# SlugSat Winter Quarter Report
# Senior Design Project 2016-2017

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# Project Overview

## Introduction

Following in the trail of the many educational satellites that have already been launched, the UCSC CubeSat project is working towards placing a small satellite into low earth orbit (LEO). The main payload of this satellite will be a linear transponder for communications use by amateur radio operators. Through this process, students will develop spacecraft design and manufacturing capabilities at the University of California, Santa Cruz.

### The CubeSat Model

CubeSats are in a class of spacecrafts called nanosatellites. The CubeSat specification was developed in the late 1990's by Cal Poly and Stanford University. Since then this model has become a popular, cost-effective platform used by government, academia and industry ("What Are SmallSats and CubeSats?"). By designing a satellite that fits within this model, the UCSC CubeSat project hopes to gain access to launch opportunities.

Generally CubeSats exist as a secondary payload on a larger mission. Building and sending commercial satellites to space is an extremely expensive effort, and risk needs to be mitigated as much as possible. The CubeSat model provides a framework to give launch providers confidence that the CubeSats will not interfere with the primary payload. This creates specific design constraints on the satellite to mitigate risk. These design constraints are fully described in the CubeSat Design Specification ("CubeSat Design Specification").

Figure 1 shows a typical CubeSat structure that is designed to meet the CubeSat specifications. In addition to the form factor, there are specific requirements on size and mass distribution that need to be considered.

**Figure 1**: 1U CubeSat Chassis
Source: "CubeSat Kit 1U Chassis." N.p., n.d. Web. 15 Mar. 2017.

## Current Senior Design Team

This year's senior design team is focusing on the amateur radio payload including antenna, transponder, and command receiver design. Our current team is comprised of electrical and computer engineering students with coursework in analog and RF design. Our team does not have any background in satellite design which has a steep learning curve, so research into amateur satellites and the CubeSat model has been an essential part of developing the project.

This year, we will develop the overall design for this satellite and the communications subsystem, laying the groundwork for future teams at UCSC to continue the project over the coming years. As part of this goal, we've developed a Mission Requirements document (Appendix A-3), which defines the goals of the spacecraft and allows us to evaluate designs in order to satisfy those specifications. In addition, we've evaluated some of the major trade studies in designing the spacecraft and are beginning to design and build the communication subsystem.

In addition to the satellite design, we've also worked on developing a program here at UCSC that will continue after we've graduated. We've reached out to other CubeSat programs for assistance including Radio Amateur Satellite Corporation (AMSAT), Cal Poly's PolySat, and the US Naval Academy's (USNA) HFsat. In addition we've created links with the regulatory body that governs amateur radio satellite communications, the International Amateur Radio Union (IARU).

Lastly, we've reached out to students that may want to continue developing this project. This has primarily involved outreach through UCSC Amateur Radio Club, bringing in students with an interest in the project and integrating them with the current research of our team.

# Mission Design

We began by specifying the overall goals of the satellite, and the requirements that affected the various subsystems. As stated in our Mission Requirements document (Appendix A-3), our primary mission is to enable "reliable SSB and CW communications between Amateur Radio Operators via satellite relay". This obviously drives requirements in the communications subsystem. However, less obvious is that it also flows into the other subsystems, determining the amount of power we need to generate in order to operate the communications system, the level of control we need over our spacecraft orientation to point our antennas, and the specific orbit of our spacecraft. These requirements are specified in a document (Appendix A-3) such that we can refer to them when designing the individual subsystems.

## Orbit Design

Part of the design of our spacecraft involves determining where it should be located in space to serve its purpose. For our amateur radio satellite, we must make sure that the amateur radio community is able to successfully make contacts using it. In order to do this, we performed a study of the orbital parameters that affected the communication systems of our satellite(Appendix A-8).  We then looked at how each of these affected our ability to achieve our goal, regulations that limit our selection, and whether we would be able to find a launch opportunity to these orbits.

### Orbit Parameters

The main requirement driving our orbit choice is the accessibility of the satellite to the amateur radio community. In order to achieve that goal, we'll describe a few parameters of merit in the design of satellite orbits.

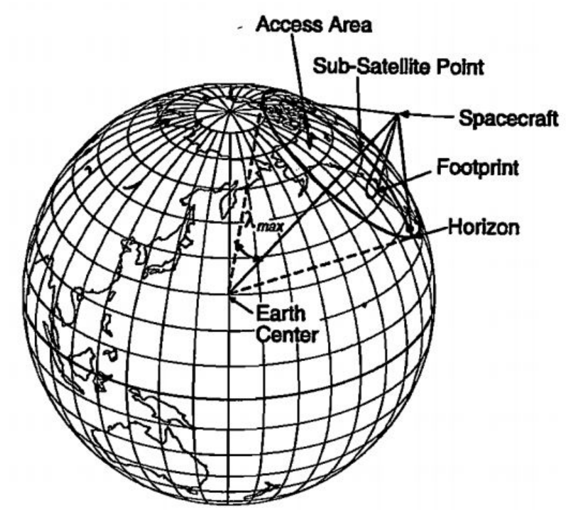


**Figure 2**: View Areas of an Orbiting Satellite

Source: Larson, Wiley J., and James Richard Wertz, eds. *Space Mission Analysis and Design*. 2nd ed. Torrance, Calif. : Dordrecht ; Boston: Microcosm ; Kluwer, 1992. Print. Space Technology Library.

The footprint of the satellite is the area the antenna can see at any instant. Figure 2 illustrates how this can be visualized as a cone pointing down from the spacecraft towards the Earth. Any two radio amateurs that are located within this area can communicate with each other by using our satellite as a relay. The access area includes all potential footprints of the antenna at a single instant if it's orientation is variable.

This footprint is a function of two parameters: the beamwidth of the antenna and the altitude of the satellite. At higher altitudes, the surface area of the cone projected on the earth gets larger.

In addition to the instantaneous footprint of the satellite, we must also look at the ground coverage of the satellite. Not all orbits cross the same positions on the Earth for the same amount of time. Figure 3 shows a probability density function of the latitude of the satellite with multiple traces for satellites at circular orbits of different inclination.

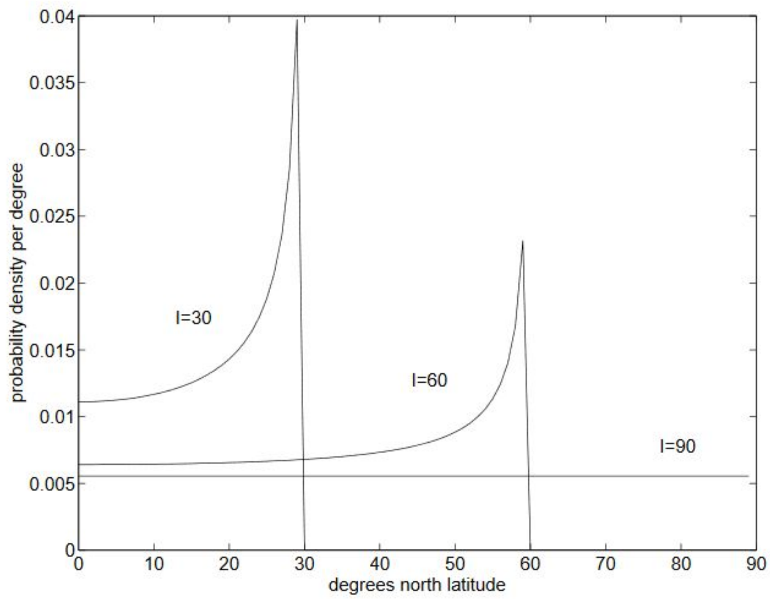


**Figure 3**: Probability Density of Spacecraft Latitude for Circular Orbits
Source: Washburn, Alan. “Earth Coverage by Satellites in Circular Orbit.” Web. 15 Mar. 2017.

From the probability density graphs we can observe that satellites with small inclinations spend the majority of their time at the latitude of that inclination and never exceed it. As we are designing a communications satellite for radio amateurs at a variety of latitudes, we should tend towards a high inclination orbit that covers a larger area of the earth more equally.

### Launch Availability

In addition, we researched the orbits of the CubeSats already in orbit in order to get an idea of launch availability for secondary payloads. The majority of satellites fall into two categories: those launched from the ISS and those launched into polar orbits.

Those launched from the ISS have altitudes of about 400 km and an inclination of about 51 degrees (Appendix A-8). This is the exact opposite of what we want, as the low orbit leads to a smaller footprint and the inclination determines that the satellite spends most of it’s time over that latitude.

However, those launched into polar orbits have attitudes between 500-700 km and inclinations of between 95 and 100 degrees (Appendix A-8). This is an appropriate orbit for our purpose, giving us a larger footprint and equal time over each area of the Earth. As such, we can plan for this orbit, knowing that launch opportunities are available.

## Payload

Our primary payload is a linear transponder for use by amateur radio operators. This transponder operates in a broadcast architecture, receiving transmissions from operators on the ground and transmitting them to all listening operators within the footprint of the satellite. After working on a trade study (Appendix A-2) to determine what frequency bands to use, we determined that we could best service the amateur radio community by using the 15 meter band for uplink and the 10 meter band for downlink, for the reasons outlined in that document.

Currently, as there are no active amateur radio satellites using these bands, there is some uncertainty related to their propagation characteristics. In the past, RS-12 and RS-13 had 10/15m communication transponders for amateur radio but their propagation characteristics were not well documented. We spoke to Bob Bruninga, member of HFsat, and carried out independent research but did not find useful information about HF satellite communications. We then spoke to Professor Vesecky who directed us to Canada's Enhanced Polar Outflow Probe (e-POP) satellite. With this help, we are making progress towards our analysis into the propagation characteristics of HF signals to LEO.

In addition, this design gives us an opportunity to use our linear transponder to study HF propagation as a scientific secondary mission. As this research remains within the scope of the amateur satellite service, it may increase our chance of selection by the launch initiatives. To gather data about propagation characteristics, Bob Bruninga suggested adding to the current AMSAT satellite status page where Amateur Radio operators could add additional information about over the horizon communication. Another method to gather data for a scientific mission would be to have a beacon on the downlink. This beacon could then be viewed on a website like PSK Reporter automatically which would reduce the chances for human error.

## Regulation

CubeSats generally use amateur frequency bands which requires them to fit within the amateur satellite service. The most important rules to keep in mind with regards to regulation are the two definitions below.

> "Amateur Service: A radiocommunication service for the purpose of self-training, intercommunication and technical investigations carried out by amateurs, that is, duly authorised persons interested in radio technique solely with a personal aim and without pecuniary interest."
>
> "Amateur-Satellite Service: A radiocommunication service using space stations on Earth satellites for the same purposes as those of the amateur

service." ("Electronic Code of Federal Regulations - Title 47. Part 97")

Our CubeSat must fit within the scope of the Amateur Satellite Service because an amateur radio transponder is currently the primary payload of the satellite. An experimental license can be obtained to circumvent these definitions, but then other amateurs cannot use the transponder which counteracts the mission goal. Frequency coordination must be obtained and the documents in the CubeSat Developer Resources provided by Cal Poly provide useful information on this process.

## Satellite Design

To design part of the communications subsystem, significant systems level design had to be completed to help define requirements for communication. The satellite design and mission are still flexible, but after researching and analyzing other designs like the FOX project with AMSAT and HFsat with the USNA we have helped narrow down design goals. A typical PCB stackup for a CubeSat in the Fox series of satellites is shown in figure 4. While this does not represent our design, it provides a visual representation of the requirements of a satellite design such as dimension, general features, mass, and materials.

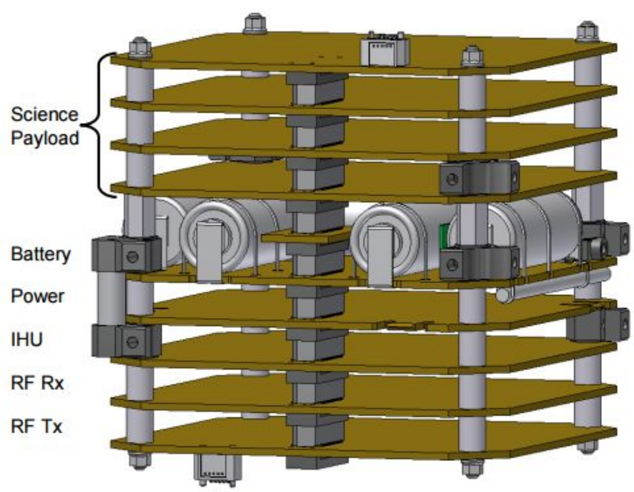


**Figure 4**: Internal Structure of Fox-1 CubeSat Electronics
Source:"AMSAT Fox Project." N.p., n.d. Web. 15 Mar. 2017.

The visual representation of a CubeSat design shows the small portion that this year's senior design team is trying to accomplish with respect to the scope of the overall mission. We are designing the equivalent of the bottom two RF transmit and receive boards, and there is still a lot of work to be done.

## Design Requirements

Design requirements are based off the CubeSat specifications and mission requirements for our linear transponder payload. The design requirements take into account the harsh demands of the space environment and its effects on spacecraft design. They are enumerated in our Mission Requirements document (Appendix A-3).

## Power Budget

In determining the power budget for the CubeSat we have focused on the system's power generation and consumption, adding the contributions from each stage, designing towards a positive total sum for the power budget. Also our current power budget is based on a 1U CubeSat, the choice of size could change in the future.

Power for CubeSats is generally provided by two interchanging sources where the primary source is determined by the CubeSats orbital position. While the CubeSat is not in umbra and penumbra eclipse power is provided by solar panels strapped to the outside panels of the CubeSat. While the CubeSat is in umbra and penumbra eclipse(Appendix A-5), power is provided by either lithium-ion or nickel-cadmium batteries(Lynch and Wallace).

The power generated by one 1U panel covered with solar cells can produce a maximum amount of power of roughly 4 Watts(DHV-CS-10 Solar Cell). The batteries on a 1U CubeSat can generate about 6 Watts of power(Lynch and Wallace). In our design the transmitter stage of the linear transponder is the biggest power consumer with a maximum power consumption of 2 Watts- 4 Watts (Appendix A-5).

Two power budgets (see tables 1 and 2) have been composed based on whether the power is being sourced by the solar panels or the batteries, which is determined by the CubeSats orbital position. Based on simulation(Appendix A-5) and other CubeSats(Appendix A-5), we have determined a satellite in LEO is eclipsed roughly 24% of its orbit or roughly 23 minutes during an approximate 1 hour orbit (Ibid). This reasoning led to the two preliminary power budgets provided below.

**Table 1**: Power Budget of CubeSat in Eclipse

| Subsystem | Max. Power | Min. Power | Typical |
|---|---|---|---|
| Solar Panels | 0 Watts | 0 Watts | 0 Watts |
| 2 Batteries(Li-ion) | + 6 Watts | + 4 Watts | + 5.6 Watts |
| Linear Transponder | - 4 Watts | 0 Watts | - .5 Watts |

| | |
|---|---|
| Worst Case | 0 Watts |
| Typical | + 5.1 Watts |

Source: Appendix A-5 , Lynch and Wallace

**Table 2**: Power Budget of CubeSat in Sunlight

| Subsystem | Max. Power | Min. Power | Typical |
|---|---|---|---|
| Solar Panels | + 4 Watts | + 2.04 Watts | + 3 Watts |
| 2 Batteries(Li-ion) | + 6 Watts | + 4 Watts | + 0 Watts |
| Linear Transponder | - 4 Watts | 0 Watts | - .5 Watts |

| | |
|---|---|
| Worst Case | - 2.04 Watts |
| Typical | + 2.5 Watts |

Source: Appendix A-5, Lynch and Wallace

These power budgets are to be greatly expanded upon in the Spring quarter as we pick electrical components to implement our RF system. Using these values, the power consumption of the RF board will be specified. The power system will be built by future members of CubeSat, therefore they will specify it in the power budget. For now we are using the solar panel/battery model outlined above. Note that lithium ion batteries were chosen initially for the given power budget above and in appendix 5, but in our final power budget the lithium ion batteries might be replaced with nickel-cadmium batteries due to the risks involved in flying lithium batteries in space (Thirion).

## Attitude Control

The attitude control subsystem of a satellite stabilizes its orientation relative to a specific reference. This is driven by the requirements of the antennas and instruments of a spacecraft. Whereas a space telescope might be oriented with respect to the celestial sphere, for our purposes as a communications satellite we are referenced to the earth.

The specific pointing requirement for our satellite is based on the antenna design, a process which is ongoing. The goal of the attitude control system is to orient the satellite such that the antenna provides maximum coverage over the ground path. Once our antenna design has developed further, we will determine our necessary pointing accuracy and stability from its radiation pattern.

### Thermal Considerations

The thermal environment of space will affect performance and operations lifetime of our system. When visiting the PolySat team, they mentioned this highest satellite temperature they had seen in orbit was around 90°C. As such, when designing their electronics, they used parts certified for the industrial temperature range of -40°C to 85°C. AMSAT's Fox-1 Thermal Subsystem report describes their electronics as being designed for -40C to +50C (Jansson). As parts certified for the industrial rating are widely available and keeping in mind the maximum on-orbit temperature seen by PolySat, we will choose parts that meet the -40C to +85C industrial temperature rating (Appendix A-3).

Testing our system in a thermal chamber to monitor its response over the wide temperature fluctuations is an important step in the overall satellite design. Once a prototype is complete, the system should be tested over a wide range of temperatures to verify that it is operational in the harsh space environment.

### Radiation

One of the difficulties of the space environment is the presence of particle radiation where high-energy particles strike the spacecraft and can cause damage to electronic systems. If these particles strike the microelectronic circuits within the spacecraft this can cause temporary or permanent damage to the device. There are many mechanisms producing these particles so the consideration of radiation can be quite difficult.

In order to mitigate these effects, spacecraft designers can choose parts that have been proven through flight heritage or ground testing to be less susceptible to radiation damage. However, parts that have been proven to be "rad-hard" often are very expensive. Another method is to shield susceptible components with some other material. This solution has an obvious weight penalty, especially relevant for a nanosatellite.

In our talks with Cal Poly and AMSAT, we asked about their strategies for avoiding the risk from radiation events. Cal Poly used no radiation hardened parts and did not attempt to test their parts on the ground. They used modern ICs and microcontrollers, utilizing the advanced processing power and mass savings and considering the possibility of a radiation induced failure as an acceptable risk.

AMSAT took a more risk-averse position. They modeled the specific radiation environment of their spacecraft at its location and the radiation shielding granted by its structure. They then put a strong emphasis on using parts that are radiation tested or have flight heritage. They attempted to use discrete transistors as much as possible rather than ICs. In addition, they use NASA derating guidelines for their components (Biddle and Monteiro).

Our plan is closer to the AMSAT position. We've eliminated the high risk components identified by AMSAT and have the same part selection preferences including their derating guidelines (Appendix A-3). However, we are not currently doing radiation shielding modelling of the spacecraft. In addition, we are open to variances to those part selection guidelines based on performance, mass, and schedule requirements.

## Communications Design

The communications design comprises the main focus of our team's unit design work. So far this has included specifying the ground station information, creating a link budget, completing a frequency trade study, and antenna design. After completing the frequency trade study, we determined that more research on ionospheric effects would need to be completed to understand the effect on HF propagation which has become part of our critical path for our mission timeline.

### Ground Station Information

In order to serve the Amateur Radio community, we are designing our satellite link budget using a typical amateur radio satellite operator's ground station. In order to derive a minimum requirement for this ground station, we asked AMSAT what ground station they used in the link budget for their Fox series of satellites. They said that they used the Yaesu FT-817 with a portable antenna. As we have an HF satellite, we've assumed this to be portable dipole antennas for both uplink and downlink. After confirming this with guides for working the now defunct RS-12 HF satellite, we feel that the Yaesu FT-817 provides an acceptable minimum ground station for analysis purposes (Appendix A-3).

### Link Budget

The link budget is a central section of our team's design effort because it is where all of the unit level design sections come together to describe the system performance as a whole. Having a good link analysis is crucial to our mission success, so we looked at multiple different sources for good link budget information. We started out by developing our own link budget calculator, but moved on toward already established link budget calculators, such as the ones developed by Jan King. (King)

Jan King's link budgets contain more information and serve as a good educational tool, but the spreadsheets contained other details that were not relevant to our project. We finally decided to use Microwave Office to complete the link analysis because it allows for much easier analysis of the system in regards to noise and spectral content. We plan to use Microwave Office in the future for updating our link budget.

For the uplink a nominal  -91.12dBm signal will be at the receive antenna based off path loss and ground station equipment (Appendix A9). The path loss for this calculation was based off a 10 degree orbit for XW-2E, another CubeSat which may have similar orbit characteristics to our satellite. This requires more research, in reality this number will be lower.  The noise level will be dominated by terrestrial sources both manmade and from lightning, but galactic noise also plays a role in the ground station receiver. More research needs to be conducted into the ionosphere and its effect on link budget calculations. This is part of our critical path as the received signal strength significantly affects the rest of the communications system design.

The logical extension of the initial link budget is to expand it through the linear transponder system chain. As of now a link budget through the transponder chain has been drawn up in Google Sheets, using hypothetical electrical components along with their gain, noise figures, and third intercept point. These parameters will become more solidified as we prototype and test our RF board stages. Throughout next quarter these parameters, determined by design and part selection, will be entered into the system chain link budget using Microwave Office. Then in  an iterative fashion we will use the link budget to inform component design, and those component specifications to create a more accurate link budget.

### Frequency Trade Study

The frequency trade study was an investigation to determine the best choice of uplink and downlink frequencies for our system. The study considered several parameters of merit which are too extensive to list here but can be found in Appendix A-2. We concluded that the HF spectrum is the best selection for our design. Less path loss and less doppler shift outweigh the benefits of higher data rate capabilities at higher frequencies because we are focused on amateur communications. Developing our transponder to operate at HF frequencies would open up satellite communications to a wider audience because of the easier operating conditions without additional equipment investment.

### Ionospheric Propagation

The propagation of signals within the frequency bands that we chose is important to us for two reasons. Firstly, we need to know that communication with the satellite is possible in order to satisfy our primary mission goal of enabling “reliable SSB and CW communications between Amateur Radio Operators via satellite relay” (Appendix A-2). Secondly, we need to use our understanding of propagation through the ionosphere to create an accurate link budget that allows us to design a successful transponder.  In order to achieve the former, more urgent goal, we researched propagation information related to RS-12, a currently defunct HF satellite. In order to achieve the latter goal, we began research into the theoretical aspects of radio propagation in the ionosphere, developing an understanding that will lead to a quantitative analysis of our link.

### *RS-12 Research*

Launched by Russia in 1991, RS-12 has a 40 kHz linear transponder onboard with the ability to be operated in a few different modes, one of which has a 15 meter uplink and 10 meter downlink (Capon). To research the difficulty operating the satellite, we looked into the ARRL archive of magazine issues and were able to find some reference guides intended for Amateur Radio operators.

The common theme of these articles is that RS-12 was a good satellite for beginner operators, especially when compared to the U/V satellites (Messano). Amateur Radio operators were able to contact RS-12 with their existing HF ground stations and dipoles. There were cases of conversations between operators on 15 meters unintentionally making their way into the satellite (Brogdon).

Based on this research, we believe that we can comfortably say that though we need to do more theoretical research to determine the signal attenuation through the ionosphere, it is possible to build a successful, reliable transponder using 15 meter uplink and 10 meter downlink. Furthermore, based on this and the reports of operating ease, the previous result of our Frequency Trade study holds (Appendix A-2).

### *Theoretical Analysis*

Frequency collision in the ionosphere is an important parameter due to the reflection and attenuation of radio waves. The ionosphere is composed of three layers all of which contribute to signal attenuation. The D layer is responsible for absorption of HF frequencies below the 20 meter band. However, for signals in the 15 meter band the D layer has little to no effect. The E layer is thought of as a wild card as it's level of attenuation is highly variable. The main attenuation in the HF band comes from the F layer. The F layer is broken down into two parts the F1 and F2 layers, where the F2 layer is the main contributor (Poole).

The lack of specific information on ionospheric propagation on the HF bands motivated our group to contact other Amateur Radio operators that may have information on HF attenuation in the F layers. Contact with the Amateur Radio community allowed for research to progress in several directions and with the help of professor John Vesecky the research was narrowed down. In this study the main focus was whether or not the 15 meter uplink is feasible. To characterize the feasibility, the critical frequency (CF) was studied and determined to be between 6-13 MHz. The critical frequency is typically determined using an ionosonde, which is a device that sends various frequencies directly upward towards the ionosphere and reads the reflected waves, when it reaches a point that there are no reflections the CF is determined.

From our studies we have found that the CF around the HF bands tends to be between 6-13 MHz which can be used to find the Maximum Usable Frequency (MUF). The MUF is the largest frequency that can be used to communicate between two points via reflection. Using a

15 meter the ideal MUF would be approximately 20 MHz to allow our specified frequency range to breach the ionosphere and hit the satellite at LEO. With the information in mind the angles at which the signals can be sent vary from $\theta \in (60, 120)$ assuming a CF of 10 MHz which directly affects the antenna design.

## Antenna Design

Since antenna design was a new topic for our team, research had to be conducted in order to familiarize ourselves with the fundamentals of antenna design. Initially our team started to explore antenna designs that had been implemented in the past by other CubeSat projects at places like Cal Poly and AMSAT but we realised that this was the incorrect approach to take given our lack of knowledge on antenna design and theory.

After several discussions with team members and our managers, we decided that the best approach would be to start understanding antenna theory and parameters. In order to get a grasp on parameters, our team read sections from the ARRL Antenna Handbook that were applicable, held regular meetings with Professor Petersen and our teaching assistant Becker Sharif, and conducted independent research. The result was an understanding of parameters of merit such as gain, directivity, antenna aperture, bandwidth and polarization.

We now understand that directivity/gain is an important parameter because it will measure how effective the antenna is. As such, our goal is to design an antenna as omnidirectional as possible because omni-directional antennas are used when the transmit location is unknown or far away. Due to the uncertainty of the orientation of the CubeSat in LEO at all times, an omni directional antenna would be the best choice.  A directional antenna on the other hand requires knowledge of the receive and transmit signals at all times.

Since maximum power transfer between the ground and satellite antennas requires both uplink and downlink antennas to be aligned in the same direction, circularly polarized antennas will be designed. E field of a circularly polarized antenna rotates $360^0$ every RF cycle. Hence there is a higher chance that the ground station will pick up signals from the satellite. However one trade off of a circularly polarized antenna is that it broadcasts a signal in multiple planes which means that it’s power transfer is about half as much as a linearly polarized antenna. In other words, the electric field vectors of the transmit and receive side are misaligned half the time in case of a circularly polarized antenna. Still circularly polarized antenna is the best choice solely because the use of a linearly polarized antenna would mean radiation wholly in one plane, a situation that isn’t ideal in case of a CubeSat.  More information on parameters of merit can be found in Appendix A-7.

Along with research, our antenna team also learned to create simulations in a tool called 4nec2. This step was also challenging because the team wasn’t familiar with the tool. However, after following tutorials from the 4nec2 website, the team was able to simulate a simple dipole antenna (see figures 24 and 25). The research (see Appendix A-7) acted as a guide while creating simulations since parameters like gain and directivity were kept in mind. The team is currently working towards completing a simulation of a dipole antenna mounted on a cubelike object keeping in mind the directivity. Some factors that prevented this goal to be achieved earlier were lack of experience with 4nec2 and lack of knowledge on basic antenna theory.

A dipole antenna has been suggested for our spacecraft but we have not yet come up with performance specifications as a team. Some performance specifications that our team will decide are the directivity of the antenna, the antenna efficiency, and whether or not our spacecraft will use antennas as a part of the attitude control system. Specifically, the antenna designer will collect information on power of the signal being transmitted by the ground station and the power of the signal being received by the ground station. Based on path loss study, power at the receive antenna was calculated to be -91.12 dBm but the team is still researching and negotiating this parameter amongst ourselves(Appendix A-9).The justification for this calculation has also been provided in the link budget section on page 13. Once these parameters of merit are established, we will chose an antenna that best fits our needs.

Another measurable goal for early Spring quarter is to have a physical prototype of a dipole antenna, and realise its S- parameters using the VNA kit. This will be an iterative process which will involve adjustments to the antenna design, and re simulating based on S-parameter results.

## Linear Transponder

The linear transponder listens to a section of the 15 meter band then filters it, changes its frequency, amplifies and retransmits it back down to Earth. In order to understand how to design our transponder, we first started by reverse engineering existing designs. By looking at the block diagrams of other projects, then attempting to understand the reasons the designers using each component, we were able to develop the skills to design our own transponder.

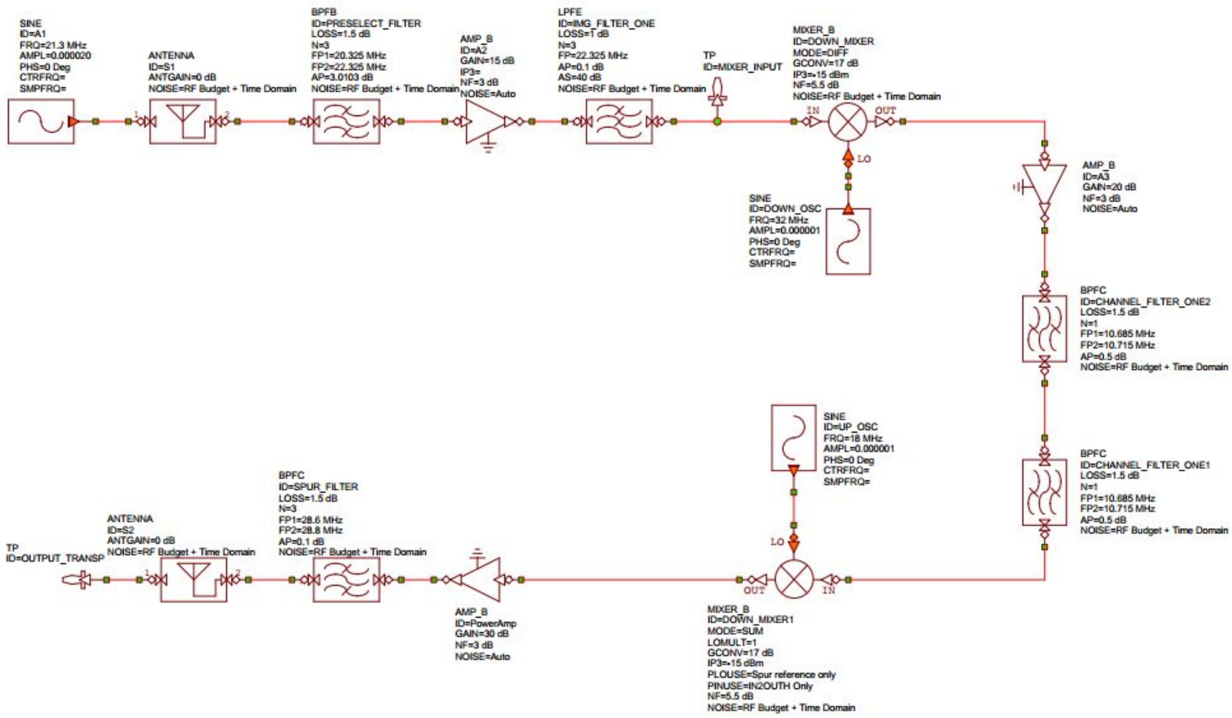


**Figure 5**: Block Diagram of Linear Transponder

Initially, we drew the blocks by hand but then acquired a copy of AWR's Microwave Office to lay out the blocks in software (see fig. 5). We were able to analyze individual spurs and determine which components of the diagram caused them.

After coming to a transponder design that appeared to work in software, we began developing its individual components as part of our RF Hardware Design final projects. The results of this design will allow us to update the Microwave Office simulation to more accurately model our transponder.

## Local Oscillator (LO)

The system's local oscillators generate all of the necessary signals to be passed into mixer stages for frequency conversion throughout the receiver and the linear transponder. Our team has decided to implement the local oscillators with phase locked loops. We have made this decision because PLLs, when used for frequency synthesis, offer a wide range of possible frequencies with low phase noise and a stable, precise output frequency which can be temperature stable if the reference signal is temperature compensated.(Signetics PLL Application Book)

### Phase Locked Loop (PLL)

The two local oscillators provide the signals for both mixing stages of the linear transponder. The 32 MHz oscillator is used to mix our 15 meter input signal down to our 10.7 MHz intermediate frequency for filtering. The other LO outputs a signal at 18 MHz to then mix this intermediate frequency back up to our 10 meter output frequency.

A block diagram of the two LO systems is provided for reference (see figure 6), though the design is subject to change. Each LO system will be composed of one PLL synthesis chip. Both of these chips share a reference signal from a stable crystal oscillator. Each loop will drive its own voltage-controlled oscillator (VCO) into phase lock with the reference oscillator. The PLL chips use programmable frequency dividers to lock one VCO at 32 MHz and the other VCO at 18 MHz. This provides for  frequency stable oscillation signals at the output of each LO system. These VCO outputs will be sent as inputs to their respective mixing stages.

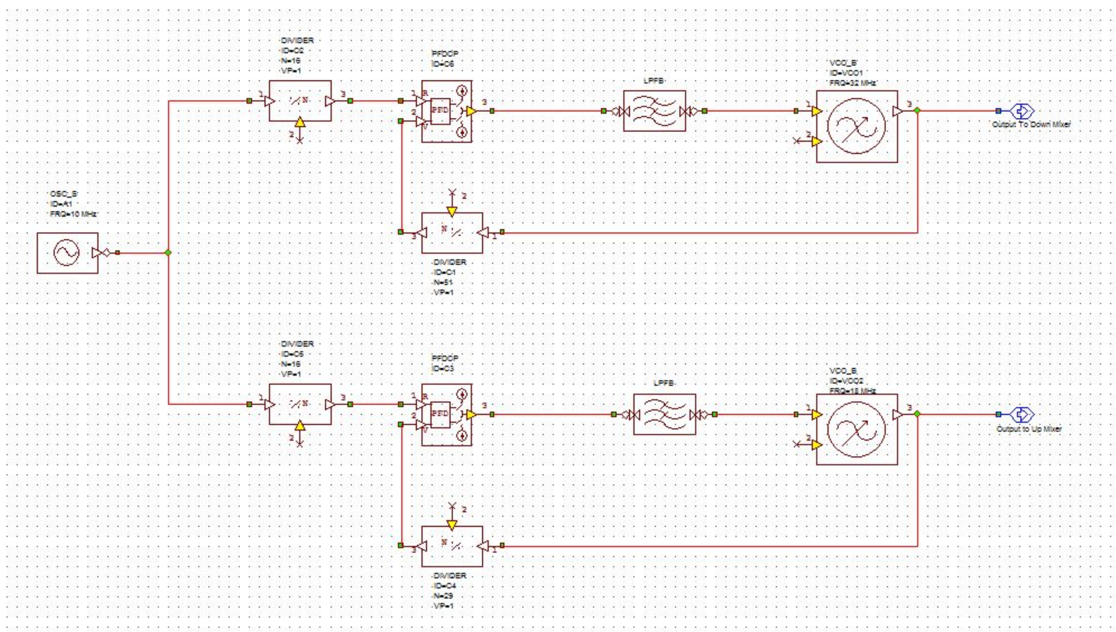


**Figure 6**: Block Diagram of PLL Subsystem

The PLL synthesizer chips will be controlled by an onboard microcontroller (see figure 6). which will communicate with the PLL chips through a standard serial interface protocol. The necessary performance characteristics are still being determined for the LO systems as we research and learn more about how to characterize the performance of PLLs used for this purpose.

## Filter Design

A key part of our linear transponder design is the various filters that prevent unwanted signals from being amplified and retransmitted from the device. The linear transponder will need four filters in total: preselect, image, channel, and output.

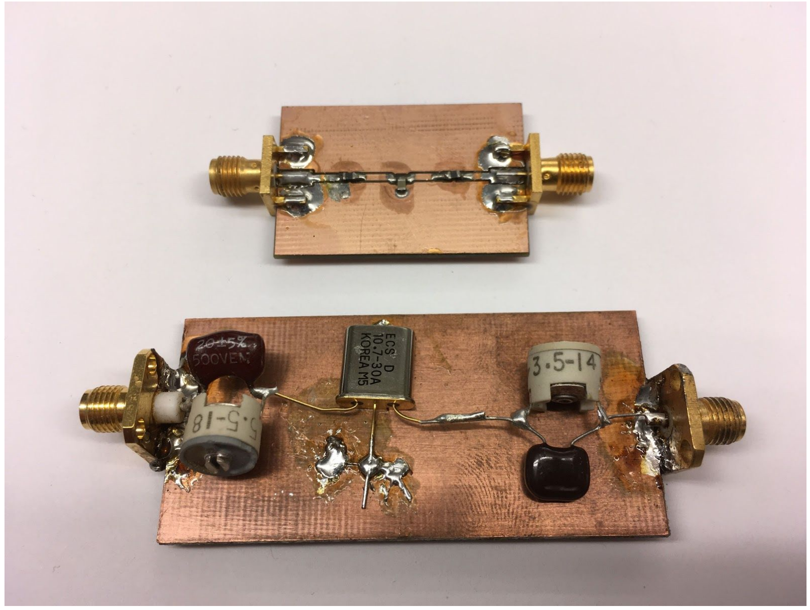

**Figure 7**: Lowpass Butterworth Filter (top) and Crystal Filter (bottom)

Initially, we started by working from theory and developed two lowpass Butterworth filters of different types and one bandpass Butterworth filter (see figure 7). After assembling the various components on a circuit board, we used a signal generator and spectrum analyzer to trace a magnitude plot of the filter. Both lowpass filters worked with some minor modifications. However, the bandpass filter showed a 45 dB insertion loss. Attempts to rectify this are ongoing and will continue throughout the Spring quarter in order to develop filters for the transponder.

## Preselect

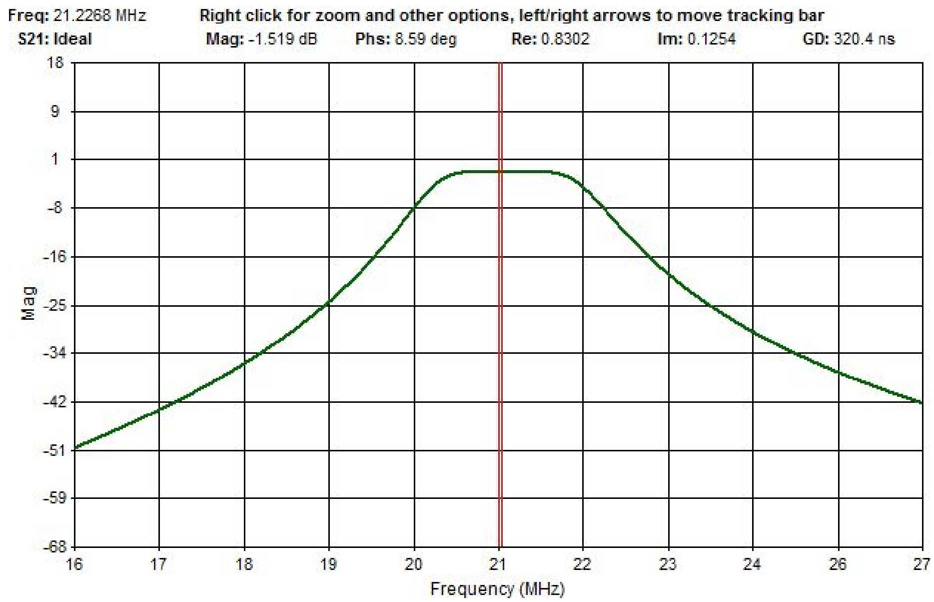


**Figure 8**: Magnitude of Simulated Preselect Filter

The preselect filter eliminates unwanted signals before they reach our low noise amplifier. In addition, it filters out the unwanted image frequencies so that they do not superimpose with our desired signal in the mixer. The passband of the filter (see figure 8) should be wide enough to allow all desired signals to pass through.

This filter is currently modeled as a third-order Butterworth bandpass filter having insertion loss of 1.5dB, a 2 MHz bandwidth, and a center frequency of 21.325 MHz.

### Image

The image filter is placed before the mixer for two reasons. First, it assists the preselector in filtering out the unwanted images of our signal. Secondly, it is designed to impedance match the output of the low noise amplifier to the input of the mixer. Currently, we are using the SA602A mixer for prototype purposes, which has an input impedance of 1.5 kOhm. The low noise amplifier is under development and once we have an estimate of the output impedance, we will design the image filter.

### Channel

The channel filter sets the bandwidth of the linear transponder. This includes filtering out the adjacent command signal. In order to do this, the channel filter must have sharp skirts. In our design this is achieved via a crystal filter. After looking at a variety of filter technologies, we found a two-pole crystal filter centered at 10.7MHz with a 30 kHz 3-dB bandwidth. This range of crystal filters also comes in varieties with more poles if a sharper rolloff is needed.

Development of a small prototype board is ongoing and will include one of these filters with proper impedance matching. It will then be characterized using the network analyzer to verify correct behavior.

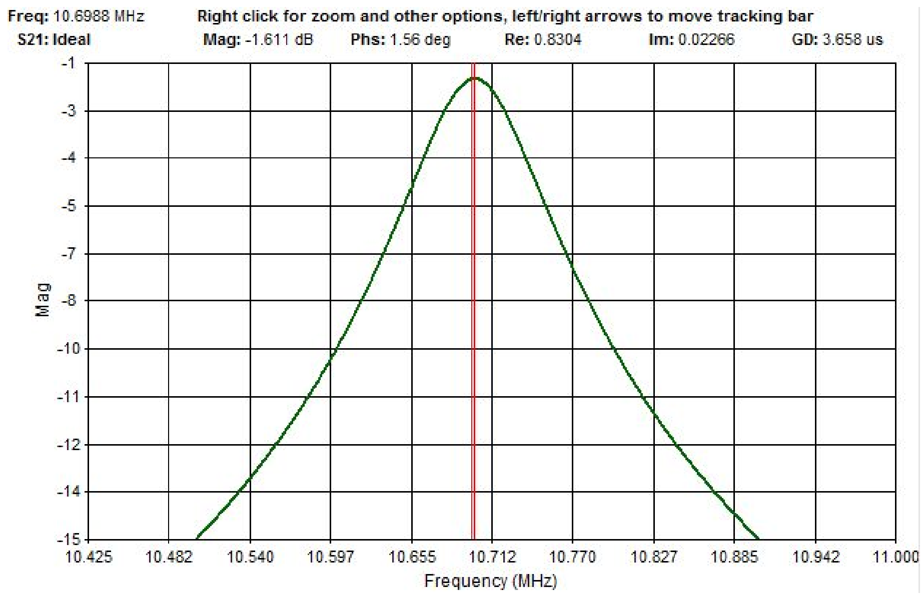


**Figure 9**: Magnitude of Simulated Crystal Filter

Currently, this filter is represented in Microwave Office as a 2nd order Chebyshev filter with the passband ripple, bandwidth and center frequency of the crystal filter. The magnitude plot of this filter is shown in figure 9.

### Output Filter

As a power amplifier has some nonlinearities, harmonic distortion will cause frequency multiples of the input signals to be present on its output. In order to prevent out-of-band transmissions, a low-pass filter follows the power amplifier to remove these spurs. This filter has not yet been developed.

## Low-Noise Amplifier

The LNA should amplify a very low-power signal without significantly degrading its signal-to-noise ratio. Therefore, the amplification of noise present at its input should be kept minimal. This is done through impedance matching, choosing the right amplifier type, and selecting low-noise biasing conditions.

Two LNA designs are currently being developed in conjunction with the RF design course. The first design uses a JFET and the second design uses a BJT. Both designs are making good progress towards completion. The LNA noise figure is designed between 2 and 4 dB with a gain close to 15dB. These numbers need further justification with our link analysis, but we have started designing towards these specs in an effort to use our 157 lab time for purposes of advancing our progress. We are currently planning on using the single ended output from the LNA to drive the SA602A mixer which will interface with the PLL oscillator.

The construction of the second LNA consisted of transistor selection, input/output impedance matching, board layout, and testing using the RF signal generator and vector network analyzer. Consideration was made to amplifier type, topology, gain, frequency operation, biasing, load terminations, and feedback.

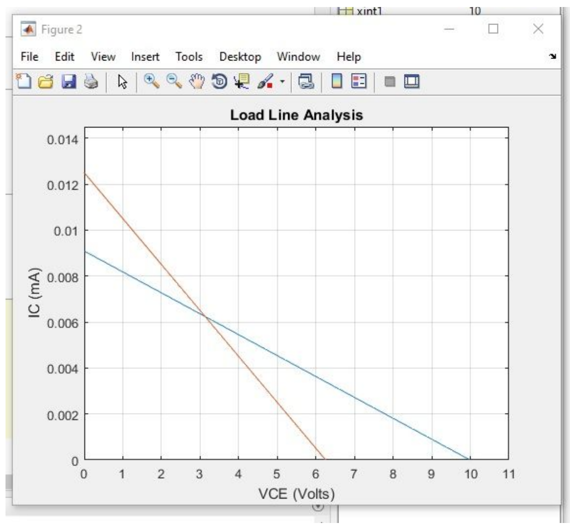


**Figure 10**: Load Line Analysis to demonstrate proper biasing

The design used the MMBT2222A transistor, a general purpose NPN in a SOT-23 package, which provides a noise figure of 4 dB. The BJT Biasing lecture notes that Petersen provided facilitated the process of computing the optimal bias points of the transistor. For verification, the plot was then graphed using MATLAB as demonstrated in figure 10.

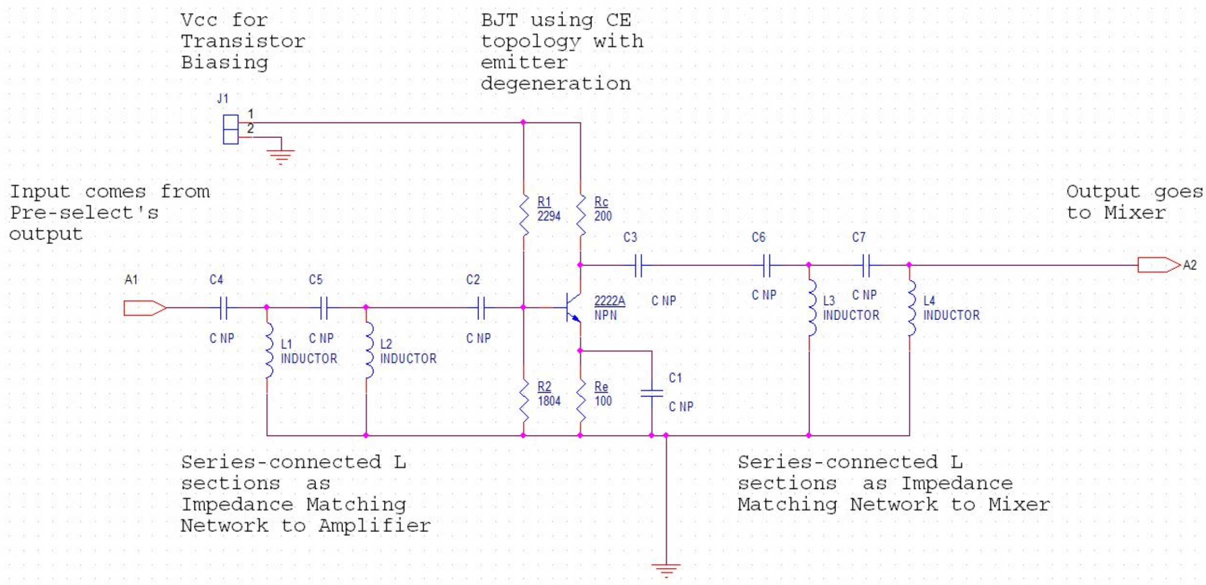


**Figure 11**: Schematic of Low Noise Amplifier design

The amplifier schematic in figure 11 includes series-connected L sections for impedance matching the input signal to the input of the amplifier. A series-connect L section will have low Q and wider bandwidth which allows for maximum power transfer over a wider range of frequencies. This impedance matching network should perform better than L, PI, and T networks. The topology of the transistor was designed as a common emitter because it offers high power gain and medium input and output resistances. A buffer stage will be added to the output of the transistor if needed which will be determined after testing. There is another series-connected L section for impedance matching the output of the amplifier to the input of the mixer. Capacitor values for the input, output, and bypass areas were chosen based on the receiver’s uplink frequency operation. An SMA connector on either end of the board allows for testing and debugging.

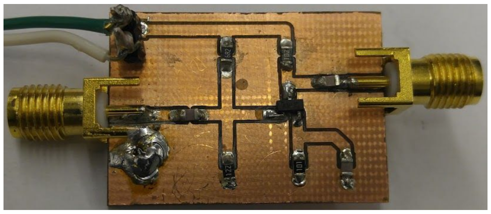

**Figure 12**: PCB of Amplifier

The amplifier in figure 12 was intentionally created without the input and output impedance matching networks. Omitting the networks was the first step in verifying that the amplifier met design specifications. The next steps that will be taken in the design are to take measurements and record data, add impedance matching networks, combine the preselect and amplifier on a single board, then re-test and take new measurements. An iterative process is needed for verification purposes.

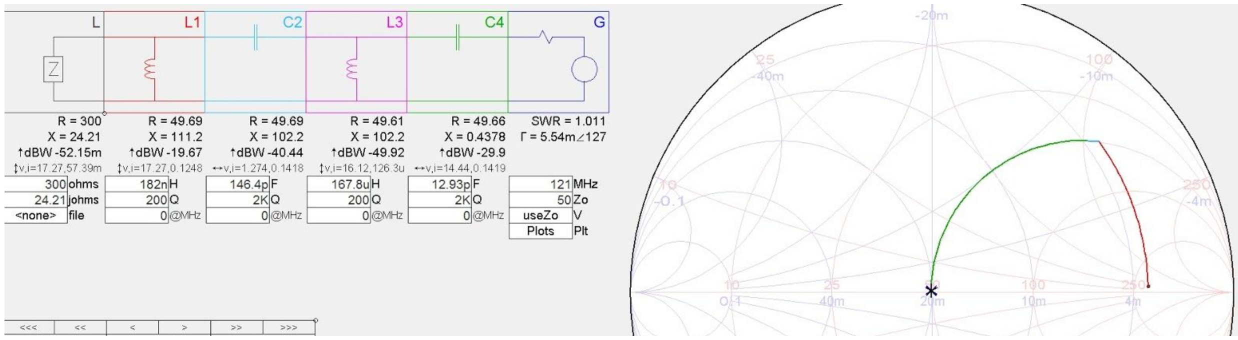


**Figure 13**: SimSmith Software to verify impedance matching networks

The validity of the designed impedance matching networks will be done using SimSmith; Figure 13 shows this process for an L-section network. The SimSmith software provides the designer with two basic graphs, the smith chart and a scattering parameter chart. This general RF circuit analysis program has multiple functionalities but we will use it to verify the impedance matching networks that we design. The signal flow of this program is read from right (source) to left (load) based on convention and the creation of schematics is done using a drag and drop feature.

## Automatic Gain Control

Automatic gain control (AGC) ensures that the signal received is amplified if the signals power is too low for processing and is limited if its power is too large for processing. This allows the receiver to have greater dynamic range without introducing overloading or excessive intermodulation products to the proceeding stages. Figure 14 shows a typical AGC block diagram, where the RF signal is passed into a loop and compared with a reference voltage and the difference is fed as a feedback control voltage for a voltage controlled amplifier that will amplify or attenuate the RF input signal yielding an output signal that matches the reference signal.

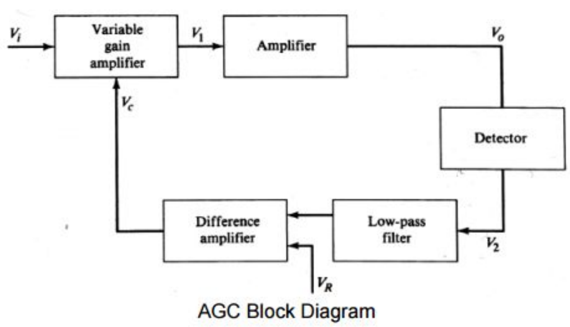


**Figure 14**: Block Diagram of Automatic Gain Control

Source: Rosu, Iulian. “Automatic Gain Control in Receivers.” N.p., n.d. Web. 15 Mar. 2017.

With respect to the SlugSat design, the team will be using AGC to stabilize the gain of the IF amps to ensure that we do not overload the PA stage. As a comparison the TURKSAT block diagram, shown in figure 15, can be used to demonstrate how the AGC will be implemented as a way to limit the power output in the transmit stage.

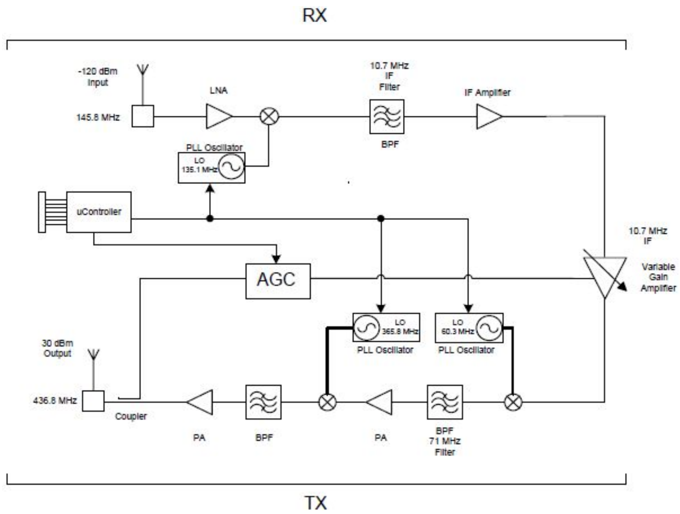


**Figure 15**: TurkSat Automatic Gain Control Diagram
Source: Osman Ceylan et al. “VHF – UHF Linear Transponder Design for TURKSAT – 3USAT.” Berlin: N.p., 2011. Web. 15 Mar. 2017.

There is still work being done to determine where the AGC will be used or if it will be needed for both stages.

# Program Development

Developing a satellite at a university is a multi-year process. As such, outreach is crucial to mission success. By making ties with members of the CubeSat community and engaging with other UCSC undergraduates, we hope to build a program that will successfully develop and launch our satellite.

## Outreach

To gain understanding of the process of designing and building a satellite, we’ve reached out to a number of external groups including the Cal Poly College of Engineering, AMSAT, IARU and the US Naval Academy. As students without previous experience in satellite design, developing connections with members of the Amateur Radio and CubeSat communities is key to our success.

### Cal Poly College of Engineering

Justin Foley, a full-time staff engineer working for the CubeSat project at Cal Poly, invited us to learn more about satellite testing and integration processes at their campus. Cal Poly first developed the CubeSat framework with Stanford in the 1990’s and has since then been able to monetize the testing and integration of other CubeSats by verifying their functionality before launch. While this is still far away for the project at UCSC, Cal Poly would be a valuable contact to keep in the future when the satellite is closer to completion.

### AMSAT

AMSAT's Vice President of Engineering, Jerry Buxton, met with our team for an hour and primarily discussed the Fox series of CubeSats. The Fox series of satellites is designed by AMSAT and it takes advantage of university research programs and NASA launch availability to get amateur radio repeaters and transponders in space. To improve chances of selection for a NASA sponsored launch, having a science payload along with an amateur radio communications system is useful.

### IARU

Arthur Feller with The IARU helped clarify questions regarding requirements for communications coordination in amateur bands. Our main takeaway from meeting with Arthur was that we should avoid getting an experimental license and that a science mission should be related to radio technique so it falls within the definition of the amateur satellite service. Arthur also mentioned other people we could contact if we have any technical questions including Tom Clark (K3IO), Bob Mcguire (N4HY), and Bob Bruninga (WB4APR) with the USNA. We also learned that AMSAT has an annual technical symposium in the fall which people working on the project may be able to attend.

### USNA - HFsat

We contacted Bob Bruninga about the HFsat that is being developed at the US Naval Academy because we are considering using similar frequency bands to their project, 15 meter uplink and 10 meter downlink. Their project is interested in HF propagation characteristics and emergency communication, along with adding another satellite to the Automatic Packet Reporting System (APRS) satellite network on 2 meter (Bruninga).

## Outreach to Continuing Students

To succeed in building a complete satellite and obtaining a launch opportunity, future student participation is crucial to the project's success. To gain more members, we have started to prepare presentation material which can be used to gather interest from other students in the project. So far, we have discussed the UCSC CubeSat with members of the amateur radio club but we plan to reach out to a wider audience next quarter.

### ARC meetings

Weekly meetings with the Amateur Radio Club are used to help retain student interest and involvement in the CubeSat project. Regular members are encouraged to work on CubeSat as their senior design project and they are briefed on possible design aspects that they could begin looking into.

### Introduction Document

An introduction document detailing the scope of CubeSat project has been started so that new members can refer to it as a guide. The document contains an explanation of the purpose of a CubeSat, a brief overview of division of labor, and our team's scope. It is currently a work in progress, and new material is being added as our team develops the satellite.

## Launch Opportunities

Purchasing a launch is well outside the means of the project budget, consequentially the UCSC CubeSat is looking for a launch opportunity through government and corporate sponsored educational launch programs. Some of these educational launch providers are United Launch Alliance (ULA), NASA's CubeSat Educational Launch of Nanosatellites (ELaNa) initiative and the US Air Force's University Nanosat Program.

ULA started their program in 2016 which allowed university educational projects to compete for 6 free launch slots. While the future of this project is not clear, more competitions may be available in the future ("CubeSats STEM Program - United Launch Alliance").

NASA's CubeSat Launch Initiative has selected 152 CubeSat missions from across the US. While the CubeSat Launch Initiative applications have come to an end in 2016, CubeSat launches overall have been growing and NASA has played a large role in giving American universities a chance to participate in the growing nanosatellite industry. While the future of NASA CubeSat opportunities are not certain, the Educational Launch of Nanosatellites (ELaNa) program may be their source. NASA's goal with ELaNa is to attract and retain students in STEM fields (Heiney).

The US Air Force's University Nanosat Program would be an excellent opportunity because it would provide a source of funding for the program. The application is open in the late summer/early fall of every even numbered year. This program is a four year, concept to flight ready, spacecraft competition ("University Nanosat Program").

## Gantt Chart

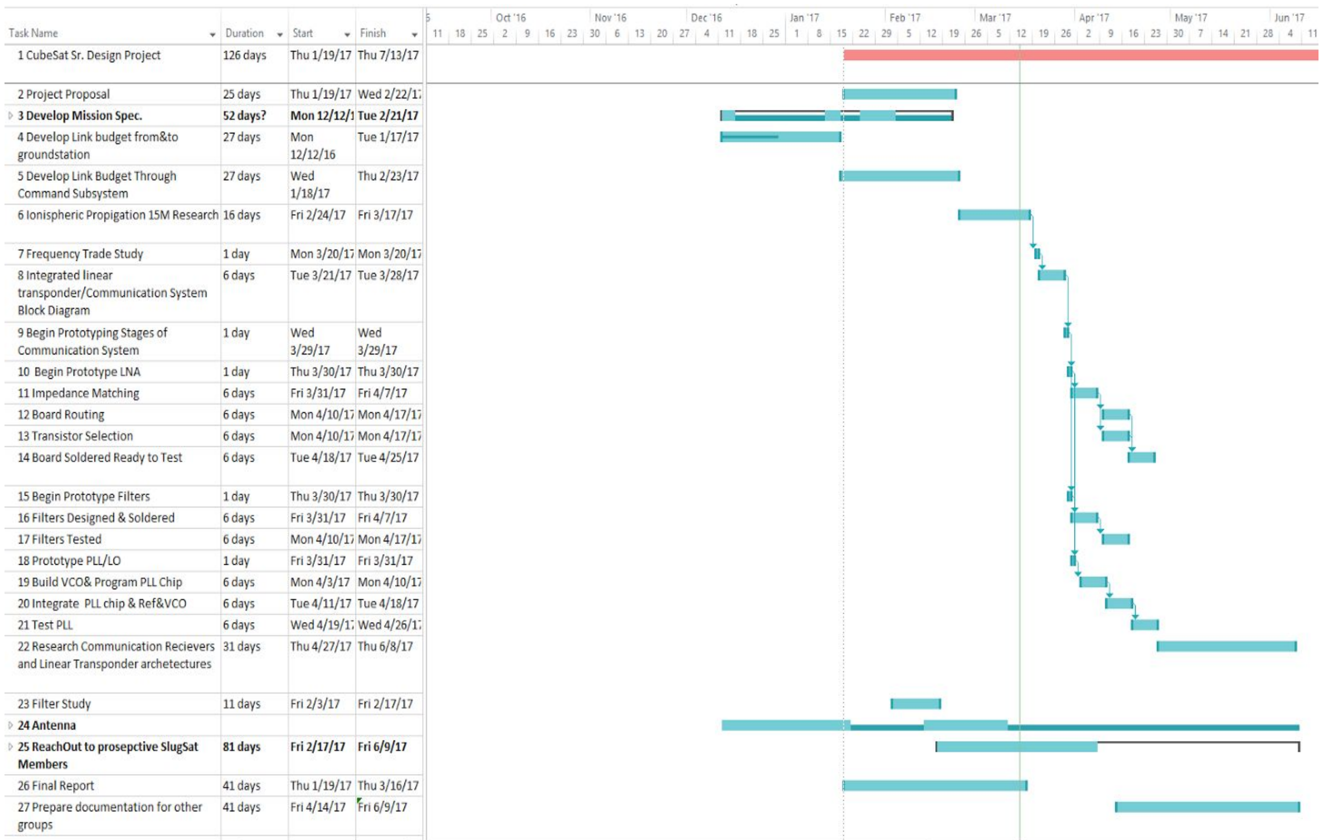


**Figure 16**: Gantt chart overview

The Gantt chart, figure 16, helped us in identifying the critical paths to our design. A critical path is one that will impact the whole project if missed. Our earlier critical paths included the Mission Requirements, Channel Selection, and the Deliverables documents.

The completion of the Mission Requirements (Appendix A-3) document allowed the team to state our objectives which helped us strategize towards completing our deliverables. We would not have been able to plan accordingly without this document in place. The Frequency Trade Study (Appendix A-2) was a key aspect of our design because it determined values and parameters crucial to the development of the link budget which affects our entire design. Without this document, the team would not be move forward in the creation of the link budget. The Deliverables document provided an agreement between what the team plans to deliver and what management is satisfied with accepting which guided the team's efforts, setting deadlines and shifting focus. Without this document in place, the team's focus would be misaligned with that of management and we would not deliver on time.

The newest critical path to our design is the investigation of the ionosphere. This study has the potential of impacting the whole project because if we determine the 15 meter band is unsuitable, our design would require fundamental changes. More specifically, changing the frequency of the uplink will change filter requirements, oscillator frequencies, amplifier selection, and antenna design so it is important to make this decision as soon as possible. This critical paths to our design are shown in the Gantt Chart Critical Path document (Appendix A-6).

A milestone is an action or event that marks a significant change in development. An honest review of the hard dates included in the Gantt chart show that major milestones were indeed met. Major milestones included the development of the Mission Specifications document, agreeing on set deliverables that Professor Petersen approved of, the development of a link budget, designing a block diagram that continuously gets updated to reflect new changes, and the creation of a final report to summarize the team's standing.

The success of this project required a division of labor into three distinct teams consisting of a command receiver team, linear transponder team, and an antenna team. Each member within a team was assigned and expected to perform a technical and non-technical role.

The command receiver team consisted of Matt Carberry, Matt Moranda, and Eric Wells.
The linear transponder team consisted of Marcel Tress and Eric Ortega. The antenna team sole member was Navneet Kaur. The technical duty for each member of all teams was RF design. Technical and non-technical duties are presented in the team charter. After working together over the Winter quarter, the transponder and command receiver teams merged due to their integrated nature.

A bi-weekly meeting structure was decided upon because the team saw benefit in providing each member with an opportunity to present their ideas which helps keep everyone updated. We followed this structure throughout Winter quarter and it proved to help each member strive to meet their goals by the next meeting, set goals for the next week, hold each other accountable, and feel part of a team effort.

Spring goals can be broken into two sections: the antenna and the payload. For the antenna, we will deliver a prototype with the interface hardware necessary for integration with the payload. The deliverable will be include testing and simulation for verification purposes. For the payload, we will deliver a bench prototype consisting of the circuit design of the command receiver and transponder capable of processing input and translating signals between the transponder frequencies. A full description of the deliverables can be referenced in our Deliverables document (Appendix A-4).

# Conclusion

The learning curve for university satellite design has been difficult considering our team had no prior experience in this area. We accounted for this challenge by reaching out to experts in Amateur Radio and at education institutions. As a part of an accredited university, there are opportunities available which would give our project access to space but it will require the effort of other interested students to ultimately achieve this goal. We understand that the long term success of this project depends on future students, so we have started to integrate students from the amateur radio club into our project and plan on future outreach.

The progress we made Winter quarter has put us on track to meet our goals, and we have started unit level design on the receiver and oscillators. We completed a significant portion of the systems level design required for the satellite and conducted research in order to create a framework for our project that could lead to a launch opportunity in the future. We are on track toward meeting our goal of designing a command receiver, antenna and transponder prototype outline as mentioned in the deliverables document (Appendix A-4).

# Appendix

## A-1 CubeSat Team Charter

# CubeSat Team Charter

### SDP EE/CE 129A

Title: UCSC CubeSat
Sponsor: Stephen Petersen

## Objective

Following in the trail of the many educational satellites that have already been launched, the UCSC CubeSat project is working towards placing a satellite into low earth orbit (LEO). The main payload of this satellite will be a linear transponder for communications use by amateur radio operators.

This year's team will develop the overall mission specifications for the satellite and then to design the linear transponder and command channel receiver for the communications subsystem of the project. This will result in a final deliverable of a working linear transponder and command receiver portion that are ready for environmental testing and subsequent integration into a satellite.

## 2. Team Members:

Our current team is comprised of electrical and computer engineering students with a background in Analog and RF coursework. Our team does not have any background in satellite design which has a steep learning curve, so research into amateur satellites and the CubeSat model has been an essential part of developing the project.

Erick Ortega
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(415)-606-5993

Marcel Tress
Electrical Engineering
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Eric Wells
Electrical Engineering
efwells@ucsc.edu
(831)-345-4786

Matt Moranda
Electrical Engineering
mdmorand@ucsc.edu
(209)-658-1866

Navneet Kaur
Electrical Engineering
nkaur13@ucsc.edu
(831)-295-1068

## 3. Division of Labor:

We have identified three main areas requiring design work, the linear transponder, the command receiver and the antenna system. The command receiver team consists of Matt Carberry, Eric Wells, and Matt Moranda. The linear transponder team consists of Marcel Tress and Eric Ortega. The antenna team only consists of Navneet Kaur. The transponder and command receiver teams have since merged due to their integrated nature. Technical and non-technical duties are outlined below:

| | | |
|---|---|---|
| Matt Carberry | Technical: RF Design | Non-technical: Team Librarian |
| Matt Moranda | Technical: RF Design | Non-technical: Team Manager |
| Eric Ortega | Technical: RF Design | Non-technical: Team Scribe |
| Eric Wells | Technical: RF Design | Non-technical: Treasurer |
| Marcel Tress | Technical: RF Design | Non-technical: Team Manager |
| Navneet Kaur | Technical: Antenna Design | Non-technical: Outreach Coordinator |

## 4. Code of Conduct

**Tardiness and absence** from meetings is generally not acceptable, but we all understand there are cases where tardiness or absence may occur. Tardiness to multiple meetings will require an explanation and prior notification and absence to a meeting must have a valid reason and requires notification to the group.

**Each team member is expected to dedicate 20 hours of work per week to this project**. In order to facilitate collaboration, a significant portion of this time should be spent working in the assigned project space.

**All documentation, diagrams and hardware design files must be kept in a version control system**. This is crucial for other people to join the project, the documentation must be accessible to outsiders.

**To monitor progress, a Gantt chart** will be maintained by the team to keep track of tasks and monitor progress. If a task timeline needs to be revised, it will be discussed during our bi-weekly meetings.

**Our team will hold required bi-weekly meetings.** Meeting 1 is to propose plans whereas meeting 2 is for reporting on progress and discussing the project with management. We will require respectful behavior. This means we must listen to all members, participate in all discussions, accept constructive criticism, accept majority decisions, treat all members with respect and voice opinions and ideas.

## 5. Conflict Resolution:

Conflicts will be addressed immediately and brought up in the next meeting.A majority decision by the team will determine how the conflict is settled and unresolved conflicts will be brought to the attention of an instructor.

## 6. Finances:

Before any purchase, the buyer must write a proposal indicating detailed part information and price. Authorization will be granted by the person funding the project. If additional funding is necessary, each team member is required to submit a proposal to their appropriate college for funding.

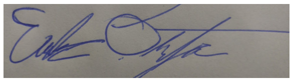
## 7. Conditions of Termination:

Failure to follow the code of conduct will place that individual in probation. A member in probation who fails to show improvement within two weeks will be directed to an instructor upon the agreement of all team members.

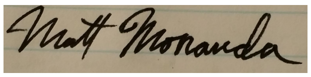
## 8. Amendments to this binding document

3/14/17 Significant revisions reflecting our current workflow and notes from Professor Petersen have been reflected in the new document.

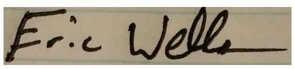
## 9. Agreement:



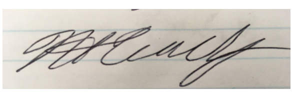
Name: Erick Ortega
Date: December 9, 2016; updated 3/14/17



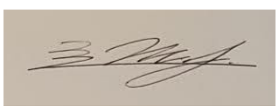
Name: Matt Moranda
Date: December 9, 2016; updated 3/14/17



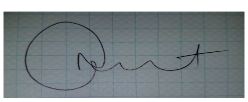
Name: Eric Wells
Date: December 9, 2016; updated 3/14/17



Name: Matt Carberry
Date: December 9, 2016; updated 3/14/17



Name: Marcel Tress
Date: December 9, 2016; updated 3/14/17



Name: Navneet Kaur
Date - December 10, 2016; updated 3/14/17

# A-2 Frequency Trade Study

The team analyzed three frequency selection cases for the linear transponder design, and through our analysis the 10m/15m HF satellite performs the best among our metrics for comparison.

<u>Case 1: V/A (2m/10m)</u>

| | | | |
|---|---|---|---|
| Up | 2 m | 144 MHz VHF | Band: 144-148 MHz |
| Down | 10 m | 28 MHz HF | Band: 28 – 29.7 MHz |

<u>Case 2: U/V (70cm/2m)</u>

| | | | |
|---|---|---|---|
| Up | 70 cm | 420 MHz UHF | Band: 420 – 450 MHz |
| Down | 2m | 144 MHz VHF | Band: 144 – 148 MHz |

<u>Case 3: (10m/15m)</u>

| | | | |
|---|---|---|---|
| Up | 10m | 28 MHz HF | Band: 28 – 29.7 MHz |
| Down | 15m | 21 MHz HF | Band: 21 – 21.45 MHz |

### Metrics of Comparison

There are three overall metrics by which we will evaluate the suitability of each case: accessibility, performance, and regulatory ease. Accessibility covers the ability of the average amateur radio operators to work the satellite, including equipment availability and operating difficulty. Performance encompasses the different performance metrics (SNR, etc) that would change, relative to the other case. Regulatory ease covers the difficulty of getting approval from the IARU and FCC to use those bands for our satellite.

### Accessibility

All of these frequency bands are generally approachable to people with amateur satellite capabilities. The HF band(10m/15m) surpasses our other cases in terms of doppler shift and pointing requirements on the ground station.

### Equipment Availability

When specifying their baseline groundstation, AMSAT uses the humorously named Yaesu FT-1634. This is actually a pair of Yaesu FT-817, which is a portable 5 Watt transceiver tunable from HF to 70cm.  Based on their research, we will also use this as a baseline rig for our assessment.

Often, these rigs are used with Arrow-style handheld satellite communication antennas. For this, we will use the Arrow II Satellite antenna as our baseline. This is a 3-element 2m Yagi on the same boom as a 7-element 70cm Yagi.3

For the 10 meter antenna, we will assume a portable dipole. Though other antennas that may suit our purpose more could be built, a dipole would be quite available. The 10m 15m option is unique in the way it can be operated with a simple HF rig.

As such, there is a minor inconvenience related to needing two antennas to operate, but overall, we will see the accessibility to both satellites as equal.

### Operating Difficulty

This section introduces the topic of doppler shift and explains how it contributes to the difficulty of operating a satellite.

### Doppler Shift[1]

For SSB/CW, the doppler shift impacts operations by requiring more tuning during a satellite pass. The doppler shift is more pronounced with higher frequencies and is less noticeable at lower frequencies. Hence, the 70 cm band will experience the greatest shift, ranging between +/- 9.76 kHz, because it is the highest frequency band in our study. In contrast, the 10 m band which is the lowest frequency band in our study will experience a shift between +/- 659 Hz. Therefore, we should try to avoid using a 70 cm band since it will have the greatest doppler shift unless other metrics are of more importance and/or we can overcome the shift using some auto/manual correction.

| | 15m | 10 m | 2 m | 70 cm |
|---|---|---|---|---|
| Doppler Shift | +/- 477 Hz | +/- 659 Hz | +/- 3.27 kHz | +/- 9.76 kHz |

**Table 3**: Doppler shift per pass, based on a 800 km circular orbit

When analyzing doppler shift, the difference in frequency between the uplink and downlink is an important parameter. In an inverting transponder, the doppler shifts of the two frequencies subtract while in the non-inverting transponder the doppler shifts add for the overall performance at the receiving station on ground. The HF band performs the best in terms of doppler shift.

### Ground Station Pointing Requirements

The ground station pointing requirements can be reduced on HF because the antenna does not need to have as high of a gain to communicate with the spacecraft due to a reduced path loss.

### Performance

This section looks into different aspects of performance such as SNR, Data rates, and Regulatory ease.

[1] http://www.qsl.net/vk3jed/doppler.html

## Signal-to-Noise Ratio

While this information has not been quantified, people with the IARU advisory panel mentioned concerns about man made noise on the 2m band. This would raise the overall noise temperature of our system.

### Maximum Data Rate

Based on the FCC Part 97 rules, the maximum symbol rate for the 10m, 2m, and 70cm bands are set as follows.

| | 15 m | 10 m | 2 m | 70 cm |
|---|---|---|---|---|
| Max Legal Symbol Rate | 300 bauds | 1200 bauds | 19.2 k bauds | 56 k bauds |
| Max Legal Bandwidth | N/A | N/A | 20kHz | 100kHz |

**Table 4**: The maximum symbol rate for different frequency bands

We looked into two forms of demodulation, namely BPSK and QPSK. For BPSK the bandwidth usage would be greater (2*$f_H$ ) and the demodulation would be limited by the bandwidth of the carrier signal. The end signal extracted would be the band limited version of the original signal. QPSK can be thought of as two independent BPSK signals and can therefore use half the bandwidth needed. Using QPSK will also allow for a higher data rate, 2 bits/ bit interval, compared to BPSK.

## Regulatory Ease

We've started the frequency coordination process to discuss regulatory ease by contacting our national amateur satellite organization AMSAT and the IARU satellite advisor.

The main distinction comes between amateur satellites and those that require an experimental license. The purpose of an amateur satellite is to provide communication resource for the general amateur community and/or self training and technical investigations relating to radio technique. As such, any additional payload that operates via our transponder must conform to either one of those purposes. In addition, amateur satellites must be operated by those acting "solely with a personal aim and without pecuniary interest."

If we were to get an experimental license, there would be additional regulatory hurdles. In addition, the IARU will no longer coordinate 2 meter frequencies for experimental licenses. Therefore, both the U/V and V/A options would be unavailable. We plan to avoid the need for an experimental license. After analyzing the regulation environment we determined all the frequencies studied have equal merit for regulatory ease. The purpose of the spacecraft mission drives regulation, not amateur frequency band selection.

## Preliminary Research

This section outlines areas of research that the team used as a starting point.

2 m Band

General

- Lots of machines are linked to 2 meters

Used as an Up-Link

- International Amateur Radio Union recommends avoiding the use of this band as an up-link, due to popular demand and interference from illegals.
- Data rate is limited to 19.6 kilobaud and a bandwidth of 20 kHz

Used as a Down-Link

- IARU is fine with using this band as a downlink
- 2m band carries a doppler shift around +/- 3 kHz
- Path loss of about 133 dB
- Most equipment operates at VHF/UHF

10 m Band

General

- Most heavily affected by sunspots and the sunspot cycle which can be erratic

Used as a Down-Link

- Path loss of approximately 119 dB
- Doppler shift of +/- 2.44
- Easily heard with a dipole antenna
- Lower path loss allows for antennas with less pointing requirements

70 cm Band

General

- The lowest frequency amateur UHF band
- Popular
- Limited to 56 kilobaud and a bandwidth of 100 kHz
- There are powerful radars on this band that may cause interference to amateur receivers.

Used as an Up-Link

- Will want to make sure to have equipment that can tune at frequency increments of 5 kHz to account for doppler shift.
- Doppler shift effect of +/- 9 kHz
- Path Loss of approximately 143 dB

15 m Band

- Sunspot cycle affects the Ionospheric absorption/ reflection in F layer.
- Doppler shift can vary between +/- 477 Hz
- Path loss of approximately 116 dB
- lower path loss allows for antennas with less pointing requirements

## Conclusion

Based off our parameters of merit, the HF spectrum is the best frequency for our design. Less path loss and less doppler shift outweigh the benefits of higher data rate capabilities at higher frequencies because we are focused on amateur communications. Currently, there are not as many options for HF users to communicate via satellites and by developing our transponder to HF frequencies we would allow more access to a different band.

# A-3 Requirements Specification

## Principal Requirements and Constraints for Spacecraft Design

# Mission

## Operations Concept

### Primary Objective

To enable reliable SSB and CW communications between Amateur Radio Operators via satellite relay.

### Secondary Objective

To develop spacecraft design and manufacture capabilities at University of California, Santa Cruz.

## Spacecraft life and reliability

### Mission Duration

Mission duration is one year of transponder operation.

### Success Criteria

There are two criteria for mission success:

> Successful transmission between two separate ground stations within the visible footprint using single-sideband transmission via the linear transponder
>
> Successful spacecraft response to command uplink

## Communication Architecture

As our Telemetry/Control communications and payload communications systems are integrated, we have two separate requirements.

> Our Telemetry/Control System requires a point-to-point communications architecture for communication to one ground station at a time.
>
> Our payload transponder acts as a relay and demands a broadcast architecture, relaying transmissions from the ground to multiple ground stations with unknown positions.

# Payload

## Physical Parameters

### Size & Shape

The payload should fit on a single PCB designed to be mechanically compatible with the CubeSat Kit PCB Specification.

### Weight

There is currently no weight specification. The CubeSat specification drives our payload weight and we are unsure of structure or battery weights. As such, until such time as we can determine these, we will assume our payload has no weight requirements within reason.

## Operations

### Duty Cycle

The payload is planned to operate continuously after deployment, in both sunlight and eclipse.

## Pointing

### Reference

The spacecraft should be aligned such that the boresight of the antennas is aligned with the nadir.

### Accuracy

There is no quantitative requirement for pointing accuracy.

### Stability

There is no quantitative requirement for stability accuracy.

## Slewing

There is no slewing requirement on the spacecraft beyond that of the initial slew to the pointing requirement.

## Environment

### Maximum/Minimum Temperatures

The payload drives no temperature requirements.

### Cleanliness

The payload drives no cleanliness requirements.

# Orbit

## Defining Parameters

Based on evaluation of existing CubeSat orbits, we have identified common orbits which will ideally predict secondary payload space for future missions. As such, our CubeSat may be designed for mission success within this range of orbits for maximum opportunity.

### Attitude

Based on 25-year deorbit requirements, maximum altitude of a 1U CubeSat without an active deorbit system is about 700 km. [1]

The majority of CubeSats not launched from the ISS have altitudes between 500 km and 700 km.

### Inclination

The majority of CubeSats not launched from ISS have inclinations between 95 and 100 degrees.

### Eccentricity

Analysis of the eccentricity of the orbits of existing CubeSats shows nearly all satellites in circular or near-circular orbits.

# Environment

## Temperature

In accordance with the PolySat electrical lead’s recommendation, all components of the CubeSat should work within the industrial temperature range of -40 to 85°C. This is a wider range that encompasses the range of the AMSAT Fox System Requirements.

## Radiation Dosage

There is no quantitative radiation tolerance requirement. However, specific parts are excluded due to their known susceptibility. In addition, parts should be derated in accordance with NASA derating guidelines. This information is derived from the AMSAT Fox project Radiation Mitigation presentation.

### Engineering Guidelines

- Prefer COTS parts that have been tested
    - Do not use parts that have tested poorly
- Prefer spaceflight heritage if possible
- Prefer discrete semiconductors to ICs
    - ICs from TI tend to test well
- Untested or sensitive CMOS parts must have latchup protection circuitry (FPF20xx)
- Passive components can generally be considered safe

### Banned Parts

- Any 555 timer
- Any part with an internal charge pump
- All low-dropout voltage regulators and high-side switches with N-channel or NPN pass transistors (LP2941-LP2953)
- BiCMOS linear components (LTC2052)
- Active temperature sensors (AD590)

### NASA Derating Guidelines

| PART TYPE | RECOMMENDED DERATING LEVEL |
|---|---|
| Capacitors | Max. of 60% of rated voltage |
| Resistors | Max. of 60% of rated power |
| Semiconductor Devices | Max. of 50% of rated power<br>Max. of 75% of rated voltage<br>Max. junction temperature of 110℃ |
| Microcircuits | Max. supply voltage of 80% of rated voltage<br>Max. of 75% of rated power<br>Max. junction temperature of 100° |
| Inductive Devices | Max. of 50% of rated voltage<br>Max. of 60% of rated temperature |
| Relays and Connectors | Max. of 50% of rated current |

**Figure 17**: NASA Derating Guidelines Summary

Source: Biddle, Alan, and Tony Monteiro. "Space Radiation Mitigation for Fox-1." N.p., 2012. Web. 15 Mar. 2017.

## Particles and Meteoroids

There is currently no requirement for particle or meteoroid survivability.

### Space Debris

There is currently no requirement for survivability related to impact with space debris.

# Launch

## Launch Strategy

We plan to use secondary payload space offered via educational launch initiatives such as NASA's ELaNa (Educational Launch of Nanosatellites) and ULA's CubeSat launch program.

This includes the integration of the satellite into a deployer, most commonly a P-POD type, as designed by Cal Poly, San Luis Obispo.

## Environment

### Vibration

Vibration testing may be needed in accordance with the requirements of the launch provider. [Note specific testing stages before launch]

### Shock

Shock testing may be needed in accordance with the requirements of the launch provider. [According to a PolySat representative, only Delta II launches currently have shock requirements for CubeSat payloads.]

## Interfaces

Based on the CubeSat standard, for the satellite to be integrated into their deployer, there are some required interfaces. The section numbers within the CubeSat specification are noted the requirements.

### RBF Pin

The CubeSat shall include an RBF pin. [3.3.7] (RBF - Remove Before Flight)
The RBF pin shall cut all power to the satellite once it is inserted into the satellite.[3.3.7.1]
The RBF pin shall be removed from the CubeSat after integration into the P-POD.[3.3.7.2]
The RBF pin shall protrude no more than 6.5 mm from the rails when it is fully inserted into the satellite. [3.3.7.3]

### Deployment Switch

The CubeSat shall have, at a minimum, one deployment switch on a rail standoff, per Figure 7. [3.3.2]

In the actuated state, the CubeSat deployment switch shall electrically disconnect the power system from the powered functions; this includes real time clocks (RTC). [3.3.3]

The deployment switch shall be in the actuated state at all times while integrated in the P-POD. [3.3.4]

In the actuated state, the CubeSat deployment switch will be at or below the level of the standoff. [3.3.4.1]

If the CubeSat deployment switch toggles from the actuated state and back, the transmission and deployable timers shall reset to t=0. [3.3.5]

The RBF pin and all CubeSat umbilical connectors shall be within the designated Access Port locations, green shaded areas shown in Appendix B. [3.3.6]

Note: All diagnostics and battery charging within the P-POD will be done while the deployment switch is depressed. [3.3.6.1]

# Ground-System Interface

## Degree of Autonomy

The linear transponder should operate throughout the mission. However, there is no requirement for autonomous operations by the satellite. All changes will be commanded from the ground station.

## Ground Stations

The primary ground station is the UCSC Amateur Radio Club satelite station.

# A-4 Deliverables Documents

Mission

For the Winter quarter deadline, we will have a Mission Requirements document defining our mission objectives and the metrics by which we achieve success in those objectives.

## Winter Goals

### Antenna

For the Winter quarter deadline, for the purpose of developing skill with the 4nec2 software, we will have a finished simulation of a dipole antenna. In addition, we will create candidate models of the CubeSat structure in order to model our antenna design preliminarily.

### Payload

The payload will consist of a linear transponder chain and a command receiver. For the Winter quarter deadline, we will have detailed block diagrams for our proposed design. In addition, we will have documentation justifying the design choices made for each aspect of the design.

## Spring Goals

### Antenna

For the final deadline, the deliverable from the antenna team will be simulations and an agreed upon final design, including the interface hardware necessary for integration to the payload.The final design includes a prototype antenna and the assembled and tested interface hardware.

### Payload

For the final deadline, the payload team should have a bench prototype of the payload/communications system as defined below and documentation describing its design, specifications and operations.

A bench prototype consists of the circuit design of the command receiver and transponder. It will process input at the specified command frequency and translate input signals between the specified transponder frequencies, however not necessarily fitting the form factor requirement. As an example, the bench prototype may consist of multiple boards connected with coax.

The prototype will receive a signal anywhere within the assigned transponder input bandwidth and translate it to a single output frequency within the assigned transponder output bandwidth. The performance will be documented with respect to transponder gain, receiver input sensitivity, noise factor, IP3, and out-of-band signal rejection.
The command receiver prototype will accept a command signal on its receiver input frequency and turn that information into a digital format.

# A-5 Power Budget Report

Introduction:
Even though actually building the Electrical Power Subsystem(EPS) is not within the scope of our mission, it is important to reference the EPS of other communications driven CubeSats and to create a useful power budget that we can design our communications hardware around.Note that the number one failure in CubeSat missions are consequences of a negative power budget. In specifying our power budget we realized that developing power budgets is an iterative process and we will have to make adjustments to the power budget as we make design decisions throughout development. At this early stage though there are a few things that we can specify.

In researching other similar 1U CubeSat power systems, we discovered that it is common to use a battery and solar panels to generate power for the CubeSat. By strapping solar cells to the walls of the CubeSat it is possible to use the solar cells to power the communications hardware within the satellite while the solar cells are in full sunlight and to use the battery to power the communications hardware while the CubeSat is experiencing umbra and penumbra eclipse.

The following is a report summarizing the findings of our research and ultimately how these findings led to an estimation of the power budget for our CubeSat.

Power Generation:
Firstly when drawing up a power budget it is important to know how much power the EPS actually provides.Typical Li-ion cells can provide an amount of 2-3wH depending on their charge (Friedel and McKibbon). Looking at a commercial solar cell panel for one side of a 1U CubeSat we see it provides 2.41 Watts max power (Thirion). Then we see that our CubeSat would have 5 of these panels as one side of the cube would be designated for antennas and communication ports. Looking at a MATLAB plot of the orientation of a CubeSat versus the sides of the CubeSat being exposed to sunlight in figure 18. This orientation is derived from the keplerian elements of past CubeSats. The reason these CubeSats elements are usable is because if we look at a histogram of past Low Earth Orbit (LEO) missions organized by their altitude and angle of inclination shown in figures 19 & 20, we see that statistically we have the highest probability of our satellite being flown in a near polar LE0. This mean that at worst the CubeSat would have only 1 panel receiving sunlight when it is not eclipsed. The maximum amount of panels receiving light would be 1.7 which means a max output in this scenario of 4.097 Watts.

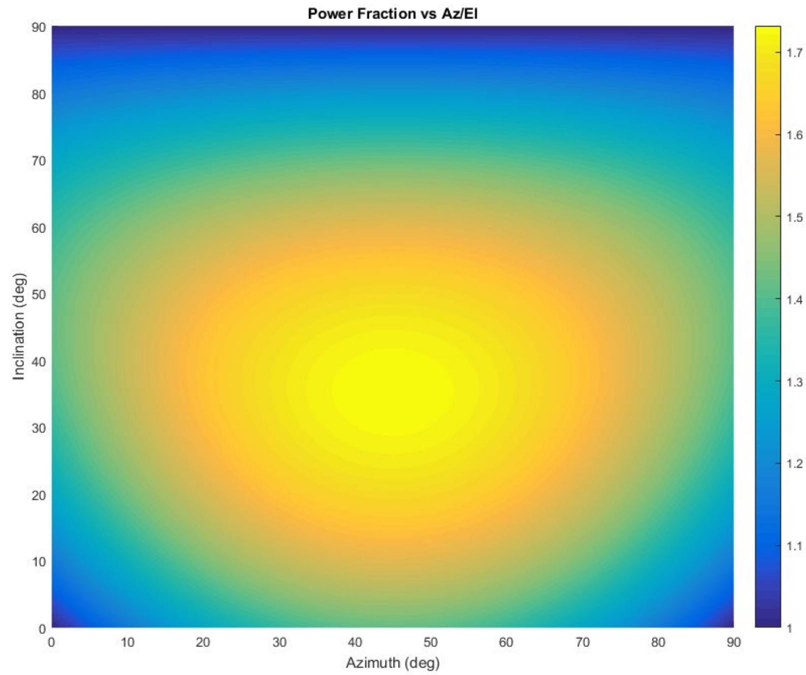



**Figure 18**: Number of Solar Panels Illuminated for Various Orientations

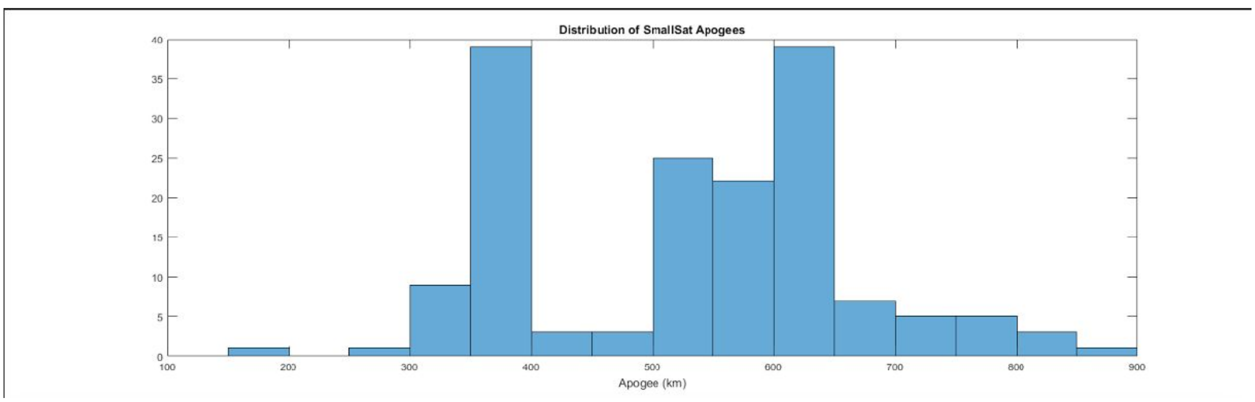



**Figure 19**: Apogee Distribution of Existing Small Satellites

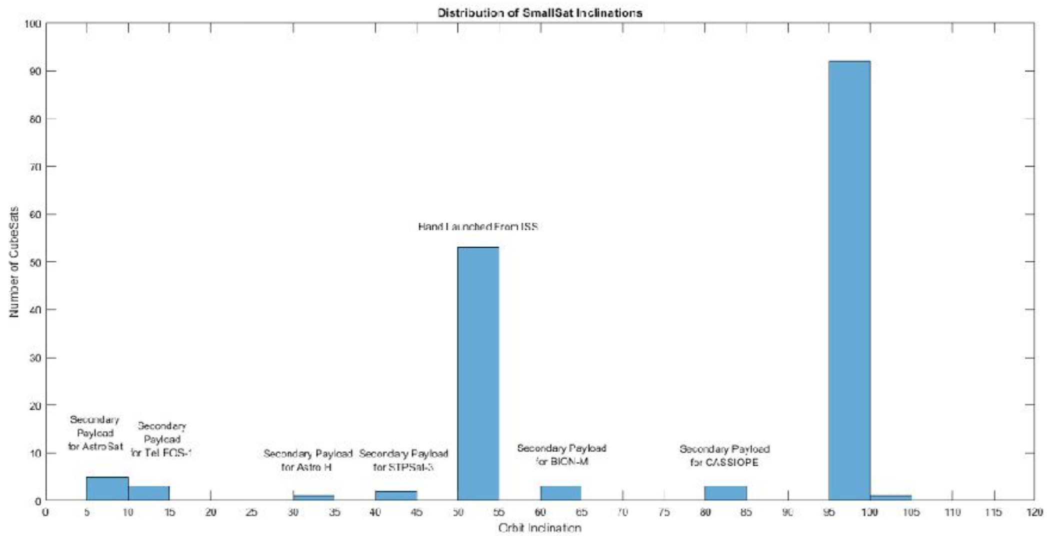



**Figure 20**: Inclination Distribution of Existing Small Satellites

Power Consumption:
In general because of the cold conditions of space, the Electronic Power System(EPS) might have to provide power for a heater to keep the batteries from getting too cold (Friedel and McKibbon). The power consumption of this heater is around 500mW. Also, when not in eclipse, the EPS must always provide power to the actual batteries from the solar cells to keep them close to fully charged (Ibid). In sunlight, 21 mW are always provided by solar cells via the EPS to keep the batteries charged and 500 mW are provided to the the heaters when they are needed to keep the batteries warm (Ibid). Since we are leaning towards a tumbling satellite design we no longer have to allocate power for an attitude control system. Looking at other linear transceiver designs we see that in general the maximum amount of power this circuit consumes is 3W ("DHV-CS-10 CubeSat Solar Panels"). If we decide to have an entire transceiver for the communications system than we would have a max power consumption of 2W-4W for this system. These approximations are based on the specifications of other transceiver designs made for 2m/70cm operation (Ceylan et al.).

Here we will run through a drawing up a power budget using typical and worst case values.To determine the worst case we see that the EPS is significantly affected based on whether it is using batteries or solar panels as it power source. This depends on whether the satellite is eclipsed or not. To determine when the satellite is eclipsed we need to know the likely orbit of the satellite. Referring to figures 2-3 we see the highest probability is that the CubeSat will have a near polar orbit. Using the open source NASA General Mission Analysis Tool and some general Keplerian elements for CubeSats in LEO and near polar orbit provided in a student's thesis (Hanley et al.) we were able to simulate an approximation of a probable orbit for our satellite and generate an eclipse report over a 24 hour period of orbit. The satellite orbit simulation images are given in figure 21 and the eclipse report is given in table 5.

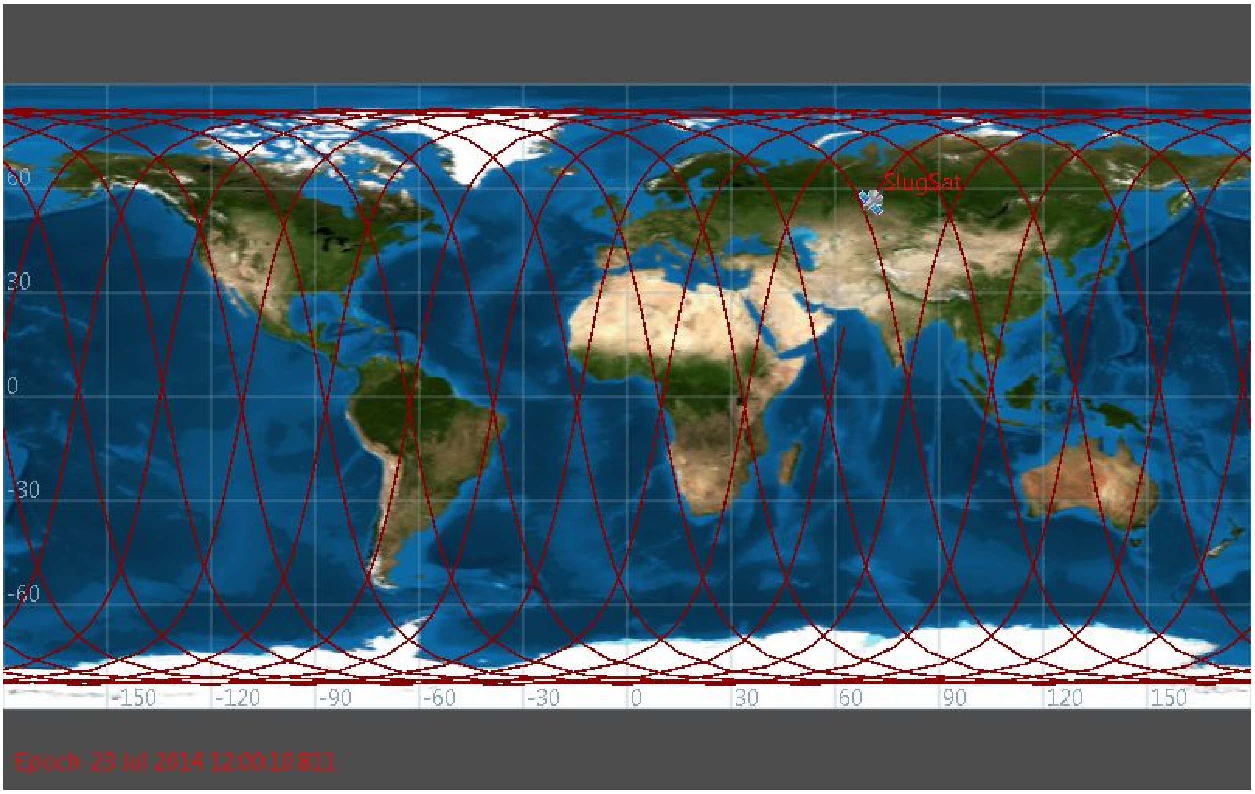



**Figure 21**: Ground Track of a Satellite in Circular Polar Orbit

**Table 5**: Eclipse Report for a CubeSat Orbit

| Start Time (UTC) | Stop Time (UTC) | Duration (s) | Occ Body | Type | Event Number | Total Duration (s) |
|---|---|---|---|---|---|---|
| 22 Jul 2014 12:35:17.657 | 22 Jul 2014 12:35:38.559 | 20.901143609 | Earth | Penumbra | 1 | 1375.6428125 |
| 22 Jul 2014 12:35:38.559 | 22 Jul 2014 12:57:52.733 | 1334.1743157 | Earth | Umbra | 1 | 1375.6428125 |
| 22 Jul 2014 12:57:52.733 | 22 Jul 2014 12:58:13.300 | 20.567353175 | Earth | Penumbra | 1 | 1375.6428125 |
| 22 Jul 2014 14:11:57.636 | 22 Jul 2014 14:12:18.534 | 20.898228278 | Earth | Penumbra | 2 | 1375.7608638 |
| 22 Jul 2014 14:12:18.534 | 22 Jul 2014 14:34:32.832 | 1334.2975043 | Earth | Umbra | 2 | 1375.7608638 |
| 22 Jul 2014 14:34:32.832 | 22 Jul 2014 14:34:53.397 | 20.565131237 | Earth | Penumbra | 2 | 1375.7608638 |
| 22 Jul 2014 15:48:37.579 | 22 Jul 2014 15:48:58.475 | 20.896452677 | Earth | Penumbra | 3 | 1375.8617556 |
| 22 Jul 2014 15:48:58.475 | 22 Jul 2014 16:11:12.877 | 1334.4013089 | Earth | Umbra | 3 | 1375.8617556 |
| 22 Jul 2014 16:11:12.877 | 22 Jul 2014 16:11:33.441 | 20.563994022 | Earth | Penumbra | 3 | 1375.8617556 |
| 22 Jul 2014 17:25:17.468 | 22 Jul 2014 17:25:38.363 | 20.894533116 | Earth | Penumbra | 4 | 1375.9463146 |
| 22 Jul 2014 17:25:38.363 | 22 Jul 2014 17:47:52.852 | 1334.4887176 | Earth | Umbra | 4 | 1375.9463146 |
| 22 Jul 2014 17:47:52.852 | 22 Jul 2014 17:48:13.415 | 20.563063945 | Earth | Penumbra | 4 | 1375.9463146 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 22 Jul 2014 19:01:57.419 | 22 Jul 2014 19:02:18.316 | 20.896815718 | Earth | Penumbra | 5 | 1375.8969288 |
| 22 Jul 2014 19:02:18.316 | 22 Jul 2014 19:24:32.750 | 1334.4343202 | Earth | Umbra | 5 | 1375.8969288 |
| 22 Jul 2014 19:24:32.750 | 22 Jul 2014 19:24:53.316 | 20.565792883 | Earth | Penumbra | 5 | 1375.8969288 |
| 22 Jul 2014 20:38:37.378 | 22 Jul 2014 20:38:58.274 | 20.895981824 | Earth | Penumbra | 6 | 1375.9517166 |
| 22 Jul 2014 20:38:58.274 | 22 Jul 2014 21:01:12.766 | 1334.4911014 | Earth | Umbra | 6 | 1375.9517166 |
| 22 Jul 2014 21:01:12.766 | 22 Jul 2014 21:01:33.330 | 20.564633352 | Earth | Penumbra | 6 | 1375.9517166 |
| 22 Jul 2014 22:15:17.380 | 22 Jul 2014 22:15:38.272 | 20.892462682 | Earth | Penumbra | 7 | 1376.1211581 |
| 22 Jul 2014 22:15:38.272 | 22 Jul 2014 22:37:52.941 | 1334.6683444 | Earth | Umbra | 7 | 1376.1211581 |
| 22 Jul 2014 22:37:52.941 | 22 Jul 2014 22:38:13.501 | 20.560351037 | Earth | Penumbra | 7 | 1376.1211581 |
| 22 Jul 2014 23:51:57.415 | 22 Jul 2014 23:52:18.304 | 20.889031235 | Earth | Penumbra | 8 | 1376.2809107 |
| 22 Jul 2014 23:52:18.304 | 23 Jul 2014 00:14:33.138 | 1334.8337541 | Earth | Umbra | 8 | 1376.2809107 |
| 23 Jul 2014 00:14:33.138 | 23 Jul 2014 00:14:53.696 | 20.558125328 | Earth | Penumbra | 8 | 1376.2809107 |
| 23 Jul 2014 01:28:37.548 | 23 Jul 2014 01:28:58.437 | 20.888811839 | Earth | Penumbra | 9 | 1376.2982876 |
| 23 Jul 2014 01:28:58.437 | 23 Jul 2014 01:51:13.288 | 1334.8514297 | Earth | Umbra | 9 | 1376.2982876 |
| 23 Jul 2014 01:51:13.288 | 23 Jul 2014 01:51:33.846 | 20.558046119 | Earth | Penumbra | 9 | 1376.2982876 |
| 23 Jul 2014 03:05:17.572 | 23 Jul 2014 03:05:38.461 | 20.889562438 | Earth | Penumbra | 10 | 1376.2850899 |
| 23 Jul 2014 03:05:38.461 | 23 Jul 2014 03:27:53.297 | 1334.8359424 | Earth | Umbra | 10 | 1376.2850899 |
| 23 Jul 2014 03:27:53.297 | 23 Jul 2014 03:28:13.857 | 20.559585036 | Earth | Penumbra | 10 | 1376.2850899 |
| 23 Jul 2014 04:41:57.538 | 23 Jul 2014 04:42:18.428 | 20.890578954 | Earth | Penumbra | 11 | 1376.2663171 |
| 23 Jul 2014 04:42:18.428 | 23 Jul 2014 05:04:33.243 | 1334.8149800 | Earth | Umbra | 11 | 1376.2663171 |
| 23 Jul 2014 05:04:33.243 | 23 Jul 2014 05:04:53.804 | 20.560758084 | Earth | Penumbra | 11 | 1376.2663171 |
| 23 Jul 2014 06:18:37.463 | 23 Jul 2014 06:18:58.353 | 20.890501002 | Earth | Penumbra | 12 | 1376.2914885 |
| 23 Jul 2014 06:18:58.353 | 23 Jul 2014 06:41:13.194 | 1334.8404111 | Earth | Umbra | 12 | 1376.2914885 |
| 23 Jul 2014 06:41:13.194 | 23 Jul 2014 06:41:33.754 | 20.560576406 | Earth | Penumbra | 12 | 1376.2914885 |
| 23 Jul 2014 07:55:17.293 | 23 Jul 2014 07:55:38.180 | 20.887535694 | Earth | Penumbra | 13 | 1376.4450176 |
| 23 Jul 2014 07:55:38.180 | 23 Jul 2014 08:17:53.179 | 1334.9984774 | Earth | Umbra | 13 | 1376.4450176 |
| 23 Jul 2014 08:17:53.179 | 23 Jul 2014 08:18:13.738 | 20.559004485 | Earth | Penumbra | 13 | 1376.4450176 |
| 23 Jul 2014 09:31:57.283 | 23 Jul 2014 09:32:18.166 | 20.883828902 | Earth | Penumbra | 14 | 1376.5300776 |
| 23 Jul 2014 09:32:18.166 | 23 Jul 2014 09:54:33.257 | 1335.0909375 | Earth | Umbra | 14 | 1376.5300776 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 23 Jul 2014 09:54:33.257 | 23 Jul 2014 09:54:53.813 | 20.555311209 | Earth | Penumbra | 14 | 1376.5300776 |
| 23 Jul 2014 11:08:37.421 | 23 Jul 2014 11:08:58.302 | 20.880826819 | Earth | Penumbra | 15 | 1376.6237753 |
| 23 Jul 2014 11:08:58.302 | 23 Jul 2014 11:31:13.493 | 1335.1909282 | Earth | Umbra | 15 | 1376.6237753 |
| 23 Jul 2014 11:31:13.493 | 23 Jul 2014 11:31:34.045 | 20.552020264 | Earth | Penumbra | 15 | 1376.6237753 |

Number of individual events : 45
Number of total events : 15
Maximum duration (s) : 1376.6237753
Maximum duration at the 15th eclipse.

Looking at Table 5 we see that the average eclipse time per orbit is 22.9 minutes. This means about 24% of the orbits are eclipsed. This means 24% of each orbit we have a worst case scenario where the batteries are supplying all of the power while the heater is on because the temperature drops in the absence of sunlight. Here I will run through some mock power budgets in eclipse and outside of eclipse.

**Table 6**: Power Budget With Eclipse:

| Subsystem | Max Power | Min Power | Typical |
|---|---|---|---|
| Solar Panels | 0 | 0 | 0 |
| 2 Batteries | + 6W | + 4W | + 5.6W |
| Battery Heater | 0W | - 500mW | - 500mW |
| Linear Transponder | - 3W | - 1W | - 2.8 W |

| | |
|---|---|
| Worst Case | + .5W |

| | |
|---|---|
| Typical | + 2.3W |

**Table 7**: Power Budget Without Eclipse:

| Subsystem | Max Power | Min Power | Typical |
|---|---|---|---|
| Solar Panels | + 4.097W | + 2.04W | + 3W |
| 2 Batteries | + 6W | + 4W | + 0W |
| Battery Heater | 0W | - 500mW | - 0W |
| ESP | 0W | - 5mW | - 5mW |

| | | | |
|---|---|---|---|
| Linear Transponder | - 3W | - 1W | - 2.8 W |

| | |
|---|---|
| Worst Case | - 1.46W |
| Typical | + 195 mW |

Conclusion:
This mock satellite could always operate with a positive power budget if it draws on its batteries when needed, which is not ideal. Ideally the batteries are only given charge during the periods of sunlight and used during eclipse.

# A-6 Gantt Chart Critical Path

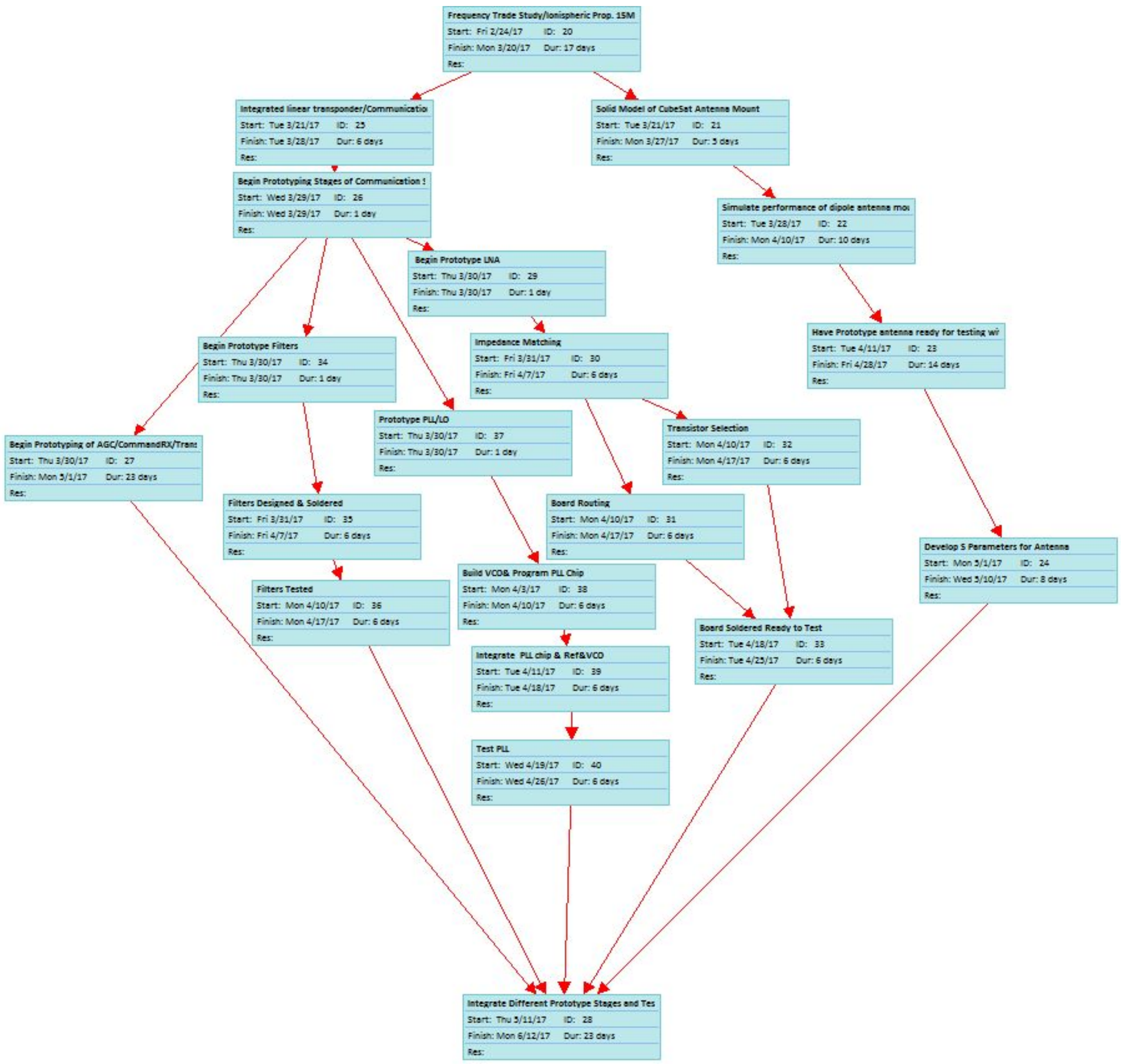



**Figure 22**: Gantt Chart Critical Path

# A-7 Antenna Research and Simulations

Antenna Parameters and Fundamentals- Research was conducted on the fundamental parameters of antennas in order to familiarize the team with basic antenna theory.

**Directivity/Gain [W/W]-**
The ability of an antenna to focus energy in a particular direction when transmitting or the ability of an antenna to receive energy better from a particular direction. Directivity can be mathematically expressed in terms of gain.

$$Gain \square\ 10 \log db_i$$

where $db_i$ is the gain with respect to an isotropic antenna, a physically unrealizable antenna that radiates equally in all directions. As such, an isotropic antenna is only used as a reference. For example, the gain of a dipole antenna is 2.14 $db_i$

**Polarization [h,v, circ.]-**
The orientation of the electric field vector with respect to the earth's surface.

- Linear Polarization

Linearly polarized antennas broadcast radio waves on a singular plane, either vertical or horizontal.
h-

- Circular Polarization

E field of a Circularly Polarized antenna rotates $360^0$ every RF cycle. Since the antennas broadcasts a signal in multiple planes, it's read range is about half as much as a linearly polarized antenna.

**Aperture [$m^2$]-**
An area in space  over which an antenna extracts energy from a passing radio wave is called the antenna aperture. In other words, an aperture could be defined as the area perpendicular to the direction of an incoming radio wave which would intercept the same amount of power from the wave produced by an antenna transmitting it. The larger an Antenna's aperture, the more power it can collect from a given field.

We can represent an effective aperture of an antenna for realistic antennas like a dipole but it isn't possible to do for an isotropic antenna.

**Bandwidth-**
The range of frequencies over which an antenna can operate correctly.

**Reciprocity** -
Antennas are linearly reciprocal devices which means that the parameters mentioned above apply equally for transmitting and receiving signals.

**Definition of a radiation pattern-**
A graph showing the antenna's gain in any direction around the antenna. This graph is called an antenna's radiation pattern. The antenna receives and transmits with the same pattern. Azimuthal and Elevation radiation patterns are two radiation patterns that will be explored in this report.

**Azimuthal Radiation**- Shows the antenna's gain in the horizontal direction around the antenna. As if looking down on the antenna from above, azimuthal radiation pattern shows how well the antenna receives and transmits in all horizontal directions. The distance from the center of the graph to the solid line (blue in this case) is the strength of the signal that the antenna receives and transmits.

**Elevation Radiation**- This radiation pattern looks at the antenna from the side to see how well it transmits and receives at different angles above horizontal plane. The radiation pattern can change depending on the frequency (change in frequency leads to change in wavelength).

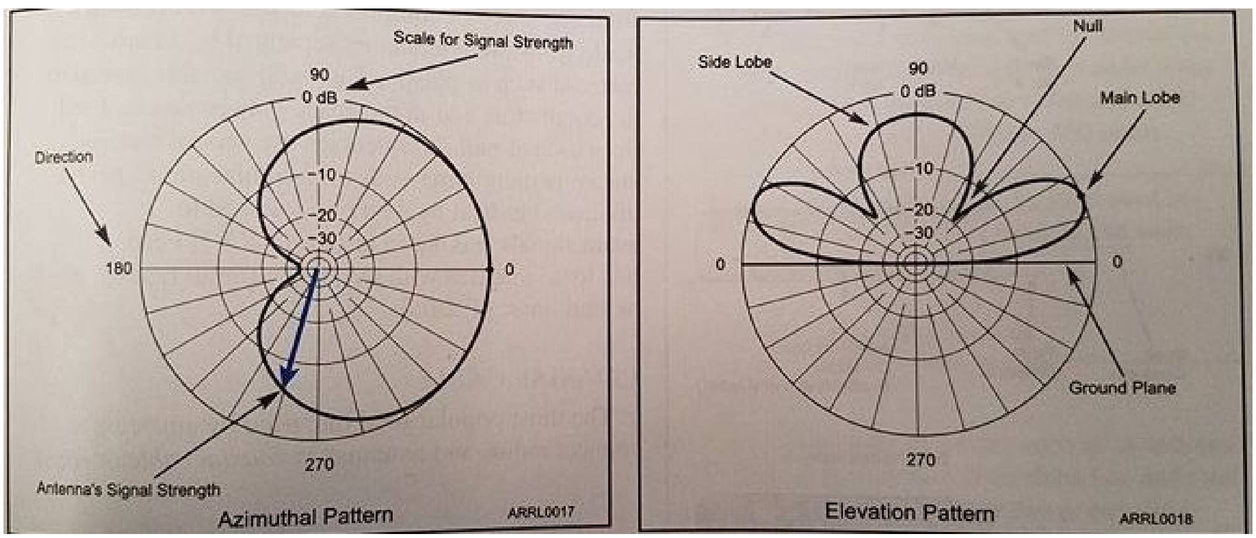



**Figure 23**- Azimuthal and Elevation Patterns
Source: Silver, H. Ward, and American Radio Relay League. *The ARRL Antenna Book for Radio Communications*. Newington, CT: American Radio Relay League, 2013. Print.

**Feedline -** used to connect a radio to antenna in order to deliver radio signals to and from antennas. Feed lines are constructed from two conductors separated by an insulating material such as plastic. The most common feedline used by amateurs is a coaxial cable or coax (characteristic impedance, of 50 ohms). Characteristic impedance is not the same as impedance of a conductor. Instead characteristic impedance is the ratio of amplitudes of voltage and current of a single wave propagation along the line.

**Feed Point**- The connection of antenna and feed line is called feed-point.

**Feed Point Impedance**- The ratio of radio frequency voltage to current at an antenna's feed point.

**What feed point impedance depends on** - An antenna's feed point impedance at a specific frequency depends on how its physical dimensions compare to the wavelength at that frequency. Feed point impedance varies with frequency.

**Dipole Antenna Radiation Patterns-**
A dipole is a simple type of antennas built with "two electrical parts". Dipoles are made from straight conductors of wires with the feed- point usually in the middle. Dipoles radiate the strongest broadside (with the side turned to a particular thing) and weakest off the ends. Figures 24 & 25 show radiation patterns generated from 4nec2 simulation tool for a simple dipole antenna.

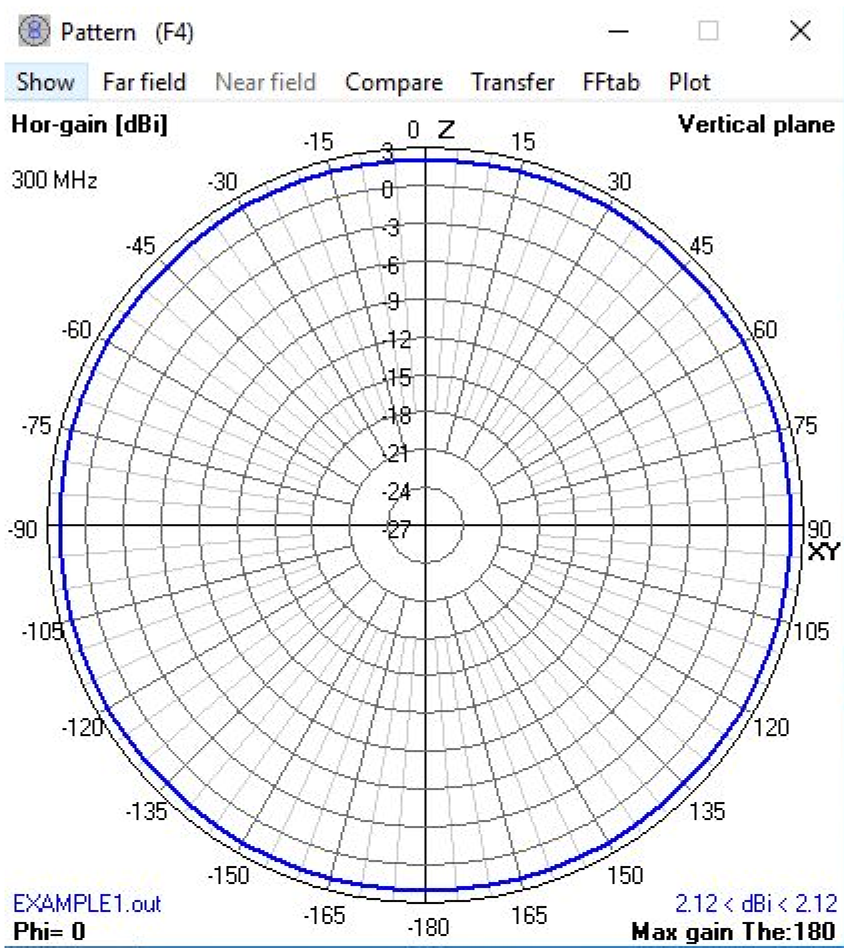



**Figure 24** - Elevation Patterns of Dipole
Source: 4nec2 Simulation

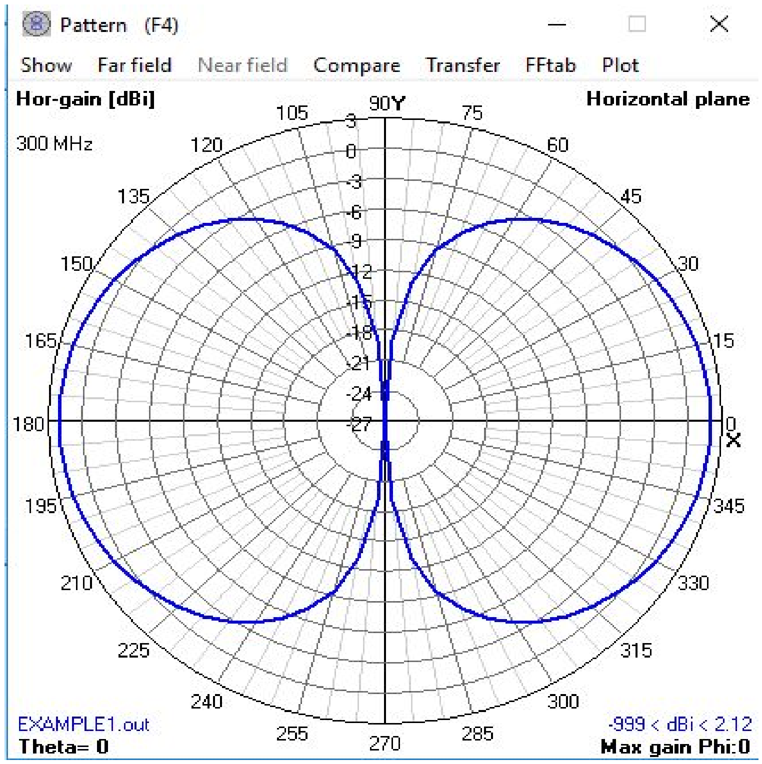



**Figure 25**- Azimuthal Radiation Pattern of a Dipole in 2D
Source: 4nec2 Simulation

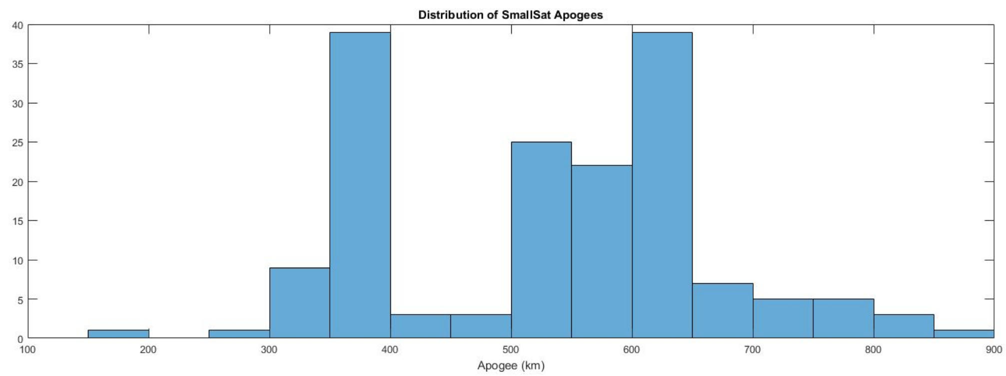
# A-8 Orbit Analysis

## Defining Parameters

Based on evaluation of existing CubeSat orbits, we have identified common orbits and have therefore the potential secondary payload space for future missions

### Attitude

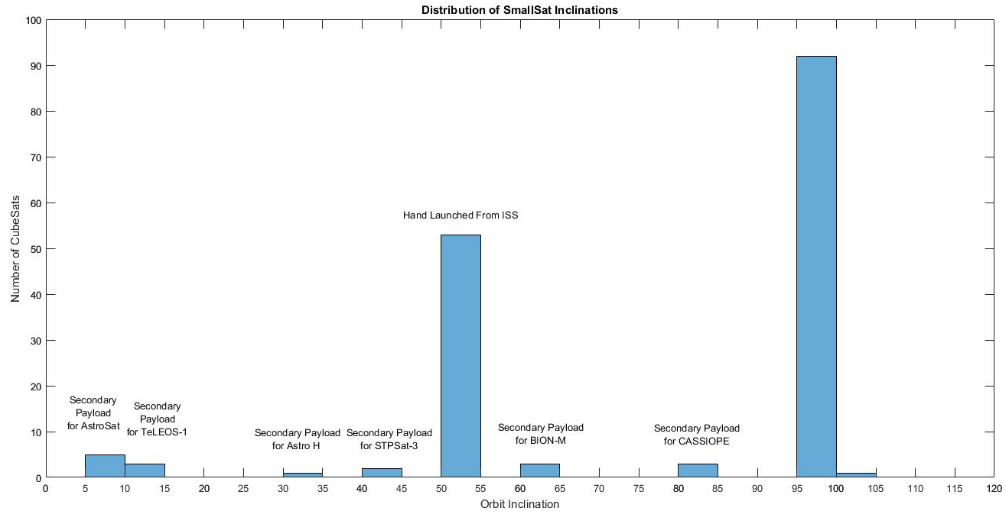
Most CubeSats exist within two bands of altitudes, shown here as a distribution of the




number of CubeSats in each bin of apogee height. The first band is slightly less than 400 km, this describes all CubeSats launched from the International Space Station, which has an altitude of approximately 401 km. The second band is from 500 km to 650 km, which encompasses a majority of the non-ISS launched CubeSats.
In addition, there is another constraint on altitude. Based on 25 year deorbit requirements, the maximum altitude of a 1U CubeSat without an active deorbit system is about 700 km.

### Inclination

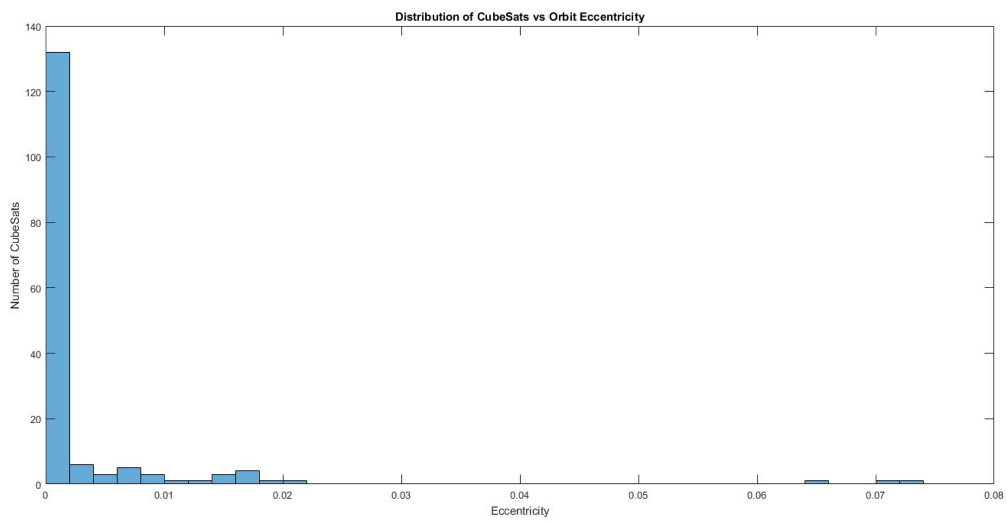
Once again, by looking at existing CubeSat launches, we find the common inclinations separated into two bands.




The first between 50 and 55 degrees describes all satellites launched from the ISS. The second between 95 and 100 degrees, describes the vast majority of the other satellites.

## Eccentricity

Analysis of the eccentricity of the orbits of existing CubeSats shows nearly all satellites in circular or near-circular orbits.



# A-9 Link Budget Spreadsheet

| | Symbol | Units | Source | Command (Uplink) | Telemetry and Data(Downlink) | Additional Notes: | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | f | MHz | Input parameter | 29.00 | 21 | | | |
| Transmitter Power | P | Watts | Input parameter | 5.00 | 0.4 | | | |
| Transmitter Power | P | dBW | 10 log(P) | 6.99 | -3.98 | | | |
| Transmitter Line Loss | L_l | dBW | Input parameter | 0.00 | 0 | | | |
| Transmit Antenna Beamwidth | Theta_t | deg | Input parameter | 180.00 | 78 | Based off Dipole, will need to change with Navneet's input | | |
| Peak Transmit Antenna Gain | G_pt | dBi | Input parameter | 3.50 | 0 | Should be about 2.15dBi for a dipole? | | Variables dependent on design |
| Transmit Antenna Pointing Offset | e_t | deg | Input parameter | | 0 | | | Verified Ground Station Information |
| Transmit Antenna Pointing Loss | L_pt | dB | Eq. (13-21) | 0.00 | 0.00 | | | better than expected |
| Transmit Antenna Gain (net) | G_t | dBi | G_pt + L_pt | 3.50 | 0.00 | | | worse than expected |
| Eqivalent Isotropic Radiated Power | EIRP | dBW | P+L_l+G_t | 10.49 | -3.98 | | | |
| | | | | | | | | |
| Propagation Path Length | S | km | Input parameter | 1760.00 | 1760.00 | | | |
| Space Loss | L_s | dB | Eq. (13-23a) | -126.61 | -123.80 | | | |
| Propagation & Polarization Loss | L_a | dB | Figure 13-10 | -1.50 | -1.5 | | | |
| | | | | | | | | |
| Peak Receiver Antenna Gain | G_rp | dBi | | 0.00 | 12 | | | |
| Receive Antenna Beamwidth | theta_r | deg | | 78.00 | 35.5 | | | |
| Receive Antenna Pointing Error | e_r | deg | Input parameter | 80.00 | 0 | | | |
| Receive Antenna Pointing Loss | L_rp | dB | Eq. (13-21) | -12.62 | 0 | | | |
| Receive Antenna Gain | G_r | dBi | G_rp + L_pr | -12.62 | 12.00 | | | |
| | | | | | | | | |
| System Noise Temperature | T_s | K | Table 13-10 | 1295.00 | 375 | | | |
| Data Rate | R | bps | Input parameter | 1200.00 | 300.00 | Significantly effects margin, needs to be more accurate. | | |
| E_b/N_0 | E_b/N_0 | dB | Eq. (13-13) | 36.44 | 60.80 | | | |
| Carrier-to-Noise Density Ratio | C/N_0 | dB-Hz | Eq. (13-15a) | 67.24 | 85.58 | | | |
| Bit Error Rate | BER | - | Input parameter | 1.00E-07 | 1.00E-07 | | | |
| Required E_b/N_0 | Req. E_b/N_0 | dB | Fig 13-9 | 11.20 | 11.20 | | | |
| Implementation Loss | - | dB | Estimate | -2.00 | -2.00 | | | |
| Margin | - | dB | 1 - 2 + 3 | 23.24 | 47.60 | | | |
| | | | | | | | | |
| Power after receive antenna: | -91.12 | dBm | | | | | | |

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