 July**	
XI-IV†		HAUSAT 1*	Libertad-1	SEEDS (2)†	AggieSat2	
		ICE Cube 1*	MAST†		BEVO1	
		ICE Cube 2*			**23 September**	
		ION*			BEESAT†	
		KUTEsat*			ITUpSAT1†	
		Mea Huaka*			SwissCube†	
		MEROPE*			UWE-2†	
		NCube1*				
		RINCON 1*				
		Sacred*				
		SEEDS*				
		16 December				
		GeneSat-1†				

†Indicates satellite still active

*Indicates launch vehicle failure

C. A BRIEF HISTORY OF NPS' SMALL SATELLITE DESIGN PROGRAMS AND THEIR COMMUNICATION SYSTEMS

In 1982, the Naval Postgraduate School (NPS) created the Space Systems Academic Group (SSAG). It was developed to provide a curriculum for the space cadre and provide military officers with space systems experience [11]. The SSAG helped developed two curriculums, Space Systems Operations (366) and Space Systems Engineering (591). They also have a Small Satellite Design Program, which is designed to give both undergraduate and graduate students real world hands-on experience with small satellite design. The classification of small satellites can mean many different sizes. Table 2 lists the different classes of small satellites.

Table 2. Small Satellite Classification by Mass (From [12])

Spacecraft Class	Mass Range
Microsatellite	10 - 100 kg
Nanosatellite	1 - 10 kg
Picosatellite	0.1 - 1 kg
Femtosatellite	0.01 - 0.1 kg

1. PANSAT

The Naval Postgraduate School’s first small satellite stated being designed in March of 1989. Petite Navy Satellite (PANSAT) was designed as a tumbling communications satellite, which included all the traditional satellite subsystems except attitude control. PANSAT included an experiment that provided a global messaging system, which used spread spectrum techniques within the UHF amateur band. On a historical day for NPS, October 29, 1998, PANSAT was launched from the space shuttle Discovery. As seen in Figure 2, PANSAT operated for almost four years and is still in orbit today [11]. The spacecraft operates in the amateur radio band with a center frequency at 436.5 MHz, has a bit rate of 9842 bps and 9 MB of message storage [14]. The 9842 bps is the spread-spectrum mode of PANSAT used for the messaging system: spacecraft command and control was accomplished with a narrow 78.1 kbps channel that overrode the spread-spectrum mode.

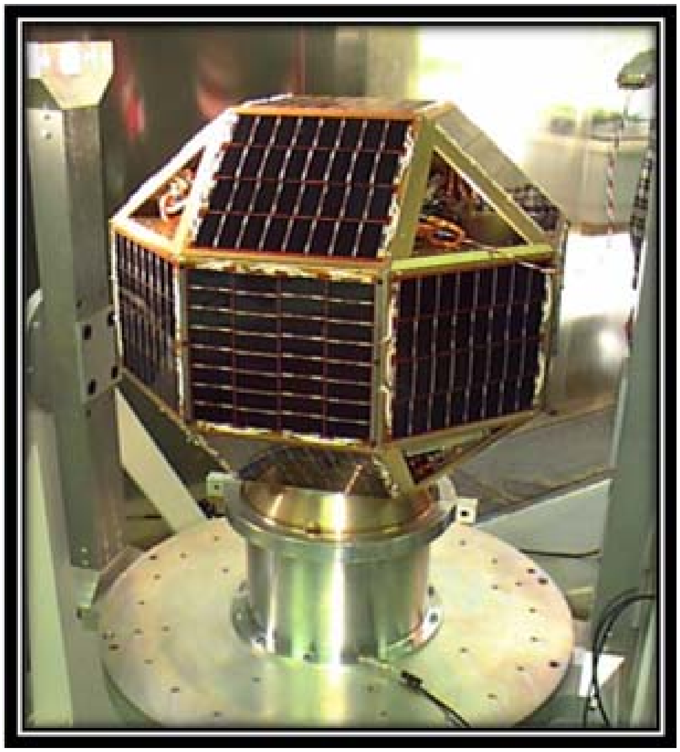

Figure 2. PANSAT During Testing

2. NPSAT1

In 1999, the SSAG started the second small satellite design process which was named the NPS Spacecraft Architecture and Technology Demonstration Satellite (NPSAT1) seen in Figure 3. NPSAT1 is still being completed but will be a test bed for small satellite technology and include multiple experiments. It is a three-axis stabilized spacecraft that contains a Configurable Fault Tolerant Processor (CFTP), a Solar cell Measurement System (SMS), a COTS camera, and two Naval Research Laboratory experiments: a Coherent Electromagnetic Radio Tomography (CERTO) beacon and Langmuir probe [2].

Communications with NPSAT1 is in two different frequency bands. The uplink is in the L-Band at 1.767 GHz and the downlink is in the S-Band at 2.207 GHz. The separation of the two frequencies allows for full duplex transmission without any interference [15].

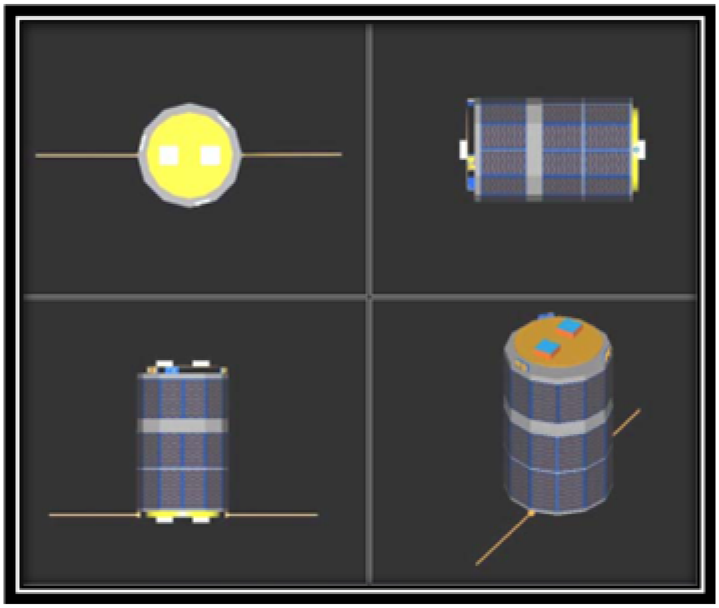

Figure 3. Computer Generated Model of NPSAT1 (From [13])

3. TINYSCOPE

One of NPS's current CubeSats being designed is the Tactical Imaging Nanosatellite Yielding Small Cost Operations for Persistent Earth Coverage (TINYSCOPE). As seen in Figure 4, this 6U, a combination of two 3Us, spacecraft is being designed to provide real time tactical imagery to the war fighter on the ground. One TINYSCOPE is being developed with the bigger picture in mind of having a full constellation that will provide worldwide coverage. In a recent interview, TINYSCOPE's Program Manager said the transceiver TINYSCOPE is currently projected to use is the Microhard IP2421, which has a center frequency at 2.4 GHz and a data rate up to 1.1 Mbps. He also mentioned that the program is trying to procure a transceiver with a much higher frequency in hopes of obtaining a much higher data rate to provide the real time video, but cost is the constraint.

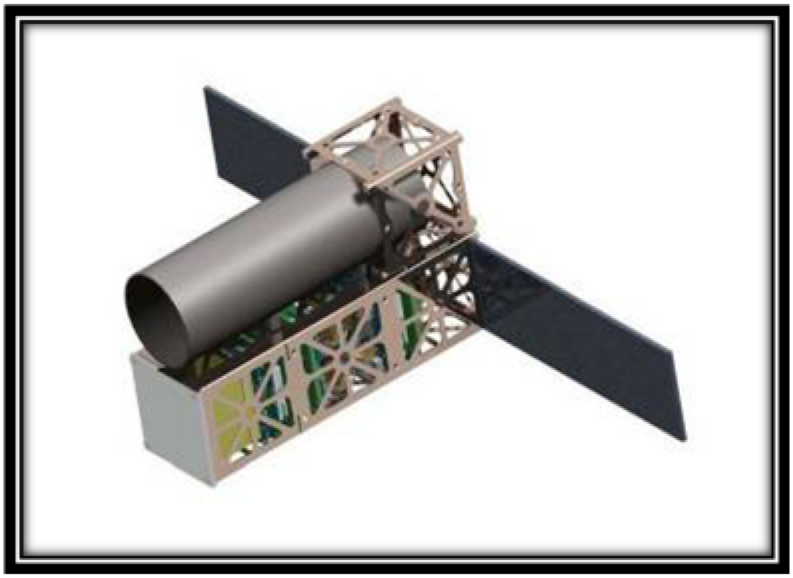

Figure 4. TINYSCOPE CubeSat Concept (From [2])

4. NPS-SCAT

NPS' first CubeSat to be designed, built and tested is Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT or SCAT). NPS-SCAT, seen in Figure 5, is a 1U CubeSat that contains a Solar Cell Measurement System (SMS), an Electrical Power System (EPS), a Command and Data Handling (C&DH) system, and two Telemetry Tracking and Command (TT&C) systems. The primary payload of this CubeSat will test solar cells and measure their degradation over time as a result of the harsh conditions of space. The TT&C sub-systems will be explained in much greater detail in this thesis.

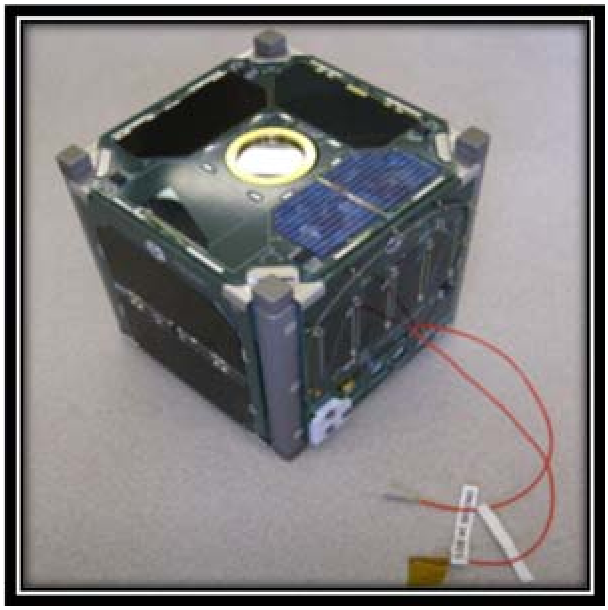

Figure 5. NPS-SCAT

D. THESIS OBJECTIVES

The object of this thesis is to discuss and explain in detail the design, testing, integration, and operations of the two TT&C systems used onboard NPS-SCAT. NPS-SCAT’s two TT&C systems will provide full telemetry for the solar cell testing experiment using the amateur frequency band. The transceivers for the TT&C systems have been tested and the results documented. The testing results for each transceivers antenna are also documented. Then the transceivers were integrated with their antenna and both TT&C systems integrated with their respective ground station. This thesis also includes the process for successfully obtaining an approved Amateur Satellite (AMSAT) license for two ground stations used to communicate with the spacecraft. Finally, conclusions and recommendations for future work on CubeSats at NPS are discussed.

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II. DISCUSSION OF NPS-SCAT'S MISSION AND COMMUNICATION REQUIREMENTS

A. NPS-SCAT CONCEPT OF OPERATIONS

1. Overview

The Concept of Operations (CONOPS) for NPS-SCAT was developed by past CubeSat team members with the idea of gathering solar cell measurements and transmitting the telemetry to a ground station for analyzing. The analysis will determine the solar cells' efficiency and degradation over time due to the harsh space environment. The CONOPS was tailored to the spacecraft's operational capabilities, the success of the solar cell experiment and the data requirements. The CubeSat's operations were divided into two sequences, the start-up sequence and the normal operations sequence. The normal operations sequence is controlled by a Salvo scheduler that controls multiple tasks. Salvo is the operating system within the C&DH. The normal operations sequence is subdivided into seven tasks: the beacon antenna deploy task, the collect data task, the MHX wakeup task, the transmit MHX task, the receive MHX task, the beacon transmit task, and the receive beacon task. Each task has a priority from 1 to 5 and the scheduler runs the highest priority task based on a timer or an interrupt. The two sequences and seven tasks will be fully explained in the following paragraphs. A complete graphic description of the CONOPS can be found in Appendix A.

2. Start-Up Sequence

As NPS-SCAT sits in a CubeSat Deployer, it has all of its systems turned off and the batteries are at their ideal storage voltage. Once the spacecraft is deployed from its launcher, the C&DH (Pumpkin FM430 Flight Module) is powered on and the startup sequence will commence. The first executed commands, as seen in Figure 6, are turning off the SMS, the primary transceiver and the secondary transceiver ensuring they are off and not using power. Then the sequence will delay for a minimum of 30 minutes allowing the spacecraft to get sufficient separation distance from the launch vehicle. Next, the program checks to see if the beacon antenna is deployed and then Salvo will initialize allowing the Salvo scheduler to run tasks.

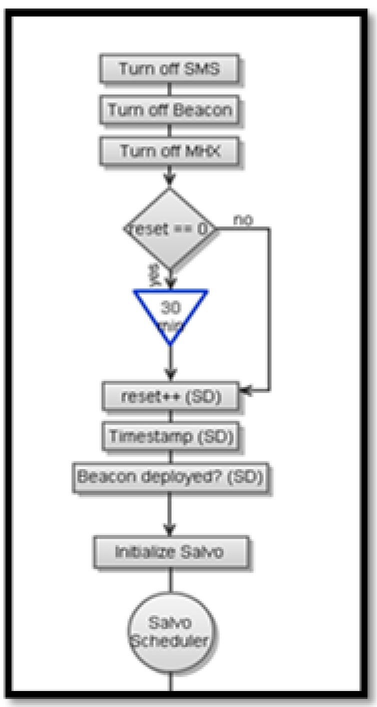

Figure 6. Startup Task

3. Normal Operations Sequence

a. Beacon (Secondary Transceiver) Antenna Deploy Task

The first task run by the Salvo scheduler is the beacon antenna deploy task and it does not finish this task until the antenna is deployed. The task consists of continuously checking the EPS' battery voltage until the CubeSat has charged its batteries to approximately 8.5 volts. Next, the beacon antenna deployment circuitry will deploy the antenna and turn on the beacon. Lastly, the beacon antenna deployment task will check to make sure the antenna deployed. If the beacon did deploy, the task will end and if not, the task will run again to deploy the antenna for a maximum of five times. Once the antenna has been deployed or it has tried to deploy five times, the beacon antenna task, seen in Figure 7, will not be used again.

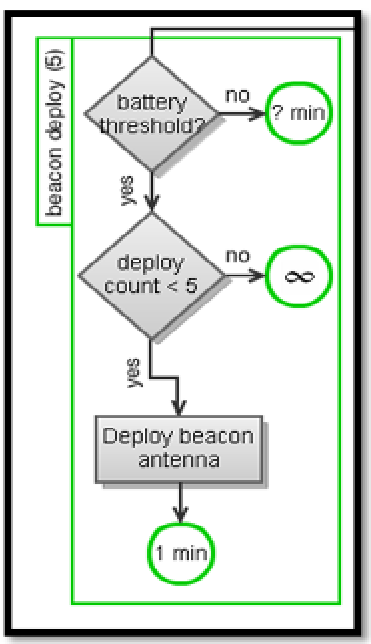

Figure 7. Beacon Antenna Deploy Task

b. Data Collect Task

The data collect task seen in Figure 8 starts by again checking SCAT's batteries to make sure there is enough power to continue. If there is not, the task is delayed for one minute and the batteries are checked again. Once there is enough battery power, the task starts collecting data. First, it collects a time stamp followed by getting the temperatures from the temperature sensors and the battery voltage from both batteries. Then the task checks to see if it can see the sun. If it can, the SMS turns on, the sun angle is captured, the data points for the I-V curves are collected, the sun angle is collected again, and the SMS turns off. An I-V curve is a plot of solar cell current versus voltage, which will be used to determine the solar cells efficiency. Next, the data is written to the Secure Digital (SD) memory card with another time stamp where it will be stored until it is transmitted to the ground. If it cannot see the sun, the first time stamp, the temperatures, the battery voltages, and a second time stamp are stored on the SD card. Finally, the task will be delayed for ten to fifteen minutes before it runs again. This task has a priority of three and will be continually run as long as it is the highest priority.

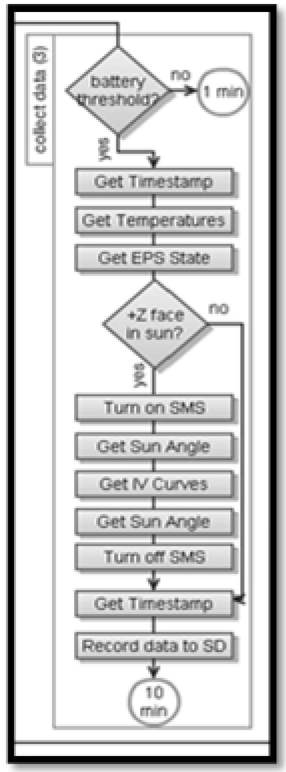

Figure 8. Collect Data Task

c. MHX (Primary Transceiver) Wakeup Task

The MHX (Primary Transceiver) wakeup task starts by checking the EPS to make sure there is enough voltage to turn on the transceiver. If there is not, it checks the batteries every minute until the battery voltage is sufficient. If or when there is enough battery voltage the MHX2400 transceiver turns on. Then the MHX tries to link up with the ground station. If the link is connected, this task is interrupted by the transmit MHX task. The MHX wakeup task seen in Figure 9 is then delayed until the transmit MHX task is completed. Next, the MHX is turned off and the task is delayed for approximately 85 minutes. The delay allows the CubeSat to complete another orbit before turning this task on again. If the link cannot be established, the MHX turns off and delays for two minutes before running the task again. This task has a priority of two and will be run while it is the highest priority.

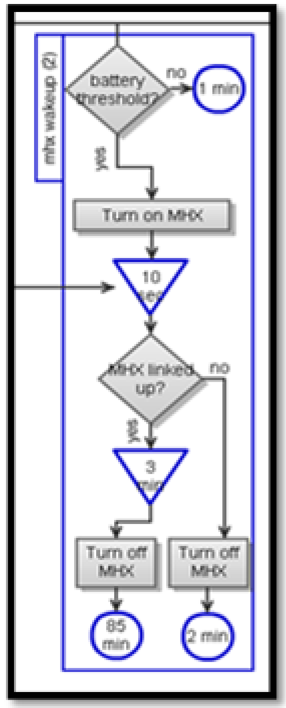

Figure 9. MHX Wakeup Task

d. *Transmit MHX (Primary Transceiver) Task*

The transmit MHX task seen in Figure 10 is only executed when the MHX transceiver on SCAT has linked up with another MHX transceiver. The first command for this task is to check the batteries to make sure there is voltage for the transceiver to transmit the data stored on the SD card. If the EPS validates that the voltage is sufficient, the MHX will transmit data from SD card as long as the link is still connected or until all the data is sent. Then the task will end. If there is not enough voltage to transmit data, the task will end. This task has a priority of one and is an interrupt task but can only be utilized when the MHX on SCAT is linked with another MHX. An interrupt task is a task that can interrupt the task, which is currently being executed. If for some reason the MHX2400 is stuck on in the transmit mode, the radio will drain the battery in approximately 120 minutes.

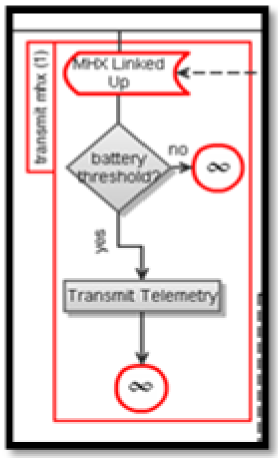

Figure 10. Transmit MHX Task

e. Receive MHX (Primary Transceiver) Task

The receive MHX task can only be utilized if the MHX wakeup task is executing, the MHX on SCAT is linked with another MHX and the interrupt is requested. This task allows the MHX on the CubeSat to receive commands from a ground station. Again the EPS' voltage has to be verified that it is at an acceptable level and if it is, the MHX will receive commands and pass them to the C&DH. Once the commands are processed, this task is complete until it is requested via the interrupt next time. The receive MHX task seen in Figure 11 has a priority of one and is an interrupt task but can only be utilized within the MHX wakeup task. One important function that the receive MHX task is required to do is receive a command to turn off the beacon. If for some reason the beacon is stuck on and interfering with other radios on the same frequency, a command will be sent to the MHX2400 to turn off the beacon.

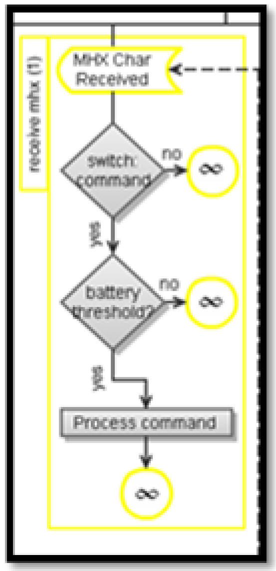

Figure 11. Receive MHX Task

f. Beacon (Secondary Transceiver) Transmit Task

The beacon (Secondary Transceiver) transmit task seen in Figure 12 begins just like the other tasks by checking the battery voltage to see if it is sufficient to run the task. If there is not enough battery capacity, it continuously checks until the voltage is high enough for the beacon to transmit. Once the battery voltage is high enough, the beacon transmits a short message saying "This is NPS-SCAT." Then the task checks to see if it has been five minutes since the last time it transmitted any telemetry data from the SD card. If it has been five minutes, the beacon transmits telemetry data, delays and then starts the task over. If it has not been five minutes since the last telemetry data has been sent, the task delays and then starts over. This task is run at a priority of four and will continuously run as long as it is the highest priority. If for some reason the beacon is stuck on in the transmit mode, the beacon will drain the battery in approximately 155 minutes.

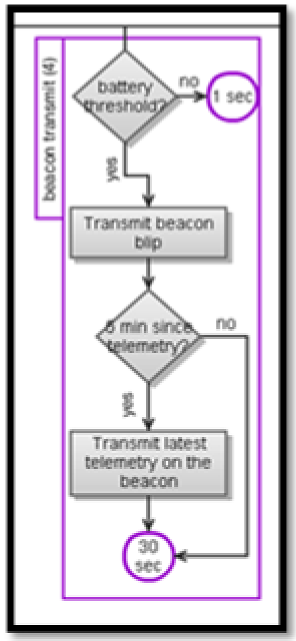

Figure 12. Beacon Transmit Task

g. Receive Beacon (Secondary Transceiver) Task

The final task to be discussed is the receive beacon task seen in Figure 13. This is an interrupt task with a priority of one and can only be utilized when the SCAT is in line-of-site with a ground station. If a ground station sends a command to the CubeSat, this task begins by checking the EPS' battery voltage to see if it sufficient to execute the command. If it is, the command is processed and the task ends. If the battery voltage is not high enough, the task is ended.

One important function that the beacon is required to do is receive a command to turn off the

MHX2400. If for some reason the MHX2400 is continuously transmitting and interfering with other radios on the same frequency, a command will be sent to the MHX or the beacon to turn off the MHX2400.

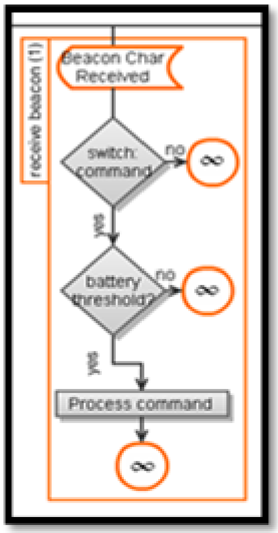

Figure 13. Receive Beacon Task

B. DATA REQUIREMENTS FOR EACH SYSTEM

1. Overview

Allowing the satellite to function by carrying tracking, telemetry, and command data or mission data between its elements is the purpose of a satellite's communication system [16]. The complexity of a TT&C system is determined by the requirements of the spacecraft and the ground station. The minimum data requirements define mission success so it is critical that the TT&C system can meet them.

The data baseline for NPS-SCAT is defined by the Solar Cell Measurement Systems (SMS) data and the spacecraft's system health. The minimum data requirement is a combination of the SMS data, the temperature sensors data, the Clyde-Space 1U Electrical Power System data and the FM430 Flight Module data. Both of SCAT's TT&C systems must meet the minimum data requirements in order to have mission success. Appendix B shows each system's data requirements, which equates to approximately 720 bytes excluding the overhead. Each system's data requirements will be discussed in great detail in the upcoming sections.

2. Solar Cell Measurement System (SMS)

The payload for NPS-SCAT is a Solar Cell Measurement System, seen in Figure 14, which allows the spacecraft to measure currents, voltages, and temperatures from the experimental solar cells. Those measurements are then analyzed with sun angle measurements obtained from a Sinclair Interplanetary Two-Axis Digital Sun Sensor. These data can then be used to generate I-V curves for comparison with pre-flight measurements.

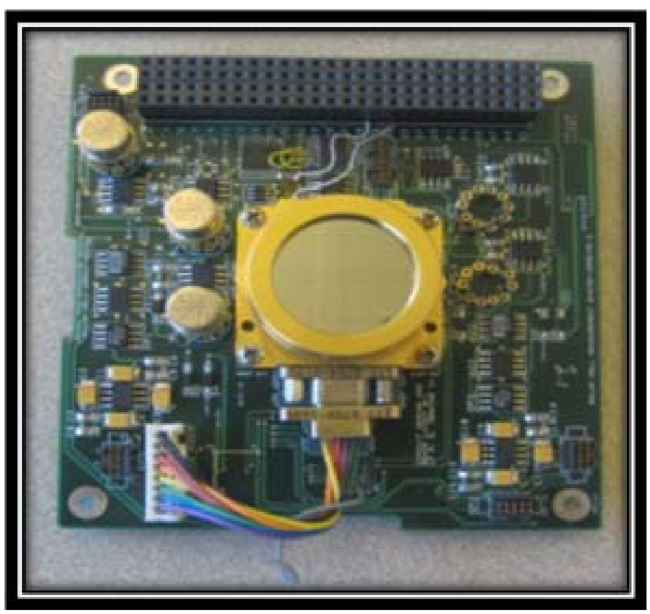

Figure 14. Solar Cell Measurement System (SMS)

An I-V curve similar to the one in Figure 15 shows the open circuit voltage, the short circuit current, and the knee of the curve. The line for the I-V curve must have sufficient points for the plot to be accurate enough to be used in the analysis of the solar cells. The NPS-SCAT team decided that 100 data points equating to 150 bytes are required to plot a useable I-V curve. Each of the four solar cells to be evaluated by NPS-SCAT will have an I-V curve associated with them. The SMS data equates to approximately 654 bytes per orbit.

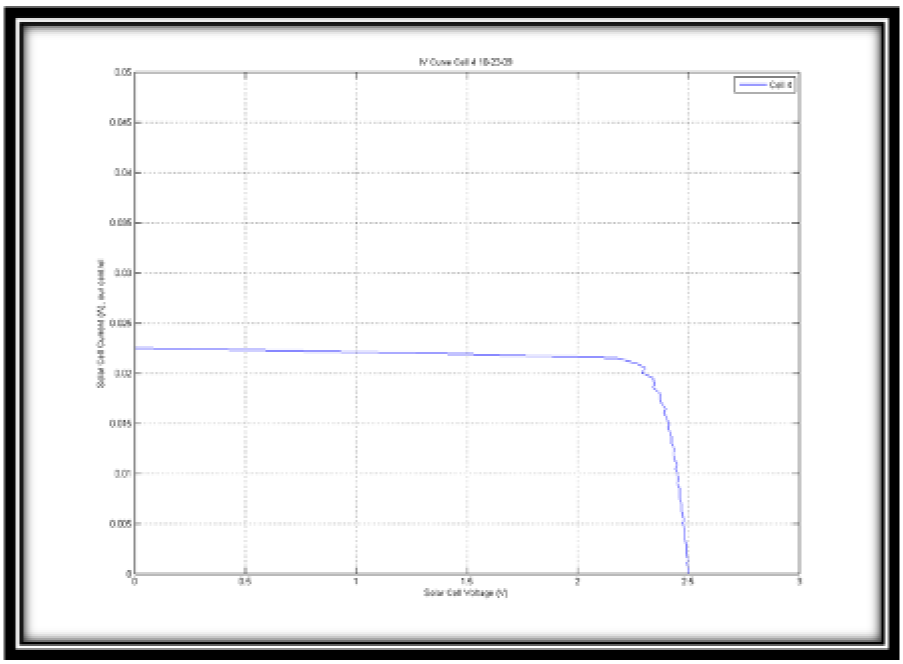

Figure 15. Example I-V Curve

3. Electrical Power Supply (EPS)

The purpose of the Electrical Power System is to store, distribute, and control the spacecraft’s power [16]. With this in mind, the EPS is a critical component of the communications system. The EPS also generates pertinent data that is used to evaluate the CubeSat’s performance.

Power is a very critical component of any satellite but especially in a CubeSat because it is so limited. The power must be monitored so that the CubeSat can continue to operate and obtain mission success. The Clyde Space 1U EPS seen in Figure 16 will provide data for each subsystem's voltage and current draw that will later be sent to the ground station allowing for the monitoring of the spacecraft's health. The EPS' data is approximately 50 bytes which can be found in Appendix B.

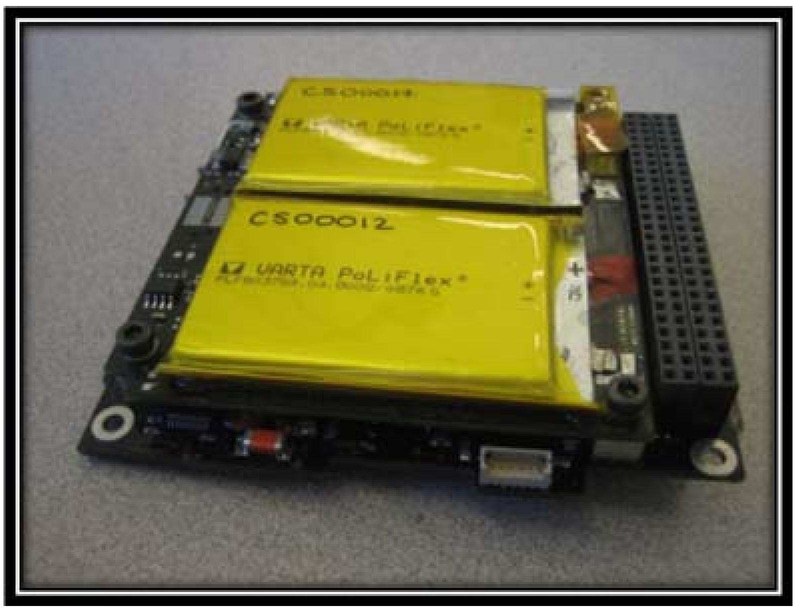

Figure 16. Electrical Power System with Batteries

4. Temperature Sensors

Another important source of data that is pertinent for understanding a spacecraft's environment and health is the temperature sensors seen in Figure 17. There are a total of 15 MAX6633 temperature sensors strategically placed throughout the satellite. These sensors will be used to more accurately characterize the efficiency of the solar cells. The temperature sensor data is about 30 bytes.

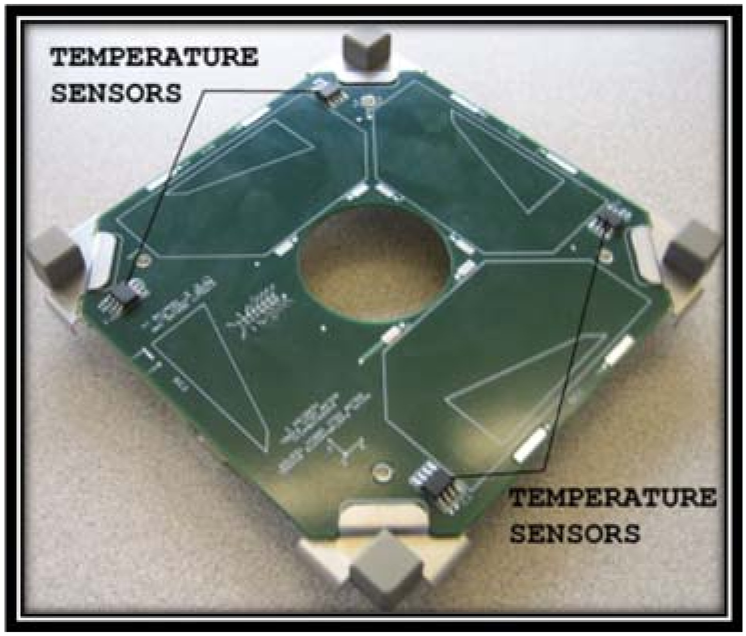

Figure 17. Temperature Sensors

5. FM430 Flight Module

The FM430 flight module is the processor for the satellite. All the telemetry generated within the spacecraft will be sent to the FM430 seen in Figure 18. Once the telemetry is processed the FM430 will store the data on the SD card until it is routed to the correct communications system for transmission to the ground station. Though the FM430 does not generate much original data, it is a critical component that works together with the communications systems.

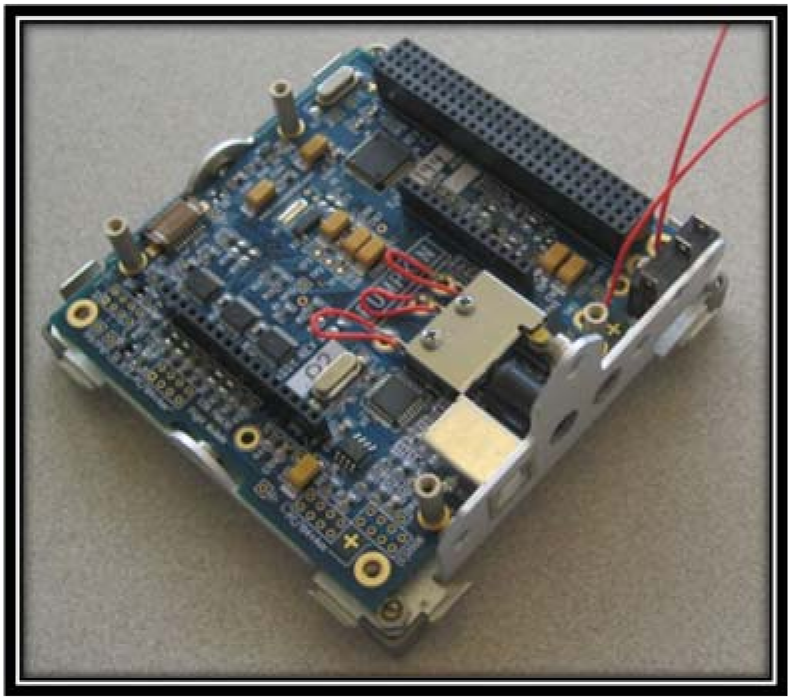

Figure 18. Pumpkin FM430 Flight Module

C. POWER REQUIREMENTS FOR TRANSCEIVERS

1. Primary Radio (Microhard Systems MHX2400)

The primary radio used in NPS-SCAT is the Microhard Systems Inc. MHX2400 as seen in Figure 19. One of the most important factors in choosing the MHX was the power requirement for transmitting telemetry. The link between the MHX on NPS-SCAT and the ground station has to be closed to allow data to pass and a certain amount of power is required to close this link. The COTS solution that the MHX provided seemed to have power consumption that would fit in to the power budget of SCAT and still be able to close the link. To determine the amount of power the MHX requires, a current draw test needed to be conducted. The current draw test is discussed in Chapter III.B.4.a. The current draw for the MHX is fixed so the preferred method to modify the power draw is to operate at the maximum power but manage the duty cycle. To manage the best duty cycle, the radio will try to communicate with the ground station every two minutes. Once the link has been established, data will be passed and when the link is dropped, the transceiver will be turned off for approximately 85 minutes. Turning on and off the MHX will be controlled by the FM430 and is described in greater detail in Chapter II.A.3.c.

Figure 19. Microhard Systems Inc. MHX2400

2. Secondary Radio (UHF Transceiver Designed by Cal Poly)

The “beacon” is actually a UHF Transceiver and has lower power requirements than the MHX. The beacon, as seen in Figure 20, was designed by the Cal Poly CubeSat program as a follow on to their CP CubeSat series beacons. The beacon’s power usage is lower than the MHX partially because it operates at a lower frequency, which requires less power to close the link. The data rate of the beacon is also significantly less therefore less energy-per-bit is required. Even though the power draw is less for the beacon compared to the MHX, a current draw test needed to be conducted to determine the amount of power the beacon requires. The current draw test is described in detail in Chapter III.C.3.a. Because the power draw is so low, the beacon will stay powered on once it is turned on unless the FM430 needs to shut it off because of low battery voltage.

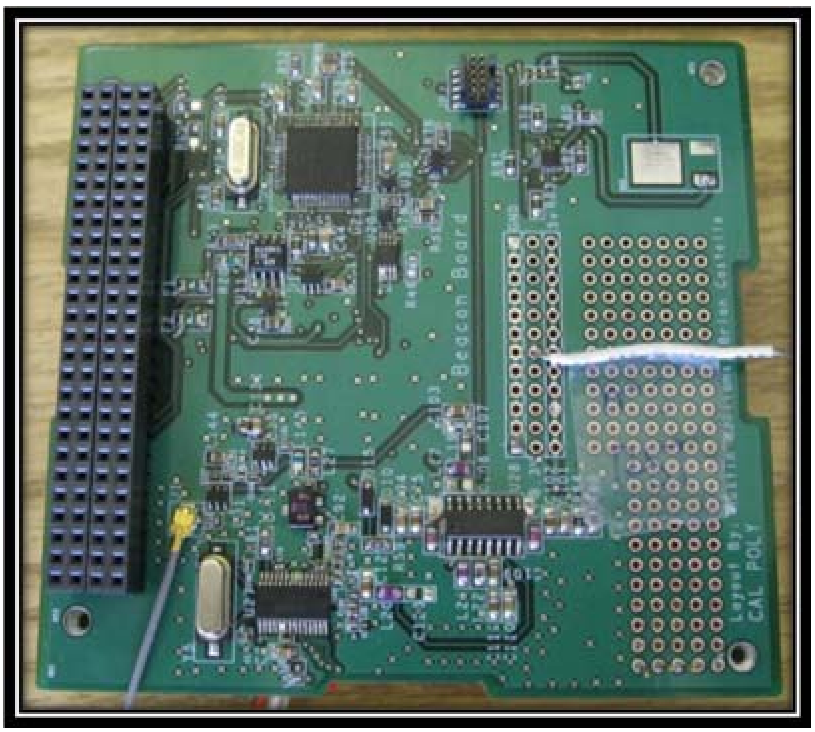

Figure 20.   Beacon (UHF Transceiver)

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III. SCAT TRANSCEIVERS METHODOLOGY AND TESTING

A. PAST WORK ON SCAT TRANSCEIVERS

1. Primary Transceiver

One of the primary focuses of NPS-SCAT is to develop a baseline of system designs that can be used in future NPS CubeSats leveraging COTS technology. With that thought in mind, the Microhard System Inc. MHX2420 appeared to be a great fit for the Pumpkin 1U CubeSat Skeleton Structure and FM430 Flight Module that comes integrated within the structure [17]. The first concept of the NPS-SCAT communications design is discussed by Alexander L. Bein in his thesis from September 2008. Because of the simplicity of integrating the MHX2420, it was originally selected as the primary transceiver for the NPS-SCAT prototype. The MHX2420 has a center frequency of 2.4 GHz, which is located in the ISM band. A link budget was calculated using the transceiver and the ground station at NPS, which includes a three-meter dish with a ten-watt bi-directional amplifier. The main reason for selecting the MHX2420 was because the link budget showed the link would close [18].

Follow on testing of the MHX2420 was conducted by thesis student Matthew P. Schroer. Matt’s thesis describes the MHX2420’s specifications, his link budget calculations, and key performance parameter, namely power and sensitivity testing [7]. While testing was being conducted, Matt determined that the MHX2420 required more power than the spacecraft could support. This was due to the current draw that the transceiver needed while transmitting. At that point it was decided by the NPS-SCAT team to look at an earlier version of the transceiver, the MHX2400. The MHX2400 was used in a CubeSat, GENESAT-1, built by NASA. The two students who worked on the communications system published a paper and based on their results it looked like the MHX2400 would work for NPS-SCAT [19]. The MHX2400 specifications and testing will be discussed in greater detail in Chapter III.B.1.

2. Secondary Transceiver (Beacon)

A beacon transmitter was not originally in the plans for NPS-SCAT. The utility and need for a beacon or second transceiver became apparent as the program progressed through the early part of 2009. Past CubeSat programs had incorporated a beacon or another transceiver as risk mitigation to the primary transceiver. As discussed in great detail in Matt’s thesis, the design coordination for NPS-SCAT’s beacon began with Cal Poly in May 2009. Cal Poly had built their own beacon/transceiver boards, which they used on their CP series CubeSats [7]. As discussions and design progressed, the beacon actually became a UHF transceiver that would be used as a beacon but also could be a backup transceiver for the MHX 2400. The design and testing of the beacon will discussed further in Chapter III.C.

B. PRIMARY TRANSCEIVER SPECIFICATIONS AND TESTING

1. MHX 2400 Specifications

The MHX2400 is a high-performance embedded wireless data transceiver. Operating in the 2.4000 to 2.4835 GHz ISM band, this spread-spectrum module is capable of providing reliable wireless data transfer between most types of equipment that uses an asynchronous serial interface. Some additional features are; 49 sets of user-selectable pseudo-random hopping patterns intelligently designed to offer reliability and high tolerance to interference, built-in CRC-16 error detection and auto re-transmit to provide 100% accuracy and reliability of data, and ease of installation and use – the MHX2400 module uses a subset of standard AT style commands. The specifications for the MHX2400 are in Table 5 [20].

Table 3. Microhard Systems Inc. MHX2400 Specifications (From[19])

Parameter	Value
Band	2.4 GHz ISM
Transmission Method	Freq Hopping Spread Spectrum
Serial Data Rate	Up to 115kbps
RF Output Power	Up tp 1W, selectable
Power Consumptions (RX/TX)	1.15W / 4.38W
Sensitivity (@25°C)	-105 dBm
Maximum Throughput	83kbps (no delay)
Weight	75 grams
Size	90 mm X 53 mm X 25 mm

2. Link Budget

Past performance is an important factor when choosing a space qualified radio to perform the command and control of a spacecraft. However, a calculated link budget on the radio is just as important. The link budget provides the designer with values of transmitter power and antenna gains for various links in the system. It is therefore one of the key items in space system design, revealing many characteristics of the overall system performance [21]. A link budget can estimate the viability of the radio given certain parameters. For NPS-SCAT, a link budget for the uplink and downlink are required. Spacecraft Design is one of the classes at NPS and the Space Mission Analysis and Design (SMAD) book was used. The book describes in great detail how to properly design an entire spacecraft with all its systems to include computing a link budget. An excel worksheet for computing the link budget was also designed by SMAD. The link budget worksheet was used compute the link budgets for SCAT.

a. Uplink

The MHX2400 uplink budget as seen in Table 4 was computed using the SMAD Communications System – Uplink excel worksheet. The worksheet requires a number of inputs and then, using the inputs, computes outputs ultimately obtaining a sufficient link margin of at least 3 dB. The link budget worksheet has basically five sections, four which require parameter inputs and the fifth is the computed link budget.

The first section includes two transceiver characteristics, a frequency and a data rate. The frequency used for the MHX2400 is 2.415 GHz, which is in the middle of the hop pattern used by SCAT because it is in the amateur band. The data rate used is 115.2 kbps, which is the wireless data rate for the transceiver and it cannot be adjusted.

Then next section is the ground station inputs. The output power for the ground station is 10 watts, which includes a high power amplifier (HPA). A line loss of 3.60 dB is used. This number is a standard line loss used in the NPS ground station provided by Mr. David Rigmaiden, NPS' Small Satellite Lab Manager. An antenna efficiency for the ground transmitter is 55% which is a standard number recommended by SMAD. The ground transmitter’s antenna diameter is 3.04 meters. The pointing error for the ground station was given by Mr. Rigmaiden to be 1.0 degree.

Section three is the geometry and atmosphere inputs. There was a minimum and maximum altitude given by the launch integration team where SCAT may be launched. The minimum altitude is 450 km and the maximum is 600 km. The elevation angle was also a variable that was changed from 10 degrees to 45 degrees to 89.99 degrees. A total of six uplink budgets were computed with a combination of both altitudes and all three elevation angles.

The spacecraft receiver inputs are in section four of the worksheet. An antenna efficiency of 80% was used based on the Voltage Standing Wave Rations (VSWR) measurements of the patch antenna being used with the MHX2400. Further explanation of the patch antenna’s efficiency is in Chapter IV.C.3. Because the worksheet is setup for the diameter of an antenna in meters and SCAT’s antenna is a half-wave dipole antenna, the diameter is a made up number of 0.04 m that coincides with a 0 dB peak antenna gain.

The last section is the actual computed link budget section. All of the inputs above are used in equations used from the SMAD book to compute values. These same values were also used in the carrier-to-noise ratio testing in Chapter III.B.4.c. The most important calculated number of the link budget is the margin. As described in SMAD, a link margin of at least 3 db is required to complete the link. The uplink margin at 450 km with and elevation angle of 10 degrees is 12.80 dB which means the link will close based on the provided inputs. Appendix C contains all six uplink budget in one worksheet.

Table 4. MHX2400 Uplink Budget at 450km and 10 Degree Elevation Angle

Return to Navigator — **Communications System - Uplink**

(All information on this sheet is contained in the block from Cell A1 to Cell Q33)

Section 1:											
Frequency	2.415	2.415	GHz	Data rate	1.152E+05	1.152E+05	bps	Probability of Bit Error		1.00E-05	
Wavelength		1.24E-01	m					Required Eb/No		9.60	dB
Section 2:				**Section 3:**				**Section 4:**			
Ground Transmitter				Geometry & Atmosphere				Spacecraft Receiver			
Output power	10.00	10.00	W	Altitude	450.000	450.000	km	Antenna efficiency	80.0%	80.0%	
Output power		10.00	dB	Planet angular radius		69.08	deg	Antenna diameter	0.04	0.04	m
Line loss	-3.60	-3.60	dB	Elevation angle	10.00	10.00	deg	Peak antenna gain		-0.60	dB
Antenna efficiency	55.0%	55.0%		Nadir angle		66.91	deg	Half-power beamwidth		210.85	deg
Antenna diameter	3.04	3.04	m	Planet central angle		13.09	deg				
Peak antenna gain		35.13	dB	Propagation path length		1570.039	km	Pointing error	0.000	0.000	deg
Half-power beamwidth		2.86	deg					Antenna pointing loss		0.00	dB
EIRP		41.53	dB	Atmospheric attenuation at zenith		-0.060	dB				
				Rain attenuation		0.000	dB	System noise temperature		688.00	K
Pointing error	1.00	1.00	deg	Increase in system noise temp		0.00	K	G/T		-28.97	dB
Antenna pointing loss		-1.47	dB								

Section 5:			
Link Budget			
EIRP		41.53	dB
Space loss		-164.02	dB
Atmospheric attenuation		-0.65	dB
Rain attenuation		0.00	dB
G/T		-28.97	dB
Antenna pointing losses		-1.47	dB
Eb/No		24.40	dB
C/No		75.01	dB
Implementation loss		-2.00	dB
Margin		12.80	dB

b. Downlink

To evaluate a complete communications link, a downlink budget must also be calculated. The SMAD worksheet for the downlink budget is in Table 5. The inputs are very similar to those of the uplink with a few exceptions. In the downlink budget, the spacecraft transmitter and the ground receiver parameters are required instead of ground transmitter and the spacecraft receiver. Only the inputs that changed from the uplink budget will be described.

In the spacecraft transmitter section, an output power of 1 watt was used. This number came from the specifications for the MHX2400. A line loss of 0.20 dB was used. In the ground receiver section, the only input is the antenna diameter which remains 3.04 meters. This input is the same as the uplink ground transmitter diameter.

Similar to the uplink budget, once all the input parameters have been entered, the worksheet calculates the downlink budget. Again, the important number is the margin, which must be greater than 3 dB. As seen in Table 7, the downlink margin at 450 km with an elevation angle 45 degrees is 12.38 dB, more than enough to close the link. Appendix C contains all six downlink budgets in one worksheet.

Table 5. MHX2400 Downlink Budget at 450km and 45 degrees Elevation Angle

Return to Navigator **Communications System - Downlink**

(All information on this sheet is contained in the block from Cell A1 to Cell Q33)

Section 1:			
Frequency	2.42	2.415	GHz
Wavelength		1.24E-01	m
Section 2:			
Spacecraft Transmitter			
Output power	1.00	1.00	W
Output power		0.00	dB
Line loss	-0.20	-0.20	dB
Antenna efficiency	80.0%	80.0%	
Antenna diameter	0.04	0.04	m
Peak antenna gain		0.00	dB
Half-power beamwidth		196.73	deg
EIRP		-0.20	dB
Pointing error	0.00	0.000	deg
Antenna pointing loss		0.00	dB
Duty cycle (per orbit period)		100.0%	

Data rate	1.152E+05	1.152E+05	bps
Section 3:			
Geometry & Atmosphere			
Altitude	450.000	450.000	km
Planet angular radius		69.08	deg
Elevation angle	45.00	45.00	deg
Nadir angle		41.34	deg
Planet central angle		3.66	deg
Propagation path length		616.684	km
Atmospheric attenuation at zenith		-0.060	dB
Rain attenuation		0.000	dB
Increase in system noise temp		0.00	K

Probability of Bit Error		1.00E-05	
Required Eb/No		9.60	dB
Section 4:			
Ground Receiver			
Antenna efficiency		55.0%	
Antenna diameter	3.04	3.04	m
Peak antenna gain		35.13	dB
Half-power beamwidth		2.86	deg
Pointing error		0.286	deg
Antenna pointing loss		-0.12	dB
System noise temperature		260.00	K
G/T		10.98	dB

Section 5:

Link Budget

EIRP		-0.20	dB
Space loss		-155.91	dB
Atmospheric attenuation		-0.38	dB
Rain attenuation		0.00	dB
G/T		10.98	dB
Antenna pointing losses		-0.12	dB
Eb/No		32.35	dB
C/No		82.97	dB
Implementation loss		-2.00	dB
Margin		20.75	dB

3. Data Budget

The data budget is another important calculation for determining whether the MHX2400 will be able to transmit all the data collected by NPS-SCAT. Data budgets for altitudes of 450 km and 600 km were calculated as seen in Table 6. From Chapter II.B., the telemetry data excluding overhead data is approximately 720 bytes. After discussions with Peter Reinhardt (MIT Intern-Student and C&DH software programmer), it was ascertained that the total telemetry will be approximately 787 bytes.

Table 6. NPS-SCAT Data Budget (Primary Radio)

NPS-SCAT Data Rate Budget (Primary Radio)			
Orbit Altitude	*450km*	*600km*	*Units*
Size of Full Telemetry File (Includes 4 I-V Curves & Overhead)	787	787	*bytes*
Number of Collects per Orbit	4	4	*collects*
Data Collected per Orbit	3148	3148	*bytes*
Number of Orbits per Day	15.36	14.71	*orbits*
Data Collected per Day	48353.28	46307.08	*bytes*
Primary Radio Data Rate	9600	9600	*bps*
	960	960	*Bps*
Time to Transmit Primary Telemetry Daily	50.37	48.24	*seconds*
Number of Ground Station Passes per Day at a minimum elevation angle of 30 degrees	3	4	*passes*
Average Time per Pass	153.21	205.73	*seconds*
Total Time Over Head	459.63	822.92	*seconds*

NPS-SCAT will be programmed to collect telemetry four times per orbit. This is based on an orbit period of approximately 90 minutes. More than half that time the spacecraft will be in the sun and it will collect data every ten minutes. Therefore, 787 bytes per collect and 4 collects per orbit equates to 3148 bytes. Next, Satellite

Tool Kit (STK) was used to model NPS-SCAT orbiting the earth at altitudes of 450 km and 600 km. Figure 21 shows an STK depiction in 2D of NPS-SCAT orbiting the earth with the ground station located in Monterey. The number of orbits per day as modeled by STK is 15.36 for 450 km and 14.71 for 600 km. The number of orbits multiplied by the amount of data equals about 46000 to 48000 bytes per day. The MHX serial baud rate connection will be 9600 bps at approximately 10 bits per byte gives 960 Bps. When the data collected per day is divided by the MHX2400 serial data rate in bytes, it will take about 48 to 50 seconds to transmit a day’s collection of data. Again, STK was used to model NPS-SCAT and NPS’ ground station to calculate the number of passes per day and the length of each pass. At a 30 degree elevation angle above the horizon, NPS-SCAT will be able to see the ground station for about 460 to 820 seconds a day. Since it only takes up to 50 seconds to transmit a day’s collection of data, there is more than enough time for SCAT to link with the ground station and transmit all of its onboard data.

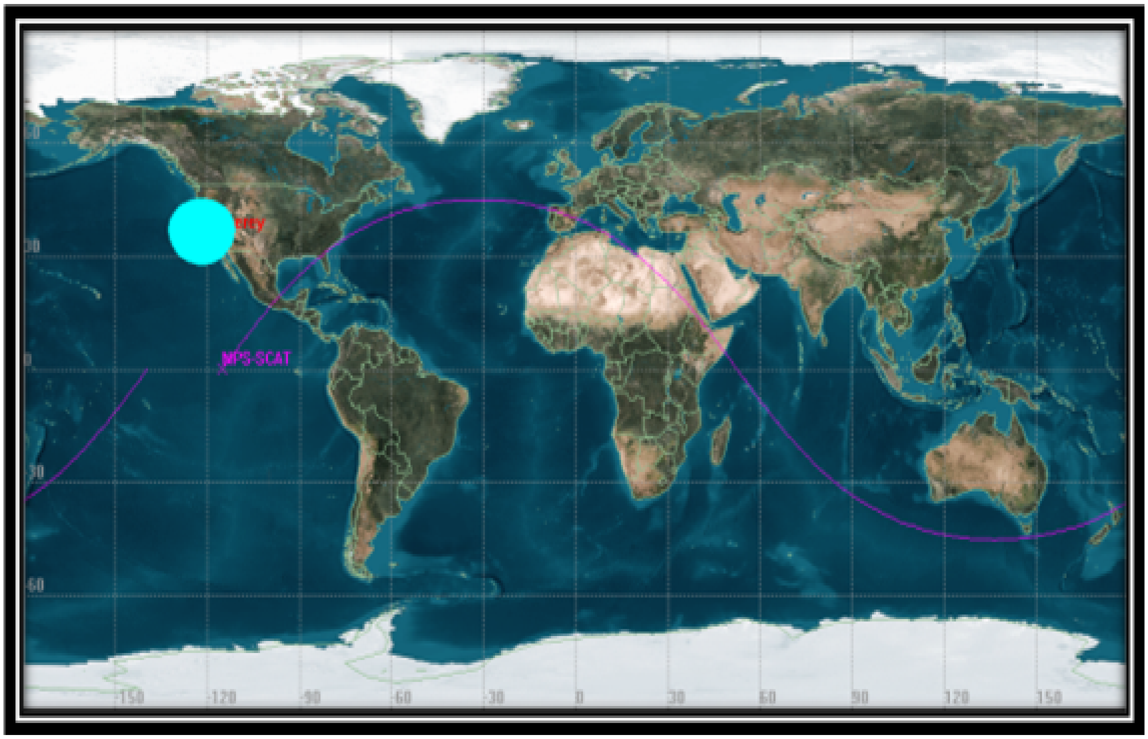

Figure 21. STK with NPS-SCAT Orbiting at 450km

4. Radio Testing

a. Current Draw

To determine the MHX's power consumption a test was setup using two MHX2400's with development board kits, and an oscilloscope with a Hall Effect current probe connected to it. Justin Jordan, a lab assistant, modified one of the MHX2400 development boards by attaching two test wires directly to voltage line of the MHX2400 as seen in Figure 22.

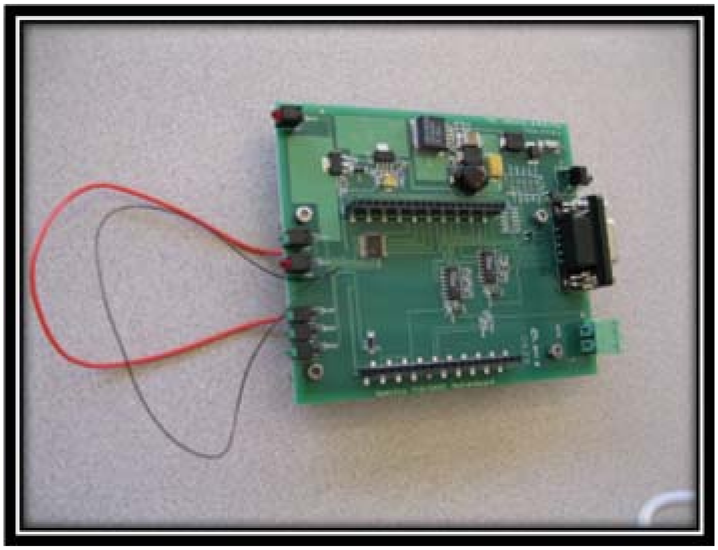

Figure 22. MHX2400 Modified Development Board

The current probe that was attached to the oscilloscope was then clamped around the test wires to measure the MHX’s current draw. The mean and peak currents were measured using the oscilloscope while the MHX was in three different states; sitting idle, receiving and while it was transmitting. The tests showed three distinct states of current draw. The data rate for the test was 115.2 kbps, which is the only configuration for the wireless rate. The serial connection data rate was held constant a 9.6 kbps for all three collections. Also the transmitting power was held constant at 1 watt. After the currents for the three states were collected, the data was used to compute the results in Table 7. The results showed that the MHX2400 could not be left on all the time for power considerations and would have to be run on an appropriate duty cycle.

Table 7. Microhard Systems Inc. MHX2400 Mean and Peak Power

Microhard Systems Inc. MHX2400		
	Mean Power (Watts)	Peak Power (Watts)
Standby	1.50	1.50
Receiving	1.63	4.70
Transmitting	2.00	4.80

b. Carrier-To-Noise

Considering the difficulties of maintaining a terrestrial wireless link such as a cell phone or a wireless laptop, it is somewhat surprising that satellite links, which cover a much greater distance, are even possible. One of the biggest factors for wireless links is noise. When a signal originates from a satellite, it is virtually noise free. There are many different factors that contribute to the noise of a system such as atmospheric absorption, the antenna's temperature, which is factored in to sky noise, and the effects of rain. There is also path loss due to the distance. All of these were accounted for when calculating the link budgets in Chapter III.B.2.a and III.B.2.b.

The margin included in the link budgets showed that the link would be closed in all cases, which meant that data could be passed. To prove that the MHX could pass data in accordance with the link budget, a carrier-to-noise test was setup. A laptop was connected to an MHX2400 and its development board inside a shielded chamber as seen in Figure 23. A cable from the MHX2400's antenna port was connected to a connector on the inside of the shielded chamber.

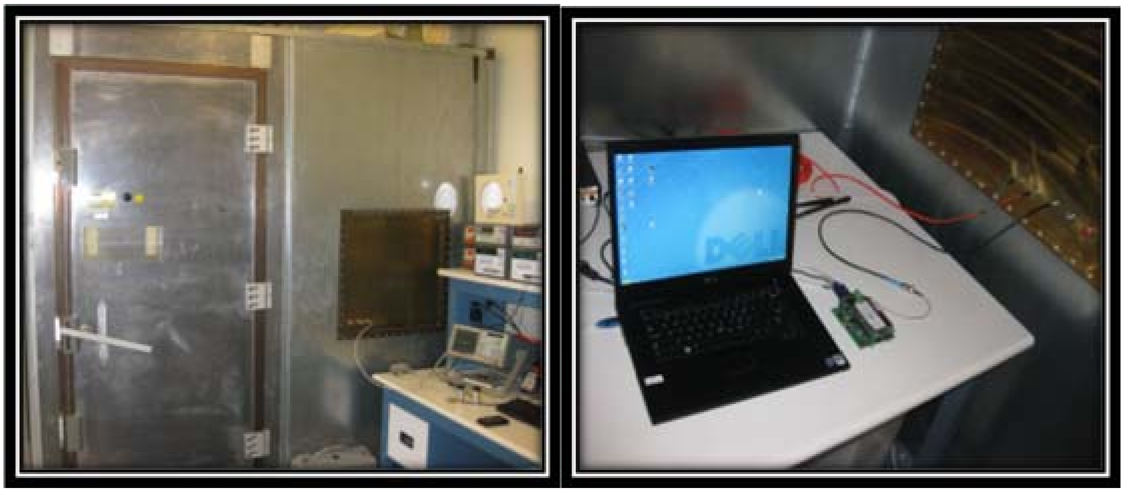

Figure 23. MHX2400 Carrier-To-Noise Test: Shielded Chamber (left) and Inside Shielded Chamber (right)

Another cable was run from the outside of the chamber on the same connector as MHX's antenna cable inside the chamber and attached to an attenuator. Attenuators, filter, splitters, amplifiers, power supplies, a frequency generator, and a spectrum analyzer were connected together as seen in Figure 24. A block diagram of the carrier-to-noise test setup is in Appendix D. The configuration of attenuators, filter, splitters, amplifiers, frequency generator, and a spectrum analyzer provided a way for the noise of the system and signal power to be adjusted. The output of the setup was then connected to another MHX2400 with a development board, which was connected to a computer, completing the link.

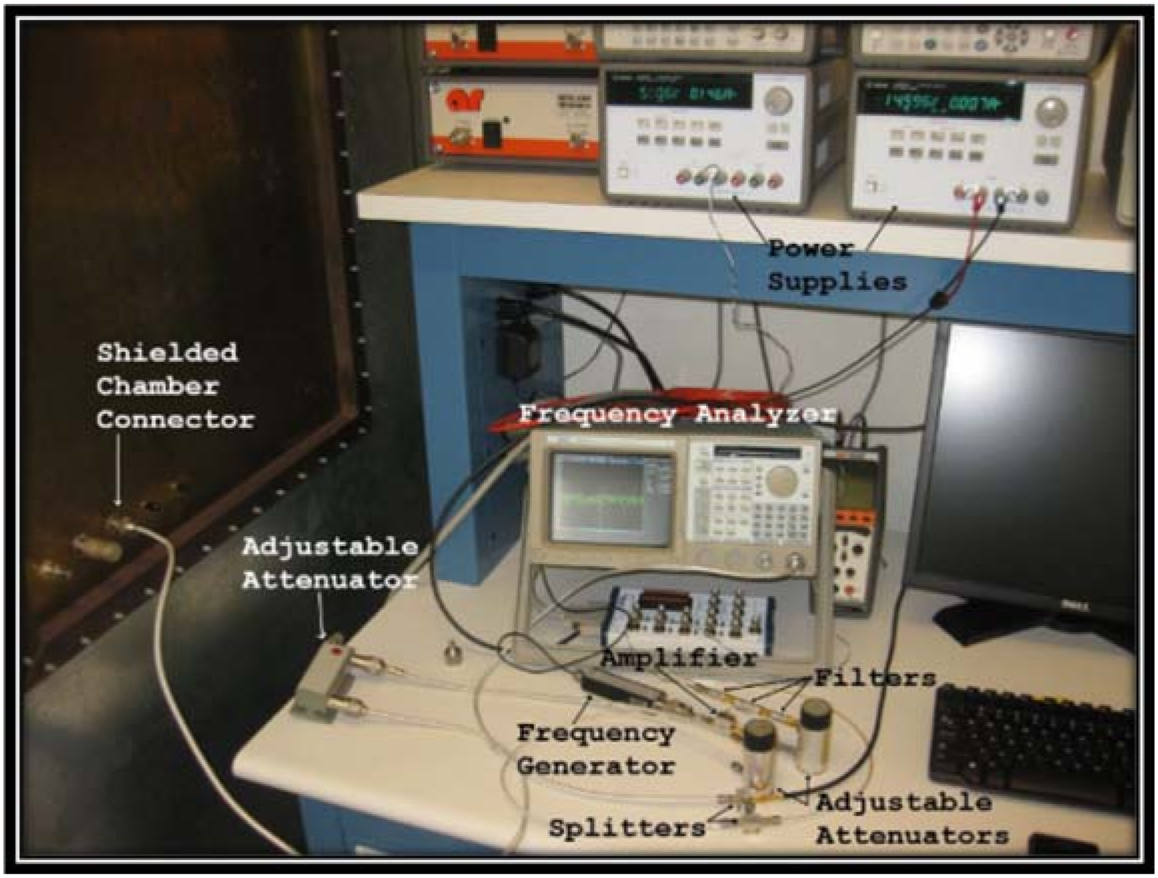

Figure 24. MHX2400 Carrier-To-Noise Test Oscilloscope, Attenuators, Splitters, Amplifiers, Power Supplies and Frequency Generator

To verify data could pass from one MHX2400 through the noise and complete the link to the other MHX2400, a Python program was written by NPS's Small Satellite Software Engineer Jim Horning. The program was written to pass a data file from the master MHX2400, inside the chamber, through the simulated noise to the slave MHX2400, outside the chamber, and display the file on the other computer. This setup allowed for testing the link budget using a carrier-to-noise test.

Before the carrier power and the noise power could be dialed into the adjustable attenuators seen in

Figure 23, the carrier-to-noise needed to be calculated. Similar to the link budgets, multiple calculations were completed to account for the 450 km and 600 km altitudes and also the three elevation angles of 10, 45, and 90 degrees. The calculated data can be seen in Appendix E. Next, the calculations were analyzed and the worst case scenario was determined. It was determined if the MHX could pass data through the worst-case noise and lowest carrier power, then it could pass data in all the other cases as well. As testing started, it was difficult to determine the best way to proceed. It was decided to keep the noise power constant at -120 dB since it was a few dB worse than the worst case. The noise power attenuator was adjusted until the spectrum analyzer showed the noise power fairly constant at -120 dB. Then carrier power was adjusted in approximately 10 dB decrements decreasing from -75 to -105 dB. Different files sizes and serial baud rates were tested to maximize the throughput of the transceivers. As seen in Table 8, all files sizes at 9.6 kbps were able pass through the noise and complete the link just as the link budget showed. As the serial baud rate increased, the size of the files that could pass through the link diminished. The reasons for this are unknown but future tests could possibly determine the cause.

Table 8. MHX2400 Carrier-To-Noise Testing

MHX2400 CARRIER-TO-NOISE TESTING

C (Received Power)	-75.0				-84.0				-96.0				-105.0				dBm
N (Noise Power)	-120.0				-120.0				-120.0				-120.0				dBm/Hz
C/N (Carrier-To_Noise)	45.00				36.00				24.00				15.00				dBm/Hz
	FILE SIZE (kB)																
BAUD RATES	**1.4**	**2.7**	**4.0**	**5.2**	**1.4**	**2.7**	**4.0**	**5.2**	**1.4**	**2.7**	**4.0**	**5.2**	**1.4**	**2.7**	**4.0**	**5.2**	
9.6k																	
14.4k																	
19.2k																	
38.4k																	
57.6k																	
115.2k																	

Carrier-To-Noise Data

450 km			
Elevation Angle	10 (Worst Case)		deg
	Uplink	Downlink	
C (Received Power)	-94.61	-82.86	dBm
N (Noise Power)	-113.23	-117.46	dBm/Hz
C/N (Carrier-To-Noise)	18.62	34.60	dBm/Hz

600 km			
Elevation Angle	10 (Worst Case)		deg
	Uplink	Downlink	
C (Received Power)	-96.42	-84.67	dBm
N (Noise Power)	-113.23	-117.46	dBm/Hz
C/N (Carrier-To-Noise)	16.81	32.79	dBm/Hz

c. Configurations

The MHX2400 can be easily configured to meet a wide range of needs and applications. When operating in data mode, the MHX has an asynchronous interface with equipment data that is sent/received on the RF channel. It also has a command mode that is used for configuring and programming the module. In addition to the data and command mode, there is a third mode of operations called diagnostics mode [20]. NPS-SCAT will use the data and command modes of the MHX2400.

Data Mode is the normal operating mode for the MHX2400. While in data mode, the MHX is communicating with at least one other MHX. There are three possible elements to an MHX2400 communications network; one transceiver configured as the Master, zero or more transceivers configured as Repeaters, and one or more transceiver configured as Slaves. The function of the Master is to provide synchronization for the network and to control the flow of data. The function of the slave is to search for synchronization with the Master [20]. NPS-SCAT will contain the Master MHX2400 and NPS-SCAT’s ground station will be the Slave MHX2400. There will be no repeaters used at this time. For NPS-SCAT to send data to the ground station it must be in data mode.

The MHX2400 firmware is designed such that users can customize the operations of the transceiver through an AT Command Interface. This device is ideal for interfacing with a microcontroller or Windows-based software. This makes it easy to configure the MHX by manually inputting AT Commands, which modifies the S-Register parameters seen in Figure 25 [21]. A development board containing an MHX2400 connected to a computer with Tera-Term software is how the S-Register parameters were configured for NPS-SCAT.

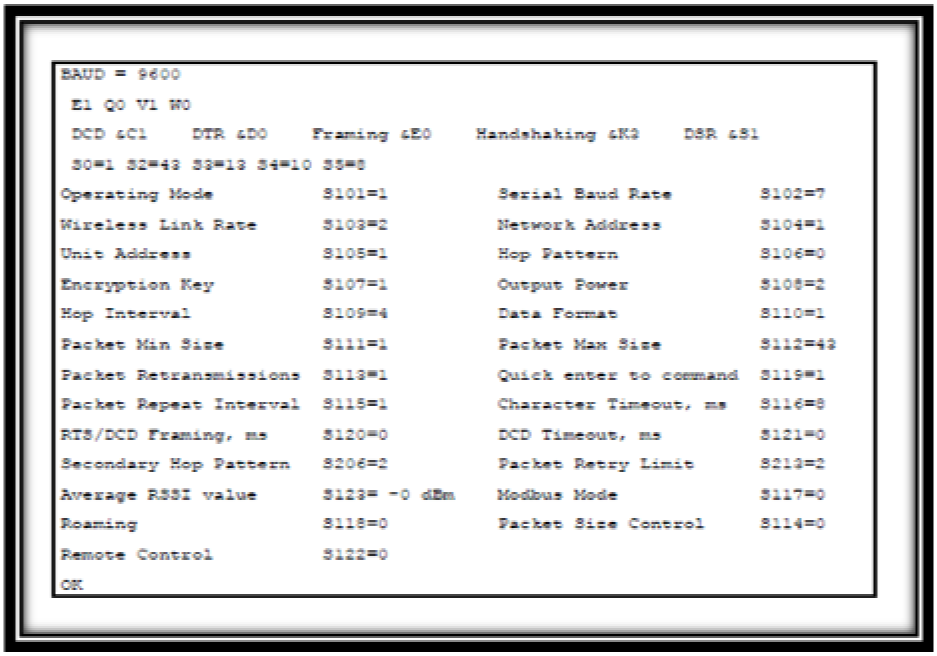

Figure 25. MHX2400 AT Command Interface (From [20])

The MHX2400 was equipped with factory default settings that were adjusted to meet the mission for NPS-SCAT. The commands that were used to change the AT Command Interface, put the transceiver in command mode, and put the transceiver in data mode are in Table 9.

Table 9. MHX2400 Commands and Description

Commands	Description
+++	Command Mode
ata	Data Mode
at&v	View AT Command Interface
atS1XX=Y	Changes Register S1XX to Y
at&w	Writes the New Registery Change to Memory

The configuration settings for both the Master and the Slave MHX2400 are somewhat arbitrary and can changed based on the desires of the developer. Though the settings are arbitrary, they are important for maximizing the use of the radios to meet the operational mission. The settings for the Master and the Slave must be carefully matched and documented to ensure that the transceivers will communicate.

Register S101 is the operating mode that defines whether the radio is a Master (NPS-SCAT) or a Slave (Ground Station). The serial baud rate is controlled in S102 which ranges from 2400 to 115200 bps. Based on testing documented in Chapter III.B.4.b, 9600 bps will be used. Fast with Forward Error Correction in Register S103 was used to ensure correct data will be received. The Network Address (S104) and the Unit Address (S105) are arbitrary and were chosen to represent the two space curriculums and the class year at NPS. Register S108 is the Hop Pattern between 2.4012 and 2.4312 GHz. It was chosen because it is in the amateur band, which allows NPS' ground station to operate without an FCC license. The Output Power corresponding to 1 Watt in S108 provides the maximum power out for the transceiver. The Hop Interval (S109) of 20 ms helps the radios to stay synchronized at greater distances compared to a faster hop interval. The Data Format (S110) and Minimum Packet (S111) were left as defaults. The Maximum Packet size for the Master was 74 bytes and 152 bytes for the Slave. For a Hop Interval of 20 ms, 152 bytes was recommended for the Slave in the operation manual and it suggested half that for the Master. A Packet retransmission of 4 was chosen to increase the possibility of receiving the data but more than 4 would greatly decrease the throughput. Registers S114 through S135 were left as defaults because it was not necessary to adjust them. Register 206 is the Secondary Hop Pattern which was also chosen because it is in the amateur band. S213 is the Packet Retry Limit, which allows the Master to retransmit a packet a number of times before it is dropped. A complete list of the configurations for both the Master and the Slave are in Appendix F.

C. SECONDARY TRANSCEIVER (BEACON) SPECIFICATIONS AND TESTING

The first beacon board received from Cal Poly was not really a beacon board but a modified C&DH board, which they used on their CP series CubeSats that contained a beacon. The board had been modified such that the C&DH PIC on the board was not programmed. They hardwired a connection from the COMM PIC that could be interfaced with the FM430, which NPS-SCAT is using as its C&DH. The modified board was to be used for establishing a connection to the FM430 while Cal Poly was designing and testing the beacon board that would be integrated into NPS-SCAT. The modified board was supposed to be used by connecting it to the FM430, which would send data to the COMM PIC and it would send out the data. It would also allow the NPS team to establish beacon commands and a beacon duty cycle. After much time spent trying to connect the modified beacon board to the FM430 by the C&DH system lead, there was no success establishing any communications. The modified beacon board was sent back to Cal Poly because it was thought the board did not work. Designing and testing the new beacon board was progressing for the Cal Poly beacon team. Cal Poly checked the modified beacon board that was sent back to them and they were able to make it work using their equipment. They sent it back to NPS and this time David Rigmaiden and Jim

Horning spent hours trying to make the modified board work. The MSP-430 development board could talk to the modified beacon board but it did not respond as expected. After much troubleshooting and multiple phone calls with Cal Poly the troubleshooting stopped due to the new bacon board being almost finished.

In April of 2010, Cal Poly held the 7th Annual Cal Poly CubeSat Workshop. The author and NPS engineers spent the first two days of the conference working with the new beacon board and their ground station in their CubeSat lab. Using equipment from NPS, a laptop, and the MSP430 development board coupled to a beacon interface board, hours were spent trying to get the beacon board to talk to Cal Poly’s ground station. There are two ways for the beacon board to communicate with the ground station. First, the MSP430 was used to command the beacon board to send data to the ground station. Then the data could be read on the ground station’s computer. Second, the ground station could send a command to the beacon telling it to send data. The beacon would then respond by transmitting data back to the ground station. After much help from David Rigmaiden, Jim Horning, Travis Heffernan (Cal Poly Student), Sean Fitzsimmons (Cal Poly Student), Justin Foley (Cal Poly Student), and Austin Williams (Cal Poly Student), the beacon board, using NPS’ equipment, established communications with Cal Poly’s ground station and data was passed.

Following the conference, the beacon board was hand delivered to NPS. The NPS ground station was not setup to communicate with the beacon because it was originally unknown how the board would work or what equipment and software were needed. Time was spent with David Rigmaiden and Jim Horning configuring the ground station with MixW software to communicate with the beacon board similarly to Cal Poly's. The ground station's setup is discussed in detail in Chapter V.C.1. Once the ground station was setup, the FM430 was used to command the beacon to send data. On command, the ground station would receive data from the beacon. The next step was to use the ground station to command the beacon to send data to it. After many hours of changing ground station software configurations, the beacon would not respond to the commands. A second receiver (ICOM PCR1500), a sniffer, was setup to make sure the ground station was actually sending out commands. After changing MixW configuration settings, the ground station was sending out correct commands and the sniffer was receiving the command. Then commands were once again sent to the beacon but it would not respond. After multiple phone calls and configuration exchanges with Cal Poly, a working CubeSat from the CP series CubeSats with a working beacon was brought to NPS by Cal Poly - Justin Foley. Using NPS' ground station, commands were sent to the CubeSat and it responded instantly. It was decided to send the beacon board back to Cal Poly for troubleshooting. Thanks to Brian Tubb (Cal Poly Student), it was discovered that a register in the software code was incorrect and the beacon board would not work with a frequency of 431.846 MHz. The register was changed along with the frequency to 437.335940 MHz and the beacon was once again working. Once the beacon board returned to NPS in July 2010, it was again tested with the ground station. The beacon was commanded by the MSP430 to send data to the ground station and it was received. Next, the ground station was used to command the beacon to send data and, finally, the data was received.

1. UHF Transceiver (Beacon) Specifications

The NPS-SCAT beacon board, as designed by Cal Poly, has not had any documents published on its exact specification. But, NPS-SCAT's beacon board was designed to be very similar to that of the CP series CubeSat C&DH boards and those specifications have been documented. Cal Poly's C&DH board is combined with their beacon and NPS-SCAT uses the FM430 as the C&DH board and a separate beacon board. The beacon board was designed with three main components which include a communications controller, a transceiver and an amplifier as well as multiple other supporting components.

The communications controller is the Microchip PIC18LF6720. The communications controller was chosen for its large amount of flash memory (256 kbytes) for program storage, large static RAM (4 kbytes) for run-time variables, support for the Inter-IC Communication (I^2C) bus (the protocol used to communicate with the main satellite bus), and its extreme low power requirements. The beacon board's transceiver is Chipcon CC1000. The CC100 provides, in a single device IC, the RF modulation necessary to transmit data using AX.25 protocol and is a low-power part drawing approximately 24 mA at full transmit power. The RF amplifier used on the beacon board is the RF Microdevices RF2117. The RF2117 amplifier is designed for use with RF signals between 400 and 500 MHz. This part is also capable of operating with a voltage supply of 3 volts, which provides a significant reduction in power consumption over the typical 5-volt supply. It also sinks a maximum of 1,100 mA of current [22].

The beacon is unique in its transmitting and receiving data rates. It is designed with a receiving baud rate of 600 bps. As in all communications systems, the lower the baud rate the more stable the communications link is. The beacon was designed with a lower receiving baud rate for two reasons. The first reason is for a more stable link and the second is because the commands sent to spacecraft are few and typically short. The beacons transmitting baud rate was designed at 1200 bps. This is double the receiving baud rate, but still low enough for establishing a stable data link.

2. Link Budget

The link budgets for the beacon were computed in the same manner as the link budgets for the MHX2400. Link budgets for both altitudes of 450 km and 600 km had three different elevation angles of 10, 45 and 90 degrees. Appendix G shows all the calculated link budgets.

a. Uplink

The uplink budget for the beacon was calculated the same way as the MHX2400 using the SMAD excel worksheet. As seen below in Table 10, there were changes to most of the inputs except for section three, Geometry and Atmosphere. In section one, the frequency for the beacon will be approximately 438 MHz and the data rate for the uplink is 600 bps. In section two, the ground transmitter output power is 10 Watts and the line loss is 3.10 dB.

This information was obtained from conversations with David Rigmaiden]. The antenna for the ground transmitter does not have a diameter because it is a Yagi antenna so the numbers have to be estimated. The antenna has a gain of 18.95 dB with a pointing error of about 5 degrees [23]. The diameter of the antenna was adjusted to 2.60 meters, which correlated to a peak antenna gain of 18.95 dB. In section four, the antenna efficiency was left as the default because this is a typical antenna efficiency for a spacecraft. Again, the antenna diameter on the spacecraft is not circular so the diameter was adjusted to 0.29 meters which gave an antenna peak gain 0 dB. In section five, all the calculations show the link will clearly close. A link margin of 3 dB is required to close the link and the uplink budget in Table 10 shows a margin of 34.16 dB. Therefore once the spacecraft is in sight of the ground station and is at least 10 degrees above the horizon, data will be passed based upon the input parameters.

Table 10. UHF Transceiver Uplink Budget at 600km and 10° Elevation Angle

Return to Navigator | **Communications System - Uplink**

(All information on this sheet is contained in the block from Cell A1 to Cell Q33)

Section 1:			
Frequency	0.438	0.438	GHz
Wavelength		6.84E-01	m
Data rate	6.000E+02	6.000E+02	bps
Probability of Bit Error		1.00E-05	
Required Eb/No		9.60	dB

Section 2:			
Ground Transmitter			
Output power	10.00	10.00	W
Output power		10.00	dB
Line loss	-3.10	-3.10	dB
Antenna efficiency		55.0%	
Antenna diameter	2.60	2.60	m
Peak antenna gain		18.95	dB
Half-power beamwidth		18.42	deg
EIRP		25.85	dB
Pointing error	5.00	5.00	deg
Antenna pointing loss		-0.88	dB

Section 3:			
Geometry & Atmosphere			
Altitude	600.000	600.000	km
Planet angular radius		66.07	deg
Elevation angle	10.00	10.00	deg
Nadir angle		64.18	deg
Planet central angle		15.82	deg
Propagation path length		1932.257	km
Atmospheric attenuation at zenith		-0.060	dB
Rain attenuation		0.000	dB
Increase in system noise temp		0.00	K

Section 4:			
Spacecraft Receiver			
Antenna efficiency		55.0%	
Antenna diameter	0.29	0.29	m
Peak antenna gain		0.00	dB
Half-power beamwidth		163.19	deg
Pointing error	0.000	0.000	deg
Antenna pointing loss		0.00	dB
System noise temperature		688.00	K
G/T		-28.38	dB

Section 5:			
Link Budget			
EIRP		25.85	dB
Space loss		-151.00	dB
Atmospheric attenuation		-0.65	dB
Rain attenuation		0.00	dB
G/T		-28.38	dB
Antenna pointing losses		-0.88	dB
Eb/No		45.76	dB
C/No		73.54	dB
Implementation loss		-2.00	dB
Margin		34.16	dB

b. Downlink

The downlink budget for the beacon, seen in Table 11, is very similar to the uplink budget. Section one only had the data rate changed to 1200 bps and section three is identical. Section two shows the spacecraft transmitter inputs and the first input to the spreadsheet was the output power which is 1 Watt [22]. The line loss of the spacecraft was estimated to be 1.00 dB. The antenna diameter is 0.29 meters as described in the uplink budget. The parameters in section four are for the ground receiver and they are the same as the ground transmitter. Section five contains the downlink calculations to include the link margin of 27.48 dB. This is 24 dB greater than the required 3 dB, which means the link should close based on the input parameters.

Table 11. UHF Transceiver Downlink Budget at 600km and 10° Elevation Angle

Return to Navigator — **Communications System - Downlink**

(All information on this sheet is contained in the block from Cell A1 to Cell Q33)

Section 1:			
Frequency	0.44	0.438	GHz
Wavelength		6.84E-01	m
Section 2:			
Spacecraft Transmitter			
Output power	1.00	1.00	W
Output power		0.00	dB
Line loss	-1.00	-1.00	dB
Antenna efficiency		55.0%	
Antenna diameter	0.29	0.29	m
Peak antenna gain		0.00	dB
Half-power beamwidth		163.19	deg
EIRP		-1.00	dB
Pointing error	0.00	0.000	deg
Antenna pointing loss		0.00	dB
Duty cycle (per orbit period)		100.0%	

Data rate	1.200E+03	1.200E+03	bps
Section 3:			
Geometry & Atmosphere			
Altitude	600.000	600.000	km
Planet angular radius		66.07	deg
Elevation angle	10.00	10.00	deg
Nadir angle		64.18	deg
Planet central angle		15.82	deg
Propagation path length		1932.257	km
Atmospheric attenuation at zenith		-0.060	dB
Rain attenuation		0.000	dB
Increase in system noise temp		0.00	K

Probability of Bit Error		1.00E-05	
Required Eb/No		9.60	dB
Section 4:			
Ground Receiver			
Antenna efficiency		55.0%	
Antenna diameter	2.60	2.60	m
Peak antenna gain		18.95	dB
Half-power beamwidth		18.42	deg
Pointing error	5.000	5.000	deg
Antenna pointing loss		-0.88	dB
System noise temperature		260.00	K
G/T		-5.20	dB

Section 5:			
Link Budget			
EIRP		-1.00	dB
Space loss		-151.00	dB
Atmospheric attenuation		-0.65	dB
Rain attenuation		0.00	dB
G/T		-5.20	dB
Antenna pointing losses		-0.88	dB
Eb/No		39.08	dB
C/No		69.87	dB
Implementation loss		-2.00	dB
Margin		27.48	dB

3. Data Budget

The data budget for the beacon was very easy to calculate. All the parameters that were used for calculating the MHX2400's data budget (Chapter III.B.3) were used to calculate the beacon's data budget except for the data rate. The downlink data rate for the beacon is 1200 bps. As seen in Table 12, if the spacecraft is launched into a 450 km circular orbit, it will require 402.94 seconds to transmit one day's collection of data. The total time overhead at 450 km with a 30-degree elevation angle above the horizon is 459.63 seconds. According to these calculations, the beacon will be able to transmit all of NPS-SCAT's collected data on a daily basis.

Table 12. NPS-SCAT Data Rate Budget (Beacon)

NPS-SCAT Data Rate Budget (Secondary Radio)			
Orbit Altitude	*450km*	*600km*	*Units*
Size of Full Telemetry File (Includes 4 I-V Curves & Overhead)	787	787	*bytes*
Number of Collects per Orbit	4	4	*collects*
Data Collected per Orbit	3148	3148	*bytes*
Number of Orbits per Day	15.36	14.71	*orbits*
Data Collected per Day	48353.28	46307.08	*bytes*
Primary Radio Data Rate	1200	1200	*bps*
	120	120	*Bps*
Time to Transmit Primary Telemetry Daily	402.94	385.89	*seconds*
Number of Ground Station Passes per Day at a minimum elevation angle of 30 degrees	3	4	*passes*
Average Time per Pass	153.21	205.73	*seconds*
Total Time Over Head	459.63	822.92	*seconds*

4. Radio Testing

a. Current Draw

The power requirements for the beacon were also needed for the power budget. A similar test was setup to that which was used for the MHX2400. The beacon, the FM430 and the beacon development board were connected to a laptop contain Tera Term software. Software was written by Jim Horning and Peter Reinhardt that was downloaded to the FM430 that would command the beacon to transmit data to ground station. Once again, an oscilloscope that included a Hall Effect current probe as seen in Figure 26 was used to measure the beacon’s current draw.

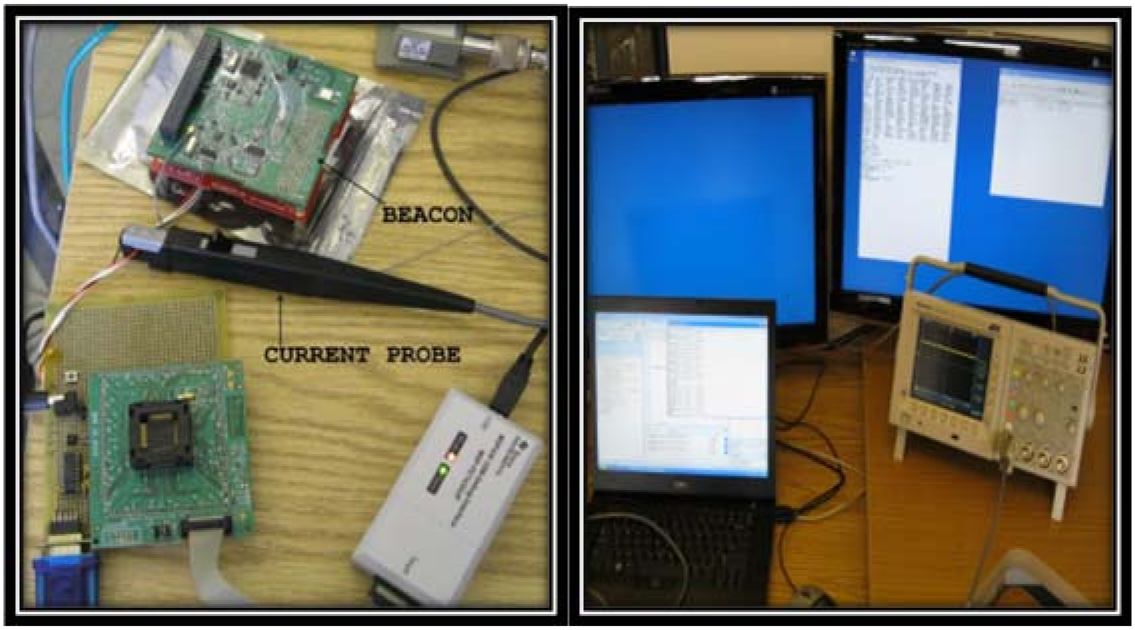

Figure 26. Beacon Current Draw Test

The current probe was placed around the 5-volt wire connecting the MSP430 to the beacon. Then the current draw was measured while the beacon was in three different states; standby, receiving, and transmitting. While all the equipment was on, the current draw was measured while the beacon was in standby mode and read from the oscilloscope. The standby mean and maximum currents were 0.014 and 0.020 amps respectively. To measure the receiving mean and maximum currents, commands were sent from the ground station to the beacon and again the beacon's current draw was measured using the Hall Effect current probe and oscilloscope. The receiving mean and maximum currents were 0.016 and 0.022 amps respectively. The last measurement was the beacon transmitting data. The MSP430 commanded the beacon to transmit a 255 byte file to the ground station. The measured transmitting mean and maximum currents were 0.390 and 0.416 amps respectively.

The collected data was then used to compute the mean and peak power seen in Table 10. Based on these results and discussions with the Electrical Power System (EPS) Student Lead the beacon's power requirements are low enough to possibly leave the beacon on at all times. Further analysis by the EPS engineer is planned before the final decision is made.

Table 13. Beacon (UHF Transceiver) Mean and Peak Power

Beacon (UHF Transceiver)		
	Mean Power (Watts)	Peak Power (Watts)
Standby	0.07	0.10
Receiving	0.08	0.11
Transmitting	1.95	2.08

b. Carrier-To-Noise

Similar to the carrier-to-noise testing conducted for the MHX2400, a test was conducted for the beacon. The link budget calculations suggested that the beacon would be able to transmit data every time is was passing over the ground station with a minimum elevation look angle of ten degrees. To verify the link budget calculations, a carrier-to-noise test was setup. The block diagram of the test setup is in Appendix H.

The beacon carrier-to-noise test setup equipment included: laptop with Tera Term software, MSP430 and development board, beacon board and development board, shielded chamber, attenuators, splitters, an amplifier, a filter, a frequency generator, a spectrum analyzer, power supplies, a frequency receiver, a computer with MixW software, cables and connectors.

As seen in Figure 27, the laptop, MSP430 and beacon were setup inside the shielded chamber.

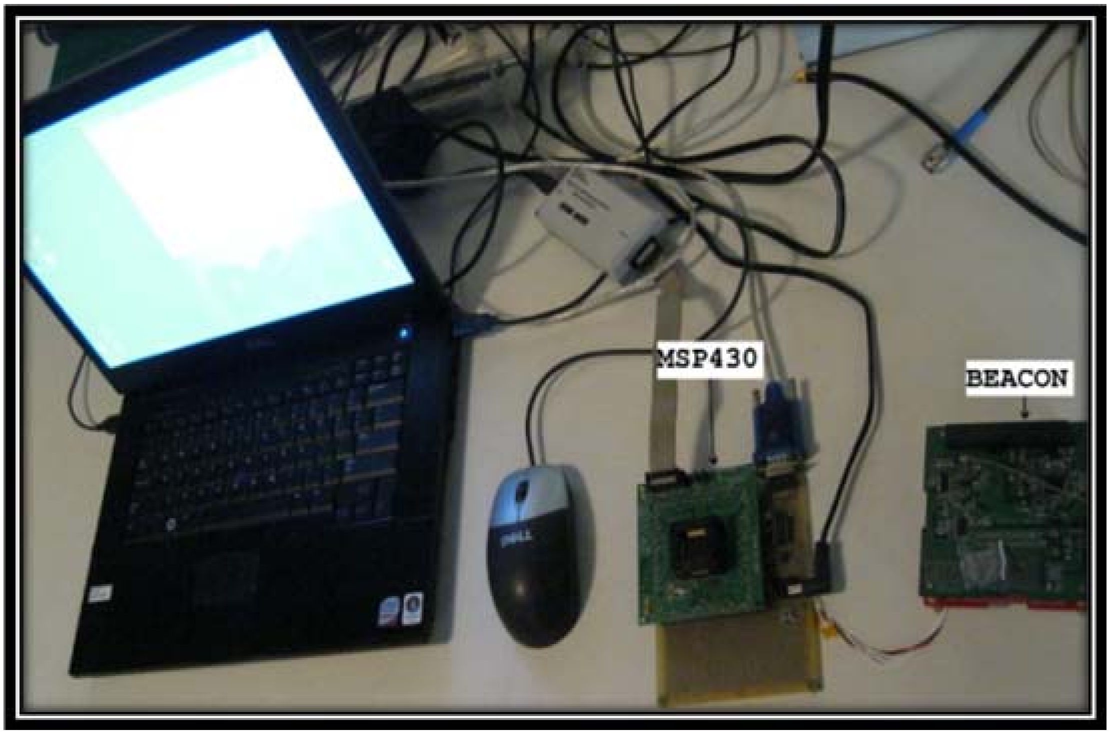

Figure 27. Beacon Carrier-To-Noise Test Setup Inside Shielded Chamber

A coax cable connected to the beacon’s antenna port and to the connection in the side of the shielded chamber. The attenuators, filter, splitters, amplifiers, power supplies and a frequency generator were connected together, as seen in Figure 28. This configuration of components provided a way to simulate the noise for the carrier-to-noise test. The last connection was to connect the output of configuration to a receiver, which was connected to a computer simulating a ground station.

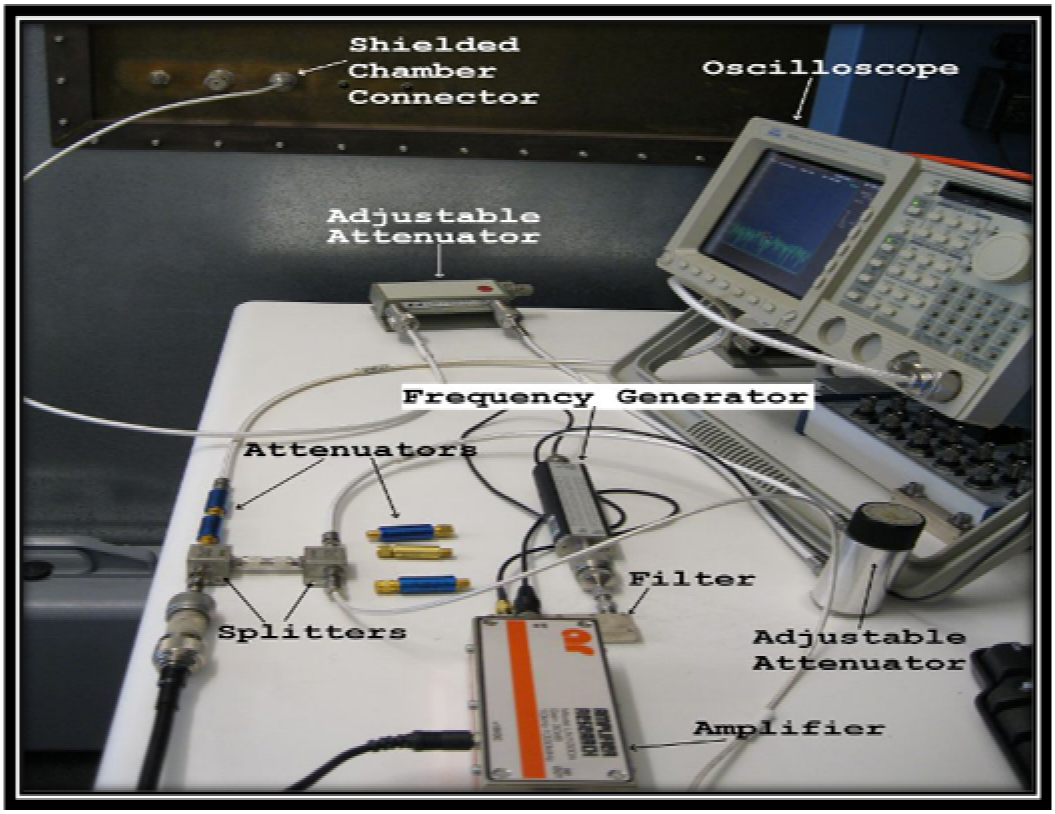

Figure 28. Beacon Carrier-To-Noise Test Oscilloscope, Attenuators, Splitters, Amplifiers, Power Supplies and Frequency Generator

The objective of the carrier-to-noise test was to simulate the link connection from the spacecraft to the ground station. Noise and carrier power calculations were computed based on the link budgets and can be found in Appendix I. Similar to the link budgets, multiple calculations were completed to account for the 450 km and 600 km altitudes and also the three elevation angles of 10, 45, and 90 degrees. Next, the calculations were analyzed and the worst case scenario was determined. It was determined if the beacon could pass data through the worst-case noise, then it could pass data in all the other cases. Completing the testing was much faster with the beacon because of the similar testing already completed with the MHX. The noise power was kept constant at -135 dB because it was the average worst case according to the calculations. The noise power attenuator was adjusted until the oscilloscope showed the noise power fairly constant at -135 dB. Then carrier power was adjusted in approximately 2.5 to 5.0 dB decrements decreasing from -90.0 to -102.5 dB. A data file consisting of 250 bytes was transmitted four times at different carrier powers. The size of the data file was chose based on the limits of the beacon. The number of times the data file was transmitted, four, was chosen because the maximum size of one data collect is 787 bytes. This proved the beacon would be able to transmit the data collected. As seen in Table 14, the beacon was able to transmit the desired data when the carrier power was at least greater than -100.0 dB. As the carrier power got lower, the link was able to acknowledge the spacecraft was there but the transmitted data file was not received. These results showed that the spacecraft will need to be higher than the worst case of a 10-degree elevation angle above the horizon.

Table 14. Beacon Carrier-To-Noise Testing Results

TESTING INPUTS/OUTPUTS

C (Received Power)	-102.50				-100.00				-95.00				-90.00				dBm
N (Noise Power)	-135				-135				-135				-135				dBm/Hz
C/N (Carrier-To_Noise)	32.50				35.00				40.00				45.00				dBm/Hz
	FILE SIZE (Bytes)																
BAUD RATE	**250.0**				**250.0**				**250.0**				**250.0**				
	x1	**x2**	**x3**	**x4**	**x1**	**x2**	**x3**	**x4**	**x1**	**x2**	**x3**	**x4**	**x1**	**x2**	**x3**	**x4**	
1.20k																	

Carrier-To-Noise Data

450 km					
Elevation Angle	10 (Worst Case)		90 (Best Case)		deg
	Uplink	Downlink	Uplink	Downlink	
C (Received Power)	-94.88	-102.78	-83.77	-91.63	dBm
N (Noise Power)	-132.44	-136.67	-132.44	-136.67	dBm/Hz
C/N (Carrier-To-Noise)	37.56	33.89	48.67	45.04	dBm/Hz

600 km					
Elevation Angle	10 (Worst Case)		90 (Best Case)		deg
	Uplink	Downlink	Uplink	Downlink	
C (Received Power)	-96.68	-104.58	-86.26	-94.13	dBm
N (Noise Power)	-132.44	-136.67	-132.44	-136.67	dBm/Hz
C/N (Carrier-To-Noise)	35.76	32.09	46.18	42.54	dBm/Hz

IV. SCAT ANTENNA CONSTRUCTION METHODOLOGY AND TESTING

A. PAST WORK ON NPS-SCAT TRANSCEIVER ANTENNAS

1. Primary Radio Antenna

The early antenna design for the MHX2400 had three major constraints. One, the antenna had to operate in the frequency range of the transceiver, 2.40 – 2.48 GHz. Second, the antenna had to have a reasonable front-to-back Omni-directional pattern due to the spacecraft being a tumbler. The third constraint was the antenna had to fit within the CubeSat standard; meaning it could not be outside the constraints of the allowed CubeSat volume. Matt Schroer, the prior NPS-SCAT TT&C team lead, selected a patch antenna designed by Spectrum Control Inc. and designed a way to mount the antenna for testing seen in Figure 29. Matt's thesis [7] describes in great detail, the analysis for choosing the antenna, the suggested process for mounting the antenna and documented testing.

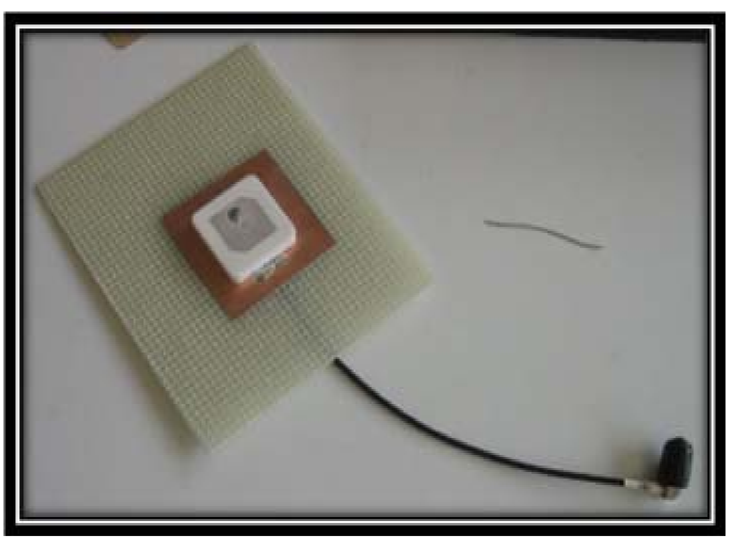

Figure 29. NPS-SCAT Primary Radio Patch (After [7])

2. Secondary Radio Antenna

The beacon’s antenna had very similar constraints to that of the MHX2400. The antenna was also required to be an affective Omni-directional antenna and it also had to fit within the constraints of the CubeSat volume. The one difference between the beacon antenna and the MHX antenna is that the beacon antenna had to operate in the 430 – 438 MHz frequency range. A deployable half-wave dipole antenna was selected by Matt and the analysis for choosing this type of antenna is documented in his thesis [7]. The idea for investigating a half-wave dipole antenna and its deployment structure came from the CP series of satellites designed by Cal Poly. The antenna and its deployment are mounted to the y+ face solar panel as seen in Figure 30.

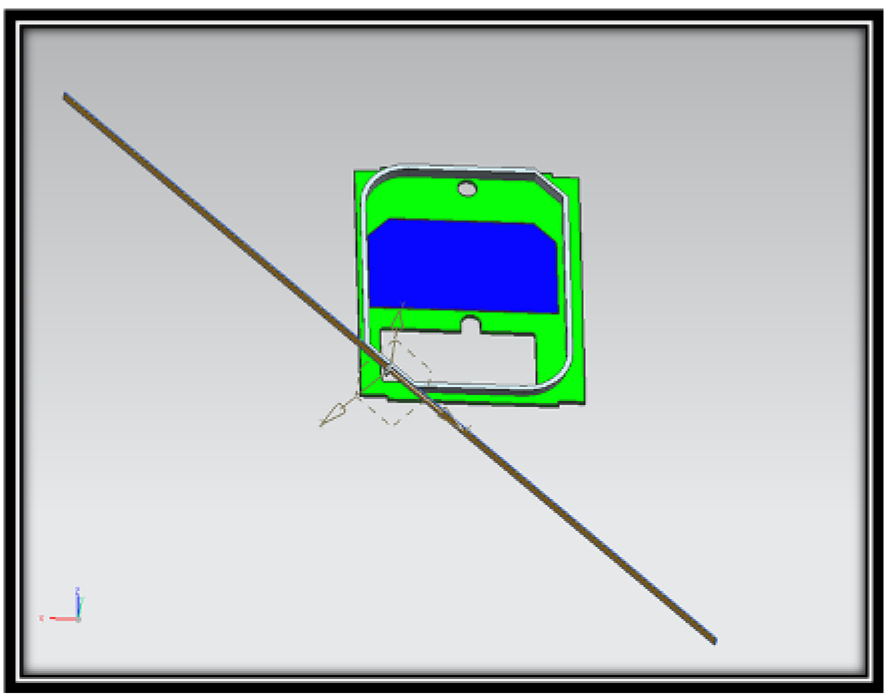

Figure 30. NPS-SCAT Beacon Antenna Structure (After[7])

B. PRIMARY TRANSCEIVER ANTENNA

1. Design

The patch antenna, as previously designed, needed to be integrated into the CubeSat via the +z solar panel. The patch antenna design included a copper ground plane that is 45 mm by 45 mm. This antenna configuration would produce a Voltage Standing Wave Ratio of approximately 1.89 dB [7]. The antenna ground plane component needed to be integrated into the +z solar panel. The patch antenna and ground plane could not be mounted to the top of the +z solar panel because this would not allow enough clearance between the top of the antenna and the allowable height of the CubeSat. The clearance given from the P-POD specification is 6.5 mm above the CubeSat structure. A square hole cutout was designed in the top of the +z solar panel, as seen in Figure 31, which provided the acceptable clearance between the top of the antenna and the top of the allowable CubeSat volume.

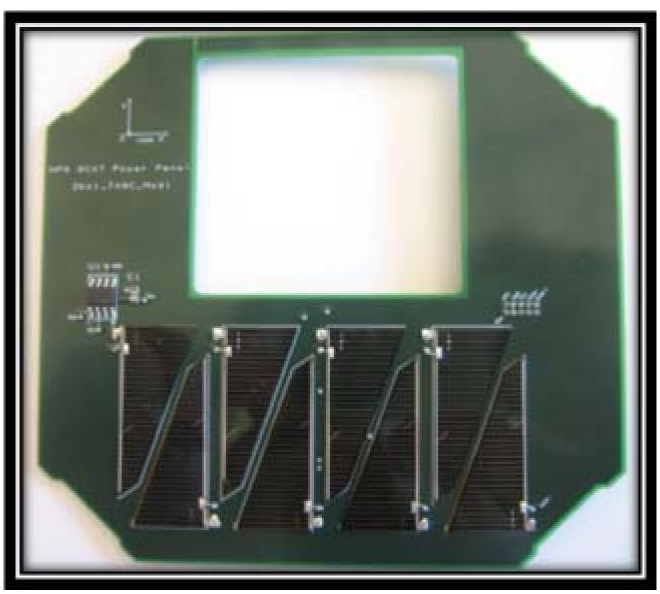

Figure 31. +z Solar Panel With Patch Antenna Cutout

The difficulty with this design was attaching the antenna and ground plane component to the +z solar panel. Before continuing with the integration of the antenna and ground plane component to +z solar panel, there was a discussion which entailed answering the question, “does the antenna need to have the copper ground plane or can it just be mounted directly to the CubeSat structure?” Testing the patch antenna with it directly mounted to the CubeSat structure, as seen in Figure 32, is described in Chapter IV.B.3.

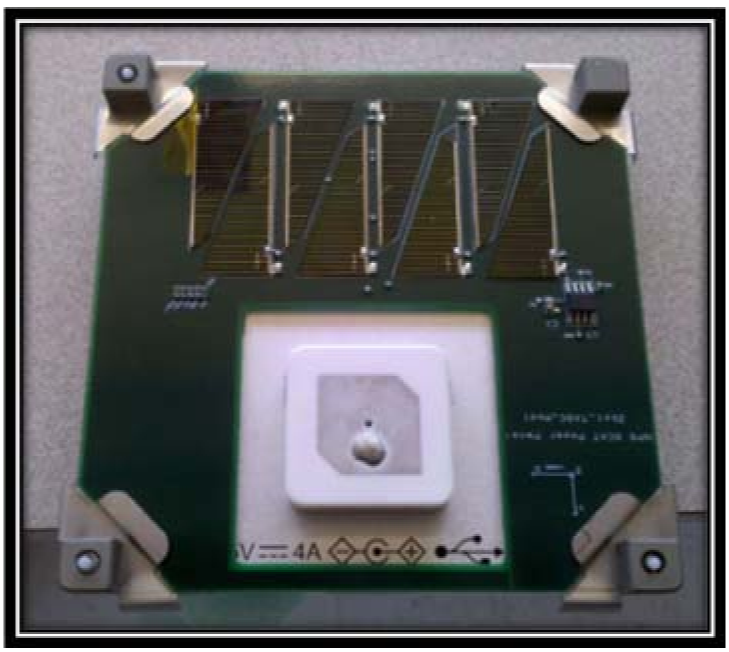

Figure 32. Patch Antenna Attached To CubeSat Structure

2. Specifications

A patch antenna is essentially a metal conducting plate suspended over a ground plane by a substrate [7]. To support the NPS-SCAT methodology, the COTS antenna that will be integrated into NPS-SCAT is a Spectrum Controls Inc. patch antenna with the part number PA28-2450-120SA.

The specifications of the Spectrum Controls Inc. data sheet states the antenna may be either right or left hand circularly polarized, has a center frequency of 2450 MHz, a VSWR ration of 2:1, bandwidth of 120 MHz, and a 4.0 dB gain for a 45 mm by 45 mm ground plane. The dimensions of the dielectric antenna are a 2.8 mm square with a height of 6.36 mm. There is also an additional 1 mm solder point that protrudes above the radiating surface [24].

3. Antenna Testing

The Primary transceiver antenna testing was conducted in two phases. The first phase consisted of testing the patch antenna mounted directly to the CubeSat structure to determine the voltage standing wave ration. The second phase of testing included testing within the anechoic chamber, which produced the antenna gain patterns.

a. VSWR

In telecommunications, voltage standing wave ratio (VSWR) is the ratio between the maximum and the minimum voltage along an electrical transmission line. For example, a VSWR of 1.2:1 denotes maximum voltage is 1.2 times great than the minimum voltage [25]. Another way to understand VSWR is to compare it to electronics. In electronics, in order to get maximum power to a load, the load impedance is required to match the generator impedance. Any difference, or mismatching, of these impedance will not produce maximum power transfer. This is also true of antennas and transmitters. Because antennas are usually not connected directly to the transceiver, a feedline is required to transfer power between the two. If the feedline has no loss, and its impedance matches both the transmitter's output impedance and the antennas input impedance, then maximum power will be delivered to the antenna with no transmission loss. If the impedances do not match exactly, there is some transmission loss as seen in Table 15 [26].

Table 15. Voltage Standing Wave Ratio and Transmission Loss (After [26])

VSWR	Transmission Loss (dB)	VSWR	Transmission Loss (dB)	VSWR	Transmission Loss (dB)
1.00	0.000	1.26	0.056	1.60	0.24
1.01	0.0002	1.27	0.060	1.65	0.27
1.02	0.0005	1.28	0.064	1.70	0.31
1.03	0.0011	1.29	0.068	1.75	0.34
1.04	0.0018	1.30	0.073	1.80	0.37
1.05	0.0028	1.31	0.078	1.85	0.4
1.06	0.0039	1.32	0.083	1.90	0.44
1.07	0.0051	1.33	0.087	1.95	0.47
1.08	0.0066	1.34	0.092	2.00	0.5
1.09	0.0083	1.35	0.096	2.10	0.57
1.10	0.0100	1.36	0.101	2.20	0.65
1.11	0.0118	1.37	0.106	2.30	0.73
1.12	0.0139	1.38	0.112	2.40	0.8
1.13	0.0160	1.39	0.118	2.50	0.88
1.14	0.0185	1.40	0.122	2.60	0.95
1.15	0.0205	1.41	0.126	2.70	1.03
1.16	0.0235	1.42	0.132	2.80	1.10
1.17	0.0260	1.43	0.137	2.90	1.17
1.18	0.0285	1.44	0.142	3.00	1.25
1.19	0.0318	1.45	0.147	3.50	1.61
1.20	0.0353	1.46	0.152	4.00	1.93
1.21	0.0391	1.47	0.157	4.50	2.27
1.22	0.0426	1.48	0.164	5.00	2.56
1.23	0.0455	1.49	0.172	6.00	3.08
1.24	0.049	1.50	0.18		
1.25	0.053	1.55	0.21		

The VSWR test was conducted in NPS' Microwave Lab with the help of Mr. Bob Broadston. The CubeSat was assembled with solar panels and antennas. The patch antenna VSWR test was conducted twice. One test was conducted with +y solar panel that did not include a beacon antenna and once with +y solar panel which included the beacon antenna as seen in Figure 33.

Figure 33. Voltage Standing Wave Ratio Testing

To conduct the test, a spectrum analyzer was attached to the patch antenna. Then the spectrum analyzer measures the VSWR based on the frequency input. Data was collected and plotted in MATLAB. The MATLAB code is in Appendix J. The plots in Figure 34 show the VSWR for the patch antenna directly mounted to the CubeSat structure with and without the beacon antenna attached. With the beacon antenna attached and the patch antenna directly to the CubeSat structure, the VWSR at 2.42 GHz is approximately 1.42. This equates to a 0.132 dB transmission loss. The frequency of 2.42 GHz was chosen for the center frequency because it is the center of the hop pattern for the MHX2400 in the amateur frequency band as discussed in Chapter III.B.4.c. Because the VSWR was very good, even better then the with the copper ground plane (VSWR with copper ground plane was 1.67 at 2.44 GHz [7]), the decision was made to continue with testing to determine the antenna's gain pattern.

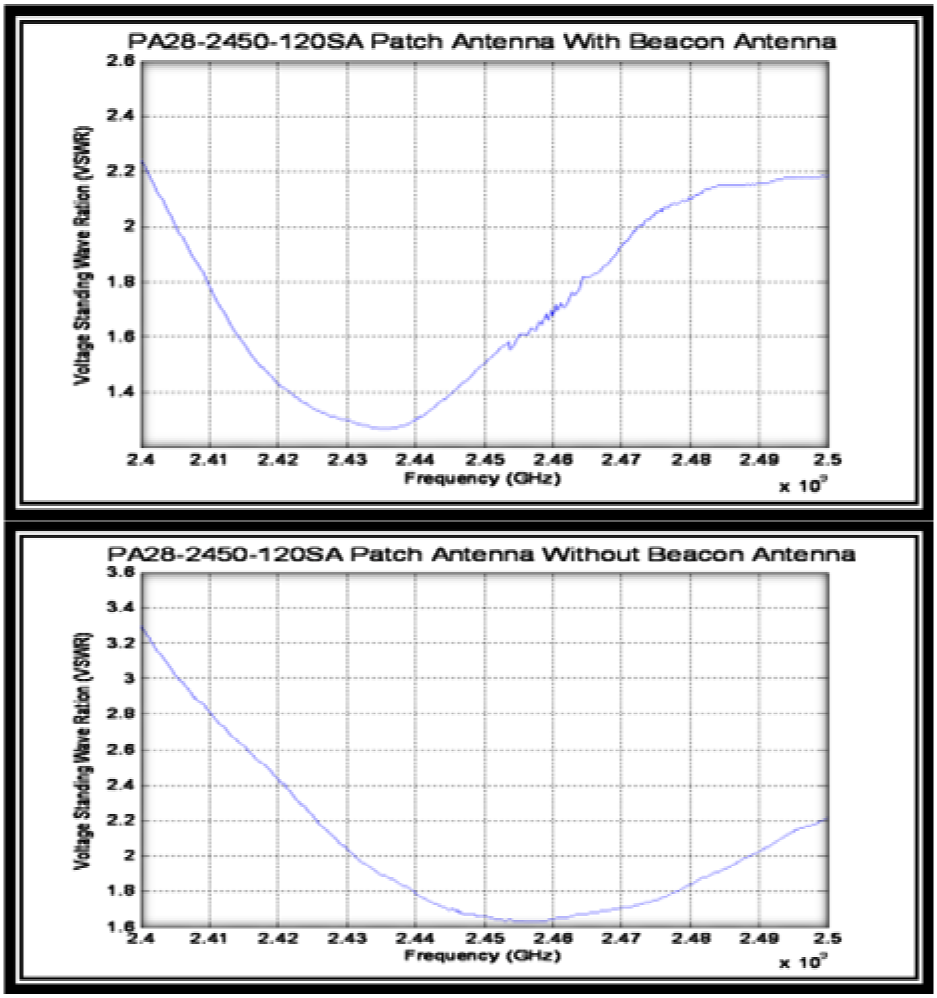

Figure 34. Patch Antenna VSWR Plots

b. Anechoic Chamber and Antenna Patterns

A radio frequency "anechoic chamber" is a shielded room whose walls have been covered with a material that scatters or absorbs so much of the incident energy that is can simulate free space [28]. The anechoic chamber is used to measure the antenna radiation pattern. The actual gain of the antenna is not measured directly but is inferred from measuring the returns of the test antenna and comparing them to the returns of the reference antenna. The difference between the two antennas is subtracted from the gain of the reference to calculate the gain of the test antenna [7].

The anechoic chamber at NPS is designed to measure frequencies above 3 GHz but according to Mr. Bob Broadston, the chamber will be sufficient to test the patch antenna at 2.42 GHz. Though this introduces a slightly inaccurate measurement and pattern, it is the best option available for testing the antenna in a controlled environment. Due to the layout of the chamber, meaning limited space, the chamber is not a perfect rectangle so this adds a few more inaccuracies but it is acceptable for the testing required. Appendix K shows a schematic drawing of NPS' anechoic chamber's equipment. The patch antenna mounted directly to the CubeSat structure was setup in the anechoic chamber as seen in Figure 35.

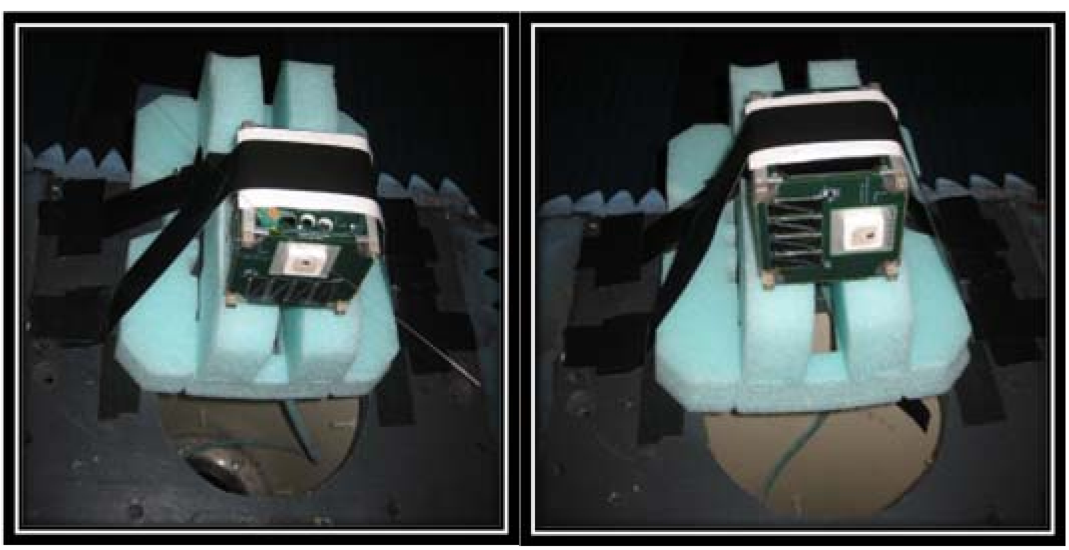

Figure 35. Patch Antenna Anechoic Chamber Test Setup

There were four different antenna gain patterns produced from data gathered during the anechoic chamber testing. The data was then plotted in MATLAB using the polardb function. The MATLAB code can be found in Appendix J. The first pattern produced was the reference pattern, which is used to determine the patch antenna's gain but is not in Figure 36. Two antenna gain patterns were produced without the beacon antenna attached to the +y solar panel, one pattern with the antenna upright and the other pattern with antenna rotated 90 degrees. Then two additional patterns were produced with the beacon antenna attached. The reason for doing the test with and without the beacon antenna was to see if the position of the beacon antenna affected the patch antenna's pattern. The four patch antenna gain patterns in Figure 36 were compared and led to the conclusion that the placement of the beacon antenna did not significantly affect the patch antenna gain. The antenna gain patterns show the 360-degree gain of the antenna and the front-to-back ratio. The front-to-back ratio is the difference between the gain of the antenna in front compared to the back. Based on the antenna gain patterns the patch antenna front-to-back ratio is approximately 15 dB. When the spacecraft's antenna is pointing in the nadir direction, the antenna will have a slightly positive gain and even when the spacecraft is ± 90 degrees off of nadir, the gain is only approximately -5 dB. From the link budget calculations in Chapter III.B.2 the margins are all greater than 5 dB which leads to the conclusion that this patch antenna will be the MHX2400's antenna and integrated into NPS-SCAT.

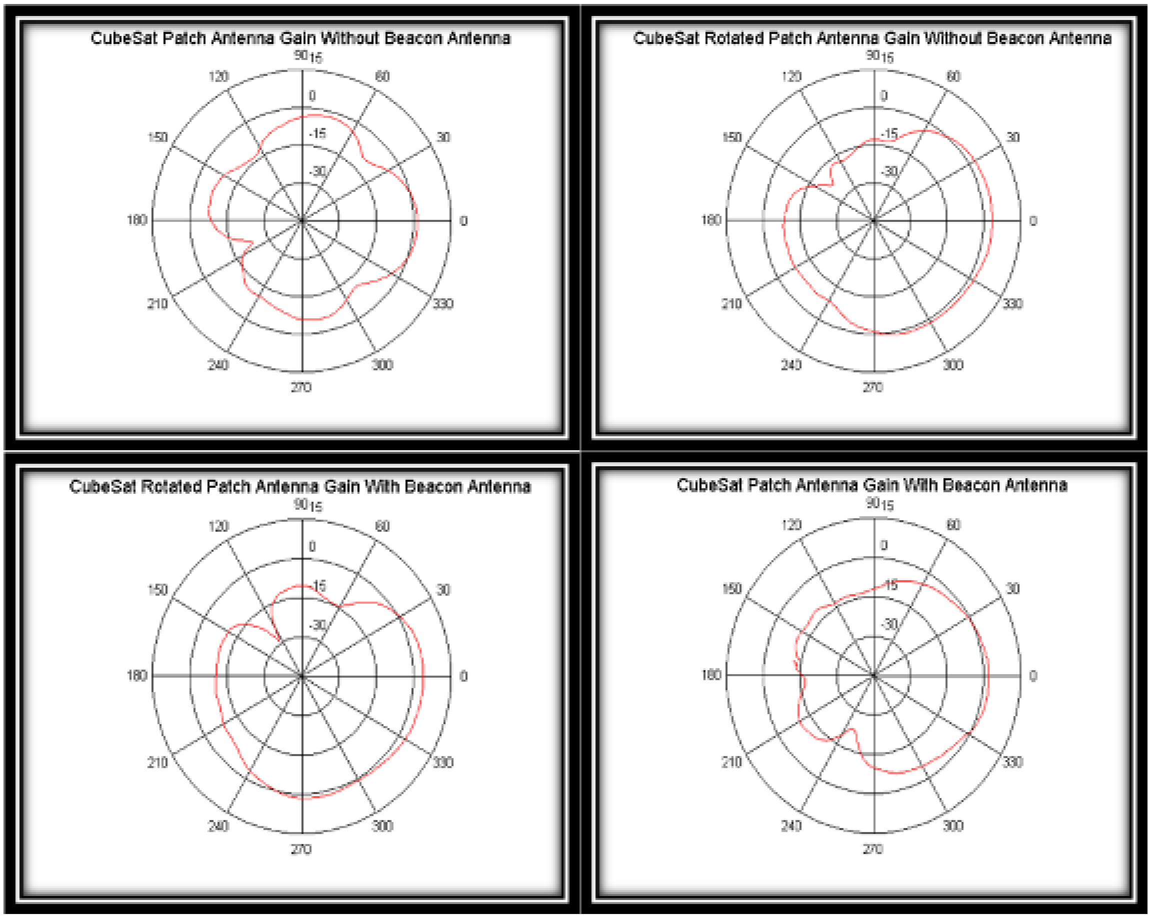

Figure 36. Patch Antenna Gain Patterns

C. SECONDARY TRANSCEIVER (BEACON) ANTENNA

1. Design

A center-fed half-wave dipole antenna is possibly one of the simplest antennas to construct, but works very well if designed correctly. The original design for NPS-SCAT's beacon antenna, as seen in Figure 30, was to purchase spring steel, similar to that used in a tape measure, and construct the half-wave dipole antenna from that material. Before the 1/4" wide spring steel was purchased, the antenna was constructed out of 1/4" copper beryllium as seen in Figure 37. Beryllium copper is a much better conductor than spring steel, but the beryllium copper has much more memory. Once the beryllium copper antenna was wrapped around the antenna storage unit for more than a week, it would not spring back to its original state.

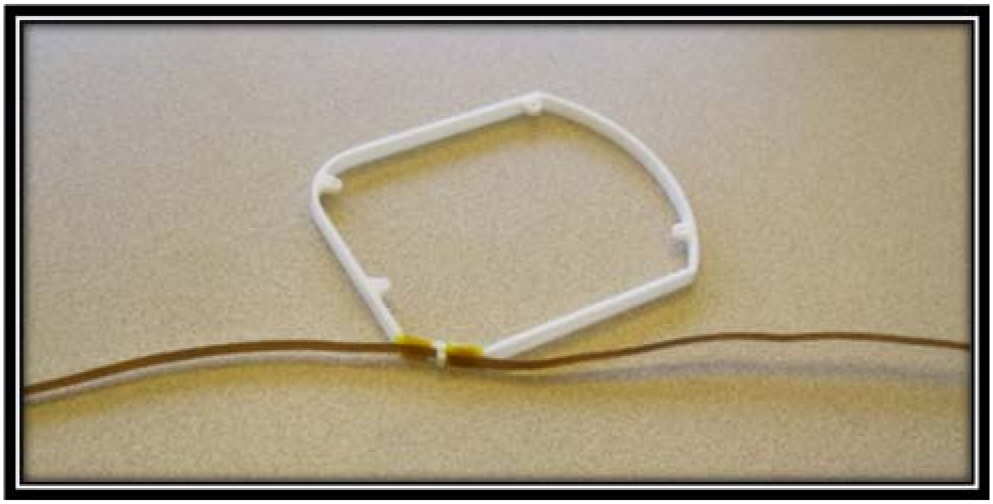

Figure 37. First Beacon Antenna Design with Beryllium Copper

The second design of the beacon antenna was to use spring steel piano wire with a diameter of 0.37 mm. Spring steel is not as good of a conductor as copper, but it is good enough and it has very little memory. The piano spring steel was mounted to a test board and wrapped in a deployed status. After a week of storage, the antenna was deployed, and it sprung back to its original state. The next step in the design was mounting the antenna to the +y solar panel. Because spring steel is not easy to solder, a clever way to mount the antenna was designed. Two 1/4" pieces of copper tubing were filled with solder and then one end of each piece of the antenna was inserted into the solder filled tubing. Then, the antenna ends with the copper solder to them were mounted to the +y solar panel as seen in Figure 38. Once the antenna was soldered it still looked like there could be a way to reinforce the antenna. An antenna cap was designed, as seen in Figure 38, that overlaps the top of the soldered antenna and secures it to the +y solar panel; in addition it also secures the antenna coax connection from the beacon board.

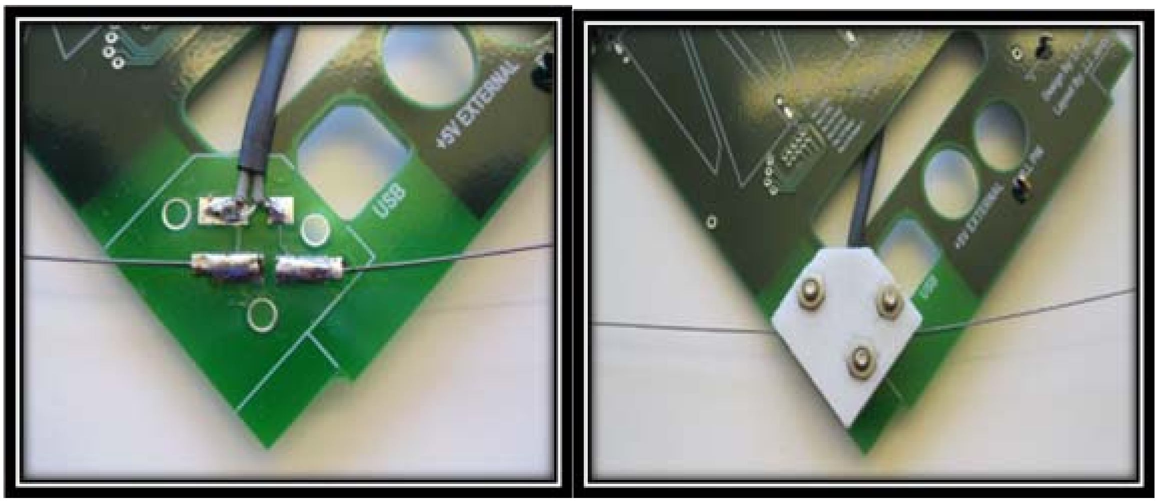

Figure 38. Mounting The Beacon Antenna

All antennas have a feed impedance. This is the impedance that is seen at the point in the antenna where the coax cable is connected to the antenna. To ensure that maximum power is transferred between the transmitter and the antenna, it is necessary to ensure that the transmitter, the antenna, and the coax have impedances that match. A half-wave center fed dipole antenna in free space has and impedance of 73.13 ohms making it ideal to feed with a 75 ohm feeder. The impedance of a typical coax cable is 50 ohms. Because of the differences in the impedances, it is necessary to design a balun to achieve maximum power transfer. An impedance matching circuit used by Cal Poly in their CP series CubeSat was the first design tested. For reasons unknown, the circuit would not give the results desired. Therefore, a Pawsey Stub balun, as seen in Figure 39, was designed to convert the unbalanced coax to a balanced output.

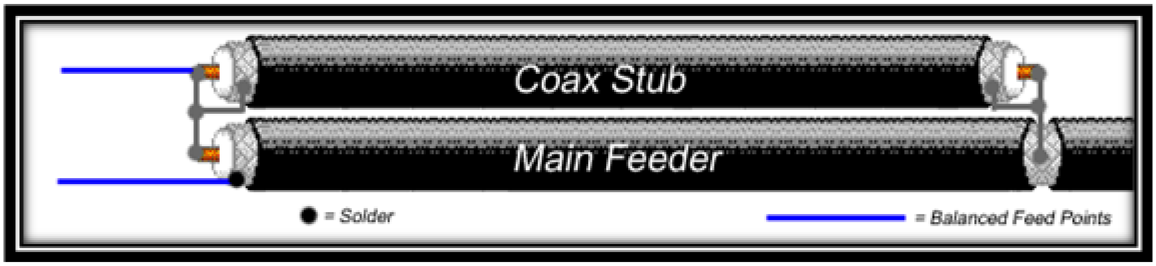

Figure 39. Pawsey Stub Balun (From [29])

The last part of the design process for the beacon antenna was the pre-deployment storage setup and the deploying of the antenna once the spacecraft is on orbit. The original design for storing the antenna, as seen in Figure 30 and 37, was to wrap the 1/4” spring steel or copper beryllium around a 1/4" high rail. Because the antenna design was changed, the storage setup for the antenna had to be redesigned as well. As seen in Figure 40, fishhook shaped brass fittings were installed around the border of the +y solar panel. This is a simple yet affective storage setup. To complete the setup, small eyelets were bent in each end of the antenna. Fishing line is then tied to the eyelets and attached to two nichrome wires as seen in Figure 40. Once NPS-SCAT is launched and on orbit, a deployment circuit will heat up the nichrome wires, which will melt the fishing line and deploy the antenna.

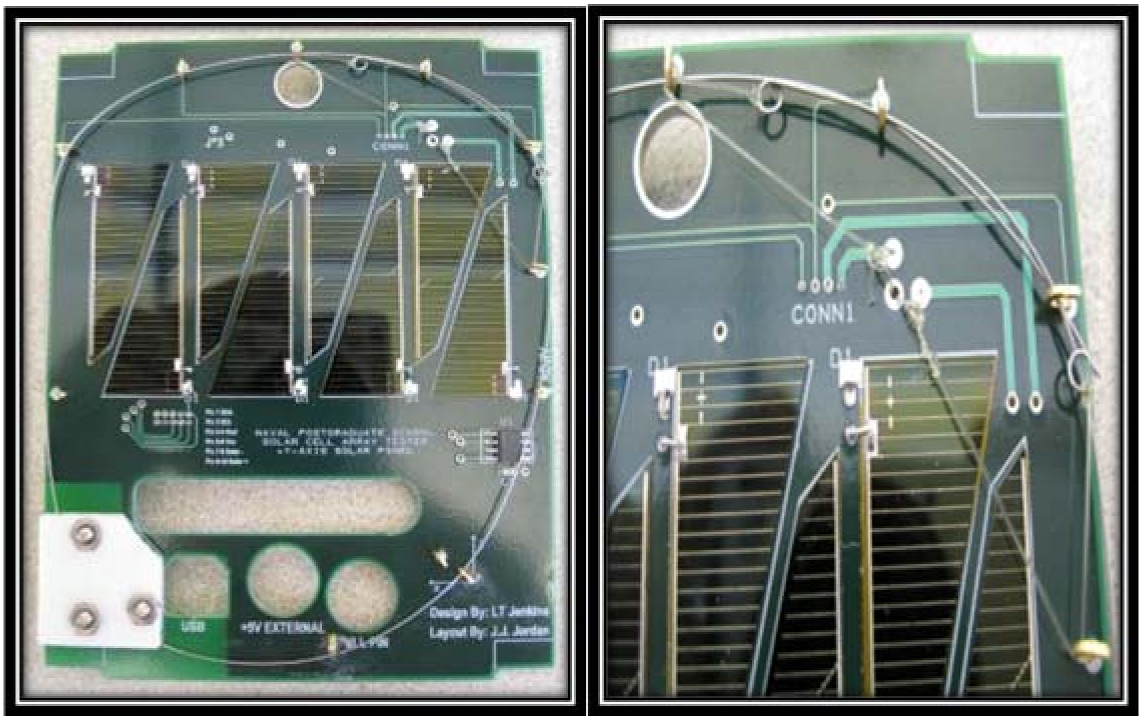

Figure 40. Beacon Antenna Storage Setup

2. Specifications

To get the desired frequency of a half-wave dipole antenna, the length of the antenna has to be cut to an exact length. As the length of the antenna is increased, the frequency decreases and vice versa. Equation (4-1) was found to be the most accurate way to compute the length of the antenna [30].

$$\frac{300(MHz)}{Freq(MHz)} \times 0.935 \times 0.5 \Rightarrow \_\_\_(meters) \qquad (4\text{-}1)$$

With the operating frequency known at 438 MHz, it was easily input into the equation to determine the antenna length to be 32.02 cm.

As mentioned in Chapter IV.C.1, the Pawsey Stub balun converts the unbalanced coax cable to a balanced output, which is needed to achieve maximum power out between the transmitter and the antenna. The length of the stub balun is required to be a certain length in order to match the impedance of the coax to that of the antenna. The length of the Pawsey Stub balun is determined in a similar way to that of the length of the antenna. Equation (4-2) was used to determine the length of the stub, which equated to a length of 11.64 cm [30]. All coax cable has a velocity factor, which is a fraction of the speed at which the signal would travel through free space.

$$\frac{300(MHz)}{Freq(MHz)} \times 0.68(Velocity\_Factor) \times 0.25 \Rightarrow \underline{\quad}(meters) \tag{4-2}$$

3. Antenna Testing

The beacon antenna test was accomplished in much the same fashion as the patch antenna testing as described in Chapter IV.B.3.

a. VSWR

Once the beacon antenna was designed to include an antenna length of 32.02 cm and the Pawsey Stub balun length of 11.64 cm, it was tested. The beacon antenna was attached to a tripod, as seen in Figure 41, and connected to the network/spectrum analyzer.

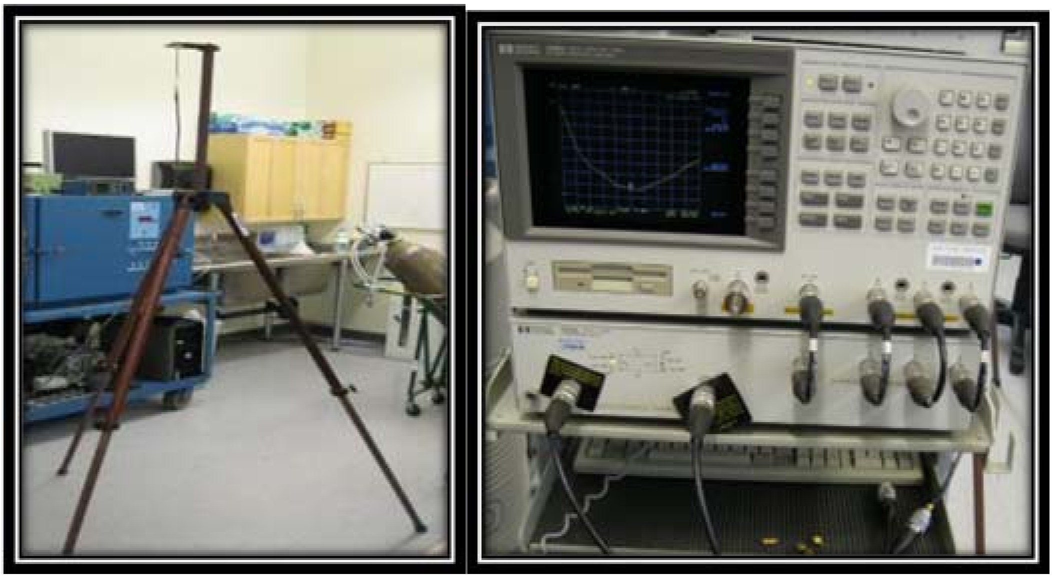

Figure 41. Voltage Standing Wave Ratio Test Setup

The network/spectrum analyzer was first calibrated and then measured the VSWR. The antenna had to be tuned to match the Pawsey Stub balun by adjusting the length. Once the antenna was tuned, the VSWR was measured at the center frequency of 438 MHz, which equated to 1.65 dB. As can be seen in Table 15, the transmission loss is 0.27 dB. This is sufficient for NPS-SCAT given the margin calculated in the beacons link budget. The graph of the half-wave dipole antenna’s VSWR is seen in Figure 42.

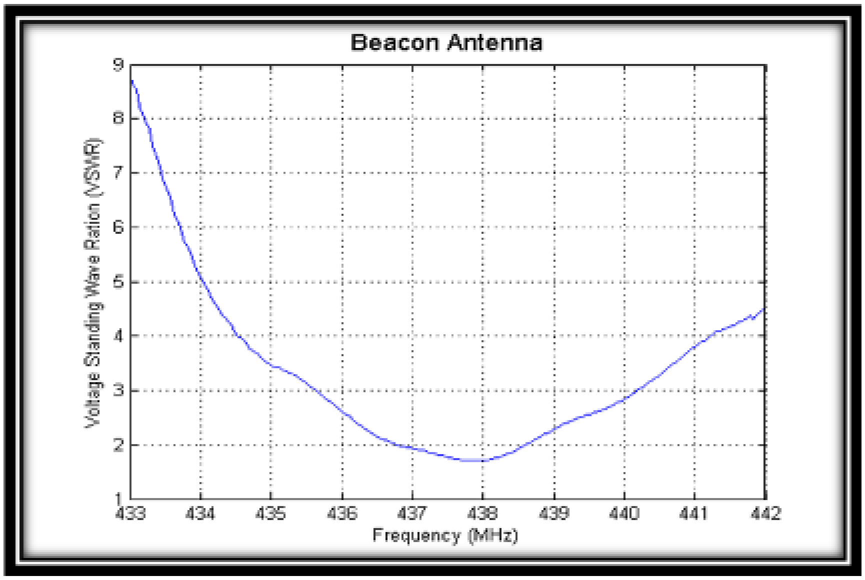

Figure 42. Beacon Antenna Voltage Standing Wave Ratio

b. Antenna Gain Pattern Testing

The NPS anechoic chamber could not be used for computing the beacon's antenna gain patterns, because the frequency is lower than the chamber can support. The NPS anechoic camber was designed to only test antennas with frequencies of 3.0 GHz and higher. Therefore, to determine the beacon's antenna gain pattern, a clever way to test the antenna was constructed. As mentioned in Chapter IV.B.3.b, the anechoic chamber is designed to measure only the returns of the test antenna and compare them to the returns of a reference antenna in a controlled environment. Since there was not a controlled environment available, an open space between two buildings was used. To conduct the test, a spectrum analyzer, two PCB Log Periodic antennas, a crystal oscillator at 437.25 MHz with a battery, and the beacon antenna mounted on a CubeSat structure were used. The first step in developing the beacon antenna gain patterns was to setup two tri-pods 15 meters apart. This distance was chosen because it is best to measure antenna radiation at a minimum of ten times the wave length. The beacons wave length is 70 cm, ten times 70 cm is seven meters, and therefore it was doubled to 15 meters. Once the tripods were setup, the path loss for 15 meters was calculated using the same SMAD worksheet as was used in the link budget section. The path loss at 15 meters equates to 48.80 dB. Then the spectrum analyzer was connected to both the antenna cables, bypassing the antennas, and connected to the crystal oscillator to get a reference level, which was 11.2 dB. Next, the spectrum analyzer was connected to one PCB Log Periodic antenna and 15 meters away, a second PCB Log Periodic antenna was connected to the crystal oscillator. Then a second reference level was measured at -30.5 dB. By taking the difference in the two reference levels and the path loss, it was determined that each PCB Log Periodic antenna has a gain of 3.55 dB. Once the gain of the PCB Log Periodic antenna was known, the beacon antenna was connected to the oscillator in the place of one of the PCB Log Periodic antennas. The same measurements and calculations were computed to find the gain of the beacon antenna, which is -1.0 dB. Once the test was setup, data was collected for two different gain patterns. The first antenna gain pattern test was conducted with both the PCB Log Periodic antenna and the beacon positioned vertical as seen in Figure 43. The beacon antenna was rotated 360 degrees in 15-degree increments and the beacon antenna’s radiation was collected on the spectrum analyzer. Once the data was collected, MATLAB was used to plot the antenna gain pattern using the polardb function. The plot of the beacon antennas gain pattern seen if Figure 44 shows that the gain in the vertical direction is approximately -1 dB.

Figure 43. Beacon Antenna Gain Pattern Test

In order to collect the data for the horizontal gain pattern, both the PCB Log Periodic and beacon antenna were rotated to the horizontal position. Once again, the beacon antenna was rotated 360 degrees and the antennas radiation was collected by the spectrum analyzer in 10 degree increments. MATLAB was again used to plot the collected data and the beacon antennas gain pattern in the horizontal position can be seen in Figure 44. The horizontal gain pattern shows the classic figure 8 pattern that is common for all have-wave dipole antennas. The antennas gain in the strongest position is about -1 dB, but at the knolls it is more than -15 dB. According to the beacons link budget as discussed in Chapter III.C.2, there is more than enough margin to close the beacons link; therefore, the antenna will meet the mission for NPS-SCAT.

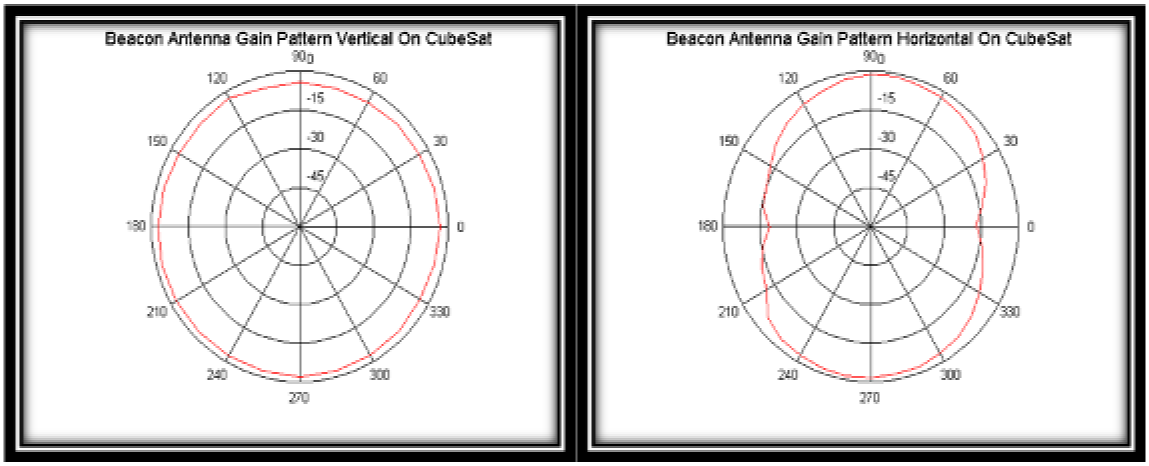

Figure 44. Beacon Antenna Gain Pattern

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V. SCAT GROUND STATION METHODOLOGY AND FREQUENCY COORDINATION

A. PAST WORK: GROUND STATIONS AND FREQUENCY COORDINATION

An earth station or ground station is a terrestrial terminal station designed for extra planetary telecommunications with spacecraft. Ground stations communicate with spacecraft by transmitting and receiving radio waves in a defined frequency band. When a ground station successfully transmits radio waves to a spacecraft (or vice versa), it establishes a telecommunications link [21]. NPS has two ground stations that have been setup to communicate with different spacecrafts. One ground station is setup in the L and S-Band and one ground station is setup in the UHF/VHF bands. Frequency coordination for obtaining licenses for the grounds stations is necessary before the ground stations can be fully operated.

1. MHX2400 Ground Station

The ground station that will be used for the MHX2400 is the ground station in the L and S-Band. This ground station was setup for communicating with NPSAT1, which is waiting to launch. The ground segment includes a 3.04-meter parabolic dish antenna, which is operated through a general purpose computer that sends commands to the controller, which steps the azimuth/elevations motors. The general purpose computer controls the ground station through an orbital propagator software embedded in the Northern Lights Software’s Nova program. The computer, via the software, relays commands through the modem, through a frequency synthesizer, which mixes the intermediate frequency with the carrier frequency, back to the modem and then out the antenna. Receiving data back from NPS-SCAT will be completed in a similar reverse order from the antenna to the modem to the computer. Other inputs to the computer include a weather station, a video camera that watches the entire ground station, and a GPS. The general purpose computer controlling the ground station can be remotely logged into allowing the ground station to be controlled from any computer on the NPS network. A thesis entailing the setup of the ground station and its components was completed by Luke Koerschner [15].

2. Beacon Ground Station

The ground station that will be used for NPS-SCAT's beacon will be the one setup for UHF/VHF communications. The ground station's hardware consists of a transceiver, an antenna, a TNC, a tracking device, and a general purpose controlling computer. The transceiver, as seen in Figure 45, is an ICOM IC-910H with two operating modes, one which is in the 70 cm amateur band 420 to 480 MHz. This frequency range is perfect for the beacon at 438 MHz. The antenna tower is about ten meters high and includes two circular polarized Yagi-Uda antennas and a discone antenna. Due to the Yagi antennas being circularized, they are capable of receiving any orientation of linear polarized signals. The discone antenna is used to provide a broadband omni-directional antenna that does not require tracking for operations. The TNC is a Kantronic KPC-9612 Plus.

Figure 45. UHF/VHF Ground Station Transceiver and Antenna (From [23])

The TNC consists of a microprocessor, a modem, and software, which provides a command line interface. The TrakBox is a tracking device that was designed from a kit purchased from Tucson Amateur Packet Radio (TAPR). In host mode, TrakBox allows itself to be remotely controlled by a computer. Nova software, which is also used in the MHX2400 ground station, is used to control the direction and elevation the antenna is pointing. The design of the ground station was constructed through a thesis by Nikolas Biedermann [23].

3. Frequency Coordination

During the initial frequency coordination discussions, it was thought that NPS would be able to use the same frequency spectrum that previous CubeSats had used in the amateur band. After much research, it was discovered that because NPS was a federal agency, the use of amateur frequencies might not be possible. After further research, Matt Schroer contacted the Navy-Marine Corps Spectrum

Center (NMSC) to obtain ground station licenses for both the MHX2400 and the beacon. The NMSC was contacted but a license was not pursued. Another method for obtaining licensing for the ground stations was to do it the same way NPS did it for PANSAT. It was discovered that NMSC was contacted for a ground station license and the request was adjudicated allowing the school to coordinate directly with the Federal Communications Commission (FCC) and approval was granted. There was very little coordination with the Radio Amateur Satellite Corporation (AMSAT-NA) because it was assumed that there were too many restrictions for a federal institution. AMSAT coordination and restrictions will be discussed in detail in Chapter V.C.2. The last area where frequency coordination was conducted was with the FCC. Research was done and an application was filled out to request a license from the FCC but not submitted. Additional information about the previous frequency coordination can be found in Schroer's thesis [7]

B. GROUND STATIONS SETUP

1. MHX2400 Ground Station

The ground station setup for the MHX2400 is still in progress. So far, there have been multiple upgrades to new equipment. A new thrust bearing was installed, which supports the dish so that the force from the wind does not wear out the rotor. The azimuth control motor was moved from the top of the mast to the bottom of the mast, which will provide better pointing accuracy. The elevation rotor motor was replaced. The elevation motor assembly had 15-20 lbs of unnecessary steal trimmed off to prevent wear on the elevation motor. There is still much work needed to be completed on the MHX ground station, which will be discussed in Chapter V.A.3.b.

2. Beacon Transceiver Ground Station

The ground station for the beacon had a few minor changes to prepare it for full operations with NPS-SCAT. The same transceiver, antenna, tracking device, and general purpose computer will be used for NPS-SCAT. The update to the ground station which allowed successful communications with NPS-SCAT was all in software and removing the hardware TNC. The software used to interface with the spacecraft is MixW. MixW is the software that Cal Poly uses to communicate with their CP series CubeSats and since Cal Poly designed and assembled NPS-SCAT’s beacon, it only makes sense to use the same software. MixW is state of the art digital mode software used by amateur radio operators: its features include a voice and data keyer for Single Side Band (SSB), Frequency Modulation (FM), and Amplitude Modulation (AM) modes. MixW does not require a TNC to operate because it contains a software TNC. The only requirement for MixW is a computer running Window 9x, ME, NT, 2000, XP or Vista operating system, and a compatible soundcard [31].

Because of all the different operating modes within MixW, the software required setting changes to be compatibility with NPS-SCAT. Two versions of MixW were configured for the ground station as seen in Figure 46. One for the transmitting to SCAT at 600 bps and one for receiving TT&C at 1200 bps. There are two major changes in the settings that must be changed before communicating with

SCAT. For transmitting, the modem setting must be changed to 'VHF Custom AFSK', the 'Baudrate' must be set to 600, 'Tone1' has to be set to 1100 Hz, and 'Tone2' must be 2300 Hz. The Sound Device settings need to be changed as well. The 'Input' and 'Output' must be set to SoundMAX HD Audio. The Sound Device is a crucial component because this is what sends the data to the ICOM radio, which transmits to the spacecraft. The receiving settings are similar to the transmit settings but must be setup correctly to receive from the satellite. The important change that has to be made is changing the modem settings. The modem must be changed to 'VHF 1200 baud (Standard, 1200/2200 Hz)'. A pictorial of transmit and receive settings for the beacon ground station can be found in Appendix L and M.

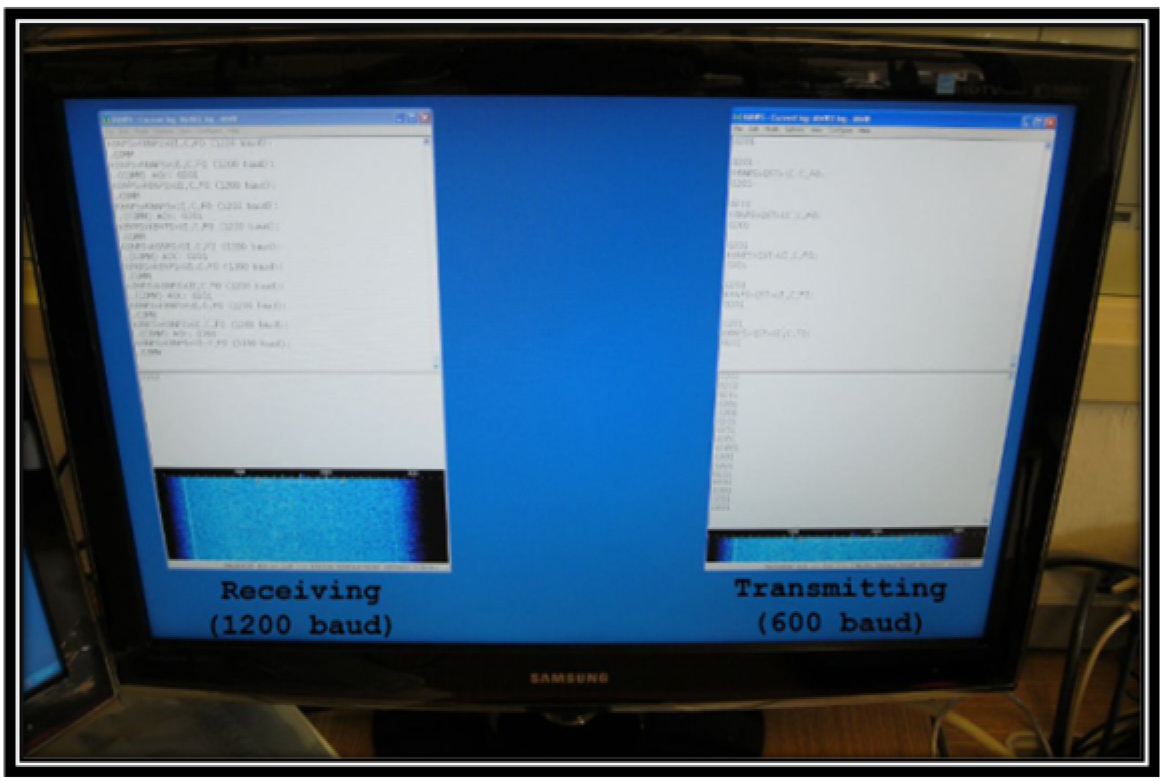

Figure 46. MixW Software

C. SCAT FREQUENCY APPLICATION PROCESS

Frequency coordination allows for maximizing the use of radio frequency spectrum and minimizes interference. The Radio Amateur Satellite Corporation is a non-profit scientific and educational corporation established in 1969. Its goal is to foster amateur radio's participation in space research and communications while managing the frequency spectrum and minimizing interference [32]. Amateur radio satellites frequency coordination is provided by the International Amateur Radio Union (IARU) through its Satellite Advisor, a senior official appointed by the IARU administrative Council. The IARU Satellite Advisor is assisted by an Advisory Panel of qualified amateurs from all three IARU Regions.

There are several critical restrictions that must be justified to use the amateur frequency spectrum. First, the purpose of the satellite must be intended to provide a communications resource for the amateur community or provide self-training and technical investigation relating to radio technique [32]. NPS-SCAT will be available for the amateur community to communicate with and information about NPS-SCAT is available online at http://sp.nps.edu/NPS-SCAT. This information will include operating frequencies and the data format. Second, the operator of the station must be serving solely for personal gain with no pecuniary interest [32]. The ground station for NPS-SCAT will be licensed by the amateur radio club at NPS and is discussed in Chapter V.C.1. Finally, the communications over the Amateur band may not be concealed in any manner. This restricts encoding or encrypting the signal for anything other than “space telecommand [32].” Only the telecommand of NPS-SCAT will be encoded. All of the critical restrictions were justified therefore the Amateur Satellite Frequency Coordination Request (ASFCR) was submitted as described in Chapter V.C.2.

1. Coordination with NPS Radio Club, K6NPS

One of the restrictions that had to be met for obtaining a ground station license for NPS-SCAT was that the operator of the station must be serving solely for personal gain with no pecuniary interest [32]. As long as one student working with the NPS-SCAT program possess an amateur radio operators license this restriction can be satisfied. Also because of this restriction, it was decided that the NPS amateur radio club (K6NPS) would hold the ground station license. Multiple meetings were held with Professors Todd Weatherford and Andrew Parker, the NPS radio club license holders, to discuss the AFSCR licensing process. It was agreed upon that the NPS radio club would use the ground station along with the small satellite lab. After the ASFCR was filled out, Professor Todd Weatherford signed it.

2. Amateur Satellite Frequency Coordination Request

For over 100 years, amateur radio operators have maintained an effective tradition of self-regulation. Amateur are expected to coordinate their use of frequencies. Coordination of many terrestrial stations, repeaters and beacons is through IARU member national societies and local coordinating committees. Frequency coordination for amateur radio satellites is provided by the IARU Satellite Advisor and his Advisory Panel. These are the people who will be approving the ASFCR. The ASFCR provides a way for the amateur to describe the satellite and the ground stations.

Along with Mr. David Rigmaiden and coordination with Mr. Arthur Feller, the ASFCR was completed as seen in Appendix N. There were five sections that included multiple subsections to be filled out. The first section was the Administrative section. This section allows the amateur to name the spacecraft (NPS-SCAT), the licensee of the space station (K6NPS), and the organization (NPS). Section two is where the mission and the systems of the NPS-SCAT are described to include the frequencies requested. It is also the section which describes the ground stations (the MHX and the beacon), telemetry transmission (how amateurs can use the spacecraft), and the launch plan (location and date) for the spacecraft. The third section requires additional detailed information for the transmitting and receiving ground stations. The forth section is the certification section where the amateur verifies that the application has been filled out honestly and to the best of his knowledge. The fifth and final section is the signature section affirming section four. After completing the application, it was sent to the IARU Satellite Advisor by email to satcoord@iaru.cor and wozane@gmail.com on June 2, 2010 [33]. Approval for the application is still in progress by the Satellite Advisor and the Advisory Panel.

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VI. FUTURE WORK AND CONCLUSION

A. FUTURE WORK AND CONCLUSION

1. MHX2400

a. Conclusions

The testing conducted on the MHX2400 demonstrated that it is a great candidate to use on a 1U CubeSat. Based on the current draw test, the radio will not require more power than what the Clyde Space EPS can produce. As seen in the link budgets and the carrier-to-noise testing, it has sufficient data rates to pass the data required by NPS-SCAT. One problem with the MHX2400 is that it is very hard to find and procure. Microhard Systems Inc. no longer produces the MHX2400, so a different radio will need to be tested for future use. The MHX2420 was tested before the MHX2400 and its transient current draw is too high and is, therefore, not a good candidate when using the Clyde Space EPS.

A valuable lesson learned while testing the MHX2400 was to make sure the configuration settings are the same on both the master and the slave radios. Also knowing the correct altitude of the spacecraft allows for the link budgets and the carrier-to-noise testing being more accurate and will eliminate multiple tests.

b. Future Work

If there is time before NPS-SCAT launches, further carrier-to-noise testing could be completed with the MHX2400. The carrier-to-noise testing does a great job of stressing the radio's link in a space like environment.

Further testing that could be completed includes: one, changing data rates and data file sizes to see if a higher data rate could be used, and two, changing the configuration settings to see if this affects the data rate or the size of the file that could be sent. Additional work should include writing the test procedures that were used for testing the MHX.

For future spacecraft, a different radio other then the Microhard System Inc. MHX2400 will have to be procured and tested because the MHX2400 is no longer manufactured. The MHX2420 was procured and tested, as described in Matt Schroer’s thesis, but its current draw is more than the Clyde Space EPS can support. Detailed documentation of the MHX2400 testing including the link budgets need to be added to the NPS-SCAT website.

2. MHX2400 Antenna

a. Conclusions

The testing conducted with the Spectrum Control Inc. patch antenna produced favorable results for using it with NPS-SCAT. The testing equated to a VSWR of 1:1.42, which is only a 0.132 dB transmission loss. The anechoic chamber testing provided a front-to-back ratio of about 15 dB. Both the VSWR and anechoic chamber testing showed that the patch antenna could be mounted directly to the Pumpkin CubeSat structure and use the structure for its ground plane. This made integrating the patch antenna much simpler than using an additional ground plane.

b. Future Work

Much of the work for the patch antenna has been completed. Future work should include writing procedures for testing the patch antenna. Also refining and writing a procedure for mounting the patch antenna. Detailed documentation of the patch antenna needs to be added to the NPS-SCAT website.

3. MHX 2400 Ground Station

a. Conclusions

There was not much work completed on setting up the ground station for the primary transceiver, but new equipment was upgraded. All the components for the ground station are available for setup but, due to time constraints, the work was not completed.

b. Future Work

There is much work to be done in setting up the ground station for the primary receiver. All the components need to be aligned. The general purpose computer, 3.04 meter antenna, the high power amplifier, and the MHX2400 slave radio all need to be setup for operation on the roof of Spanagel Hall. The 3.04-meter dish has new supports for the feed which need to be mounted. The box that will house the MHX2400 needs to be constructed and mounted to the antenna. The box which houses the general purpose computer needs remodeled and updated for operations. The new Common Ground Architecture (CGA) software needs to be setup for both tracking the spacecraft and processing the data that is received. The CGA software has many capabilities, some include: auto scheduling the spacecrafts passes, auto tracking based on TLE from the spacecraft, and auto downloading and logging of TT&C. Once the ground station is setup, an end-to-end test with the spacecraft and the ground station needs to be conducted. Detailed documentation of the ground station needs to be written and added to the NPS-SCAT website.

4. Beacon (UHF Transceiver)

a. Conclusions

The testing conducted on the beacon proved that it will work as required for NPS-SCAT. The computed link budgets showed the link would close and the carrier-to-noise testing complimented the link budget. The carrier-to-noise test confirmed that once the spacecraft was above a ten-degree look angle from the horizon, the link would close and the TT&C data will be passed to the ground station.

b. Future Work

There is a second version of the beacon board being built by Cal Poly with minor changes. Once the board is received, the current draw and carrier-to-noise testing will need to be conducted to qualify the board. Additional testing with larger files should be completed. The testing procedures need to be written for future beacon testing. Also, the testing results and the link budgets need to be posted to the NPS-SCAT website.

5. Beacon Antenna

a. Conclusions

The testing conducted with the half-wave dipole antenna and Pawsey stub balun produced favorable results for using it with NPS-SCAT. The testing equated to a VSWR of 1:1.65 dB, which is only a 0.27 dB transmission loss. The antenna gain pattern testing showed that the half-wave dipole antenna has sufficient gain to complete the link, allowing the beacon to transmit the TT&C data. Both the VSWR and antenna gain pattern testing verified that the half-wave dipole antenna is a good antenna to use with NPS-SCAT and future CubeSats.

b. Future Work

Additional tuning of the half-wave dipole antenna and the Pawsey stub should be conducted. This is a very time consuming and tedious process. The antenna has to be cut longer than the computed 32.02 cm and then tuned by cutting the antenna and watching the frequency change on the network/spectrum analyzer. Also tuning the Pawsey stub balun is very finicky. It has to be cut to the exact length of 11.64 cm and then connected to the antenna where it can be checked on the frequency analyzer. If both the antenna and the stub balun are tuned properly, the VSWR on the spectrum analyzer will be below 2 dB. Also, the plotted pattern of the combination will be very smooth without additional low points. The testing procedure for making and testing the antenna and stub balun need to be written. The test results also need to be added the NPS-SCAT website.

6. Beacon Ground Station

a. Conclusions

The beacon ground station is almost completely functional. The ground stations general purpose computer, transceiver and antenna are all working. The MixW software that is being used as the interface for communicating with the spacecraft is working great. Commands can be sent to the spacecraft; it processes the commands and then sends data back to the ground station. The ground station will work great for communicating with NPS-SCAT

b. Future Work

Future work on the ground station entails developing at least two additional software programs; one program for tracking the spacecraft and the other for processing the data once it is received from the spacecraft. Also, documentation needs to be written describing all the ground station components and posted to the NPS-SCAT website.

7. Amateur Satellite Frequency Coordination Request

a. Conclusions

The ASFCR for licensing both ground stations for the MHX2400 and the beacon have been submitted to the IARU Satellite Advisor and Advisory Panel. The license has yet to be approved.

b. Future Work

Additional follow-up needs to be conducted with the IARU Satellite Advisor and Advisory Panel for obtaining the ground station licenses. All of the documentation required by the ASFCR needs to be added to the NPS-SCAT web site.

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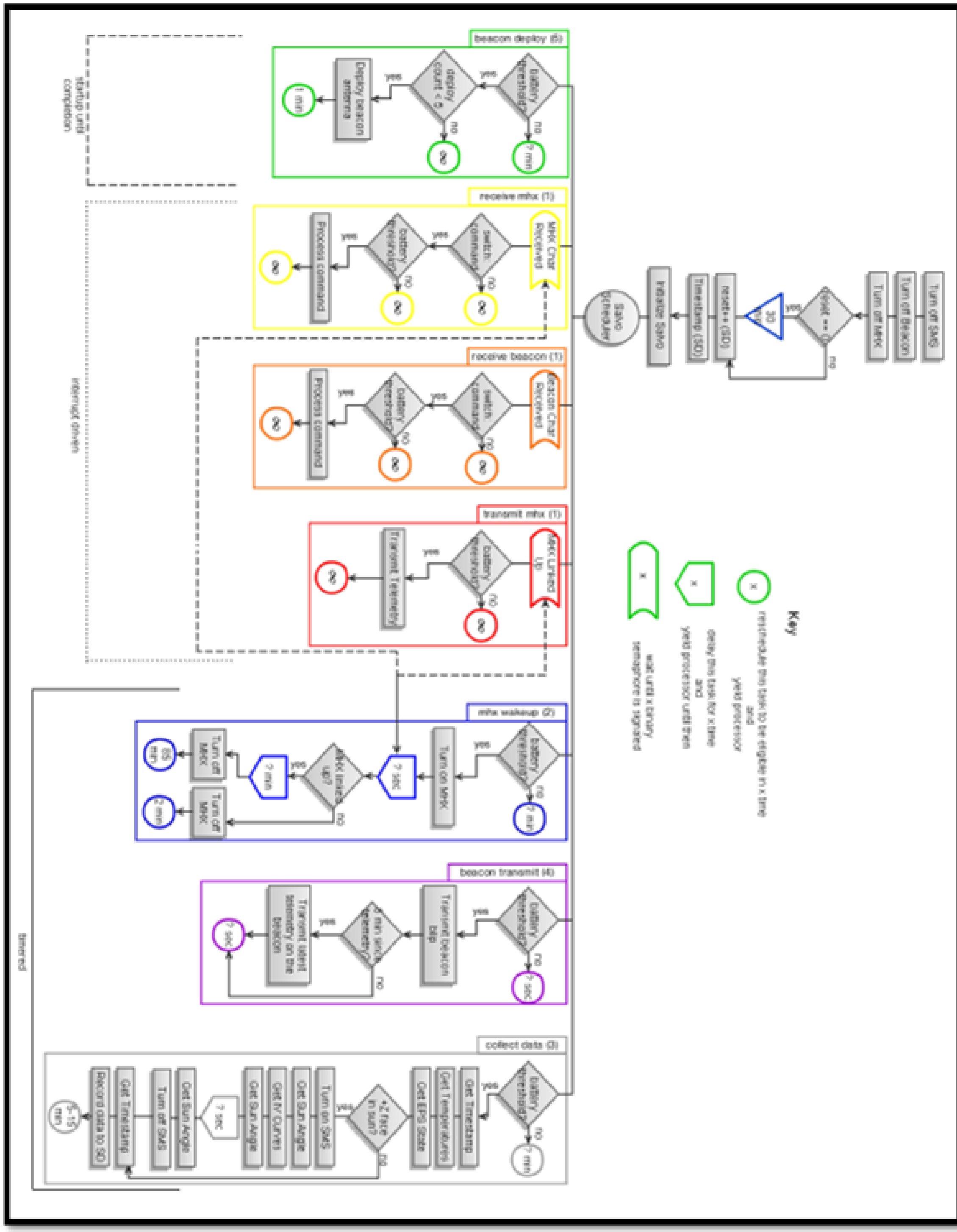
APPENDIX A: NPS-SCAT CONOPS



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APPENDIX B: SYSTEM DATA REQUIREMENTS

Bytes	Section	Name	Description
4	**Header**		
4		Prefix	"SCAT"
	Payload		
2		Reset Count	The number of times NPS-SCAT has rest since launch.
1		Beacon Deploy	Whether or not the beacon has been deployed successfully.
4		Datapoint number	A unique number (incremented) to identify this data point.
4		Start timestamp	The time when the data collection began.
4		End timestamp	The time when the data collection ended.
40		EPS	The full state of the EPS.
8		Sun sensor start	The full sun vector (three floats) and the temperature (one float) at the start of data collection.
8		Sun sensor end	The full sun sensor data at the end of data collection.
30		Temperature sensors	The raw data from 15 temperature sensors on solar cells and test cells.
2		IV Curve Cell 1 DAC	The DAC is incremented by this float value for each datapoint.
150		IV Curve Cell 1 ADC	Each IV curve has 100 12-bit ADC values, using bit packing we get down to 150 bytes.
2		IV Curve Cell 2 DAC	The DAC is incremented by this float value for each datapoint.
150		IV Curve Cell 2 ADC	Each IV curve has 100 12-bit ADC values, using bit packing we get down to 150 bytes.
2		IV Curve Cell 3 DAC	The DAC is incremented by this float value for each datapoint.
150		IV Curve Cell 3 ADC	Each IV curve has 100 12-bit ADC values, using bit packing we get down to 150 bytes.
2		IV Curve Cell 4 DAC	The DAC is incremented by this float value for each datapoint.
150		IV Curve Cell 4 ADC	Each IV curve has 100 12-bit ADC values, using bit packing we get down to 150 bytes.
2	**Postfix**		
2		CRC	The checksum on the message.
721	**Total Size**		

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APPENDIX C: MHX2400 LINK BUDGETS FOR 450KM AND 600KM TO INCLUDE ELEVATION ANGLES OF 10°, 45° & 90°

MHX 2400 Link Budget Alt-450km

(yellow)	Inputs
(light blue)	Numbers Calculated by SMAD or Default

	UPLINK		DOWNLINK		UPLINK		DOWNLINK		UPLINK		DOWNLINK	
Frequency	2.42	GHZ	2.42	GHZ	2.42	GHZ	2.42	GHZ	2.42	GHZ	2.42	GHZ
Wevelength	1.24E-01	m	1.24E-01	m	1.24E-01	m	1.24E-01	m	1.24E-01	m	1.24E-01	m
Data Rate	115.20	kbps	115.20	kbps	115.20	kbps	115.20	kbps	115.20	kbps	115.20	kbps
Probability of Bit Error	1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-05	
Required Eb/No	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB
Geometry &Atmosphere												
Altitude	450.00	km	450.00	km	450.00	km	450.00	km	450.00	km	450.00	km
Planet Angular Radius	69.08	deg	69.08	deg	69.08	deg	69.08	deg	69.08	deg	69.08	deg
Elevation Angle	10.00	deg	10.00	deg	45.00	deg	45.00	deg	89.99	deg	89.99	deg
Nadir Angle	66.91	deg	66.91	deg	41.34	deg	41.34	deg	0.01	deg	0.01	deg
Planet Central Angle	13.09	deg	13.09	deg	3.66	deg	3.66	deg	0.00	deg	0.00	deg
Propigation Path Length	1570.04	km	1570.04	km	616.68	km	616.68	km	450.00	km	450.00	km
Atmospheric Attenuation at Zenith	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB
Rain Attenuation	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB
Increase in System Noise Temp	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K
Ground(G)/Spacecraft(SC) Transmitter	G		SC		G		SC		G		SC	
Output Power	10.00	W	1.00	W	10.00	W	1.00	W	10.00	W	1.00	W
Output Power	10.00	dB	0.00	dB	10.00	dB	0.00	dB	10.00	dB	0.00	dB
Line Loss	-3.60	dB	-0.20	dB	-3.60	dB	-0.20	dB	-3.60	dB	-0.20	dB
Antenna Efficiency	55.00	%	80.00	%	55.00	%	80.00	%	55.00	%	80.00	%
Antenna Diameter	3.04	m	0.04	m	3.04	m	0.04	m	3.04	m	0.04	m
Peak Antenna Gain	35.13	dB	0.00	dB	35.13	dB	0.00	dB	35.13	dB	0.00	dB
Half-Power Beamwidth	2.86	deg	196.73	deg	2.86	deg	196.73	deg	2.86	deg	196.73	deg
EIRP	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB
Pointing Error	1.00	deg	0.00	deg	1.00	deg	0.00	deg	1.00	deg	0.00	deg
Antenna Pointing Loss	-1.47	dB	0.00	dB	-1.47	dB	0.00	dB	-1.47	dB	0.00	dB
Ground(G)/Spacecraft(SC) Receiver	SC		G		SC		G		SC		G	
Antenna Efficiency	80.0	%	55.0	%	80.0	%	55.0	%	80.0	%	55.0	%
Antenna Diameter	0.04	m	3.04	m	0.04	m	3.04	m	0.04	m	3.04	m
Peak Antenn Gain	0.00	dB	35.13	dB	0.00	dB	35.13	dB	0.00	dB	35.13	dB
Half-Power Beamwidth	196.73	deg	2.86	deg	196.73	deg	2.86	deg	196.73	deg	2.86	deg
Pointing Error	0.00	deg	0.28	deg	0.00	deg	0.28	deg	0.00	deg	0.28	deg
Antenna Pointing Loss	0.00	dB	-0.12	dB	0.00	dB	-0.12	dB	0.00	dB	-0.12	dB
System Noise Temp	688.00	K	260.00	K	688.00	K	260.00	K	688.00	K	260.00	K
G/T	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB
Link Budget												
EIRP	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB
Space Loss	-164.02	dB	-164.02	dB	-155.91	dB	-155.91	dB	-153.17	dB	-153.17	dB
Atmospheric Attenuation	-0.65	dB	-0.65	dB	-0.38	dB	-0.38	dB	-0.36	dB	-0.36	dB
Rain Attenuation	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB
G/T	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB
Antenna Pointing Losses	-1.47	dB	-0.12	dB	-1.47	dB	-0.12	dB	-1.47	dB	-0.12	dB
Eb/No	25.00	dB	23.97	dB	33.38	dB	32.35	dB	36.14	dB	35.11	dB
C/No	75.62	dB	74.59	dB	83.99	dB	82.97	dB	86.76	dB	85.73	dB
Implementation Loss	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB
Margin	**13.40**	dB	**12.38**	dB	**21.78**	dB	**20.75**	dB	**24.54**	dB	**23.51**	dB

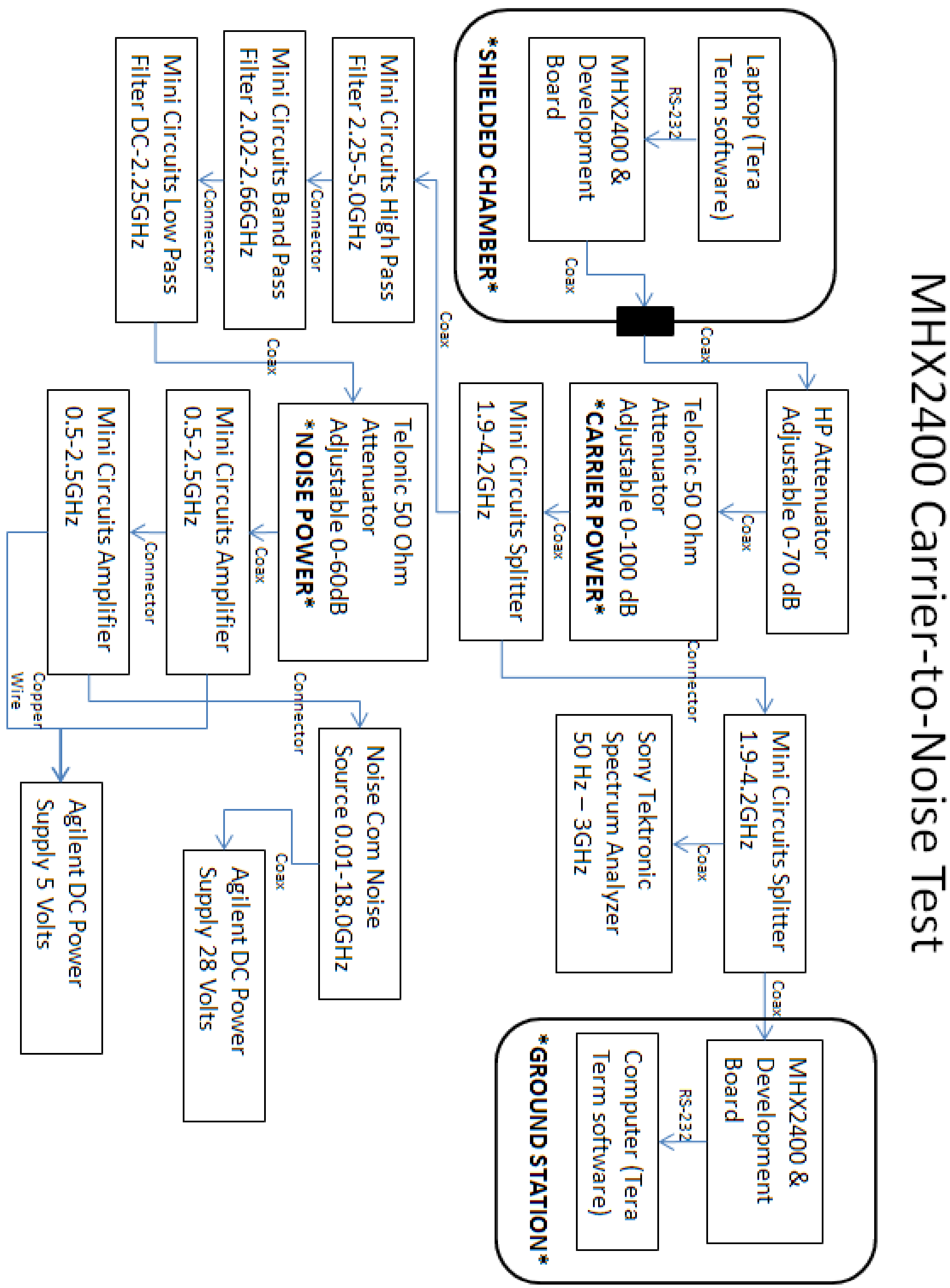
MHX 2400 Link Budget Alt-600km

Inputs (yellow cells)

Numbers Calculated by SMAD or Default (light blue cells)

	UPLINK		DOWNLINK		UPLINK		DOWNLINK		UPLINK		DOWNLINK	
Frequency	2.42	GHZ	2.42	GHZ	2.42	GHZ	2.42	GHZ	2.42	GHZ	2.42	GHZ
Wevelength	1.24E-01	m	1.24E-01	m	1.24E-01	m	1.24E-01	m	1.24E-01	m	1.24E-01	m
Data Rate	115.20	kbps	115.20	kbps	115.20	kbps	115.20	kbps	115.20	kbps	115.20	kbps
Probability of Bit Error	1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-05	
Required Eb/No	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB
Geometry &Atmosphere												
Altitude	600.00	km	600.00	km	600.00	km	600.00	km	600.00	km	600.00	km
Planet Angular Radius	66.07	deg	66.07	deg	66.07	deg	66.07	deg	66.07	deg	66.07	deg
Elevation Angle	10.00	deg	10.00	deg	45.00	deg	45.00	deg	89.99	deg	89.99	deg
Nadir Angle	64.18	deg	64.18	deg	40.26	deg	40.26	deg	0.01	deg	0.01	deg
Planet Central Angle	15.82	deg	15.82	deg	4.74	deg	4.74	deg	0.00	deg	0.00	deg
Propigation Path Length	1932.26	km	1932.26	km	814.83	km	814.83	km	600.00	km	600.00	km
Atmospheric Attenuation at Zenith	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB
Rain Attenuation	0.00	db	0.00	db	0.00	db	0.00	db	0.00	db	0.00	db
Increase in System Noise Temp	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K
Ground(G)/Spacecraft(SC) Transmitter	G		SC		G		SC		G		SC	
Output Power	10.00	W	1.00	W	10.00	W	1.00	W	10.00	W	1.00	W
Output Power	10.00	dB	0.00	dB	10.00	dB	0.00	dB	10.00	dB	0.00	dB
Line Loss	-3.60	dB	-0.20	dB	-3.60	dB	-0.20	dB	-3.60	dB	-0.20	dB
Antenna Efficiency	55.00	%	80.00	%	55.00	%	80.00	%	55.00	%	80.00	%
Antenna Diameter	3.04	m	0.04	m	3.04	m	0.04	m	3.04	m	0.04	m
Peak Antenna Gain	35.13	dB	0.00	dB	35.13	dB	0.00	dB	35.13	dB	0.00	dB
Half-Power Beamwidth	2.86	deg	196.73	deg	2.86	deg	196.73	deg	2.86	deg	196.73	deg
EIRP	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB
Pointing Error	1.00	deg	0.00	deg	1.00	deg	0.00	deg	1.00	deg	0.00	deg
Antenna Pointing Loss	-1.47	dB	0.00	dB	-1.47	dB	0.00	dB	-1.47	dB	0.00	dB
Ground(G)/Spacecraft(SC) Receiver	SC		G		SC		G		SC		G	
Antenna Efficiency	80.00	%	55.00	%	80.00	%	55.00	%	80.00	%	55.00	%
Antenna Diameter	0.04	m	3.04	m	0.04	m	3.04	m	0.04	m	3.04	m
Peak Antenn Gain	0.00	dB	35.13	dB	0.00	dB	35.13	dB	0.00	dB	35.13	dB
Half-Power Beamwidth	196.73	deg	2.86	deg	196.73	deg	2.86	deg	196.73	deg	2.86	deg
Pointing Error	0.00	deg	0.28	deg	0.00	deg	0.28	deg	0.00	deg	0.28	deg
Antenna Pointing Loss	0.00	dB	-0.12	dB	0.00	dB	-0.12	dB	0.00	dB	-0.12	dB
System Noise Temp	688.00	K	260.00	K	688.00	K	260.00	K	688.00	K	260.00	K
G/T	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB
Link Budget												
EIRP	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB	41.53	dB	-0.20	dB
Space Loss	-165.83	dB	-165.83	dB	-158.33	dB	-158.33	dB	-155.67	dB	-155.67	dB
Atmospheric Attenuation	-0.65	dB	-0.65	dB	-0.38	dB	-0.38	dB	-0.36	dB	-0.36	dB
Rain Attenuation	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB
G/T	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB	-28.37	dB	10.98	dB
Antenna Pointing Losses	-1.47	dB	-0.20	dB	-1.47	dB	-0.20	dB	-1.47	dB	-0.20	dB
Eb/No	23.20	dB	22.17	dB	30.96	dB	29.93	dB	33.64	dB	32.62	dB
C/No	73.81	dB	72.79	dB	81.57	dB	80.55	dB	84.26	dB	83.23	dB
Implementation Loss	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB
Margin	**11.60**	dB	**10.57**	dB	**19.36**	dB	**18.33**	dB	**22.04**	dB	**21.02**	dB

APPENDIX D: MHX2400 CARRIER-TO-NOISE BLOCK DIAGRAM



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APPENDIX E: CARRIER-TO-NOISE CALCULATIONS FOR THE MHX2400 AT 450KM AND 600 KM

Carrier-To-Noise FOR MHX2400

Frequency	2.400	GHz
Speed of Light	299792500	m/s

Altitude	450000	m
Earth Radius	6378115	m
Total Distance	6828115	m

	450 km						
Elevation Angle	10		45		89.99		deg
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	
Angular Radius	69.08	69.08	69.08	69.08	69.08	69.08	deg
Naider Angle	66.91	66.91	41.34	41.34	0.01	0.01	deg
Earth Central Angle	13.09	13.09	3.66	3.66	0.00	0.00	deg
Propigation Path Length	1570038	1570038	616684	616684	450000	450000	m
EIRP	41.53	-0.20	41.53	-0.20	41.53	-0.20	dB
Free Space Loss	-164.02	-164.02	-155.91	-155.91	-153.17	-153.17	dB
Atmospheric Attenuation	-0.65	-0.65	-0.38	-0.38	-0.36	-0.36	dB
Pointing Loss	-1.47	-0.12	-1.47	-0.12	-1.47	-0.12	dB
Gound Antenna Gain	0.00	35.13	0.00	35.13	0.00	35.13	dB
Rx Low Noise Amplifier Gain	0.00	17.00	0.00	17.00	0.00	17.00	dB
C (Received Power)	**-124.61**	**-112.86**	**-116.23**	**-104.48**	**-113.47**	**-101.72**	**dB**
C (Received Power)	**-94.61**	**-82.86**	**-86.23**	**-74.48**	**-83.47**	**-71.72**	**dBm**
System Noise Temp	688.00	260.00	688.00	260.00	688.00	260.00	K
N_o (Noise Power)	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**dB**
N_o (Noise Power)	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**dBm**
C/N_o (Carrier-To-Noise-Density)	**75.61**	**91.59**	**83.99**	**99.97**	**86.75**	**102.73**	**dBm**
Receiver Noise Bandwidth	500.00	500.00	500.00	500.00	500.00	500.00	kHz
N (Noise Power)	**-143.23**	**-147.46**	**-143.23**	**-147.46**	**-143.23**	**-147.46**	**dB/Hz**
N (Noise Power)	**-113.23**	**-117.46**	**-113.23**	**-117.46**	**-113.23**	**-117.46**	**dBm/Hz**
C/N (Carrier-To-Noise)	**18.62**	**34.60**	**27.00**	**42.98**	**29.76**	**45.74**	**dBm/Hz**

Carrier-To-Noise FOR MHX2400

Frequency	2.400	GHz
Speed of Light	299792500	m/s

Altitude	600000	m
Earth Radius	6378115	m
Total Distance	6978115	m

	600 km						
Elevation Angle	10		45		89.99		deg
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	
Angular Radius	66.07	66.07	66.07	66.07	66.07	66.07	deg
Naider Angle	64.18	64.18	40.26	40.26	0.01	0.01	deg
Earth Central Angle	15.82	15.82	4.74	4.74	0.00	0.00	deg
Propigation Path Length	1932255	1932255	814831	814831	600000	600000	m
EIRP	41.53	-0.12	41.53	-0.12	41.53	-0.12	dB
Free Space Loss	-165.83	-165.83	-158.33	-158.33	-155.67	-155.67	dB
Atmospheric Attenuation	-0.65	-0.65	-0.38	-0.38	-0.36	-0.36	dB
Pointing Loss	-1.47	-0.20	-1.47	-0.20	-1.47	-0.20	dB
Receive Antenna Gain	0.00	35.13	0.00	35.13	0.00	35.13	dB
Rx Low Noise Amplifier Gain	0.00	17.00	0.00	17.00	0.00	17.00	dB
C (Received Power)	**-126.42**	**-114.67**	**-118.65**	**-106.90**	**-115.97**	**-104.22**	**dB**
C (Received Power)	**-96.42**	**-84.67**	**-88.65**	**-76.90**	**-85.97**	**-74.22**	**dBm**
System Noise Temp	688.00	260.00	688.00	260.00	688.00	260.00	K
N_o (Noise Power)	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**dB**
N_o (Noise Power)	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**dBm**
C/N_o (Carrier-To-Noise-Density)	**73.80**	**89.78**	**81.57**	**97.55**	**84.25**	**100.23**	**dBm**
Receiver Noise Bandwidth	500.00	500.00	500.00	500.00	500.00	500.00	kHz
N (Noise Power)	**-143.23**	**-147.46**	**-143.23**	**-147.46**	**-143.23**	**-147.46**	**dB/Hz**
N (Noise Power)	**-113.23**	**-117.46**	**-113.23**	**-117.46**	**-113.23**	**-117.46**	**dBm/Hz**
C/N (Carrier-To-Noise)	**16.81**	**32.79**	**24.58**	**40.56**	**27.26**	**43.24**	**dBm/Hz**

APPENDIX F: MHX2400 RECOMMENDED SETTINGS

MHX2400 Recommended Radio Settings					
Register	Function	Master Radio (NPS-SCAT)	Slave Radio (Ground Station)	Notes	Default Setting? (Y/N)
S101	Operating Mode	1	3	1=Master Point to Multipoint; 3=Slave	Y
S102	Serial Baud Rate	7	7	7=9600 bps	Y
S103	Wireless Link Rate	4	4	4=Fast with Forward Error Correction	N
S104	Network Address	36610	36610	Master & Slave Must Have Same Network Address (Arbitrary)	N
S105	Unit Address	59110	59109	Master & Slave Must Have Unique Network Address (Arbitrary)	N
S106	Hop Pattern	8	8	8=2.4012-2.4312 GHz (Amateur Band)	N
S107	Encryption Key	1	1	Arbitrary; Master=Slave	y
S108	Output Power	6	6	6=1 Watt	Y
S109	Hop Interval	4	4	4=20ms; As hop interval slows radio stays synched better at greater distances	Y
S110	Data Format	1	1	1=8 bits, No Parity, 1 Stop	Y
S111	Min Packet Size	1	1	1= 1 byte	Y
S112	Max Packet Size	74	152	Optimal Packet Size for 20 ms Hop Interval	N
S113	Packet Retransmission	4	4	More Could Increase Capability & Decrease Throughput	N
S114	Packet Size Control	0	0	For Slave; When set to 1 it overrides the Master	y
S115	Packet Repeat Interval	1	1	Defines A Range of Random Numbers the Slave Will Use As The Next Slot To Send The Packet	y
S116	Character Timeout	8	8	8= If There Is A Gap of 8 Milliseconds, The Modem Will Transmit Data	Y
S117	Modbus Mod	0	0	0=Disabled	Y
S118	Roaming	0	0	0=Disabled	Y
S119	Quick Enter CMDMode	1	1	Delays data mode 5 secs on startup	Y
S120	RTS/DCD Framing	0	0		Y
S121	DCD Timeout	0	0		Y
S122	Remote Control	0	0	For Slave; When Set To 1 It Allows Master Full Remote Control Access	y
S123	Average RSSI	Output	Output	Displays Receive Sig Strenght from distant unit	Y
S124	TDMA Duty Cycle	0	0		Y
S125	TDMA Max Address	200	200	Valid When S102=2 (Point-To-Point)	y
S126	Data Protocal	0	0	0=Input-Transparent & Output-Transparent	Y
S127	Address Filtering	0	0	0=Slave Will Receive And Transmit Data To Master Without Restriction	Y
S128	Multicast Association	0	0	0=Don't Care When S127=0	Y
S129	Secondary Master	0	0	0=Only One Master	Y
S130	No Sync Data Intake	0	0		Y
S135	Serial Channel Mode	0	0	0=RS-232 Mode	Y
S206	Secondary Hop Pattern	9	9	9=2.4012-2.4312 GHz (Amateur Band)	N
S213	Packet Retry Limit	4	4	For Slave; If It Does Not Receive Acknowledgement from Master It Will Retransmit 4 Times Before Packet Is Dropped	N

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APPENDIX G: BEACON LINK BUDGETS FOR 450KM AND 600KM TO INCLUDE ELEVATION ANGLES OF 10°, 45° & 90°

Beacon 433MHz Link Budget Alt-450km

Inputs

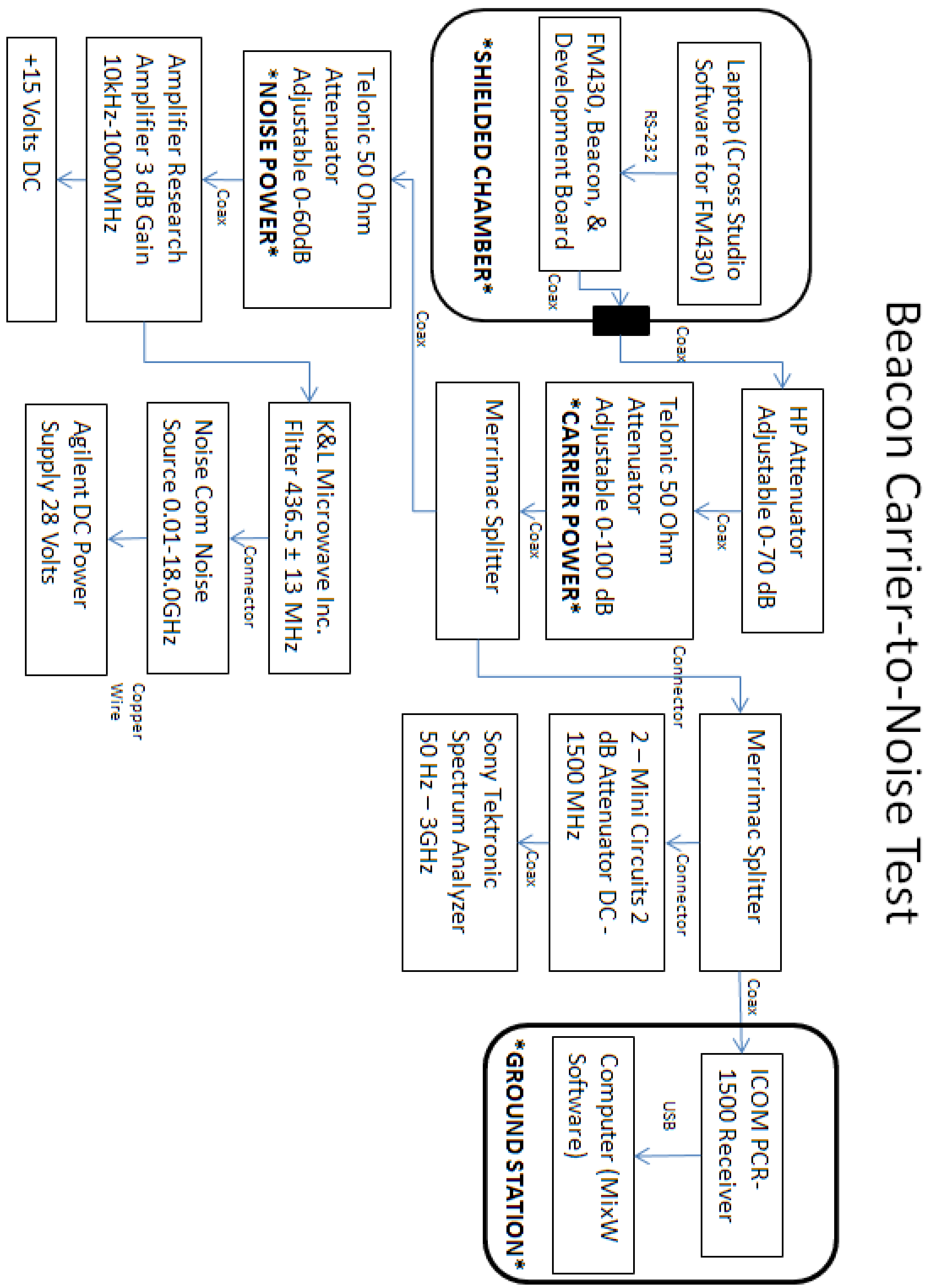
Numbers Calculated by SMAD or Default

	UPLINK		DOWNLINK		UPLINK		DOWNLINK		UPLINK		DOWNLINK	
Frequency	0.438	GHZ	0.438	GHZ	0.438	GHZ	0.438	GHZ	0.438	GHZ	0.438	GHZ
Wevelength	6.84E-01	m	6.84E-01	m	6.84E-01	m	6.84E-01	m	6.84E-01	m	6.84E-01	m
Data Rate	0.600	kbps	1.20	kbps	0.600	kbps	1.20	kbps	0.600	kbps	1.20	kbps
Probability of Bit Error	1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-05	
Required Eb/No	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB
Geometry &Atmosphere												
Altitude	450.00	km	450.00	km	450.00	km	450.00	km	450.00	km	450.00	km
Planet Angular Radius	69.08	deg	69.08	deg	69.08	deg	69.08	deg	69.08	deg	69.08	deg
Elevation Angle	10.00	deg	10.00	deg	45.00	deg	45.00	deg	89.99	deg	89.99	deg
Nadir Angle	66.91	deg	66.91	deg	41.34	deg	41.34	deg	0.01	deg	0.01	deg
Planet Central Angle	13.09	deg	13.09	deg	3.66	deg	3.66	deg	0.00	deg	0.00	deg
Propigation Path Length	1570.04	km	1570.04	km	616.68	km	616.68	km	450.00	km	450.00	km
Atmospheric Attenuation at Zenith	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB
Rain Attenuation	0.00	db	0.00	db	0.00	db	0.00	db	0.00	db	0.00	db
Increase in System Noise Temp	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K
Ground(G)/Spacecraft(SC) Transmitter	G		SC		G		SC		G		SC	
Output Power	10.00	W	1.00	W	10.00	W	1.00	W	10.00	W	1.00	W
Output Power	10.00	dB	0.00	dB	10.00	dB	0.00	dB	10.00	dB	0.00	dB
Line Loss	-3.10	dB	-1.00	dB	-3.10	dB	-1.00	dB	-3.10	dB	-1.00	dB
Antenna Efficiency	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%
Antenna Diameter	2.60	m	0.29	m	2.60	m	0.29	m	2.60	m	0.29	m
Peak Antenna Gain	18.95	dB	0.00	dB	18.95	dB	0.00	dB	18.95	dB	0.00	dB
Half-Power Beamwidth	18.42	deg	163.19	deg	18.42	deg	163.19	deg	18.42	deg	163.19	deg
EIRP	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB
Pointing Error	5.00	deg	0.00	deg	5.00	deg	0.00	deg	5.00	deg	0.00	deg
Antenna Pointing Loss	-0.88	dB	0.00	dB	-0.88	dB	0.00	dB	-0.88	dB	0.00	dB
Ground(G)/Spacecraft(SC) Receiver	SC		G		SC		G		SC		G	
Antenna Efficiency	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%
Antenna Diameter	0.29	m	2.60	m	0.29	m	2.60	m	0.29	m	2.60	m
Peak Antenn Gain	0.00	dB	18.95	dB	0.00	dB	18.95	dB	0.00	dB	18.95	dB
Half-Power Beamwidth	163.19	deg	18.42	deg	163.19	deg	18.42	deg	163.19	deg	18.42	deg
Pointing Error	0.00	deg	5.00	deg	0.00	deg	5.00	deg	0.00	deg	5.00	deg
Antenna Pointing Loss	0.00	dB	-0.88	dB	0.00	dB	-0.88	dB	0.00	dB	-0.88	dB
System Noise Temp	688.00	K	260.00	K	688.00	K	260.00	K	688.00	K	260.00	K
G/T	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB
Link Budget												
EIRP	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB
Space Loss	-149.20	dB	-149.20	dB	-141.08	dB	-141.08	dB	-138.34	dB	-138.34	dB
Atmospheric Attenuation	-0.65	dB	-0.65	dB	-0.38	dB	-0.38	dB	-0.36	dB	-0.36	dB
Rain Attenuation	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB
G/T	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB
Antenna Pointing Losses	-0.88	dB	-0.88	dB	-0.88	dB	-0.88	dB	-0.88	dB	-0.88	dB
Eb/No	47.57	dB	40.88	dB	55.94	dB	49.26	dB	58.71	dB	52.02	dB
C/No	75.35	dB	71.67	dB	83.73	dB	80.05	dB	86.49	dB	82.81	dB
Implementation Loss	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB
Margin	**35.97**	dB	**29.28**	dB	**44.34**	dB	**37.66**	dB	**47.11**	dB	**40.42**	dB

Beacon 433MHz Link Budget Alt-600km

							Inputs					
							Numbers Calculated by SMAD or Default					
	UPLINK		DOWNLINK		UPLINK		DOWNLINK		UPLINK		DOWNLINK	
Frequency	0.438	GHZ	0.438	GHZ	0.438	GHZ	0.438	GHZ	0.438	GHZ	0.438	GHZ
Wevelength	6.84E-01	m	6.84E-01	m	6.84E-01	m	6.84E-01	m	6.84E-01	m	6.84E-01	m
Data Rate	0.600	kbps	1.200	kbps	0.600	kbps	1.200	kbps	0.600	kbps	1.200	kbps
Probability of Bit Error	1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-05		1.00E-03	
Required Eb/No	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB	9.60	dB
Geometry &Atmosphere												
Altitude	600.00	km	600.00	km	600.00	km	600.00	km	600.00	km	600.00	km
Planet Angular Radius	66.07	deg	66.07	deg	66.07	deg	66.07	deg	66.07	deg	66.07	deg
Elevation Angle	10.00	deg	10.00	deg	45.00	deg	45.00	deg	89.99	deg	89.99	deg
Nadir Angle	64.18	deg	64.18	deg	40.26	deg	40.26	deg	0.01	deg	0.01	deg
Planet Central Angle	15.82	deg	15.82	deg	4.74	deg	4.74	deg	0.00	deg	0.00	deg
Propigation Path Length	1932.26	km	1932.26	km	814.83	km	814.83	km	600.00	km	600.00	km
Atmospheric Attenuation at Zenith	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB	-0.06	dB
Rain Attenuation	0.00	db	0.00	db	0.00	db	0.00	db	0.00	db	0.00	db
Increase in System Noise Temp	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K	0.00	K
Ground(G)/Spacecraft(SC) Transmitter	G		SC		G		SC		G		SC	
Output Power	10.00	W	1.00	W	10.00	W	1.00	W	10.00	W	1.00	W
Output Power	10.00	dB	0.00	dB	10.00	dB	0.00	dB	10.00	dB	0.00	dB
Line Loss	-3.10	dB	-1.00	dB	-3.10	dB	-1.00	dB	-3.10	dB	-1.00	dB
Antenna Efficiency	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%
Antenna Diameter	2.60	m	0.29	m	2.60	m	0.29	m	2.60	m	0.29	m
Peak Antenna Gain	18.95	dB	0.00	dB	18.95	dB	0.00	dB	18.95	dB	0.00	dB
Half-Power Beamwidth	18.42	deg	163.19	deg	18.42	deg	163.19	deg	18.42	deg	163.19	deg
EIRP	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB
Pointing Error	5.00	deg	0.00	deg	5.00	deg	0.00	deg	5.00	deg	0.00	deg
Antenna Pointing Loss	-0.88	dB	0.00	dB	-0.88	dB	0.00	dB	-0.88	dB	0.00	dB
Ground(G)/Spacecraft(SC) Receiver	SC		G		SC		G		SC		G	
Antenna Efficiency	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%	55.00	%
Antenna Diameter	0.29	m	2.60	m	0.29	m	2.60	m	0.29	m	2.60	m
Peak Antenn Gain	0.00	dB	18.95	dB	0.00	dB	18.95	dB	0.00	dB	18.95	dB
Half-Power Beamwidth	163.19	deg	18.42	deg	163.19	deg	18.42	deg	163.19	deg	18.42	deg
Pointing Error	0.00	deg	5.00	deg	0.00	deg	5.00	deg	0.00	deg	5.00	deg
Antenna Pointing Loss	0.00	dB	-0.88	dB	0.00	dB	-0.88	dB	0.00	dB	-0.88	dB
System Noise Temp	688.00	K	260.00	K	688.00	K	260.00	K	688.00	K	260.00	K
G/T	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB
Link Budget												
EIRP	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB	25.85	dB	-1.00	dB
Space Loss	-151.00	dB	-151.00	dB	-143.50	dB	-143.50	dB	-140.84	dB	-140.84	dB
Atmospheric Attenuation	-0.65	dB	-0.65	dB	-0.38	dB	-0.38	dB	-0.36	dB	-0.36	dB
Rain Attenuation	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB	0.00	dB
G/T	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB	-28.38	dB	-5.20	dB
Antenna Pointing Losses	-0.88	dB	-0.88	dB	-0.88	dB	-0.88	dB	-0.88	dB	-0.88	dB
Eb/No	45.76	dB	39.08	dB	53.52	dB	46.84	dB	56.21	dB	49.52	dB
C/No	73.54	dB	69.87	dB	81.31	dB	77.63	dB	83.99	dB	80.31	dB
Implementation Loss	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB	-2.00	dB
Margin	34.16	dB	27.48	dB	41.92	dB	35.24	dB	44.61	dB	37.92	dB

APPENDIX H: BEACON CARRIER-TO-NOISE BLOCK DIAGRAM



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APPENDIX I: CARRIER-TO-NOISE CALCULATIONS FOR THE BEACON AT 450KM AND 600 KM

Carrier-To-Noise For Beacon (UHF Transceiver) 450 km

Frequency	438	MHz
Speed of Light	299792500	m/s

Altitude	450000	m
Earth Radius	6378115	m
Total Distance	6828115	m

	450 km						
Elevation Angle	10		45		89.99		deg
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	
Angular Radius	69.08	69.08	69.08	69.08	69.08	69.08	deg
Naider Angle	66.91	66.91	41.34	41.34	0.01	0.01	deg
Earth Central Angle	13.09	13.09	3.66	3.66	0.00	0.00	deg
Propigation Path Length	1570038	1570038	616684	616684	450000	450000	m
EIRP	25.85	-1.00	25.85	-1.00	25.85	-1.00	dB
Free Space Loss	-149.20	-149.20	-141.08	-141.08	-138.38	-138.34	dB
Atmospheric Attenuation	-0.65	-0.65	-0.38	-0.38	-0.36	-0.36	dB
Pointing Loss	-0.88	-0.88	-0.88	-0.88	-0.88	-0.88	dB
Gound Antenna Gain	0.00	18.95	0.00	18.95	0.00	18.95	dB
Rx Low Noise Amplifier Gain	0.00	0.00	0.00	0.00	0.00	0.00	dB
C (Received Power)	**-124.88**	**-132.78**	**-116.49**	**-124.39**	**-113.77**	**-121.63**	**dB**
C (Received Power)	**-94.88**	**-102.78**	**-86.49**	**-94.39**	**-83.77**	**-91.63**	**dBm**
System Noise Temp	688.00	260.00	688.00	260.00	688.00	260.00	K
N_0 (Noise Power)	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**dB**
N_0 (Noise Power)	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**dBm**
C/N_0 (Carrier-To-Noise-Density)	**75.34**	**71.67**	**83.73**	**80.06**	**86.45**	**82.82**	**dBm**
Receiver Noise Bandwidth	6.00	6.00	6.00	6.00	6.00	6.00	kHz
N (Noise Power)	**-162.44**	**-166.67**	**-162.44**	**-166.67**	**-162.44**	**-166.67**	**dB/Hz**
N (Noise Power)	**-132.44**	**-136.67**	**-132.44**	**-136.67**	**-132.44**	**-136.67**	**dBm/Hz**
C/N (Carrier-To-Noise)	**37.56**	**33.89**	**45.95**	**42.28**	**48.67**	**45.04**	**dBm/Hz**

Carrier-To-Noise For Beacon (UHF Transceiver) 600 km

Frequency	438	MHz
Speed of Light	299792500	m/s

Altitude	600000	m
Earth Radius	6378115	m
Total Distance	6978115	m

	600 km						
Elevation Angle	10		45		89.99		deg
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	
Angular Radius	66.07	66.07	66.07	66.07	66.07	66.07	deg
Naider Angle	64.18	64.18	40.26	40.26	0.01	0.01	deg
Earth Central Angle	15.82	15.82	4.74	4.74	0.00	0.00	deg
Propigation Path Length	1932255	1932255	814831	814831	600000	600000	m
EIRP	25.85	-1.00	25.85	-1.00	25.82	-1.00	dB
Free Space Loss	-151.00	-151.00	-143.50	-143.50	-140.84	-140.84	dB
Atmospheric Attenuation	-0.65	-0.65	-0.38	-0.38	-0.36	-0.36	dB
Pointing Loss	-0.88	-0.88	-0.88	-0.88	-0.88	-0.88	dB
Receive Antenna Gain	0.00	18.95	0.00	18.95	0.00	18.95	dB
Rx Low Noise Amplifier Gain	0.00	0.00	0.00	0.00	0.00	0.00	dB
C (Received Power)	**-126.68**	**-134.58**	**-118.91**	**-126.81**	**-116.26**	**-124.13**	**dB**
C (Received Power)	**-96.68**	**-104.58**	**-88.91**	**-96.81**	**-86.26**	**-94.13**	**dBm**
System Noise Temp	688.00	260.00	688.00	260.00	688.00	260.00	K
N_o (Noise Power)	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**-200.22**	**-204.45**	**dB**
N_o (Noise Power)	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**-170.22**	**-174.45**	**dBm**
C/N_o (Carrier-To-Noise-Density)	**73.54**	**69.87**	**81.31**	**77.64**	**83.96**	**80.32**	**dBm**
Receiver Noise Bandwidth	6.00	6.00	6.00	6.00	6.00	6.00	kHz
N (Noise Power)	**-162.44**	**-166.67**	**-162.44**	**-166.67**	**-162.44**	**-166.67**	**dB/Hz**
N (Noise Power)	**-132.44**	**-136.67**	**-132.44**	**-136.67**	**-132.44**	**-136.67**	**dBm/Hz**
C/N (Carrier-To-Noise)	**35.76**	**32.09**	**43.53**	**39.86**	**46.18**	**42.54**	**dBm/Hz**

APPENDIX J: MATLAB CODE FOR VSWR AND ANTENNA GAIN PATTERN

```
%VSWR for CubeSat With Patch Antenna and Beacon Antenna
load -ascii 'fd1.txt';
f=linspace(2.4e9,2.5e9,401);
figure(1);
plot(f,fd1(:,1))
title('PA28-2450-120SA Patch Antenna With Beacon Antenna','Fontsize',13);
xlabel('Frequency (GHz)', 'Fontsize', 10);
ylabel('Voltage Standing Wave Ration (VSWR)', 'Fontsize', 10);
grid on

%VSWR for CubeSat With Patch Antenna and Without Beacon Antenna
load -ascii 'fd2.txt';
figure(2)
plot(f,fd2(:,1))
title('PA28-2450-120SA Patch Antenna Without Beacon Antenna','Fontsize',13);
xlabel('Frequency (GHz)', 'Fontsize', 10);
ylabel('Voltage Standing Wave Ration (VSWR)', 'Fontsize', 10);
grid on

% Load Data and set up Matrices
 M=csvread('Adjusted_Plot_Data.csv', 1, 0);
 a=M(1:181,1:2);
 b=M(:,4:5);
 c=M(:,7:8);
 d=M(:,10:11);
 e=M(:,13:14);

%Reference Gain Antenna Pattern
figure(3);
polardb(a(:,1),a(:,2),'r')
title('Reference Gain Patter','Fontsize',13);

%CubeSat Patch Antenna Gain Without Beacon Antenna
figure(4);
polardb(b(:,1),b(:,2)+(17.25-(0.16443630-(-15.55811000))-(-15.55811000)),'r')
title('CubeSat Patch Antenna Gain Without Beacon Antenna','Fontsize',13);

%CubeSat Rotated Patch Antenna Gain Without Beacon Antenna
%c=[];
figure(5);
polardb(c(:,1),c(:,2)+(17.25-(0.16443630-(-13.68799))-(-13.68799)),'r')
title('CubeSat Rotated Patch Antenna Gain Without Beacon
Antenna','Fontsize',13);

%CubeSat Patch Antenna Gain With Beacon Antenna
figure(6);
polardb(d(:,1),d(:,2)+(17.25-(0.16443630-(-15.07324))-(-15.07324)),'r')
title('CubeSat Patch Antenna Gain With Beacon Antenna','Fontsize',13);

%CubeSat Rotated Patch Antenna Gain With Beacon Antenna
figure(7);
polardb(e(:,1),e(:,2)+(17.25-(0.16443630-(-13.21191))-(-13.21191)),'r')
title('CubeSat Rotated Patch Antenna Gain With Beacon
Antenna','Fontsize',13);
```

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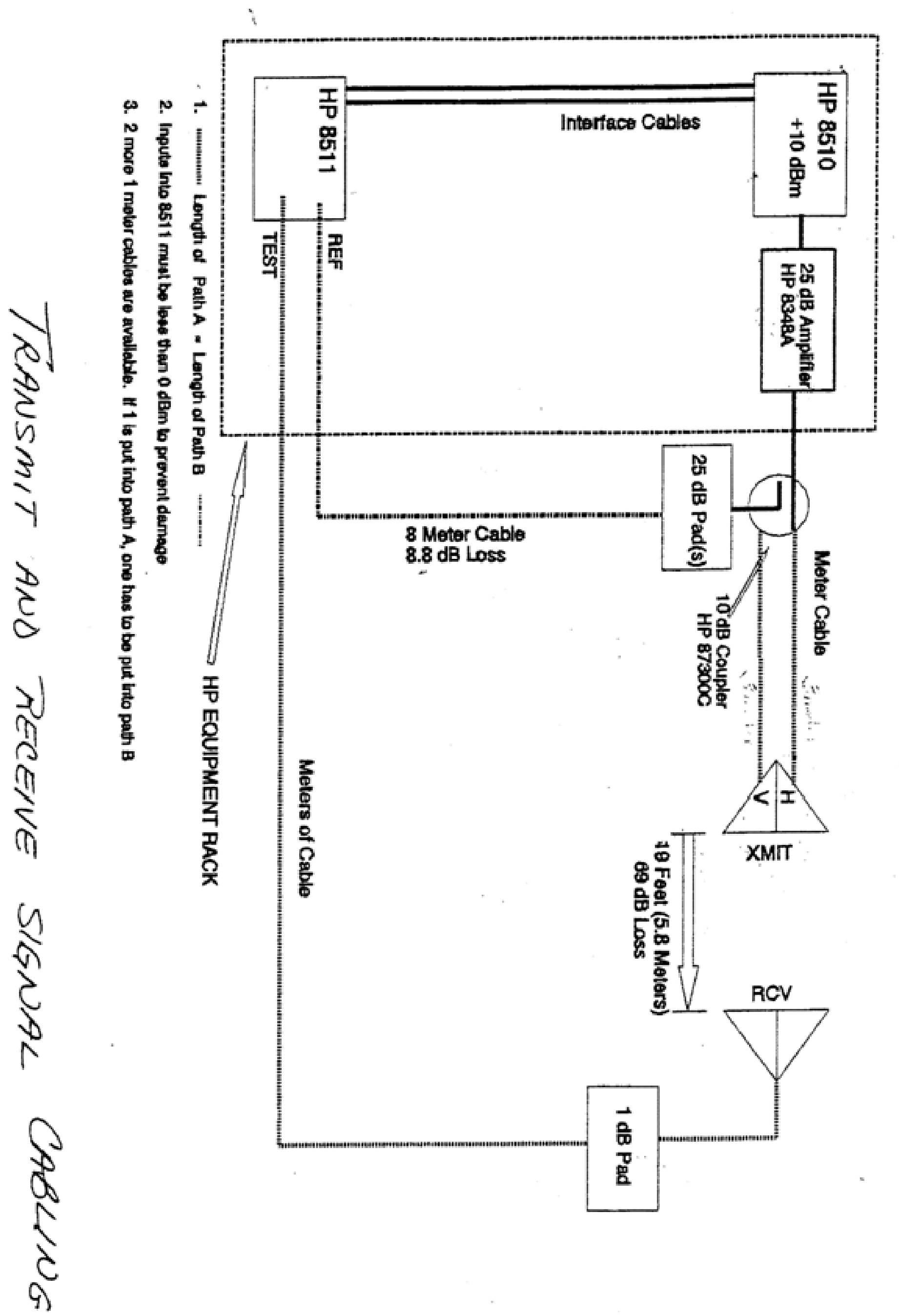
APPENDIX K: NPS’ ANECHOIC CHAMBER SCHEMATIC (FROM [7])



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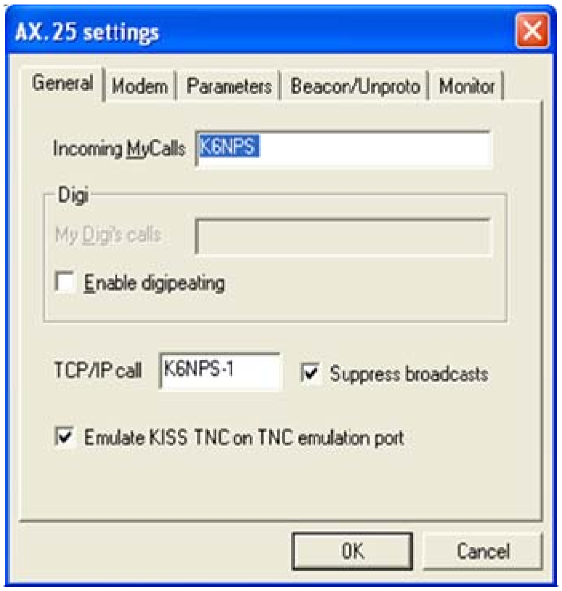
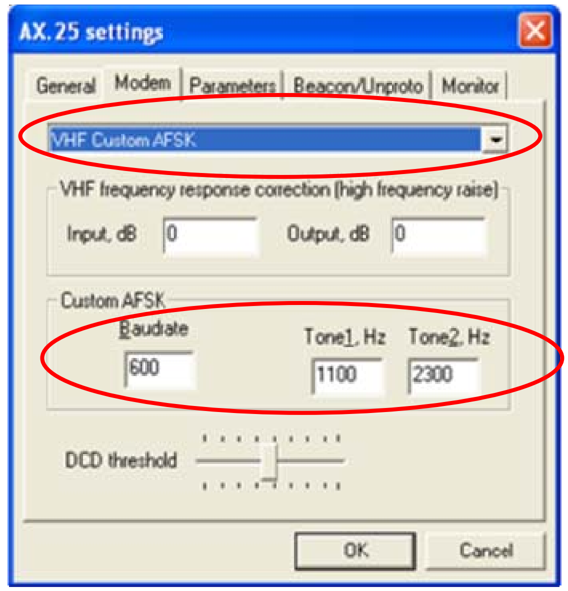
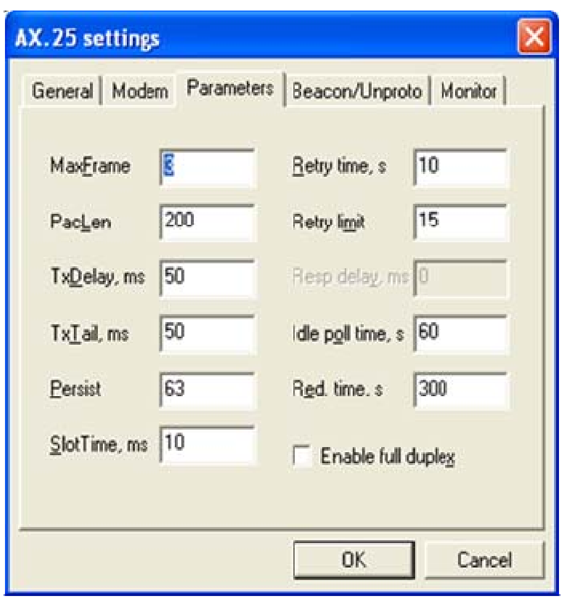
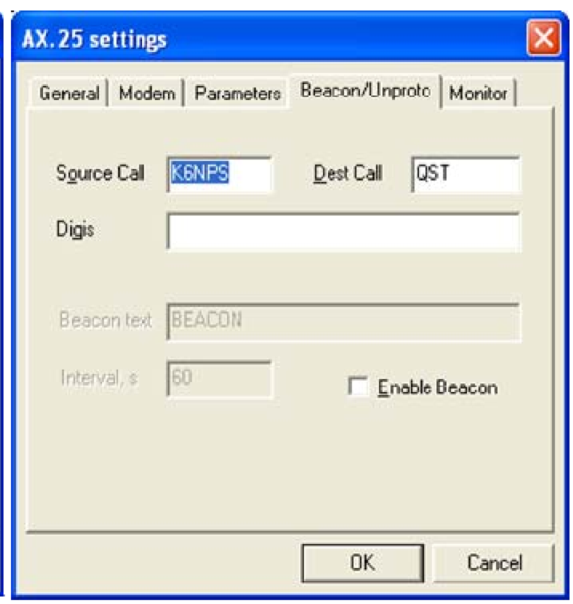
APPENDIX L: BEACON GROUND STATION MIXW TRANSMIT SETTINGS

Mode=> Mode Setting=>

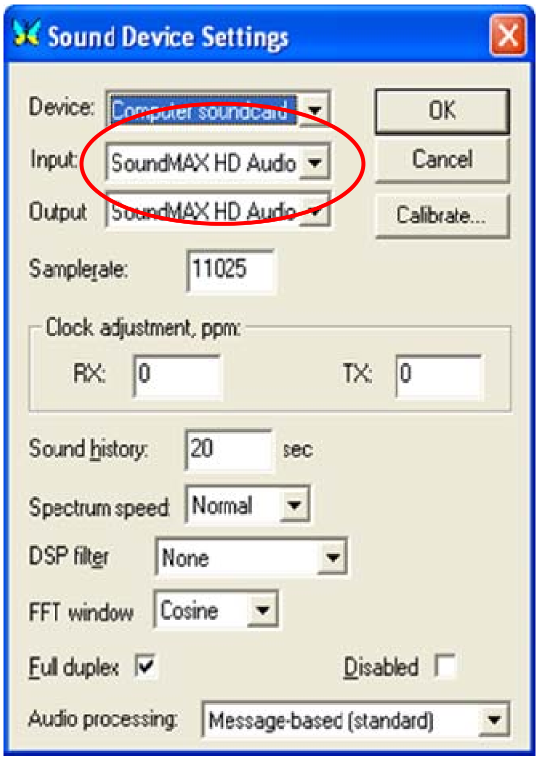




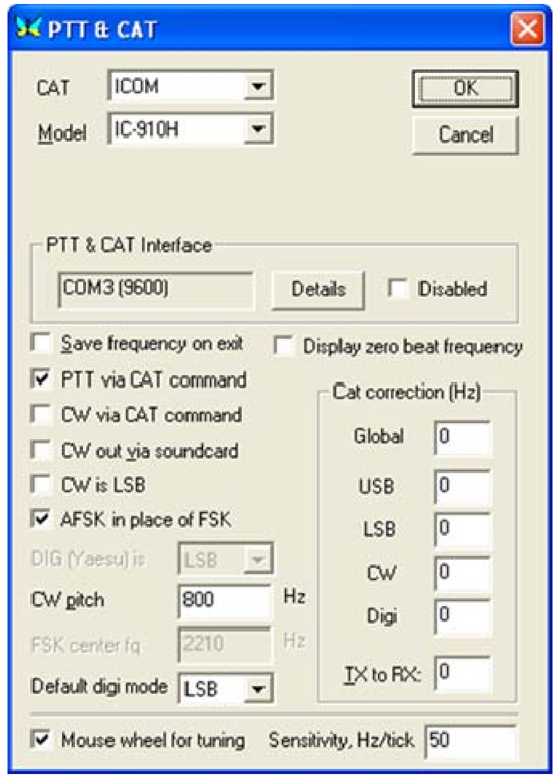




Configure=>Sound Device Settings

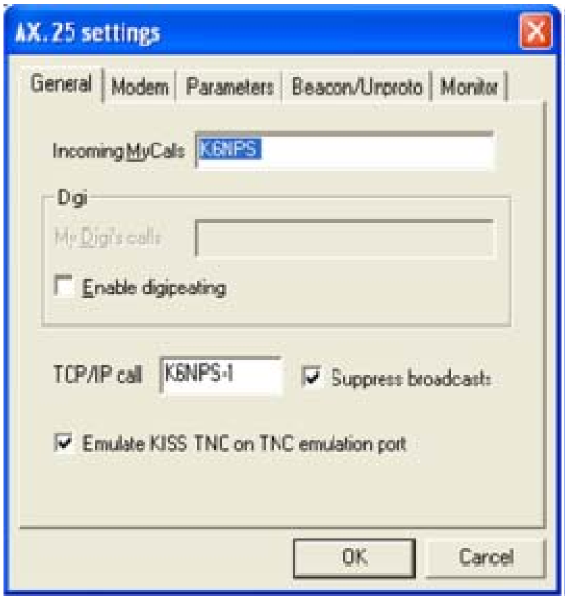


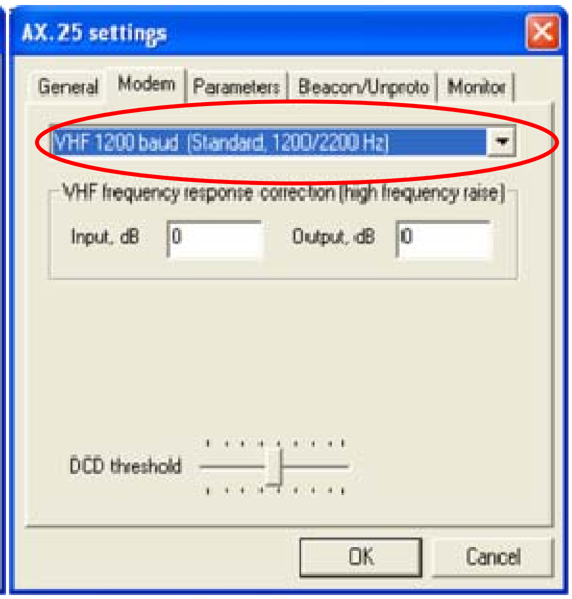
Configure=>TRCVR CAT/PTT

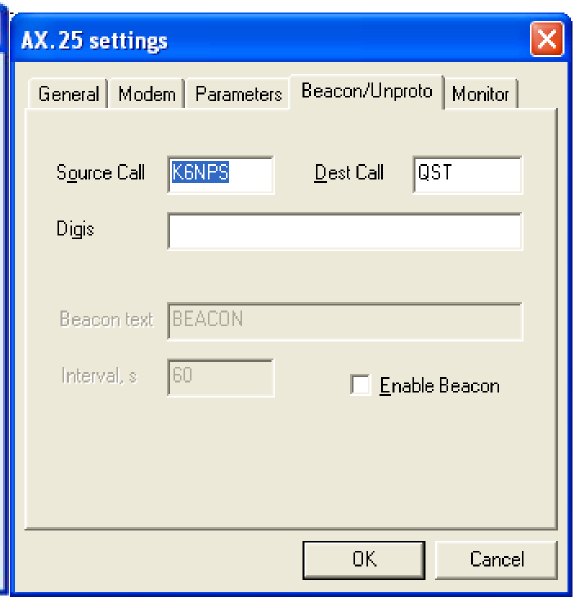


APPENDIX M: BEACON GROUND STATION MIXW RECEIVE SETTINGS

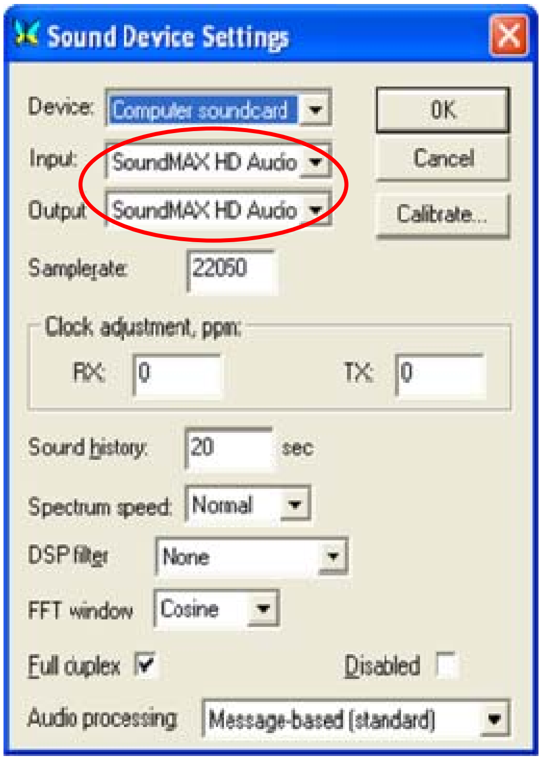
Mode=> Mode Setting=>



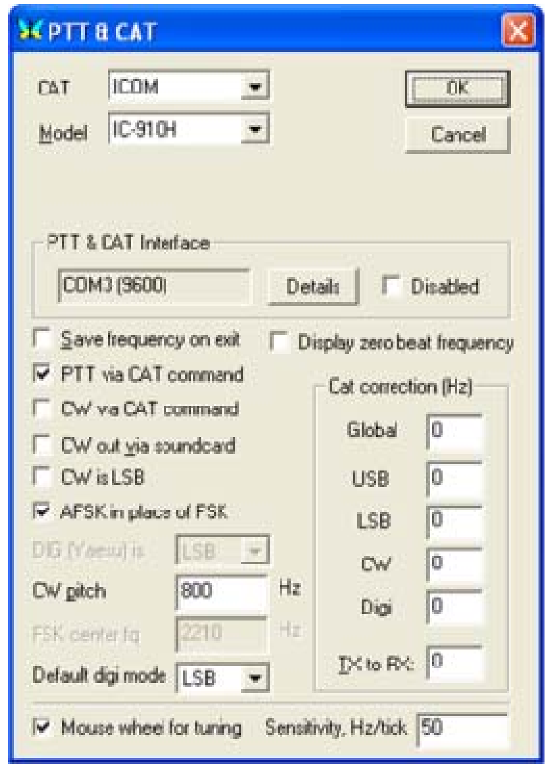




Configure=>Sound Device Settings



Configure=>TRCVR CAT/PTT



APPENDIX N: AMATEUR SATELLITE FREQUENCY COORDINATION REQUEST

The International Amateur Radio Union

Since 1925, the Federation of National Amateur Radio Societies
Representing the Interests of Two-Way Amateur Radio Communication

AMATEUR SATELLITE FREQUENCY COORDINATION REQUEST

(Make a separate request for each space station to be operated in the amateur-satellite service.)

Administrative information:

1	**SPACECRAFT (published)**	
1a	Name before launch	NPS-SCAT
1b	Proposed name after launch	NPS-SCAT
1c	Country of license	USA
2	**LICENSEE OF THE SPACE STATION (published)**	
2a	First (given) name	Todd
2b	Last (family) name	Weatherford
2c	Call sign	K6NPS
2d	Postal address	NPS Code EC/WT Bldg 232 Room 424 Monterey, CA 93943
2e	Telephone number (including country code)	1-831-656-3044 1-831-656-7539(Alt)
2f	E-mail address	trweathe@nps.edu
2g	Licensee's position in any organization referenced in item 3a.	Associate Prof of Electrical & Computer Engineering
2h	List e-mail addresses of those who should receive copies of correspondence.	drigmaiden@nps.edu (David Rigmaiden) jhnewman@nps.edu (James Newman)
3	**ORGANISATIONS (published) — complete this section for EACH participating organization**	
3a	Name of organization	Naval Postgraduate School (NPS) Small Satellite Lab, Space Systems Academic Group
3b	Physical address	Naval Postgraduate School
3c	Postal address	777 Dyer Rd, Room 200 Monterey CA 93940
3d	Telephone number (including country code)	1-831-656-7539
3e	E-mail address	drigmaiden@nps.edu; alternate jhnewman@nps.edu
3f	Web site URL	
3g	National Amateur Radio Society (including contact information)	American Radio Relay League 225 Main Street Newington, CT 06111-1494 +1(860)594-0200
3h	National Amateur Satellite organization (including contact information)	AMSAT-NA 850 Sligo Ave. Suite 600 Silver Spring, MD 20910 +1(301)589-6062

3i	Have you involved your National Amateur Satellite organization and/or National Amateur Radio Society? Please, explain.	Yes, exchanged emails with Arthur Feller (W4ART). Email: afeller@ieee.org

Space station information:

4	**SPACE STATION (published)**	
4a	Mission(s). *Describe in detail what the space station is planned to do. Use as much space as you need.*	The primary mission for NPS's Solar Cell Array Tester (NPS-SCAT) CubeSat is to test solar cells. The CubeSat will use a sun sensor to collect data for solar cell characterization.
4b	Planned duration of each part of the mission.	The expected mission life of NPS-SCAT is 12 months. After completion of mission, the satellite can continued to be used for Amateur satellite tracking through satellite beacon operations.
4c	Proposed transmitting frequency plan. *List each frequency or frequency band (e.g. 435-438 MHz) with output power, ITU emission designator,[1,2] and associated antenna gain and pattern.*	The NPS-SCAT CubeSat will contain two half duplex amateur radio systems, an MHX 2400 (S-Band, 2.4 GHz) and a UHF Transceiver (UHF, 435 MHz). MHX 2400: The primary system consists of a frequency-hopping spread spectrum transmitter operating between 2.4012 and 2.4476 GHz. The transmitter on the CubeSat will operate with an emission type of 350KF1D and output EIRP of 0dBW or less. This transmitter will be used for the primary space telemetry for the satellite and will be available to other amateur users on a limited basis. Antenna gain and pattern based upon hemispherical patch antenna. UHF Transceiver: The secondary system consists of a UHF transmitter operating between 435 and 438 MHz. The transmitter will operate with an emission type of 5K0D1D and output EIRP of 0dBW or less. This transmitter will be used for backup space telemetry for the satellite and will provide a limited telemetry beacon for all amateur radio users. Antenna pattern based and gain based upon standard ½ wave dipole. Antenna gain and patterns can be located at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
4d	Proposed receiving frequency plan. *List each frequency or*	The NPS-SCAT CubeSat will contain two half duplex amateur radio systems, an MHX 2400 (S-Band, 2.4

[1] ITU admission designators are explained at: http://life.itu.int/radioclub/rr/ap01.htm. (Thank you, 4U1ITU.) Effect of Doppler shift is NOT included when determining bandwidth.

[2] If using a frequency changing transponder, indicate the transmitting bandwidth. Effect of Doppler shift is NOT included when determining bandwidth.

	frequency band with output power, ITU emission designator,[3,4] noise temperature, and associated antenna gain and pattern.	GHz) and a UHF Transceiver (UHF, 435 MHz). MHX 2400: The primary system consists of a frequency-hopping spread spectrum receiver operating between 2.4012 and 2.4476 GHz. The receiver on the CubeSat will operate with an emission type of 350KF1D and output EIRP of 0dBW or less. This receiver will be used for the primary space telecommand for the satellite and will be available to other amateur users on a limited basis. Antenna gain and pattern based upon hemispherical patch antenna. UHF Transceiver: The secondary system consists of a UHF receiver operating between 435 and 438 MHz. The receiver will operate with an emission type of 5K0D1D and output EIRP of 0dBW or less. This receiver will be used for backup space telecommand for the satellite and will provide a limited telemetry beacon for all amateur radio users. Antenna pattern based and gain based upon standard ½ wave dipole. Antenna gain and patterns can be located at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
4e	Physical structure. *General description, including dimensions, mass, antennas and antenna placement, etc. Give URL's for drawings.*	This is a standard 10cm CubeSat. Total mass less than 1.33 kg. A patch antenna will used for the MHX 2400. The UHF transceiver has a deployable antenna. The drawings of the physical structure can be found at http://sp.nps.edu/NPS-SCAT/
4f	Functional Description. *Describe each sections function within the satellite.*	Command and Data Handling S/S: This system, using a microcontroller (Pumpkin CubeSat Kit FM430), controls the flow of information from the onboard sensors and collects information for later transmission. Additional information about the C&DH can be found at: http://sp.nps.edu/NPS-SCAT/subsystems/cdh/cdh.html COMMs S/S: The information collected by the microcontroller will be transmitted to ground via the MHX 2400 or the UHF transmitter. Both communication systems consist of a processor, transceiver, and RF amplifier. Additional information about the Comms S/S can be found at: http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html Power S/S: The satellite uses the Clyde Space 1U EPS to provide power to the remaining subsystems.

[3] ITU admission designators are explained at: http://life.itu.int/radioclub/rr/ap01.htm. (Thank you, 4U1ITU.) Effect of Doppler shift is NOT included when determining bandwidth.

[4] If using a frequency changing transponder, indicate the receiving bandwidth. Effect of Doppler shift is NOT included when determining bandwidth.

		To recharge the onboard battery, there are solar panels used to generate power when the satellite is in the sun. Additional information about the Power S/S can be found at: http://sp.nps.edu/NPS-SCAT/subsystems/eps/eps.html The payload of the NPS-SCAT satellite is the Solar Cell Measurement System (SMS) which utilizes a circuit board, a sun sensor, and temperature sensors to gather the characteristics of a solar cell.Additional information about the SMS can be found at: http://sp.nps.edu/NPS-SCAT/subsystems/sms/sms.html
4g	Power budget. *Describe each power source, power consuming section, power storage, and overall power budget.*	NPS-SCAT uses the Clyde Space Electrical Power System (EPS) PCB and battery board (two Lithium Polymer batteries). There are two ITJ solar cells on 3 faces, and eight UTJ TASC cells on the 2 faces. Power production averages 1.45 W over and entire orbit. The complete power budget is located at http://sp.nps.edu/NPS-SCAT/subsystems/eps/eps.html
5	**TELECOMMAND (NOT published)**	
5a	Telecommand frequency plan. *Provide telecommand frequencies or frequency bands, ITU emission designator(s), link power budget(s), and a general description of any cipher system, etc.*	The NPS-SCAT CubeSat will contain two half duplex amateur radio systems, an MHX 2400 (S-Band, 2.4 GHz) and a UHF Transceiver (UHF, 435 MHz). MHX 2400. The primary system consists of a frequency-hopping spread spectrum receiver operating between 2.4012 and 2.4476 GHz. The receiver on the CubeSat will operate with an emission type of 350KF1D and output EIRP of 0dBW or less. This receiver will be used for the primary space telecommand for the satellite and will be available to other amateur users on a limited basis. Antenna gain and pattern based upon hemispherical patch antenna. UHF Transceiver: The secondary system consists of a UHF receiver operating between 435 and 438 MHz. The receiver will operate with an emission type of 5K0D1D and output EIRP of 0dBW or less. This receiver will be used for backup space telecommand for the satellite and will provide a limited telemetry beacon for all amateur radio users. Antenna pattern based and gain based upon standard ½ wave dipole. Cipher System: Only high level UHF transceiver spacecraft control commands will be encrypted. Other UHF transceiver commands will be accessible to all amateurs. The link budgets for both the MHX 2400 and the beacon are located at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
5b	Positive transmitter control. *Explain how telecommand stations*	There is a single command to turn off the UHF Transceiver and the MHX 2400. The command to

	can turn off the space station transmitter(s) immediately, even in the presence of user traffic and/or main computer system failure. Be sure to read the paper available at: http://www.iaru.org/satellite/sat-freq-cocrd.html.	shut off the UHF Transmitter can be sent from any ground station. The command to shut off the MHX 2400 can be sent from ground stations using the MHX 2400 for CubeSats. If the space craft has not communicated with a ground station within 48 hours, the periodic beacon signal will automatically shut off until it is queried from the ground. This will be an interrupt programmed in the microcontroller. Also, the power budget will not allow for the UHF Transceiver to continuously transmit for a complete 2 hours.
5c	Telecommand stations. *List telecommand stations, including contact details, which will be established before launch, to meet the requirement for immediately turning off the space station transmitter.* Be sure to read: RR 22.1 and RR 25.11. Text is included in the paper available at http://www.iaru.org/satellite/sat-freq-cocrd.html.	Current coordination is ongoing with other sites to ensure redundant capability to turn off the UHF Transceiver and/or MHX 2400. A program is being generated that can be posted to our website if either radio needs to be shut off. The program will allow any ground station to turn off the UHF Transceiver or MHX 2400 as long as they are compatible with the UHF Transceiver and/or MHX 2400. The UHF ground station at NPS consists of an M2 Inc 436CP42 Ultra Gain Circular Polarized Yagi antenna and controlling computer system. The ground station is currently tracking and communicating with Cal Poly CubeSats and will be tested with NPS-SCAT before launch. The MHX 2400 transmitter ground station consists of a 3.4 meter dish, a low noise amplifier, a MHX 2400 transmitter and a windows based controlling computer system. The ground station will be end-to-end tested with the NPS-SCAT before launch. There is a single command to turn off the UHF Transceiver and the MHX 2400. The command to shut off the UHF Transmitter can be sent from any ground station. The command to shut off the MHX 2400 can be sent from ground stations using the MHX 2400 for CubeSats. If the space craft has not communicated with a ground station within 48 hours, the periodic beacon signal will automatically shut off until it is queried from the ground. This will be an interrupt programmed in the microcontroller. Also, the power budget will not allow for the UHF Transceiver to continuously transmit for a complete 2 hours. Contact info for the command station: David Rigmaiden 831-656-7539 832-656-7522(Alt) drigmaiden@nps.edu
6	**Telemetry (published)**	
6a	Telemetry frequencies *List all telemetry frequencies or frequency bands, ITU emission designators, and link budgets.*	The NPS-SCAT CubeSat will contain two half duplex amateur radio systems, an MHX 2400 (S-Band, 2.4 GHz) and a UHF Transceiver (UHF, 435 MHz).

	Give the URL with telemetry decoding information.	MHX 2400: The primary system consists of a frequency-hopping spread spectrum transmitter operating between 2.4012 and 2.4476 GHz. The transmitter on the CubeSat will operate with an emission type of 350KF1D and output EIRP of 0dBW or less. This transmitter will be used for the primary space telemetry for the satellite and will be available to other amateur users on a limited basis. Antenna gain and pattern based upon hemispherical patch antenna. UHF Transceiver: The secondary system consists of a UHF transmitter operating between 435 and 438 MHz. The transmitter will operate with an emission type of 5K0D1D and output EIRP of 0dBW or less. This transmitter will be used for backup space telemetry for the satellite and will provide a limited telemetry beacon for all amateur radio users. Antenna pattern based and gain based upon standard ½ wave dipole. The link budgets for both the MHX 2400 and the beacon are located at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
6b	Telemetry formats and equations *Describe telemetry format(s), including telemetry equations. NOTE: Final equations must be published as soon as available.*	Two versions of telemetry have been identified: primary telemetry and secondary telemetry. Primary telemetry will include all measurements by the Solar Measurement System and comprehensive system health. Secondary telemetry will include an abbreviated measurements by the Solar Measurement System and instantaneous system health measurements. Telemetry equations can be found in Matt Schroer's thesis (Pg 24-31) located at http://sp.nps.edu/NPS-SCAT/technical/technical.html
6c	Is the telemetry transmission format commonly used by radio amateurs? If not, describe how and where it will be published. Be sure to read: RR 25.2A. Text is included in the paper available at: http://www.iaru.org/satellite/sat-freq-coord.html.	Yes, the telemetry decommutation format can be found at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
7	**Launch plans (published)**	
7a	Planned launch date	No earlier than April 2010
7b	Launch agency	Operationally Responsive Space (ORS) / Space Test Program (STP)
7c	Launch location	Kwajalein Atoll, Marshall Islands
7d	Planned orbit. *Include planned orbit apogee, perigee, inclination, and period.*	Estimated Orbit Min: Apogee: 450 km, Perigee: 450 km, Inclination: 45 deg., Period: 94.7 min Max: Apogee: 600 km, Perigee: 600 km, Inclination: 45 deg., Period: 97.8 min
7e	List other amateur satellites	Expected:

	expected to share the same launch.	University of Southern California Utah State University Aerospace Corporation University of Florida Space and Missile Defense Command United States Naval Academy Air Force Research Lab

Earth station information:

8	**Typical Earth station — transmitting**	
8a	Describe a typical Earth station used to transmit signals to the planned space station.	The UHF transmitter ground station at NPS consists of an M2 Inc 436CP42 Ultra Gain Circular Polarized Yagi antenna with rotator, an ICOM VHF/UHF all mode transceiver IC-910H and a windows based controlling computer system. The MHX 2400 transmitter ground station consists of a 3.4 meter dish, a low noise amplifier, a MHX 2400 transmitter and a windows based controlling computer system. A more in depth description of the transmitter ground station can be found at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
8b	Link budget. *Show complete link budgets for all Earth station transmitting channels, except telecommand.*	A complete link budget (including transmitting) can be found at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
9	**Typical Earth station — receiving**	
9a	Describe a typical Earth station to receive signals from the planned satellite.	The UHF receiver ground station at NPS consists of an M2 Inc 436CP42 Ultra Gain Circular Polarized Yagi antenna with rotator, an ICOM VHF/UHF all mode transceiver IC-910H and a windows based controlling computer system. The MHX 2400 receiver ground station consists of a 3.4 meter dish, an MHX 2400 transmitter and a windows based controlling computer system. A more in depth description of the receiver ground station can be found at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html
9b	Link budget. *Show complete link budgets for all Earth station receiving channels.*	A complete link budget (including receiving) can be found at http://sp.nps.edu/NPS-SCAT/subsystems/comms/comms.html

Additional information:

Do not attach large files. Indicate the URL where the information is available.

10	Please, supply any additional information that may assist the Satellite Advisor to coordinate your request(s). We have a launch opportunity in April 2011. The CubeSat must be delivered around the beginning of February, 2011.

Certification:

11	[X] The licensee of the planned space station has reviewed all relevant laws, rules, and regulations, and certifies that this request complies with all requirements to the best of his/her knowledge.
	[ ] The licensee of the planned space station has reviewed all relevant laws, rules, and regulations and disagrees with IARU interpretations of Treaty requirements. The IARU Satellite Advisor is asked to consider the following interpretation. Explanation follows.

* Please tick appropriate box.

Signature:

12	[signature]	5-26-2010
	Signature of space station licensee.	Date submitted for coordination.

Rev. 1.7 Nov 2009

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