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Satellite TT&C for Cubesats with Applications for Grissom-1

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SATELLITE TT&C FOR CUBESATS-WITH APPLICATIONS FOR GRISSOM-1

THESIS

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AFIT-ENY-MS-22-M-280

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THESIS

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Abstract

The Grissom-1 mission (GM1), slated to launch in 2023, is the first in a series of 6-Unit CubeSat satellites built and operated by the Air Force Institute of Technology's (AFIT's) Center for Space Research and Assurance (CSRA). The GM1 is unique in that it represents the pathfinder for a standardized 6U bus that may be replicated for future missions to host a variety of technical and scientific payloads, as prioritized by the Department of Defense (DoD), requiring flight demonstration or access to the orbital environment. Mission success for GM1 depends on a comprehensive campaign of testing and assessment to confirm the components, design, and assembly of all systems and subsystems within the satellite. This thesis specifically focuses on the testing and analysis of all communication links between the spacecraft, the ground system, and the Satellite Operations Center (SOC). Specific to the GM1, analysis is performed on the spacecraft's Cadet software-defined radio (SDR) and its communication capabilities with the Mobile CubeSat Command and Control (MC3) network, the NI USRP-2292 ground station SDR, and COSMOS Command and Control (C2) software. Testing and assessment occurred in both lab settings and simulated operational scenarios.

This thesis includes characterization of individual components, anechoic chamber downlink and uplink signal measurement results, and link margin calculations. Experimental data describing the results of each test, including operational tests from various locations around Wright-Patterson Air Force Base (WPAFB) using the local instance of an MC3 ground station, are also included. The research culminates in a full characterization of the Cadet SDR, an analysis of the GM1 to MC3 communication interaction, and any limitations revealed as attributable to the 6U spacecraft.

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SATELLITE TT&C FOR CUBESATS-WITH APPLICATIONS FOR GRISSOM-1

I. Introduction

The Grissom-1 Mission (GM1), slated to launch in September 2023, is the first in a series of 6-Unit CubeSat satellites built and operated by the Air Force Institute of Technology (AFIT) Center for Space Research and Assurance (CSRA). The GM1 mission is a technical demonstration of AFIT's 6-unit CubeSat Grissom series bus. With additional mission planned in the future, the success of this mission will lead the groundwork for future missions to come. This document will cover the extensive preparation and execution of testing and analysis of the primary command and telemetry communication links between the spacecraft, the ground system, and the Satellite Operations Center (SOC).

1.1 Overview

When designing and testing a CubeSat, there are several systems that must be incorporated to have a fully functioning space vehicle. These systems are not only standard for a CubeSat, but required for any satellite that has the intention of transmitting, receiving, and collecting data.

This effort begins by defining the entire uplink and downlink communication system supporting the GM1 mission, from the Command and Control (C2) station to the Software Defined Radio (SDR) on board GM1 CubeSat. The specific subsystem of interest in this communications architecture is the Tracking, Telemetry, and Command (TT&C) capability of the GM1.

For purposes of uplinking commands to the space vehicle, the AFIT SOC will be using a C2 software developed by Ball Aerospace called COSMOS [1]. COSMOS is a suite of applications that can be used to control a set of embedded systems and will be used by the GM1 to control a ground station SDR located on the Mobile CubeSat Command and Control (MC3) Network as developed and managed by the Naval Postgraduate School (NPS) [2].

The MC3 Network is a group of ground stations connected together through a virtual private network to allow for authorized users to contact their CubeSats and maintain their missions. Each MC3 node utilizes identical equipment to create a standard communication process and protocol at each location. For all planned communications, the AFIT C2 station will be required to schedule each contact with a CubeSat using the MC3 Network. In order for the AFIT CSRA to gain access to the ground stations, they must schedule the passes through a program called Satellite Agile Transmit Receive Network (SATRN).

SATRN is modular software that runs on the MC3 network. It provides an interface for bent-pipe communication between the User's Satellite Operations Center (SOC) and the User's spacecraft. A space craft operator interacts with SATRN primarily through a web-based client deployed at the SOC. This scheduling software will allow access to all available MC3 ground stations. One of the major benefits of using the MC3 network in collaboration with SATRN scheduling and control software is the access GM1 has to multiple ground contact locations utilizing standardized hardware and contact protocols without having to rely on a single station at Wright-Patterson Air Force Base (WPAFB).

When the AFIT C2 team receives authorization to utilize a ground station, the C2 software, COSMOS, will feed commands to a National Instruments USRP-2922 SDR [3] located at the appropriate MC3 ground stations. The USRP-2922 can be programmed to transmit and receive signals on frequencies ranging from 400 MHz to 4.4GHz, making it a highly useful SDR for conducting space operations. The output of the USRP-2922 connects to the high gain Yagi antenna and is programmed to track any CubeSat to make a contact. During a contact, the SDR will transmit commands required to maintain and operate the CubeSat. Specific to GM1, the on-board Cadet Plus SDR will be receiving all UHF transmissions from the ground station.

The Cadet Plus radio [4] is a split band, full duplex, store and forward radio. The radio is equipped with dual Advanced RISC Machines (ARM) processors (Master and Slave) and separate spacecraft UHF and S-band adapters for antenna connections to support simultaneous reception and transmission for full duplex RF data communications between Cadet and the MC3 Station. The Cadet Plus radio is our primary SDR of interest and will be involved with majority of testing involving the communication subsystem.

Defining the downlink from the GM1 CubeSat to the MC3 Ground Station, the Cadet Plus will transmit from an S-Band patch antenna its telemetry and state of health. This is done simultaneously with the uplink connection from the AFIT C2 team. The recieved signal is then passed to the USRP-2922 for demodulation and recovery of the data, which is then sent to the C2 station. The information at the C2 station will be used for mission operations such as tracking the GM1's health and also used to plan future communication ground passes.

All components in the uplink and downlink communication link must be working in order to contact the GM1 CubeSat. Detailed testing and evaluation will be required in order to ensure the communication link will be successful after launch.

1.2 Research Motivation

The GM1 is a proof of concept mission to show that AFIT is capable of successfully building and operating a satellite for research missions. The current configuration of the GM1 CubeSat is capable of communication at a Low Earth Orbit (LEO) altitude, but has not been tested or built for orbits at a higher altitude. The primary objective of this thesis research will test and solve the communication limits of the GM1 CubeSat bus operating on the MC3 Network. Additionally, what modifications can be made at the MC3 WPAFB ground station to extend the limitations of the GM1 CubeSat. The analysis will start by proving the current mission's communication link can be met, then solving the current maximum communication link utilizing the established bit rate, uplink and downlink frequencies, GM1 hardware, and MC3 Network configuration. The final analysis will be modifications that can be taken to support a geosynchronous and Lunar orbit. These modifications will utilize changing the bit rates and MC3 hardware.

1.3 Research Objective

Overall, the overarching objective of this research is to characterize the performance of the GM1 CubeSat communication subsystem and its performance on the MC3 Network. This will be met by meeting four sub-objectives. The first sub-objective will involve testing and characterizing the on board SDR, uplink and downlink antennas in the GM1 baseline configuration. The second sub-objective is characterization of the MC3 Network SDR, uplink and downlink antennas, and all loss factors associated with satellite communications. The third sub-objective is to use the measured and calculated values for the communication links of the GM1 configuration and assess the simulated performance of the GM1 spacecraft at geosynchronous and Lunar distances. These simulations will account for all modifications to the MC3

Network how these solutions were developed and how they ensure the link margin is closed. Finally, the fourth sub-objective will determine the maximum data transfer at each simulated orbit. The data rate will be determined based off the bit rate used to close the link margin.

1.4 Thesis Overview

This thesis follows a five-chapter format. Chapter I provides detailed research motivation and objectives defining the scope of what will be modeled for the GM1 mission. Chapter II presents the background information related to the testing and studying relevant to build a basic understanding of the testing and analysis conducted in this thesis. The information required for this thesis focuses around space system communication and trade offs required to increase communication distances. Chapter III describes the methodology used in developing the experimental set up to derive and prove the expected values for GM1 regarding antenna gain are accurate. Using information obtained from the testing GM1 will be discussed in results section. Chapter IV describes the results and meaning from the experimental set up, and applies the values to model the communication link between GM1 and MC3 Network. Results will go into depth and discuss the trade offs of increasing the communication distance of GM1. Chapter V presents research conclusions and discusses recommendations for future work and mission capabilities for GM1.

II. Background

To preform and comprehend in depth testing of the GM1 SDR Cadet PLUS, multiple concepts of Electromagnetic (EM) waves and telecommunications must be understood. Once a body of knowledge is understood, calculations from testing can be used to determine the Radio Frequency (RF) Link Budget. Figure 1 describes the problem that must be solved to communicate with a satellite. As there are no communication cables that runs from a satellite back to earth, all communication must be through the transmission of RF. This chapter will start with the basics of the RF Link Budget and build on to the existing infrastructure and components that will be used to complete GM1.

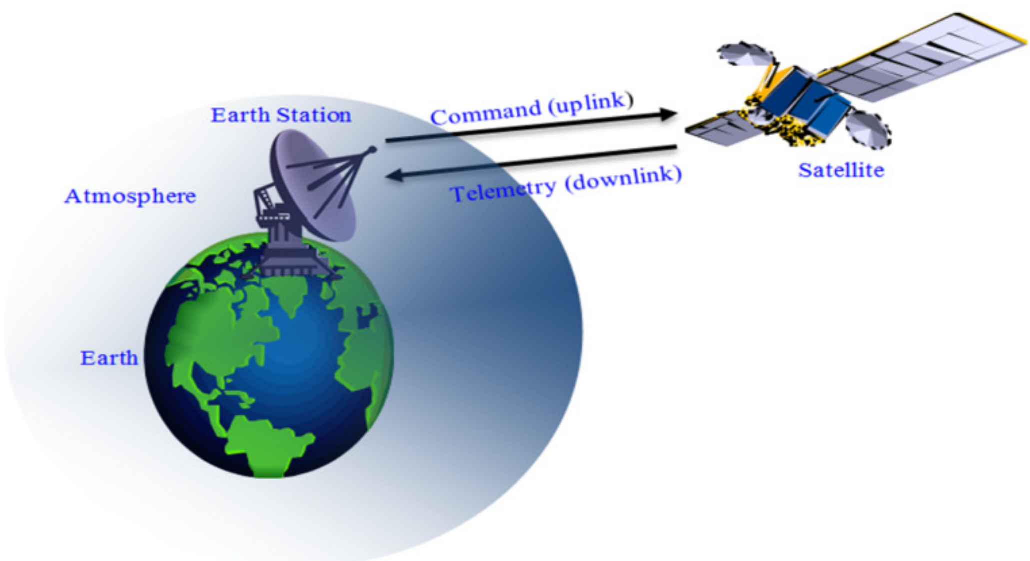

Figure 1: RF Communication Link [5]

2.1 RF Link Budget

When a satellite passes over a ground station, there must be a sufficient Signal to Noise Ratio (SNR) at the receiver transmit signals to and from the satellite. Using a link budget equation an analysis can be done to calculate all the gains and losses to ensure there is sufficient SNR. This can be described mathematically by Equation 1, and graphically by Figure 2 [6].

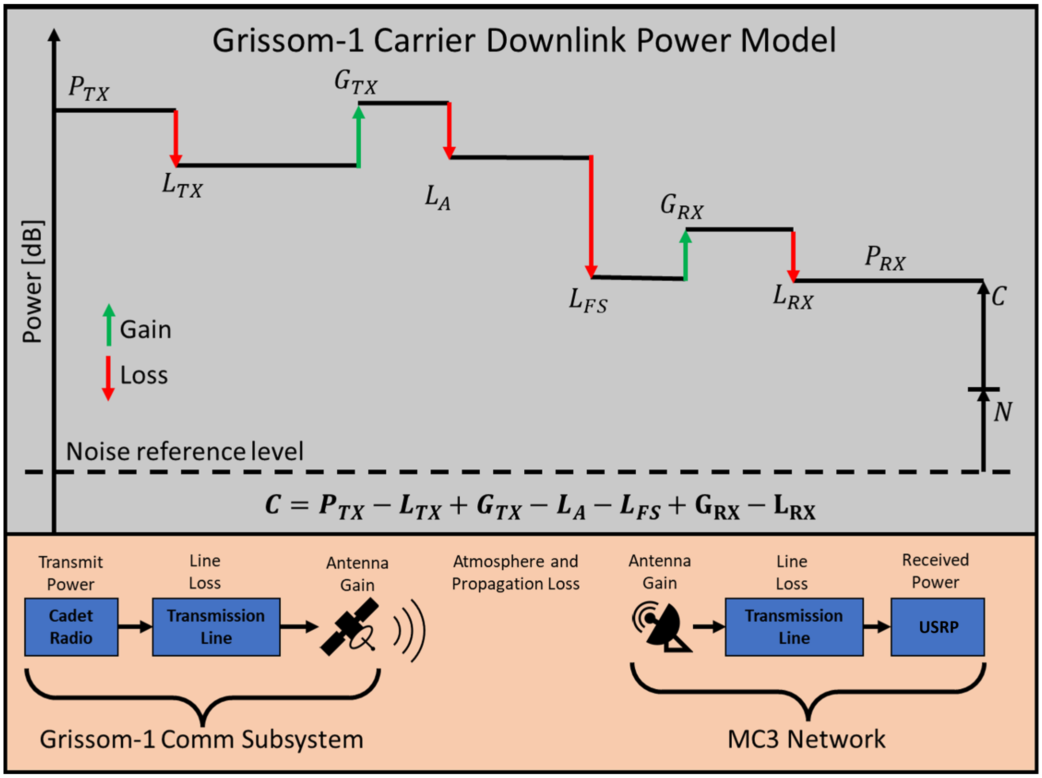

Figure 2: Link Margin Calculations

$$
\begin{aligned}
P_{RX_{Linear}} &= \frac{P_{TX}G_{TX}G_{RX}}{L_{TX}L_{FS}L_{P}L_{RX}} \\
P_{RX} &= P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{FS} - L_{P} - L_{RX} \\
E_b &= P_{RX} - R_b \\
E_b/N_0 &= P_{RX} - R_b - N_0
\end{aligned}
\tag{1}
$$

In this section, the RF Link Budget will be broken down to the basics of wireless communication with a satellite and then further investigate additional loss factors that can contribute to the link margin not closing properly.

Link Budget	Gain/Loss Component	Unit
P_{RX}	Received Power	dBw
P_{TX}	Transmitter Output Power	dBw
G_{TX}	Transmitter Antenna Gain	dBi
G_{RX}	Receiver Antenna Gain	dBi
L_{TX}	Transmit Feeder & Associated Losses	dB
L_{FS}	Free Space Loss or Path Loss	dB
L_P	Miscellaneous Signal Propagation Losses	dB
L_{RX}	Receiver Feeder & Associated Losses	dB
E_b	Energy per bit	dB
R_b	Bit Rate	dB
E_b/N_0	Signal-to-Noise Ratio	dB
N_0	Noise Floor	dB

Table 1: RF Link Budget Terms

2.1.1 Radio Frequency

Communication with any satellite always involves passing information using wireless methods such as RF. When the term RF is used, it is referring to the an EM radiation that is propagating though the universe. An EM wave propagates in one direction with an electronic and magnetic field component. The electric wave component can be received and transmitted by antennas. Radio waves are similar to light waves, as they travel at the speed of light. Though this is very fast, there is still a finite time required for RF signals to reach a distance. RF waves propagates freely through some media, but things like metal will prevent the signal from traveling and will attenuate [7]. This means that all communication between the operator and the satellite must have clear line of site in order to be effective.

In further detail, EM waves are characterized by three parameters: amplitude, frequency, and phase. The amplitude of a wave refers to the intensity of the wave. The amplitude is important because if it is not large enough at transmission, it will not be properly detected at the receiver. Secondly, the frequency of a wave is determined by the number of oscillations or cycles per second. Figure 3 shows a break down of radio waves banks by their categories. For the interest of this thesis the only frequency range that will be used is the UHF.

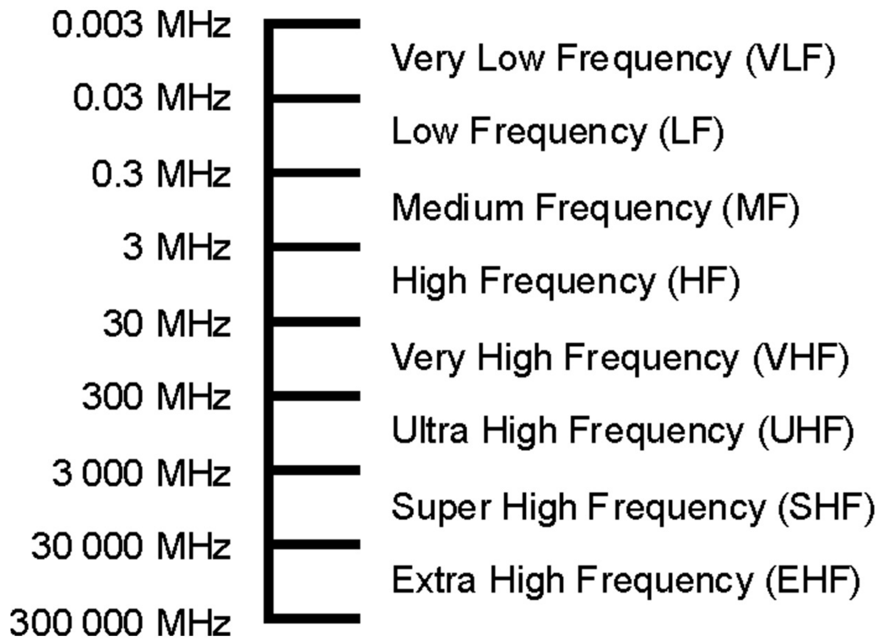

Figure 3: Radio Frequency Bands [7]

In order to capture important RF signals that are propagating around, antenna theory must be used. This is the science behind radio antennas that convert power applied to develop EM waves [7]. The basics of how antennas work can be described using Maxwell's equations [7]. As current is moving through the antenna it produces an electromagnetic wave. The design of an antenna is key and will produce the desired gain required for the specific application. The higher the gain allows for the signal to propagate through space and be received further away. If the received power is too low, then the receiver cannot properly understand the information in the wave. An antenna transmitting a signal converts electronic signals to electromagnetic waves and an antenna that is receiving converts electromagnetic waves to an electronic signal.

2.1.2 Radio Antennas

Radio antennas are designed and selected based off their specific gain and directivity. This describes how the EM energy is focused within a high intensity and how the focusing of the antenna is relative to an isotropic radiator [7]. There are three different categories of antennas called isotropic, directional, and omni-directional. An isotropic antennas radiate power equally in all directions equally, this is a theorized antenna that can not be manufactured. Omni-directional antennas are described by their radiation of equal power in all directions in one plane. They are practical antennas that don't require pointing to be effective. Some examples of omni-directional antennas are whip, ground plane, and dipole antennas [7]. Directional antennas are described by their radiation in a particular direction compared to other directions and have a beam width which refers to how wide the main lobe is. The narrower the beam means a higher gain at the boresight and the lower the effective gain is when not within the main lobe. These antennas are typically called high gain antennas and examples are horn, Yagi, and parabolic reflector antennas. For parabolic reflector antennas, the larger the physical size of this antenna correlates to a higher gain and operating frequency. In Figure 4 the three categories of antennas are explained by their radiation of EM waves.

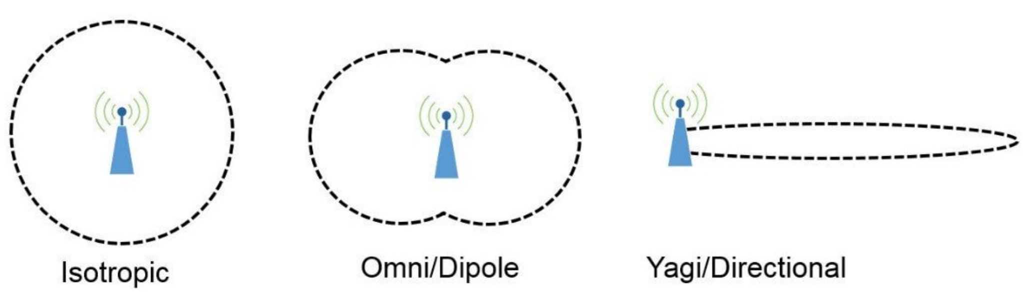

Figure 4: Antenna Propagation

2.1.3 Satellite Ground Pass

A Station Ground Pass is an important maneuver for any spacecraft. This is where the communication between the spacecraft and the operations take place. The ground station pass is determined by orbital elements such as the semi-major axis, the eccentricity, and inclination. The larger the semi-major axis, the more time the spacecraft has to communicate with the ground station. The higher the eccentricity of a spacecraft the more inconsistent the ground station pass over velocity will be. Finally, the inclination will determine the angle that the spacecraft passes over from North to South. If an inclination is $0°$, the spacecraft will always pass over from West to east, if the inclination is $90°$ the vehicle will pass from North to South [6].

Figure 5 it defines the azimuth angle, or angle of the spacecraft as it approaches the ground station. The azimuth is typically the angle off from true north where the satellite is traveling as it approaches for a pass. Also defined in Figure 5 is the elevation angle. As the spacecraft rise above the horizon, or $0°$, it will pass overhead to $90°$. As the satellite passes in the field of view to the ground station, the elevation and azimuth angles will change. The change in elevation and azimuth angles requires software and proper planning to point the ground station antenna at the satellite to obtain maximum gain for the link margin.

Figure 6 shows the potential view angle of a satellite. As the satellite passes over the earth, it is able to communicate with any ground station in the ground track sphere. In Figure 6, ρ is equal to the largest distance away from a ground station that is in the spacecrafts line of site, and θ is the angle of the earth that the space craft is able to see at any given time. In a low earth orbit the velocity of the satellite is roughly 7.5 km/s. As the spacecraft passes overhead it will track where the ground station is and transmit its required data. The time the ground station is in line of site of the spacecraft will determine how long the ground station

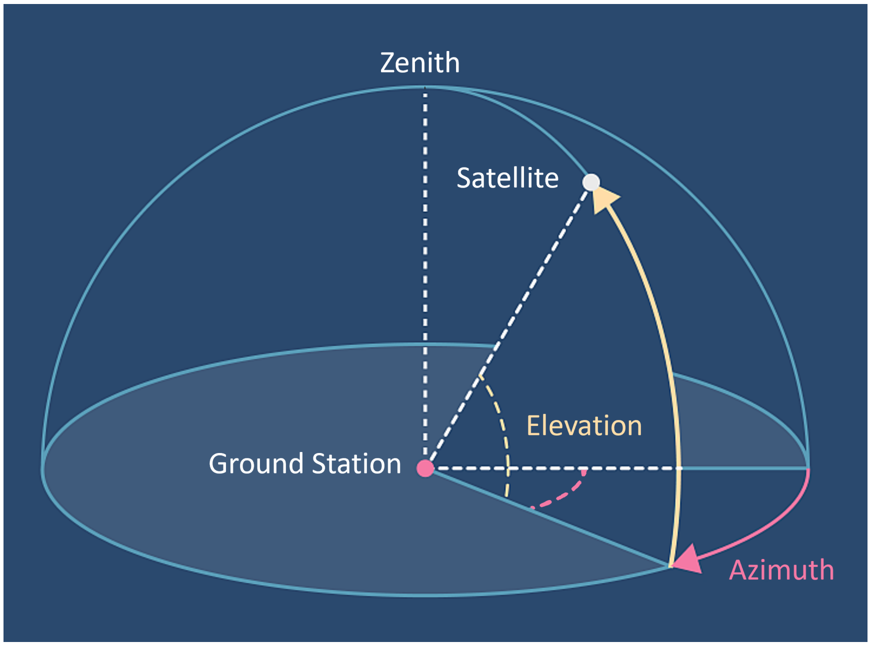

Figure 5: Illustration of Azimuth and Elevation angles

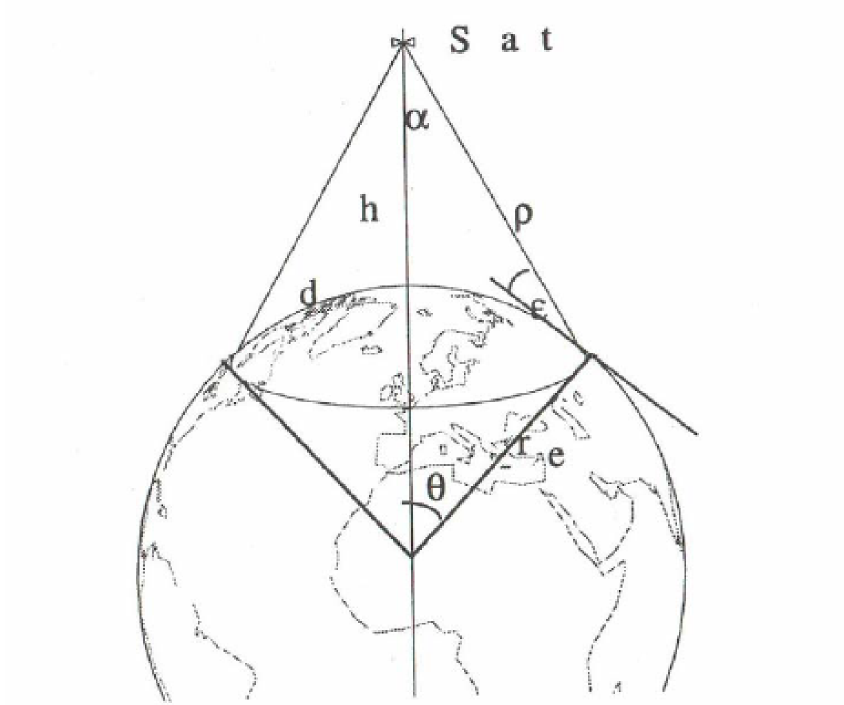

Figure 6: Satellite Footprint [8]

can communicate with the satellite. If the ground track does not pass directly over the center of the visibility circle, the communication time with the ground station is diminished. Overall, this means the average time over a ground station will be 5 minutes under the best conditions [6].

2.1.4 Free Space Loss (FSPL)

Free Space Loss is the loss in signal strength that occurs whenever a diverging wave shaped signal is traveling in the void of space [7]. FSPL is defined by equation 2 in dB where d is the distance in meters and λ is the wavelength of the signal being propagated. As a diverging EM wavefront propagates through free space, the power decreases proportionally to the square of the distance. FSPL assumes that the signal will spread out as an ever increasing sphere and as the signal spreads over a wider area, the energy will have decreased energy density to cover this area. As FSPL increases, it will grow too large and decrease the signal below the noises floor and a receiver can no longer interpret the signal from the transmitter. In calculation of the budget link analysis, this loss equation will be the primary loss factor for the GM1 bus as the potential limits are tested.

$$L_{FS} = 20log_{10}(4\pi d/\lambda) \tag{2}$$

2.1.5 Rain Point Loss

Rain attenuation is a dominate loss factor in rain, especially at 10 GHz and above. Figure 8 shows the different regions of the United States and their rain factors. Utilizing a model developed by Crane, we can estimate the loss associated with rain attenuation. In the UHF Band, the rain associated with this roughly equates for .01 dB, however as the frequency increase this loss can significantly impact the signal.

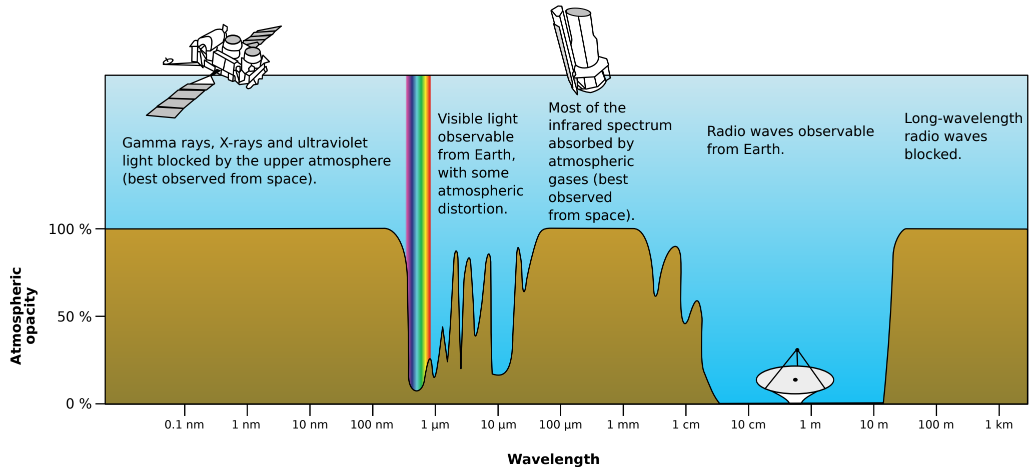

Figure 7: Atmospheric Electromagnetic Opacity [9]

There are other loss factors that RF must deal with such as gaseous absorption, cloud attenuation, melting layer attenuation, and troposheric refraction effects [10]. Additional factors that can decrease the RF Link Budget are Sandstorms [11]. Rain attenuation is a factor found in theRF Link Budget under the miscellaneous loss propagation. This loss is important to consider as the MC3 Network is hosted in different locations across the United States of America.

2.1.6 Communication Modulation

Transmitting data by single bits is a very slow process and will use large bandwidths of data while other methods can be used to transmit data. Bits of data are modulated onto a RF waveform using a digital modulation technique. This can be done by varying amplitude, frequency, and phase of a signal. A digital modulation receiver observes the received signal in the presence of noise and makes decisions about what was most likely transmitted. Based off the modulation scheme, we can predict the likelihood of an error, this is called the Bit Error Rate (BER) probability. If the BER probability is too high, then the satellite will not be able to properly receive data from the ground station. SNR is inversely related to the BER probability, this

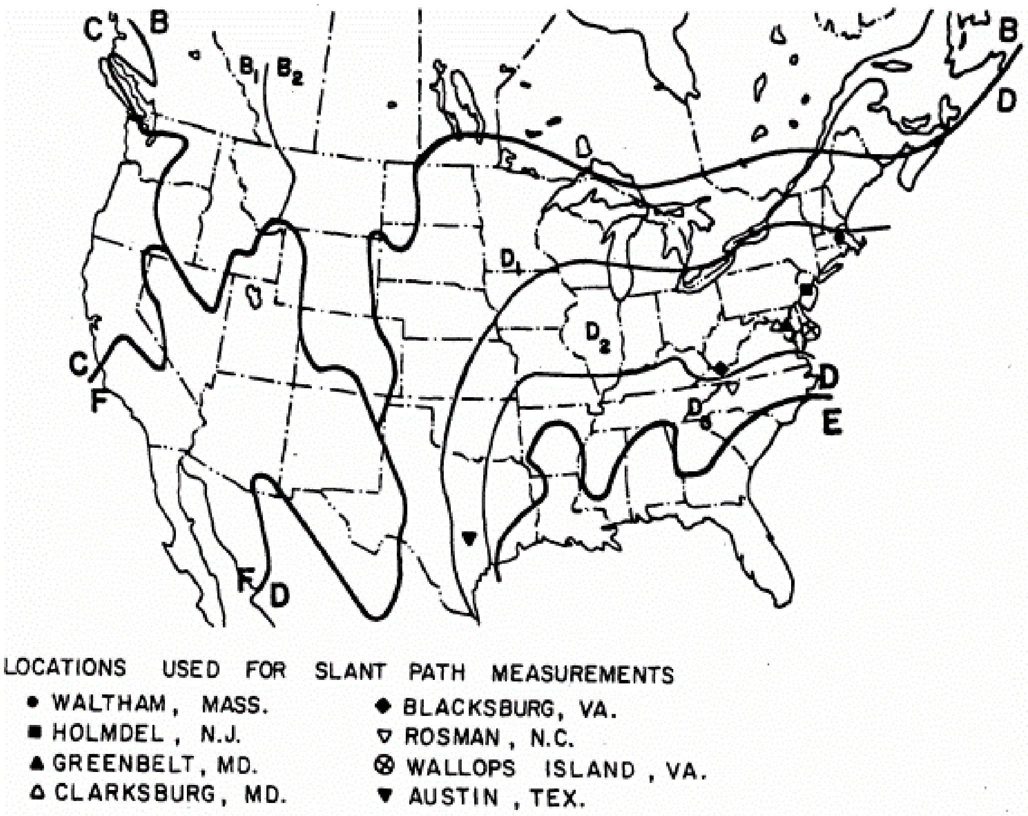

Figure 8: Rain Point Loss [12]

means that the higher the SNR is the less likely the receiver is to make a mistake when interpreting the signal [6].

2.1.7 N_0

Noise is calculated using Boltzmann's constant and converted to a decibel to help calculate the SNR. The standard value of noise is -228.6 dB and then an associated noise temperature is added to calculate the noise floor. The noise temperature typically correlates to a frequency and can be generalized for easier calculations[6].

$$\begin{aligned} N_{0_{Linear}} &= kT_s = & (1.38 \times 10^{-23})T_s \\ N_0 &= 10log_{10}(k) + 10log_{10}(T_s) = & -228.6 + 10log_{10}(T_s) \\ N_{0_{UHF}} &= -228.6 + 23.4 = & -205.2dB \\ N_{0_S} &= -228.6 + 21.3 = & -207.3dB \end{aligned} \tag{3}$$

2.1.8 Calculating Signal to Noise Ratio

Calculating SNR is a simple equation of signal strength from the radio under testing divided by the noise that is present in the medium [6].The RF link margin is dependent on the SNR because regardless of the signal strength being transmitted, if the signal is not larger than the noise, zero communications will be understood. SNR can be related from $\frac{E_b}{N_0}$ to a Carrier to Noise Ratio (CNR) shown as $\frac{C}{N_0}$ by multiplying (or adding if in decibel) the BER probability. The higher the CNR is, the better the relation to signal. Once you ensure the CNR is high enough, you can subtract the BER probability for your SNR value and check if the signal is strong enough for proper communication. If the RF budget link has a low SNR outside the required BER probability, then the ability to transmit to the spacecraft will have to wait until it is closer to the ground station. This will diminish the time available to pass information to the spacecraft, and can lead to an incomplete the data transfer.

2.2 CubeSat

This section will cover the basic communication subsystems and how they work together in order to have satellite operations. Figure 9 describes the general flow for a satellite communication. Most of the process involves physical connection between systems, but the most critical portion is the transmission and reception between the ground station and the satellite.

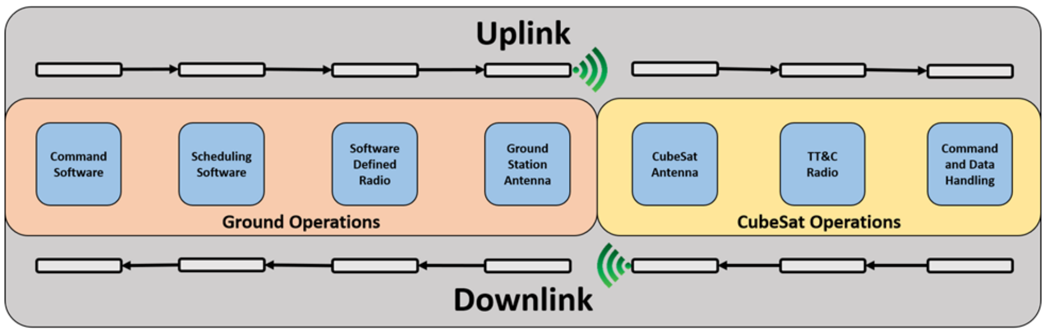

Figure 9: Up-link and Down-link Communication Path

2.2.1 SDR

Software Defined Radio's a relatively new technology and the name was coined in the 1990's by Joseph Mitola [13]. The purpose of this technology is that with one piece of hardware a user is able to capture, demodulate, and access RF signals across a potentially wide frequency range all by adjusting software parameters [13]. Figure 10 shows the timeline of communication milestones and the progression from the discovery to electricity until the development of the software defined radio. In 1991 the first attempt to develop a SDR called the Speak EASY 1. SDR's are a critical component for communications because the modulation schemes and data rates can be adjusted without the need to build a new radio for each requirement. In recent years the SDR has been improved to not only can receive signals, but transmit signals in a wide swath of RF [13].

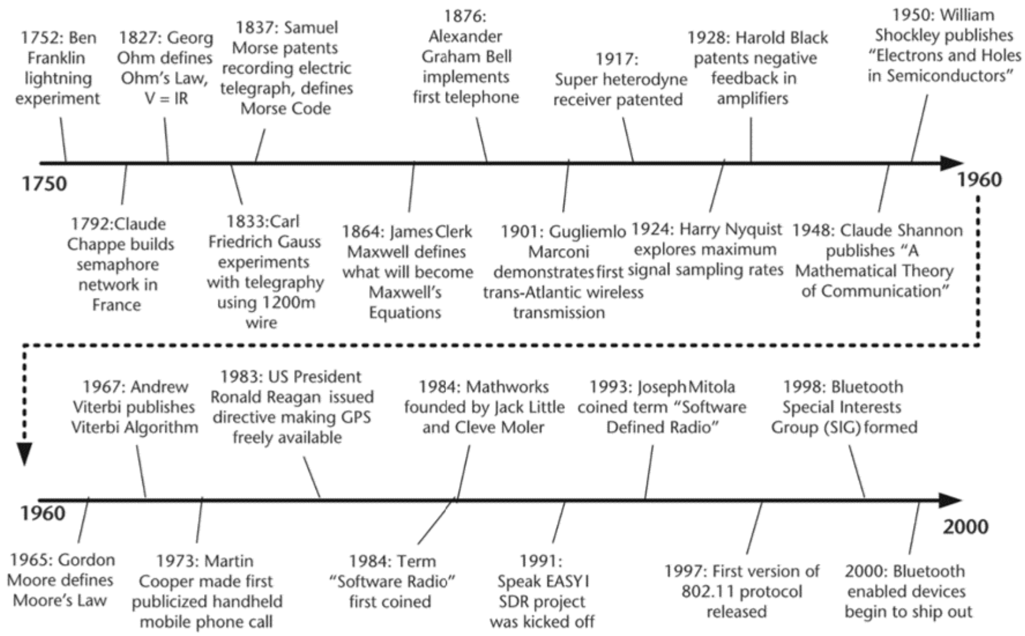

Figure 10: Timeline of several key milestones in communications [13]

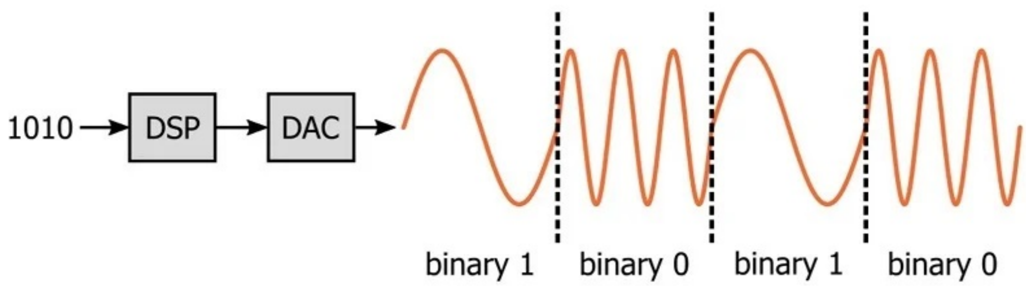

Figure 11: Digital Modulation [14]

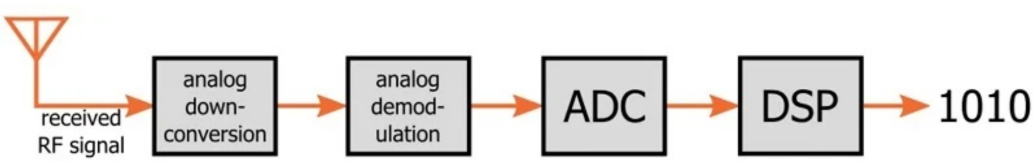

Figure 12: Demodulation and Data Recovery [14]

Traditional radios, normally refereed to as analog superheterodyne receivers, were entirely hardware based using analog components. These radios had very limited applications when built, and could only transmit or receive with a fixed modulation type. When looking at SDR, there is a basic need to understand analog to digital conversion and vise versa. In Figure 11, a process called Digital to Analog Converter (DAC) conversion is shown as an integral part to convert from digital numbers to a transmittable signal. This is the method of taking a binary code word and converting to an analog voltage level with appropriate reconstruction filters. The output of a DAC process is an analog waveform that has discrete amplitude values [13]. There is also an opposite of digital to analog, shown in Figure 12, and this process converts an analog signal into a digital discrete set of information, also known as digital demodulation.

A major component involved with any SDR is the software component. These devices are complicated and not just relaying a radio signal like a car radio, but converting a signal into bits of information. This process requires matching the coding scheme, and ensuring that the transmitting radio can be interpreted by the receiving radio [6].

2.2.2 TT&C Radios

TT&C Radios that are used on board space vehicles are the main and sometimes the only way to communicate with a ground station. These components are key, like many other components, to ensure the mission success. A TT&C radio is a radio that has been designed and tested to sustain launch and the hostile environment that space is for electronics. It is commonly a SDR due to the multiple frequencies it can use and flight heritage. The TT&C radio is normally selected based off of its power consumption, transmit power, bit rate, transmit frequency, and receiver frequency

[6]. All these requirements are used to build an RF link budget to determine how successful the communications from the ground station to the spacecraft will be.

Radios on board a spacecraft have two major functions, modulation and demodulation. Modulation is the conversion of converting of data into RF, this will transmit from the spacecraft to the ground station. Demodulation is the conversion of received RF signal to data, this is the information that is received from the ground station to command the spacecraft.

2.2.3 Ground Station Antennas

Ground station antennas are selected based off the capabilities of the missions they anticipate to conduct. When looking at the RF link budget analysis, the gain of the ground station antenna is dependent upon many factors such as the size, weight, cost, and operating frequency. Additionally, for a given operating frequency, a larger antenna will have a larger gain [6].

There are two antenna types that are common in ground station communication, Yagi and parabolic reflector (dish) antennas. Both the Yagi and dish antennas are considered efficient, however they both have side lobes of radiation. This is typical with nearly every antenna design, but overall they have a forward directional radiation shown in Figure 13. The Yagi antennas are smaller than dish antennas, yet still have a high gain. One reason selecting a Yagi antenna is beneficial can be a roof not being able to support the weight of a dish antenna. The selection of a high gain antenna is important because CubeSat's have limited power to use and can not afford a high power radio to transmit the signal.

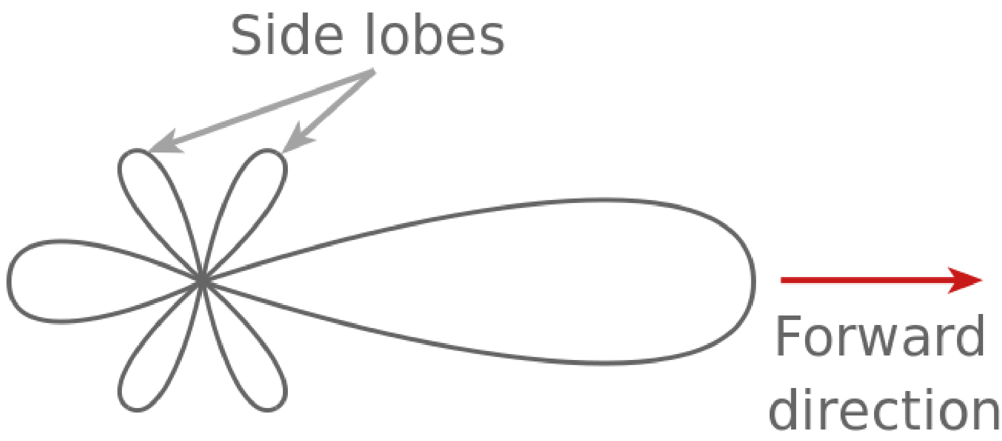

Figure 13: Yagi Antenna Radiation Pattern [7]

2.2.4 CubeSat Antennas

Antennas for CubeSats are selected based off of mission requirements. The main requirement used in this decision is from the missions payload [6]. If the payload in a CubeSat doesn't require the use of an accurate Attitude Determination and Control System (ADCS), then most practical option is to use a low gain antenna, with higher power transmission, and lower bit rate. If the mission requires a high accuracy of pointing, then there is an ability to use a high gain antenna while utilizing the existing requirement of an accurate ADCS. When looking at the signal-to-noise ratio, a positive trade off for using a high gain antenna is it relieves the power transmission requirement from the SDR or it can give the ability to transmit data at a higher bit-rate.

In Figure 14, the antenna gain patterns of a high gain antenna and a low gain antenna are shown. The gain pattern that is more directional to Earth will require an Attitude Determination and Control System (ADSC) to point accurately at the ground station, otherwise the high gain antenna will propagate the signal away from the ground station. When looking at the low gain antenna, if the satellite were to start pointing at a direction to the left of Earth, the antenna pattern is still large

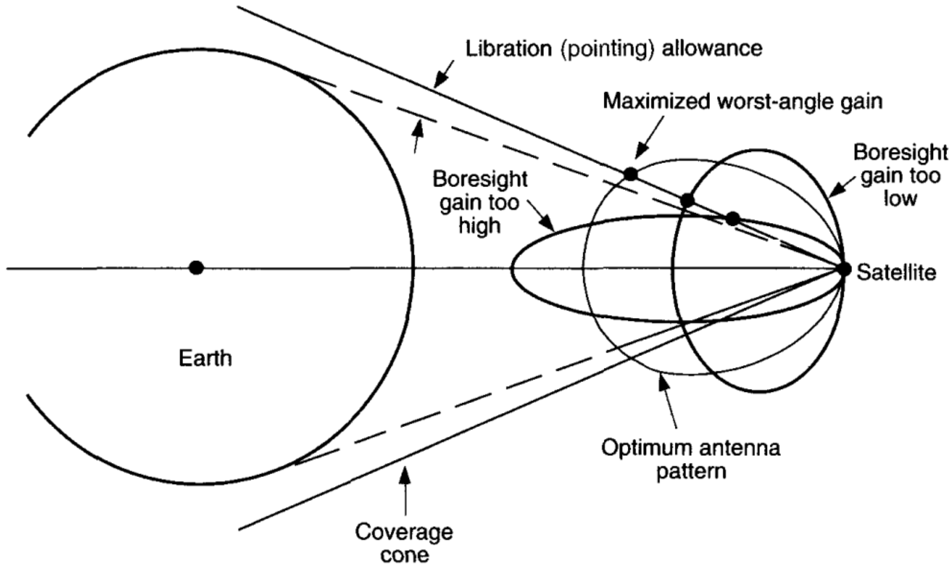

Figure 14: Antenna Gain Patterns [15]

enough that signal could be received at the ground station. This is important because it allows for communication to be maintained regardless of the poor pointing angle of the satellite [7].

2.2.5 C2 Software

C2 of a satellite requires several functions. These range from powering a subsystem on and off, changing a subsystem operating mode, deploying solar cell arrays, uploading computer programs, control spacecraft guidance and attitude [16]. To communicate with a satellite, the Command-and-Control system needs to create a command to be transmitted to the satellite. This is done using various applications, but all do very similar tasks. The software creates a command message in correct format that will be understood by the satellite, and then encodes the data [16]. The data remains queued for transmission until the scheduling software allows for the C2 to begin the up-link and down-link process. In a down-link setting, the data that was received from the satellite is decoded and presented to the ground controllers in a format that they can interpret and understand.

2.2.6 Distributed Ground Stations and Scheduling

A scheduling application is used to coordinate the use of shared ground stations distributed across the globe, and allows for command to occur geographically separate from the command team. The purpose of a shared-use scheme is to minimize cost for users and maximize ground station coverage. A shared scheduling application can normally be used through a Virtual Private Network (VPN) tunnel, where the software will schedule contacts based off of the parameters of the satellite's location within its orbit and which ground station is in view [2]. The software deconflicts any scheduling conflicts, and approves or rejects the desired contact requested by the command center [2]. Once accepted, the uploaded commands will be sent to appropriate ground station when the satellite is overhead. This then begins the RF transmission to the satellite when it begins its pass.

2.2.7 Additional Subsystems

Important spacecraft components that assist the TT&C function are the Command and Data Handling (CD&H) and the ADSC. The CD&H subsystem may be considered by some as not included in the TT&C. However, this is an important component to discuss when studying and analysing a SDR. The key point of the command and data handling is to be the brains of the spacecraft while the SDR is essentially the ears and mouth of the spacecraft. All information that is being brought in and sent out must be handled by the computer in the CD&H. Within the CD&H is stored data that need to be forwarded to a ground station later. Along with the CD&H is the ADSC subsystem. This component is used to detumble the spacecraft and point the spacecraft antennas at the ground station during a pass[6]. The ADSC is key to increasing the SNR. If the ADSC is pointing in the wrong direction, then the antenna's beam width of the propagating RF will be offset causing a lower gain to reach the receiver and therefore decrease the SNR to unusable signal strength [6]. In the case of a low gain antenna, this requirement to point through a ground station pass becomes less important, but if the satellite ends in a state where the transmission to a ground station is being pointed from a side lobe of an antenna, the SNR can go from closed link margin to receive data from the satellite. Because of this, the CD&H is very important to be functioning during a ground pass.

2.2.8 MC3 Network

The MC3 Network is a key component that allows for AFIT CSRA to be able to effectively launch a CubeSat and have a backbone for monitoring and controlling future missions. The MC3 Network is composed of multiple ground stations called Nodes with identical equipment. Each Node enables UHF and S-Band communications to low-Earth orbiting satellites [2].

2.2.9 MC3 Network Geographic Distribution

The MC3 Network is composed of several ground stations that can be used by all users who have authorization from the MC3. The distribution of the MC3 Network allows for a cube sat to have more opportunities to communicate with their C2 team. This also allows for more data to be dumped and have less opportunity for the CubeSat to exceed memory requirements because of limited downlink time.

2.2.10 MC3 Network Interconnection

A major tool that the MC3 utilizes to ensure constant deconfliction of operations without human intervention is called SATRN. SATRN is a collection of software applications that consists of three applications: SATRN Client, Server, and Ground Control. These three applications are web-based tools that SATRN provides an interface through a bent-pipe communications between the mission owners C2 and their spacecraft[2].

Looking more into the SATRN Client, the application's primary function is to provide an interface for the spacecraft operators to plan their next transmission. To schedule a ground contact, the user must enter in a Two-Line Element Set (TLE) of the spacecraft, and SATRN Client will determine information such as when the spacecraft is over a ground station, and if there is for availability to use that ground station. SATRN Client calculates orbit propagation from the entered data and determines the best time to schedule a session[2].

The next application is called SATRN Server. This application's primary function is to be the schedule arbitrator and preform deconflicting scheduling for all SATRN users. The application is responsible for coordinating the sessions between the SATRN client and the SATRN Ground Control software[2].

The final application is SATRN Ground Control, which manages the connection of users to their satellites via a ground station. This allows for users to utilize any ground station located within the MC3 network. The primary function of this software is to configure the SDR's for ground stations to contact and control satellites. During a session with the SATRN Ground Control, mission operators have a bent-pipe between their Mission Operation Command and satellite.[2].

While using SATRN, the client begins by calculating the orbit of a satellite that they wish to make a contact by utilizing a MC3 ground station. Once they have the ground track and time of pass, the software will schedule this session. As the time approaches to preform the operation, the server opens a path from the C2 to the ground site. In this window it is the operators responsibility to detect, track, and transmit all information required for this satellite. Once this period has concluded and the satellite is out of reach, the server closes the network connection to the C2.

2.2.11 MC3 Software Defined Radio

The National Instrument USRP-2922, seen in Figure 15, is the standard SDR radio used by the MC3. On the transmission side, the USRP-2922 operates at a frequency range of 400 MHz to 4.4 GHz with a frequency step of less than 1kHz. It can output power from 50 mW to 100 mW or 7 dBm to 20 dBm. The USRP-2922 is used on the MC3 to transmit at UHF between 449.75-450.25 MHz and the S-Band at 2025-2110 MHz.

On the USRP-2922 receiving side, the frequency range and step are still 400 MHz and 4.4 GHz and have a maximum instantaneous real-time bandwidth of 20 MHz. The USRP-2922 is used on the MC3 to receive signals at 915 MHz and 220-2290 MHz. This device meets all the specifications required for a CubeSat Ground station communications SDR [3].

2.2.12 MC3 Network Ground Station Communication

The MC3 is interconnected by multiple ground stations, which create a network. The MC3 Network was designed so each ground station utilizes identical hardware to assist C2 teams and create seamless use of the network without regard to the location. Using the SATRN client creates access to these nodes and increases access for mission owners to communicate with their CubeSat at a higher rate. Once a time is scheduled to communicate with a CubeSat using the SATRN client, the next location of the CubeSat is calculated and the contact is planed. [2]

It should be noted that even if a contact occurs while using a C2's local MC3 Node, the mission owners must follow the same network path regardless of location. For

Figure 15: NI USRP-2922 [3]

example, even though AFIT hosts the Wright-Patterson Air Force Base (WPAFB) MC3 Node, the procedure to use the WPAFB node is identical to a node anywhere on the network. Their is no ability to use the ground station equipment outside of SATRN programming and IP network tunneling.[2]

2.2.13 MC3 Mission Owner Roles

Even though the the Naval Post Graduate school developed and owns the MC3 Network[2], there are DOD regulations and procedures to obtain access to their network [17]. For example, users must provide the S2I2 Division with a mission overview, proper security classification guide and documentation, a status of frequency assignment application defined by the National Telecommunications and Information Administration (NTIA), and information about each spacecraft must include a completed Small Sat Information worksheet.[2] The user's responsibility include defining a Mission Operation Center (MOC), coordinating with the NTIA to obtain transmit and receive frequency authorization for each of their spacecraft, and developing software implementation that is compatible with the MC3. This software includes the mission's C2 tools, command scheduler, and front-end processor. Finally, all data being passed through the MC3 is required to be encrypted and decrypted by the user in accordance with CNSSP No. 12 and DODI 8581.01 when applicable [2].

2.2.14 MC3 SDR Testing

A recent thesis comparing existing the MC3 Network's SDR against three other leading technologically capable radios were tested at the Naval Postgraduate School. In the thesis, a trade study against commercial SDR's were conducted for their capability. The primary purpose of the thesis was to identify if the existing radio being used is efficient and is on par with the current technology of other SDR's. Within the thesis a number of instruments were used that will be required for the test and verification of the Cadet PLUS radio that will be flying on the GM1 Mission. The performance measurement experiment is described in Figure 16. The test conducted involved incrementally decreasing the input power of the test signal while the noise in the system was maintained at a constant. This allowed for the measurement and comparison of BER [18]. Once the BER is known, this allows for the adjustment of power, encoding scheme, and bits per second capable by the radio.

While the test procedures are for a ground station SDR, the methods of the test can be utilized for the methodology of how the Cadet PLUS SDR should be tested. Woods tests verified the receiving capabilities of four commercially available radios while also comparing their user friendliness. Tests that were conducted were the noise figure, phase figure, image rejection, receiver sensitivity, BER performance, dynamic range, and an additional test of Graphical User Interface (GUI) performance and

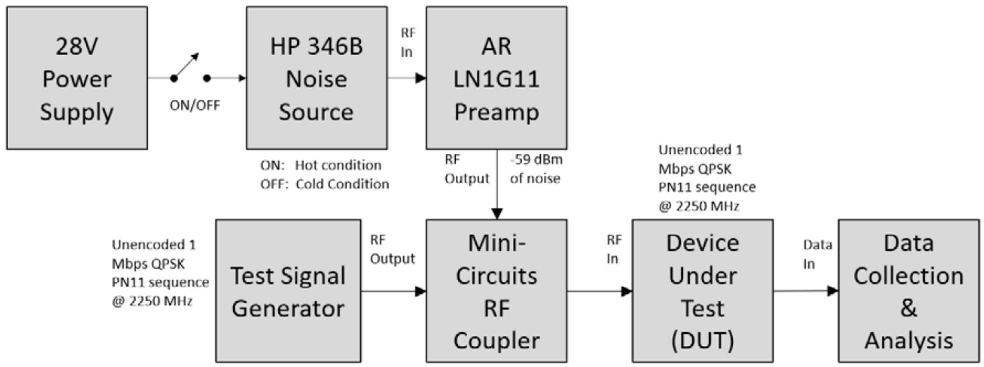

Figure 16: BER performance measurement experimentation [18]

experience results [18]. The groundwork of this test helps develop a path moving forward to assist the testing of the GM1 6U CubeSat bus.

In Woods' test for noise figure, he sets up the experiment to measure the noise in the controlled environment. He calls this his cold condition where he had the least amount of interference. After taking his initial measurement he calibrated insertion noise in his device under testing and took a second measurement. The magnitude of the noise floor that he measured between both conditions was compared and used to calculated. This noise figure was essential in calculating his SNR. Using a spectrum analyzer, he was able to calculate and calibrate his expected noise figure during preamplification of his hardware [18].

In the second experiment conducted to test the phase figure, Woods measured the jitter inside the local oscillator of his SDR under testing/ This test involved sending 1 Mbit per second Quadrature Phase Shift Keying (QPSK) modulated bit sequences and recording the output file. The signals were saved into files and pushed into a Python script to reconstruct the expected 2047-bit packet. Using this data, Woods was able to identify the phase figure of each device under testing to help calculate his expected phase noise[18].

Image rejection testing was conducted as an experiment to test how the SDR mixing process and down-conversion of incoming signals operate. Woods transmitted a known frequency file in 10dB increments from -70dBm to -20dBm and recorded each received image. He then compared the results of his expected image vs his received image to determine the clarity of his SDR under testings ability to convert analog signals to digital[18].

Finally, the last test that Wood conducted which is of use for the GM1 Cadet PLUS testing was a receiver sensitivity experiment. Woods conducted this experiment by sending a 1-Mbps QPSK modulated signal and incrementally attenuated the signal until the BER increased beyond an effective measurement. This test shows the minimum capability of the devices under testing and what the lowest received signal can be before loss of information occurs[18].

III. Methodology

Chapter Overview

This chapter describes the methodology used to answer the question of the Grissom-1 Mission (GM1) communication limitations in its current configuration. While utilizing the Mobile CubeSat Command and Control (MC3) Network, the GM1's abilities will be measured to determine maximum altitude for minimum acceptable performance. The current configuration of both GM1 and MC3 will then be modified to determine potential configuration changes to expand the range of the following Grissom missions. Missions to be analyzed are Low Earth Orbit (LEO), geosynchronous orbit, and a Lunar orbit. The Methodology will first discuss the configuration of GM1 CubeSat communication subsystem and the MC3 Network standard configuration used at all nodes. To ensure the GM1 communication configuration operates as designed, a series of tests will be described and defined to ensure the loss within the Grissom-1 communication subsystem is within expected tolerance. After these numbers have been calculated an explanation of the simulation of additional missions will be logically explained. The parameters used to describe the current configuration will be methodically changed to attempt to optimize the communication of the Grissom-1 to MC3 network communication and allow for further orbital missions to be possible.

3.1 Grissom-1 Communication Subsystem

The Grissom-1 main communication subsystem under research is comprised of a Cadet PLUS Software Defined Radio (SDR), S-Band Antenna, and UHF dipole Antenna.The MC3 Network is comprised of a 3-meter parabolic dish antenna for S-Band, a yagi antenna for UHF, NI USRP-2974 SDR, SATRN Ground station radio controllers, and COSMOS for command generation and parsing of satellite telemetry. In Figure 2, the downlink power model and how each component correlates to a gain and a loss is shown.

The Cadet Plus SDR is a split band, full duplex, store and forward radio that has separate spacecraft UHF and S-band SMA antenna connections to support simultaneous reception and transmission for full duplex RF data communication between the Cadet and Earth Station.The Cadet also provides an RS-422 interface to an on board computer and allows for configuration of the uplink, downlink frequency, data rates, data modulation, and output transmit power. These configurable variables have all been predefined by the AFIT GM1 design team and will be used accordingly in following simulations of the communication testing of the GM1 maximum communication distance in LEO, geosynchronous orbit, and Lunar orbits. [4] The GM1 mission S-Band antenna and UHF dipole antenna are built to be utilized in their respective frequencies and can not be changed.

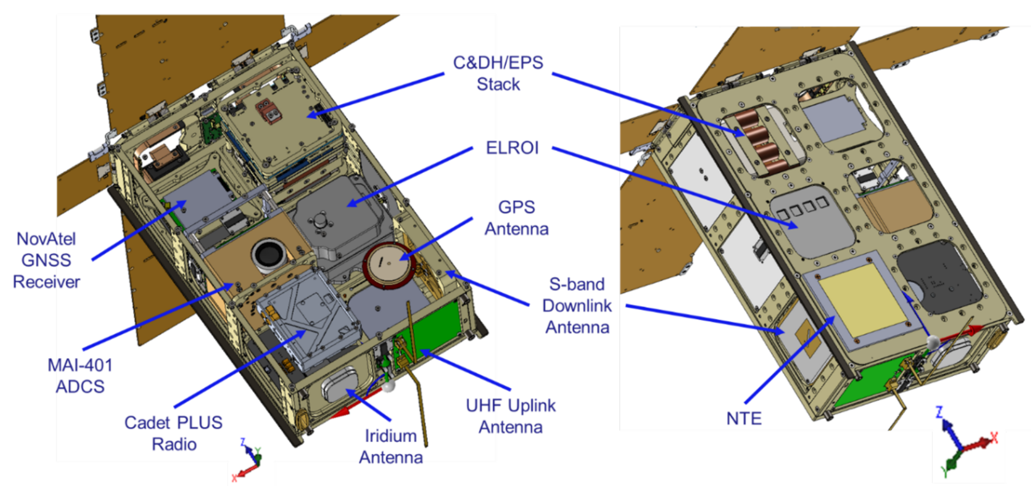

Figure 17: GM1 Design (1)

In Figures 17 and 18, the GM1 design with components is shown. On the bottom left of Figure 18 the dipole antenna and S-band antenna can be seen. These components of the communication system are the main communication antennas. The SDR

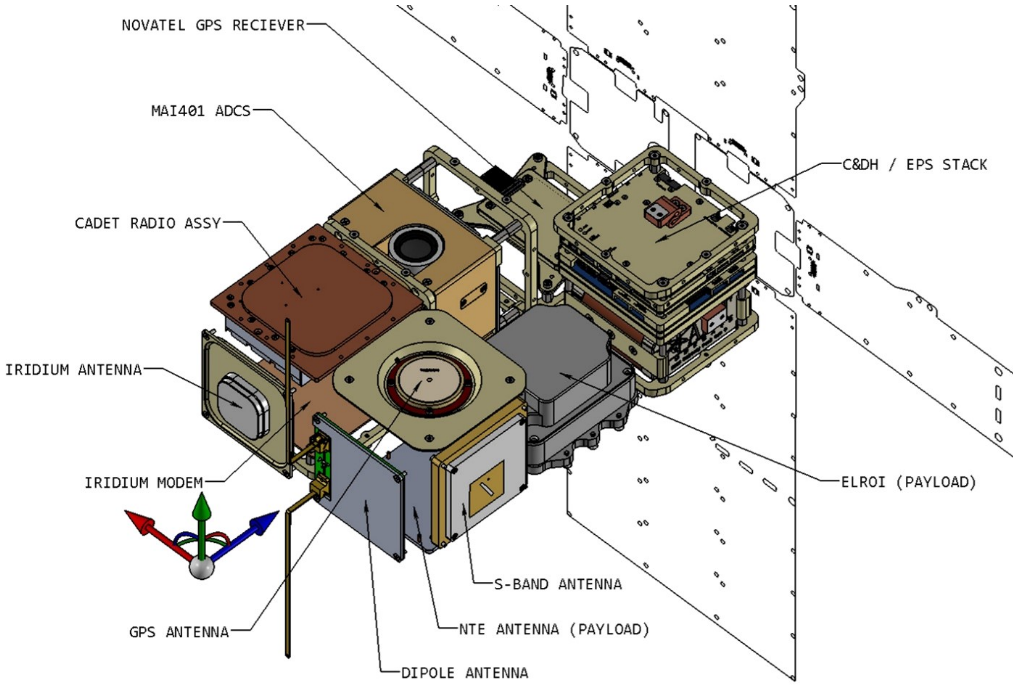

Figure 18: GM1 Design (2)

used to generate downlink commands is shown as the Cadet Radio Assembly, which is facing inward of the CubeSat.

On the ground, the MC3 Network is designed around the NI USRP-2974. The USRP SDR is a stand-alone device built with an Field Programmable Gate Arrays (FPGA) and an Intel i7 on-board processor which can be provisioned with a Linux real-time operating systems. The USRP is programmable to the on-board processor an open-source software workflow to deterministically control the output transmission on the MC3 Network.The USRP-2974 is ideal for prototyping a range of advanced research applications that include stand-alone LTE or 802.11 device emulation; Medium Access Control (MAC) algorithm development; multiple input, multiple output (MIMO) systems; heterogeneous networks; LTE relaying; RF compressive sampling; spectrum sensing; cognitive radio; beam-forming; and direction finding. The USRP has a two channel transmitter and receiver that operate from 10MHz to

6GHz and have a less than 1 kHz frequency step. The maximum output power from the SDR is 5mW to 100mW (7 to 20 dBm) with a transmit gain range of 0-31.5 dB and a receiver gain range of 0-37.5 db, and maximum input power for the receiver is 10 dBm. Additionally the NI USRP-2974 is capable of Demodulating FSK, BPSK, QPSK, OQPSK, and GMSK.[3]

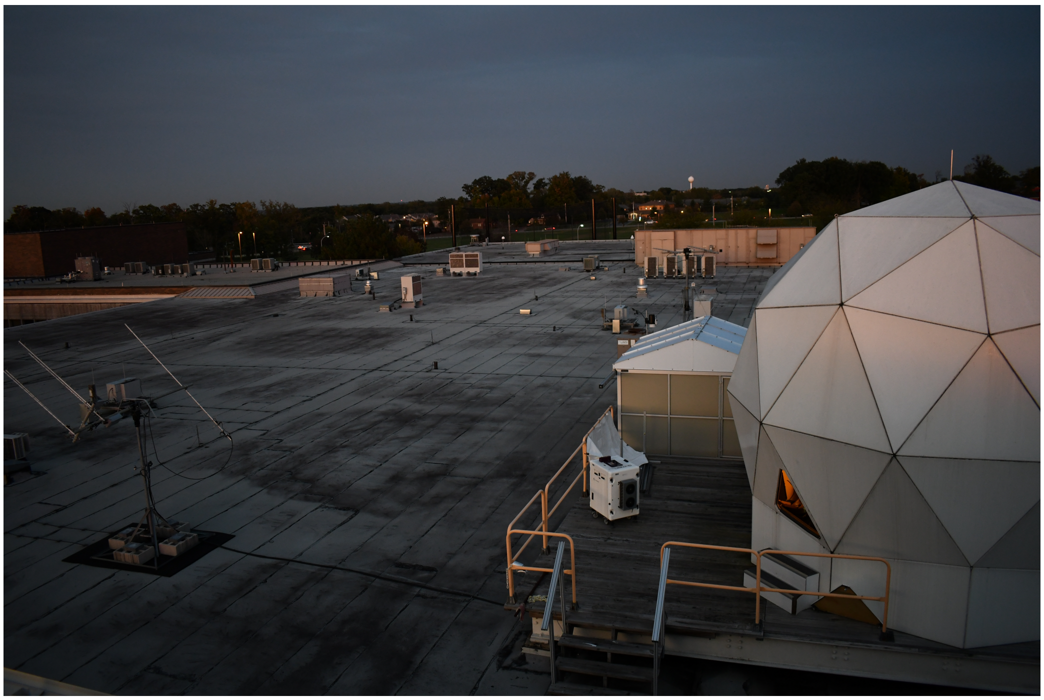

Figure 19: WPAFB MC3

The selected antennas seen in 19, specifically for the WPAFB MC3 Node, are a UHF Yagi antenna and an S-Band Parabolic antenna. The Yagi antenna utilized by the Wright-Patterson Air Force Base (WPAFB) MC3 Node is used to transmit the uplink data between 449.75-450.25 MHz and has a gain of 16 dBi. The MC3 USRP SDR will TX power of 75 W, and EIRP of 31.7 dBw.

The 3 Meter parabolic dish antenna, seen in Figure 20 and 21, is the M2 AZEL 1000s. This antenna is characterized with a gain of 33 dBi at 2210-2245 MHz, and beam width is E=13 degrees and H=13 degrees. Though both antennas have the capabilities to transmit and receiver, they are only used for their specific role on the

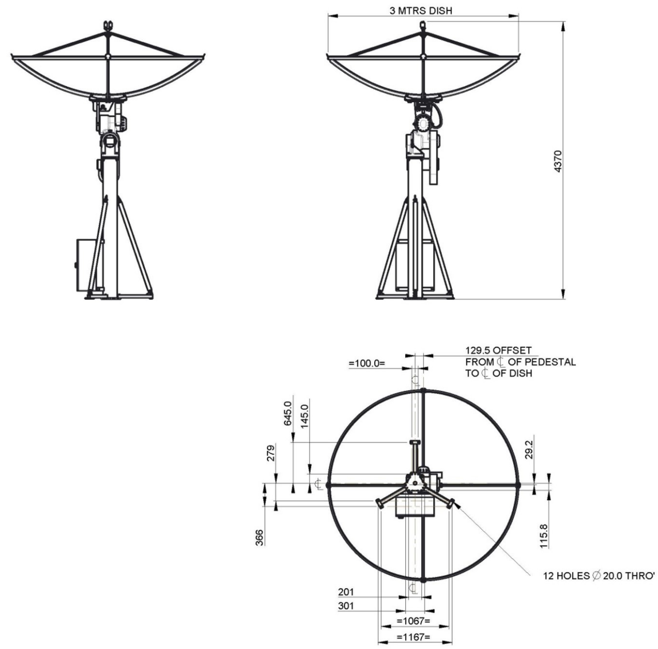

Figure 20: MC3 Dish Antenna

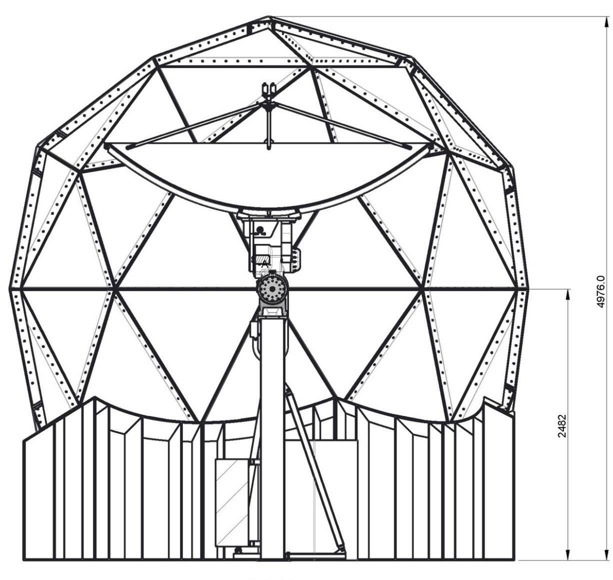

Figure 21: MC3 Dish Antenna Dome

MC3.

3.2 Testing and Expected Results

This section will discuss the testing procedures that involve the characterization of the antennas used to transmit and receive signal from the ground station. Testing will be conducted in an anechoic chamber of the Cadet Plus SDR to determine power usage, strength of transmitted signals in the S-Band, and the gain of the UHF antenna when receiving an incoming signal. Testing of the Cadet Plus SDR will be conducted on a prototype board by transmitting and receiving signals from a simulated MC3 network in a lab settings. These tests will involve transmitting COSMOS commands and documenting the performance from the SDR at various signal strengths. Testing in the anechoic chamber will utilize a point to point test method with free space loss calculated and used to determine the gain of each antenna. Once gains have been calculated an operational test of communication between COSMOS software to the Cadet Radio, and commands from the Cadet Radio back to COSMOS. This will give a simulation or day-in-the-life simulation of the GM1 CubeSat and be used to ensure proper communication can be achieved between the two systems prior to the September 2022 launch. All characterization and evaluations of the communication subsystem will be used for modeling the GM1 and help with designing the future Grissom 6U missions.

Setup	Test propose	Frequency
1	Baseline equipment measurement and line loss	450 MHz
2	Test antenna gain measurement	450 MHz
3	CubeSat antenna gain measurement	450 MHz
4	Baseline equipment measurement and line loss	2.2 GHz
5	Test antenna gain measurement	2.2 GHz
6	CubeSat antenna gain measurement	2.2 GHz
7	Cadet SDR transmission power measurement	2.2 GHz
8	USRP SDR transmission power measurement	450 MHz
9	Communication operational test	450 MHz & 2.2 GHz

Table 2: Experimental Setup List

Figure 22: Experimental Setup 1

Experimental setup 1, Figure 22, demonstrates a calibration of the lab equipment for the CubeSat uplink frequency. This will detect and account for any line loss between the Signal Generator at 450 MHz and the Spectrum Analyzer. This demonstration also helps calibrate the Spectrum Analyzer to ensure the measurements are taken consistently.

$$P_{RX} = P_{TX} - L_{TX} - L_{RX} = P_{TX} - 2(L_{TX}) \tag{4}$$

Mathematically Equation 4 describes the power measured by the spectral analyzer that is equal to the power of the signal generator minus the loss in the lines. The loss in transmission for this setup is equal to two times transmission loss in the equation. This is done because the transmission lines will be separated in half and connected to a transmitting antenna and a receiving antenna.

Experimental setup 2, Figure 23, begins the first calibration test to determine the dBi and free space loss calculation.The test antennas are identical and assume to have the same transmission and receiver gain. The SMA adapters and connectors used to reach the antennas in an anechoic chamber will be used in experimental setup 1 when conducting measurements of line loss and ensure each measurement can isolates the two variables of antenna gain and free space loss.

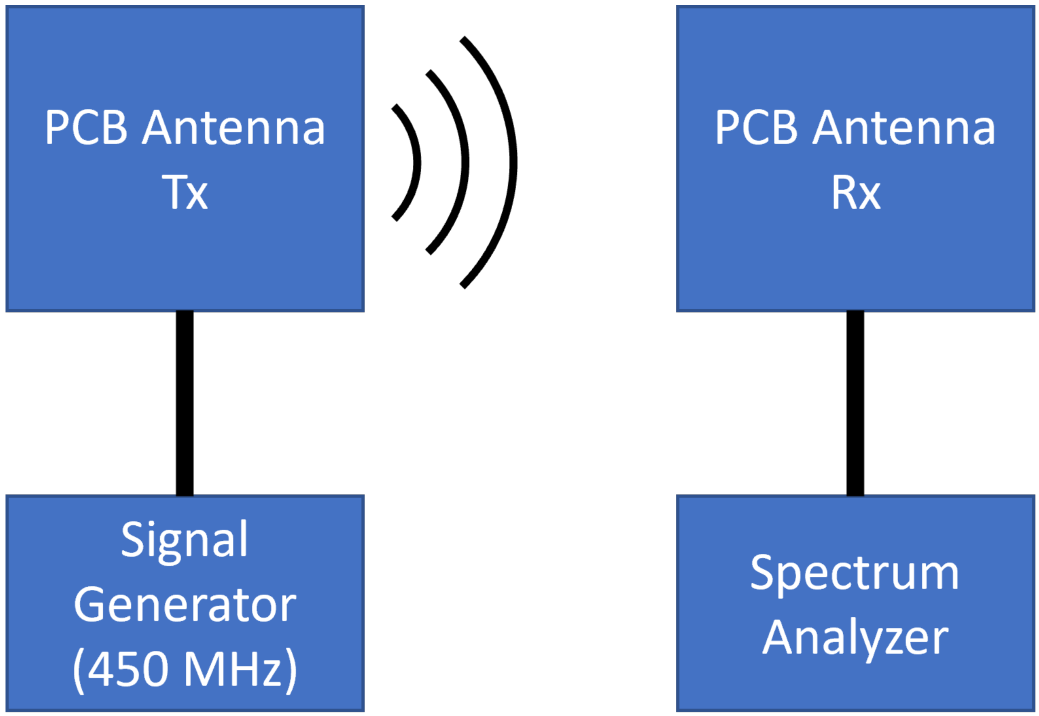

Figure 23: Experimental Setup 2

$$\begin{aligned} P_{RX} &= P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{RX} - L_{FS} \\ G_{TX} &= G_{RX} \\ L_{TX} &= L_{RX} \\ L_{FS} &= 20log(4\pi d/\lambda) \\ P_{RX} &= P_{TX} + 2G_{TX} - 2L_{TX} - 20log(4\pi d/\lambda) \end{aligned} \tag{5}$$

Equations 5 describes the experiment in experimental setup 2 in dB. It solves for the gain of the test antennas and free space loss, while utilizing the previously measured loss in the transmission and receiver lines.

Experimental set up 3, Figure 24, builds off of experimental setup 2 by replacing the receiver test UHF antenna with a CubeSat dipole antenna that will be used for the GM1 mission. The calculation of the GM1 antenna gain will be used by subtracting the dBm from experimental setup 2 along with subtracting the previous gain from the

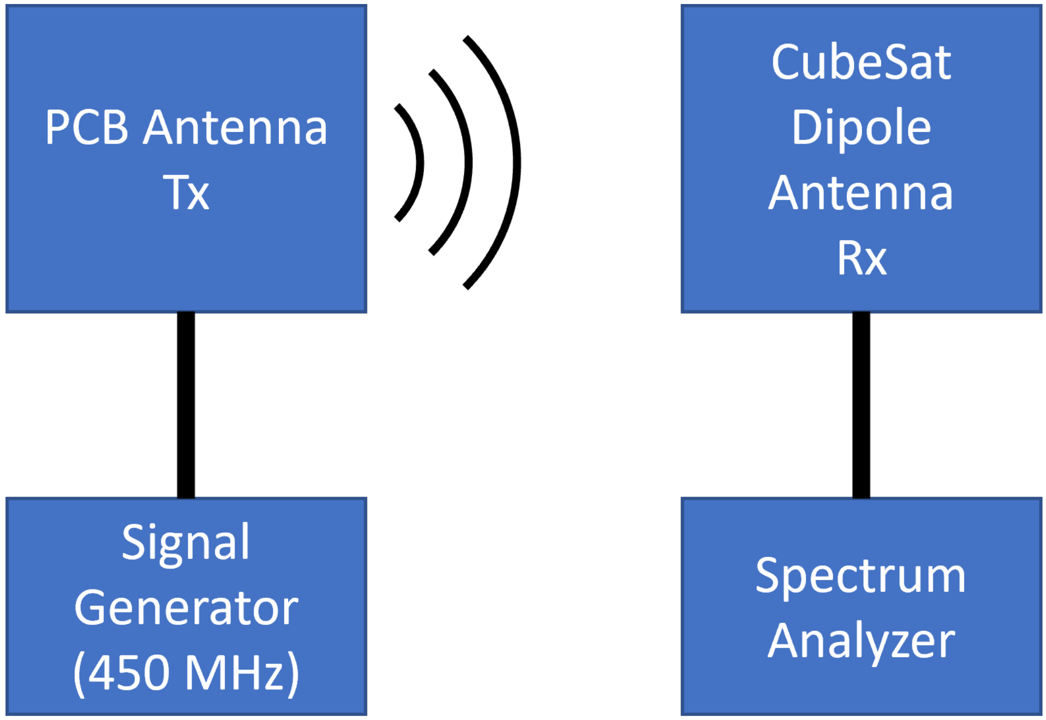

Figure 24: Experimental Setup 3

test UHF antenna also calculated in experimental setup 2. This value calculated at 450 MHz will then be used for remaining simulations and calculations for my results.

$$G_{RX} = P_{RX} - P_{TX} - G_{TX} + L_{TX} + L_{FS} + L_{RX} \tag{6}$$

Equation 6 solves for the gain of the replaced receiver antenna that will be used on the CubeSat GM1. After solving for the test antenna gain, transmission losses, and the free space loss. The reading on the Spectrum analyzer should give a measurement of what the dipole antenna gain is.

Experimental setup 4, Figure 25, demonstrates a calibration of the lab equipment for the CubeSat transmission frequency. This will detect any line loss between the Signal Generator at 2.2 GHz. This demonstration also assists in calibration of the Spectrum Analyzer to ensure the readings are consistent. Equation 4, used to solve

Figure 25: Experimental Setup 4

for the gain in setup 1, can be applied for this configuration to find the loss in the line for 2.2 GHz.

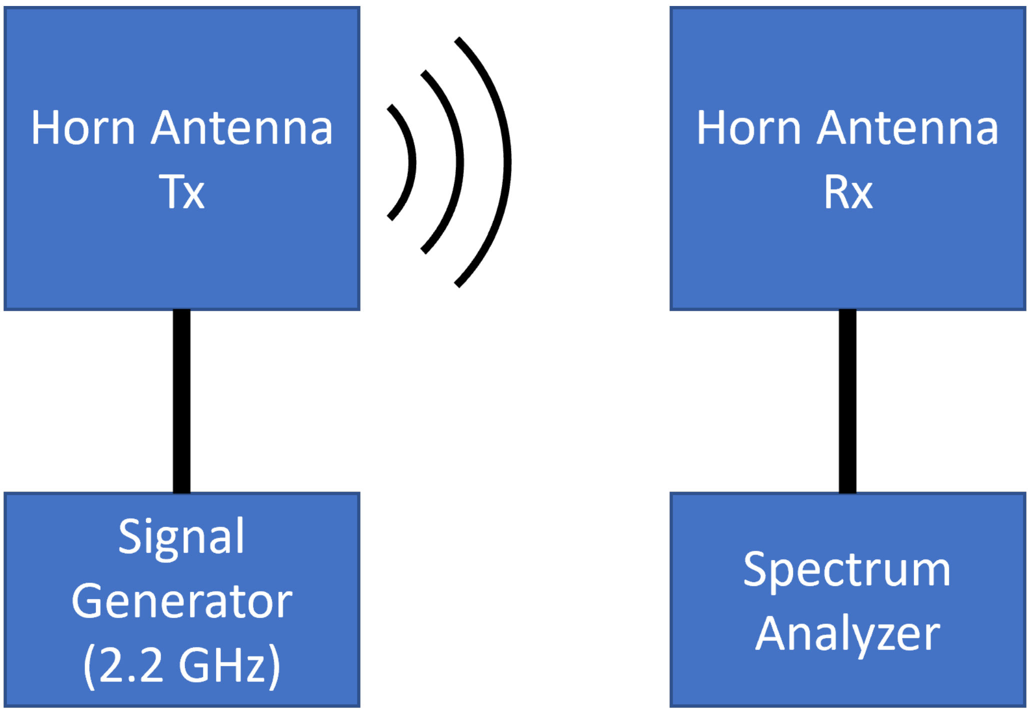

Figure 26: Experimental Setup 5

Experimental setup 5, Figure 26, begins the first calibration test to determine the dBi and free space loss calculation at 2.2 GHz. The test antennas will be made of the same material and structure and assume the same transmission and receiver gain. The SMA adapters and connectors used to reach the antennas in an anechoic chamber will be used in experimental setup 4 when conducting measurements of line loss and ensure this measurement isolates the two variables of antenna gain and free space loss. Equation 5 can be applied from setup 2 to setup 5.

$$L_{FS} = 20log(4\pi d/\lambda) = 20log(4\pi d/.1363) \tag{7}$$

Due to the change in wavelength, the equation found in experimental setup 2 can be applied, but with different numbers. The wavelength for 2.2 GHz is equal to .1363 meters and has a higher free space loss than a 450 MHz signal.

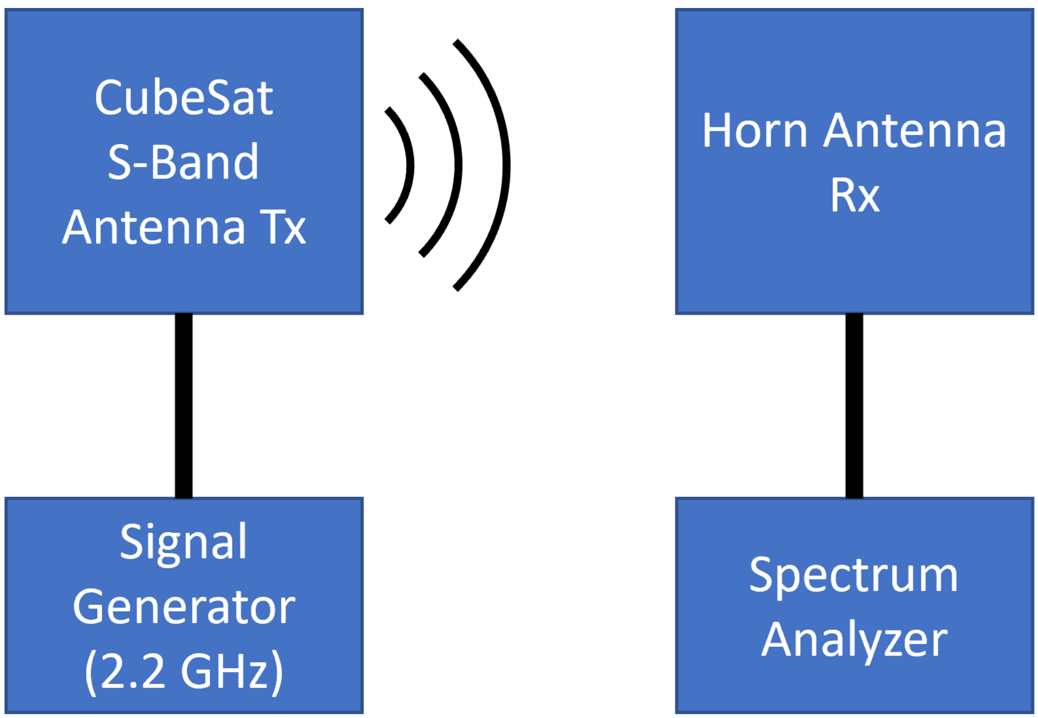

Figure 27: Experimental Setup 6

Experimental set up 6, Figure 27, builds off of experimental setup 5 by replacing the receiver Horn antennas with a CubeSat S-Band patch antenna that will be used for the GM1 mission. The calculation of the GM1 S-Band antenna gain will be used by subtracting the dBm from experimental setup 5 along with subtracting the previous gain from the Horn antenna also calculated in experimental setup 5. This value calculated at 2.2 GHz will then be used for remaining simulations and calculations for my results.

$$G_{TX} = P_{RX} - P_{TX} - G_{RX} + L_{TX} + L_{FS} + L_{RX} \tag{8}$$

Similar to Equation 5, Equation 8 solves for the replaced antenna on the transmission antenna rather than the receiver antenna. At this point the power transmitted and received along with the loss in transmission and receiver lines and free space loss have been solved and measured. This will ultimate find the true gain of the S-Band patch antenna.

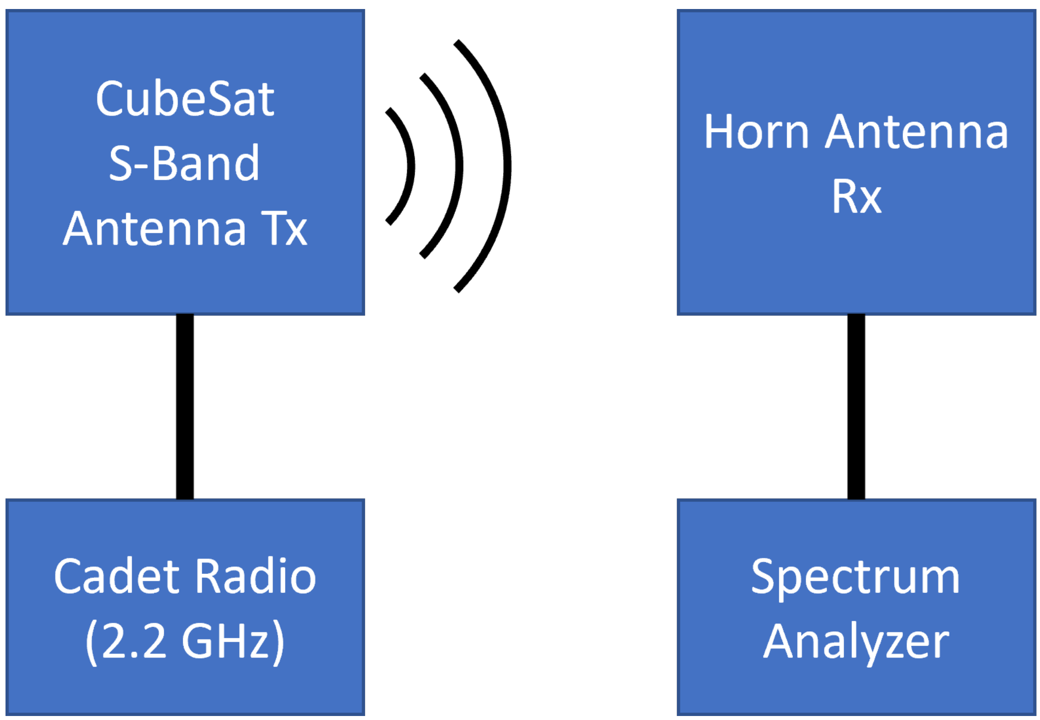

Figure 28: Experimental Setup 7

Experimental set up 7 will build off of set up 8 by replacing the Signal Generator with the Cadet Plus SDR. This test will be used to measure the signal strength that the SDR can output in power without the need for attenuation. This value calculated at 2.2 GHz will be used for the remaining simulations and calculations for my results.

$$P_{TX} = P_{RX} - G_{RX} - G_{TX} + L_{TX} + L_{FS} + L_{RX} \tag{9}$$

In Equation 9, we replace our controlled transmission power with the cadet radio. From documentation we are told that we should expect 2 Watts or 3 dBw, and by having all other components solved for this should give us the answer we are looking for when we use the spectrum analyzer to measure the received power.

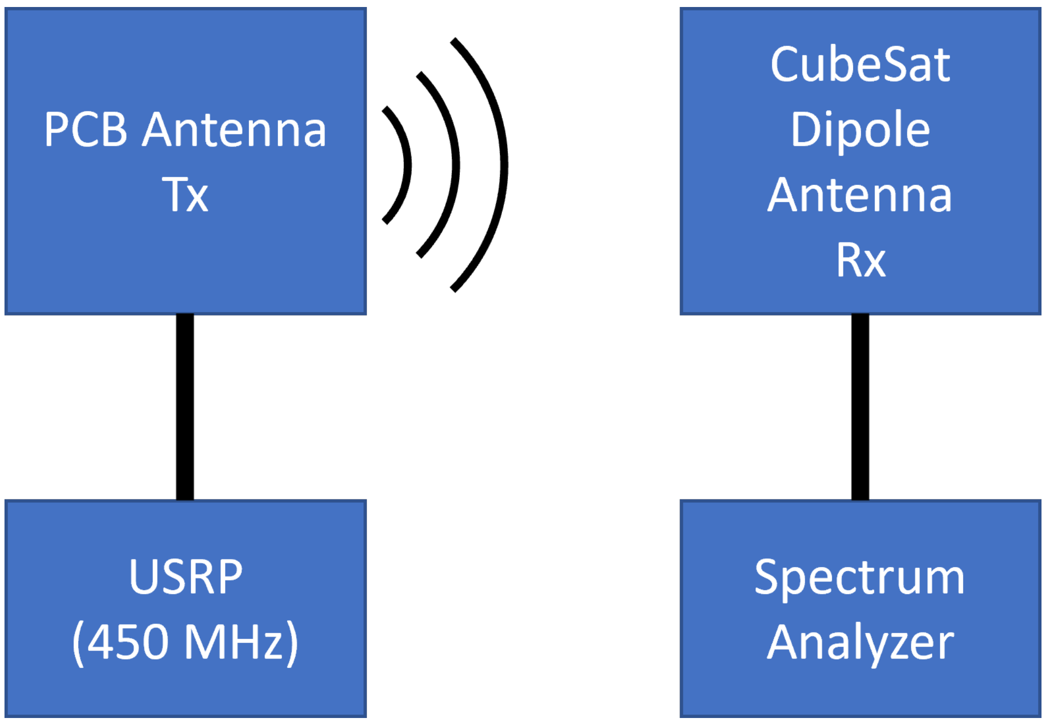

Figure 29: Experimental Setup 8

Experimental set up 8 builds off of set up 3 by replacing the signal generator with the lab USRP test radio. This radio will be used to help create a complete circuit testing of the Cadet Radio in set up 9. By measuring the signal strength of the USRP, it gives a baseline of the transmission power and also ensures that we do not provide higher power into the Cadet Plus beyond its documented limitations.

Reusing Equation 9, we apply all the solved values for 450 MHz to solve for the power output of the USRP. This value is expect to be beyond the measurement capabilities of the Cadet Radio. Because of this, connecting it directly to the radio will cause harm to the component and should not be tested in that configuration.

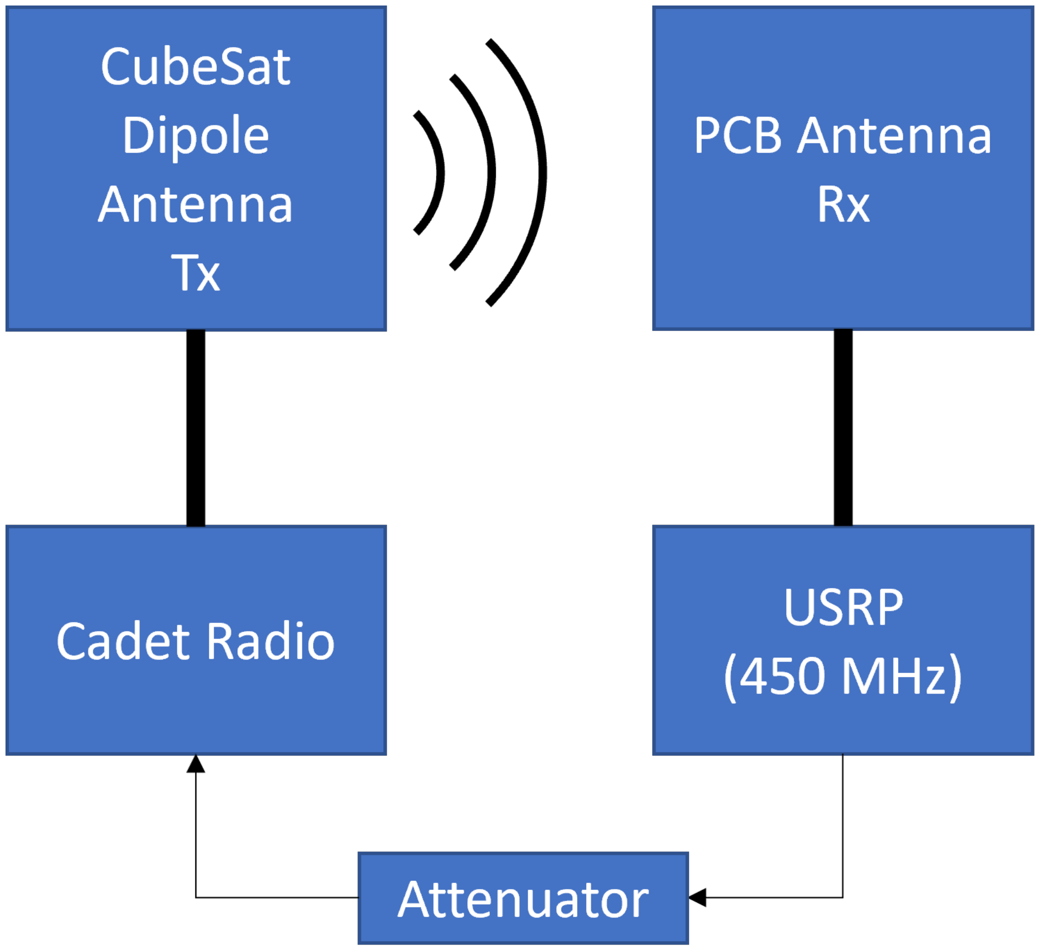

Figure 30: Experimental Setup 9

Experimental set up 9 tests a full CubeSat transmission setup to verify the cadet radio communication functionality. In this test we will also be able to measure the power usage of the cadet radio while operating under its ideal conditions. This experiment builds off the experimental setup of 7 where the Cadet radio transmits data from the radio, through the 450 MHz dipole antennae, into the test antenna. We are replacing the spectrum analyzer with the USRP SDR. The USRP will then receiver the signal from the Cadet radio, interpret the signal through the software COSMOS, and then relay a different command through an attenuated source back into the Cadet radio. This will simulate the functionality of the Cadet radio's 2.2GHz transmission ability while also receiving commands at 450 MHz.

There will be no experimental test from the USRP through free space into the Cadet Radio because the USRP is not a comparable SDR to the MC3 Networks radio. The test results would be inconclusive. Additionally, the power input into he Cadet radio is substantially lower than the output of the USRP. Due to the risk of breaking equipment, this test will be disregarded.

After completing these experimental measurements, this will allow for the simulation of a LEO, geosynchronous orbit, and Lunar ground station pass. The values for the MC3 Network will be taken as face value due to the high power of the network and the inaccuracy of conducting tests on the rooftop of AFIT.

To solve for our ground pass we will need to solve for several equations, starting with the Power received. This equation will utilize all the values solved in the experimental testing excluding the free space loss.

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{FS} - L_P - L_{RX} \tag{10}$$

To solve for the Free Space Loss, we will need to find the distance away from the Earth assuming that the orbit the GM1 CubeSat is flying in is circular. We will then need to solve all distances from the ground station at every angle from 3 to 90 degrees. We anticipate that the lower the antenna has to point, the longer the distance will be, and the higher the Free Space Loss will be. In Figure 31, we see geometry can be applied to this problem and solved at each angle change.

$$Distance = (R_{\oplus} + SatAlt)(cos(\theta + asin(((R_{\oplus})/(R_{\oplus} + SatAlt))\cos(\theta)))/\cos(\theta)) \tag{11}$$

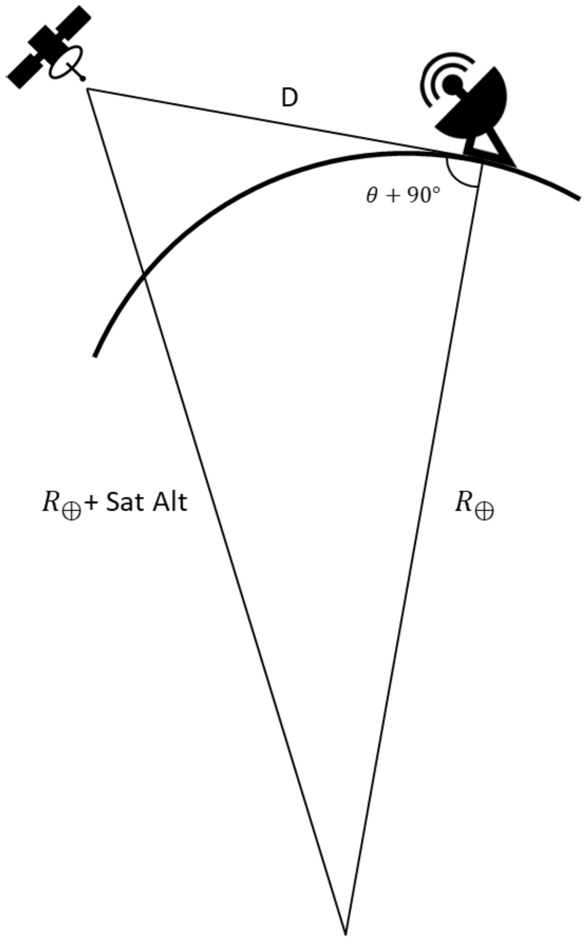

Figure 31: Radio Link Geometry

Once the Distance for all angles from 5 to 90 degrees are calculated, free space loss can be applied to each instance. This angle is one of the only things changing in the estimation of loss. Equations 12 and 13 apply to 450 MHz and 2.2 GHz respectfully. Once the Free Space Loss is solved then the equation for estimated receiver power from the CubeSat in its specified orbit and the received power expected from the CubeSat back to the MC3 Network.

$$L_{FS} = 20log(4\pi d/\lambda) = 20log(4\pi d/.66) \tag{12}$$

$$L_{FS} = 20log(4\pi d/\lambda) = 20log(4\pi d/.14) \tag{13}$$

After solving for the expected power, the expected SNR needs to be solved. This is done by taking the assigned bit rate and converting that value into a logarithmic value. After its been converted it can used to solve the SNR.

$$R_b = 10log10(R_{b_{Linear}}) \tag{14}$$

The noise floor is defined by Equation 15. This takes the noise floor that we can measure and adds a temperature constant because increased temperature will also increase the noise in the signal.

$$N_0 = -228.6 + 10log_{10}(T_s) \tag{15}$$

After solving for all variables and converting to decibels the Signal to Noise Ratio (SNR) can then be solved with simple subtraction used in Equation 16. The SNR required for communication is determined by the Bit Error Rate (BER) probability (P_b), modulation scheme, and desired Link Margin. When determining required dB for a chart can be referenced to determine the statistical loss expected when operating at a signal to noise ratio. These to values can be seen in a lookup table, or a graph like figure 32, to determine the required decibel. For each modulation scheme there is a different BER value for any given SNR.

$$E_b/N_0 = P_{RX} - N_0 \tag{16}$$

$$(E_b/N_0)_{Excess} = E_b/N_0 - LinkMargin - (E_b/N_0)_{required} \tag{17}$$

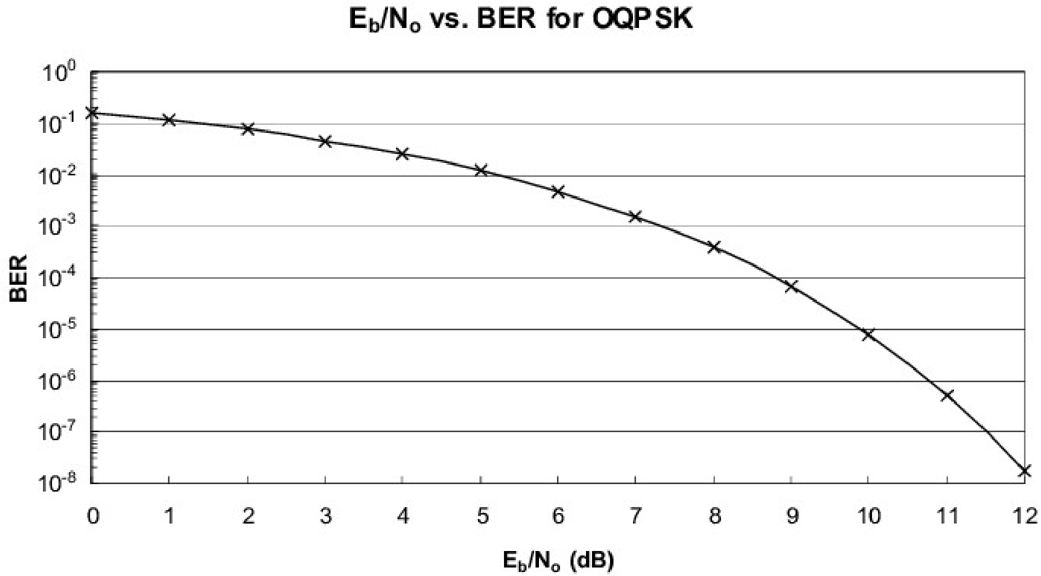

Figure 32: Bit Error Rate Probability of OQPSK Modulation [19]

The SNR excess value must be at or greater than zero otherwise the signal will be lower than the noise floor and not be interpreted by the ground station for the downlink or interpreted by the Cadet Radio for the uplink.

Once the SNR excess is calculated it allows for other variables to be changed in order to see the results. In the Results section, each equation will be solved with specific scenarios that need to be tested. They will also test all degrees of inclination from 5 to 90 in order to build an analysis of what the ground station is and is not capable of. Finally, variables will be manipulated to see what potential solution is available to close the Link Margin.

IV. Results and Analysis

4.1 Chapter Overview

This chapter details results obtained while conducting experimental test 1 through 9 along with analysis of the communication link analysis at various orbital altitudes. Each link analysis will be calculated with a view angle of 5 degrees and a nadir, or 90 degree view angle. The first analysis that will be conducted is for the current Grissom-1 Mission (GM1) and Mobile CubeSat Command and Control (MC3) configuration. To determine future missions of the GM1, there will be adjustments made the ground station to provide a solution to solve the link margin for higher altitude missions. Finally, when all results are calculated recommendations for future missions are discussed.

4.2 Experimental Testing

Through tests evaluated in the anechoic chamber antenna parameters and a functionality were tested on GM1 communications system were tested. Through simple monitoring of the system, the uplink and downlink frequencies were 450 MHz and 2.2 GHz respectively. The uplink and downlink data rates were set to 9.6 kbps for uplink and 200 kbps for downlink. The Cadet PLUS radio pulled a maximum of .38 Amps at 12.4 Volts utilizing 4.7 Watts.

In Figure 33, the signal generator configuration is shown. The settings for the signal generator are set to 450 MHz as the output frequency at a power level of 19 dBm, or 75 mW. The value of 19dBm was selected because it is the highest output power from the generator and does not exceed the power limits of the signal analyzer, Cadet PLUS Radio, or Test Software Defined Radio (SDR).

In Figure 34, the measurement is taken for experimental set up 1 shown in Figure

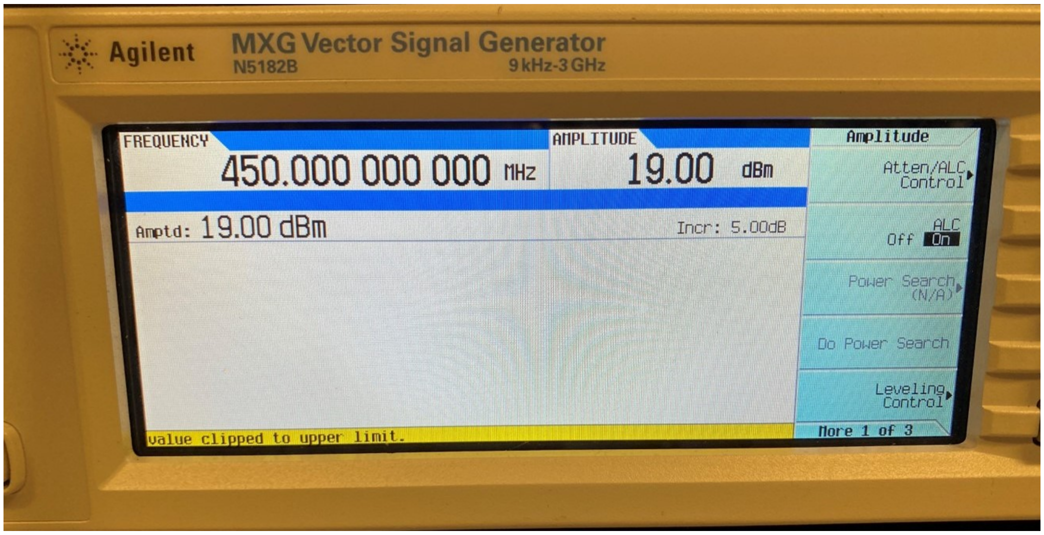

Figure 33: 450 MHz Signal Generator

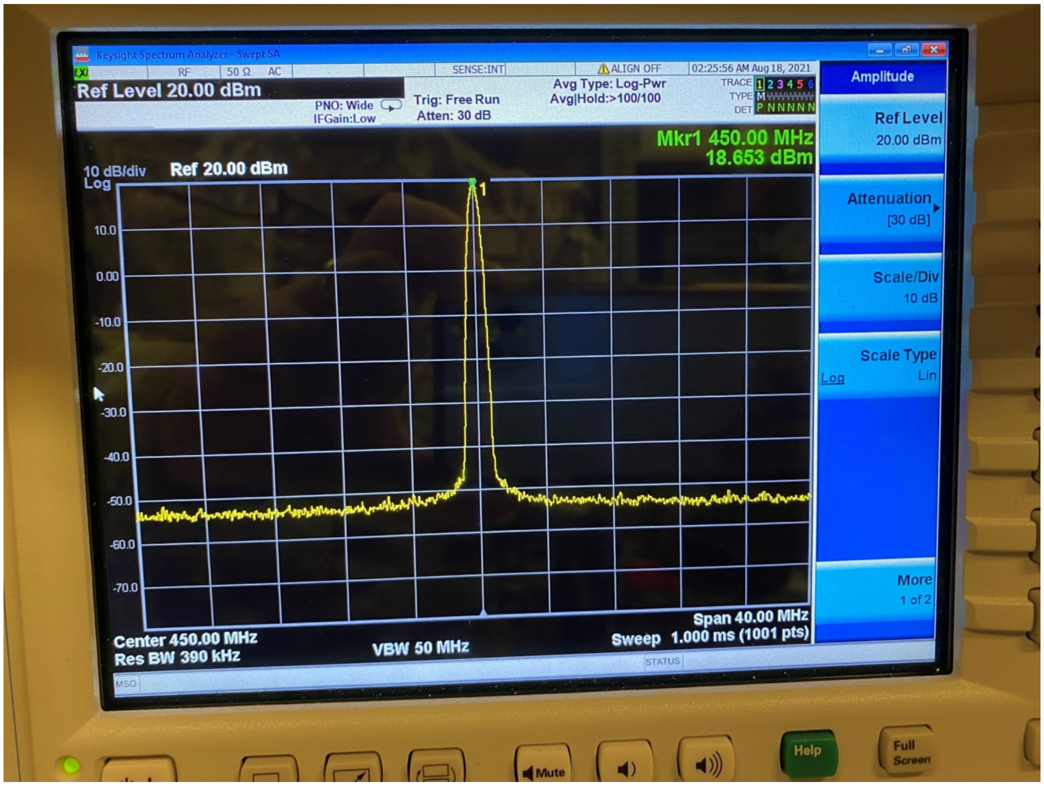

Figure 34: 450 MHz Line Loss Test

22. This value is the output power from the signal generator, through the test cables, and into the signal analyzer. The value shown is 18.653 dBm, which shows that the cables produce a .347 dB loss from the generator to the analyzer.

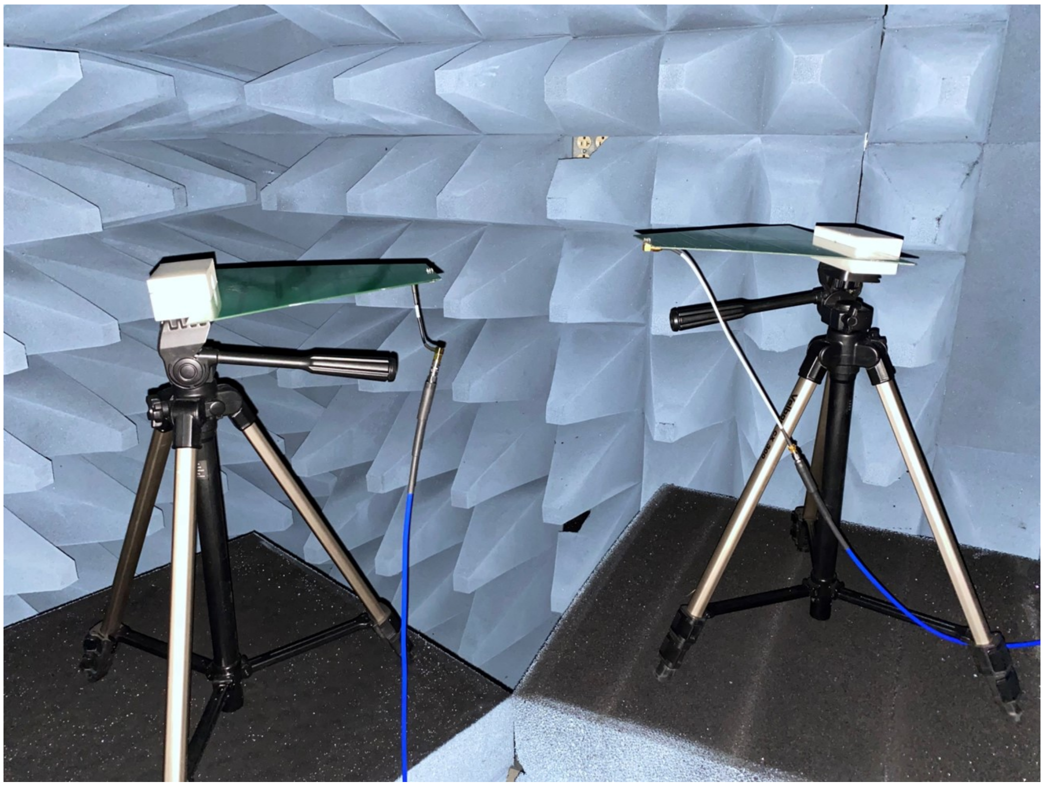

Figure 35: Free Space Loss and Test Antenna Calibration

In Figure 35, two identical UHF test antennas were connected to the signal analyzer and the signal generator and placed 30 cm apart in an anechoic chamber. The signal generator was then turned on transmitting a 19 dBm signal and then measured with the signal analyzer. This value measured is used to then verify the UHF test antenna's meet the manufacture specification, which is specified as 3 dB.

To verify that the UHF test antennas had a near 1 dB gain matching the manufactures description, the measurements conducted for 450 MHz with test antennas need to be subtracted from the measurements taken from the 450 MHz test with a single test antenna and the Grissom-1 dipole antenna. If the difference in gain is

1 dB to the test antenna's specified gain, then the Grissom-1 dipole antenna meets manufacture's description.

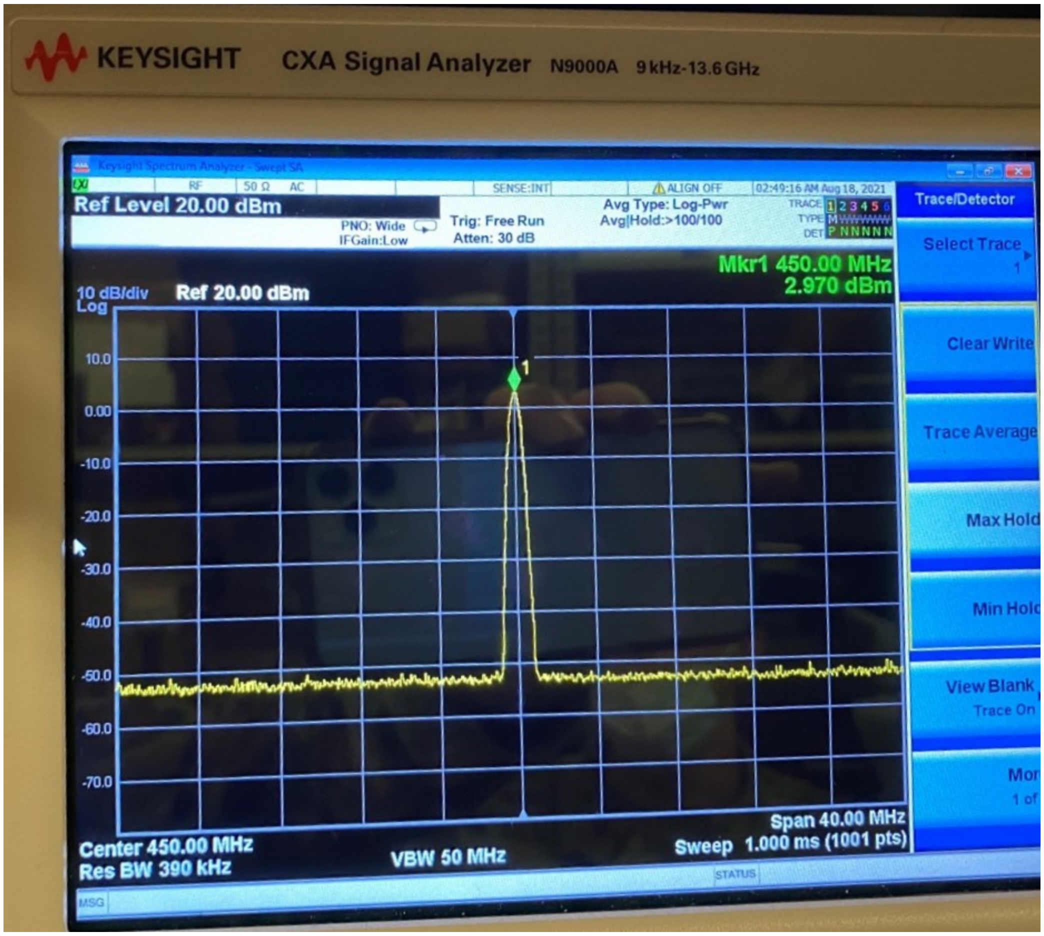

Figure 36: 450 MHz Free Space Loss and Test Antenna Calibration Measurement

In Figure 36, the measurement is taken for experimental setup 2 shown in Figure 23. The measured value on the signal analyzer is 2.97 dBm which indicates a loss of 16.03 dB from the signal that was generated. The question then is, what happened to the signal? In this experimental set up there were several loss factors that were applied to this signal that created a lower received signal. The measured value was initially assumed to be a decrease of free space loss by 15.2 dB using equation 12 with a distance of 30 cm, however when attempting to calculate the gain of each antenna, there was too much loss between connections to determine the proper value 18.

$$
\begin{aligned}
P_{RX} &= P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{RX} - L_{FS} \\
P_{RX} &= P_{TX} + 2G_{TX} - 2L_{TX} - L_{FS} \\
G_{TX} &= (P_{RX} - P_{TX} + 2L_{TX} + L_{FS})/2 \qquad (18) \\
G_{TX} &= (2.97 - 19 + .35 + 15.2)/2 \\
G_{TX} &= -.24dBi
\end{aligned}
$$

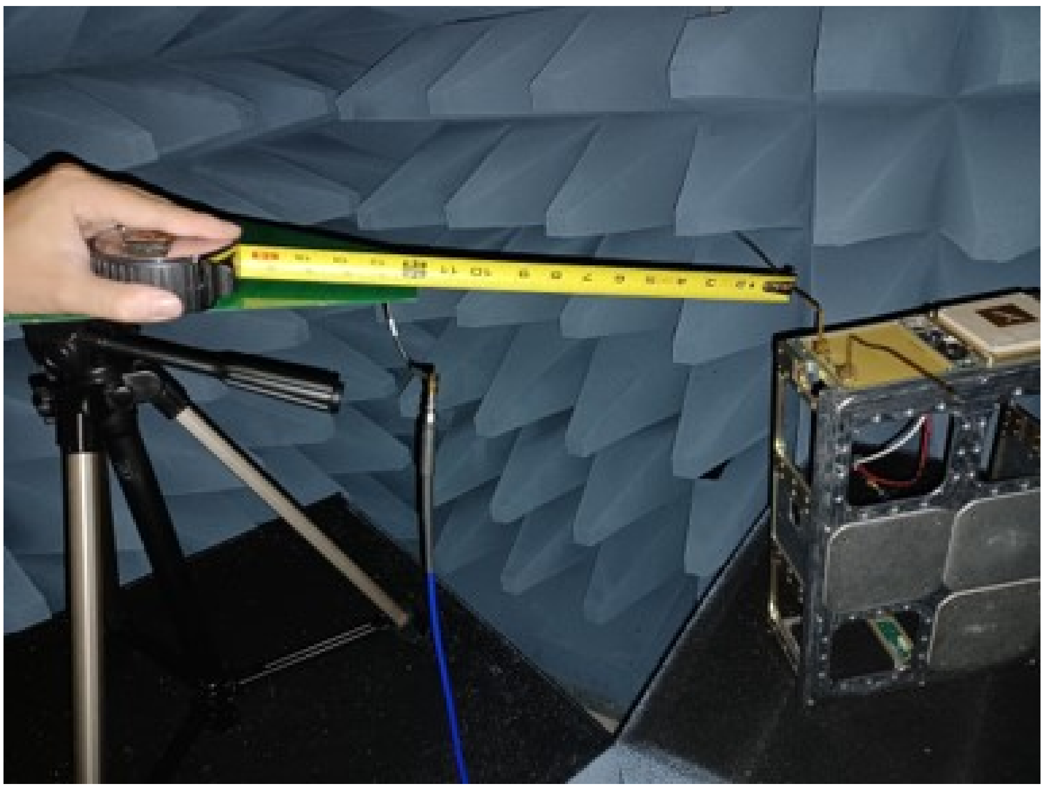

Figure 37: GM1 Dipole Antenna Test Setup

In Figure 37, we replace the UHF test antenna with the dipole antenna that is used on the GM1 CubeSat. The antennas were placed 30 cm apart and use the value of free space loss of 15.2 dB. We then apply the same equation from 18 to 19 using the new signal analyzer measurement in Figure 38.

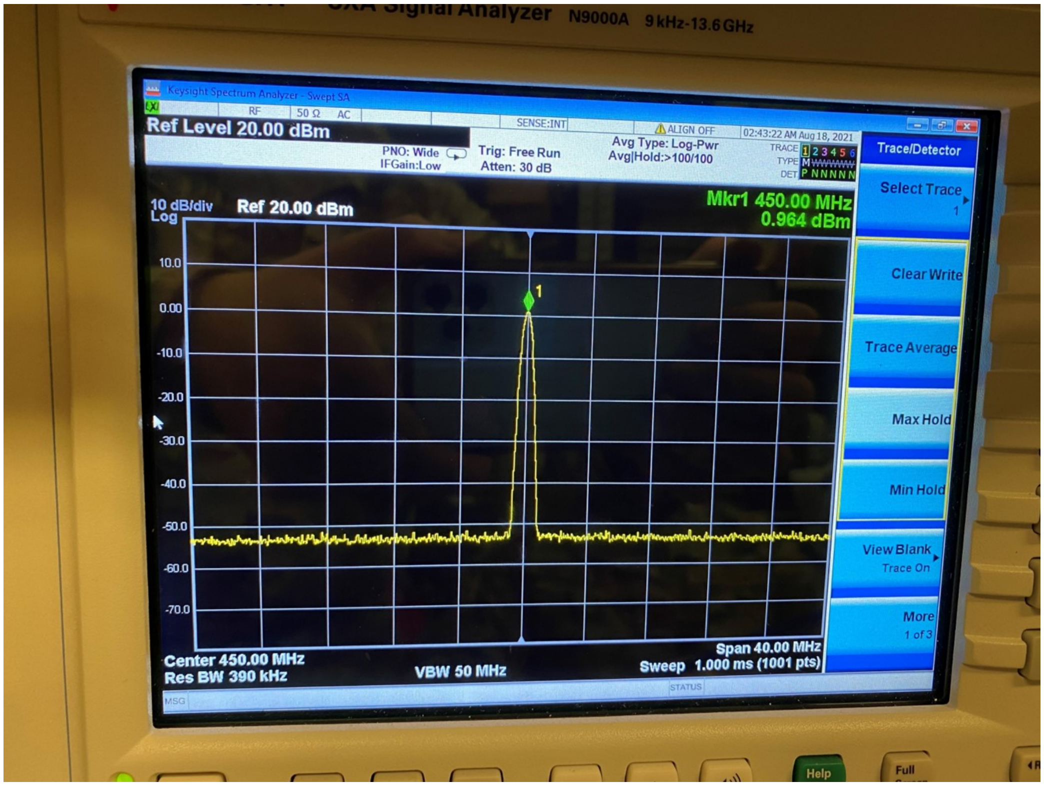

Figure 38: GM1 Dipole Antenna Measurement

$$
\begin{aligned}
P_{RX} &= P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{RX} - L_{FS} \\
P_{RX} &= P_{TX} + G_{TX} + G_{RX} - 2L_{TX} - L_{FS} \\
G_{RX} &= (P_{RX} - P_{TX} - G_{TX} + 2L_{TX} + L_{FS}) \\
G_{RX} &= (0.964 - 19 + .24 + .69 + 15.05) \\
G_{RX} &= -2.05 dBi
\end{aligned}
\tag{19}
$$

The calculated value for the 450 MHz antenna gave a negative antenna gain and a gain that is expected. This expected value does not meet the estimated the dipole antenna gain of 2.15 dBi. With the dipole antenna at quarter wavelength of 450 MHz, the measured value is -2.05 dBi is significantly different than anticipated values. This difference could be attributed to the distance apart not being far enough for a full wave to form. The maximum distance allowed in the anechoic chamber and with the available equipment could only allow for 30 cm. For the remainder of calculations, the value of 2.15 dBi will be used for all link margins.

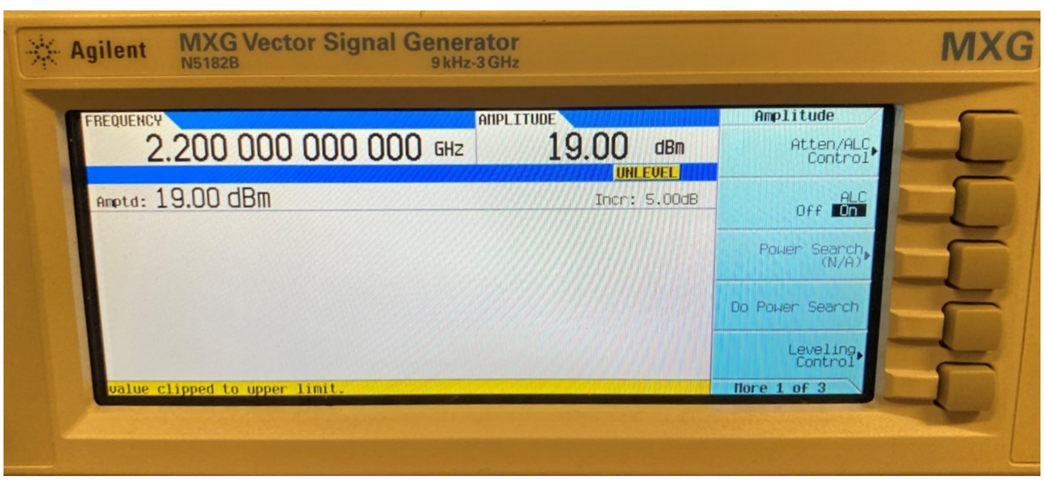

Figure 39: 2.2 GHz Signal Generator

In Figure 39, the signal generator configuration is shown. The settings for the signal generator are set to 2.2 GHz as the output frequency at a power level of 19 dBm, or 75 mW. The value of 19dBm was selected because it is the highest output power from the generator and does not exceed the power limits of the signal analyzer, Cadet PLUS Radio, or Test SDR.

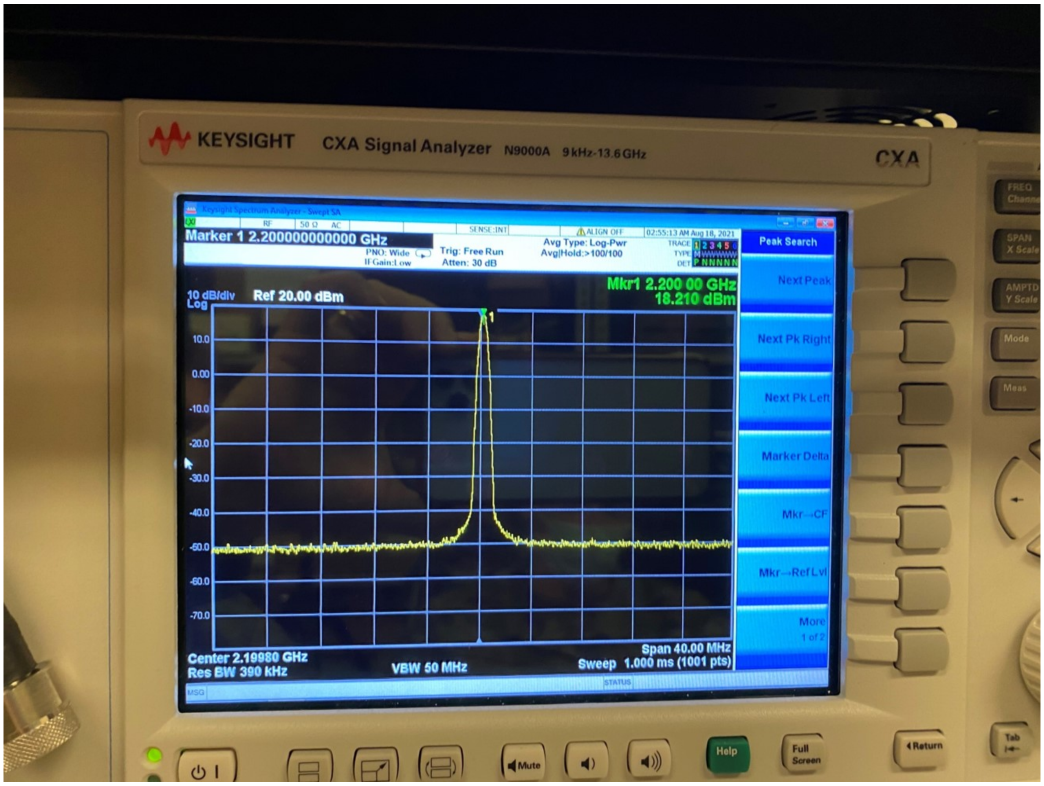

Figure 40: 2.2 GHz Line Loss Measurement

In Figure 40, the measurement is taken for experimental set up 4 shown in Figure 25. This value is the output power from the signal generator, through the test cables, and into the signal analyzer. The value shown is 18.21 dBm, which shows that the cables produce a .79 dB loss from the generator to the analyzer.

In Figure 41, two identical Horn antennas were connected to the signal analyzer and the signal generator and placed 30 cm apart in an anechoic chamber. The signal generator was then turned on transmitting a 19 dBm signal and then measured with the signal analyzer. This value measured is used to then verify the UHF test antenna's meet the manufacture specification, which is specified as 3 dB.

To verify that the S-Band test antennas had a near 5 dB gain matching the man-

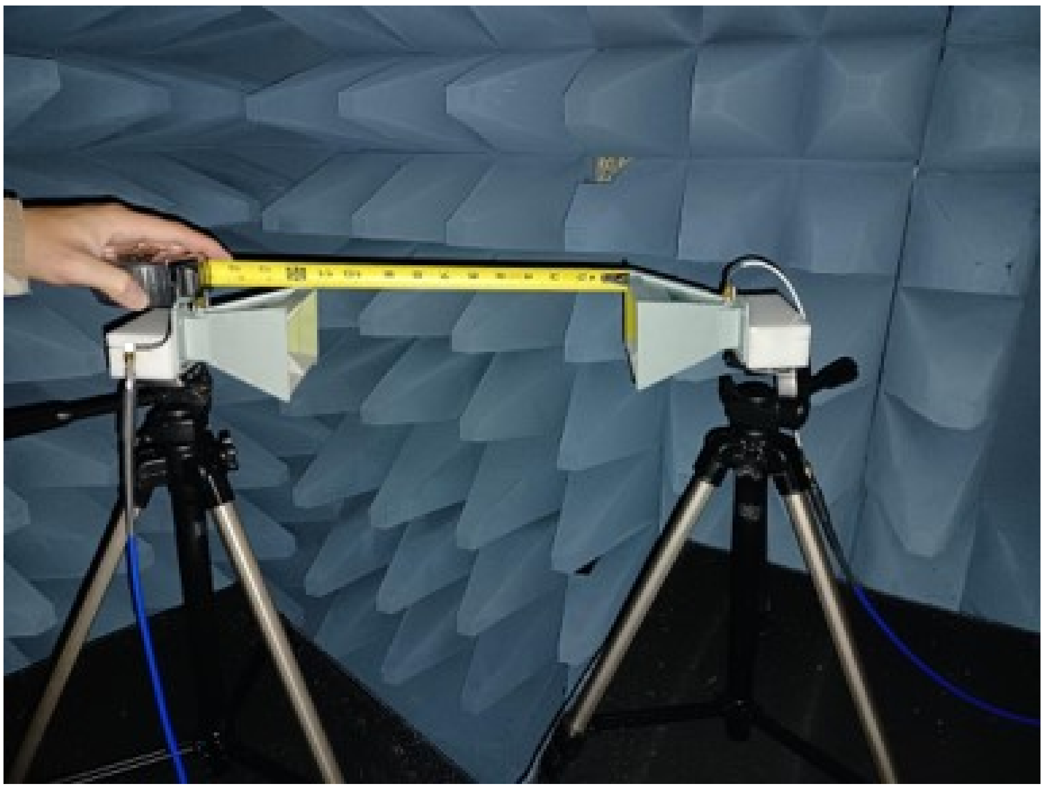

Figure 41: 2.2 GHz Free Space Loss and Test Antenna Calibration Setup

ufactures description, the measurements conducted for 2.2 GHz with test antennas need to be subtracted from the measurements taken from the 2.2 GHz test with a single test antenna and the Grissom-1 S-band patch antenna. If the difference in gain is 5 dB to the test antenna's specified gain, then the Grissom-1 S-band patch antenna meets manufacture's description.

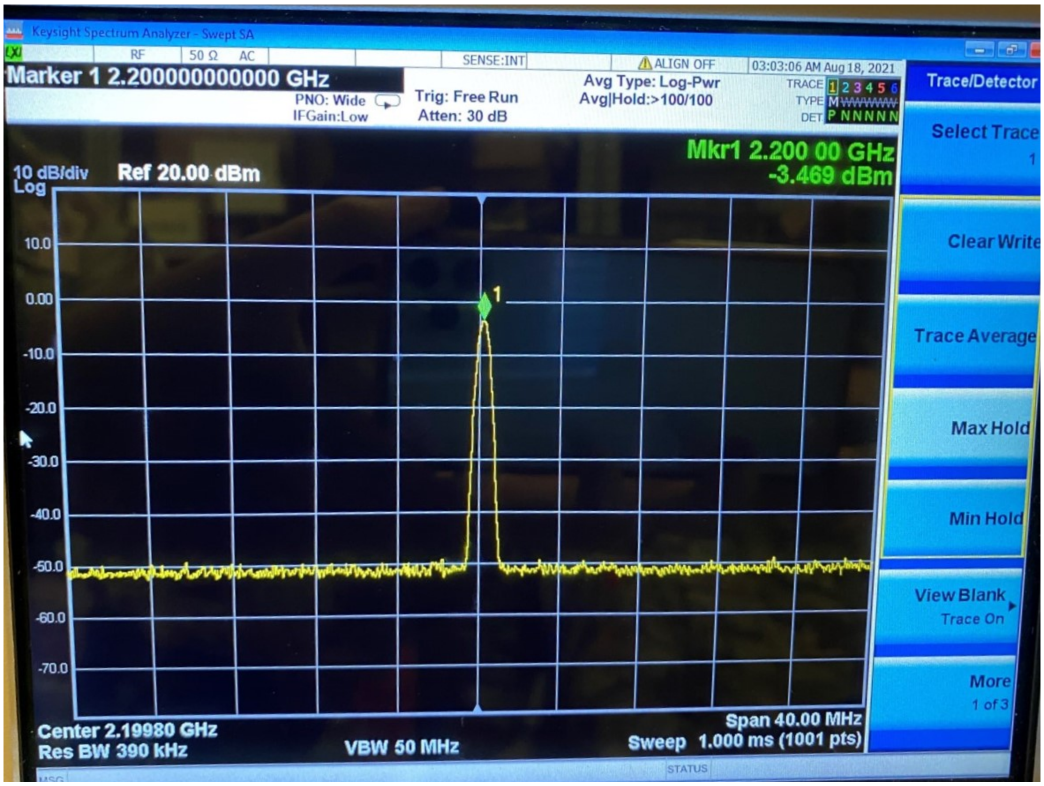

Figure 42: 2.2 GHz Free Space Loss and Test Antenna Calibration Measurement

In Figure 42, the measurement is taken for experimental setup 5 shown in Figure 26. The measured value on the signal analyzer is -3.469 dBm which indicates a loss of 22.469 dB from the signal that was generated. The measured value decrease more than the 450 MHz free space loss because the wavelength for 2.2 GHz is much smaller. The free space loss calculated from the using equation 13 with a distance of 30 cm is 28.83 dB, however after further research, the true distance is from each antenna's wave guide. This made the distance apart actually 40 cm with a free space loss of

31.3 dB. Applying these values, the solution calculated for the horn antenna gain is shown in 20.

$$G_{TX} = (P_{RX} - P_{TX} + 2L_{TX} + L_{FS})/2$$
$$G_{TX} = (-3.47 - 19 + .79 + 28.83)/2 \tag{20}$$
$$G_{TX} = 3.58dBi$$

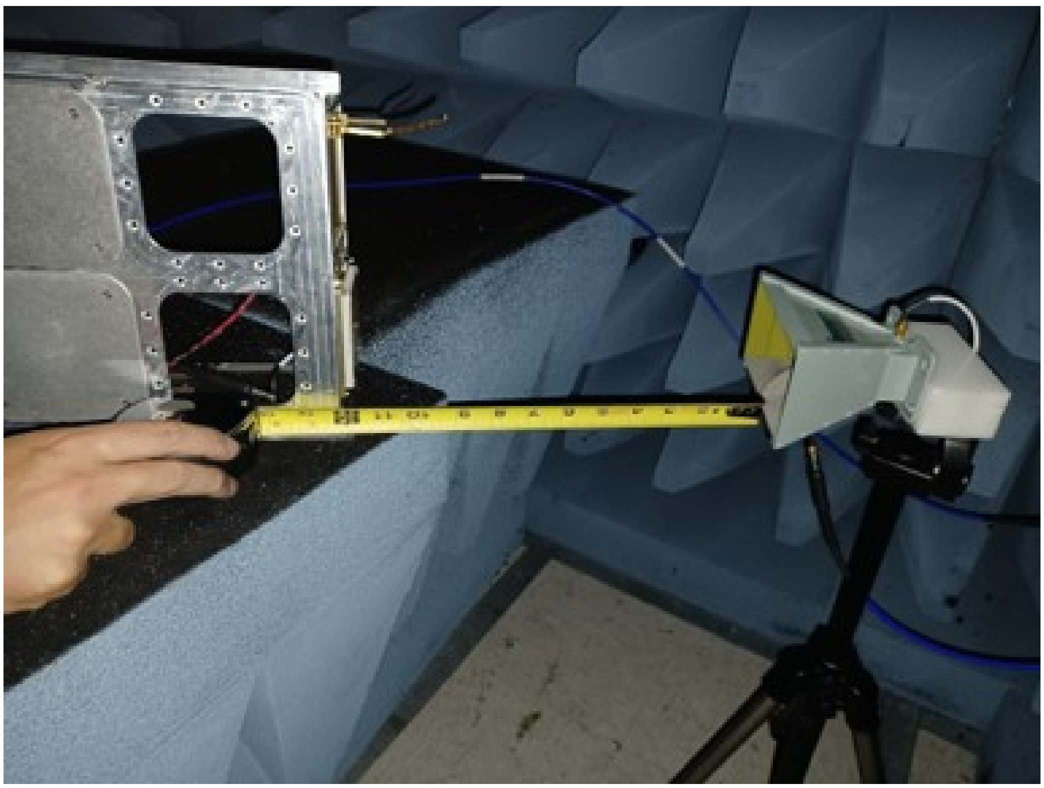

Figure 43: GM1 S-Band Patch Antenna Test Setup

In Figure 43, we replace the Horn test antenna with the S-band Patch antenna that is used on the GM1 CubeSat. The antennas were placed 35 cm apart and use the value of free space loss of 30.17 dB. We then apply Equation 19 to our 2.2 GHz, but solve for the transmitting antenna rather than the receiver antenna using the new signal analyzer measurement in Figure 38.

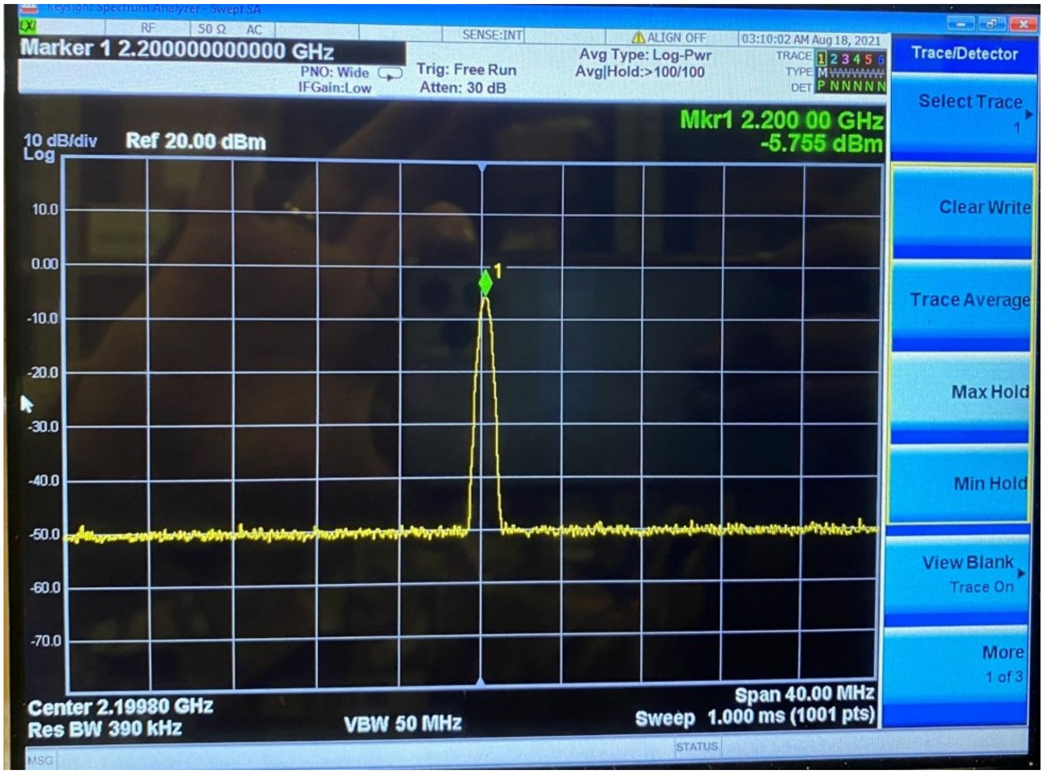

Figure 44: GM1 S-Band Patch Antenna Test Measurement

$$
\begin{aligned}
G_{TX} &= (P_{RX} - P_{TX} - G_{RX} + 2L_{TX} + L_{FS}) \\
G_{TX} &= (-5.755 - 19 - 3.58 + .79 + 28.83) \\
G_{TX} &= 1.4dBi
\end{aligned}
\tag{21}
$$

The calculated value for the 2.2 GHz antenna gave is measured at 1.4 dBi antenna gain. This value did not meet the manufacture specifications of 6 dBi which can be calculated assuming an angle of radiance of 85 degrees. This difference in measured value vs expected could also be due to not being far enough apart. This limitation is due to the small anechoic chamber and not having the ability to place the antennas further apart. For calculations moving forward the value of 6 for the S-Band patch antenna will be used.

$$
\begin{aligned}
G_T &= 29000/(\theta_{Tdeg})^2 \\
G_{TX_{S-Linear}} &= 29000/(85)^2 = \qquad 4 \\
G_{TX_S} &= 10log_{10}(4) = \qquad 6dBi
\end{aligned}
\tag{22}
$$

Using the same configuration as Figure 43 and following the flowchart shown in Figure 28, the signal generator was replaced with the Cadet PLUS Radio to test sending commands with COSMOS. The configuration of the Cadet PLUS Radio is shown in Figure 45. This test was conducted to ensure that the dBm coming out of the Cadet is low enough that it will not damage the COSMOS test SDR. As shown in Figure 46, the measured power is -13.745 dBm, or .042 mW.

Using the same configuration shown in Figure 47 and following the flowchart shown in Figure 29, using the Test SDR with an uplink of 450 MHz, the Cadet radio is set to receive OQPSK modulation. A Measurement was taken shown in Figure 48 to ensure the signal from the test SDR would not harm the Cadet Radio. After the measurement was taken, the signal analyzer was replaced with the Cadet Radio, and the output of the cadet radio (2.2 GHz) was connected tot he USRP. This was then conducted to ensure the Cadet Radio and COSMOS software can communicate with one another.

Figure 45: COSMOS Cadet PLUS Configuration

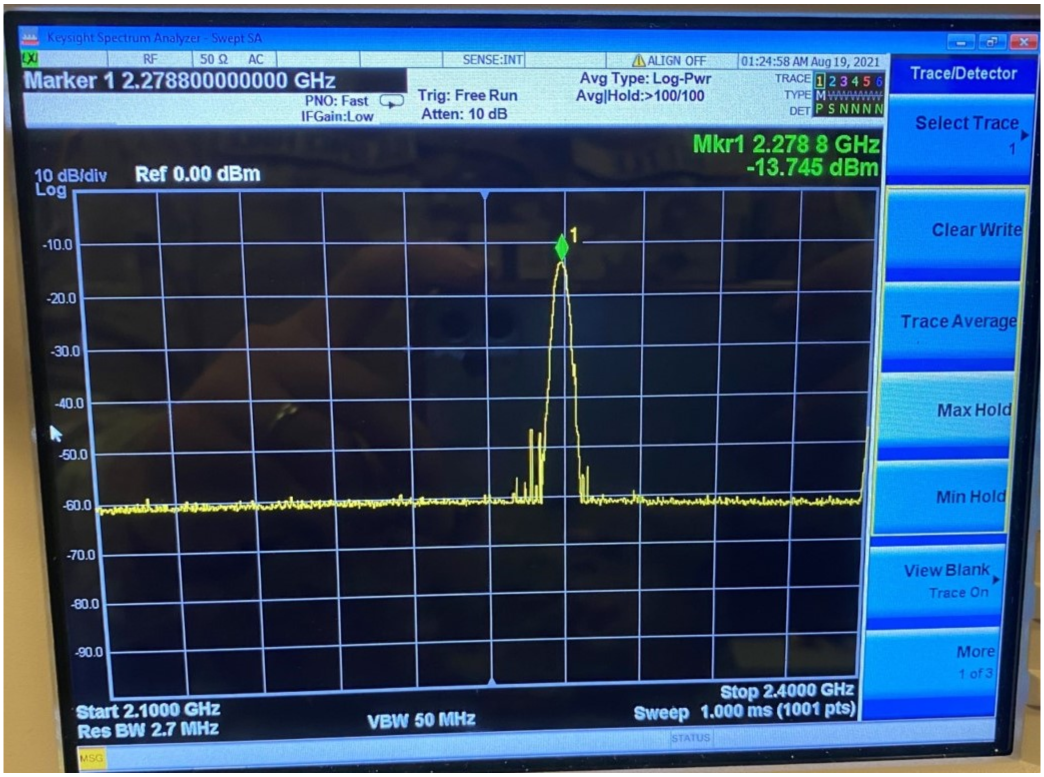

Figure 46: Experimental Cadet Radio Signal Strength

Figure 47: Cadet PLUS Uplink Test Configuration

Figure 48: Cadet PLUS Uplink Test Measurement

4.3 Link Margin Calculations

In order to determine if the GM1 CubeSat is capable of communicating with the MC3 Network, the Link Margin must be calculated. To evaluate if the communication link can successfully transmit and receive all information, the following power model must have the carrier signal above the noise floor. To calculate the Carrier signal we must incorporate all gain and loss factors with the transmission power. Once we have calculated for the Carrier signal, we can subtract the noise expected in at that wavelength. This will give us our Carrier to Noise Ratio (CNR). After calculating CNR we can subtract the bitrate (Rb), which will leave us with our Signal to Noise Ratio (SNR). Once SNR has been calculated, we can verify the required dB is above the required bit error rate and link margin.

The characterization of the MC3 network was completed in Matlab and source code can be viewed in the Appendix. While working in Matlab, the MC3 Network is defined a half sphere of the geographic location of the MC3 Node along with the GM1 Cubesat Cadet Radio and the free space loss parameter. With these three values, an SNR value was generated for each Elevation angle. In the figures that will be generated in this chapter there are three different test orbits under investigation, LEO (500 km), Geosynchronous (42,164 km), Lunar (400,000 km). Additionally, all orbits have an eccentricity of zero. The right ascension of ascending node, argument of perigee, and true anomaly are solved for initially by starting the orbit propagation above the Wright-Patterson Air Force Base (WPAFB) MC3 node. For Low Earth Orbit (LEO), the inclination is set to 90 degrees and the rotation of the earth is neglected. This is to ensure a direct overhead pass of the ground station under perfect conditions. For Geosynchronous, an inclination of 30 degrees was selected and is placed at the same latitude as the WPAFB MC3 node. Finally, the Lunar orbit is circular and placed with an inclination of 28.58 degrees to be similar to the moon. The semi major axis is also equal to the moons apogee.

4.3.1 Expected MC3 Antenna Values

For the MC3 Network, the 3-meter dish antenna is described with having a 33 dBi gain.[20] To verify that this value makes sense, a calculation of the gain can be completed using equation 23. Using an efficiency value of 60% and a transmission frequency of 2.2 GHz the antenna gain can be calculated to a value that is 1.6 dBi off from the data sheet. For all link margin calculations, 33 dBi will be used.

$$\begin{aligned} G_{RX_{S-Linear}} &= (\eta)((\pi D f_0)/c)^2 \\ G_{RX_{S-Linear}} &= (.6)(((\pi)(3)(2.2 \times 10^9)/(3 * 10^8))^2 = & 2866 \\ G_{RX_S} &= 10log_{10}(2866) = & 34.6dBi \end{aligned} \tag{23}$$

For the MC3 Network UHF antenna gain, a simple Yagi antenna gain equation can be used. The antenna is described as having a gain of 16 dBi from documentation.[20] The MC3 Network Antenna has 24 elements which is substitute for N. This theoretical value is identical to the expected value for the MC3 Yagi antenna, and will be using 16 dBi for all link margin calculations.

$$\begin{aligned} G_{TX_{UHF-Linear}} &= 1.66 * N \\ G_{TX_{UHF-Linear}} &= 1.66 * 24 = & 39.84 \\ G_{TX_{UHF}} &= 10log_{10}(39.84) = & 16dBi \end{aligned} \tag{24}$$

4.3.2 Transmitter Power

The MC3 Network utilizes a NI USRP-2922 to transmit through the UHF antenna to communicate with the GM1. The USRP is set to transmitt at 750 Watts for all communication with GM1. Additonally, the Cadet radio will be transmitting at 2 Watts for all S-Band communication to the MC3 Network. These values are converted to a decibel and will be used for the link margin calculations.

$$\begin{aligned} P_{TX} &= 10log_{10}(W) \\ P_{TX_{UHF}} &= 10log_{10}(750) = \quad 18.75dB \\ P_{TX_S} &= 10log_{10}(2) = \quad 3dB \end{aligned} \tag{25}$$

4.3.3 Atmospheric Loss

The atmospheric loss is the total loss through the air at 90 degrees and 5 degrees. If a satellite is pointing nadir to the ground station, there is a shorter distance the wavelength must travel through the Earth's atmosphere. Using equation 26, the maximum and minimum expected loss from the atmosphere is calculated for both uplink and downlink frequencies at 90 and 5 degrees.

$$\begin{aligned} L_{AA90_{UHF}} &= 0.3 \\ L_{A_{UHF_{min}}} &= L_{AA90_{UHF}}/(sin(90) = \quad 0.3dB \\ L_{A_{UHF_{max}}} &= L_{AA90_{UHF}}/(sin(5) = \quad 3.44dB \\ L_{AA90_S} &= 0.03 \\ L_{A_{S_{min}}} &= L_{AA90_S}/(sin(90) = \quad 0.03dB \\ L_{A_{S_{max}}} &= L_{AA90_S}/(sin(5) = \quad 0.34dB \end{aligned} \tag{26}$$

4.3.4 Free Space Loss

The main loss factor that drives the ability for the MC3 Network to communicate with the GM1 is Free Space Loss. This loss factor is the only dynamic condition when calculating the signal strength of the GM1 link margin. The transmit power, antenna gains, transmit line loss, atmospheric loss, receiver loss, data rate, and noise are all static values throughout the ground pass that is a one time calculation per orbit. With the free space loss, described by Equation 27 calculated per elevation angle, this then allows a calculation from 0 - 90 degrees of signal strength in dB.

$$L_{FS} = 20 * log_{10}(4\pi * D * f/c) \tag{27}$$

Free Space Loss	450 MHz [dB]	2.2 GHz[dB]
LEO (Min)	139.49	153.30
LEO (Max)	151.86	165.60
Geosynchronous (Min)	176.59	190.30
Geosynchronous (Max)	177.79	191.57
Lunar (Min)	197.55	211.30
Lunar (Max)	197.68	211.45

Table 3: Anticipated Free Space Loss by Orbit Altitude

Utilizing the signal strength can indicate if communication is possible with the Grissom-1 CubeSat when it is in a line-of-site. At lower elevation angles there is a farther distance between the CubeSat and the ground station, which indicates the higher free space loss. However, when this is calculated for a CubeSat in a geosynchronous or Lunar orbit, the difference in distance at 5 and 90 degrees look very similar because of the relative distance increase.

The distance away from the ground station in a circular orbit can calculated, shown in Equation 11 and Figure 31, using the Law of Sine rearranged to calculate only the opposite length if the hypotenuse is the satellite altitude from the center of the earth and the adjacent length is the altitude of the ground station from the center of the earth. After solving for the distance of the ground station to the satellite per every elevation angle degree, it can be saved into a matrix and then correlated to calculate the free space loss at any given frequency.

After calculating the distance from the ground station at every integer per elevation angle in a circular LEO mission, the free space loss can be calculated to determine if the Link margin can be solved. As shown in Fig. 49, the closer to a nadir angle, or 90 degrees, the less free space loss interferes with the communication subsystem.

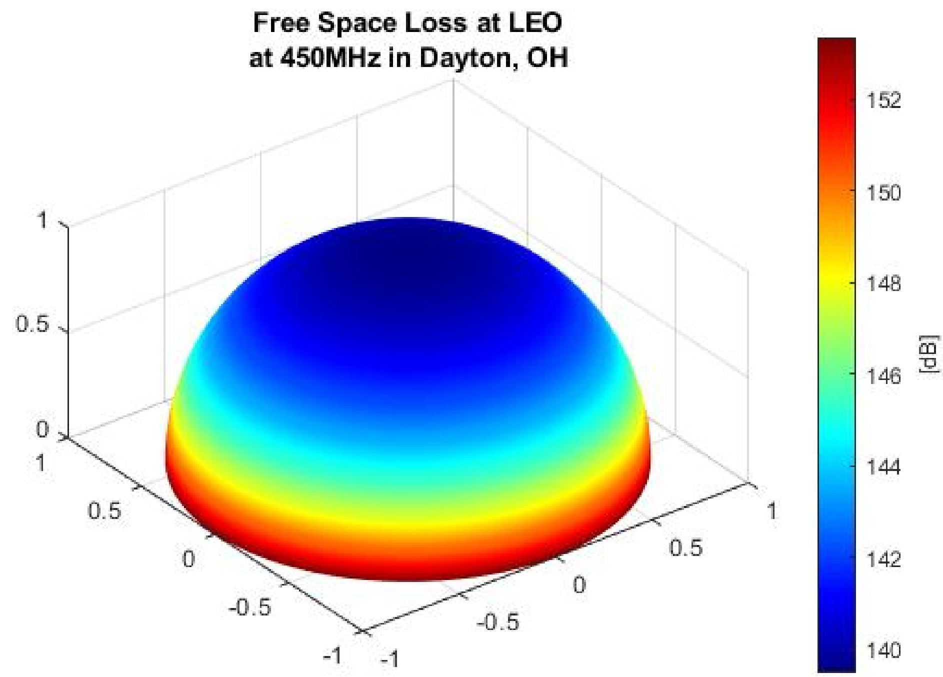

Figure 49: L_{FS} vs $Degree$

4.3.5 Bit Rate

Bit rate, or Rb, is a set data speed used to communicate between the Cadet Plus Radio and the MC3 Network. The values selected by the GM1 team are 9.6 kbps for 450 MHz and 200 kbps for 2.2 GHz. These two data rates are listed within the Cadet configuration documentation as programmable data rates. If we wanted to decrease the bit rate for either uplink or downlink, we would have to reference the data sheet for both the GM1 hardware and the MC3 hardware. For potential future missions, a lower bit rate of 600 bps is available for the lowest downlink data rates.

To utilize the bit rate value and incorporate it into our carrier signal, we need to convert these values in to a dB. Once converted this value can then be added to our signal to determine the carrier signal.

$$\begin{aligned} R_b &= 10log_{10}(bps) \\ R_{b_{UHF}} &= 10log_{10}(9600) = \quad 39.8dB \\ R_{bS} &= 10log_{10}(200000) = \quad 53.01dB \end{aligned} \tag{28}$$

4.3.6 Carrier Signal

The carrier signal is a modulated signal containing information used to communicate between a transmitter and receiver. The signal is denoted in dB as the power detected by the receiver. As shown in Equation 29, to calculate the carrier signal the transmission power and antenna gains are added and all losses are subtracted from the signal. In Table 4, the carrier signal is calculated for all orbits at their minimum and maximum values. This signal can be used to determine SNR. To determine the SNR, the Bit Error Rate (BER) can be subtracted from the carrier signal and determine if the properly receiver can demodulate the signal.

$$
\begin{aligned}
C_{UHF_{min}} &= P_{TX_{UHF}} + G_{TX_{UHF}} + G_{RX_{UHF}} - L_{FS_{UHF_{min}}} - L_{A_{UHF_{min}}} \\
C_{UHF_{min}} &= 18.75 + 16 + (-2.1) - 139.5 - .3 \\
C_{UHF_{min}} &= -107.14dB \\
C_{UHF_{max}} &= P_{TX_{UHF}} + G_{TX_{UHF}} + G_{RX_{UHF}} - L_{FS_{UHF_{max}}} - L_{A_{UHF_{min}}} \\
C_{UHF_{max}} &= 18.75 + 16 + (-2.1) - 151.9 - 3.44 \\
C_{UHF_{max}} &= -122.66dB \\
C_{S_{min}} &= P_{TX_S} + G_{TX_S} + G_{RX_S} - L_{FS_{S_{min}}} - L_{A_S} \\
C_{S_{min}} &= 3 + 6 + 33 - 153.3 - .03 \\
C_{S_{min}} &= -120.55dB \\
C_{S_{max}} &= P_{TX_S} + G_{TX_S} + G_{RX_S} - L_{FS_{S_{max}}} - L_{A_S} \\
C_{S_{max}} &= 3 + 6 + 33 - 165.6 - .34 \\
C_{S_{max}} &= -123.94dB
\end{aligned}
\tag{29}
$$

Carrier Signal	450 MHz [dB]	2.2 GHz[dB]
LEO (Min)	-107.14	-115.95
LEO (Max)	-122.66	-128.54
Geosynchronous (Min)	-144.24	-152.95
Geosynchronous (Max)	-148.59	-154.57
Lunar (Min)	-165.20	-173.95
Lunar (Max)	-168.48	-174.45

Table 4: Carrier Signal Strength by Orbit Altitude

4.3.7 E_b

To calculate the Signal (E_b), we will need to subtract the bit rate. As seen in equation 30, if the carrier signal and the bit rate values are in decibel, then a simple subtraction will give the E_b value desired.

$$E_b = C - R_b \tag{30}$$

E_b	450 MHz [dB]	2.2 GHz[dB]
LEO (Min)	-146.94	-168.96
LEO (Max)	-162.46	-181.61
Geosynchronous (Min)	-184.04	-205.96
Geosynchronous (Max)	-188.39	-207.58
Lunar (Min)	-205.00	-226.96
Lunar (Max)	-208.28	-227.46

Table 5: Signal Strength by Orbit Altitude

4.3.8 N_0

Noise is calculated using Boltzmann's constant and converted to a decibel. The standard value of Noise is -228.6 dB and the values of Ts = 219 K for 450 MHz and Ts = 135 K are converted to a decibel, 23.4 for 450 MHz and 21.3 for 2.2 GHz, to generalize the temperature in clear weather [6]. With these values we can calculate a bandwidth-independent ratio of carrier power to noise power spectral density.

$$\begin{aligned} N_{0_{Linear}} &= kT_s = & (1.38 \times 10^{-23})T_s \\ N_0 &= 10log_{10}(k) + 10log_{10}(T_s) = & -228.6 + 10log_{10}(T_s) \\ N_{0_{UHF}} &= -228.6 + 23.4 = & -205.2dB \\ N_{0_S} &= -228.6 + 21.3 = & -207.3dB \end{aligned} \tag{31}$$

4.3.9 Signal to Noise

The SNR ratio, or E_b/N_0, is a ratio of the signal strength between the transmitted signal and the noise at its given frequency. To solve for this value we simply take the difference between the signal and noise. In Table 6, we see the SNR values for the GM1 and MC3 Node at WPAFB.

E_b/N_0	450 MHz [dB]	2.2 GHz[dB]
LEO (Min)	53.26	38.34
LEO (Max)	42.74	25.69
Geosynchronous (Min)	21.16	1.34
Geosynchronous (Max)	16.81	-0.28
Lunar (Min)	.20	-19.66
Lunar (Max)	-3.08	-20.16

Table 6: Signal to Noise Ratio by Orbit Altitude

For all altitudes, the uplink configuration is transmitting at 450 MHz, at 9.6 kbps, and utilising OQPSK modulation and the downlink configuration is transmitting at 2.2 GHz, at 200 kbps, and utilizing a GFSK. In Figures 50 and 51, we can see the differences between altitudes and how the ability to detect the SNR is more difficult at higher orbital altitudes.

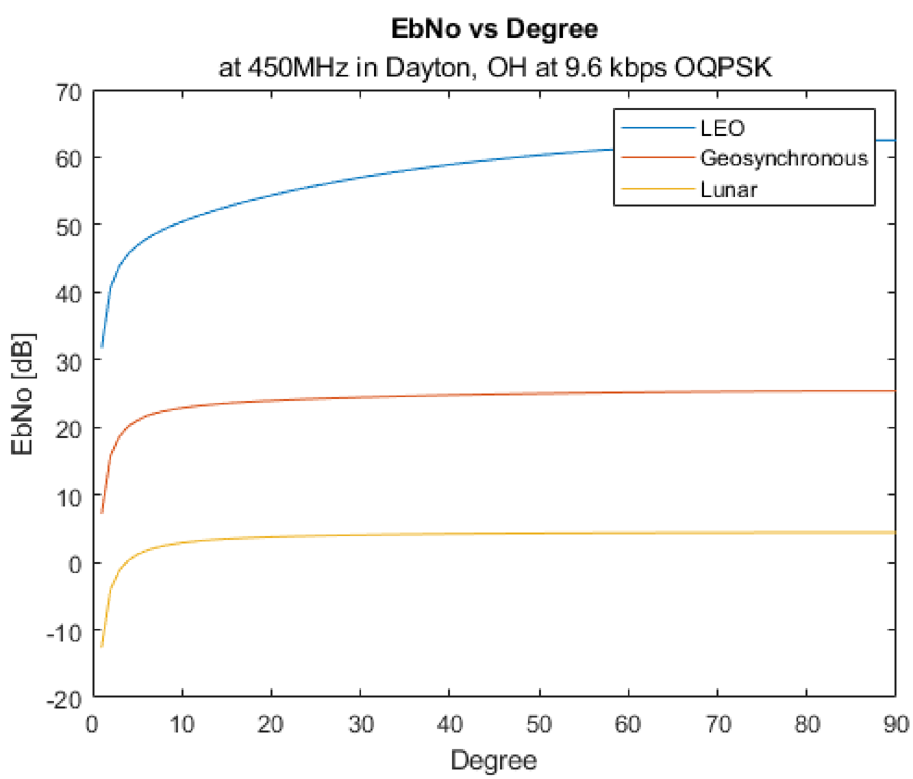

Figure 50: E_b/N_0 *vs Degree* 450 MHz

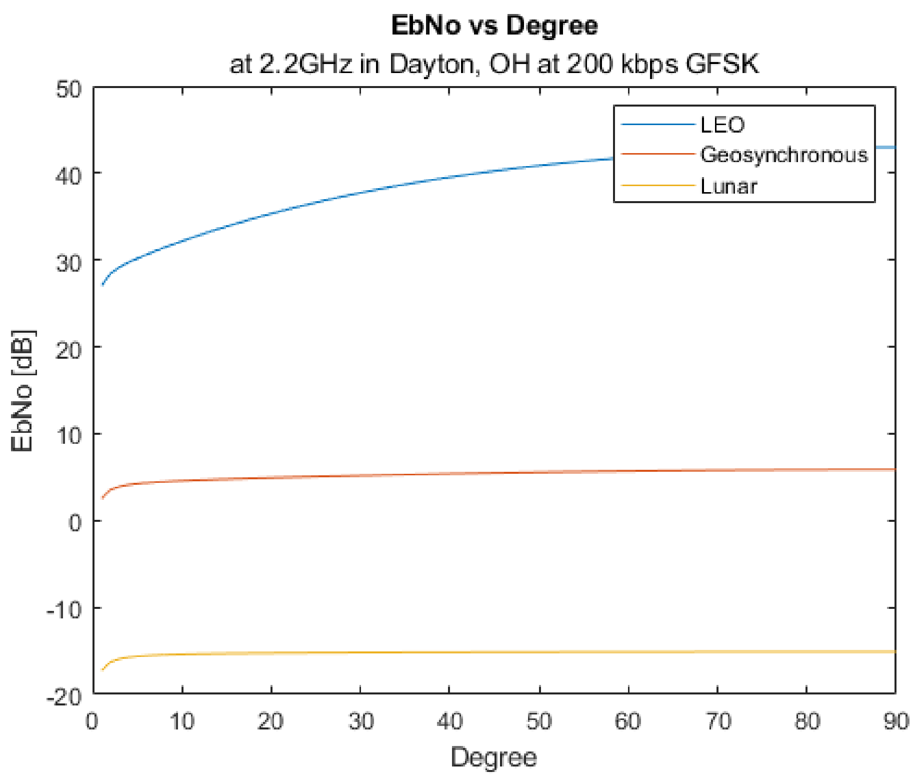

Figure 51: E_b/N_0 *vs Degree* 2.2 GHz

4.3.10 Link Margin and Bit Error Rate

The GM1 team selected 10 dB for the link margin as the SMAD[6] recommends this value to mitigate risk. This risk mitigation ensures that if other losses begin to appear or antennas and transmitters are not operating at their expected values, there is still room to ensure a strong connection can be achieved.

Bit Error Rate is selected based off how many errors are acceptable in per unit of bits. Utilizing OQPSK and GFSK and having a bit error rate allowable of 10^{-5}, the 450 MHz BER is 10 dB and 2.2 GHz is 15 dB

4.4 Link Margin Analysis

After completing all experimental tests and taking measurements, the following values were calculated for the MC3 GM1 communication link.

Uplink/Downlink Characterization	450 MHz [dB]	2.2 GHz[dB]
TX Power	18.75	3
TX Antenna	16	1.4
RX Antenna	-2.1	33
Atmosphere loss (Min)	0.3	0.05
Atmosphere loss (Max)	3.45	0.4
Signal Noise	205.2	207.3
Link Margin	10	10
Bit Rate	39.8	53.01
Required Bit Error Rate	10	15
Signal to Noise Ratio (Min)	177.75	166.64
Signal to Noise Ratio (Max)	174.60	166.29

Table 7: Current GM1 Communication Subsystem Characteristics

Table 8 shows the complete analysis of the GM1 communicating with the MC3 Network in their current configuration. For the anticipated 2023 launch of the GM1 into a low Earth orbit the link margin will be closed at all angles from 5 to 90 degrees when communicating with the Air Force Institute of Technology (AFIT)

E_b/N_0 above margin	450 MHz [dB]	2.2 GHz[dB]
LEO Min	42.51	17.94
LEO Max	26.99	5.29
Geosynchronous Min	5.41	-19.06
Geosynchronous Max	1.06	-20.68
Lunar Min	-15.55	-40.06
Lunar Max	-18.83	-40.56

Table 8: Current GM1 Communication Subsystem Link Analysis

ground station, however any higher altitude for the Grissom bus is not recommended as it will be outside of the 2.2 GHz communication abilities.

4.4.1 Geosynchronous Orbit Link Margin Correction

For this analysis, the geosynchronous orbit maximum distance away requires an inclination above 45 degrees before the ground station transmission antenna is at 5 degrees, but will have a gain above zero at any look angle above. To correct the link margin required for communication at a geosynchronous orbit, we will only need to increase the SNR at 2.2 GHz. We can ignore the negative SNR above link margin because the MC3 ground station will not be required to look below 11 degrees at the current orbit.

To increase the 2.2 GHz signal there are four options, increase the transmission power, increase the gain of the transmission antenna, increase the gain of the receiver antenna, or lowing the bit rate. The last thing that should be modified is any hardware on the GM1 CubeSat. The build of the cubesat should stay consistent between missions to create a standard bus and flight heritage. Any changes to this satellite will require testing the build to ensure that the satellite is flight ready. If the satellite is kept consistent, then only the payload will be the modification of the cubesat and will ensure all standard subsystems will operate normally.

Due to limited ability to change the transmission power and transmission antenna, we are left with two options, change the receiver antenna or decrease the bit rate. For specifically GEO, the best low cost option would be to change the bit rate. A CubeSat placed in geostationary or geosynchronous orbit synchronises orbit over an MC3 Node will keep in contact with the ground station through its entire orbit if the inclination is relatively small. By changing the downlink bit rate we can decrease the loss effects of the bit rate from 53.01 to 27.78 dB. This is decreasing the currently set bit rate from 200 kbps to 600 bps. The adjustment in bit rate leads to a closed link margin for geosynchronous orbit.

E_b/N_0 above margin (Lower Rb at 2.2 GHz)	450 MHz [dB]	2.2 GHz[dB]
LEO Min	42.51	43.17
LEO Max	26.99	30.52
Geosynchronous Min	5.41	6.17
Geosynchronous Max	1.06	4.55
Lunar Min	-15.55	-14.83
Lunar Max	-18.83	-15.33

Table 9: Geosynchronous Modified SNR Over Link Margin and BER by Orbit Altitude

4.4.2 Lunar Orbit Link Margin Correction

In order for the GM1 CubeSat to communicate from a distance the same as the moon, there will need to be adjustments made for both 450 MHz and 2.2 GHz. These corrections could be increasing the transmission power, gain of the transmission antenna, the receiver antenna, or lowing the required bit rate. For 450 MHz, we can make adjustments to the transmission power transmission antenna, and data rate. For the easiest solution, replacing the SDR with a 7.5 kW output allows for a communication under perfect conditions at a Lunar orbit using 450 MHz.

Adjustments required to close the link margin at 2.2 GHz without modifying the Grissom bus, would require changing the receiver antenna and the bit rate. By lowering the bit rate to 600 bps, this leaves a required gain of 52.43 dB to be covered by the antenna. In order to build an antenna large enough for this mission, the diameter for a parabolic reflector antenna would need to 14.6 m.

$$\begin{aligned} Diameter &= \sqrt{(}G_{TX}/\eta)(c/\pi f) \\ Diameter &= \sqrt{(}10^{(48.33/10)}/.6)(3 \times 10^8/(\pi(2.2 \times 10^9)) \\ Diameter &= 14.6m \end{aligned} \tag{32}$$

Requiring a parabolic reflector dish to be 14.6 meters in diameter is very impractical for AFIT and makes this mission impractical without modifications any communication components to the GM1 CubeSat. If in the future Grissom modifies the S-band antenna to be a high gain antenna, a lunar mission could be possible but this pushes the limits and capabilities of the Cadet PLUS Radio.

The furthest possible for the GM1 mission to travel without modifying hardware is a geosynchronous mission, however the maximum downlink data rate will be diminished and limit high data transfer missions.

4.5 Maximum Data Transfer

This section will discuss the maximum data that can be communicated between the GM1 and MC3 Network about LEO, geosynchronous, and Lunar orbits. In table 10, each orbit's period to complete one rotation, the period of time when the satellite is visible to the MC3 Network WPAFB Node, and the percentage of the orbit that communication can occur. For further calculations the, LEO orbit will be represented by data transferable per orbital period, Geosynchronous orbit will be represented by the data transferable per orbital period, and a Lunar orbit will be represented by data transferable in a single day due to having an almost month long period.

Orbit	Orbit (Minutes)	Visibility per Orbit (Minutes)	Percentage
LEO	94.6	7.65	8%
Geosynchronous	1436	1436	100%
Lunar	42969	19573	45%

Table 10: Communication Time Per Orbit

4.5.1 LEO Maximum Data Transfer

The ground track shown in Figure 52, is represented by a polar orbit with a 90 degree inclination passing through WPAFB. In a direct overhead pass, or best case scenario we can see that in Figure 53, longest communication periods occur at small elevation angles, and quickly passes overhead to return to longer data time to communicate with at a lower elevation angle.

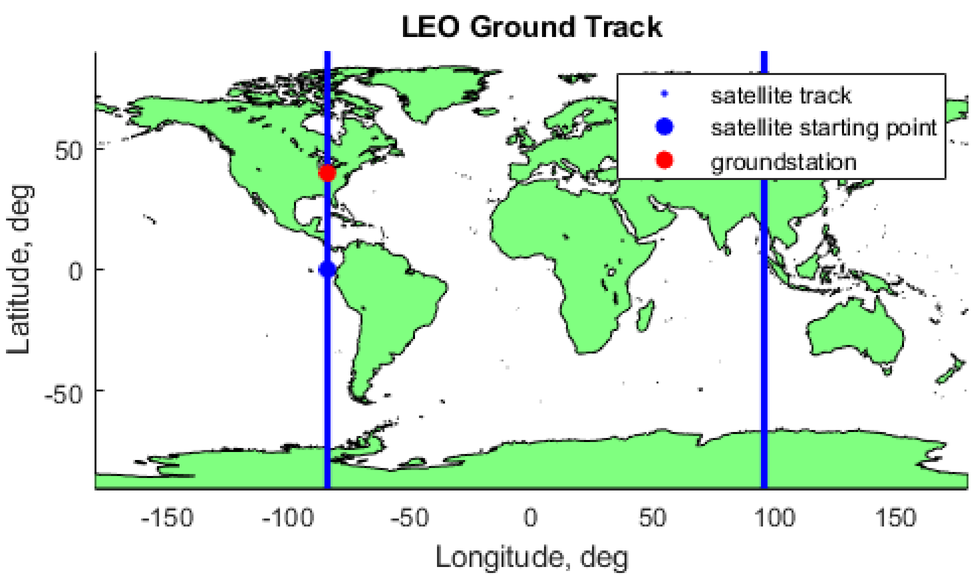

Figure 52: LEO Orbital Track

For a single period at LEO, the uplink can transfer 9.6 kbps and downlink can transfer 200 kbps. For a 7.65 minute pass the GM1 CubeSat can receive 550 KB of data and can transfer 11.48 MB of data. This data is sufficient for a low data transfer mission.

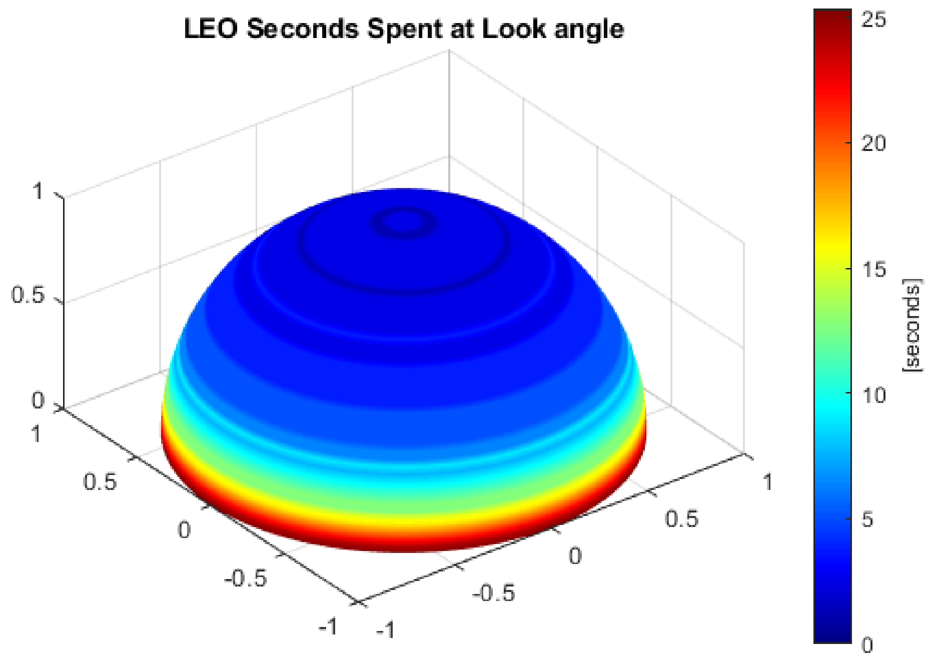

Figure 53: LEO Maximum Data Transfer

4.5.2 Geosynchronous Maximum Data Transfer

The ground track shown in Figure 54, is represented by a geosynchronous orbit with an inclination of 30 degrees. In the corrected communication scenario, the duration of communication can be seen in Figure 53. This orbit will allow for constant communication with the CubeSat without antenna tracking required, but at a much lower data rate.

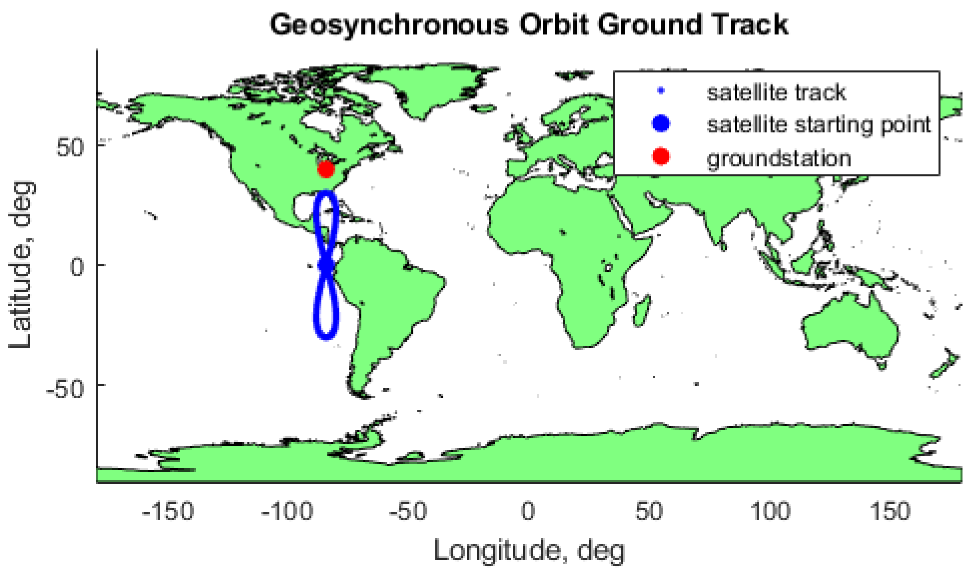

Figure 54: Geosynchronous Orbital Track

For a single period/day at Geosynchronous, the uplink can transfer 9.6 kbps and downlink can transfer 600 bps. For a 1436 minute communication window the GM1 CubeSat can receive 103.4 MB of data and can transfer 6.46 MB of data. The data transfer quantity is much lower than the LEO, and if a mission were to be conducted at that altitude, it would need to not be dependent on transferring large amounts of data.

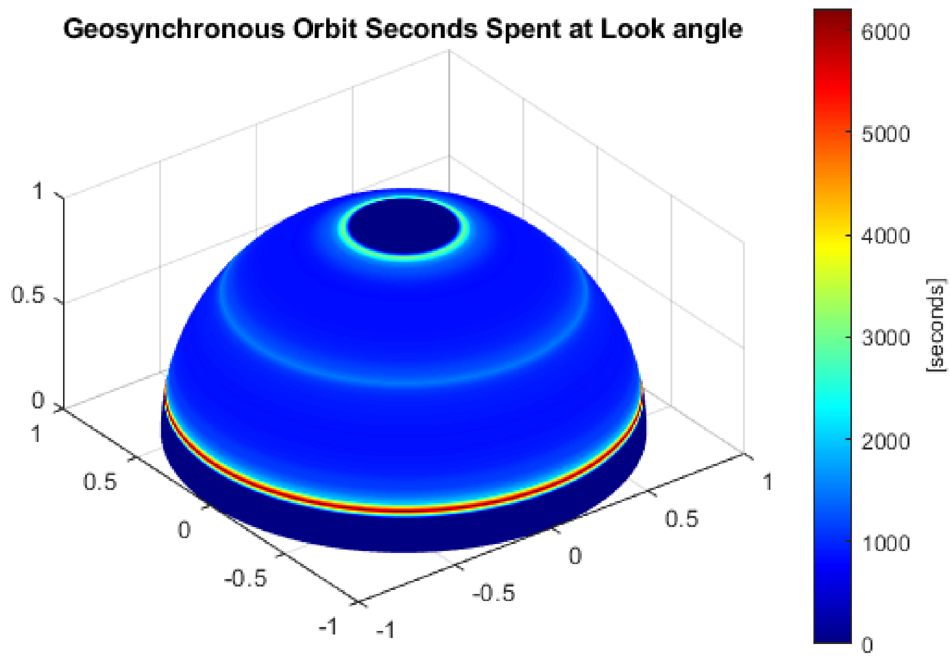

Figure 55: Geosynchronous Maximum Data Transfer

4.5.3 Lunar Maximum Data Transfer

The ground track shown in Figure 56, is represented by a single day with a semi major axis the same a the moon. The Lunar orbit is visible to the ground station 45 percent of the time. For comparison to GEO, a satellite at that altitude could transmit and receive at 600 bps, receiving and transmitting 6.46 MB of data a day. This is very small and would require a low data transfer mission to be successful.

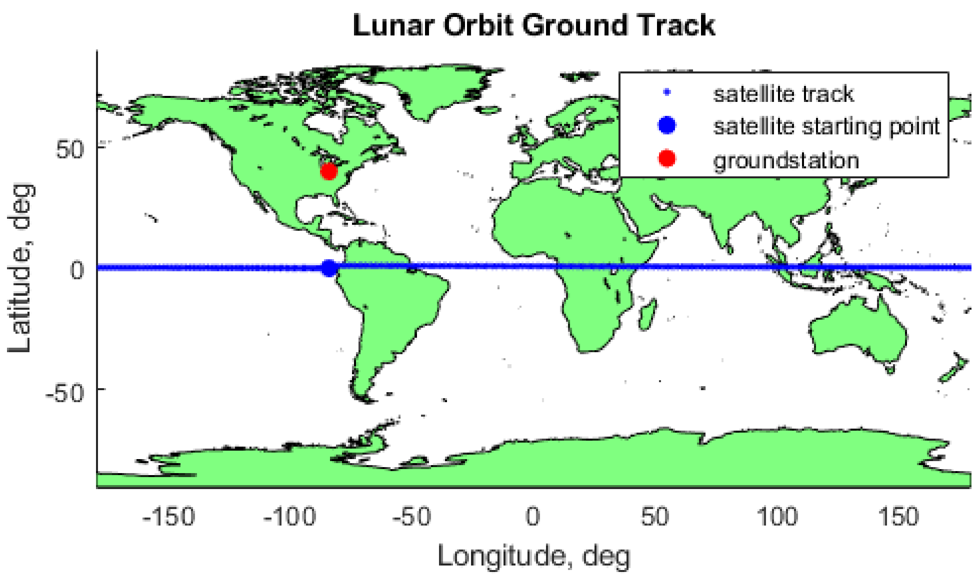

Figure 56: Lunar Orbital Track

For a single period/day at Lunar orbit, we are assuming successfully communication at this altitude and that the uplink can transfer 9600 bps and downlink can transfer 600 bps. For 45 percent communication time with 1440 minute's in a day, the maximum data the GM1 CubeSat can receive 46.72 MB and transfer is 2.92 MB of data per day. This is a very small amount of data to be transferring using constant communication protocol with a satellite.

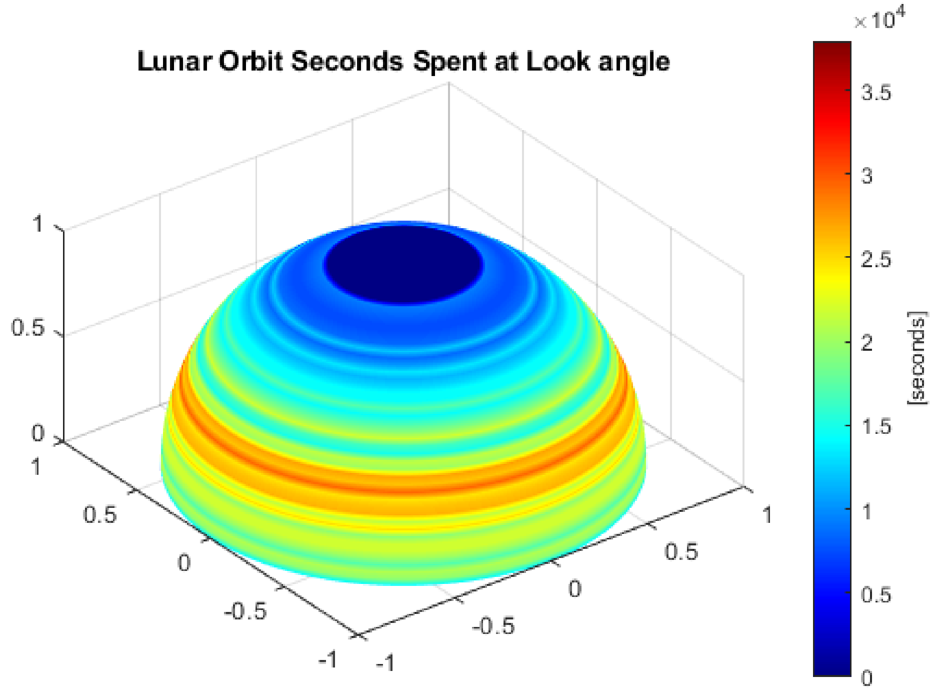

Figure 57: Lunar Maximum Data Transfer

4.6 Conclusion

Currently the GM1 mission is postured to be successful at a LEO mission with the current CubeSat build and MC3 network configuration. With minor software modifications to the MC3 downlink data rate, a geosynchronous orbital mission can be achieved. Finally, a Lunar orbiting mission is unrealistic with no modifications to the GM1 configuration, and major modifications to the existing MC3 configuration would be needed to overcome the required 20 dB for communication at a Lunar orbit.

Additionally, without modifying the GM1 communication subsystem, the data rates for its anticipated 2023 launch will be adequate for conducting its operations. For the geosynchronous and Lunar orbits, the downlink data rate will provide less than 7 MB of data with a 100% dedicated communication pipe between the GM1 and MC3 Network. This is an impossible requirement to meet as the network is shared with other users.

V. Conclusions

5.1 Summary

This research details the testing and analysis of the communication subsystem for the Grissom-1 Mission (GM1) CubeSat. The analysis conducted determines the abilities of the Grissom program's 6U CubeSat standard bus and its ability to preform higher altitude missions in the future. It calculates the Signal to Noise Ratio (SNR) to communicate from a Low Earth Orbit (LEO), geosynchronous, and Lunar orbit while utilizing consistent hardware and configuration settings. This chapter summarizes the findings of this research and answers the research question of defining the limitation of the GM1 communications. This chapter will also discuss potential future work that can be expanded on from this thesis.

5.2 Research Questions Answered

The objectives of this research have been met and the answer of modeling and analyzing the GM1 communication subsystem operating with the Mobile CubeSat Command and Control (MC3) Network has been calculated. The first objective completed was testing and characterizing the on-board Software Defined Radio (SDR) for both uplink and downlink antennas. This was completed in a lab environment utilizing the anechoic chamber by using test antennas, a spectral analyzer, and signal generator. The results when determining the values of these antennas deviated from the theoretical calculation of these antennas based off their antenna type and propagation beam width. The dipole antenna was within .05 dB from expected calculation and the S-band patch antenna calculation met the measured values in the lab setting.

The second object was completed, proving the ability to for the ground station software to communicate with the Cadet Plus SDR and then from the SDR to the ground station was proven to be successful. The modulation between both devices transmitted and interpreted both signals as expected.

The third object was met by taking all measurements and calculations required to calculate the link margin between the GM1 CubeSat and the Wright-Patterson Air Force Base (WPAFB) MC3 node. The analysis of the link margin proved that the LEO mission planned to launch September 2023 will have enough signal strength for uplink at 200 kbps utilizing a GFSK modulation, along with a downlink of 9.6 kbps utilizing an OQPSK modulation. The current configuration of the MC3 Network will also meet the requirements for a geosynchronous orbit with a lower bit rate which is modified through the ground station and Cadet PLUS Radio software.

Finally, the fourth objective met calculated the maximum data transfer at each orbit. A LEO mission has adequate time and data rates to successfully achieve a mission requiring downlink data transfer. However, moving to a geosynchronous and a Lunar orbit, with MC3 hardware is modified, the data rates and time required to transfer data will not be able to transfer more than 7 MB per day. This low quantity of data with a 100 % dedicated communication link is not practical and would not be a recommended mission for the Grissom data bus to fly.

5.3 Modification and Recommendations

Modifications that would be required to reach a further orbits for future Grissom Missions should be focused on the MC3 Network, allowing for the GM1 satellite to be used a flight heritage and an unmodified standard CubeSat for future mission.

To upgrade the MC3 for accommodation to the uplink aspect of a Lunar orbiting Grissom mission, the network would need to change one or more factors in the network, the transmission frequency, gain of the transmission antenna, or the transmission power of the ground station SDR. Modification of the MC3 to change the transmission frequency would also change operations of future Grissom CubeSats. Modification to increase the gain of the MC3 transmission antennas are a feasible solution, but also a more expensive solution for future missions. Finally, the increase of transmit power beyond the capabilities of the MC3's SDR, NI USRP-2922, are a sound technical solution with many commercial products readily available.

To solve the lacking link margin from a Lunar orbit, the MC3 network would need to upgrade the current 75 Watt output power at 450 MHz from the USRP-2922. A solution for a lunar orbit can be solved by increasing the power of the transmitter by 20 dB, or 7.5 kW. For reference, the deep space network antennas transmit at 20 kW [21]. An additional solution to the Grissom CubeSat Lunar uplink, could be to upgrade the transmit power and the gain of the transmitting antenna. The current MC3 UHF antenna is a yagi design with a gain of 16. Through upgrades of each ground station, a gain of 26 dBi can be achieved using commercially available antennas. This also requires the SDR to increase the transmit power by 10dB from 75W to 750W. This option, though modifying two components is also possible to achieved due to the increase in commercial products available at the required specifications.

5.4 Future Work

Future work in the field of RF link analysis for spacecraft and characterization of ground stations could be used to benefit other missions at Air Force Institute of Technology (AFIT). Before GM1 launches, the Grissom-P mission will launch. Characterization of this communication subsystem would be beneficial and help provide insight to ensure success for the AFIT's Center for Space Research and Assurance. The communication subsystem hardware utilized by the Grissom-P Mission differs from the GM1 mission in several ways, including the SDR.

Additional future work could also be done by talking the developed model of the

WPAFB MC3 node and applying it to all nodes in the Network. This could then be used to determine the limits of the entire network given a standard mission flown by a constellation of satellites. Determining the limits of the MC3 network would provide insight into how many satellites can be sustained without overloading the network.

VI. Appendix

Matlab code used to for link budget and orbit analysis.

Listing VI.1: test

```
% RF Budget Link
% Michael Bittle

% ALL UNITS IN DEGREES
clearvars; close all; clc; format shortG;
% Constants
RE = 6378; %km
c = 299792.458; % meters per second

% Initalization
Degrees = linspace(1,90,90);
Distance = zeros(3,90);
Loss_AA_Ap_Degree = zeros(3,90);
Loss_Free_Space = zeros(3,90);
Power_Recieved = zeros(3,90);
EbNo = zeros(3,90);
EbNo_excess = zeros(3,90);
ECIF_Angle_Duration = zeros(3,90);
ECIF_Angle_Duration_ML = zeros(3,90);
Period = zeros(1,3);
Max_Data = zeros(1,3);
Max_Data_ML = zeros(1,3);
```

```
% Required inputs
ML = 10; % Link Margin dB
Sat_alt = [500, 35786, 400000]; % Sat Altitude in km LEO,
    GEO, Cislunar
Ground_Track_Distance = 0; %Ground track distance from
    ground station in km


% Variable Inputs
ii = 3;
% 1 = Honolulu, HI
% 2 = Monterey, CA
% 3 = Dayton, OH

jj = 2;
% 1 = UHF
% 2 = S-Band

kk = 5;
% 0 = 1e0 Bit Error Rate
% 1 = 1e-1 Bit Error Rate
% 2 = 1e-2 Bit Error Rate
% 3 = 1e-3 Bit Error Rate
% 4 = 1e-4 Bit Error Rate
% 5 = 1e-5 Bit Error Rate
```

```
% 6 = 1e-6 Bit Error Rate
% 7 = 1e-7 Bit Error Rate
% 8 = 1e-8 Bit Error Rate

mm = 2;
% 1 = OQPSK
% 2 = GFSK

nn = 2;
% 1 = 9.6 kbps
% 2 = 200 kbps
% 3 = .6 kbps

oo = 1;
% 1 = LEO
% 2 = GEO
% 3 = Cislunar

[BER, EbNo_required, Modulation, Rb, Rb_Linear] = BER_ref(
    kk,mm,nn);


var1 = 1;
while var1< 4
    var2 = 1;
    while var2<91
```

```
            [f, AA, Ap, GT, No, Gain_1, Gain_2, Tx_Power, Band, Station, latitude, longitude, h] = Location_ref(ii,jj,Degrees(1,var2));
            if var2 < 90
                Distance(var1,var2) = (RE+Sat_alt(var1))*(cosd(Degrees(1,var2)+asind(((RE)/(RE+Sat_alt(var1)))*cosd(Degrees(1,var2))))/cosd(Degrees(1,var2)));
            else
                Distance(var1,var2) = Sat_alt(var1);
            end
            Loss_AA_Ap_Degree(var1,var2) = AA+Ap;
            Loss_Free_Space(var1,var2) = 10*log10((4*pi*Distance(var1,var2)*f/c)^2);
            Power_Recieved(var1,var2) = Tx_Power+Gain_1+Gain_2-Loss_AA_Ap_Degree(var1,var2)-Loss_Free_Space(var1,var2);
            EbNo(var1,var2) = Power_Recieved(var1,var2)-Rb-No;
            EbNo_excess(var1,var2) = EbNo(var1,var2)-ML-EbNo_required;
            var2 = var2+1;
        end
        var1 = var1+1;
end

% LEO
```

```
oo = 1;
% 1 = LEO
% 2 = Geosynchronous
% 3 = Lunar
[Satellite_Latitude_LEO , Satellite_Longitude_LEO , Period(
    oo), ECIF_Angle_Duration(oo,:)] = Dynamic(Sat_alt(oo),
    Distance(oo,:), longitude, latitude,
    Ground_Track_Distance, h);
[ECIF_Angle_Duration_ML(oo,:), Max_Data(oo), Max_Data_ML(
    oo)] = MarginLink(EbNo_excess(oo,:), Rb_Linear,
    ECIF_Angle_Duration(oo,:));
oo = 2;
[Satellite_Latitude_GEO , Satellite_Longitude_GEO , Period(
    oo), ECIF_Angle_Duration(oo,:)] = Dynamic(Sat_alt(oo),
    Distance(oo,:), longitude, latitude,
    Ground_Track_Distance, h);
[ECIF_Angle_Duration_ML(oo,:), Max_Data(oo), Max_Data_ML(
    oo)] = MarginLink(EbNo_excess(oo,:), Rb_Linear,
    ECIF_Angle_Duration(oo,:));
oo = 3;
[Satellite_Latitude_CisLunar, Satellite_Longitude_CisLunar
    , Period(oo), ECIF_Angle_Duration(oo,:)] = Dynamic(
    Sat_alt(oo), Distance(oo,:), longitude, latitude,
    Ground_Track_Distance, h);
[ECIF_Angle_Duration_ML(oo,:), Max_Data(oo), Max_Data_ML(
    oo)] = MarginLink(EbNo_excess(oo,:), Rb_Linear,
```

```
ECIF_Angle_Duration(oo,:));



plot(Degrees,-Loss_AA_Ap_Degree)
title("Atmospheric Loss vs Degree", "at " + f/1e6 + "MHz in " + Station + " at " + Rb_Linear/1e3 + " kbps " + Modulation)
xlabel('Degree')
ylabel('[dB]')
xlim([0,90])
legend('LEO','Geosynchronous','Lunar')

plot(Degrees,-Loss_Free_Space)
title({"Free Space Loss vs Degree", "at " + f/1e6 + "MHz in " + Station})
xlabel('Degree')
ylabel('[dB]')
xlim([0,90])
legend('LEO','Geosynchronous','Lunar')

plot(Degrees,Power_Recieved)
title("Power Recieved vs Degree", "at " + f/1e6 + "MHz in " + Station + " at " + Rb_Linear/1e3 + " kbps " + Modulation)
xlabel('Degree')
```

```
ylabel('Power [dBW]')
xlim([0,90])
legend('LEO','Geosynchronous','Lunar')

plot(Degrees,EbNo)
title("EbNo vs Degree", "at " + f/1e6 + "MHz in " +
    Station + " at " + Rb_Linear/1e3 + " kbps " +
    Modulation)
xlabel('Degree')
ylabel('EbNo [dB]')
xlim([0,90])
legend('LEO','Geosynchronous','Lunar')

plot(Degrees,EbNo_excess)
title("EbNo over Link Margin vs Degree", "at " + f/1e6 + "
    MHz in " + Station + " at " + Rb_Linear/1e3 + " kbps "
    + Modulation)
xlabel('Degree')
ylabel('EbNo [dB]')
xlim([0,90])
legend('LEO','Geosynchronous','Lunar')


graph_1 = Loss_Free_Space(oo,:);
sphere_faces = 100;                   % number of faces
```

```
[r,x,y,z,bb,c_max,c_min] = Sphere_Graph(graph_1, sphere_faces);

surf(r.*x,r.*y,r.*z,bb);  %# Plot the surface
axis equal;             %# Make the scaling on the x, y, and z axes equal
caxis manual
caxis([c_min c_max])
colormap jet
color = colorbar;
color.Label.String = '[dB]';
shading interp
grid on
axis auto
%set(gca,'XTick',[], 'YTick', [], 'ZTick', [])
title({"Free Space Loss at LEO", "at " + f/1e6 + "MHz in " + Station})

graph_2 = EbNo_excess(oo,:);
[r,x,y,z,bb,c_max,c_min] = Sphere_Graph(graph_2, sphere_faces);

surf(r.*x,r.*y,r.*z,bb);  %# Plot the surface
axis equal;             %# Make the scaling on the x, y, and z axes equal
caxis manual
```

```
caxis([c_min c_max])
colormap(flipud(jet))
color = colorbar;
color.Label.String = '[dB]';
shading interp
grid on
axis auto
%set(gca,'XTick',[], 'YTick', [], 'ZTick', [])
title({"EbNo over Margin Link at GEO", "at " + f/1e6 + " MHz in " + Station + " at " + Rb_Linear/1e3 + " kbps " + Modulation})

%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Plot the map first


graph_3 = ECIF_Angle_Duration(1,:);
sphere_faces = 100;                    % number of faces
[r,x,y,z,bb,c_max,c_min] = Sphere_Graph(graph_3, sphere_faces);
figure(3)
surf(r.*x,r.*y,r.*z,bb);  %# Plot the surface
```

```
axis equal;             %# Make the scaling on the x, y, and z axes equal
caxis manual
caxis([c_min c_max])
colormap jet
color = colorbar;
color.Label.String = '[seconds]';
shading interp
grid on
axis auto
%set(gca,'XTick',[], 'YTick', [], 'ZTick', [])
title({"LEO Seconds Spent at Look angle"})

graph_3 = ECIF_Angle_Duration(2,:);
sphere_faces = 100;                         % number of faces
[r,x,y,z,bb,c_max,c_min] = Sphere_Graph(graph_3, sphere_faces);
figure(4)
surf(r.*x,r.*y,r.*z,bb);  %# Plot the surface
axis equal;             %# Make the scaling on the x, y, and z axes equal
caxis manual
caxis([c_min c_max])
colormap jet
color = colorbar;
color.Label.String = '[seconds]';
```

```
shading interp
grid on
axis auto
%set(gca,'XTick',[], 'YTick', [], 'ZTick', [])
title({"Geosynchronous Orbit Seconds Spent at Look angle"})

graph_3 = ECIF_Angle_Duration(3,:);
sphere_faces = 100;                    % number of faces
[r,x,y,z,bb,c_max,c_min] = Sphere_Graph(graph_3, sphere_faces);
figure(5)
surf(r.*x,r.*y,r.*z,bb);  %# Plot the surface
axis equal;            %# Make the scaling on the x, y, and z axes equal
caxis manual
caxis([c_min c_max])
colormap jet
color = colorbar;
color.Label.String = '[seconds]';
shading interp
grid on
axis auto
%set(gca,'XTick',[], 'YTick', [], 'ZTick', [])
title({"Lunar Orbit Seconds Spent at Look angle"})

```

```
figure(6)
clr = 'b'; % the color of plot ( b g r m k c y )
geoshow('landareas.shp', 'FaceColor', [0.5 1.0 0.5])
hold on
axis([-180 180 -90 90]) % the limits for long and lat
xlabel('Longitude, deg')
ylabel('Latitude, deg')
plot(Satellite_Longitude_LEO,Satellite_Latitude_LEO,'.','
    Color',clr)
plot(Satellite_Longitude_LEO(1),Satellite_Latitude_LEO(1),
    'o','Color',clr,'MarkerFaceColor',clr)
plot(longitude,latitude,'o','Color','r','MarkerFaceColor',
    'r')
legend('satellite track','satellite starting point','
    groundstation')
title({"LEO Ground Track"})

figure(7)
geoshow('landareas.shp', 'FaceColor', [0.5 1.0 0.5])
hold on
axis([-180 180 -90 90]) % the limits for long and lat
xlabel('Longitude, deg')
ylabel('Latitude, deg')
plot(Satellite_Longitude_GEO,Satellite_Latitude_GEO,'.','
    Color',clr)
```

```
plot(Satellite_Longitude_GEO(1),Satellite_Latitude_GEO(1),
    'o','Color',clr,'MarkerFaceColor',clr)
plot(longitude,latitude,'o','Color','r','MarkerFaceColor',
    'r')
legend('satellite track','satellite starting point','
    groundstation')
title({"Geosynchronous Orbit Ground Track"})

% Plot map
figure(8)
geoshow('landareas.shp', 'FaceColor', [0.5 1.0 0.5])
hold on
axis([-180 180 -90 90]) % the limits for long and lat
xlabel('Longitude, deg')
ylabel('Latitude, deg')
plot(Satellite_Longitude_CisLunar(1:235),
    Satellite_Latitude_CisLunar(1:235),'.','Color',clr)
plot(Satellite_Longitude_CisLunar(1),
    Satellite_Latitude_CisLunar(1),'o','Color',clr,'
    MarkerFaceColor',clr)
plot(longitude,latitude,'o','Color','r','MarkerFaceColor',
    'r')
legend('satellite track','satellite starting point','
    groundstation')
title({"Lunar Orbit Ground Track"})

```

```
function [f, AA, Ap, GT, No, Gain_1, Gain_2, Tx_Power,
   Band, Station, latitude, longitude, h] = Location_ref(
   ii,jj,degree)

rain_point.A = 8;
rain_point.B = 12;
rain_point.C = 15;
rain_point.D = 19;
rain_point.E = 22;
rain_point.F = 28;
rain_point.G = 30;
rain_point.H = 32;
rain_point.J = 35;
rain_point.K = 42;
rain_point.L = 60;
rain_point.M = 63;
rain_point.N = 95;
rain_point.P = 145;
rain_point.Q = 115;

% Location information is pulled from lookup tables
if ii == 1
    h = 0; % km
    hr = 4.5; % km
    rpoint = rain_point.D;
```

```
    Station = 'Honolulu,Hi';
    latitude = 21.305066;
    longitude = -157.858069;
elseif ii == 2
    h = .008; % km
    hr = 4; % km
    rpoint = rain_point.E;
    Station = 'Monterey, CA';
    latitude = 36.599969;
    longitude = -121.894337;
elseif ii == 3
    h = .2; % km
    hr = 4; % km
    rpoint = rain_point.K;
    Station = 'Dayton, OH';
    latitude = 39.75895;
    longitude = -84.19161;
end

% Cadet Radio
Cadet_Radio_Power = 2; %Watts
Cadet_Radio_Power_dB = 10*log10(Cadet_Radio_Power); %dBw
Cadet_Antenna_Beamwidth_S = 180; % degrees
Cadet_Antenna_Beamwidth_UHF = 360; % degrees
Cadet_Antenna_Gain_S = 29000/(Cadet_Antenna_Beamwidth_S^2)
    ; % transmit antenna gain, linear
```

```
Cadet_Antenna_Gain_UHF = 29000/(
    Cadet_Antenna_Beamwidth_UHF^2); % transmit antenna gain
    , linear
Cadet_Antenna_Gain_S_dB = 10*log10(Cadet_Antenna_Gain_S);
    % transmit antenna gain, linear
Cadet_Antenna_Gain_UHF_dB = 10*log10(
    Cadet_Antenna_Gain_UHF); % transmit antenna gain,
    linear

% MC3 Radio (NEED DATA)
MC3_Radio_Power = 75; %Watts
MC3_Radio_Power_dB = 10*log10(MC3_Radio_Power); %dBw
%MC3_Antenna_Beamwidth_S = 3; % degrees
%MC3_Antenna_Beamwidth_UHF = 28; % degrees
%MC3_Antenna_Gain_S = 33; %29000/(MC3_Antenna_Beamwidth_S
    ^2); % transmit antenna gain, linear
MC3_Antenna_Gain_UHF = 18.5; % 29000/(
    MC3_Antenna_Beamwidth_UHF^2); % transmit antenna gain,
    linear
MC3_Antenna_Gain_S_dB = 33;%10*log10(MC3_Antenna_Gain_S);
    % transmit antenna gain, linear
MC3_Antenna_Gain_UHF_dB = 16;%10*log10(
    MC3_Antenna_Gain_UHF); % transmit antenna gain, linear


if jj == 1
```

```
    f = 450e6;
    AAz = .3;
    ah = 3.87e-5;
    av = 3.52e-5;
    bh = .912;
    bv = .88;
    T_s = 23.4;
    Gain_2 = 2.15 ; %Cadet_Antenna_Gain_UHF_dB;
    Gain_1 = MC3_Antenna_Gain_UHF_dB;
    %Gain_1 = 30;
    Tx_Power = MC3_Radio_Power_dB;
    Band = 'UHF Band';

    GT = Gain_1-T_s;
    No =-228.6+T_s;
elseif jj == 2
    f = 2.2e9;
    AAz = .035;
    ah = 1.54e-4;
    av = 1.38e-4;
    bh = .963;
    bv = .923;
    T_s = 21.3;
    Gain_1 = 6;
    Gain_2 = MC3_Antenna_Gain_S_dB;
    Tx_Power = Cadet_Radio_Power_dB;
```

```
    Band = 'S-Band';

    GT = Gain_1-T_s;
    No =-228.6+T_s;
end

Ls = (hr-h)/sind(degree);
LG = Ls*cosd(degree);
if rpoint < 10
    rp = 10/(10+LG);
elseif rpoint < 100
    rp = 90/(90+(4*LG));
elseif rpoint < 1000
    rp = 180/(180+LG);
elseif rpoint < 10000
    rp = 1;
end

AA = AAz*cscd(degree); % Also called L_atm
ac = (ah+av)/2;
bc = (ah*bh+av*bv)/(2*ac);
Ap = ac*(rpoint.^bc)*Ls*rp; % Also called L_prec

end

```

```
%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [BER, EbNo_required, Modulation, Rb, Rb_Linear] =
    BER_ref(kk,mm,nn)

if mm == 1
    Modulation = 'OQPSK';
    if kk == 1
        BER = 1e-1;
        EbNo_required = 0;
    elseif kk == 2
        BER = 1e-2;
        EbNo_required = 4.33;
    elseif kk == 3
        BER = 1e-3;
        EbNo_required = 6.75;
    elseif kk == 4
        BER = 1e-4;
        EbNo_required = 8.33;
    elseif kk == 5
        BER = 1e-5;
        EbNo_required = 7.5;
    elseif kk == 6
        BER = 1e-6;
```

```
            EbNo_required = 10.5;
        elseif kk == 7
            BER = 1e-7;
            EbNo_required = 11.33;
        elseif kk == 8
            BER = 1e-8;
            EbNo_required = 12;
        end

    elseif mm == 2
        Modulation = 'GFSK';
        if kk == 1
            BER = 1e-1;
            EbNo_required = 6;
        elseif kk == 2
            BER = 1e-2;
            EbNo_required = 10;
        elseif kk == 3
            BER = 1e-3;
            EbNo_required = 12;
        elseif kk == 4
            BER = 1e-4;
            EbNo_required = 13.8;
        elseif kk == 5
            BER = 1e-5;
            EbNo_required = 15;
```

```
    elseif kk == 6
        BER = 1e-6;
        EbNo_required = 15.75;
    elseif kk == 7
        BER = 1e-7;
        EbNo_required = 16.5;
    elseif kk == 8
        BER = 1e-8;
        EbNo_required = 17;
    end
end

if nn == 1
    Rb_Linear = 9600; %bits per second
    Rb = 10*log10(Rb_Linear);
elseif nn == 2
    Rb_Linear = 200000; %bits per second
    Rb = 10*log10(Rb_Linear);
elseif nn == 3
    Rb_Linear = 600; %bits per second
    Rb = 10*log10(Rb_Linear);

end

end

```

```
function [r,x,y,z,bb,c_max,c_min] = Sphere_Graph(Signal_dB
    ,i)

r = 1;                      % A radius value
[x,y,z] = sphere(i);        % Makes a ixi size sphere
x = x(i/2+1:end,:);         % Keep top i/2+1 x points
y = y(i/2+1:end,:);         % Keep top i/2+1 y points
z = z(i/2+1:end,:);         % Keep top i/2+1 z points

b = size(x);
aa=zeros(b(1),b(2));
bb=zeros(b(1),b(2));
cc=zeros(b(1),b(2));
j = 1;
k = 1;
while j < b(1)+1
    while k < b(2)+1
        a = floor(atand(sqrt((x(j,k))^2+(y(j,k))^2)/z(j,k)
            ));

        if a > 1
            aa(j,k) = a;
        else
            aa(j,k) = 1;
        end

```

```
        cc(j,k) = -(aa(j,k)-91);

        bb(j,k) = Signal_dB(cc(j,k));

        k = k+1;
    end
    j = j+1;
    k = 1;
end

c_max = max(Signal_dB);
c_min = min(Signal_dB);

end

function [Satellite_Latitude, Satellite_Longitude, Period,
    ECIF_Angle_Duration] = Dynamic(Sat_Altitude, Distance,
    longitude, latitude, Ground_Track_Distance, h)

mu = 3.986004415*10^5; % km^3/s^2
RE = 6378;
if Sat_Altitude == 35786
    we = 7.2921159e-5; % Earth's rotation rate rad/s
    i = deg2rad(30);

elseif Sat_Altitude > 35786
```

```
    we = 7.2921159e-5; % Earth's rotation rate rad/s
    i = deg2rad(28.58);
else
    we = 0;
    i = deg2rad(90);
end
a = Sat_Altitude + RE;
e = 0.0;
OMEGA = 0;
omega = 0;
nu = 0;
%coe = [a, e, i, OMEGA, omega, nu];

%r0_mag = (a*(1-e^2)/(1+e*cos(nu))) ;
%v0_mag = sqrt(mu/a);
Period = 2*pi*sqrt(a^3/mu);
%h_coe = r0_mag*v0_mag;
p = a*(1-(e^2));
%r0_mag = (a*(1-e.^2))/(1+(e)*cosd(nu));
r_0 = [a*cosd(nu); a*sind(nu); 0];
%v0_mag = sqrt(mu*((2/r0_mag)-(1/a)));
v_0 = [-sqrt(mu/p)*sind(nu); sqrt(mu/p)*(e+cosd(nu)); 0];

CAE=[cos(OMEGA) sin(OMEGA) 0; -sin(OMEGA) cos(OMEGA) 0; 0
   0 1];
CBA = [1 0 0; 0 cos(i) sin(i);0 -sin(i) cos(i)];
```

```
CPB = [cos(omega) sin(omega) 0;-sin(omega) cos(omega) 0; 0
    0 1];
CPE = CPB*CBA*CAE;
CEP = transpose(CPE);

r0 = CEP*r_0;
v0 = CEP*v_0;

% Propage inertial orbits
tspan = [0 Period];
X0 = [r0; v0];
options = odeset('RelTol',5e-14,'AbsTol',1e-13);
[tout, Xout] = ode45(@(t,x)TwoBP_eom(t,x,mu),tspan,X0,
   options);

% Convert to Lat/Long
Satellite_Latitude = NaN(1,length(tout));
Satellite_Longitude = NaN(1,length(tout));

delta_longitude = 2*asind((sqrt(((sin(
   Ground_Track_Distance/(2*RE))^2)/(cosd(latitude)^2)))))
   ;
sat_longitude = longitude-delta_longitude;   %Addition
   moves track to the east

for i = 1:length(tout)
```

```
    % Get GMST
    dt = tout(i);
    gamma = deg2rad(-sat_longitude) + we*dt;
    C_EN = [cos(gamma), sin(gamma), 0;
           -sin(gamma), cos(gamma), 0;
                     0,          0, 1];
    r_N = Xout(i,1:3)';
    r_E = C_EN*r_N;
    p = 1e3*r_E'; % input to ecef2lla
    lla = ecef2lla(p); % longitude, latitude
    % write to vectors
    Satellite_Latitude(i) = lla(1);
    Satellite_Longitude(i) = lla(2);
end

rr = length(Satellite_Latitude);
ss = 1;
ECIF_Distance = zeros(1,rr);

Ground_Station_ECEF = lla2ecef([latitude longitude h*1e3]); % latitude longitude altitude -> ECEF (X,Y,Z) X is prime meridian, z is North pole

while ss <= rr
     Sat_ECEF = lla2ecef([Satellite_Latitude(ss) Satellite_Longitude(ss) (a-RE)*1e3]);
```

```
    ECEF_delta = Ground_Station_ECEF-Sat_ECEF;
    ECIF_Distance(ss) = norm(ECEF_delta)/1e3;
    ss = ss+1;
end

ss = 1;
tt = 1;
ECIF_Angle_Duration = zeros(1,90); % How long is the satellite at the ground station view angle
while ss <= rr
    if ECIF_Distance(ss) > Distance(1) % is the distance farther than a 1-90 degree distance away?
        ss = ss+1;
    else % if its within 1-90 degrees
        while ECIF_Distance(ss) < Distance(tt) % if the distance is smaller than your check angle increase
            tt = tt+1;
            if tt > 90
                break
            end
        end
        ECIF_Angle_Duration(tt-1) = ECIF_Angle_Duration(tt-1)+(Period/rr); % if your distnace is larger than your check angle its the previous angle
        tt = 1;
```

```
    end
    ss = ss+1;
end

end

function [ECIF_Angle_Duration_ML, Max_Data, Max_Data_ML] = MarginLink(EbNo_excess, Rb_Linear, ECIF_Angle_Duration)
counter = 1;
ECIF_Angle_Duration_ML = ECIF_Angle_Duration;
while counter < 91
    if EbNo_excess(counter)>=0
        counter = counter+1;
    else
        ECIF_Angle_Duration_ML(counter)=0;
        counter = counter+1;
    end
end
    Max_Data = (Rb_Linear*sum(ECIF_Angle_Duration))/8e6; % Megabyte
    Max_Data_ML = (Rb_Linear*sum(ECIF_Angle_Duration_ML))/8e6; % Megabyte
end

function [xdot] = TwoBP_eom(~,x,mu)
```

```
% Seprate variables
r = x(1:3); % Position
v = x(4:6); % Velocity
r_mag = norm(r);
% Derivatives
rdot = v;
vdot = -(mu./(r_mag^3))*r;
% Define output
xdot = [rdot; vdot];
end
```

Bibliography

1. Ball-Aerospace. Cosmos documentation v5. 2018.

2. G. Minelli. (u) mobile cubesat command & communications (mc3) user's guide, 2019.

3. National Insturments. Usrp-2922 specifications. 2017.

4. E. Evans. Cadet plus radio interface control document. *AFIT Internal Document*, 2017.

5. F.E.M Tubbal, A. Alkaseh, and A. Elarbi. Telemetry, tracking and command subsystem for libyasat-1. 2016.

6. J.R. Wertz. *Space Mission Engineering : The New SMAD*. Microcosm Press, 2011.

7. I. Poole. Yagi antenna gain, directivity & front to back ratio. *Electronics Notes*, 2012.

8. A. Jamalipour. Low earth orbital satellites for personal communication networks. 1998.

9. NASA. Cubesat 101: Basic concepts and processes for first-time cubesat developers, 2017.

10. A Dissanayake, J. Allnutt, and F. Haidara. A prediction model that combines rain attenuation and other propagation impairments along earth-satellite paths. 2002.

11. S. Velayudhan. A low, cost portable ground station to track and communicate with satellites in vhf band. 2017.

12. R. Crane. A two-component rain model for the prediction of attenuation and diversity improvement. 1982.

13. T.F. Collins. *Software-Defined Radio for Engineers.* Artech House, 2018.

14. R. Keim. Introduction to software-defined radio - technical articles. *All About Circuits*, 2017.

15. V.L. Pisacane. *Fundamentals of Space Systems Second Edition.* Oxford University Press, 2005.

16. E.J. Keesee. Satellite telemetry, tracking and control subsystems, 2003.

17. Chief Information Officer Department of Defense. Information assurance policy for space systems used by the department of defense. 2010.

18. S. H. Wood. Trade study of commercial software-defined radio technologies for small satellite ground station network command and control applications. 2020.

19. I. Adly, H. F. Ragai, A. E. Elhennawy, and K. A. Shehata. Adaptive packet sizing for otap of psoc based interface board in wsn. pages 148–151, 2010.

20. C. Lomanno. Afit mc3 network. *AFIT Internal Document*, 2020.

21. NASA. Deep space network services catalog. 2015.

Acronyms

ADCS Attitude Determination and Control System. 21

ADSC Attitude Determination and Control System. 21, 23, 24

AFIT Air Force Institute of Technology. 1, 2, 4, 24, 27, 77, 80, 90

BER Bit Error Rate. 14, 16, 28, 30, 48, 72

C2 Command and Control. v, 1, 2, 22, 24, 25, 26, 28

CD&H Command and Data Handling. 23, 24

CNR Carrier to Noise Ratio. 16, 67

CSRA Center for Space Research and Assurance. 1, 2, 24

DAC Digital to Analog Converter. 19

EM Electromagnetic. 6, 8, 9, 10

FSPL Free Space Loss. v, 13

GM1 Grissom-1 Mission. 1, 4, 5, 6, 13, 28, 29, 30, 31, 50, 54, 60, 67, 68, 72, 74, 77, 78, 79, 80, 81, 83, 85, 87, 88, 89, 90

GUI Graphical User Interface. 28

LEO Low Earth Orbit. 4, 31, 67, 88, 89

MC3 Mobile CubeSat Command and Control. v, 2, 4, 5, 14, 24, 25, 26, 27, 28, 31, 34, 50, 67, 68, 72, 74, 77, 78, 80, 87, 88, 89, 90, 91

MOC Mission Operation Center. 28

NPS Naval Postgraduate School. 2

NTIA National Telecommunications and Information Administration. 27, 28

QPSK Quadrature Phase Shift Keying. 29, 30

RF Radio Frequency. v, 6, 7, 8, 9, 14, 16, 17, 20, 23, 24

SATRN Satellite Agile Transmit Receive Network. 2, 24, 25, 26, 27

SDR Software Defined Radio. v, 1, 2, 4, 6, 17, 19, 21, 23, 25, 26, 28, 29, 30, 31, 33, 34, 46, 50, 57, 79, 88, 90

SNR Signal to Noise Ratio. 6, 7, 14, 16, 24, 29, 48, 49, 67, 72, 74, 75, 78, 88

SOC Satellite Operations Center. 1, 2

TLE Two-Line Element Set. 25

TT&C Tracking, Telemetry, and Command. v, 1, 19, 23

VPN Virtual Private Network. 23

WPAFB Wright-Patterson Air Force Base. 27, 34, 67, 74, 80, 81, 89, 91

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14. ABSTRACT
This thesis describes the assessment and analysis performed to characterize the communication subsystem used for command and telemetry transmission in support of the Grissom-1 Mission (GM1). The GM1 is unique in that it represents the pathfinder for a standardized 6U bus that serves as the basis for future CubeSat missions to host a variety of technical and scientific payloads, as prioritized by the Department of Defense, requiring flight demonstration or access to the orbital environment. Lab-based testing within an anechoic chamber provided link margin data required to characterize the command and telemetry links of the GM1. Experimental data describing the results of each test are also included. The research culminates in a full characterization of the software-defined radio, an analysis of the GM1 to MC3 communication interaction, and any limitations revealed as attributable to the 6U spacecraft. Collected data supports an analysis of the limitations inherent to the current GM1 communications subsystem configuration as operated at a variety of orbital distances plus recommended augmentations to the MC3 network to support those distances.

15. SUBJECT TERMS
cubesat, communications, software defined radio (SDR),space system engineering

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