# Complete Documentation for the Eagle Space Flight Team Radio System

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September 8, 2018

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**Abstract**

This document will explain the methodology behind the Eagle Space Flight Team (ESFT) radio system, and will explain the techniques behind the system developed. The extreme circumstances that the ESFT rocket will put the communication system in requires that the system be sufficiently advanced and capable. New technologies such as software defined radios (SDR), in combination with a custom digital mode allow for the system to properly adapt to this challenging situation. Explaining why each technique, and piece of equipment, was chosen along with the benefits associated with this equipment will provide the reader with a deeper understanding of the system developed.

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# 1 Introduction

Data communication between the ground station and the vehicle during flight enables the team to have a telemetry system that will assist with several aspects of flight such as safety, mission success, and data backups in the event of a crash.

Flight success is enhanced by live visualization of telemetry data. The flight team on the ground will be able to know what is happening with the vehicle, therefore decisions can be made to send commands to the vehicle. These decisions can be to deploy the parachute, give priority to specific sensors, or abort the mission altogether.

Safety is enhanced through real-time visualization of flight data by enabling flight operators to make the decision whether or not to abort the mission based off information from the rocket. Through the monitoring of the rocket's trajectory, the team can prevent the vehicle from colliding with anything.

Streaming the sensor information to the ground during the flight means that any information gather will be stored both locally on the rocket and on the ground. This ensures that in the event of a crash the data will still be retrievable.

# 2 Antenna Design Elements

## 2.1 Antenna Length

Making the antenna the correct length allows for the most efficient transformation of the current in the circuit to electromagnetic waves. Finding this length allows for the antenna to be the same length as the resonant frequency, and transmitting or receiving at this resonant frequency makes for the most efficient use of the available energy. Based off of the desired frequency the antenna length can be calculated as:

$$Length\ in\ Feet = \frac{468}{Frequency\ in\ MHz} \tag{1}$$

Equation 1 is an empirical formula derived in 1929 and published in the 1929 edition of the ARRL handbook based on experiences with antennas for the 40 and 80-meter bands (ARRL, 2018).

## 2.2 Antenna Design

The chosen antenna is a one-half wavelength monopole antenna with an SMA connector.

A monopole antenna is a kind of antenna which consists of a single conductive element that radiates energy perpendicular to the conductive element.

SubMiniature version A (SMA) is a 50 Ω impedance coax connector designed for use from 0 Hz to 18 GHz chosen for use with the radio system due to its standard impedance and functionality at higher frequencies.

An antenna length closer to the full wavelength of the desired frequency will offer more gain compared to a shorter antenna, but an antenna length closer to a point source will offer a cleaner signal. Therefore a compromise between the two was a one-half wavelength antenna. Figure 2.1 shows the chosen antenna.

Figure 2.1: The antenna to be used on the rocket

## 2.3 Antenna Polarization

There are many possibilities for how to polarize the antenna. The most common is is vertical polarization because of its ability to follow the ground over obstacles like hills and the second is horizontal polarization which has been used primarily in television broadcast systems.

There is a third type of polarization, circular polarization, and this is the method of polarization necessary for communication with objects beyond the atmosphere. This design is needed because of a phenomenon known as Faraday rotation, and has been a driving factor in space communication designs since the 1950's.

A circularly polarized antenna is needed to correct for Faraday rotation which causes signals being sent though the Earth's atmosphere to constantly rotate phase. This means a signal sent from the rocket may be received out of phase, making it completely impossible for the base station to pick up.

Faraday rotation is impossible to predict, and at shorter wavelength frequencies can last for hours. Signals around 144 MHz normally return to normal within a few minutes, signals towards 1200 MHz can take hours to revert to their original polarization. This means that in order for a frequency in the GHz range to be achieved, the antenna should be circularly polarized (ARRL, 2018).

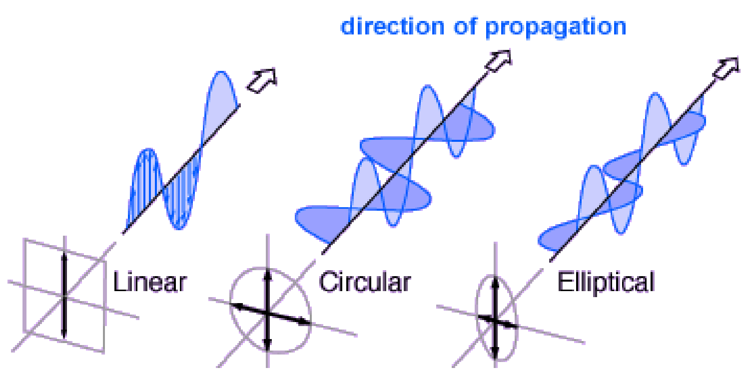


Figure 2.2: Example of different polarization types

## 2.4 Radiation Angle and Pattern

The radiation angle of the base station antenna and on-board antenna will be crucial to proper reception. Since the rocket will be both constantly spinning and moving, an omnidirectional antenna will be best suited to the situation.

On the ground a more directional antenna will be needed to obtain proper reception because of the energy lost due to an increasing distance the radio signal has to propagate. To represent the received signal strength the Friis transmission equation, equation 2, is used. From this equation it can be seen that significant amounts of gain in the receiving and transmitted antennas can greatly reduce the amount of signal loss.

$$\frac{P_r}{P_t} = G_t G_r (\frac{\lambda}{4\pi R})^2 \quad (2)$$

In this equation $G_t$ and $G_r$ is the gain of the receiving and transmitting antennas with respect to an isotropic radiator, $\lambda$ and R are in any unit of distance, and $P_r$ and $P_t$ is the received and transmitted power in dBm or dBW.

The antenna at the base station needs to be directional enough so that the gain allows for proper reception, but not too directional that signal is lost when the antenna becomes slightly misaligned. A directional circularly polarized helical antenna will be suitable for use at the base station.

Figure 2.3 is an example of an omnidirectional antenna. The radiation pattern consists of two nulls at the top and bottom of the antenna and stronger energy radiation perpendicular to the conductive element.

Figure 2.4 is an example of a directional antenna. The radiation pattern consists of a main lobe, several side lobes, and a back lobe. The amount of gain in a certain direction is defined as the ratio of the main lobe to the back lobe. This difference in gain allows for a more concentrated signal to be both received and sent from this antenna.

An important note is that both omnidirectional antennas and directional antennas radiate equivalent amounts of energy, the major difference is that directional antennas radiate energy less evenly allowing for increased gain in a certain direction.

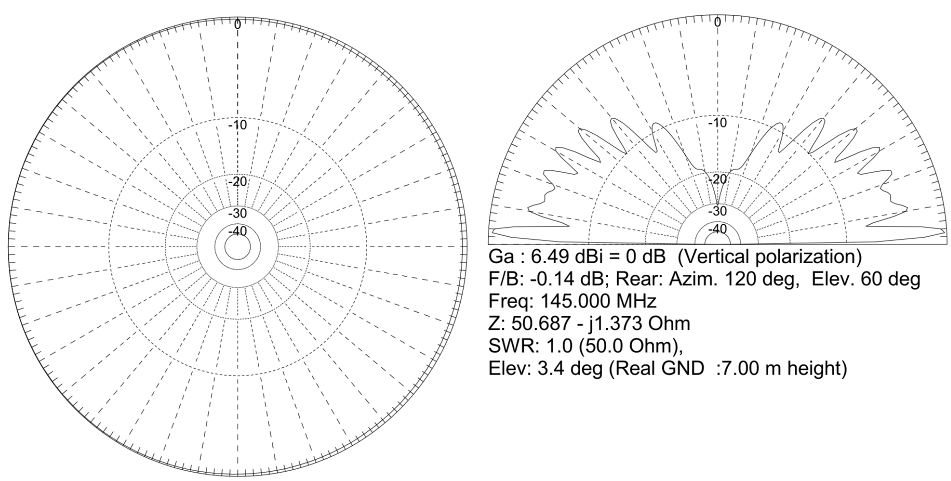


Figure 2.3: Radiation pattern for an omnidirectional antenna

These antenna patterns were modeled using MMANA-GAL, a software for HAM radio use. Some of the equations the program uses are included for clarity and to provide a more in depth understanding of the electromagnetic properties that go into radiation pattern modeling.

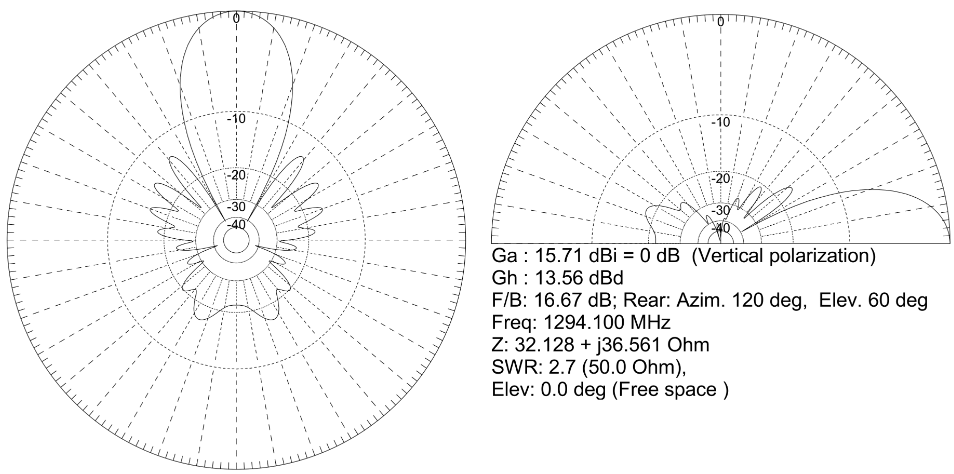


Figure 2.4: Radiation pattern for a directional antenna

Equation 3 shows the radiation intensity for an antenna given the far field components of the electrical and magnetic field vectors. The far field component of an antenna is the distance away from the antenna where the radiation pattern becomes independent of distance. As the energy is radiated out from the antenna, the near field can look very chaotic, but once this energy has settled into a regular pattern the near field becomes the far field.

$$U(\theta, \phi) = \frac{1}{2}(E_{ff}(\theta, \phi) \times H_{ff}(\theta, \phi)) \tag{3}$$

Where $E_{ff}$ is the far field component of the electrical field and $H_{ff}$ is the far field component of the magnetic field.

The amount of power radiated from the antenna given a certain radiation intensity can be seen in equation 4.

$$P_{rad} = \int_{\Omega} U(\theta, \phi) d\Omega \tag{4}$$

The directionality of an antenna can be found with equation 5 given a known radiated power and radiation intensity.

$$D(\theta, \phi) = 4\pi \frac{U(\theta, \phi)}{P_{rad}} \tag{5}$$

These equations can be used to model antenna radiation patterns given known or desired parameters such as gain or, in the case of a directional antenna, the number of elements.

# 3 Radio Frequencies and Transmission Protocols

## 3.1 Frequency Choice

The radio signal will come from outside of our atmosphere, therefore the signal must be at a high enough frequency to properly pass through the atmosphere and reach the ground station.

A standard nomenclature has been developed to refer to certain frequency ranges, and this has been denoted in table 3.1.

| Band Designator | Frequency (GHz) | Wavelength in Free Space (cm) |
|---|---|---|
| HF | 0.003 to 0.030 | 10000 to 1000 |
| VHF | 0.030 to 0.300 | 1000 to 100 |
| UHF | 0.300 to 1 | 100 to 30 |
| L band | 1 to 2 | 30 to 15 |
| S band | 2 to 4 | 15 to 7.5 |
| C band | 4 to 8 | 7.5 to 3.8 |
| X band | 8 to 12 | 3.8 to 2.5 |
| Ku band | 12 to 18 | 2.5 to 1.7 |
| K band | 18 to 27 | 1.7 to 1.1 |
| Ka band | 27 to 40 | 1.1 to 0.75 |
| V band | 40 to 75 | 0.75 to 0.40 |
| W band | 75 to 110 | 0.40 to 0.27 |

Table 3.1: Standard Frequency Letter-Band Nomenclature (IEEE Standard 521-2002)

There is less radio frequency interference (RFI) from the atmosphere as you increase in frequency. This can be seen in figure 3.1 (ARRL, 2018).

Due to the fact that as you decrease the frequency, large bandwidth signals start to occupy an increasingly large percentage of the available spectrum, so there are FCC regulations regarding digital symbol rates on certain HAM bands. Table 3.2 shows these data rate limits, and most importantly for this system, that after the 70-cm band that there is no maximum allowable symbol rate.

| Radio Band | Maximum Symbol Rate |
|---|---:|
| Below 28 MHz | 300 baud |
| 10-meter band | 1200 baud |
| 6-meter and 2-meter bands | 19,600 baud |
| 1.25-meter and 70-cm bands | 56,000 baud |
| all further bands | no limit |

Table 3.2: Maximum Allowable Symbol Rates

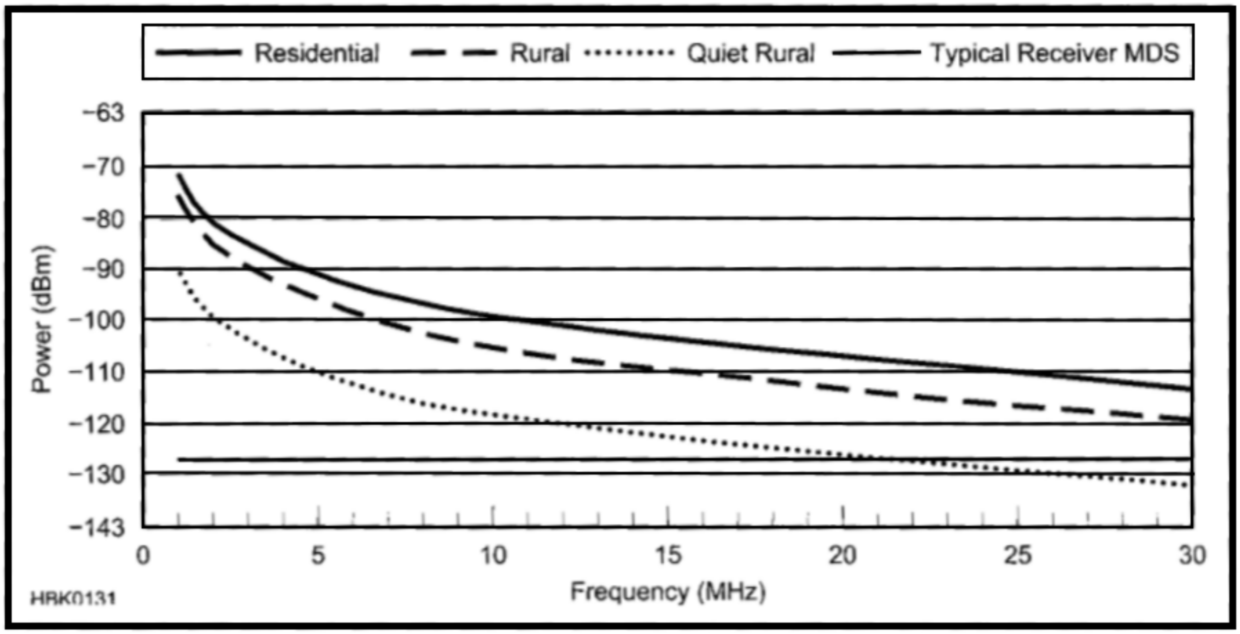


Figure 3.1: Typical Noise Levels compared to Frequency for Different Environments

Less atmospheric RFI combined with no maximum symbol rate shows that a frequency in the range of L band to S band should be attempted.

While the information presented here may suggest that a frequency in the C band or even X band should be attempted, the reality is that without a directional antenna on the transmission side the signal starts to lose radiation intensity. This is why the frequency should be limited to L or S band.

For future reference, if the team is attempting to move into the S band, 2.4 GHz should be avoided as this is the frequency on which most cell phones operate.

## 3.2 Digital Compared to Analog

An analog broadcast is a continuous stream of electrical signals that change amplitude based on changes in voltage. AM and FM radio stations are prime examples of analog modulation. An analog signal contains a continuous stream of information with no definitive states, and therefore can not be stored accurately in a computer to be recreated later without some kind of Analog to Digital Converter (ADC). These limitations have shown that an analog signal will ultimately be unsuitable or this purpose.

Digital signals are made up of discrete samples of information that are either high voltage, '1', or low voltage '0'. These signals can easily be stored by a computer for recreation later, and can be replicated as much as is needed.

Typically digital signals are sent in packets, or groupings of digital information with some added extra information to facilitate error detection. The necessary modulation and encoding techniques will be facilitated better by a digital transmission format, and that is why digital has been chosen as the mode for the ESFT rocket.

## 3.3 Types of Digital Modulation Techniques

Shift keying is a kind of digital modulation technique used to represent binary 1's and 0's using different states of a radio wave.

Phase shift keying (PSK) is a kind of modulation where the phase of the wave is changed to transmit a '1' or a '0'.

Frequency shift keying (FSK) is a kind of modulation where two different frequencies are chosen, with each different frequency describing a '1' or a '0'.

Figure 3.2 is an example of 4 bits of data, '0100', being modulated into an FSK signal. Since the radio system relies on GHz frequencies, the exact phase of the signal can not be guaranteed due to the effects of Faraday rotation, therefore FSK was the chosen modulation technique.

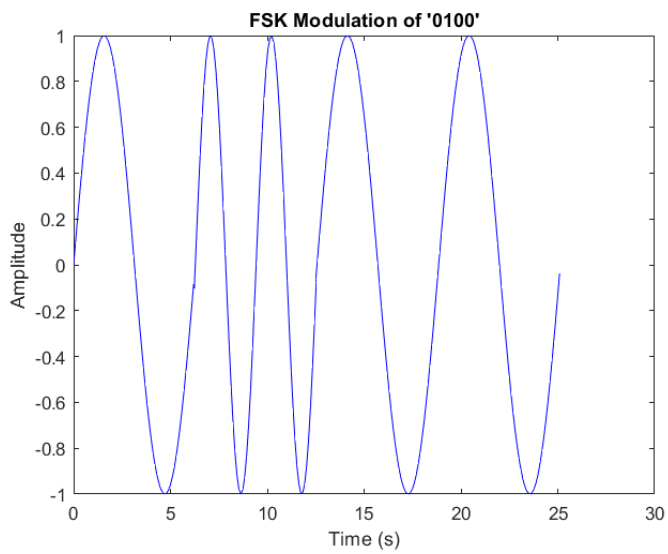


Figure 3.2: FSK Modulated Signal

Multiple frequency shift keying (MFSK) is a modulation technique where M number of tones is chosen, typically a power of two, where each tone represents a different symbol. Each symbol can be used to express the 16 different symbols of hexadecimal, where each hexadecimal symbol represents 4 bits.

Due to the large increase of hardware cost and developmental difficulty compared to the increase in data transmission rates, MFSK was ruled out. Though this modulation technique should be looked into more once the current flight hardware has been proven.

## 3.4 Gaussian Frequency Shift Keying

### 3.4.1 Theoretical

Gaussian:

$$f(x) = ae^{-(\frac{x-b}{2c})^2} \tag{6}$$

For arbitrary real constants a, b, and c.

Gaussian Curve:

$$g(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(\frac{x-\mu}{2\sigma})^2} \tag{7}$$

### 3.4.2 Impulse Response

Impulse response for a given alpha:

$$g(x) = \sqrt{\frac{\alpha}{\pi}} e^{-\alpha(x^2)} \tag{8}$$

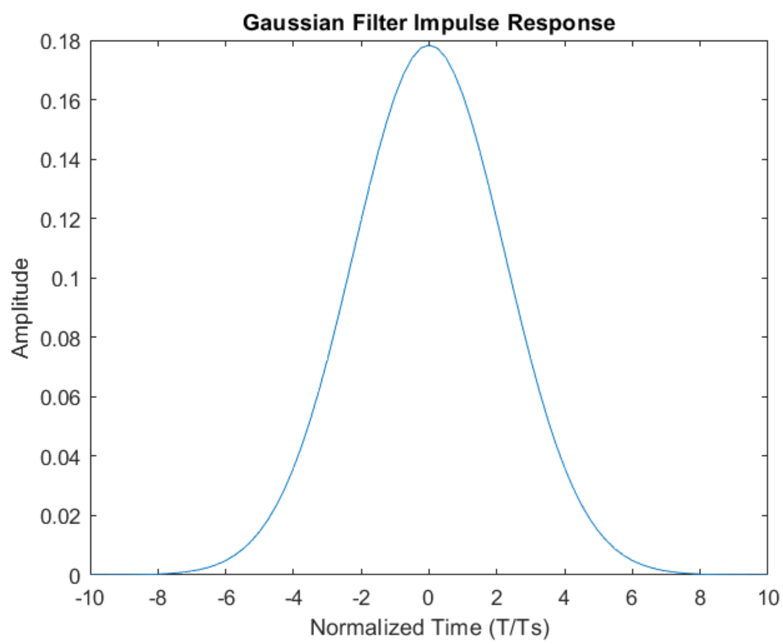


Figure 3.3: Gaussian Impulse Curve with an Alpha of 0.1

### 3.4.3 Why GFSK was chosen

The binary signal is passed through a Gaussian filter, which causes the modulated pulses to be much smoother. This reduces the side band power of the signal which saves on bandwidth and reduces interference generated by the signal.

The hardware is much simpler than any other kind of FSK technique with similar data transfer rates since the necessary hardware is easily programmable into an SDR using GNU radio.

## 3.5 Packet Scheme

The following tables will describe how the information gathered from the rocket will be organized and compressed into a hexadecimal packet. The "ESFT" at the beginning is used to mark the beginning of the packet, and the added bytes at the end are to be used for the implementation of forward error correction.

Table 3.3 describes the packet header, which will be included in every packet transmitted and denotes the time of transmission and which type of packet has been transmitted.

Table 3.5 is the configuration packet which is transmitted once every minute and contains the radio operator call sign in order to comply with FCC transmission identification regulations. The FCC mandates that an identifier in the form of your call sign be transmitted every ten minutes, and by transmitting this packet once every minute the requirement will be more than met.

Table 3.4 is a description of the data received from the sensors to be encoded into each transmitted packet. This data is transmitted in hexadecimal in order to compress the amount of data to be transmitted, and then decoded at the receiving station.

Table 3.6 shows a description of the overall format for each packet, followed by an example packet after being encoded. This is ultimately the data that will be modulated into a radio signal and received at the base station.

| Offset | Data Type | Description |
|---|---|---|
| 0 | uint16 | tick |
| 2 | uint8 | type |

Table 3.3: Packet Header Format

| Offset | Data Type | Name | Description |
|---|---|---|---|
| 3 | string | call sign | Radio Operator |
| 7 | string | version | Software version |
| 11 | uint16 | ftime | Flight seconds |

Table 3.5: Configuration Packet Format

| Offset | Data Type | Name | Description |
|---|---|---|---|
| 3 | uint8 | state | Flight State |
| 4 | int16 | accel | m/s |
| 6 | uint16 | speed | m/s |
| 8 | uint16 | height | m |
| 10 | uint16 | init | m |
| 12 | uint16 | pres | Pressure Sensor |
| 14 | uint16 | temp | Temp Sensor |
| 16 | uint16 | vbatt | Battery Voltage |
| 18 | int16 | roll | Roll |
| 20 | int16 | pitch | Pitch |
| 22 | int16 | yaw | Yaw |
| 26 | uint32 | lat | Degrees |
| 30 | uint32 | lon | Degrees |

Table 3.4: Sensor Packet Format

| Offset | Name | Example | Description |
|---|---|---|---|
| 0 | length | 32 | Total length of data |
| 1 to length | packet | 6D...01 | Bytes of packet data |
| length | checksum | 88 | (sum of bytes)%256 |

Table 3.6: Overall Packet Format

Sample Packet: ESFT 2711704e884e50bb8570f11008101010007227a1c55

# 4 Transmission Rates

Baud rate, also known as symbol rate, is the number of modulation signals transmitted for a given period of time. While often closely related to bit rate, the two are fundamentally different as there can be multiple bits encoded per baud. The following two equations are from (Shannon, 1948).

The theoretical transmission capacity of a channel without noise for a given number of possible symbols is shown by the Nyquist Theorem as:

$$C = 2B \times log_2 M \tag{9}$$

Where C is the channel transmission rate in bits per second, B is channel bandwidth in Hertz, and M is possible signal levels.

The theoretical maximum transmission rate for a given channel where the signal to noise ratio is taken into account is given by the Shannon-Hartley theorem as:

$$C = B \times log_2(1 + SNR) \tag{10}$$

Where B is the bandwidth in Hertz, and SNR is the signal to noise ratio in watts. This equation assumes the theoretically maximum possible number of symbols.

By moving the center frequency into a higher frequency, the amount of spectrum available increases. This allows an increase in bandwidth without having as much of an impact on the amount of available spectrum.

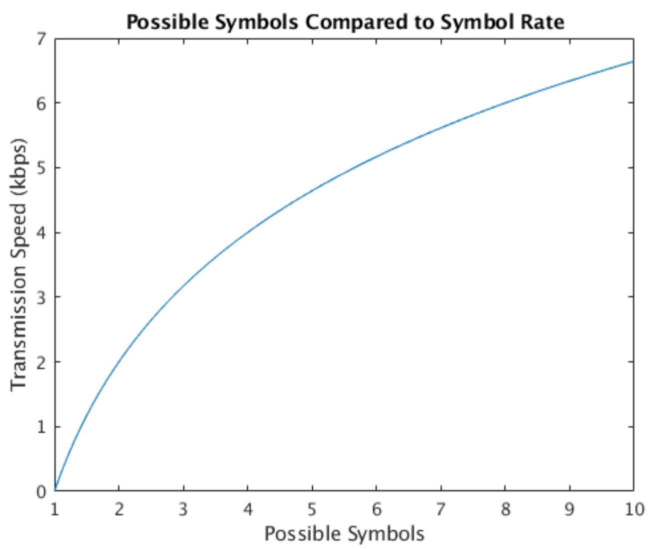


Figure 4.1: Theoretical Transmission Rates Compared to Symbols for a 1 KHz Channel

# 5 Necessary Equipment

## 5.1 Base Station

### 5.1.1 Base Station Hardware

The ground system will utilize a BladeSDR for the receiver.

This system requires the use of an appropriately powerful sound card capable of achieving upwards of 32 KHz.

An SDR setup increases compatibility with different digital systems by using a programmable FPGA transceiver.

By using software developed using the GNU Radio software library, the team can properly interface with the antenna system through the SDR.

### 5.1.2 Base Station Software

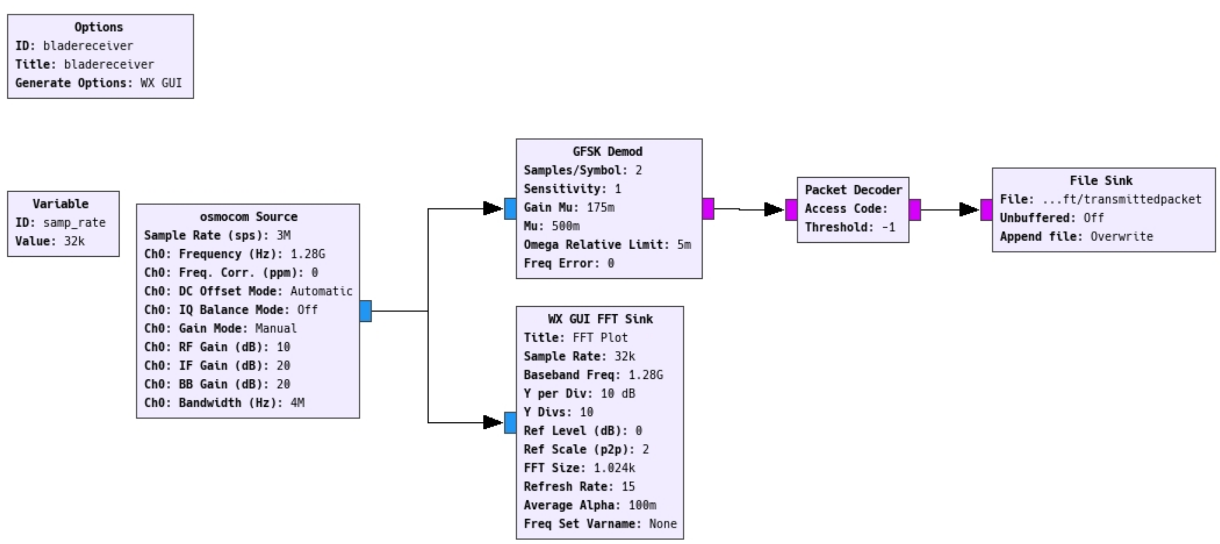


Figure 5.1: Receiver Flowchart Diagram

The oscmocom source in the diagram is the transceiver on the ground that is responsible for receiving the transmitted radio signals. The received data is then sent through a GFSK demodulation block, which turns the modulated data back into the raw binary packet data. The packet decoder block extracts the encoded information, removing extra data for error detection and finally writes the information to files on the ground station computer so that they can be displayed on screen.

## 5.2 On the Rocket

### 5.2.1 Onboard Hardware

Since the rocket will be spinning while it is going up, the signal should circularly polarize itself. However, one of the important things to make sure the electrical team knows is which direction the rocket is going to spin. Since if the base station is a fixed polarization the rocket will have to spin the same way each time. However, it is possible to utilize a relay system that allows the changing of the antenna polarization making sure the rocket will always be able to communicate with the ground station.

### 5.2.2 Onboard Software

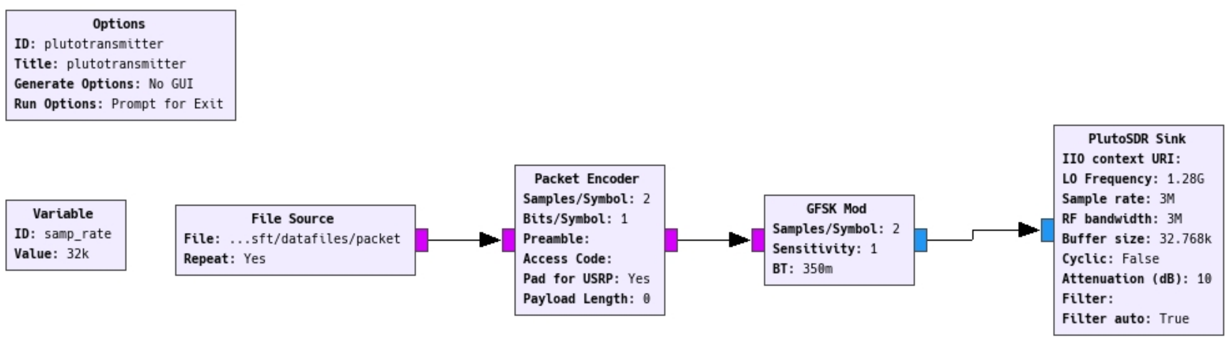


Figure 5.2: Transmitter Flowchart Diagram

The necessary data to be encoded into a packet is extracted from a file on the flight computer that was compiled by the encoder program. This data is then encoded into a packet, adding extra information to facilitate error detection. This data is then modulated and put through a Gaussian filter, which is then sent out as a radio wave by the on-board transceiver.

# 6 Licensing

## 6.1 Operation Zones

There are three International Telecommunication Union (ITU) regions that designate the privileges and responsibilities of amateur radio operation. What region the operator falls into is determined by where the radio transmission originated. This can be seen in figure 6.1 (Makins, 2018).

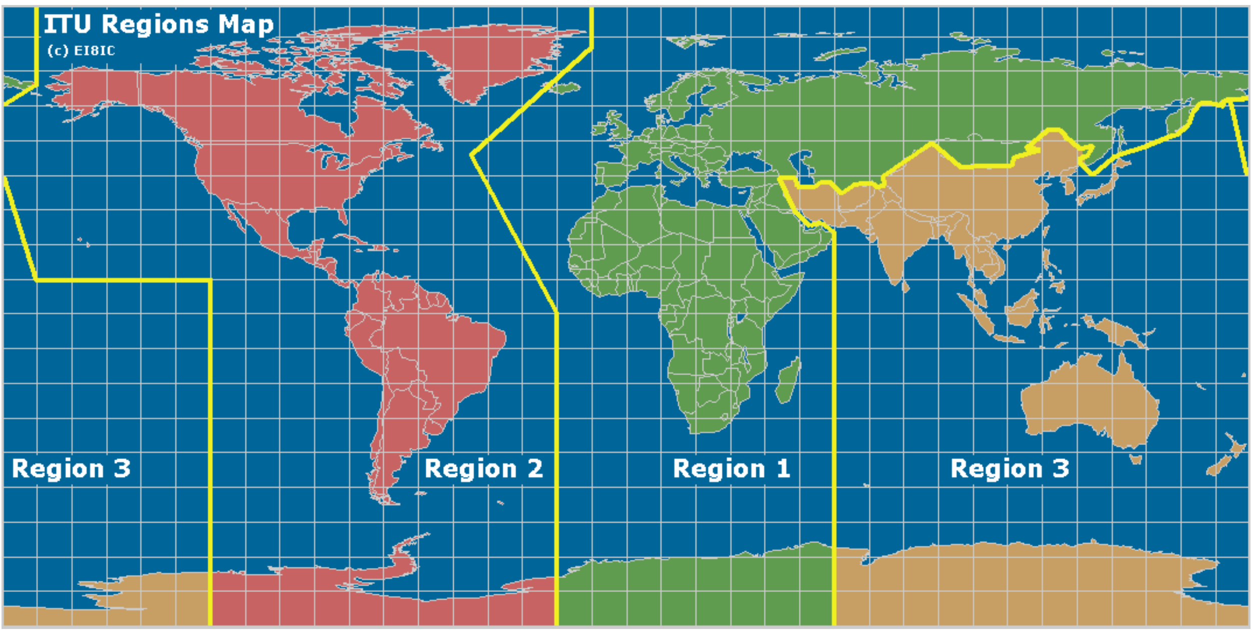


Figure 6.1: Radio Operator Zones

## 6.2 License Types and Privileges

Currently there are three types of US Amateur Radio Licenses: Technician, General, and Extra. All three can operate in the band necessary for the Eagle Space Flight Team. The highest license on the team is currently a General class license, which allows operation on all modes, most of the amateur spectrum below 30 MHz, and all other frequencies up to microwave frequencies.

## 6.3 Allowed Frequencies

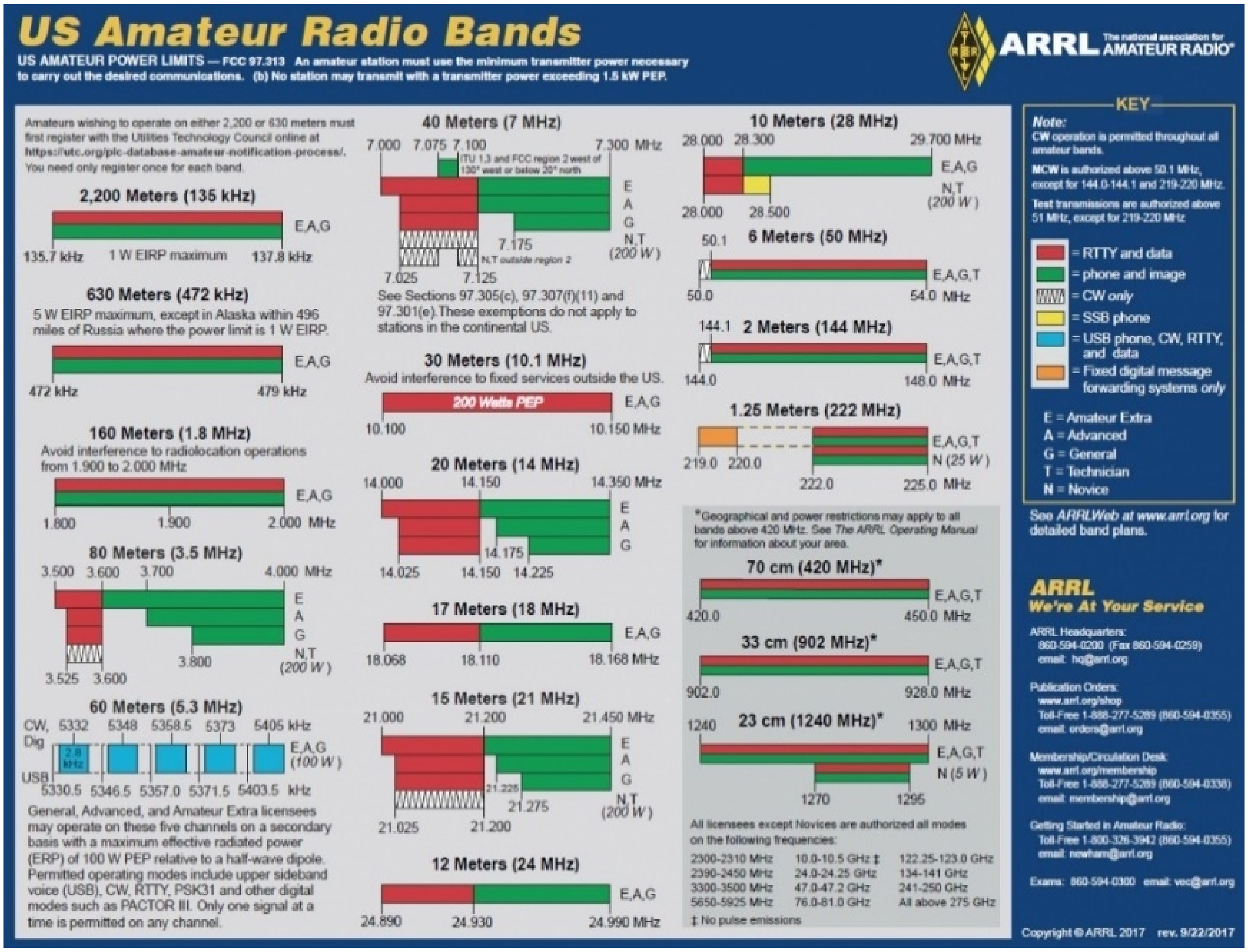


Figure 6.2: ARRL Frequency Chart

In figure 6.2 (ARRL, 2017), the possible frequencies are denoted. The radio system is currently operating on the 23-cm HAM band, which requires a control operator who holds atleast a technician class license.

# 7 Environmental Factors

## 7.1 Faraday Rotation

The largest and most important affect the atmosphere has on radio signals is Faraday Rotation, an effect that happens because of magnetically charged particles moving rapidly through the air. This shift in magnetic charge causes a phase shift in the radio signal that makes it impossible for a non-circularly polarized antenna to receive it. The problem is solved by using a circularly polarized antenna.

## 7.2 Ground Reflection

If the transmitted radio waves reflect off the ground and back into the main lobe of the radio signal, there can be severe signal loss. This is called multipathing and occurs when a radio wave is reflected off a surface in a way that causes the transmitted signal to arrive at the receiver from two or more directions.

The major effect of ground reflection is that two waves will be received at different phases at the same frequency, which will cause the two received signals to combine and cancel each other out.

In order to determine the path difference of the two signals equation 11 is used (Rappaport, 2002).

$$\Delta d = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \tag{11}$$

Where $h_t$ is the height of the transmitter above the ground plane, $h_r$ is the height of the receiver above the ground plane, and $d$ is the horizontal distance between the receiver and transmitter.

After having found the path difference between the receiver and transmitter the phase difference can be approximated by equation 12.

$$\Delta\phi \approx \frac{2\pi\Delta d}{\lambda} \tag{12}$$

Where $\lambda$ is the wavelength in meters. The closer the phase difference becomes to a multiple of $\pi$ the more severe the distortion will become (Rappaport, 2002).

# 8 Conclusion

The design of the Eagle Space Flight Team radio system consists of two SDR units. The programmable FPGA boards equipped with radio transceivers are operating in the GHz frequencies to provide the necessary data transfer rates and reception quality.

Considering the requirements of the ESFT rocket, the communications payload will have to be incredibly robust, while simultaneously offering significant data transfer rates at large distances. This system accomplishes this by using a GFSK modulation scheme to provide the necessary spectral efficiency, yet limits the total bandwidth by eliminating side bands.

The issue of distance is solved by the use of high gain directional antennas, which allows the transmitted power to be received at a high enough signal-to-noise-ratio so that the base station can properly decode the information. All of this combined with proper operation from the ground station will supply ESFT with one of the most advanced communication systems of any Embry-Riddle organization.

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