CANADIAN CUBESAT PROJECT: EE COMUNICATIONS – UHF

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Abstract

The Canadian Space Agency CubeSat Project is a 3-year long initiative in which 15 schools across Canada were given the opportunity to design, construct, test, and launch a small satellite (2U) into a low earth orbit (LEO). The small satellite (CubeSat) will be launched from the International Space Station and will be equipped with two 180-degree cameras to send 360-degree images and videos to a ground station on Earth. Western University has given fourth year engineering students the opportunity to design and build the CubeSat as part of a 3-year, multidisciplinary project. The project consists of two separate CubeSat designs, operating at different frequencies, that will be compared at the end of the first year to determine which frequency band should be selected. The intent of the first year's project is to analyze the viability of a design using the Ultra High Frequency band (0.3-1 GHz) in comparison to the S-band (2-4GHz) for sending 360-degree images and videos to the ground station. The Ultra High Frequency (UHF) Communications team was responsible for providing comprehensive research and preliminary designs on antennas, modulation schemes, while creating and maintaining a link budget to model the communication link.

Contribution of the Team Members

Sean Amyot

Sean carried out preliminary research on other CubeSat projects and the Canadian Space Agency's communications material. Sean developed the link budget and completed all associated calculations within the link budget. He coordinated with Sam and Michael on incorporating the antenna and modulation specifications into the link budget model to ensure accuracy. Sean also assisted with prototype testing, data collection, and data processing. Sean took on these responsibilities due to his experience and familiarity with excel functions. He would be content to work on the same project aspects if we completed another CubeSat project.

Sam Kloppenburg

Sam completed research on modulation theory and encoding techniques. Sam completed the modulation scheme tradeoff study, implementing the MATLAB and MATLAB BERTool software programs to analyze the benefits and drawbacks of each technique. Sam assisted with prototype building, troubleshooting, and testing. Sam completed Commercial Off The Shelf (COTS) component research for both transceivers and antennas for space segment. Sam completed these tasks due to the elective courses he has taken this year and his interest in modulation and prototyping. Based on the experience we have had, Sam would still take on the same responsibilities.

Michael Burgess

Michael led preliminary research of antenna theory related to CubeSat communication systems. He also completed antenna tradeoff studies and completed all antenna calculations. Michael assisted with prototype building, troubleshooting, and testing. Michael also completed research on COTS components for the ground segment components. Michael took on these tasks due to his interest in antennas and his 4th year technical elective course. He would complete the same tasks if given the opportunity to choose again.

Acknowledgments

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Table of Contents

1. Introduction/Background 9
   1.1 Problem Statement 9
   1.2 Background Information/ Detailed Literature Review 9
      a. Antennas 9
      b. Encoding 14
      c. Modulation 15
   1.3 Project Objectives 17
2. Design Approach 18
   2.1 Concept Generation 18
   2.2 Concept Evaluation and Selection 20
3. Design Analysis 23
   3.1 Selection Engineering Techniques/Software tools 23
   3.2 Use of Engineering Techniques/Software tools 25
   3.3 Complete Analysis/Calculations 27
      a. Modulation Scheme Trade-Off 27
      b. Antennas 34
      c. Link Budget 34
   3.4 Final Design Overview 49
   3.5 Prototype Design Overview 52
4. Results and Validation 55
   4.1 Testing Strategy/ Validation Protocols 55
   4.2 Final Results and Validation 60
5. Conclusions, Future Work and Recommendations 65
6. References 67
Bibliography 67

List of Tables

Table 1: Polarization Combinations 14
Table 2: MPSK, MFSK Bandwidth Efficiency and Eb/No values 31
Table 3: MQAM Bandwidth Efficiency and Eb/No values 31
Table 4: Coherent and Non-coherent MSK Bandwidth Efficiency and Eb/No values 32
Table 5: Link budget results for final design 60
Table 6: Link budget results for test #2 angle 0 61
Table 7: Link budget results for test #2 angle 180 61

List of Figures

Figure 1: Radiation Pattern Explanation 10
Figure 2: Dipole Radiation Pattern 12
Figure 3: Radiation Pattern with Beam width 12
Figure 4: Linear vs Circular Polarization 13
Figure 5: BPAM Scheme [2] 14
Figure 6: OOK Signal [4] 16
Figure 7: 2FSK Signal [5] 16
Figure 8: 2PSK Signal [5] 17
Figure 9: CubeSat subsystem interaction 19
Figure 10: Transceiver Decision Matrix 22
Figure 11: Antenna Selection Matrix 22
Figure 12: MATLAB Bit Error Rate Analysis Tool (BERTool) user interface. 24
Figure 13: Example of Matlab Antenna Toolbox 25
Figure 14: Communication link 27
Figure 15: MPSK Modulation Curves 29
Figure 16: MFSK Modulation Curves 29
Figure 17: MSK and M-QAM Modulation Curves 30
Figure 18: MPSK, MQAM, MFSK and MSK schemes plotted on the BEP 32
Figure 19: Link budget inputs sheet 35
Figure 20: Orbital measurements and distances 36
Figure 21: Link budget orbit sheet 37
Figure 22: Link budget transmitter sheet, uplink 38
Figure 23: Link budget transmitter sheet, downlink 38
Figure 24: Link budget antennas sheet 39
Figure 25: Link budget receiver’s sheet, uplink 40
Figure 26: Link budget receiver's sheet, downlink 41
Figure 27: Link budget modulation sheet 41
Figure 28: Link budget losses sheet, atmospheric and ionospheric 42
Figure 29: Link budget losses sheet, antenna 44
Figure 30: Radiation Pattern of EnduroSat Satellite Antenna 44
Figure 31: Pointing Losses Calculation Satellite 45
Figure 32: Downlink budget summary sheet 48
Figure 33: System block diagram 49
Figure 34: ISIS Ground Station 52
Figure 35: Modified prototype system block diagram 53
Figure 36: Prototype cost table 54
Figure 37: TD Waterhouse Football field 55
Figure 38: Braemar Valley 56
Figure 39: Final prototype 56
Figure 40: Separation distances for test #1 58
Figure 41: Configuring "satellite" antenna for test #2 59
Figure 42: View of testing from "ground station" antenna for test #2 59
Figure 43: Separation distances for test #2 60
Figure 44: Antenna Angle Test at 48.08m (TD Stadium) 63
Figure 45: Antenna Angle Test at 78.36m (TD Stadium) 63

Figure 46: Antenna Angle Test at 108.11m (TD Stadium) 64
Figure 47: Antenna Distance Tests at TD Stadium 64
Figure 48: Antenna Distance Test at Braemar Valley 65

1. Introduction/Background

1.1 Problem Statement

The goal of the CubeSat project is for Western Engineering students to gain experience in the space domain, working alongside the Canadian Space Agency (CSA) to develop a CubeSat. As part of the communications team, we are developing the communications system for a nanosatellite (CubeSat) located in a low Earth orbit. The satellite, and communications system, will operate in the Ultra High Frequency range (UHF), which is 300 MHz – 1 GHz. The main objective of the CubeSat is to send 360° immersive images and videos to a ground station on Earth.

1.2 Background Information/ Detailed Literature Review

The literature review for this project involved antenna theory, propagation losses for the link budget, encoding, and modulation schemes.

a. Antennas

The first thing that someone should look at when selecting an antenna is the radiation pattern. Different antennas will focus this energy in different patterns and the geometry on how they focus signal is shown in the radiation pattern. A radiation pattern is essentially a graphical way to show how the energy is focused [1].

The radiation pattern can be shown in many ways and each of these ways are useful for different reasons. These different representations are listed below:

- *3D representation*

  The following are common ways of showing these radiation patterns. In Figure 1 (a), (b), (c), and (d) show a 3D representation of a radiation pattern and usually are accompanied by a legend that tells values associated to each color. Although they are easier to conceptually see, the problem with these 3D depictions is that they are less exact in showing information [1].

- *Azimuth Plane Pattern*

  This depiction is thinking about the pattern as you would see from looking down from space towards the antenna. This can be seen in Figure 1 (a) compared to (e). In this, you can imagine that you are high up in space (z direction) and looking down at the pattern [1].

- *Elevation Plane Pattern*

  This depiction is thinking about the pattern as you would see from looking at the antennas pattern from when you are standing beside it. This can be seen in Figure 1 (b) compared to (f). In this, you can imagine that you are looking along the y axis towards the radiation pattern [1].

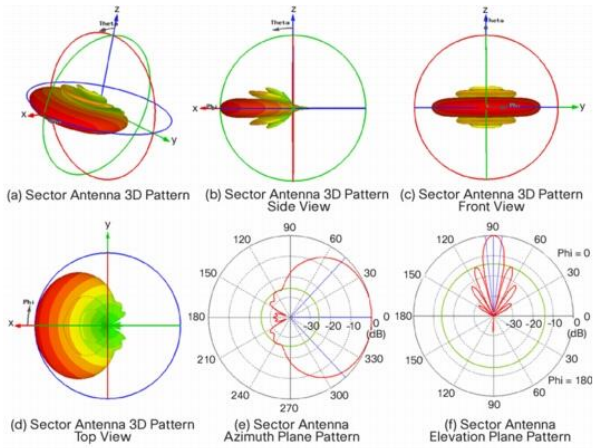


Figure 1: Radiation Pattern Explanation

Pros and Cons of each

- 3D representation shows in way that is easy to understand
- Azimuth and Elevation show cross section but allows for more precision when reading the graph (easier to tell at what angle the pattern has a specific gain value)

Along with the radiation pattern, gain is a measurement used to show how focused an antennas signal will be in a specific area. The important gain value that is usually used is the maximum gain on the main lobe of the radiation pattern. The main lobe refers to the most focused part of the antenna radiation pattern. This can be seen in Figure 1 (f) at the 90-degree point where the maximum gain occurs. This maximum gain on the main lobe is ideally pointed towards the receiving antenna and is, therefore, a very important factor for all aspects of the project. It should be noted that gain is not amplification, it is focusing energy in some areas at the expense of others and, therefore, a large gain value is not always beneficial. A higher gain value usually refers to a signal that is more direct and a lower gain refers to one that is less direct [1].

It should be noted that gain and directivity are sometimes referred to synonymously but are not the same. Gain takes feed losses into consideration as shown in Equation (1)

$$\begin{aligned} \textit{Gain} &= \textit{Directivity} - \textit{Antenna Feed losses} \\ &= \textit{Directivity} * \textit{antenna efficiency} \end{aligned} \qquad \text{Equation (1)}$$

It should be noted that gain is measured in dB, which is measured with respect to a different geometry of antenna [1]. In the measurement of decibels (dB), a reference must be chosen to compare each value to. This dB gain represents how the signal propagation changes throughout the radiation pattern but does not tell the true power being radiated.

One common unit of gain is dBi, which is a unit where the gain is compared to that of an isotropically radiated antenna. An isotropic antenna refers to an ideal antenna in which the signal propagates equally in all directions. Although this is an ideal case that is not realizable by any antenna, it can give a reference to compare antennas to. For example, a unit of 2 dBi will refer to an antenna that has a maximum gain that is 2dB in comparison to an isotropically radiated antenna.

Another common unit of measurement is dBd, where the gain is expressed in dB with respect to a dipole antenna. This compares the gain to that of a dipole antenna. A dipole antenna has a donut shaped radiation pattern as shown in Figure 2. When selecting antennas, it is important to keep these units in mind for comparison and if they are in different units, they must be converted to the same units.

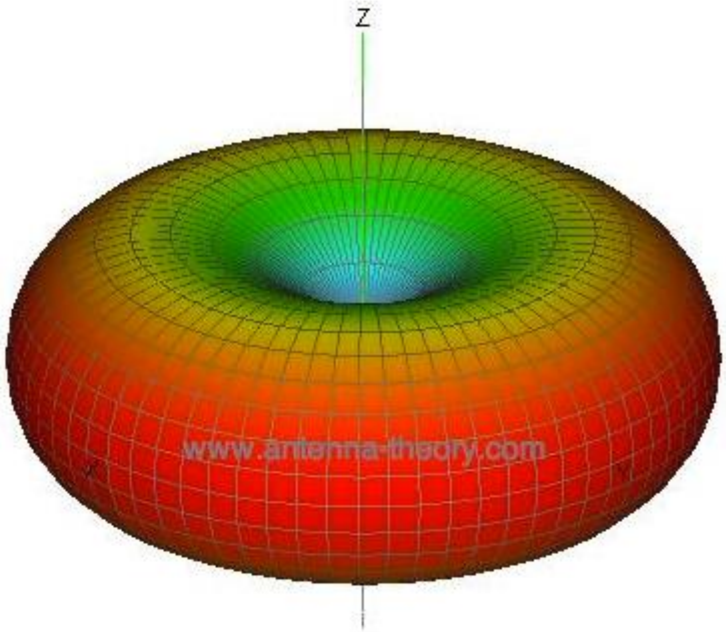


Figure 2: Dipole Radiation Pattern

In the radiation pattern, another data point that can be used to tell how direct the signal is, is called the half power beam width, or beam width for short. This is calculated as the angle in which the gain is within 3dB of the maximum gain as seen in Figure 3. The reason that 3dB is chosen is because when a gain is 3dB less, this means that the power is half of the power of the maximum gain.

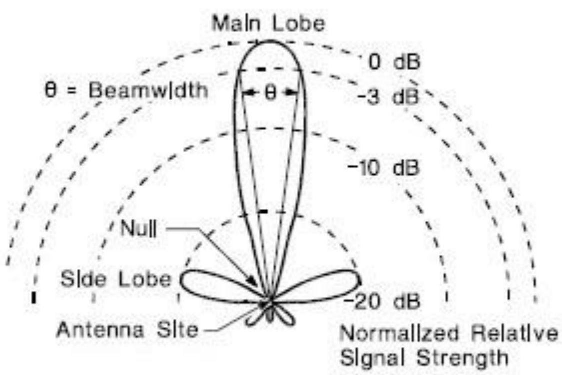


Figure 3: Radiation Pattern with Beam width

The relevance of this calculation is to show how direct a signal is. When an antenna has a high beam width and lower maximum gain, it is considered to be more omnidirectional. When it has a lower beam width and higher maximum gain, it is considered to be more directional. Both of these options are used for different situations.

Another major parameter is polarization. Polarization refers to how the signal propagates through space. As can be seen in Figure 4, the blue and green signals combine to make a red signal that propagates in one plane and is therefore linearly polarized. The circular polarized signal has two signals with a 90-degree phase shift, meaning that the combined signal will have a corkscrew-like pattern. When the signal is linearly polarized, the transmitter and receiver must both send and receive the exact same orientation to obtain the signal. For example, if the signal transmits a vertically polarized signal and is trying to receive a horizontally polarized signal, there will not be any signal obtained. Due to the nature of the communication channel, since signals can bounce off several things before hitting the ground (ex. clouds), it requires very fine adjustment of the satellite. It is very difficult to account for this signal orientation and would lead to many lost signals. This can be seen in Table 1 and is represented by an infinite loss.

If there is one signal that is circularly polarized and one that is linearly polarized, there is an extra 3dB loss as seen in Table 1. In order to optimize the design, both antennas should be circularly polarized in the same orientation (either Right Hand Polarized or both Left Hand Polarized). It can be seen in Table 1 that as long as the two signals are circularly polarized in the same direction, there is no extra loss associated with it.

While there is no definitive advantage to left-handed or right-handed orientation, both must be the same orientation to receive a signal without incurring the polarization losses. The losses associated with these polarization choices is shown in Table 1.

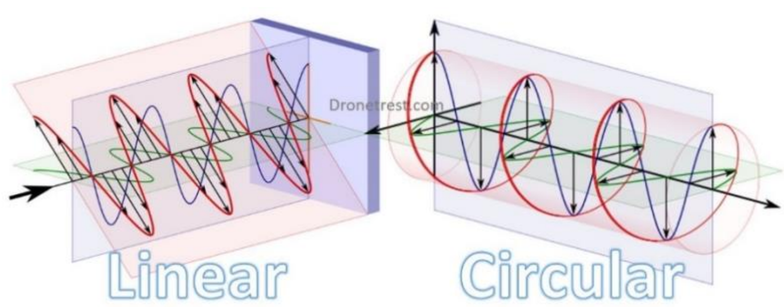


Figure 4: Linear vs Circular Polarization

Polarization combination	Polarization loss (dB)
Vertical - Vertical	0
Vertical - Horizontal	-∞
Horizontal - Horizontal	0
Circular (right or left) - Linear	-3
Circular right hand - Circular right hand	0
Circular right hand - Circular left hand	-∞

Table 1: Polarization Combinations

b. Encoding

The purpose of encoding is error detection and correction. Errors can occur in transmission because of channel noise on the signal. AWGN is the most commonly used channel model for CubeSat projects, because it is a good approximation of the transmission of data transferred in a free space application. Due to the Gaussian distribution of AWGN, a bit can be misinterpreted by the receiver if the noise added to the bit is particularly large, in other words far from the mean on the distribution. The graph in Figure 5 [2] illustrates this phenomenon based on a Binary Pulse Amplitude (BPAM) scheme. The likelihood of the received signal having enough noise to fall on the wrong side of the decision process (the y-axis in Figure 5) is determined by integrating the PDF. We know that the PDF of AWGN is dictated by Equation (2):

$$p(n) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{n^2}{2\sigma^2}\right)} \qquad \text{Equation (2)}$$

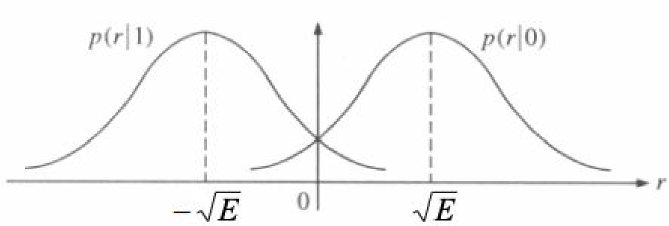


Figure 5: BPAM Scheme [2]

Therefore, the larger the difference in voltage between the two signals in this case, the less likely that noise will corrupt the signal. The other factor that affects signal error probability is the modulation scheme that is chosen, which will be discussed later in this report in the Modulation Scheme Trade-off Study.

The two main types of error correction used in CubeSat projects are FEC and ARQ. FEC is a method of assigning each encoded bit sequence to a code word, which is a way of adding redundancy to make each encoded bit sequence more unique. Both the transmitter and receiver have an identical dictionary of these code words. The code words are transmitted, and the receiver compares incoming code words to the dictionary. If a received code word does not match exactly to a code word in the dictionary, the OBP will assign the next closest code word on the list. This "closeness" is called the Hamming distance. While this method is not perfect, it will correct the vast majority of errors without the need for retransmission. Note that FEC is a unidirectional method of error correction.

ARQ is an error correction method that uses bidirectional communication to confirm that a message signal has been received correctly [3]. Once the transmitter has sent a data package, it waits for an acknowledgement message from the receiver. If the transmitter receives the acknowledgement, it prepares to send the next data package. If the transmitter does not receive the acknowledgement, it will wait for a specified amount of time before resending the message signal under the assumption that the original signal did not arrive, or it was corrupt.

c. Modulation

Digital modulation consists of three main categories; Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). Each modulation type transmits information through wireless signals in a different way, for the signals to be demodulated by the receiver.

ASK varies the amplitude of the RF carrier waveform with input from the baseband digital signal. The benefits of ASK are that it a simple and cost-effective way to transmit information. The drawback of ASK is that the signal is very susceptible to noise and can be corrupted when reaching the receiver. The simplest implementation of ASK modulation is On-Off Keying

(OOK), where a digital input of 1 is transmitted as a sine wave with a constant amplitude, and a 0 is transmitted as a sine wave with no amplitude (no carrier). A depiction of OOK modulation is displayed in Figure 6.

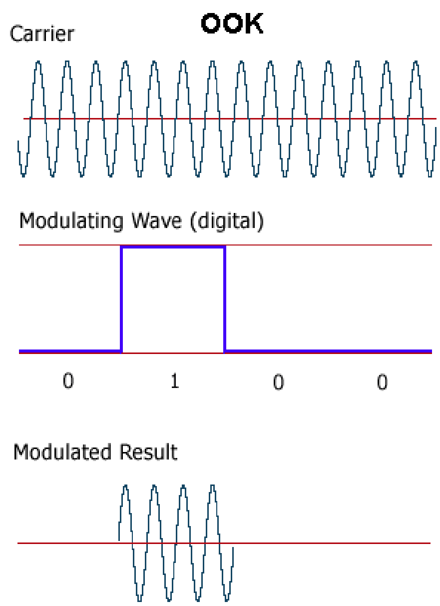


Figure 6: OOK Signal [4]

FSK varies the frequency of the RF carrier waveform with input from the baseband digital signal. The benefits of FSK are that the signals have high immunity to noise, and the system is relatively power-efficient. The drawback of FSK is that it has lower bandwidth efficiency than other modulation schemes, which will be further discussed in the modulation trade-off study section of this report. The simplest implementation of FSK is a 2FSK system where a digital input of 1 is transmitted as frequency f1, and a digital signal of 0 is transmitted as f2. A graph of a 2FSK signal is displayed in Figure 7.

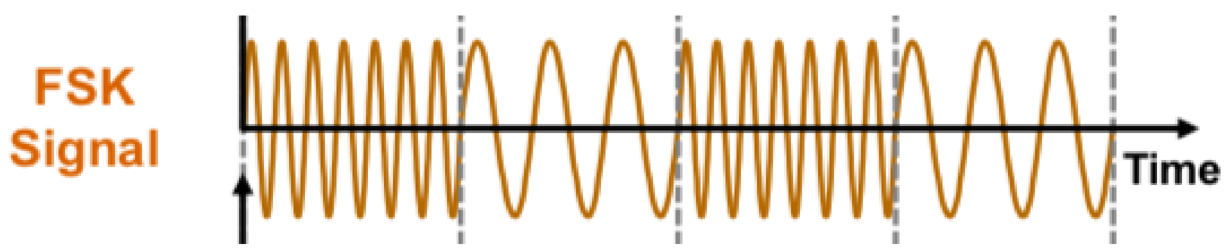


Figure 7: 2FSK Signal [5]

PSK varies the phase of the RF carrier waveform with input from the baseband digital signal. The benefits of PSK are that signals have high immunity to noise and are highly bandwidth efficient. The drawback of PSK is that it has a lower power-efficiency than other modulation schemes, which will be further discussed in the modulation trade-off study section. The simplest implementation of PSK is a 2PSK system where digital inputs of 1 and 0 are offset by 180 degrees of phase. A graph of a 2PSK signal is displayed in Figure 8.

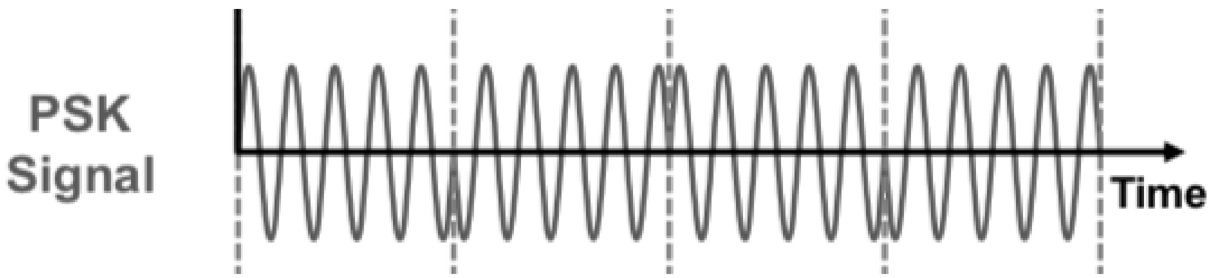


Figure 8: 2PSK Signal [5]

1.3Project Objectives

To reach the desired results for the project, the UHF communications subsystem has several objectives that must be achieved. A few of the objectives will be completed in parallel while the others depend on earlier tasks being completed.

1. Design the communication system architecture for both the satellite and the ground station. To successfully complete this task a few key components must be selected such as the antenna and the transceiver. To accomplish this objective, we will need to complete preliminary research on the components in a communication system to determine the desired qualities to ensure the optimal models are chosen. We will also need input from other subsystems such as the power team or the structures team to make sure the decision we make fits within the constraints of the other teams involved with designing the CubeSat.
2. Design and maintain a link budget that will model the communication link between the ground station and the satellite. The primary goal is to ensure the signal strength is larger than the received noise strength. The link budget will be developed in excel and will be set up such that it can be changed easily. Meaning the components and parameters can be changed and the resulting output from the link budget will change accordingly. This will

allow for us to compare the effect that different modulation schemes have on the system link.

3. Design and test a functional prototype to validate the link budget and final design. Once the link budget is complete we will use it to model our prototype communication system. The link budget will be validated if the measured results show similar trends and values to the link budget. Some values will be off by a small margin due to the losses and errors that are not calculated in the link budget such as signal reflection off the ground, or losses from the signal getting blocked by trees.
4. Have a successful communication link between ground station and the satellite. The final design components must be selected, the prototype should be designed and tested, and the link budget must be finalized before this objective can be achieved. The measure this objective, the link budget must yield a link margin that is greater than 3dB. If the link margin is greater than 3dB, the signal will be received with confidence. Having a link margin of 3dB means that the system can tolerate an additional 3 dB of losses before the signal cannot be separated from the received noise. The link margin is given by Equation (3). In this formula the required signal to noise ratio is given by the modulation scheme used to communicate the data. The formulas used in the link budget will be discussed in greater detail in 3.2.c. Link Budget.

$$Link\ Margin = received\ SNR - required\ SNR \text{ [dB]} \qquad \text{Equation (3)}$$

2. Design Approach

2.1 Concept Generation

We approached the concept generation from a big picture perspective, since many other CubeSat subsystems will interface with the communications subsystem. The overall interaction of different subsystems is depicted in Figure 9, and the communications subsystem is contained within the bold dotted line.

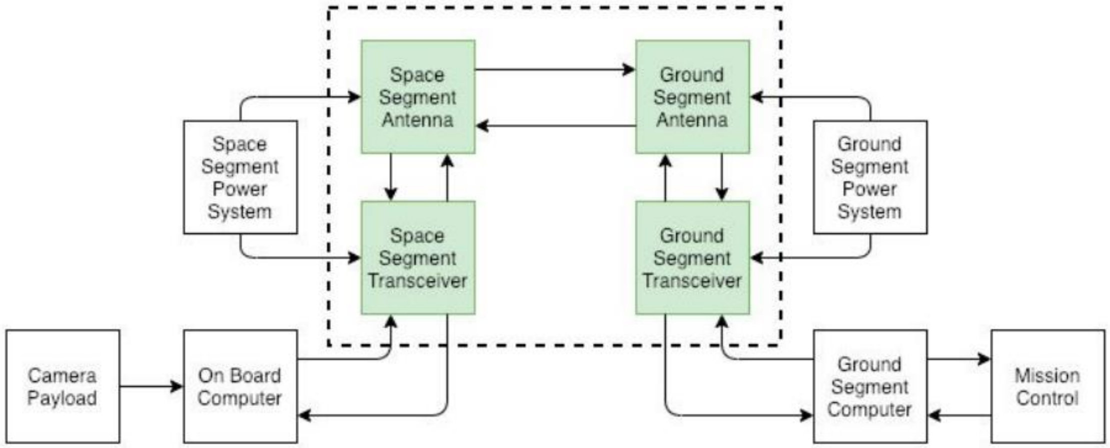


Figure 9: CubeSat subsystem interaction

The concept generation process of the communications subsystem was straightforward because it must contain specific components.

The concept generation was divided into two distinct parts, the space segment and ground segment. The reason for this separation is that the design constraints for both are different, with one being exposed to outer space, and the other to normal atmospheric conditions. Our concept generation was a process primarily involved research of components.

Space Segment

The space segment communications subsystem will consist of a transceiver, an antenna, and wiring which connects these parts to their dependent subsystems. The transceiver is the most complex component of our subsystem and based on its complex nature we will be purchasing a transceiver off the shelf. The antenna will also be purchased from a supplier. The benefits of a homemade antenna were weighed; however, we will need a very reliable and proven antenna design, therefore we will be buying a compatible off-the-shelf antenna. When considering the type of antenna that was ideal for our application, we initially planned to use a patch antenna. Patch antennas are useful because they do not require any deployment mechanism. We quickly realized that the patch antenna would not be compatible with the rest of the CubeSat's subsystems because the structures team required the antenna to be located midway along the length of the CubeSat. This meant that our antenna needed to have protruding rods to properly radiate information, leading our concept generation process to choose a quad monopole antenna that would deploy antenna rods once in orbit.

Ground Segment

Fortunately, the ground segment components are not constrained by size, weight or power. This make us much more flexible in our design approach. The ground segment transceiver and antenna can be significantly more powerful than those in space. The transceiver will be purchased from a manufacturer who specializes in CubeSat components, similar to the space segment. Initially, we considered using a dish antenna for our ground segment, due to the wide range of frequencies it can accommodate. Upon further research, we decided that a Yagi-Uda antenna would be much more suitable because we could match the circular polarization of our space segment antenna and avoid potential damage due to Earth's weather. For example, high winds would have little effect on a Yagi-Uda whereas they could severely damage a dish antenna.

2.2 Concept Evaluation and Selection

This section will outline the key components and how we selected each component.

Space Segment

Based on in-depth research on different transceivers which would satisfy our design objectives and constraints, we have chosen the UHF Transceiver Type 2 (Type 2 for short), manufactured by EnduroSat. This transceiver has a variable data rate (up to 100 kbps), requires low power, and offers a wide variety of modulation schemes at a competitive price point. In addition, the Type 2 has been tested for all conditions it will encounter in outer space, reducing uncertainty and risk of system failure. The testing that Endurosat performs on the transceiver include:

- Random Vibration
- Sinusoidal Vibration
- Pyro-shock Test
- Thermal Cycling
- Thermal Vacuum
- Total Ionizing Dose

A summary of the transceiver trade-off study is contained in Figure 10. We have also completed extensive research for a suitable space segment antenna. For the antenna, we have chosen Endurosat's UHF Antenna. This antenna has a reliable burn wire deployment mechanism, low power consumption and circular polarization. These selections were made while considering components from several other manufacturers, including GOMSpace, Nano Avionics, and Innovative Solutions in Space. The antenna trade off study is summarized in Figure 11.

For the Satellite antenna, we have discovered that it is optimal to have a lower gain value (<3dB) so that signal can be sent in the maximum amount of orientations. For the ground station antenna, we have discovered that a higher gain (>15dB) is optimal because there is more control of movement on the ground antenna. Based on our literature review, we have conducted a tradeoff study of the possible modulation schemes. The first thing that we have done for this is comparing the probability of bit error to the SNR (Eb/N0). Figure 13 shows a graph of probability of bit error to SNR (Eb/N0). This will allow us to set a probability of bit error that is acceptable and find an SNR based on this for using in our link budget. Based the CSA standards, this acceptable probability is approximately 10e-5. This SNR will then be used to figure out if there is enough system link margin to be acceptable (must be above 3dB). This is shown in Figure 17.

For designing the satellite antenna, there are a variety of parameters that need to be assessed. These can mostly be found in the antenna radiation pattern. Reading the radiation pattern is assessed in the Background Information section. The radiation pattern will tell how directional the signal is. When assessing antennas for the spacecraft, the gain value was mostly used as an indication of how directional the antenna was. A low gain value represents an antenna that propagates signal in a larger area. This was chosen for the spacecraft to make a more robust design that does not require strict pointing requirements to function.

This focus on lowering pointing requirements was done because it was clear that the S-band frequency band, which was a competing design, would have a significantly higher data rate. Due to this, the team for the UHF band designed all parameters with reliability in mind. This means that every single pass, the UHF band should be able to receive a signal. For the S-band, in contrast, the satellite and ground station must have a much stricter pointing requirement to attain a signal, however, when a signal is attained, it will transfer data much quicker than a similar UHF band.

	Manufacturer	Product Name	Data Rate	Tx Power	Sensitivity	Power Consumption	Modulation	Mass	Price	Overall Score
Weighting	N/A	N/A	5	5	5	4	5	2	4	N/A
Criteria	N/A	N/A	Maximum Data Rate Available	Maximum Tx Power	Maximum Sensitivity	Minimum Power Consumption	Most Modulation Options	Minimum Mass	Minimum Price	N/A
Components	EnduroSat	UHF Transceiver Type II	6	4	5	4	6	2	6	149
	Nano Avionics	UHF Digital Radio SatCOM UHF	3	5	4	1	6	5	5	124
	Innovative Solutions for Space	VHF uplink/UHF downlink Full Duplex Transceiver	3	2	3	3	3	4	3	87
	Innovative Solutions for Space	UHF uplink/VHF downlink Full Duplex Transceiver	3	1	3	6	1	3	3	82
	SpaceQuest	TRX-U Satellite UHF Transceiver	6	6	4	1	2	1	1	100
	GOMSpace	NanoCom AX100U	3	3	2	4	4	6	4	104

Figure 10: Transceiver Decision Matrix

	Manufacturer	Product Name	Directivity	Polarization	Mounting	Power (Nom)	Power (Max)	Mass	Price	Overall Score
Weighting	N/A	N/A	6	5	2	4	4	2	3	N/A
Criteria	N/A	N/A	Low directivity (omnidirectonal)	Circular Polarization	Easy to mount on system (does not need face of cubesat)	Power Usage (Nominal)	Power Usage (Max)	Minimum Mass	Minimum Price	N/A
Components	EnduroSat	UHF Antenna	6	6	6	6	6	4	6	152
	Nano Avionics	UHF Antenna	6	6	4	3	2	6	3	115
	ISI Space	Turnstile Antenna	5	6	4	3	3	4	5	115
	ISI Space	Monopole Antenna	4	0	4	6	1	4	5	83
	ISI Space	Dipole Antenna	5	0	4	1	2	4	5	73
	ISI Space	Hybrid Antenna	5	0	4	4	4	4	5	93
	CubeSat Shop	Helios deployable antenna	4	6	2	1	1	5	2	82

Figure 11: Antenna Selection Matrix

Ground Segment

The specific transceiver for the ground station has not been selected yet. Regarding the antenna, we plan to use a Yagi Uda design that complements the circularly polarized dipole antenna we have chosen for the space segment. The ground station antenna, due to the lower pointing errors, must be more direct to compensate for the low gain on the spacecraft. This means that the antenna design requires a much higher gain and lower beam width. Being a Yagi-Uda antenna means that this design can be easily changed in the future. This will allow the team next year to optimize the gain and beam width to fit with the pointing requirements of the Ground Station teams design. This is done to make sure that the antenna will have minimal antenna pointing error.

3. Design Analysis

3.1 Selection Engineering Techniques/Software tools

Include engineering techniques/software tools selected and used. Justify why you are using this method to analyze your design

One of the primary tools used during the design process of a communication system for a CubeSat is a link budget developed in Excel. The main goal of the link budget is to ensure the proposed communication system design is viable by ensuring the received signal is greater than the received noise. The link budget is used to track all the gains and losses associated with the components used in our final design. Using the outputs from the link budget, the final design can be compared by using different modulation schemes, different final components for the antenna and transceiver to see effects on the communication link.

MATLAB BERTOOL is an engineering design software tool that was critical for completing the modulation scheme trade-off study. When the preferred modulation scheme and M-ary value are entered, BERTOOL produces a plot showing the relationship between Bit Error Rate (BER) and Bit Energy to Noise Spectral Density (Eb/No). These plots are displayed in Figure 15, Figure 16, and Figure 18. The interface for BERTOOL is displayed in Figure 12. The MATLAB code for producing this function is contained in Appendix 1.

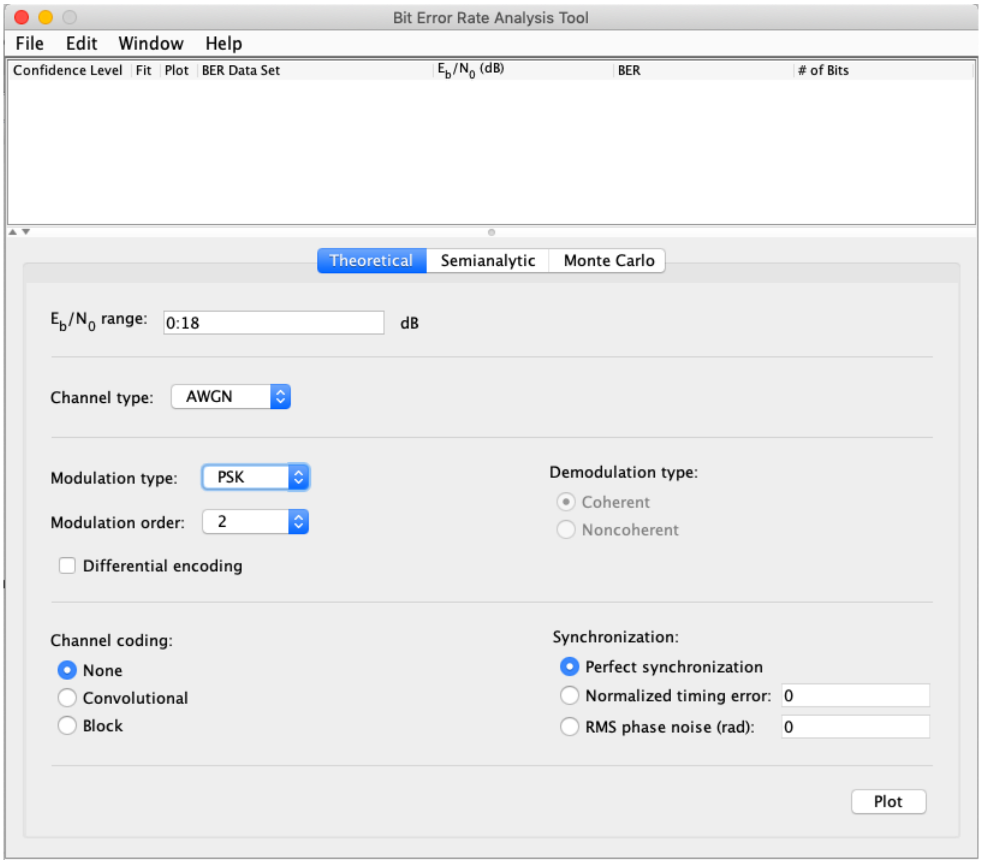


Figure 12: MATLAB Bit Error Rate Analysis Tool (BERTool) user interface.

For antenna simulation, there were several tools that were considered. The main two antenna simulation software programs that were found to be the most relevant and useful were MATLAB’s antenna toolbox and ANSYS HFSS software. For the scope of the first year of design, it was decided that ANSYS HFSS was too expensive. In following years, it may be worth looking into as it allows for a variety of simulation techniques and is able to simulate how the radiation pattern can change with their interactions with other components. This may be very useful in determining the effective radiation pattern and can show the tradeoffs for putting the antenna in different locations in the antenna. The current design has the antenna in the center of the CubeSat but this may be contrasted with putting the antenna at one of the ends, which will change the current design, but could net vastly different results.

Another antenna software that was considered and used briefly was the MATLAB antenna toolbox. This tool was used mostly due to its one-month free trial per user and its ability to simulate antennas quickly. This tool was used to simulate an optimum design of a Yagi Uda antenna. See the user interface of the antenna toolbox from MATLAB in Figure 13. It will generate many relevant graphs and design criteria such as radiation patterns and impedance matching. This will be very useful for the next year to create a more accurate design for the Ground Station antenna. For the current year, the antenna was chosen to be a Yagi Uda, however, due to the unknown pointing accuracy of the Ground Station team, the full design was not chosen. To do this, the next team should design a radiation pattern in which the gain and beam width are optimized. This means that they will need to figure out what acceptable pointing losses will be and design such that the antenna will never be below these values.

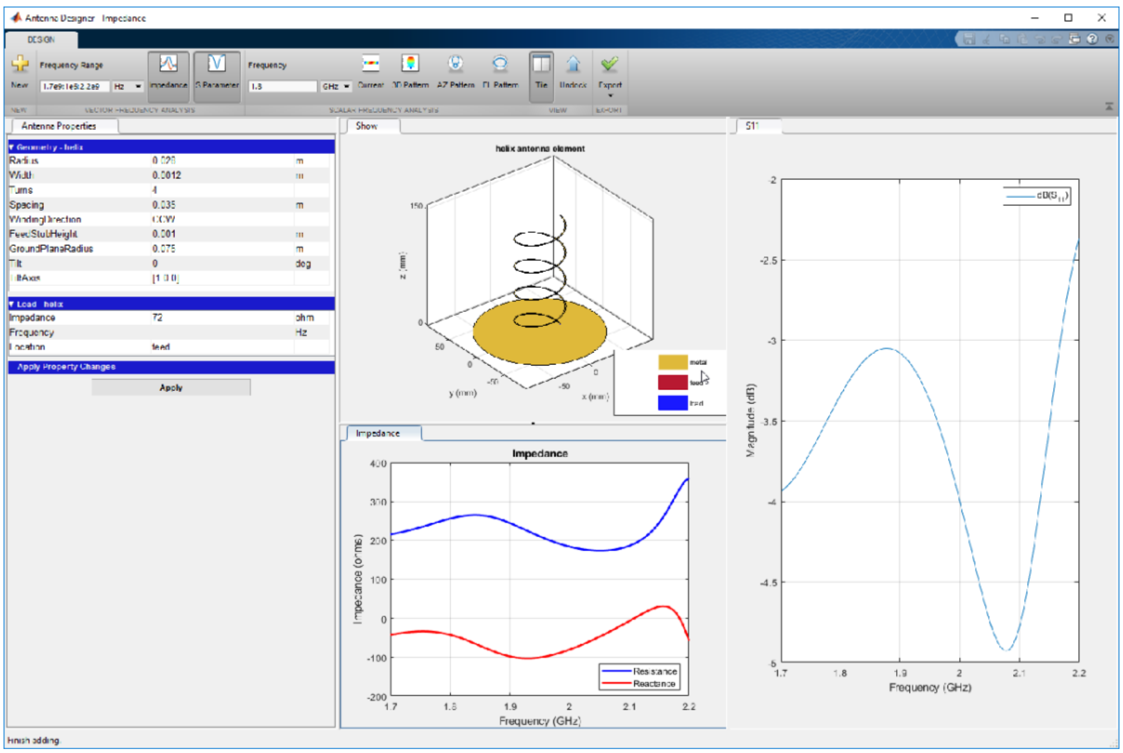


Figure 13: Example of Matlab Antenna Toolbox

3.2 Use of Engineering Techniques/Software tools

The link budget was used to validate the final design of our system by entering the parameters from each component selected. The specific power requirements for the transceiver and antenna, transceiver losses, antenna gains, and antenna losses were entered in their respective sheets in the link budget. The basic principal of the link budget is that it will calculate the signal strength (in dB) at 5 stages of the signal transmission. The link budget will first calculate the transmitted power, using data from the transmitting transceiver (satellite transceiver for the downlink). The link budget will the calculate the signal strength after the transmitted signal passes through the transmitting antenna using the gain and beam width of the transmitting antenna. The next stage of the link budget will calculate the losses associated with the transmission distance between the satellite and the ground station to arrive at the received power at the ground station (for the downlink). This signal strength will then be amplified by the ground station antenna to arrive at the received power (in dB). The difference between the transmitted power and received power is the metric used to quantify the performance of the communication system. A link margin of 3 dB or greater is said to be a good enough margin where you can confidently assume that you will receive your signal and be able to distinguish it from the received noise [6]. The link budget will also be used to model the prototype system. The expected results for each test performed will be simulated by changing certain parameters and obtaining theoretical results. The measured results from testing the prototype will be compared to the theoretical results to validate the link budget. This will give confidence that the link budget is functioning properly and is correctly modeling the final design.

For designing the communication link, the most important antenna criteria for the creation of the link budget is the radiation pattern. Since the radiation pattern was given by the manufacturer in the specification sheets of the CubeSat antenna, it was not simulated. The Ground Station antenna, however, required simulations due to the variability of design. These simulations can be created in MATLAB and will create a radiation pattern, which is important for analyzing antenna losses shown in Section 3 3.3 c Losses, along with other criteria that are important for design such as impedance matching.

As mentioned in Section 3.1, MATLAB and MATLAB BERTool are two critical software programs used in the modulation scheme trade-off study. We used them to visualize the characteristics of each modulation scheme in deciding which scheme was optimal. The implementation of MATLAB code is outline in Appendix 1.

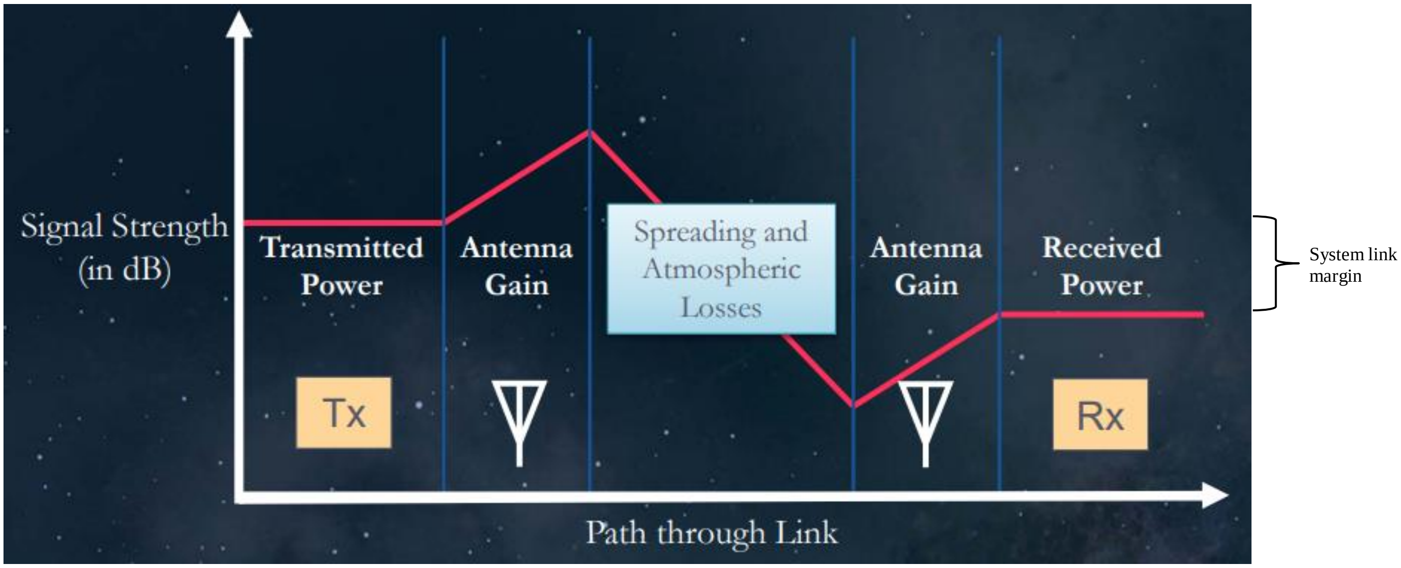


Figure 14: Communication link

3.3 Complete Analysis/Calculations

a. Modulation Scheme Trade-Off

To begin our modulation scheme trade-off study, there are several important questions we must ask ourselves. These include the following:

Do we have a target bit rate?

Due to the complexity of the components involved in a communications system, the space segment components must be Commercial off the Shelf (COTS). Due to this limitation, we must select a transceiver which has a preset data rate. The industry standard data rates for CubeSat COTS transceivers range from 1200 bps to 9600 bps. The data rate on components is constrained by the serial connection they are equipped with for data transfer to the onboard computer subsystem. Based on this constraint, we have set our target bit rate at 9600 bps.

Is our system bandwidth-limited?

Since we do not know what our bandwidth will be, we must make some assumptions regarding our approved bandwidth. We will consider our system to be somewhat bandwidth-limited, because we expect the approved bandwidth to be large. Based on discussions with individuals who have worked on CubeSat projects in the past, we expect our allocated bandwidth to be 50 kHz or greater.

Is our system power-limited?

Our system is power-limited, because we are constrained by the finite power resources onboard the space segment. For that reason, we aim to consume as little power as possible, while achieving our target data rate of 9600 bps.

The key decision of modulation is dictated by the following principle: “Shannon showed there is a fundamental tradeoff between energy efficiency and bandwidth efficiency for reliable communications.” [7]

This section will examine four main categories of modulation schemes: M-ary Phase Shift Keying (MPSK), M-ary Frequency Shift Keying (MFSK), M-ary Quadrature Amplitude Modulation (MQAM) and Minimum Shift Keying (MSK). The main method of analysis we will use for comparing modulation schemes is bandwidth efficiency. It must be emphasized that there is not one modulation scheme that is superior to the rest, but rather that each communications theory application has unique needs that are best met by a certain type of modulation scheme. In this case, we will select the scheme that best fits our system constraints and objectives. Essentially, we will choose the modulation scheme which makes the most efficient use of our allotted bandwidth, given a data rate of 9600 bps and a Bit Error Rate (BER) of 10e-5. We will also select a modulation scheme that does not require encoding if possible, in order to reduce system complexity.

The MATLAB BERTool program is a convenient way to graph the BER to SNR relationship for various modulation schemes. We used BERTool to obtain the Eb/N0 values for each scheme with a BER of 10e-5, displayed in Figure 15, Figure 16 and Figure 17.

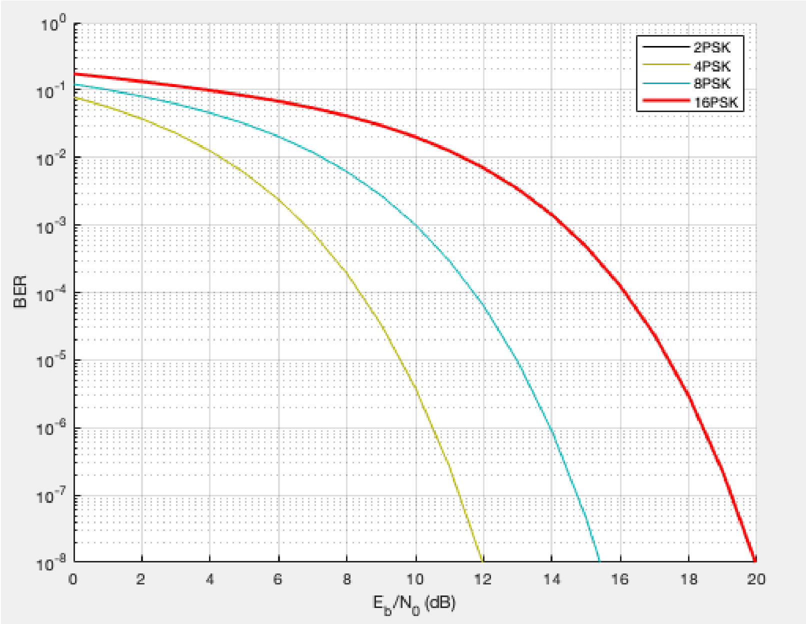


Figure 15: MPSK Modulation Curves

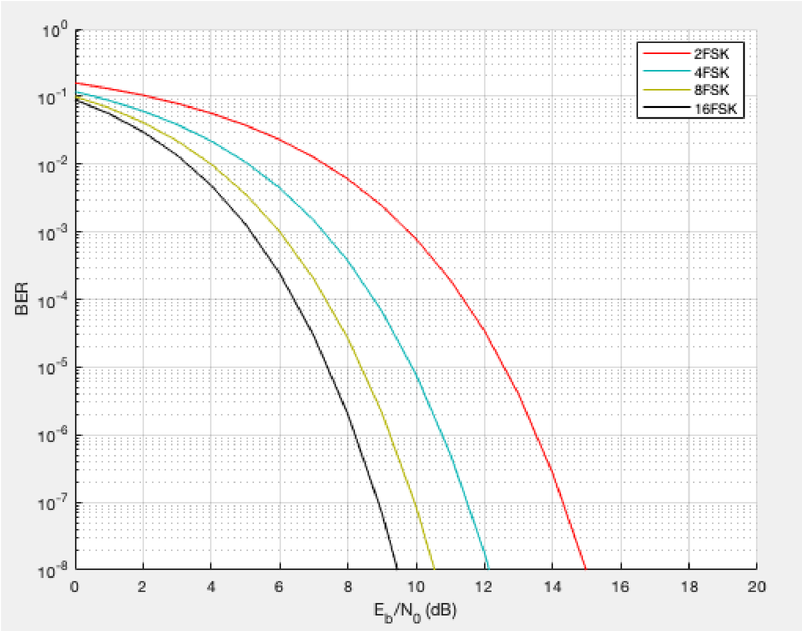


Figure 16: MFSK Modulation Curves

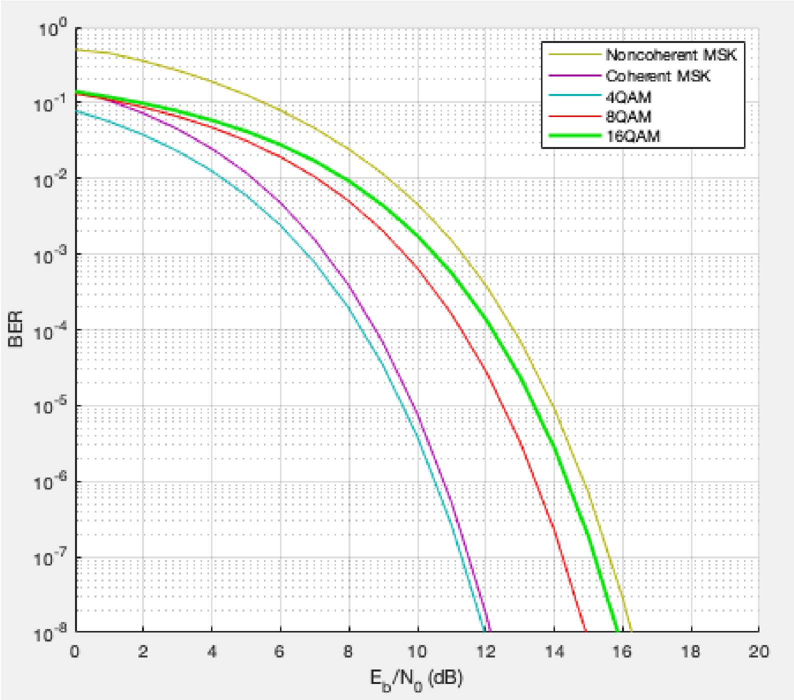


Figure 17: MSK and M-QAM Modulation Curves

From Shannon-Hartley Theorem, we know that the Channel Capacity, C, represents the theoretical maximum value for the Data Rate, R. [8] Based on this relationship, we can conclude that Equation (4) must be true. This then leads us to Equation (5) which allows us to create the Bandwidth Efficiency Plane.

$$R \leq C \qquad \text{Equation (4)}$$

$$R \leq W \times log_2(1 + SNR)$$
$$R \leq W \times log_2(1 + \frac{S}{N_0 \times W})$$
$$\frac{R}{W} \leq log_2(1 + \frac{S}{N_0 \times W})$$
$$2^{\frac{R}{W}} \leq 1 + (\frac{E_b}{N_0} \times \frac{R}{W})$$

$$\frac{E_b}{N_0} \geq \frac{2^{\frac{R}{W}} - 1}{\frac{R}{W}} \qquad \text{Equation (5)}$$

Now to determine the bandwidth efficiency of each modulation scheme we must use the following equations:

The bandwidth efficiency of M-ary PSK modulation systems are dictated by Equation (6).

$$\frac{R}{W} = log_2 M \qquad \text{Equation (6)}$$

The bandwidth efficiency of M-ary FSK modulation systems are dictated by Equation (7).

$$\frac{R}{W} = \frac{log_2 M}{M} \qquad \text{Equation (7)}$$

Based on these calculations and the plots generated in MATLAB BERTool, we can populate Table 2, Table 3, and Table 4.

M	m	R(b/s)	Rs(symb/s)	MPSK Min. Bandwidth (Hz)	MPSK R/W	MPSK Eb/N0 (dB)	Non-Coherent Orthogonal MFSK Min. Bandwidth (Hz)	MFSK R/W	MFSK Eb/N0(dB)
2	1	9600	9600	9600	1	9.6	19,200	1/2	13.4
		19200	19200	19200	1	9.6	38,400	1/2	13.4
4	2	9600	4800	4800	2	9.6	19,200	1/2	10.6
		19200	9600	9600	2	9.6	38,400	1/2	10.6
8	3	9600	3200	3200	3	13.0	28,800	1/3	9.1
		19200	6400	6400	3	13.0	57,600	1/3	9.1
16	4	9600	2400	2400	4	17.5	38,400	1/4	8.1
		19200	4800	4800	4	17.5	76,800	1/4	8.1

Table 2: MPSK, MFSK Bandwidth Efficiency and Eb/No values

M	m	R(b/s)	Rs(symb/s)	MQAM Min. Bandwidth (Hz)	MQAM R/W	MQAM Eb/N0(dB)
4	2	9600	4800	4800	2	9.6
		19200	9600	9600	2	9.6
8	3	9600	3200	3200	3	12.5
		19200	6400	6400	3	12.5
16	4	9600	2400	2400	4	13.4
		19200	4800	4800	4	13.4

Table 3: MQAM Bandwidth Efficiency and Eb/No values

M	m	R (b/s)	Rs (symb/s)	Coherent MSK Min. Bandwidth (Hz)	Coherent MSK R/W	Coherent MSK Eb/N0(dB)	Non coherent MSK Min. Bandwidth (Hz)	Non coherent MSK RW	Non coherent MSK Eb/N0(dB)
2	1	9600	9600	4800	2	9.9	4800	2	14.0

		19200	19200	9600	2	9.9	9600	2	14.0

Table 4: Coherent and Non-coherent MSK Bandwidth Efficiency and Eb/No values

Now that we have calculated the values for both bandwidth efficiency and the required Eb/No, we can plot them on the Bandwidth Efficiency Plane (BEP). The BEP is governed by the Shannon-Hartley Capacity, which is derived from Shannon-Hartley Capacity Theorem (Equation (4)). The BEP is displayed in Figure 18.

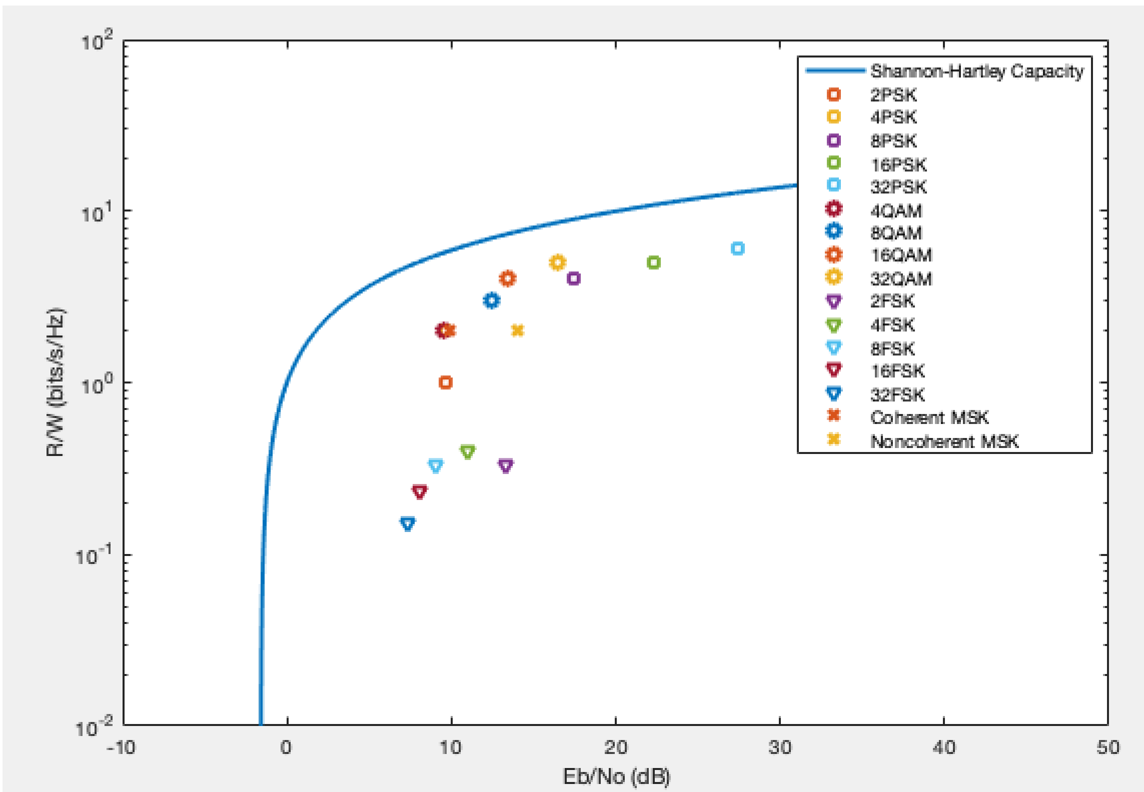


Figure 18: MPSK, MQAM, MFSK and MSK schemes plotted on the BEP

Since our system is power-limited rather than bandwidth limited, we selected the Coherent MSK modulation scheme. Coherent MSK has one of the highest bandwidth efficiencies, while requiring a very low Eb/No. In addition, there are a multitude of available COTS components that offer Coherent MSK as a modulation option. Coherent MSK modulation is a continuous-phase form of FSK with a constant envelope. The difference between the higher and lower frequencies is equivalent to exactly half the bit rate. Based on the selection of Coherent MSK as our modulation scheme, we can see that we need the following Average Received Signal-Power to Noise-Power Spectral Density, or $\frac{S}{N_0}$ to achieve our target data rate in Equation (8).

$$\frac{S}{N_0} = \frac{E_b}{N_0} \times R \qquad \text{Equation (8)}$$

$$\frac{S}{N_0}(dB \cdot Hz) = \frac{E_b}{N_0}(dB) + R(dB \cdot \frac{bit}{s})$$

$$\frac{S}{N_0}(dB \cdot Hz) = 9.9dB \cdot Hz + (10 \times log_{10}9600)dB \cdot \frac{bit}{s}$$

$$\frac{S}{N_0}(dB \cdot Hz) = 49.7dB \cdot Hz$$

Now that we have selected Coherent MSK as our modulation scheme, we must determine whether encoding is necessary to achieve the required Bit Error Rate (BER). We can find the resulting probability that the demodulator makes a symbol error by using Equation (9):

$$P_{be,MSK} = Q(\sqrt{\frac{2E_b}{N_0}}) \qquad \text{Equation (9)}$$

$$P_{be,MSK} = \frac{1}{2} \times erfc(\sqrt{\frac{E_b}{N_0}})$$

$$P_{be,MSK} = \frac{1}{2} \times erfc(\sqrt{9.9dB})$$

$$P_{be,MSK} = 4.299 \times 10^{-6}$$

Based on the above calculations, we can conclude that the communications subsystem will not require encoding, since the BER produced our selected component will more than meet the required BER of 10e-5.

Variables used in this section:

C is the Channel Capacity [bps]

W is the Channel Bandwidth [Hz]

$\frac{S}{N}$ is the Ratio of Received Signal-Power to Noise-Power [dB]

R is the Data Rate [bps]

m is the number of Bits []

T_s is the symbol duration [s]

M is the size of the alphabet []

$\frac{S}{N_0}$ is the Average Received Signal-Power to Noise-Power Spectral Density [dB]

$\frac{E_b}{N_0}$ is the Received Bit-Energy to Noise-Power Spectral Density [dB]

R is the Data Rate [bps]

$P_{be,MSK}$ is the probability that demodulator makes a symbol error []

b. Antennas

When deciding on an antenna, it is important to optimize the gain and beam width of the antenna design. For the satellite antenna, it was clear that the UHF band was unable to send as much data as the S-band. It was clear at that point that the UHF project should focus on creating a design that has a very low gain that will be able to transmit signals in almost all orientations.

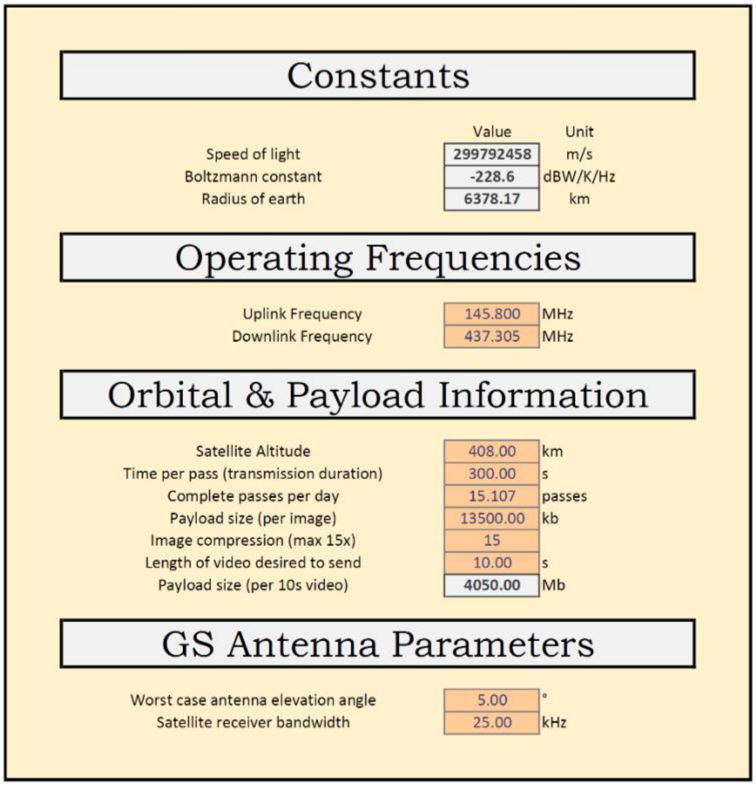
This will provide a low data transfer, however, it will require less pointing requirements and less power requirements to orient the satellite correctly.

c. Link Budget

The formulas and explanation of the methodology used in the link budget will be given below. When designing and developing the link budget, the following were used as references [6] [9].

Inputs Sheet

The inputs sheet consists of 10 inputs that the user must enter, as seen in Figure 19. The inputs are explained below.



Constants

	Value	Unit
Speed of light	299792458	m/s
Boltzmann constant	-228.6	dBW/K/Hz
Radius of earth	6378.17	km

Operating Frequencies

Uplink Frequency	145.800	MHz
Downlink Frequency	437.305	MHz

Orbital & Payload Information

Satellite Altitude	408.00	km
Time per pass (transmission duration)	300.00	s
Complete passes per day	15.107	passes
Payload size (per image)	13500.00	kb
Image compression (max 15x)	15	
Length of video desired to send	10.00	s
Payload size (per 10s video)	4050.00	Mb

GS Antenna Parameters

Worst case antenna elevation angle	5.00	°
Satellite receiver bandwidth	25.00	kHz

Figure 19: Link budget inputs sheet

- **Uplink Frequency**: this value is used as an approximation to the value we will be given. As it is year 1 of the project, the frequency has not been finalized yet and this value should be changed once the frequency is finalized.
- **Downlink Frequency:** this value is used as an approximation of the final downlink frequency. It should be changed once the frequency is finalized.
- **Satellite Altitude:** This is the altitude of the satellites orbit, and since it is being launched from the International Space Station, 408 km is the altitude used.
- **Time per pass:** 5 minutes is the value being used right now as safe approximation of communication time per pass. This value was provided by Matt Bourassa.
- **Complete passes per day:** the value of passes per day was provided by the orbit team as being 15.107. The value is rounded down to complete passes such that the link budget correctly calculates the worst-case scenario.
- **Payload size (per image):** This value approximates the size of the images in kb. Since the camera is being designed, the exact size of the images is still unknown. This value was given as an approximation by Canadensys.

- **Image compression (15x maximum):** The underlying logic of the compression is again unknown. As of right now, the compression works as linear compression (x15 will reduce the size of the images by 15).
- **Length of video desired to send:** This value is entered in seconds, to see how many passes it will take to send videos back to the ground station. (note the size of the videos is still undetermined, an assumption of 30 fps is used to calculate the size – 30*size of 1 image*length of video)
- **Worst case antenna elevation angle:** The value used is 5°. This value represents the corresponding angle between earth and the radiation pattern of the signal from the antenna. Refer to Figure 20 for a visual depiction of the elevation angle.
- **Satellite receiver bandwidth:** The bandwidth used approximates the final bandwidth the team will be granted. The application for this bandwidth has been applied for in year 1 of the project.

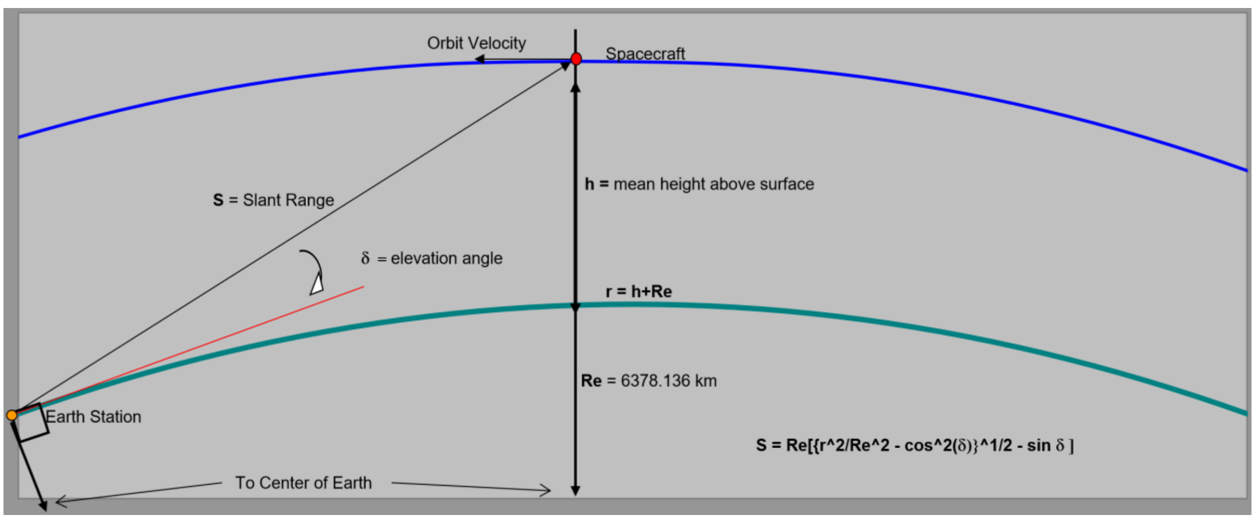


Figure 20: Orbital measurements and distances

Orbit Sheet

This sheet is used as an output sheet to show the user the losses associated with the free space transmission. Refer to Figure 21 for an image of the Orbit Sheet.

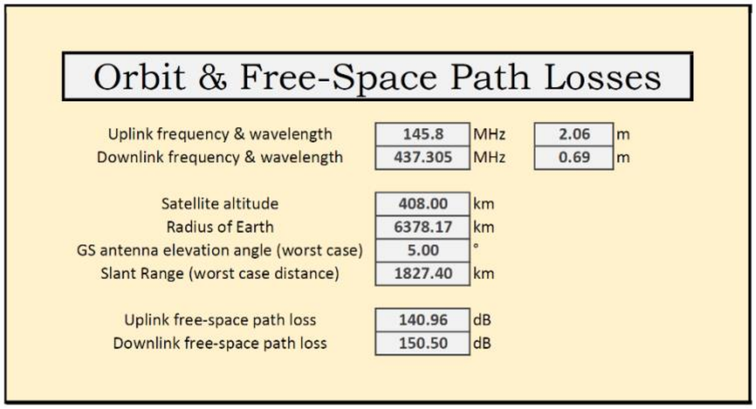


Figure 21: Link budget orbit sheet

The wavelength for the frequencies is calculated using Equation (10).

$$\lambda = \frac{c}{f} \text{ [m]} \qquad \text{Equation (10)}$$

The slant range is the worst-case distance (or maximum separation distance between the satellite and the ground station) during the orbital period. Refer to Figure 20 to view the slant range S. The slant range is calculated using Equation (11) below.

$$S = R_{earth} \cdot \left[\sqrt{\frac{(R_{earth} + Sat.Altitude)^2}{{R_{earth}}^2} - cos^2\,\theta} - sin\,\theta\right] \text{ [km]} \qquad \text{Equation (11)}$$

The Free-space path loss (expressed in decibels) is derived from Friis transmission formula and is shown in Equation (12). This equation is used to calculate the path loss for both the uplink and downlink.

$$FSPL = 20 \cdot \log_{10}\left(\frac{4\pi S f}{c}\right) \text{ [dB]} \qquad \text{Equation (12)}$$

Transmitter Sheet

The transmitter sheet is divided in two with a section for the uplink transmitter (or the transmitter on ground station) and the downlink transmitter (or the transmitter on the satellite). Both sheets are in the same format and layout. Refer to Figure 22 and Figure 23. The power delivered for the transmitters is calculated using Equation (13).

$$Power\ Delivered = trans.power - trans.losses \text{ [dBW]} \qquad \text{Equation (13)}$$

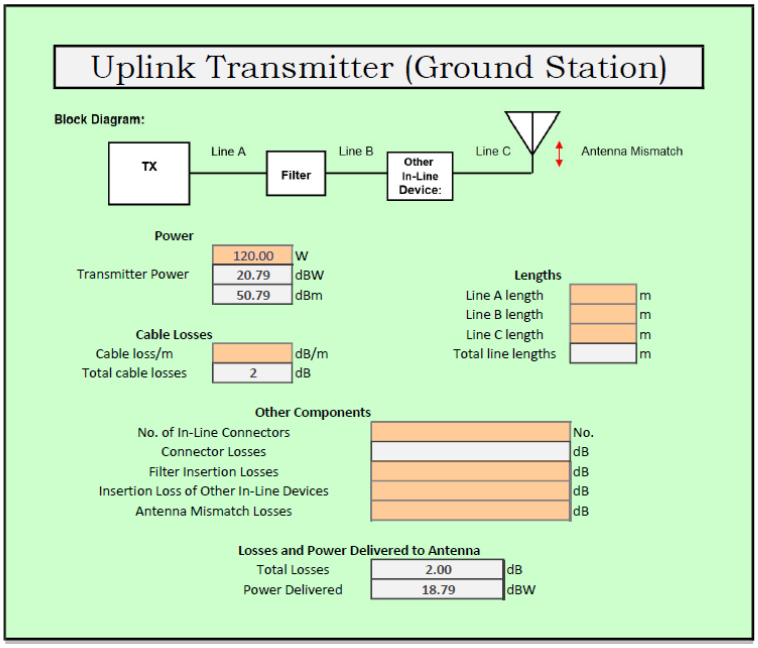


Figure 22: Link budget transmitter sheet, uplink

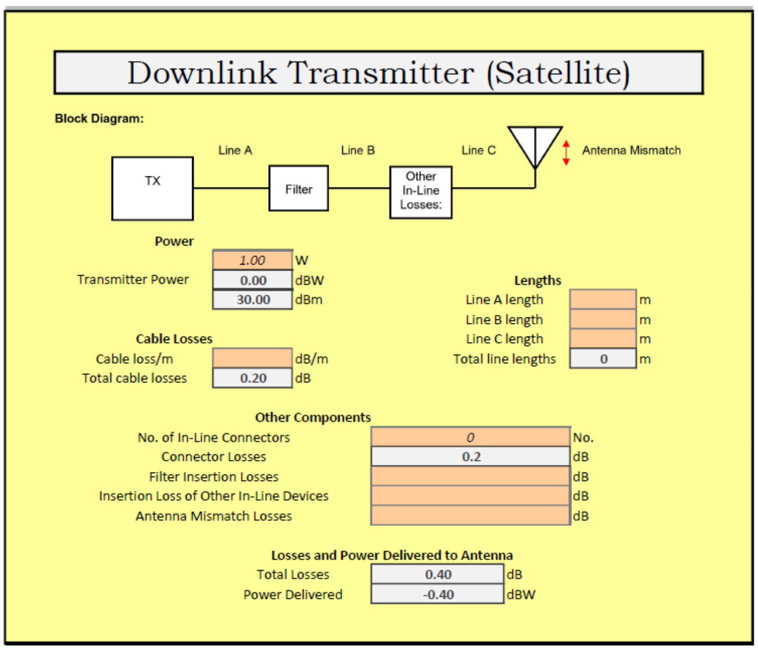


Figure 23: Link budget transmitter sheet, downlink

Antennas Sheet

The antennas sheet is divided into two sections to enter the parameters for both antennas. Refer to Figure 24 for a view of the antennas sheet in the link budget. The polarization, gain, and beam width are required parameters for each antenna.

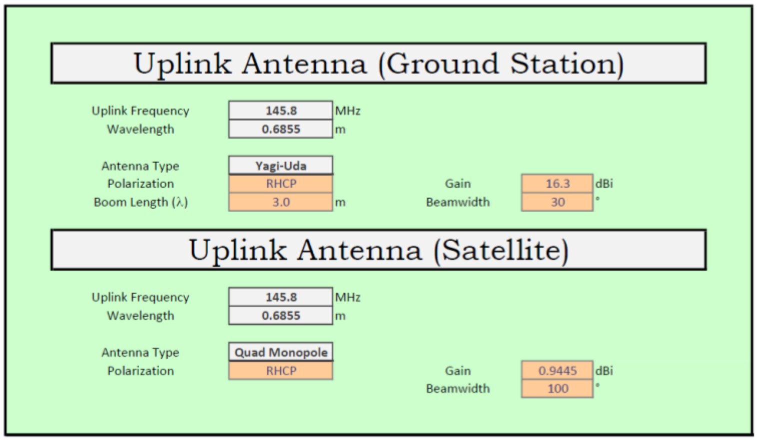


Figure 24: Link budget antennas sheet

Receivers Sheet

The receiver sheet is divided in two with a section for the uplink receiver (or the receiver on the satellite) and the downlink receiver (or the receiver on the ground station). The inputs for the receiver's sheet are the losses in the receiver (entered in dB).

A few calculations are done on the receiver sheet such as the transmission line coefficient, and the system noise temperature. The transmission line coefficient is calculated using Equation (14) and the system noise temperature is calculated using Equation (15.

$$Trans.\,Line\ Coefficient = 10^{-\frac{receiver\ losses}{10}}\ [\mathrm{dBW}] \qquad \text{Equation (14)}$$

$$Power\ Delivered = trans.\,power - trans.\,losses\ [\mathrm{dBW}] \qquad \text{Equation (15)}$$

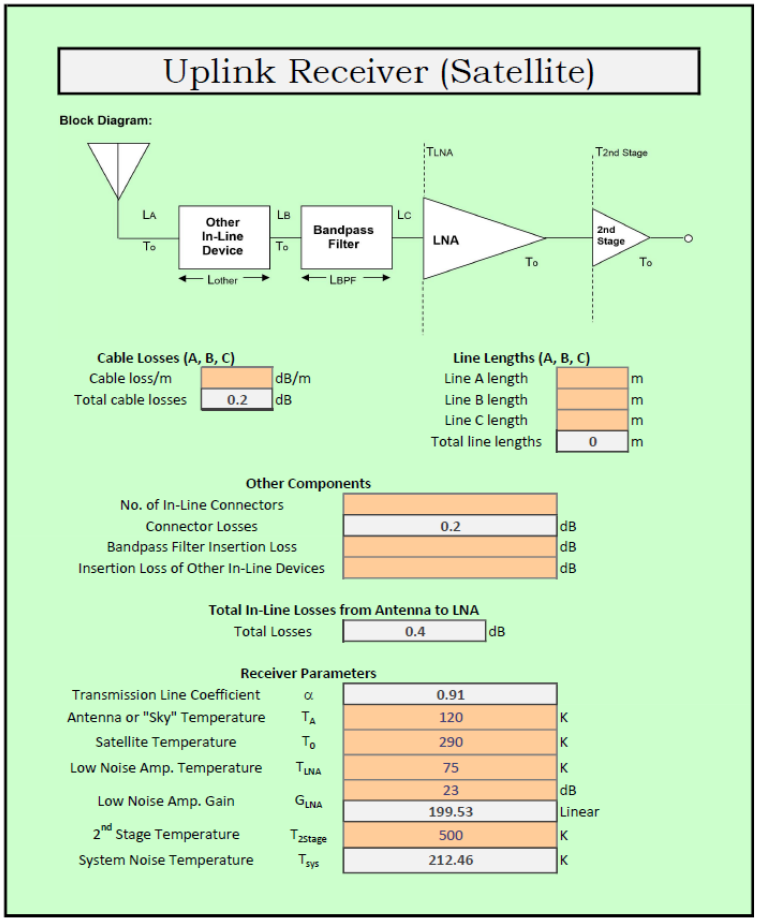


Figure 25: Link budget receiver's sheet, uplink

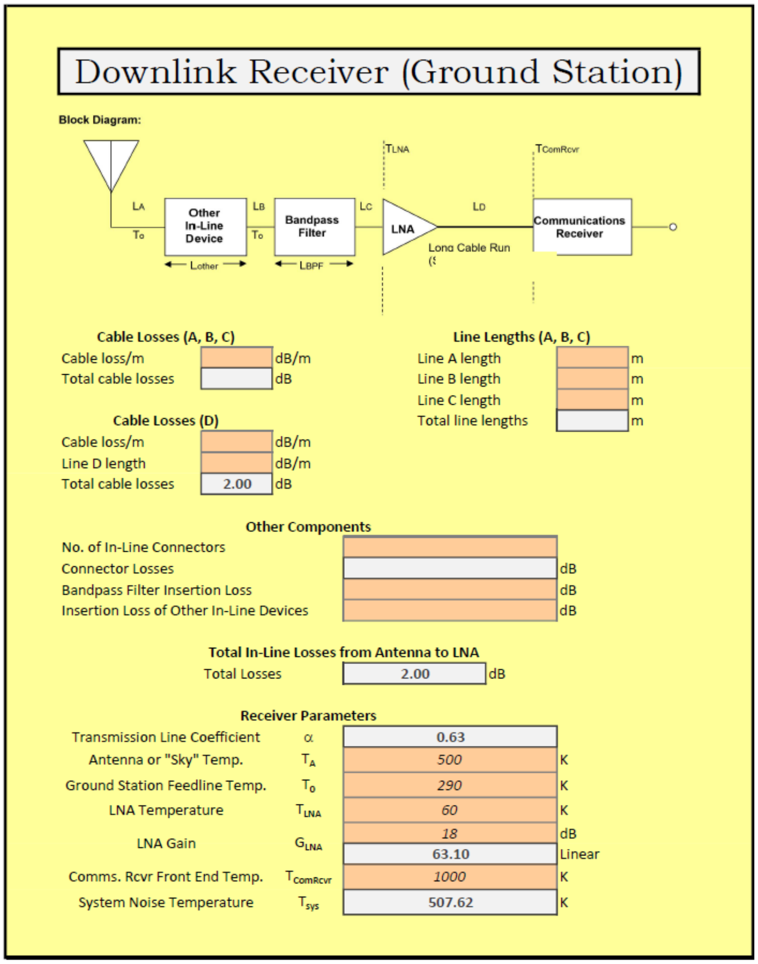


Figure 26: Link budget receiver's sheet, downlink

Modulation Sheet

The modulation sheet was set up using drop down cells, where the user could select the modulation scheme used. This would allow for the user to easily view the effects of different modulation schemes on the communication link. Refer to Figure 27 for a view of the modulation sheet.

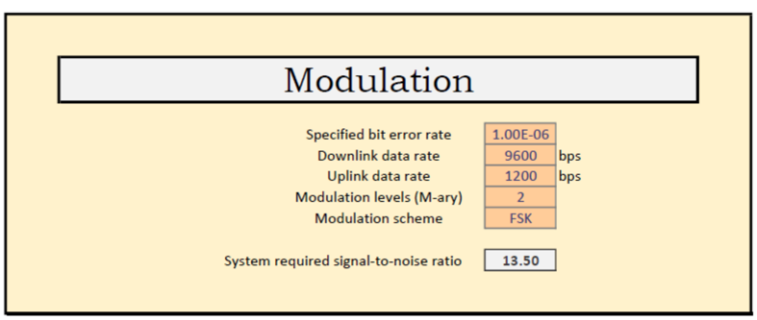


Figure 27: Link budget modulation sheet

Losses

The losses sheet calculates losses associated with the transmission through free space (atmospheric and ionospheric), and losses associated with the antennas. The atmospheric losses are due to the gases distributed along the path of transmission between the satellite and the ground station (slant range). In turn, this makes these losses dependent on the elevation angle of the ground station antenna. The data used to determine the losses in the UHF frequency range were found in [10].

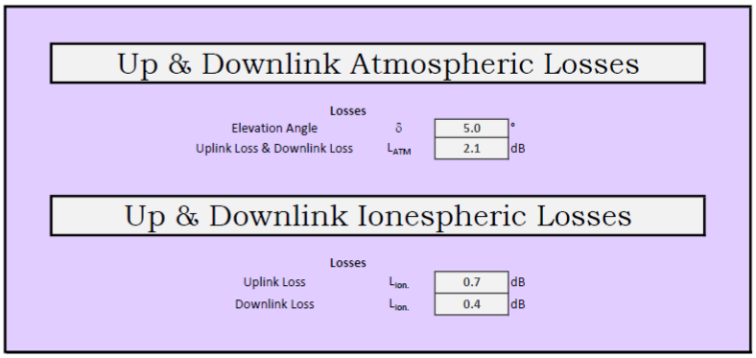


Figure 28: Link budget losses sheet, atmospheric and ionospheric

For the Antenna Pointing Losses, the link budget models how the gain will decrease when the maximum gain is not pointed towards the antenna. In Figure 29, the angle from the maximum gain of the antennas pointing at each other is recorded. These losses that accrue must be accounted for. The satellite antenna and the ground station antenna were modelled slightly differently due to the differing data that was given to us and will both be explained below. When the full ground station antenna has been designed, the radiation pattern will be given and a more accurate pointing losses can be generated.

The radiation pattern of the satellite was measured based off the manufacturer given radiation pattern shown in Figure 30. Based on this, the maximum gain was given as 0.9445 and was recorded as the 0 degree point. Each 5 degree measurement was then recorded and a table was constructed for each point on the radiation pattern. To calculate the losses, each respective gain was subtracted from the maximum gain. The radiation pattern given takes cross sections at 0, 45, 90, 135, and 180 degrees on the x-y plane. This means that it can show cross sections that include the best and worst case pointing losses. The best and worst cases were put into a table (see figure below). Note that the “Maximum Losses” (worst case pointing losses) were recorded for the link budget.

The pointing losses calculated for the ground station were calculated using the beam width and the pointing angle. This was done with a general formula that is meant to give approximate pointing losses for a Yagi Uda antenna based only on gain and beam width. This formula was found from AMSAT, a company that specializes in creating link budgets and information for Amateur Satellites [9]. This was meant to quickly test many gains and beam widths to find values that will allow our link budget to simulate other factors. A Yagi Uda antenna has been selected based on many factors such as the easily adjustable gain and beam width that it provides. The gain and beam width, however, could not be accurately designed because information regarding pointing accuracy of the ground station antenna was unknown. In the following years, the ground station antenna gain and beam width should be selected based on the pointing accuracy that can be achieved by the Ground Station Team and designed accordingly. The gain and beam width in the current model are given based on estimates on how directional our antenna should be and using values from the American Radio Relay League (ARRL) antenna book for Yagi Uda antennas [11]. When the ground station antenna has been fully designed, the team should create a radiation pattern and use values from this for a more accurate depiction of the pointing losses.

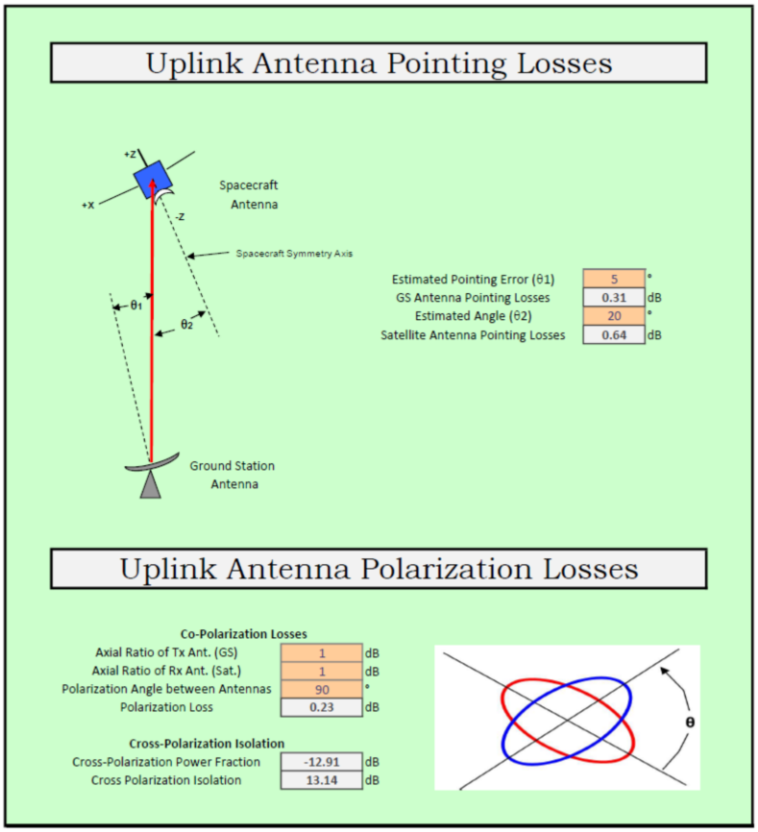


Figure 29: Link budget losses sheet, antenna

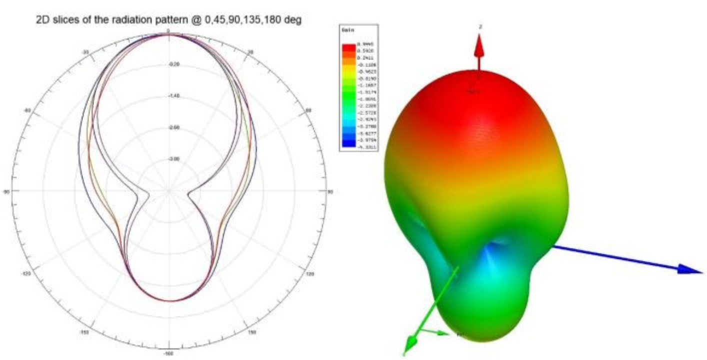


Figure 30: Radiation Pattern of EnduroSat Satellite Antenna

Degrees from max gain	minimum gain	maximum gain	Minimum Loss	Maximum Loss
0	0.9445	0.9445	0	0
5	0.9	0.9	0.0445	0.0445
10	0.7	0.8	0.1445	0.2445
15	0.6	0.7	0.2445	0.3445
20	0.3	0.5	0.4445	0.6445
25	0	0.3	0.6445	0.9445
30	-0.3	0.1	0.8445	1.2445
35	-0.7	-0.2	1.1445	1.6445
40	-1.1	0	0.9445	2.0445
45	-1.4	-0.7	1.6445	2.3445
50	-2	-0.95	1.8945	2.9445
55	-2.2	-1	1.9445	3.1445
60	-2.55	-1.2	2.1445	3.4945
65	-2.8	-1.4	2.3445	3.7445
70	-2.9	-1.45	2.3945	3.8445
75	-3.1	-1.5	2.4445	4.0445
80	-3.4	-1.6	2.5445	4.3445
85	-3.8	-1.8	2.7445	4.7445
90	-4.1	-2	2.9445	5.0445
95	-4.3	-2.2	3.1445	5.2445
100	-4.4	-2.9	3.8445	5.3445

Figure 31: Pointing Losses Calculation Satellite

Downlink Budget (and Uplink Budget)

The downlink budget and uplink budget summary pages are set up in a similar manner, the downlink budget will be explained below. Refer to Figure 32 for a summary of the downlink budget.

The sheet is separated into 5 sections, including two different methods used to calculate the link margin. The sections are: satellite parameters, downlink path, link margin method #1, link margin method #2, and data rates. The satellite parameters summarize the output power, losses, and gains associated with the satellite components selected. This allows for the satellite effective isotropic radiated power to be calculated using Equation (16).

$$EIRP = trans.power - trans.losses + trans.ant\ gain \text{ [dBW]} \qquad \text{Equation (16)}$$

The downlink path section includes the satellite antenna pointing losses, satellite to ground station polarization losses, free space path losses, atmospheric losses, ionespheric losses, rain losses, and isotropic signal level received at the ground station. The rain losses are estimated by the operator and have been included as 0 because at UHF frequencies these losses are ignored and considered zero [12]. The isotropic signal level is calculated using Equation (17).

$$Isotropic\ Signal\ Level = EIRP - sat.ant.losses - sat.ant.polarization\ losses - FSPL - atm.losses - iones.losses - rain\ losses \text{ [dBW]} \quad \text{Equation (17)}$$

The SNR method for calculating the ground station received values uses the ground station antenna gain, the ground station receiver bandwidth, theoretical received power, actual received power, received noise power, signal to noise ratio, required signal to noise ratio, and system link margin. The theoretical received power is calculated using Friis transmission formula given in Equation (18).

$$Received\ power = trans.power + trans.ant\ gain + gs.ant\ gain + FSPL \text{ [dBm]} \quad \text{Equation (18)}$$

The actual received signal power at the ground station is calculated using Equation (19). The term 'all losses' refers to: satellite antenna pointing losses, antenna polarization losses, atmospheric losses, ionespheric losses, rain losses, receiver losses.

$$Actual\ Received\ power = trans.power + trans.ant\ gain + gs.ant\ gain + FSPL - all\ losses \text{ [dBm]} \quad \text{Equation (19)}$$

The received noise power is calculated using Equation (20).

$$Received\ noise\ power = 10 \cdot \log_{10}\left(\frac{484.56 * 1.38E-23 * Sat.receiver\ BW}{0.001}\right) \text{ [dBm]} \quad \text{Equation (20)}$$

The signal to noise ratio is found using Equation (21).

$$SNR = received\ signal\ power - received\ noise\ power \text{ [dB]} \quad \text{Equation (21)}$$

The system link margin is found using Equation (22). The required SNR is determined from the modulation scheme used, as previously discussed in the Modulation section.

$$System\ link\ margin = received\ SNR - required\ SNR \text{ [dB]} \quad \text{Equation (22)}$$

The Eb/No method incorporates the data rate and bit error rate, determined by the modulation scheme chosen. This method uses ground station antenna pointing losses, ground station antenna gain, ground station transmission line losses, ground station effective noise temperature, ground station figure of merit, ground station signal-to-noise power density, system desired data rate, system Eb/No for the downlink, system BER, Eb/No threshold, and system link margin.

The ground station figure of merit (G/T) is calculated using Equation (23).

$$\frac{G}{T} = GS.ant.gain - GS.trans.line\ losses - 10 \cdot \log_{10}(eff.noise\ temp)\ [\text{dB}] \qquad \text{Equation (23)}$$

Downlink Budget

Parameter	Value	Units	Comments
Satellite			
Transmitter power output	1.00	W	
	0.00	dBW	
	30.00	dBm	
Total transmission line losses	0.4	dB	
Sat. antenna Gain	0.9445	dBi	
Effective isotropic radiated power (EIRP)	0.54	dBW	
Downlink Path			
Satellite antenna pointing losses	0.64	dB	
Sat.-to-GS antenna polarization losses	0.23	dB	
Free-Space Path losses	150.50	dB	
Atmospheric losses	2.1	dB	
Ionospheric Losses	0.4	dB	
Rain Losses	0.00	dB	*Estimated by operator, 0 for UHF band*
Isotropic signal level at GS	-153.33	dBW	
Ground Station (SNR Method)			
GS antenna gain	16.30	dBi	
GS receiver bandwidth	25000.00	Hz	
Theoretical received signal power at GS	-108.63	dBm	*Using Friis Transmission Formula [maximum]*
Actual received signal power at GS	-109.03	dbm	*Using Friis Transmission Formula [w/ losses]*
Received noise power at GS	-127.77	dBm	*Formula in CSA presentation*
Actual signal-to-noise ratio	18.74	dB	
Required signal-to-noise ratio	13.50	dB	
System link margin	5.24	dB	***Good signal reception***
Ground Station (Eb/No Method)			
GS antenna pointing loss	0.31	dB	
GS antenna gain	16.3	dBi	
GS total transmission line loss	2.00	dB	
GS effective noise temperature	507.62	K	
GS figure of merit (G/T)	-12.76	dB/K	
GS signal-to-noise power density (S/No)	62.20	dBHz	
System desired data rate	9600	bps	
	39.82	dBHz	
Telemetry system Eb/No for the downlink	22.38	dB	
System allowed BER	1.00E-06		
Eb/No threshold	13.50	dB	
System link margin	8.88	dB	***Good signal reception***
Data Rates			
Theoretical channel capacity	66038.41	bps	*Theoretical maximum using Shannon-Hartley eq.*
Actual data rate	9600	bps	
Transmission duration (per pass)	300.00	s	
Passes per day	15.11		
Data transmission (per pass)	2880.00	kb	
Images (/pass) - (no compression)	0.213		
Images (/day) - (no compression)	3.223		
Images (/pass) - (15x compression)	3.20		
Images (/day) - (15x compression)	48.342		
Videos (/pass)	0.001		
Videos (/day)	0.011		

Figure 32: Downlink budget summary sheet

3.4 Final Design Overview

A few components were selected to successfully send and receive data from the satellite to ground station and vice versa. For the full system overview (in block diagram form), refer to Figure 33. The components selected for the design were a transceiver to modulate the data, and antennas to amplify and transmit/receive the signals.

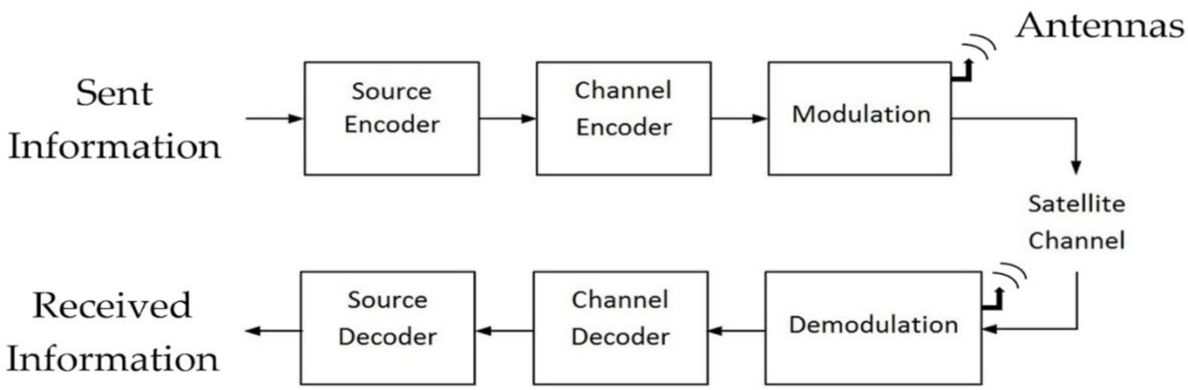


Figure 33: System block diagram

a. Transceiver

The transceiver group selected is the EnduroSat UHF Transceiver Type II. This transceiver was selected based on several criteria, including the following:

- Price
- Available data rates
- Modulation schemes
- Mass
- Power consumption

The transceiver was selected based a decision matrix, shown in Figure 10, that gave relevance weightings to each category and a corresponding score. The methodology used in the decision matrix is explained below.

Methodology

A list was developed comprising every Commercial Off The Shelf (COTS) component available on the market operating in the 430-440 MHz bandwidth. Each component was then ranked from 1 to 6 based on their capability for each category (1=weakest, 6=strongest). Each category was given a specific weighting of importance, based on how much it affects the communications subsystem outcome and other subsystems we interact with. The overall score was compiled by adding the product of the weighting and the ranking for each category.

The data rate is a metric of utmost importance, because the main purpose of the CubeSat project is to transmit pictures of Earth from space. The lower the data rate, the less pictures the CubeSat can transmit to Earth over its lifetime. Based on the modulation scheme trade-off study, it was determined that MSK is the ideal modulation
scheme. The decision process relies on an assumed bandwidth granted by the Government of Canada of 50 kHz based on the experience of other student CubeSat projects. This makes our system more power-limited than bandwidth-limited. Other M-FSK and M-PSK modulation schemes are suitable, however, are less ideal due to the higher required SNR. If the available modulation schemes didn’t match the ones that we had decided were ideal, they were given a lower score for the modulation criteria. Power consumption and mass are other important categories which affect other subsystems such as the EPS and structure/thermal subsystems, however, these are less crucial to the communications subsystem function. Our target Bit Error Rate of 10e-5 will be satisfied based on the modulation trade-off study where a 50 kHz bandwidth was assumed, therefore no encoding techniques will be necessary. Refer to Figure 10 for the transceiver decision matrix.

b. Antenna

Figure 11 shows the decision matrix that was used to determine which antenna was selected for the final design. The decision matrix used the same methodology as the transceiver where each category was weighted between 1 and 6 and each component was ranked between 1 and 6. The summation of the products is listed in the rightmost column and tells how our component was selected. The most important factor to ensure the satellite has the strongest link is directionality. The directionality of the selected antenna component can be shown in Figure 30. The directionality shows where the antenna is focussing most of its energy and, therefore, shows a depiction of where the strongest signal will be. The areas that are most red are the areas where the highest gain is shown, which shows the places where the strongest signal will be sent. For the satellite antenna, the highest importance is placed on having a very wide area where signal is strong enough to be received by the other antenna. The reason that a high importance is placed on directionality is due to the assumption that the satellite will not have extremely accurate pointing. Making it a primary concern for us to have a satellite that focuses on having minimum low areas of gain. The Endurosat antenna was selected based on the wide beam width (area where signal is within 3dB of the maximum gain) it provides, low price, low power consumption, and ease of mounting. In the link budget, the received signal power at the ground station is heavily influenced by the gain and pointing losses of antennas used.

The antenna selection for the ground station had less constraints than the satellite antenna. This allowed us to choose a highly directive antenna that draws a larger amount of power. We wanted a directional antenna design with the gain being primarily focussed in one direction. Because the ground station antenna will have an accurate pointing control system, we can choose an antenna design that optimizes gain. Since the ground station antenna will have accurate pointing control systems and a large gain, the link will be stronger for both transmitting and receiving. The two major designs considered for the ground station is a parabolic dish antenna and a Yagi-Uda antenna. Both designs can be modified to make them more (or less) directive. We have preliminarily chosen the Yagi-Uda because the parabolic dish antenna will be larger, heavier and will catch more wind loads. The Yagi-Uda can be more (or less) directive by adding or removing directing elements. The team next year will more accurately select the antenna parameters of this antenna to optimize the design for the pointing accuracy that the Ground Station team can perform. For all simulation purposes, we used a fully functional ground station that can be bought from Innovative Solutions In Space (ISIS). This is shown in Figure 34. This fully functional ground station has a gain of 15.5 dBiC that is switchable between right hand circularly polarized and left hand circularly polarized. It also has a 30-degree beam width which is thought to be enough to avoid large pointing losses. This was used for the current link budget because of these major parameters. We have also been told that as a part of the CubeSat project, that an antenna with both S-band and UHF band is being considered, making this a valid option in the future.

Figure 34: ISIS Ground Station

3.5 Prototype Design Overview

A few components were selected to successfully send and receive data from the satellite to ground station and vice versa. For the full system overview (in block diagram form), refer to Figure 33. The components selected for the prototype design were a transceiver (to modulate the data), and antennas.

We modelled the ground station and satellite system with two sets of personal computers, Arduinos, transceivers, and antennas that operate in the 915 MHz frequency band. Since we have selected Commercial off the Shelf (COTS) components for our final design, we have also chosen COTS components for our prototype to provide an accurate representation of final design performance. Having professionally manufactured components lowers the risk of components malfunctioning. To prototype our design, we sent a test signal from the satellite and receive the signal at the ground station, which was displayed on Arduino Serial Monitor. Our tests were designed to measure the effects on received power by varying the distance and ground station antenna elevation angle changes (discussed in greater detail in section 4.1 Testing Strategy/ Validation Protocols). The full system overview (in block diagram form) has been modified for the prototype and is shown in Figure 35. A summary of each component selected for the prototype system is given below.

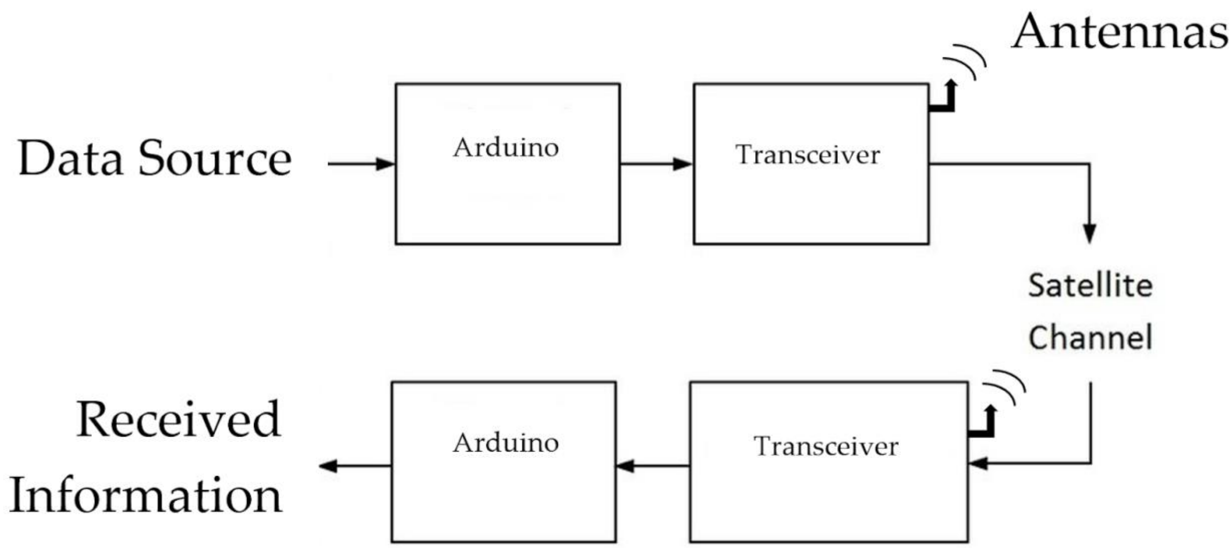


Figure 35: Modified prototype system block diagram

Arduino (ground station and 'on-board')

The Arduino was used for modelling both the transmitter and receiver circuits because Arduino's can repeat tests several times and obtain results quickly. They are also easy to program and sufficiently meet all our testing needs. Arduino's provides a cheap way to quickly and accurately obtain data. The program code that was uploaded to the Arduino is displayed in Appendix 2.

Texas Instruments CC1101-915

The TI CC1101-915 transceiver chip was selected due to its bandwidth and ease of configuration. Power output, frequency and modulation can all be adjusted when programming the CC1101-915. A comparison study of different 915 MHz transceiver/antenna modules was performed, displayed in Figure 10, and the CC1101-915 was determined the best option due to its configurability. As we cannot transmit at the intended frequency that the CubeSat will operate at (~437 MHz), we decided that the 915 MHz frequency band would be suitable. It is legal to recreationally test at this frequency and it also falls within the UHF frequency range.

Pulse Larsen w5017 Antenna

The w5017 was the optimal antenna, due to its specified frequency of 915MHz and portability. It was also a recommended antenna for our chosen transceiver chip, the CC1101-915.

In addition to these major components, we used conventional jumper wires to connect components to a bread board, as well as two logic level converters to convert voltage from 5V to 3.3V. These prototype supplies were of negligible cost. A summary of component costs is contained in Figure 36. A picture of the final prototype is displayed in Figure 39.

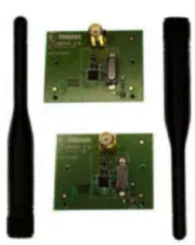
Component	Cost per component	Quantity	Total cost
Arduino Uno 	$ 24.86	2	$ 49.72
Texas Instruments CC2650 SensorTag 	$ 43.97	1	$ 43.97
Texas Instruments CC1101EMK868-915 	$164.78	1	$ 164.78
		Total	**$ 258.47**

Figure 36: Prototype cost table

4. Results and Validation

4.1 Testing Strategy/ Validation Protocols

This section should include test plans, testing strategy. Explain why you are doing these tests and what they will measure/validate your design

To test our prototype, we conduced 2 experiments to simulate different conditions that are expected during the real mission. The main criteria to choosing a testing venue is a testing venue that yields the maximum possible separation distance between antennas while having one antenna elevated relative to the other one. The locations we selected is TD Waterhouse Football Field and Braemar Valley. Refer to Figure 37 to see a bird's eye view of the first testing region and Figure 38 to see a bird's eye view of the second testing region. To test the link between transmitting and receiving tests we will perform two tests explained below. The dependent variable used for both tests is the Received Signal Strength Indicator (RSSI) in dBm.

Figure 37: TD Waterhouse Football field

Figure 38: Braemar Valley

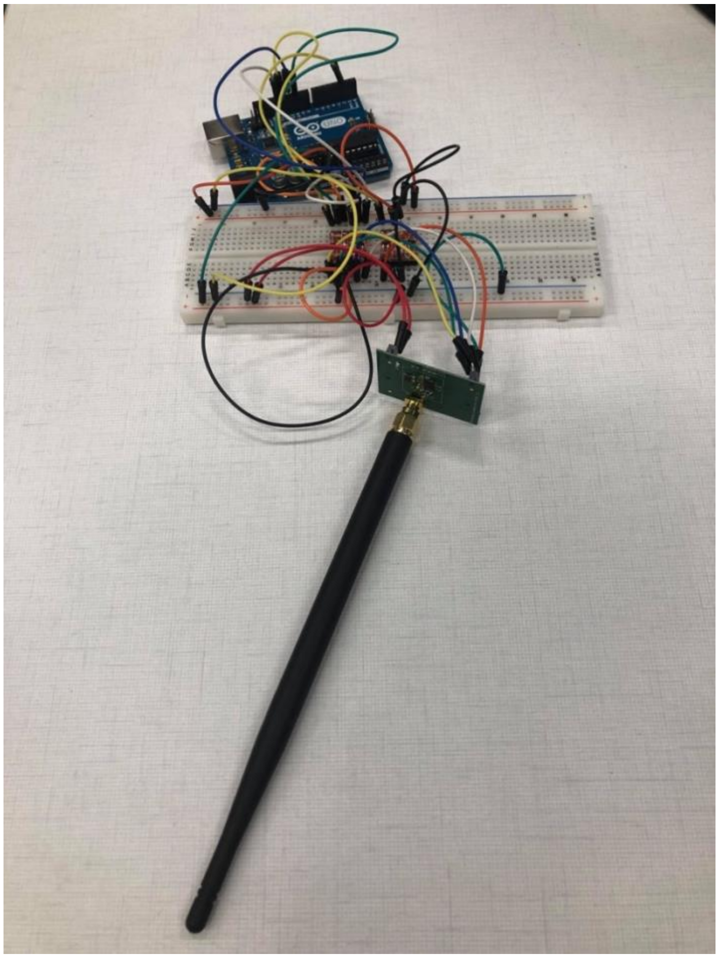


Figure 39: Final prototype

Test #1

This test relates to the final design, and the link budget because we will get the relationship between RSSI and separation distance (between antennas). The separation distance is equivalent to the slant range in the link budget. Since the link budget is modeled using the slant range (being the maximum separation distance between antennas), we want to see how the signal strength improves the closer the antennas are together. This will help give us a rough approximation of the improved performance we can expect to see when the satellite antenna is closer to the ground station than the slant range. This test was conducted at Braemar Valley because it is the longest straight line of sight area that we could find. The separation distances that we had selected for the test at Braemar Valley were 1.1 km and 2.0 km shown in

Figure 40.

Figure 40: Separation distances for test #1

Test #2

This test is meant to prove how accurately the antennas pointing losses section of our link budget works. The pointing losses section of the link budget is intended to show the difference from the maximum gain to the current angle from the area of maximum gain. As explained in the Link Budget Losses section of the report, the best case is when the maximum gain of both antennas is pointing at each other (this will be listed as 0 degrees). The antenna pointing losses occur when these antennas are not optimally pointing towards one another. In this test the angle of one antenna will be changed to test how the received signal is different for 0 degrees, 45 degrees and 90 degrees. Two additional tests, labelled 135 degrees and 180 degrees, were taken when one antenna was at 90 degrees and the other antenna were at 45 degrees and 90 degrees respectively. For all of these tests, one person was positioned at the top of the stadium and one person was positioned on the football field as shown in Figure 41 and Figure 42. For each of the above tests, a distance of 48.08m, 78.36m and 108.11m were used as shown in Figure 43. This will give 3 sets of data which can be compared to one another to ensure that a trend between antenna pointing angle and RSSI is discovered. The data is then compared to simulated data in the link budget to ensure the accuracy of the link budget.

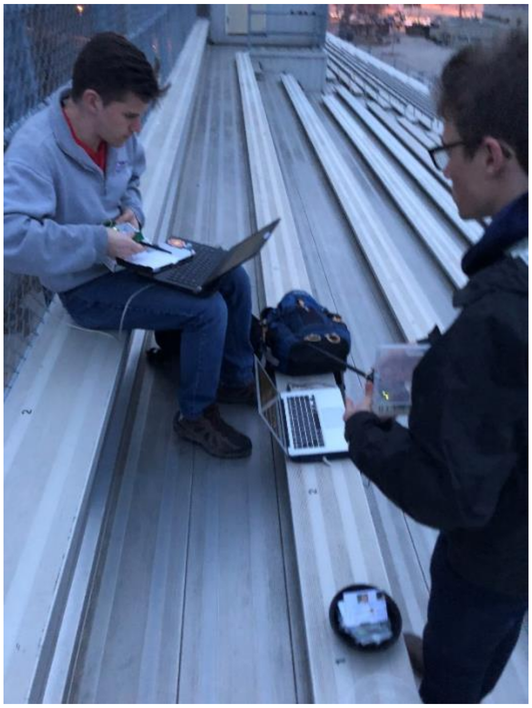


Figure 41: Configuring "satellite" antenna for test #2

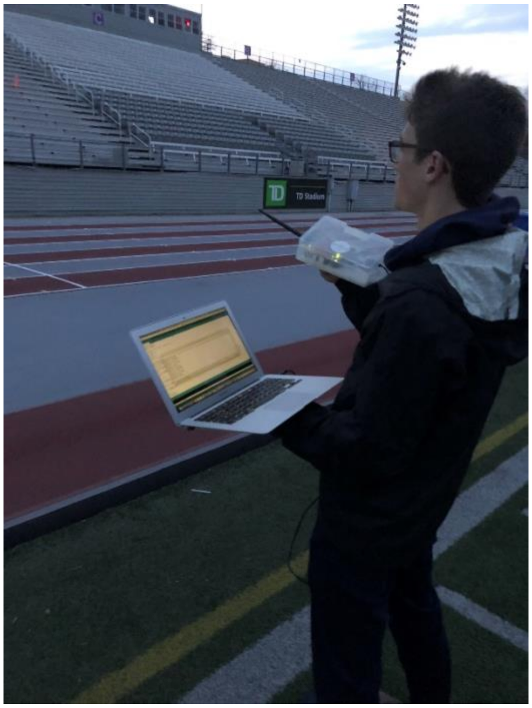


Figure 42: View of testing from "ground station" antenna for test #2

Figure 43: Separation distances for test #2

4.2 Final Results and Validation

This section will include an overview of the results obtained from the link budget for the final design. The measured results from the two tests will also be discussed along with the theoretical results expected for the prototype design. The limitations to the tests performed were also identified and will be discussed below.

The results from the link budget will be discussed by referencing Figure 14 and discussing the expected signal strength at each stage of the communication downlink.

a. Theoretical results for final design

The theoretical results from the link budget are shown below. The system link margin is 8.84, meaning the signal is clearly distinguishable from the noise and the design is viable.

Transmitted signal power	Power after Tx antenna gain	Power after path losses	Received signal power	Received noise power	System Link Margin
-0.4 [dB]	0.5445 [dB]	-153.33 [dB]	-109.03 [dBm]	-127.77 [dBm]	8.84

Table 5: Link budget results for final design

b. Theoretical results for prototype design

The theoretical results from the prototype design are shown below. As seen below in Table 6 the system link margin is well above 3 for the test done at an angle orientation of 0 degrees. This result shows that the signal should've been received at this orientation. This theoretical result was proven during the testing, as the measured signal was received as well during testing. The second theoretical result worthy of noting is the result when the antenna orientation was set to 180 degrees. When this configuration was used in the link budget, the system link margin was negative. This represents a received signal that will not be distinguishable from the noise at all.

This is consistent with the test results that were achieved while testing, the signal was only received 1/10 times and with very low strength.

Transmitted signal power	Power after Tx antenna gain	Power after path losses	Received signal power	Received noise power	System Link Margin
-17.96 [dB]	-15.96 [dB]	-115.16 [dB]	-83.16 [dBm]	-118.67 [dBm]	28.07

Table 6: Link budget results for test #2 angle 0

Transmitted signal power	Power after Tx antenna gain	Power after path losses	Received signal power	Received noise power	System Link Margin
-17.96 [dB]	-15.96 [dB]	-137.16 [dB]	-127.16 [dBm]	-118.67 [dBm]	-15.93

Table 7: Link budget results for test #2 angle 180

c. Discussion on prototype testing results

Test 1 consisted of a distance test. The objective of this test was to confirm the effect that distance has on the RSSI values. For this test, we travelled to the Braemar Valley, east of London, ON. This location offered a long, clear line of sight that we hoped would accurately simulate a satellite communicating with a ground station. This test yielded results that closely reflected our expected results. For example, at a distance of 1.1km, the expected result was -78 dBm, and the experimental result was -95dBm. The full results are displayed in Figure 48. We believe that the discrepancy between the expected and actual results is caused by obstructions on the landscape of our test location, such as trees and hydro poles. These results prove that distance negatively affects the RSSI, and that obstacles such as trees and hydro poles have a negative effect on the strength of the received signal. The issue of obstacles weakening the received signal will be of less importance when the CubeSat is orbiting earth, because there are much fewer objects that could interfere. This test also validated our modulation scheme selection, as the CC1101 transceiver was programmed to use an MSK modulation scheme.

Test 2 confirmed the effect that antenna attitude has on received power, illustrated in Figure 44, Figure 45, Figure 46 and Figure 47. We can see that the Received Signal Strength Indicator (RSSI) value was reduced when the angle of the antennas was adjusted which is the same trend we expected, based on the link budget theoretical results. Since the antennas are circularly polarized, their optimal orientation is when they are pointed parallel to each other. Hence, the worst orientation for the antennas is obtained when they are pointed directly at each other. In this case, we either lost communication or received an extremely weak RSSI value. For example, for the test at 48.08m at an angle of 90 degrees, the theoretical RSSI was -73dBm, while the experimental result was -62dBm, as shown in Figure 44. When comparing the theoretical values with the test values, we observed that the RSSI was stronger in the measured results compared to the theoretical results. We believe this discrepancy was due to the effect of the metal bleachers on which our prototype was receiving signals, acting as a dish antenna to concentrate the signals and make them stronger. This test also validated our expectations from Test 1 for distance, because the RSSI measured at equivalent antenna angles with different distances proved that distance also weakens the received signal. This information is critical for the ground station team, as they will be responsible for ensuring optimal pointing angles.

Testing Limitations

The three major limitations for this test are the ground affect in each one of the tests that we did, the cost of the components that we need, and the restriction from using our chosen frequency band for testing.

Firstly, the ground affect is caused from the antennas both being very close to the ground, this means that the signals will bounce off the ground and affect the signal in ways that would not be considered for the scope of the CubeSat project. This ground affect will skew the results in each one of the cases, however, since this will almost equally affect each one of the tests, a trend can still be seen from each one of these tests.

The second major limitation is the cost of the components. Due to this constraint, the antennas and transceivers must be tested at a low power, thus skewing the results that are given.

Lastly, the frequency band that the satellite and ground station will be communicating at, is approximately 437.305 MHz. This, however, is not a legal band to transmit at without a license, which could not be given in time for this project. The 915 MHz frequency band was chosen instead to test these results.

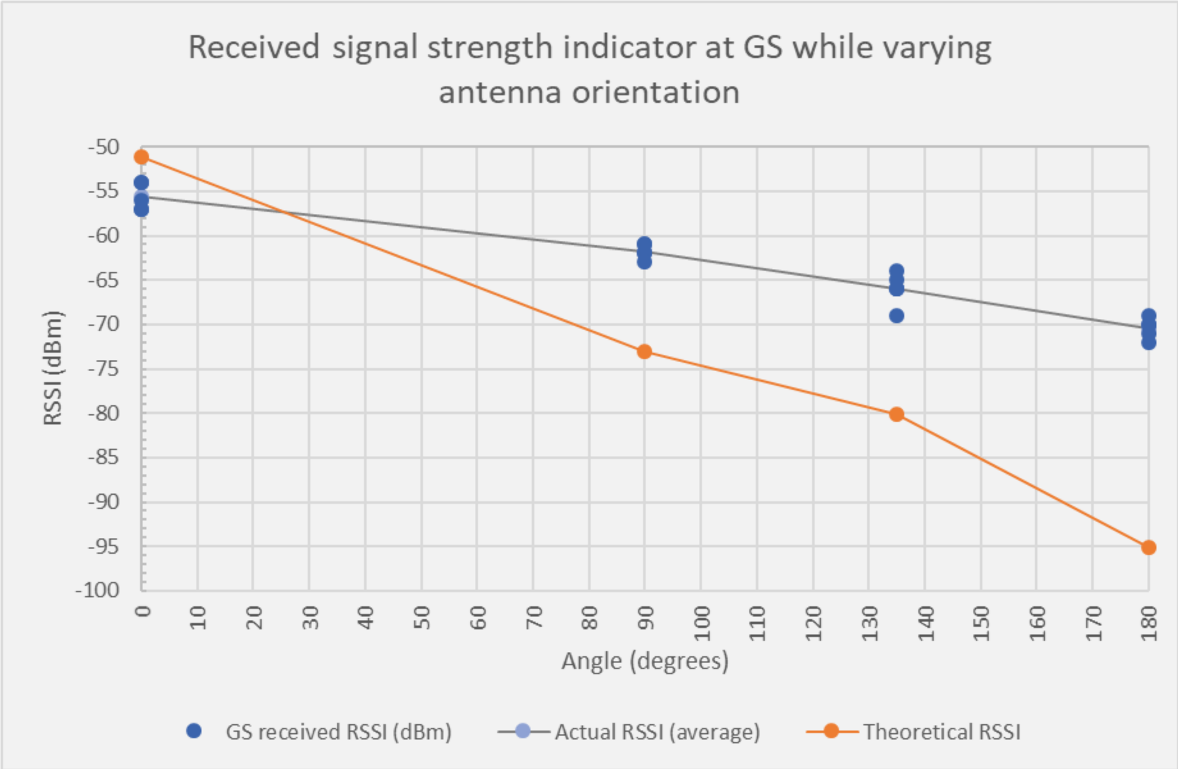


Figure 44: Antenna Angle Test at 48.08m (TD Stadium)

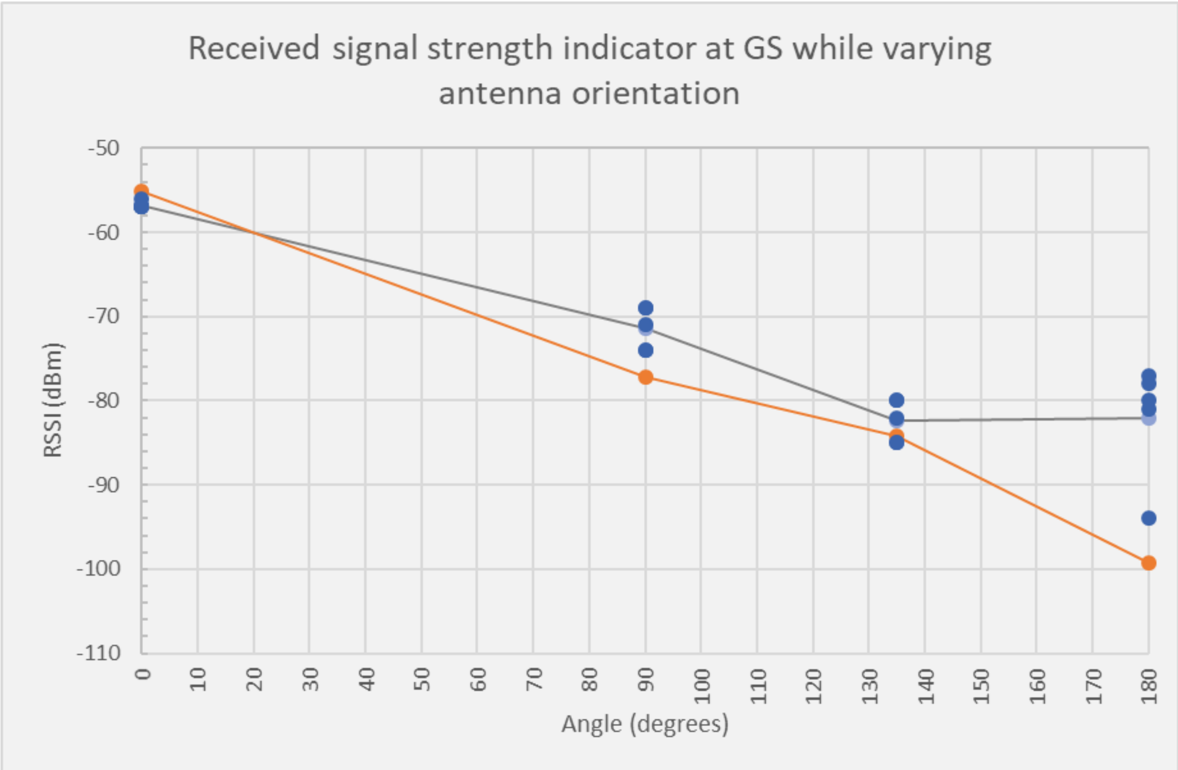


Figure 45: Antenna Angle Test at 78.36m (TD Stadium)

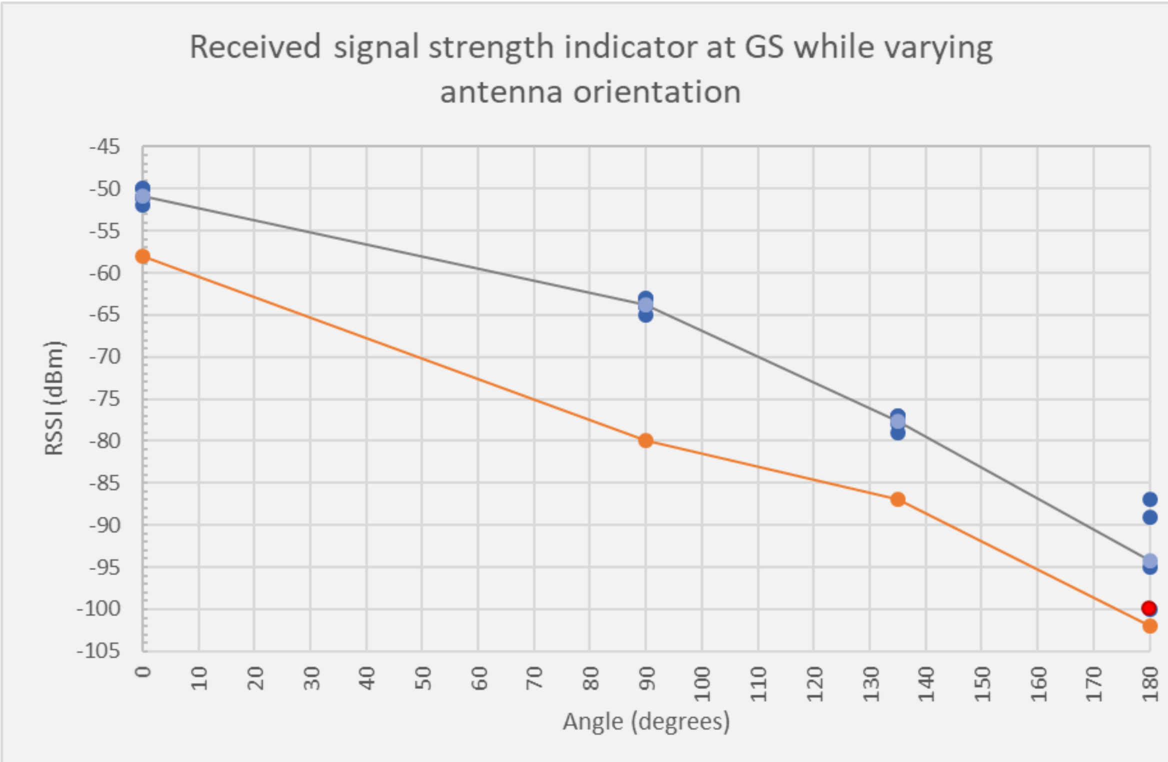


Figure 46: Antenna Angle Test at 108.11m (TD Stadium)

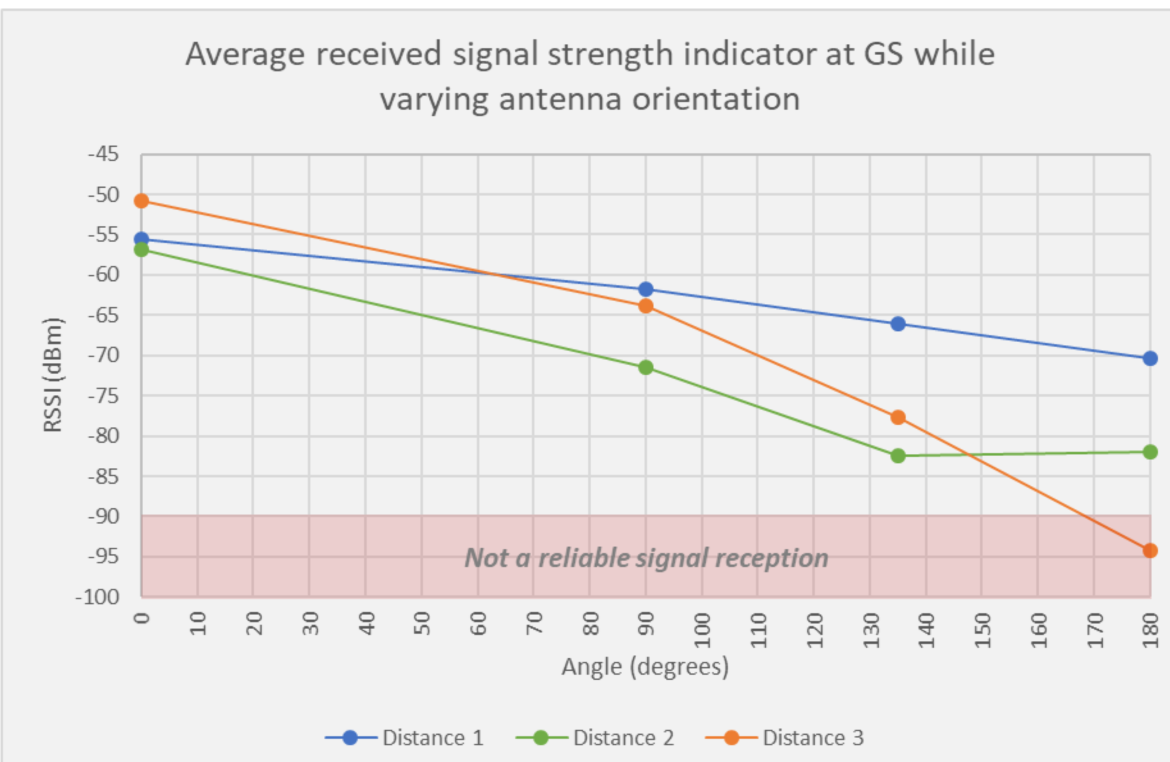


Figure 47: Antenna Distance Tests at TD Stadium

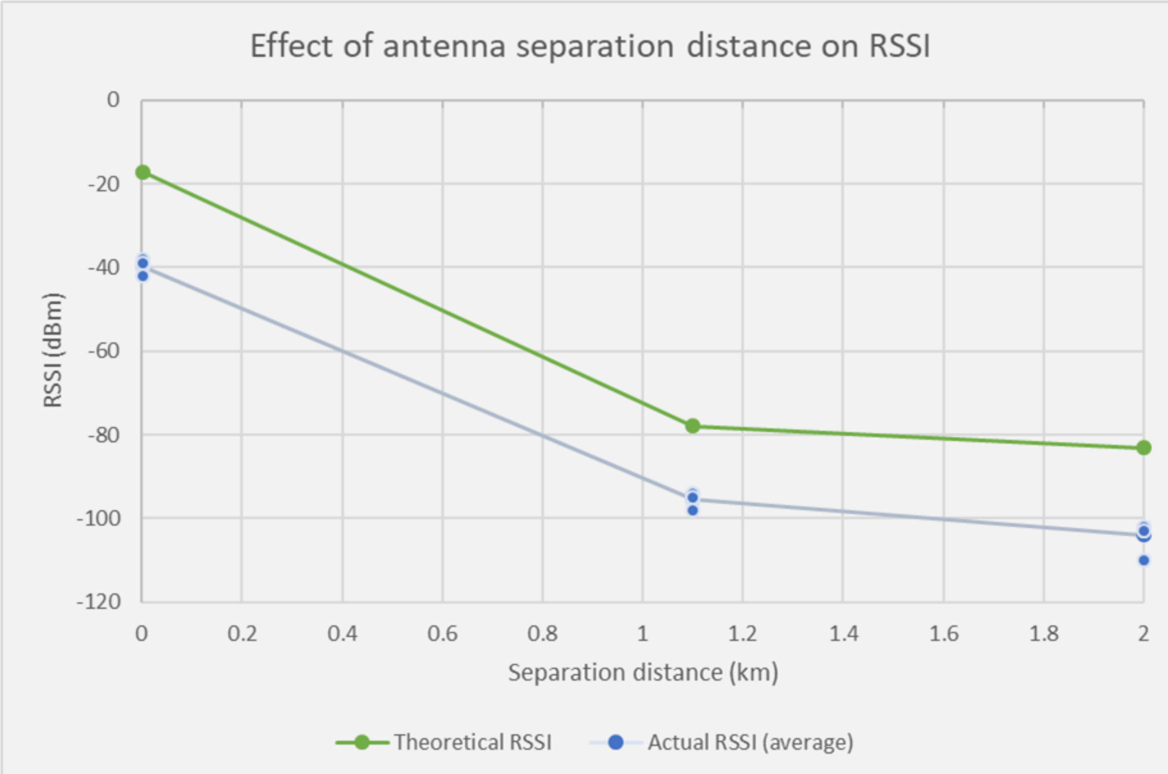


Figure 48: Antenna Distance Test at Braemar Valley

5. Conclusions, Future Work and Recommendations

The CubeSat communication subsystem has been extremely rewarding and informative to research and design. While we built the foundation for the communications subsystem, there are several next steps for future teams to work on. This involves putting the prototype through more rigorous testing to further prove the system accurately reflects its capability to operate in space. This could involve an extremely high-altitude test or testing from a hot air balloon, to simulate a purely vertical relationship between space segment and ground segment. Once the frequency license has been obtained, another goal for future teams can be purchasing the selected components and assembling the communications subsystem to be installed onto the CubeSat.

In the future, the antennas that have been selected may change. It is up to next year's team to reassess the antennas that have been selected to make sure that they match with the goal of the project. In the current design, the satellite antenna has a very wide beam width. There are only few areas in which the signal is too weak to be sent. This means that the ADCS team, which is the team responsible for accurately pointing the CubeSat, will need to use very little, to no effort in pointing the antenna to the correct orientation. This is the major benefit to having the design that was chosen. The limited power and pointing requirements on the satellite make UHF a viable option even though the data will not be able to transfer nearly as fast as the S-band design.

The ground station antenna must also be reassessed. In the current design, a Yagi-Uda antenna with a gain of 15.5 dBiC and beam width of 30 degrees has been chosen. It is up to next year's team to choose if this design is sufficient as is or if it needs to be less directional. The next year's team should also use simulation tools, such as the MATLAB Antenna Toolbox, to simulate for the optimal design for the pointing requirements of the Ground Station.

6. References

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7. Appendices

Appendix 1: BW Efficiency Plane MATLAB Code [13]

```
close all
clc
%%%%%%%%%%%%%%% Modulation and Coding %%% %
% Shannon capacity:

CW=-5:0.01:20;

SNR=(1./CW).*((2.^CW)-1);

SNR_dB=10.*log10(SNR);

% Plotting of Shannon-Hartley capacity
semilogy(SNR_dB,CW,'LineWidth',2);
hold on

%% For M-PSK
% No coding
plot(9.6,1,'sq',9.6,2,'sq',17.4,4,'sq',22.31,5,'sq',27.42,6,'sq','linewidth',
2); hold on

%plot(9.6,1,'sq',9.6,2,'sq',17.4,4,'sq',22.31,5,'sq',27.42,6,'sq','linewidth'
,2); hold on


% %% For M-QAM
%
% % No coding
plot(9.55,2,'o',12.47,3,'o',13.39,4,'o',16.5,5,'o','linewidth',3); hold on
%
% % With coding
%
plot(8.389,(22/15),'x',11.26,(33/15),'x',12.15,(44/15),'x',15.22,(55/15),'x',
16.4,(66/15),'x',21,(88/15),'x','linewidth',2); grid;hold off
%
% title('Comparison between coded and encoded M-QAM modulation over awgn
channel ')
%

%% For M-FSK

plot(13.31,(1/3),'v',11,(2/5),'v',9.1,(1/3),'v',8.1,(4/17),'v',7.3,(5/33),'v'
,'linewidth',2); hold on

% For MSK
plot(9.9,2,'x',14,2,'x','linewidth',3); hold on

legend('Shannon-Hartley
Capacity','2PSK','4PSK','8PSK','16PSK','32PSK','4QAM','8QAM','16QAM','32QAM',
'2FSK','4FSK','8FSK','16FSK','32FSK','Coherent MSK','Noncoherent MSK')
```

```
ylabel('R/W (bits/s/Hz)')
xlabel('Eb/No (dB)')
```

Appendix 2: Arduino CC1101 Code [14]

```
#include <Arduino.h>
#include <cc1101.h>
#include <ccpacket.h>

// Attach CC1101 pins to their corresponding SPI pins
// Uno pins:
// CSN (SS) => 10
// MOSI => 11
// MISO => 12
// SCK => 13
// GD0 => A valid interrupt pin for your platform (defined below
this)

#if defined(__AVR_ATmega2560__) || defined(__AVR_ATmega1280__)
#define CC1101Interrupt 4 // Pin 19
#define CC1101_GDO0 19
#elif defined(__MK64FX512__)
// Teensy 3.5
#define CC1101Interrupt 9 // Pin 9
#define CC1101_GDO0 9
#else
#define CC1101Interrupt 0 // Pin 2
#define CC1101_GDO0 2
#endif

CC1101 radio;

byte syncWord[2] = {199, 10};
bool packetWaiting;

unsigned long lastSend = 0;
unsigned int sendDelay = 5000;

void messageReceived() {
    packetWaiting = true;
}

void setup() {
    radio.init();
    radio.setSyncWord(syncWord);
```

```
    radio.setCarrierFreq(CFREQ_915);
    radio.disableAddressCheck();
    radio.setTxPowerAmp(PA_LongDistance);

    Serial.begin(9600);
    Serial.print(F("CC1101_PARTNUM "));
    Serial.println(radio.readReg(CC1101_PARTNUM,
CC1101_STATUS_REGISTER));
    Serial.print(F("CC1101_VERSION "));
    Serial.println(radio.readReg(CC1101_VERSION,
CC1101_STATUS_REGISTER));
    Serial.print(F("CC1101_MARCSTATE "));
    Serial.println(radio.readReg(CC1101_MARCSTATE,
CC1101_STATUS_REGISTER) & 0x1f);

    Serial.println(F("CC1101 radio initialized."));
    attachInterrupt(CC1101Interrupt, messageReceived, FALLING);
}

// Get signal strength indicator in dBm.
// See: http://www.ti.com/lit/an/swra114d/swra114d.pdf
int rssi(char raw) {
    uint8_t rssi_dec;
    // TODO: This rssi_offset is dependent on baud and MHz; this
is for 38.4kbps and 433 MHz.
    uint8_t rssi_offset = 74;
    rssi_dec = (uint8_t) raw;
    if (rssi_dec >= 128)
        return ((int)( rssi_dec - 256) / 2) - rssi_offset;
    else
        return (rssi_dec / 2) - rssi_offset;
}

// Get link quality indicator.
int lqi(char raw) {
    return 0x3F - raw;
}

void loop() {
    if (packetWaiting) {
        detachInterrupt(CC1101Interrupt);
        packetWaiting = false;
        CCPACKET packet;
        if (radio.receiveData(&packet) > 0) {
            Serial.println(F("Received packet..."));
            if (!packet.crc_ok) {
                Serial.println(F("crc not ok"));
```

```
            }
            Serial.print(F("lqi: "));
            Serial.println(lqi(packet.lqi));
            Serial.print(F("rssi: "));
            Serial.print(rssi(packet.rssi));
            Serial.println(F("dBm"));

            if (packet.crc_ok && packet.length > 0) {
                Serial.print(F("packet: len "));
                Serial.println(packet.length);
                Serial.println(F("data: "));
                Serial.println((const char *) packet.data);
            }
        }

        attachInterrupt(CC1101Interrupt, messageReceived,
FALLING);
    }
    unsigned long now = millis();
    if (now > lastSend + sendDelay) {
        detachInterrupt(CC1101Interrupt);

        lastSend = now;
        const char *message = "hello world";
        CCPACKET packet;
        // We also need to include the 0 byte at the end of the
string
        packet.length = strlen(message)  + 1;
        strncpy((char *) packet.data, message, packet.length);

        radio.sendData(packet);
        Serial.println(F("Sent packet..."));

        attachInterrupt(CC1101Interrupt, messageReceived,
FALLING);
    }
}
```