Test and Evaluation of GRISSOM-1 CubeSat Communication Subsystem

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ABSTRACT

The Grissom-1 mission (GM1), slated to launch in September 2022, 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). 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 paper specifically focuses on the testing and analysis of all communication links between the spacecraft, the ground system, and the Satellite Operations Center (SOC) being hosted at the Air Force Institute of Technology at Wright Patterson Air Force Base. Additionally, the paper will cover the potential for future missions for the GM1 based off the analysis of the current link. Specific to the GM1, analysis is performed on the spacecraft's Cadet Plus software-defined radio (SDR), as developed by the Space Dynamics Laboratory, and its communication capabilities with the Mobile CubeSat Command and Control (MC3) network, the National Instruments 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 paper includes characterization of individual components, anechoic chamber downlink and uplink signal measurements and results, link margin calculations, plus direct point-to-point testing results. Experimental data describing the results of each test using the local instance of an MC3 ground station software. The research culminates in a full characterization of the Cadet Plus SDR, an analysis of the GM1 to MC3 communication interaction, and any limitations revealed as attributable to the 6U spacecraft.

INTRODUCTION

The Grissom-1 mission (GM1), slated to launch in 2022, 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 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 all communication links between the spacecraft, the ground system, and the Satellite Operations Center (SOC).

BACKGROUND

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 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 command and control (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 operated 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 Network 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 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 required 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 an optimal SDR for conducting space operations. The output of the USRP-2922 connects to high gain Yagi antenna's 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 SMA 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 data from the Cadet Plus is picked up by a 3-meter parabolic antenna tracking the GM1 orbit. The data is then sent to the USRP-2922, converted from analog to digital, and sent to the AFIT 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.

PLANNED EXPERIMENTS AND EXPECTED RESULTS

This paper will characterize and evaluate the communication subsystem and how GM1 will operates on the MC3 network. The testing and characterization will start from an individual component level and build to a simulated communication link. Initial testing will 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, minimal signal strength required to receive commands in UHF. Testing of the Cadet Plus SDR will be conducted on a prototype board by transmitting and receiving signals from a simulated MC3 network in lab settings. These tests will involve transmitting COSMOS commands and documenting the performance from the SDR at various signal strengths. The final test to determine the free space loss characteristics of the GM1 CubeSat will involve a point-to-point test with the WPAFB MC3 ground station from various locations. This will allow a day-in-the-life simulation of the GM1 CubeSat and be used to ensure potential mission success of the communication system prior to the September 2022 launch. All characterization and evaluations of the communication subsystem will be used for operating the GM1 and used in designing the future Grissom 6U missions.

LAB MEASUREMENTS

Through tests evaluated in the anechoic chamber, all requirements for the GM1 communications system were tested. Through simple monitoring of the system, the uplink and downlink frequencies were 450 MHz and 2.2GHz 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 a total of 4.7 Watts.

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 meet manufacture's description.

For 2.2 GHz, the horn test antenna measured -3.47 dBm on the network analyzer. When tested with the Grissom-1 s-band antenna, a measurement of -5.75 dBm was recorded. The difference in loss dBm is 2.28 total dB. This loss would lead to the conclusion that the test antennas have a roughly 2.28 dB gain each.

Similarly, the measurements from the PCB antennas yield similar results with inconclusive measurements that differed from the data sheet. The two PCB antennas saw a measurement of 2.97 dBm, while the single PCB antenna and Grissom-1 dipole antenna saw a measurement of 0.97 dBm. This measurement would conclude that the gain of the PCB antenna at 450 MHz should be only 2 dB.

Uplink Calculations

For the uplink of 450 MHz, the Cadet radio is set to receive OQPSK modulation. Measurements for the EIRP of the MC3 network were not measured in this test, but have been recorded and tested by the AFIT CSRA team as 80.75 dB. When calculating the link margin, there must be 10 dB higher than the Bit Error Rate vs E_b/N_0. For the OQPSK, it requires a signal to noise ratio of roughly 11 dB and for a link margin of 10, that must mean the total RF budget must be 21 dB. Assumptions used to calculate the uplink E_b/N_0 is uplink transmit antenna gain is 20 dB, uplink receiver antenna gain is 0 dB (unverified in earlier test), T_{sys}=274K, total atmospheric loss is 1 dB, and the MC3 Network USRP placeholder transmits at 9 Watts.

The equation for uplink carrier power at the receiving antenna of the spacecraft is:

$$C = P_{TX} + G_{TX} + G_{RX} - L_{FS} - L_P \, , \tag{1}$$

where C is carrier power, P_{TX} is the value of the transmitter power sending the signal being analyzed, G_{TX} is the gain of the transmitting antenna, G_{RX} is the gain of the receiving antenna, L_{FS} is free-space loss, and L_P is other miscellaneous losses including atmospheric and precipitation losses – all of which are represented in dB units. Using the values presented earlier, carrier power of placeholder MC3 Network at 450 MHz:

$$\begin{aligned} C &= 10\log_{10}(9) + 20 + 0 \\ &\quad - 20\log_{10}\left(\frac{4\pi(500*10^3)(450*10^6)}{(3*10^8)}\right) - 1 \\ &= 9.5 + 20 + 0 - 139.5 - 1 \\ &= -111 \text{ dBW} \end{aligned} \tag{2}$$

Signal strength of placeholder MC3 Network is calculated using the carrier power, C and data rate, R_b:

$$\begin{aligned} E_b &= C - R_b \\ &= -111 - 10\log_{10}(9600) = -111 - 40 \\ &= -151 \text{ dB} \end{aligned} \tag{3}$$

Noise factor calculation uses Boltzman constant k and effective system noise temperature T_{sys}:

$$\begin{aligned} N_0 &= kT_{sys} \\ &= 10\log_{10}(1.38*10^{-23}*274) \\ &= -204 \text{ dBW} \end{aligned} \tag{4}$$

Signal to Noise ration of placeholder MC3 network at 450 MHz:

$$E_b/N_0 = -151 - (-204) = 53 \text{ dB} \tag{5}$$

Downlink Calculations

For the downlink of 2.2 GHz, the estimated gain of MC3 parabolic antenna at 2.2 GHz:

$$\begin{aligned} G_{RX} &= 10\log_{10}\left(\nu\left(\frac{\pi Df}{c}\right)^2\right) \\ &= 10\log_{10}\left(0.6\left(\frac{3\pi*2.2*10^9}{3*10^8}\right)^2\right) \\ &= 34.5 \text{ dBi} \end{aligned} \tag{6}$$

Carrier power of Cadet Radio at 2.2 GHz:

$$\begin{aligned} C &= 10\log_{10}(2) + 0 + 34.5 \\ &\quad - 20\log_{10}\left(\frac{4\pi(500*10^3)(2.2*10^9)}{(3*10^8)}\right) - 1 \\ &= 3 + 34.5 - 153.3 - 1 \\ &= -116 \text{ dBW} \end{aligned} \tag{7}$$

Signal Strength of Cadet Radio at 2.2 GHz:

$$\begin{aligned} E_b &= C - R_b \\ &= -116 - 10\log_{10}(200000) = -116 - 53 \\ &= -169 \text{ dB} \end{aligned} \tag{8}$$

Signal to Noise ration of Cadet Radio at 2.2 GHz:

$$E_b/N_0 = -169 - (-204) = 35 \text{ dB} \tag{9}$$

To test the downlink of 2.2GHz, the Cadet Radio is set to transmit GFSK modulation. The experimental setup to measure the Cadet Radio is described in Figure 1. The cadet radio is set to transmit data to the 6U chassis and

S-Band patch antenna. From the patch antenna it is received by the test antenna, as shown by Figure 2 and then measured using a spectrum analyzer. In Figure 3, the signal strength measured through the system is -13.745 dBm. This measurement is roughly 44 dB lower than the transmitted power, however by calculating the loss of free space in Equation 10, the expected value is calculated.

$$\begin{aligned} C &= 10\log_{10}(2) + 2.28 + 0 \\ &\quad -20\log_{10}\left(\frac{4\pi(3)(2.2*10^{9})}{(3*10^{8})}\right) - 0 \\ &= 3 + 2.28 + 0 - 48 - 0 \\ &= -43.54 \text{ dBW} \\ &= -13.54 \text{ dBmW} \end{aligned} \tag{10}$$

When calculating the link margin, it must be 10 dB higher than the Bit Error Rate vs $Eb/N0$. For the GFSK, the signal to noise ratio of roughly 14 dB is required and for a link margin of 10, that means the total RF Budget must be 24 dB. Assumptions used to calculate the downlink $Eb/N0$ is transmit antenna gain is 1 dB (unverified in earlier test), T_{sys}=274K, total atmospheric loss is 1dB and receiving antenna efficiency as 60%.

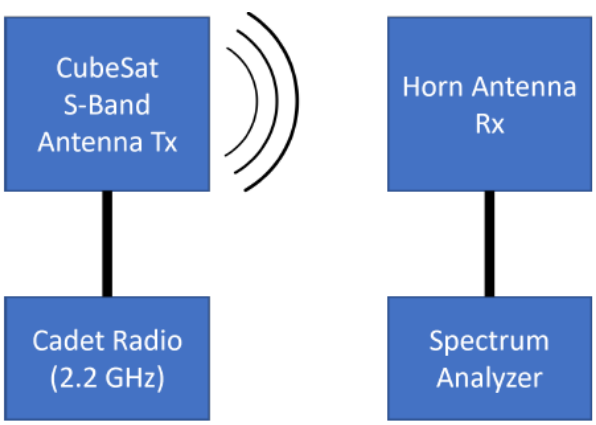

Figure 1: Cadet Radio Signal Strength Test Setup Flow Chart

ANALYSIS

Link Margin

When a satellite passes overhead, there must be a high enough link margin to properly receive and transmit signals to and from the satellite. This can be described mathematically by Equation 11.[5] In order to model this equation, each component can be analyzed individually.

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{FS} - L_{P} - L_{RX} \tag{11}$$

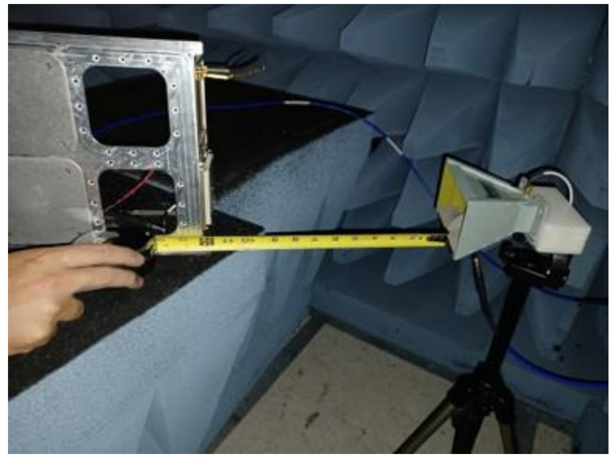

Figure 2: Cadet Radio Signal Strength Test

Figure 3: Experimental Cadet Radio Signal Strength

After proving the Cadet Radio output power was accurate in the lab, the experiment also provided measurements for the receiving antenna gain for UHF and transmission antenna gain for S-Band. The measurements taken from the MC3 Network's output power, uplink antenna gain for S-Band, and downlink antenna gains were taken from test conducted by the CSRA.

Factors that play into the miscellaneous signal loss include rain attenuation. As the MC3 Network hosted in different locations across the United States of America, the difference in rain attenuation are not the same. In Fig 4, the model for loss factor to rain created by R.K. Crane is used in my analysis. This is a dominate loss factor in rain, especially at 10 GHz and above. There are other loss factors that RF must deal with such as gaseous absorption, cloud attenuation, melting layer attenuation, and troposheric refraction effects.[6] Additional factors that can decrease the RF Link Budget are sandstorms.[7] Rain attenuation[8] is a factor found in the RF Link Budget under the miscellaneous loss propagation.

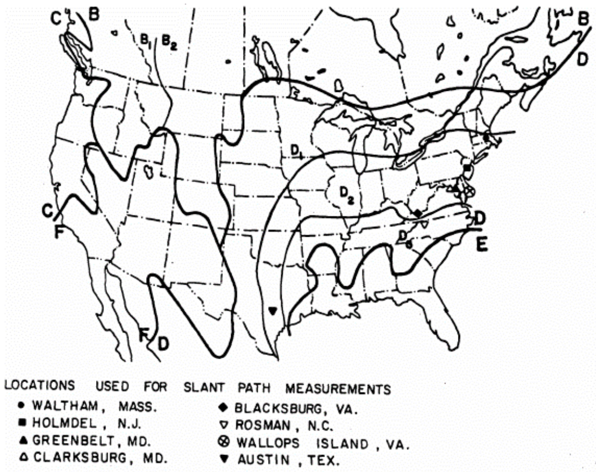

Figure 4: Rain Point Loss

Finally, the loss associated with the receiver feeder and transmitter was tested by the AFIT CSRA staff and found to be less than 1 dB for the MC3 Network, and can be considered a negligible loss in the calculation.

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 are a nearly one time required calculation. With the free space loss, described by Equation 12 calculated per elevation angle, this then allows a calculation from 0 - 90 degrees of signal strength in dB.

$$L_{FS} = 20 * \log_{10}\left(\frac{4\pi Df}{c}\right) \tag{12}$$

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 GEO or Lunar orbit, the difference in distance at 0 and 90 degrees look very similar because of the smaller relative distance increase.

The distance away from the ground station in a circular orbit can be calculated, shown in Equation 13 and Figure 5, 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.

$$D = \left(R_{\oplus} + SatAlt\right) * \left(\cos \frac{\left(\theta + \arcsin\left(\left(\frac{R_{\oplus}}{R_{\oplus} + SatAlt}\right)\cos\theta\right)\right)}{\cos\theta} \right) \tag{13}$$

After calculating the distance from the ground station at every 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 Figure 6, the closer to a nadir angle, or 90 degrees, the less free space loss interferes with the communication subsystem.

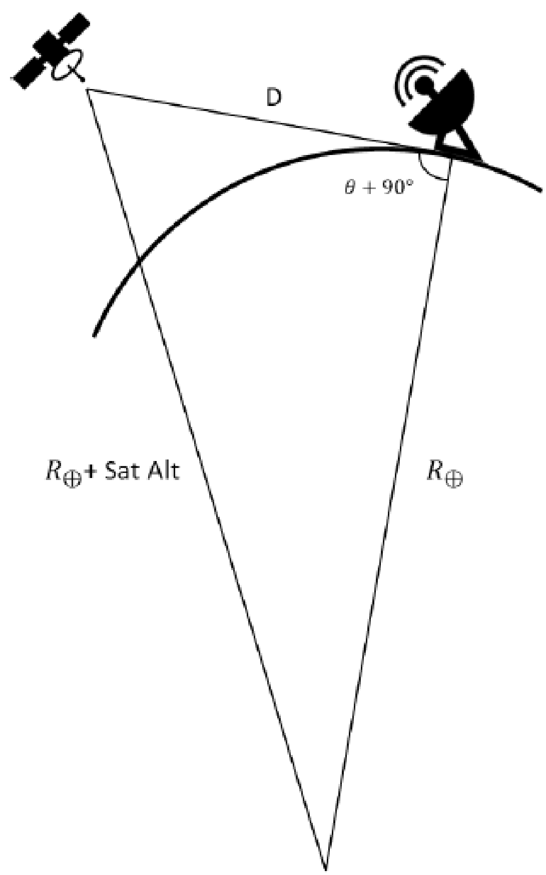

Figure 5: Radio Link Geometry

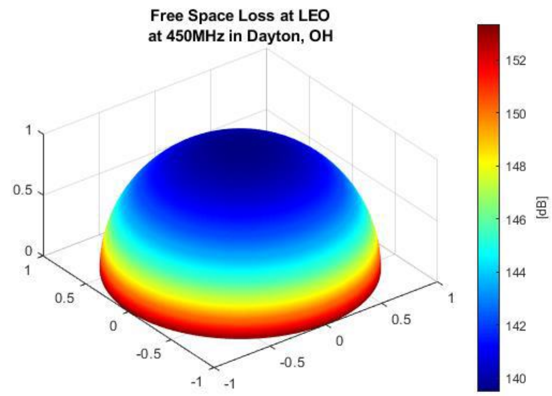

Figure 6: L_{FS} versus Degree

Signal to Noise Ratio

Once the Free Space loss is calculated, it can be used to solve for the power received at the transmitter, and then finally used to solve the Signal to Noise ratio as seen in Equation 14.

$$E_b/N_0 = P_{RX} - R_b - N_0 \tag{14}$$

The characterization of the MC3 network was done in Matlab and 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 E_b/N_0 value was generated for each Elevation angle. In the Figure 7 plot, there are three different test altitudes, LEO (500 km), GEO (42,164 km), Lunar (400,000 km). These altitudes show the signal to noise ration from the WPAFB, OH MC3 Node, while transmitting at 450 MHz, at 9.6 kbps, and utilising BPSK modulation. For the AFIT MC3 Mission planning guide, a minimum of 10 dB Margin is required during transmission. In Figure 7, it can be concluded that the LEO communication link is above the required margin, the GEO communication almost crosses into the 10 dB link margin, but the Lunar orbit is more than 20 dB below the required threshold.

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 use a flight heritage configuration and an unmodified standard CubeSat for future mission.

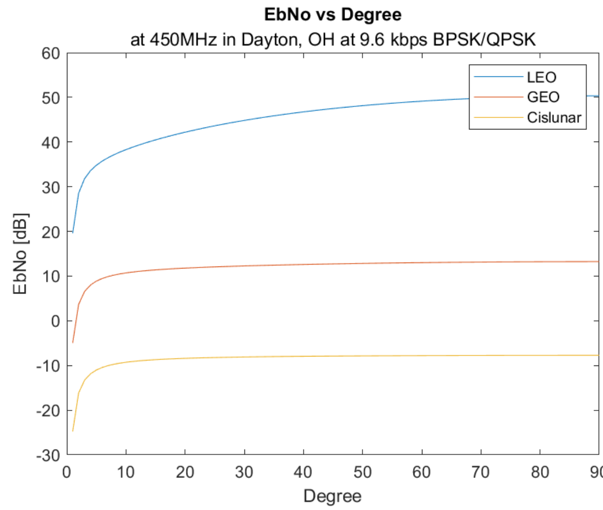

Figure 7: E_b/N_0 versus Degree

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.

To solve the lacking margin link 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.[9] 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 easier to achieved due to the increase in commercial products available at the required specifications.

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 modifications to the MC3 network, a GEO mission can be achieved with only a 1dB increase to meet the AFIT's margin link requirement of 10 dB. Finally, a Lunar orbiting mission is possible with no modifications to the GM1 configuration, but major modifications to the existing MC3 configuration to overcome the required 20 dB needed to communicate at a Lunar orbit.

REFERENCES

1. Ball-Aerospace, "COSMOS Documentation v5," 2018.

2. Naval Postgraduate School, "Mobile CubeSat Command & Communications (MC3) User's Guide," 2019.

3. National Instruments Corporation, "USRP-2922 Specifications," 2017.

4. Evans, E., "Cadet PLUS Radio Interface Control Document," 2017.

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

6. Dissanayake, A., Allnutt, A., Haidara, F., "A Prediction Model that Combines Rain Attenuation and Other Propagation Impairments Along Earth-Satellite Paths," IEEE Transactions on Antennas ans Propagation, vol 45, issue 10, Oct 1997.

7. Velayudhan, S., "A Low, Cost Portable Ground Station to Track and Communicate with Satellites in VHF Band," Thesis, Rochester Institute of Technology, 2017.

8. Crane, R. K., "A Two-Component Rain Model for the Prediction of Attenuation and Diversity Improvement," 1982.

9. Berner, J., "Deep Space Network Services Catalog," 820-100, Rev. F, National Aeronautics and Space Administration, Jet Propulsion Laboratory, Feb 24, 2015.