Official Letter of Transmittal

May 10, 2022
University of New Haven
300 Boston Post Rd.
West Haven CT, 06516

Dear Prompti Technologies,

The following report is an overview of the research, design, and progress regarding data transmission over the HF band. The data transmission occurs with the use of two antennas, a transmitter, and an SDR as the receiver. The project will demonstrate that data can be transmitted via the HF band over long distances. If completed properly, this project will characterize the HF band for transmission as much as possible.

Budget, design, and testing procedures of the project were decided on by the group and approved by faculty mentor Dr. Moshen Sarraf. This project is sponsored by Prompti Technologies. Testing for this project will continue to be conducted at the University of New Haven's Tagliatella College of Engineering.

Questions regarding the project can be sent towards our team leader, Jamal Bouajjaj at `jboua1@unh.newhaven.edu`.

Sincerely,
The HF Team

HF Characterization Project

Jamal Bouajjaj, Sean Vallie, Mackenzie Myers, and Thomas Kittelberger

May 10, 2022

Contents

List of Figures

List of Tables

1 Executive Summary

In the world of financial and stock market trading, it is desirable to reduce the latency between the machine initiating a transaction and the transaction server. Currently the transactions are done over fiber optic lines. Unfortunately, a signal through fiber optic cable propagates at around 2/3 the speed of light. Copper lines suffer from requiring repeaters, line-of-sight radio communication and satellite communication also suffers from the same issue.

Using the HF portion of this electromagnetic spectrum, one is able to transmit RF signal end-to-end over distances greater than 100km using two modes of propagation that are possible on this portion of the spectrum: groundwave propagation and skywave propagation. Particularly with skywave propagation, one can theoretically transmit signal end-to-end all around the world.

This is what project explores: attempting to characterize the HF band while exploring and experimenting on the band to determine its feasibility as a means of communication. If proven successful and reliable, this can give an upper hand in the financial market to those who utilize this band.

Due to licensing issues and the availability of equipment, the amateur radio allocation portions of the HF band will be utilized for all testing throughout this project. Within the scope of this project is also setting a University of New Haven amateur radio station, which will be utilized beyond this project by the UNewHaven amateur radio club.

2 Acknowledgments

We would like to thank Dr. Mohsen Sarraf for his guidance and recommendations throughout the project, and Mark Morton (W1MEM) for his guidance and assistance with setting up the amateur radio station.

We would like to thank our sponsor, Prompti Technologies, for their interest and funding of this project.

We would like to thank the University of New Haven for also partially funding this project to setup the UNewHaven Amateur Radio station.

Finally, we would like to credit Joe Taylor and his work on WSJT and the FT8 protocol, and the International Telecommunication Union for their recommendations and documentations.

3 Project Description

The primary goal of this project was to characterize the HF band. For the scope of this project, this includes understanding and gathering data on what conditions affect HF propagation and to what extent.

The original plan for this project was to have one location transmit data over the HF band with a certain power output, while one or more receivers measure the maximum received power. Figure 1 shows the components of that original plan as well as how some interact with one another.

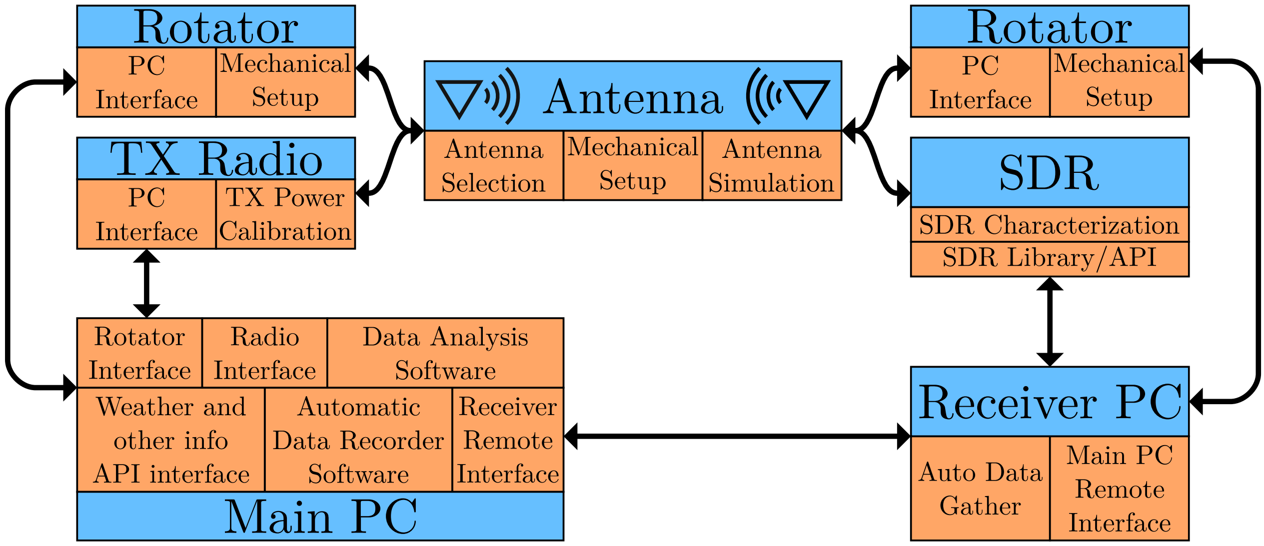

Figure 1: Overall Project

Unfortunately due to the lack of a functional transmitter site that was to be build by the University's Facilities department until April and due to other time constraint, this plan was never able to be executed.

Instead, this project's scope by the end of it changed to instead include understanding the HF band, setup a University of New Haven amateur radio station, setup a receiver site to receive transmitted signal by other operators, transmit with the amateur station when functional, receive from existent beacons, and characterize some equipment for the original plan.

The amateur radio station was setup as a hub for this project in order to both receive and transmit on the amateur band. The station will be located at the University of New Haven, with the antenna setup on the roof of Buckman Hall. The transmitter antenna will be a hex antenna, due to its reduced cost while providing some directionality. As the transmitter antenna will have some directionality, so the transmitter setup will include an antenna rotator to rotate the antenna towards the desired receiver. The rotator will be connected to a rotator controller, and the antenna will be connected to a radio transmitter. Both the transmitter and the rotator will be connected to a computer which will serve as the control center for this project. This station will outlive this project as it will be used at the University for a future amateur radio club.

This project also included setting up a receiver site to receive specific signals sent out by other operators around the world that contain their location as a grid. This data was analyzed in order to analyze the HF channel and its feasibility as a communication method.

4 Literature Search

4.1 Amateur Radio

The unlicensed portions in the HF band, ISM bands, are shown in Table 1

Center Freq.	Bandwidth
6.78 Mhz	30 khz
13.56 MHz	14 kHz
27.12 MHz	326 kHz

Table 1: ISM Bands in the HF portion of the electromagnetic spectrum

While these bands can be used for transmission, there isn't a lot of commercially available transmitters that operation within those bands. An HF ISM transceiver can be theoretically built, but that is out of this project's scope. Instead, the amateur radio band was used which covers the frequencies in the HF band shown in Table 2 in ITU Region 2. There is a lot more availability compared to the ISM band. There are commercially available antennas and transceiver available for this band, which simplifies this project.

The amateur band in the United States is regulated by the Federal Communications Commission (FCC) under 47 C.F.R Part 97[20] and requires a license to transmit on. There are 3 licenses classes available for an amateur license: Technician, General, and Extra, each proceeding one with more spectrum privileges. For the HF spectrum, the majority of the band is covered under the General license. Jamal had a Technician license at the start of this project, and upgraded to a General license during January in order to transmit on the HF spectrum.

Start Frequency	End Frequency
3.50 Mhz	4.00 Mhz
7.00 MHz	7.30 Mhz
10.10 MHz	10.15 Mhz
14.00 MHz	14.35 Mhz
18.068 MHz	18.168 Mhz
21.00 MHz	21.45 Mhz
24.89 MHz	24.99 Mhz
28.00 MHz	29.70 Mhz

Table 2: Amateur bands the HF portion of the electromagnetic spectrum

4.2 HF Propagation

HF RF (High Frequency Radio Frequency) signals can propagate three distinct ways. A graphics summary of all 3 propagation methods are shown in Figure 2.

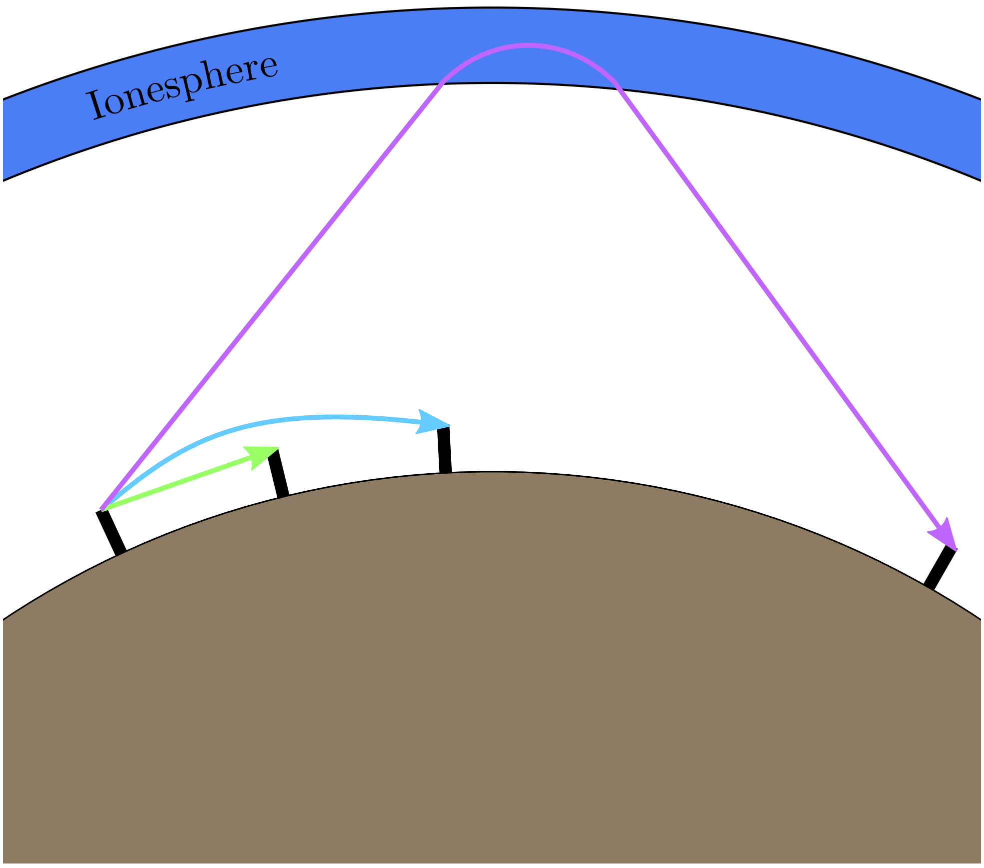

Figure 2: A graphics summary of the ways an HF signal can propagate to it's destination. The green path is with Line-Of-Sight propagation, blue is with Ground Waves, and purple is with Skywaves

Line-Of-Sight

Just like every electromagnetic wave, transmitted HF waves will travel in a straight line from the transmitter until the horizon. This propagation method, known as line-of-sight, is the most limiting offering the least propagation distance.

Ground Waves

Ground waves, also known as surface ways, is an extension of Line-Of-Sight propagation. This type of propagation can occur due to low frequency RF signals diffracting strongly around obstacles, causing them to follow the Earth's curvature. This is why for example an AM station, operating near 1Mhz, can be heard far without line-of-sight to the transmitter. The waves that can propagate this way must have a vertical polarization, with a horizontal magnetic field and a vertical electric field. The higher the frequency, the less a signal is able to propagate this way. The conductivity of the surface influences ground wave propagation, with more conductive surfaces, such as sea water, allowing for better ground wave propagation. The International Telecommunication Union (ITU) provides a recommendation to estimate the path loss of a signal with ground wave propagation: ITU-R P.368 [15].

Skywaves

The most interesting and ludicrous HF propagation method, called "Skywaves", is bouncing the radio signal off the atmosphere. When low frequency radio waves are transmitted from the Earth's surface at an angle towards the atmosphere, some of the signal is refracted back down to Earth. Skywaves offer the longest range out of all possible propagation method. Shown in Figure 3 is a visualization of skywaves.

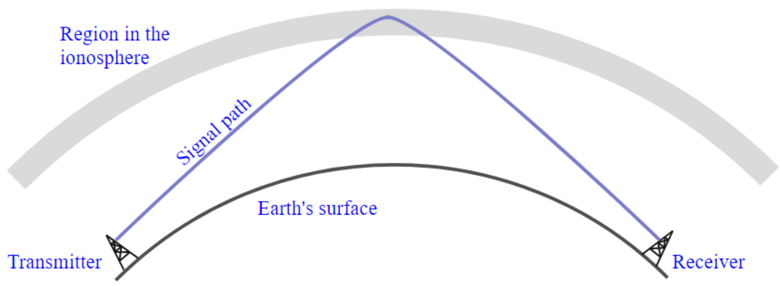

Figure 3: Skywave Propagation

Radio waves gets refracted in the atmosphere due to the electron density of the ionosphere layer. The electrons in the ionosphere comes from received radiation from the Sun ionizing atoms in that atmosphere layer. The amount of ionization, which results in a higher electron density, depends on the sun's activity and the number of sunspots. This is the largest contributor determining how well Skywave propagation can occur. Radio waves can also be absorbed in the ionosphere. This is due to the interaction between the radio wave, ionosphere electrons, and the neutral atmosphere.

While technically the radio waves gets refracted back down, it can be assumed that the signal gets a reflected from a higher "virtual height".

Layers of the Ionosphere The ionosphere can be split into 3 distinct layers, all effecting HF refraction and absorption.

D Layer The first layer, the D layer, is 48 to 90 km above the Earth's surface. This layer is mostly active during daytime, and disappears at night. The D layer is mainly ionized by solar X-Ray flares. It can also be ionized by Solar Energetic Particle. This layer mainly contributes to the absorption of radio waves without much refection. The amount of absorption is inversely proportional to the radio wave's frequency.

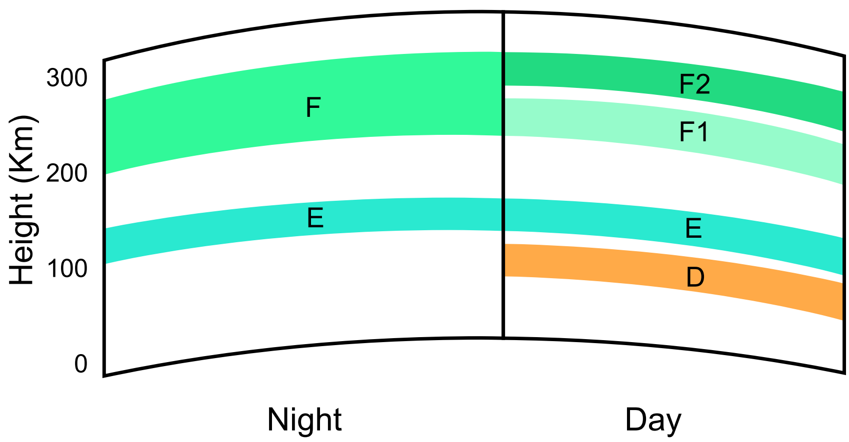

Figure 4: Ionosphere Layers

The attenuation of this layer can be predicted thru measurement of solar X-Ray flux and SEP events[9]. The National Oceanic and Atmospheric Administration (NOAA) provides this calculation.

E Layer The second layer up is the E-layer, residing from 90 to 150km above the Earth's surface. This layer attenuates the signal somewhat, but much less than the D layer. This layer does provide some refraction, with lower frequencies being reflected the most. This layer does not provide as much refection as the next layer.

F Layer The F layer resides 150 to 500km from the Earth's surface, and is the most critical for HF propagation. This layer has the highest electron density, due to it receiving the bulk of the sun's radiation, and thus is usually the most ionized. During daytime, this layer is split into two distinct layers: F_1 and F_2.

Critical Frequency If an HF signal is sent upwards, there is a maximum frequency which the signal will stop bouncing back and go right thru the atmosphere to space. This frequency is called the Critical Frequency, and can be calculated by

$$f_c = 9\sqrt{N_{max}}$$

Where f_c is the critical frequency in Hz, and N_max is the maximum electron density in m^3.

The critical frequency can be measured with devices known as an ionosonde. This devices transmits radio signals over the HF band vertically and measures the received signal, if any is received. Using this data, among the many parameters that can calculated, for the purpose of this paper the critical frequency and the virtual height of reflection are the most important.

MUF and LUF If the radio wave is sent at an angle, which it normally is for the purpose of communication, the refraction happens over a longer distance over the atmosphere. As this angle increases, with fixed ionospheric conditions, there is a frequency in which the signal will stop being refracted to earth and instead escape the ionosphere. This frequency, the Maximum Usable Frequency (MUF) can be estimated by:

$$f_{MUF} = \frac{f_c}{\cos\theta}$$

There f_{MUF} is the maximum frequency in Hz, and θ is the angle of incidence at the atmosphere.

As mentioned, the D layer mainly attenuates the RF signal. This absorption is inversely proportional to the radio wave's frequency. This inverse proportionality results in a figure called the Lowest Usable Frequency (LUF), which is the lowest frequency that can be used for ionospheric propagation before the attenuation of the signal causes its signal-to-noise to be too low for a setup.

The amount of absorption by the D layer caused by X-Rays and SEPs can be estimated individually. For X-Ray absorption,

When the LUF is greater than the MUF, for example because of solar flare, HF communication with ionospheric propagation is not possible, and a communication blackout occurs.

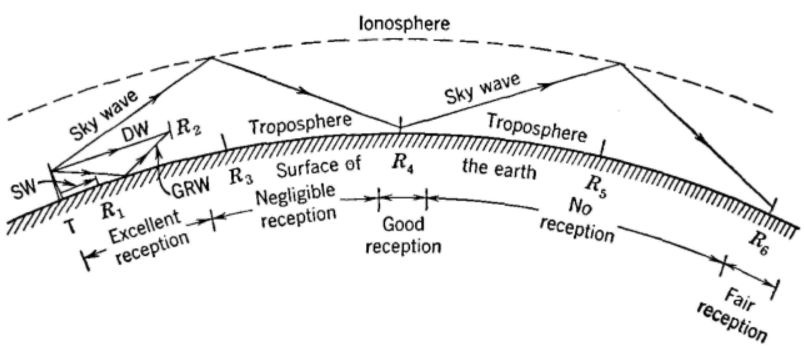

Figure 5: Visualization of multiple HF hops

HF Hop An HF hop is when a signal headed towards the ionosphere from a one location gets refracted to another location. When the signal reaches the earth, it can be reflected back unto the atmosphere creating another HF hop. A visual representation of this is shown in Figure 5.

For a single HF hop, with a signal's takeoff angle, the virtual height of reflection, and the earth's radius, we can determine the angular distance of the hop[12]. We can use Figure 6 as a visual to the geometry of this problem, provided by Reference #12.

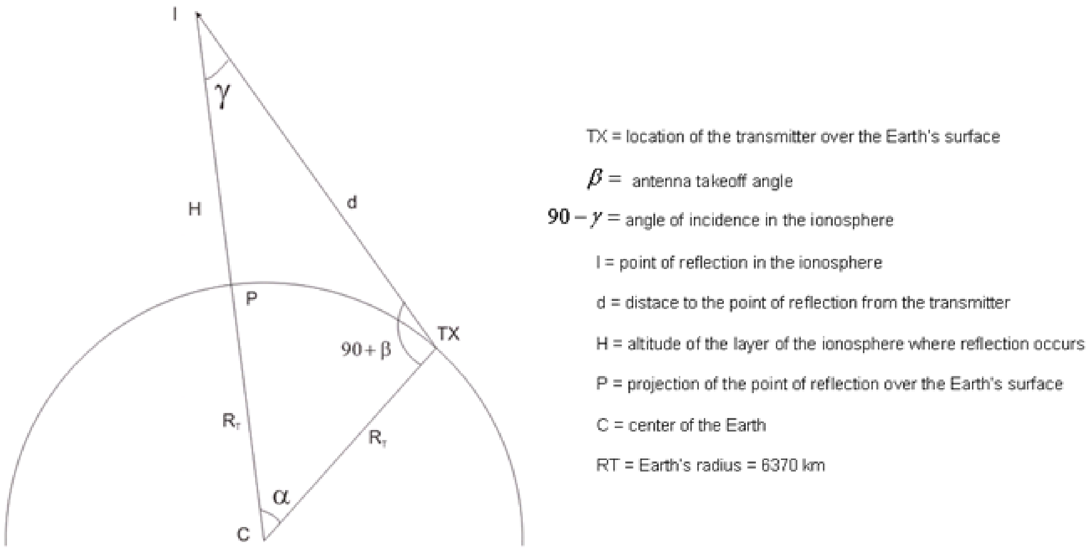

Figure 6: Geometry of one ionospheric hop

We can calculate the distance d from the transmit station to the ionosphere's virtual height with the following equation using the law of cosines and the quadratic formula:

$$d = \frac{-2R_t\cos(\frac{\pi}{2}+\beta) \pm \sqrt{(2R_t\cos(\frac{\pi}{2}+\beta))^2 + 4(R_t^2 - (R_t+H)^2)}}{2}$$

As for figuring out which d is correct (due to the $\pm$ before the square root), from our experimentation one of the distances will be negative which can be discarded.

Then we can determine the angular distance with the following equation using the law of sines:

$$a = \arcsin\left(\frac{d\sin(\frac{\pi}{2}+\beta)}{R_t+H}\right)$$

We can also determine the hop distance with

$$d_{hop} = R_t a$$

So given a transmitter site's latitude and longitude, and the angular distance of a single hop with a certain bearing, we can determine the landing point with the following equation[13] with λ denoting a longitude, ϕ denoting a latitude, and θ denoting the bearing:

$$\phi_{dest} = \arcsin(\sin(\phi_{orig})\cos(a) + \cos(\phi_{orig})\sin(a)\cos(\theta)) \quad (1)$$

$$\lambda_{dest} = \lambda_{orig} + \arctan 2(\sin(\theta)\sin(a)\cos(\phi_{orig}), \cos(a) - \sin(\phi_{orig})\sin(\phi_{dest})) \quad (2)$$

Then for the final bearing at the hop, we can take the bearing from the end to the start point and reverse it (by adding 180 degrees), which is found with

$$\lambda_\Delta = \lambda_{dest} - \lambda_{orig} \quad (3)$$

$$\theta_{new} = \arctan 2(\sin(\lambda_\Delta)\cos(\phi_{dest}, \cos(\phi_{orig})\sin(\phi_{dest}) - \sin(\phi_{orig})\cos(\phi_{dest})\cos(\lambda_\Delta))) + \pi \quad (4)$$

This new heading can be used in an iterative operation to find the receiver location for more than a single hop.

4.3 Communication Protocols

When transmitting and receiving during the course of this project, multiple RF communication protocols were used.

FT8

FT8 is a digital mode developed in order for amateur operators to make quick contacts (QSOs) in weak signal conditions. The physical signal is an 8 tone continuous-phase frequency shift keying. For a single message, there are 58 channel symbols with each symbol conveying 3 bits of information. Each symbol's duration is 0.16 seconds. A single message uses a 50Hz bandwidth, reducing the receiver signal to noise ration (due to the smaller the bandwidth, the smaller the thermal noise).

The message sent are 77 bits, and can convey predetermined message types. Each message includes a CRC checksum so the message can be checked for its validity.

One of the messages is a CQ call, meaning an operator wants to make a contact. This message includes their call sign and their maidenhead location. This location data will be crucial to Section 7.5.

This digital mode is handled by a software called WSJT-X, which also outputs the signal to noise ration of the received message.

SSTV

Another protocol used during some transmission is Slow-Scan Television (SSTV). This protocol is designed for sending images with 3kHz of bandwidth. The protocol is analog with it consisting of sending a header, then scan lines. There are different modes of SSTV with different transmission times, color, and resolution differences. The one used during the scope of this project, and the most popular one, is Robot 36 which sends the color as a YUV color model with a transmission time of 36 seconds and a resolution of 256x240.

4.4 SDR

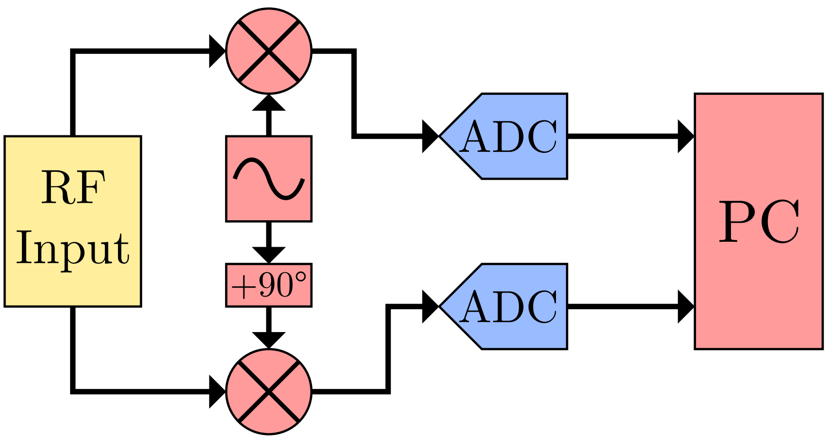

Figure 7: SDR Direct Conversion Architecture

A Software Defined Radio (SDR) is a radio where the majority of traditional radio's hardware components (demodulator, mixers, detectors, etc) are implemented by software. For a receiver SDR, which is what the rest of the document will refer to, one of the most effective SDR architectures is a Direct Conversion. This architectures involves converting the signal region of interests $[f_c - B, f_c + B]$ into a baseband signal with the frequency range $[-B, B]$, where B is half of the bandwidth of interest. This leads the converted signal into the negative frequencies, so the signal is mathematically complex. This complex signal is composed of two components, an In-Phase component I and Out-of-Phase signal Q that is 90° out of phase with the I signal. This is what is meant by an IQ signal: just a complex signal. This IQ signal is then fed into two Analog to Digital Converters (ADC), one for the I signal and the other for the Q signal, and the data is fed into a computer for further processing.

A commercial SDR may also contain an RF attenuator and Low Noise Amplifier (LNA) at the input to assist with receiving the signal. The signal going into a computer, the IQ signals, are of arbitrary values due to the unknown ADC reference voltage and other factors.

4.5 VNA

A piece of equipment the group will be using is a Vector Network Analyser (VNA). A VNA creates and feeds a sinusoidal signal of a certain frequency into the input of a Device Under Test (DUT) and measures the reflected waves at the input and optionally the transmitted wave if the DUT has an output as shown in Figure 8. The VNA sweeps the generated signal's frequency to a user-settable range, and thus is able to characterise the DUT's input and output RF characteristics.

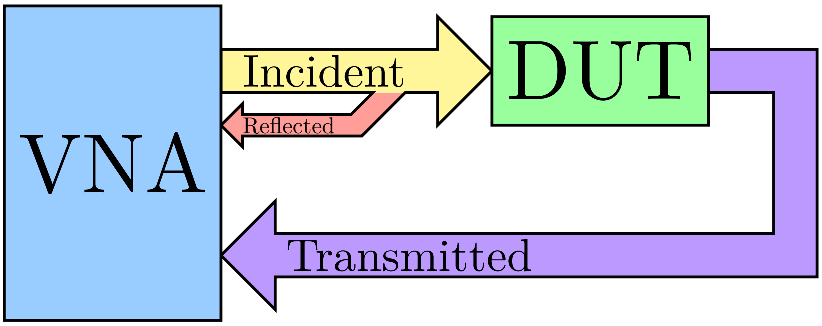

Figure 8: VNA's measurements with a DUT

An example use case, which is what the VNA will be primarily used on for this project, is the measure of how well an antenna is impedance matched. In our project, the characteristic impedance (the impedance which our systems will be matched for) is 50Ω. So the antenna's impedance across all frequencies we want to utilize should be 50Ω, which is what this equipment will measure to verify that's the case.

Reflected Waves and VSWR

If an electronic source and load impedance's aren't matched, then at RF frequencies some of the signal going into the load will be reflected right back to the source. This is undesirable as it results in wasted power and potentially destroying the source if the reflections are high. How much of the source's generated wave, also referred to as the incident wave, is reflected back is the reflection coefficient which is

$$\Gamma = \frac{V^-}{V^+}$$

Where Γ is the reflection coefficient, V^- is the reflected wave, and V^+ is the incident wave. The ideal reflection coefficient is 0, meaning there are no reflected waves. The reflection coefficient can also be calculated as a measure of the characteristic impedance (which the source impedance is at) and the load impedance by

$$\Gamma = \frac{Z_l - Z_0}{Z_l + Z_0}$$

Where Z_0 is the characteristic impedance and Z_l is the load impedance. A more useful and practical measure of impedance matching is the Voltage Standing Wave Ratio (VSWR), which is calculated by

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

. When the VSWR is 1, that means that the load is perfectly matched to the characteristic impedance. A VSWR of less than 2 is deemed as acceptable, anything above that and the system should not be used until the impedances are matched.

5 Patent Search

Patent searches were not applicable to this project.

6 Project Design

6.1 Amateur Radio Station Design

The amateur radio station will be located at the University of New Haven, West Haven and will serve as the center of operations for this project. A block diagram of this station is shown in Figure 9 that is of concern to this project.

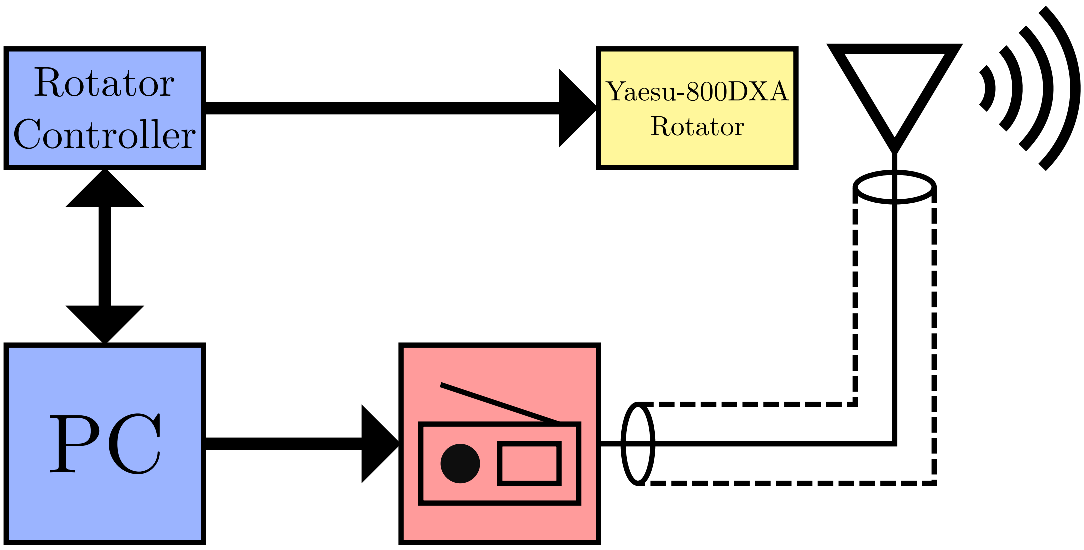

Figure 9: Transmitter Station Block Diagram

Figure 10: MFJ-1848 antenna on the roof of Buckman Hall

The primary antenna used is the MFJ-1848 Hex beam antenna. This antenna was chosen due to its relatively low cost and its directionality. This antenna was not functional until about April due to the University's Facilities department insisting that they are the only ones that can install the antenna without any antenna experience. The antenna, while functional during April, is not fully completed. A picture of this antenna on the roof is shown in Figure 10 during April.

The transmitter radio chosen was the Yaesu FT-891. This radio is from a reputable radio company, and the radio is able to output up to 100W.

The rotator to be used with the transmitting antenna will be the Yaesu-800DXA Antenna Rotator and Controller. This was selected based on the weight it could support, as well as having the necessary port to allow communication between a computer and the controller. The controller's external control port will require designing an interface module to allow a generic computer to communicate and control the rotator controller.

The amateur radio station as of the end of this project is shown in Figure 11

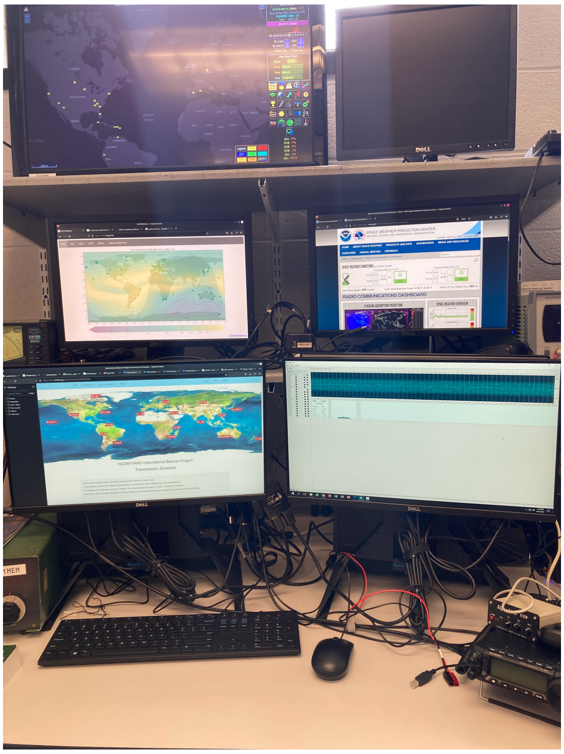

Figure 11: UNewHaven Amateur Radio Station

Rotator Selection

Initially the Yeasu G-450DC rotator for the transmitting antenna was selected based on its low cost, but after further research it was determined that the rotator would not be suitable for the setup of the antenna and mast assembly based on the weight and wind load surface area of the antenna. This prompted further research to find a rotator which would work for the given application. A more heavy-duty antenna rotator, the Yeasu G1000, was then selected and with this change it also made the connectivity to the computer easier thru the interface box it came with.

6.2 Planned Receiver Station Design

The planned receiver station was designed to be compact and easy to setup, allowing setting up multiple receiver stations easily and quickly. A block diagram of this station is shown in Figure 12.

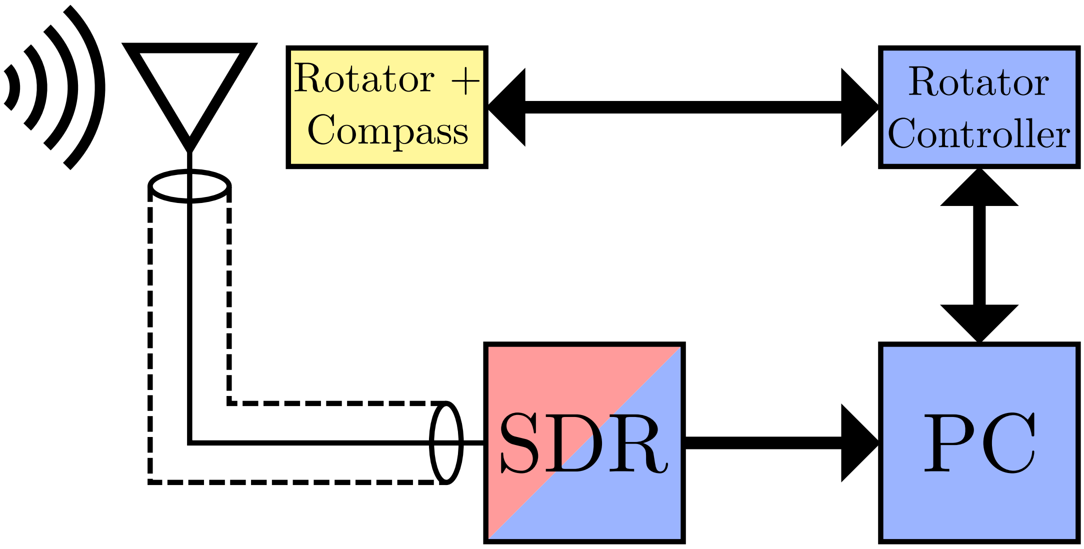

Figure 12: Receiver Station Block Diagram

The antenna used to receive the signal from the transmitting antenna will be an Ultra-Low Noise Active Loop Antenna Model ALA1530LN. This antenna was chosen due to its relatively small size and wide reception bandwidth. The SDR used will be the AirSpy HF+. This SDR was chosen for it's advertised excellent performance on the HF band.

Although the receiving antennas were not deployed to the provided locations due to time constraints, the receiving assembly was still designed and built. This setup also included a smaller loop antenna along with a smaller antenna rotator, and this rotator was also capable of being controlled remotely for the same reason as the transmitting antenna.

Rotator Selection

The rotator to be used will be the RCA VH226E Programmable Antenna Rotator. This is a light duty rotator but should work well due to the compact size and small weight of the receiving antenna. This rotator is simply a 23V AC motor with 3 inputs: One for common, one for turning the rotator clockwise, and the other for turning the rotator counterclockwise.

SDR Raw Data Handling

The SDR by itself outputs raw IQ data. This data will be fed into a GNURadio based application, where the FFT of this IQ data will be taken. The FFT data will then be converted to a power spectrum with the following governing equation:

$$P_k = \frac{1}{N^2}|X(k)|^2$$

Where N is the bin size of the FFT, $X(k)$ is the FFT of the input IQ data, and P_k is the power spectrum of the SDR's input. For the rest of this document, when the SDR's output is mentioned, it is assumed to be the FFT power spectrum unless otherwise noted.

RCA VH226E Rotator Controller

A controller for the receiver rotator, the RCA VH226E, will be designed in-house. This controller will use an Arduino as the main interface microcontroller between a computer and the circuitry to drive the rotator. The rotator will be controlled with two relays, one dictating whether the rotator is on or off and the other for dictating direction. A compass module input will also be added to this controller in order to determine the rotator's heading without relying on a calibration.

The top-level block diagram for this controller is shown in Figure 13.

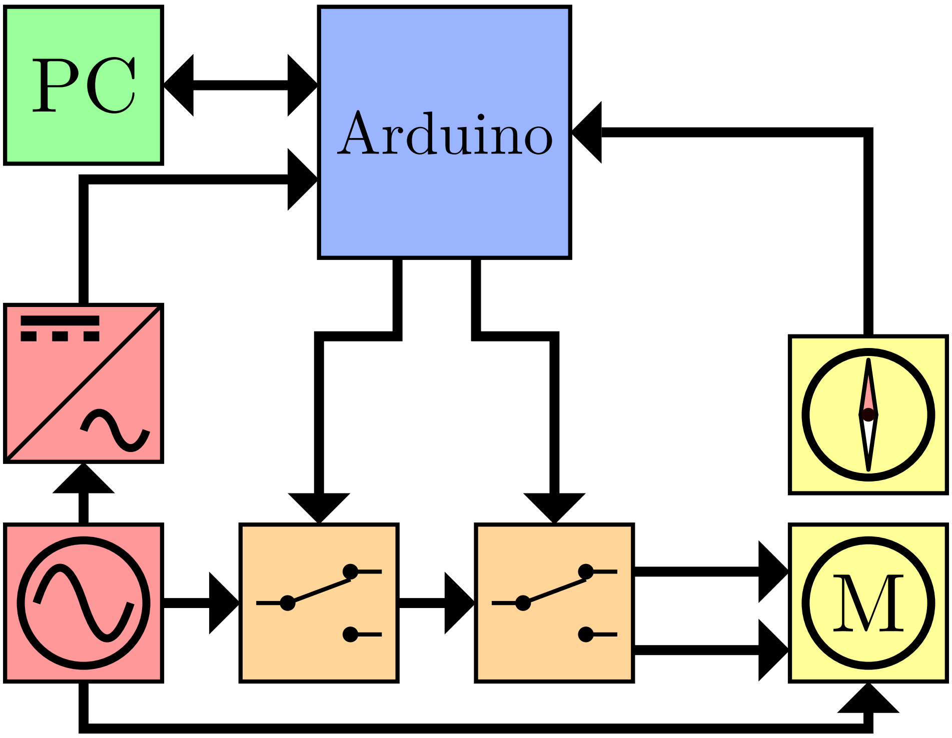

Figure 13: RCA VH226E Rotator Controller Top-Level Diagram

A custom enclosure was designed for this in-house controller, and the CAD models are shown in Figures 14 to 16

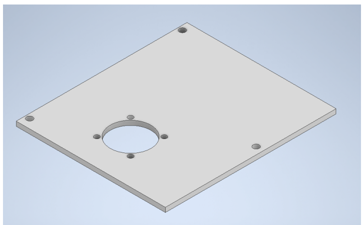

Figure 14: Enclosure Cover

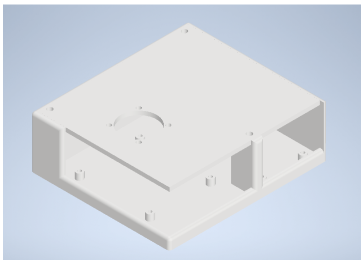

Figure 15: Enclosure Assembly

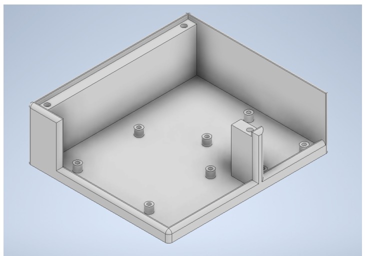

Figure 16: Enclosure Main Body

6.3 Used Home Receiver Setup Design

Figure 17: ALA1530LN at the home receiver

A receiver setup was used at Jamal's house during part of this project, which generated the data covered in Section 7.5. This setup is similar to the one described at Section 6.2 except without a rotator and compass: The loop antenna was manually aligned so the loop's plane is facing east to west.

Instead of measuring the power level as mentioned in that section, the WSJT-X software was used to exclusively receive FT8 signals. As mentioned at Section 4.3, amateur operators make a CQ call when they would like to make contact with another operator. This CQ call includes their callsign but more importantly their maidenhead location, and the WSJT-X calculates the signal to noise ration. This setup was operated from March 5th to April 10th of 2022 receiving the CQ calls and logging it.

A picture of this setup is shown at Figure 17

6.4 Characterization

In order to be able to calculate the path loss of a transmitter RF signal, it is required to calibrate the transmitter's stated transmit power and the SDR's measured input to real power. While the characterization was not fully complete due to the lack of setting up the receiver sites, some characterizations where done and the rest where planned for, which is what this section covers.

Transmitter Characterization

The transmitter radio used, the Yaesu FT-891, allows its output power to be adjusted in Watts. This needs to be measured to ensure the radio is transmitting the power it's stating it is. This will be done by connecting the radio to a spectrum analyzer, transmitting a constant tone on the radio, and analyzing the spectrum analyzer's measured input. Due to the spectrum analyzer's low maximum input power compared to the radio's transmit power, one or multiple attenuators will be used in series between the radio and spectrum analyzer to limit the analyzer's input power. During analysis of the spectrum analyzer's data, the receive power will then need to be shifted to account for the attenuators. A top-level diagram of this setup is shown in Figure 18.

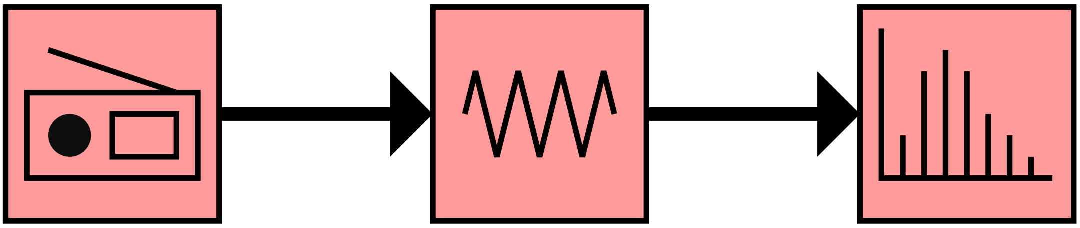

Figure 18: Transmitter Characterization Top-Level Diagram

SDR Characterization

An SDR, due to the way it functions as discussed in Section 4.4, output arbitrary values. This means that we must characterise the SDR's output with a given program to input power.

An RF signal generator will be used to output a pure sinusoidal tone at a given frequency and a constant output power. This signal will be fed into the SDR, there the SDR application will create a power spectrum FFT of the received power. The power spectrum should have a peak at the center frequency of the generated signal, and the peak should be the power transmitted by the signal generator. This peak will be recorded for a range of output power iteratively over the course of two seconds with the last 50 data points used per iteration to negate any startup transients. This data should result in a linear plot that correlates the SDR power spectrum output to real power. This correlation will be done for a variety of frequencies, SDR sample rate, and SDR build-in amplifier's gain options. A characterisation program will be created in order to automate the automation, handling setting the signal generator, receiving and calculating the SDR power spectrum's peak, and recording it into a CSV file for analysis. The SDR's center frequency will be set 50kHz away from the generated center frequency in order to negate the SDR's DC offset error.

The top-level diagram for this characterization setup is shown in Figure 19.

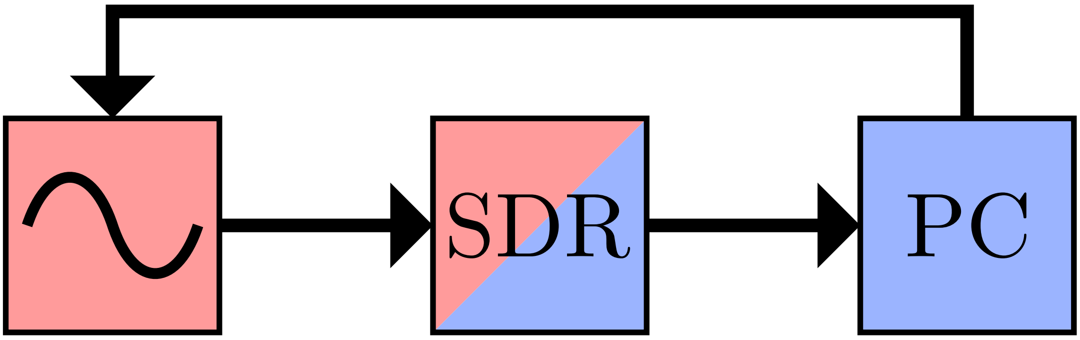

Figure 19: SDR Characterisation Top-Level Diagram

Attenuator Characterization

As mentioned in Section 6.4, one or more attenuators will be used in series between the radio and spectrum analyzer. The attenuators needs be to characterized in order to ensure a constant attenuation across the desired frequency range. This will be done by hooking up the attenuator to a spectrum analyzer's TG Source output and into the analyzer's input. The spectrum analyzer will then be setup in a *"Tracking Generator"* mode to measure the attenuation of the attenuators. A top-level diagram of this setup is shown in Figure 20.

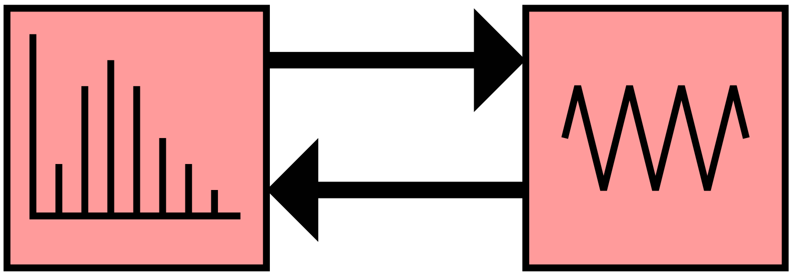

Figure 20: Attenuator Characterization Top-Level Diagram

System Characterization

After the transmitter, SDR, and attenuator characterizations are complete, one final sanity check to ensure the transmitter and receiver system will truly measure the channel path loss. This will be done by directly connecting the transmitter radio to the SDR, with an attenuator in between to limit the SDR's input power. The transmitter will be setup to transmit a tone at a certain frequency, and the SDR's output will be analyzed and converted to received power by using values from the SDR characterization in Section 6.4.

A top-level diagram of this setup is shown in Figure 21.

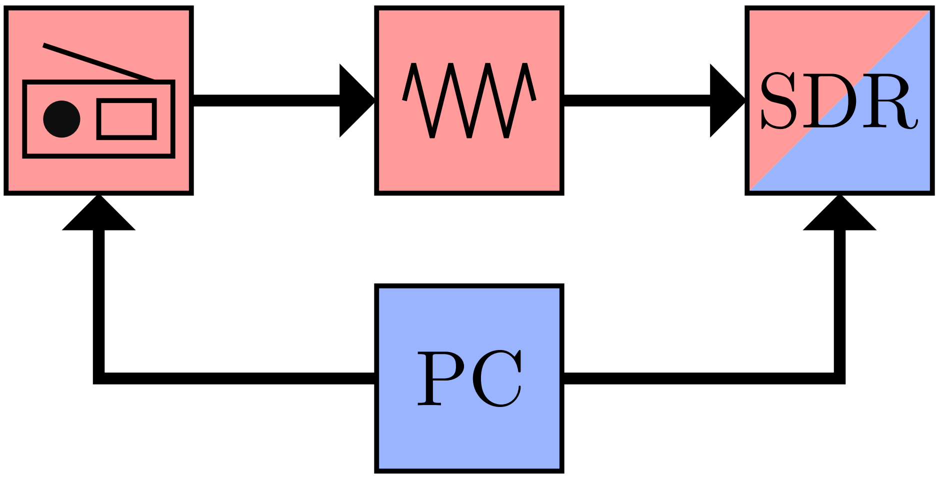

Figure 21: System Characterization Top-Level Diagram

6.5 International Beacon Project

The International Beacon Project is a project coordinated by the Northern California DX Foundation (NCDXF) and the International Amateur Radio Union (IARU) that consists of 18 CW beacons all around the world that are continuously transmitting around the clock on 5 frequencies in such a way as that only one beacon is transmitting per frequency. These beacons transmit at signals from 100W to 0.1W per transmission period. All operated beacons are shown in Figure 22

Figure 22: All International Beacon Project's operational beacons

These receptions can be received and the signal to noise ratio calculated. With an accurate enough system, one can even determine the latency in communication due to the accuracy of the beacon's transmission time, although that was not done for this project.

A program by the name of Faros[14] was used to automatically listen to an SDR receiving on a particular frequency and calculate the signal to noise ratio. This was setup at the University of New Haven from April 14th to April 21th continuously listening and logging any beacon's received SNR.

7 Data, Results, and Discussion

The majority of the progress involved researching the HF band, receiving signals at a site 30 miles north of the University, and transmitting at the University's station. Due to a constraint of time and the lack of a functional transmitter until April, the receiver site design was not deployed, although one was quickly built for the expo showing its feasibility.

7.1 Short Distance Antenna Test

At the start of the project, two GPS 27 Half Wave antennas, an Airspy HF+ SDR, and a G90 radio were purchased to begin experimenting on the HF band. An initial test was conducted with the antennas about 250 feet apart. This test was to send a Morse Code message at 28.08Mhz with the G90 radio. This message was controlled with a relay and an Arduino input to the radio. On the receiver side, the SDR was connected to the antenna with a Low Noise Amplifier in series. A program by the name of *multimon_ng* was used to automatically decode the received Morse Code message into text to ensure transmission was successful. Shown in Figure 23 is the transmitter setup, and shown in Figure 24 is the received decoded Morse Code message, showing that this test was a success.

Figure 23: Short Test Transmitter Setup

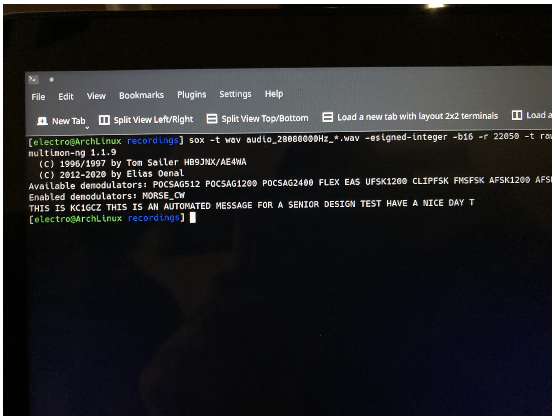

Figure 24: Short Test Received Data

7.2 Antenna Simulations

Knowing the radiation pattern of our antennas will allow us to estimate how well our antennas are transmitting at what direction. For example, for skywave propagation knowing the optimal takeoff angle will help determine which locations will be receive the signal.

Numerical Electromagnetics Code (NEC) was a programmed designed in Fortan in the 1970's by the Lawrence Livermore National Laboratory to simulate an antenna. The code is public, and has been ported and written in many libraries. The library used for this project is NEC2++ by Tim Molteno, which is a C++ application. The library offers a Python binding for it under the name PyNEC. This library only simulated the antenna, and plotting and demonstrating the data was left to the user. This is why Jamal created a Python library for PyNEC under the name PyNEC-Utilities. This library offers some nice utilities like plotting of the 3D and 2D radiation patterns.

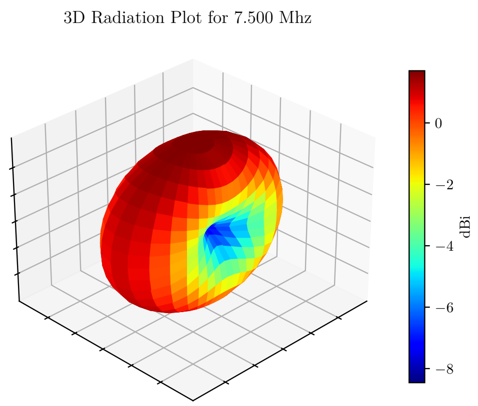

Figure 25: ALA1530LN Radiation Pattern at 7Mhz

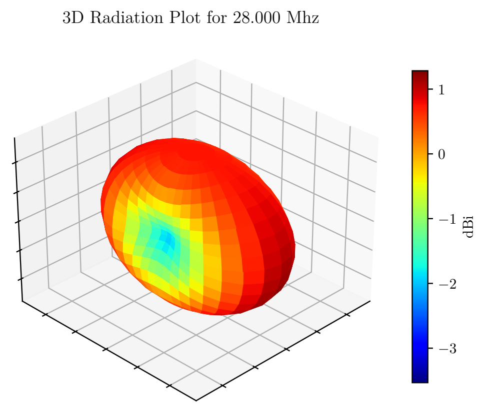

Figure 26: ALA1530LN Radiation Pattern at 28Mhz

Shown in Figures 25 and 26 are the radiation patterns for the ALA1530LN antenna that will be used in our receiver setup. Both plots have the same 3D orientation. The directionality of the antenna seems to be rotated by 90° from the lowest band of interest to the highest band of interest. This data is what partially determined our need for a rotator for the receiver setup.

Antenna Simulations mapped to an HF Hop

If we take the radiation pattern and map it out on a map with a single or multiple HF hops, we can determine the locations with the highest gains. The ALA1530LN's radiation pattern mapped from 1 to 4 hops is shown in Figure 27 with the antenna facing east to west on its plane. The grey dots show the radiation pattern's data point mapped out, and the colours in between are interpolation of the radiation pattern.

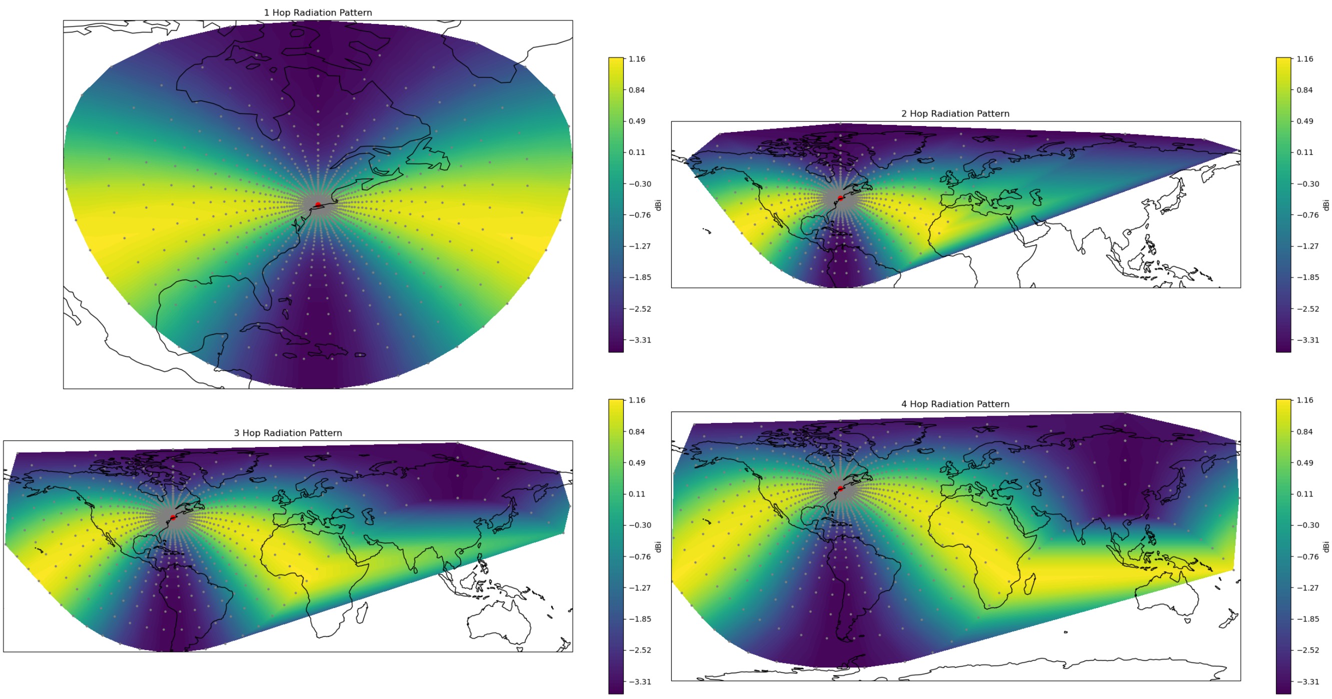

Figure 27: ALA1530 Radiation Pattern Mapping on multiple HF Hops

7.3 SDR Characterization

The script for this characterization, as mentioned in Section 6.4, was created in Python with GnuRadio's Python bindings. The program as mentioned stores a list of output power, the SDR's power spectrum's peak's average over the 50 gathered data points, and the standard deviation of those data points per SDR setting and center frequency.

Using an AirSpy HF+ SDR and a N9310A RF signal generator and the script, one of the SDRs was characterized, with the following plots showing some of the data.

Looking at Figure 28, as the signal frequency is increased the SDR's power spectrum output is decreased.

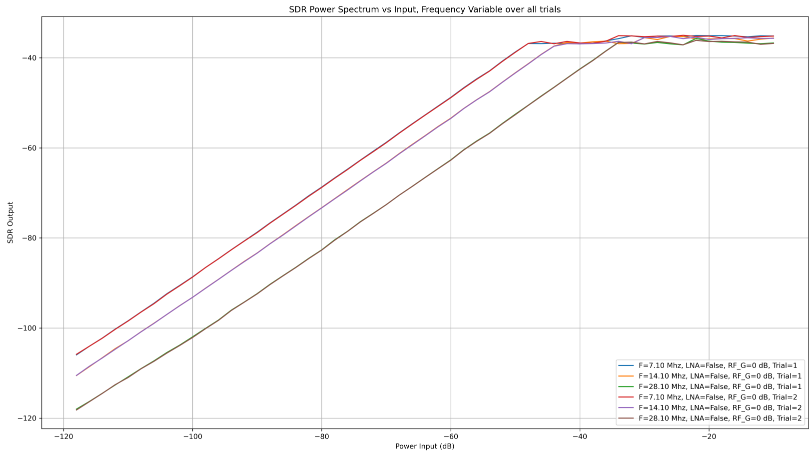

Figure 28: SDR Characterization For Different Frequencies

In Figure 29, what the RF attenuator is set to is not reflected in our measurements. We get a -2.5dB attenuation when setting the SDR's RF attenuator to -8dB, -11dB for -16dB, -15dB for -24dB, -20dB for -32dB, -32dB for -40dB, and -37dB for -48dB for 28Mhz.

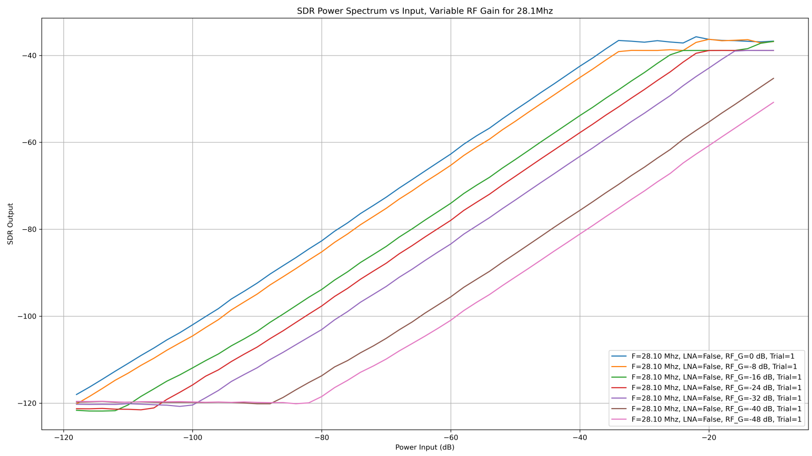

Figure 29: SDR Characterization For RG Gains

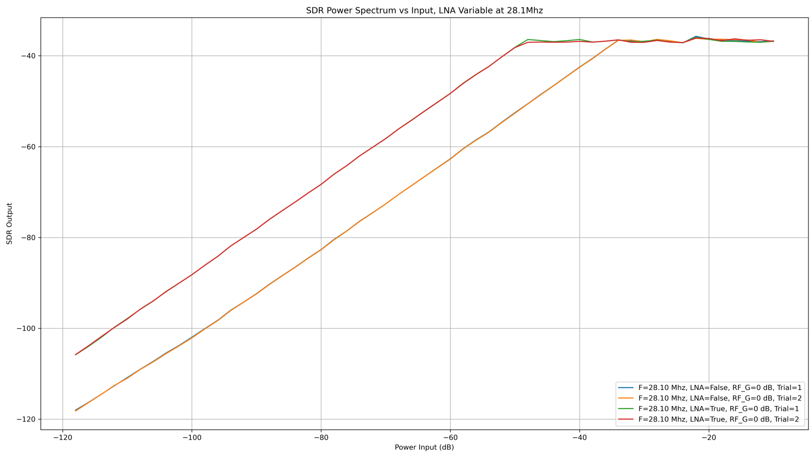

Figure 30: SDR Characterization for the LNA at 28.5Mhz

Looking at the following plots in Figures 30 and 31, a $\simeq 14db$ gain was measured when the LNA was activated.

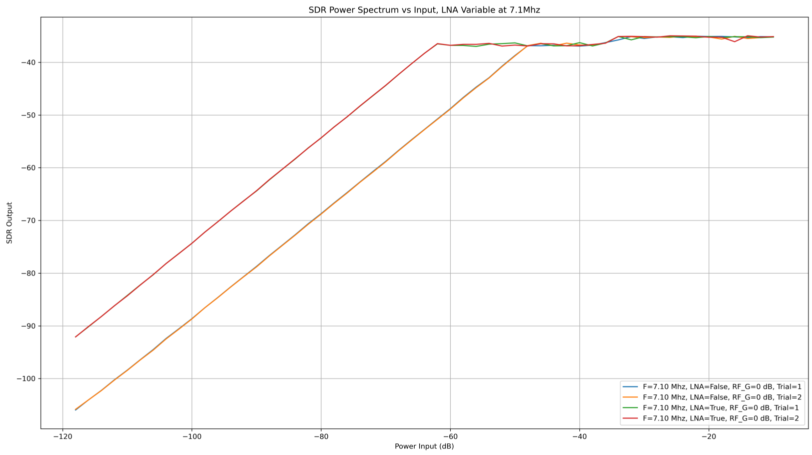

Figure 31: SDR Characterization for the LNA at 7.2Mhz

7.4 G90 Characterization

The first purchased radios before the FT891, the G90, was characterised in the setup shown in Section 6.4. The results are plotted in Figure 32. This was interesting because the claimed real transmit power did not match with the actual transmitted power as measured by the spectrum analyzer.

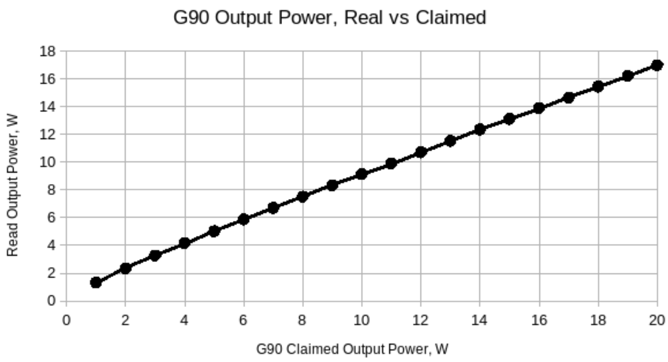

Figure 32: SDR Characterization for the LNA at 7.2Mhz

7.5 FT8 Received CQ Calls

As previously mentioned, a home receiver setup described at Section 6.3 was used to receive FT8 CQ calls, which included the signal to noise ratio of the signal and the maidenhead location of the transmitter. This data collection was done over the span of a month, from March 5th to April 10th. Something to keep in mind while analyzing this data is that we had no control of any given transmit location, which includes the antenna used and the transmit power.

The amount of CQ calls received over time is plotted and shown in Figure 33. The switch between 21Mhz and 28Mhz was done manually in the middle of the month data collection time. We can see that there is a certain region of time where any data is received. If we plot this data but ignoring the date, we get Figure 34. As we can see from that graph, all received data is between about 7am and 9pm, with the majority being between 9am and 7pm. This is because at night, the F layer isn't as active so the higher band signals (the 21 and 28Mhz signals) don't propagate as well as daytime. We can also see that 21Mhz signals are available earlier and later than 28Mhz signals.

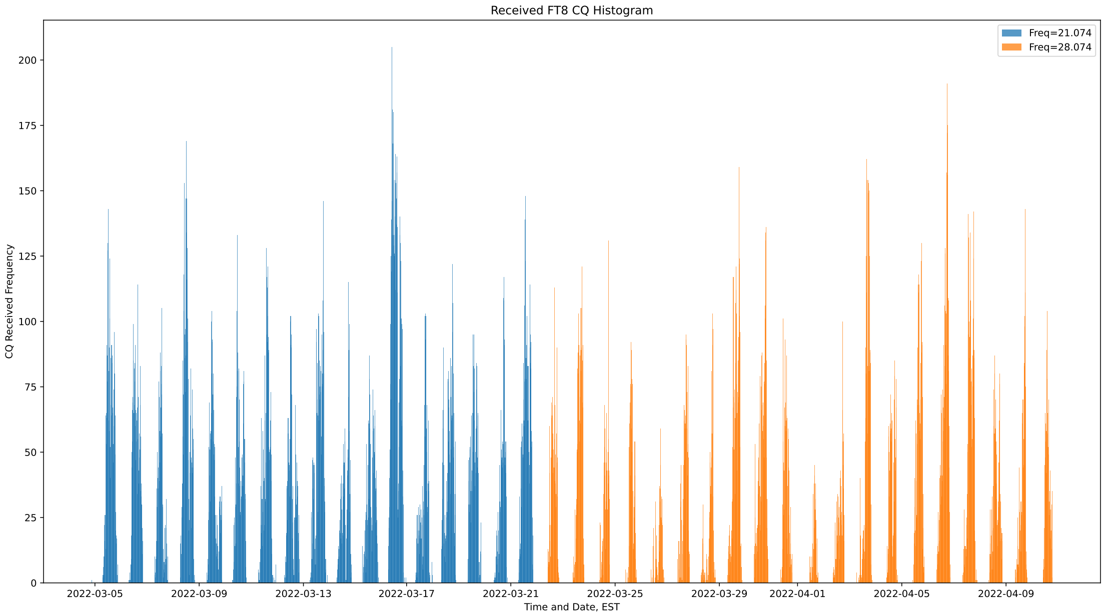

Figure 33: Received FT8 CQ calls plotted over time

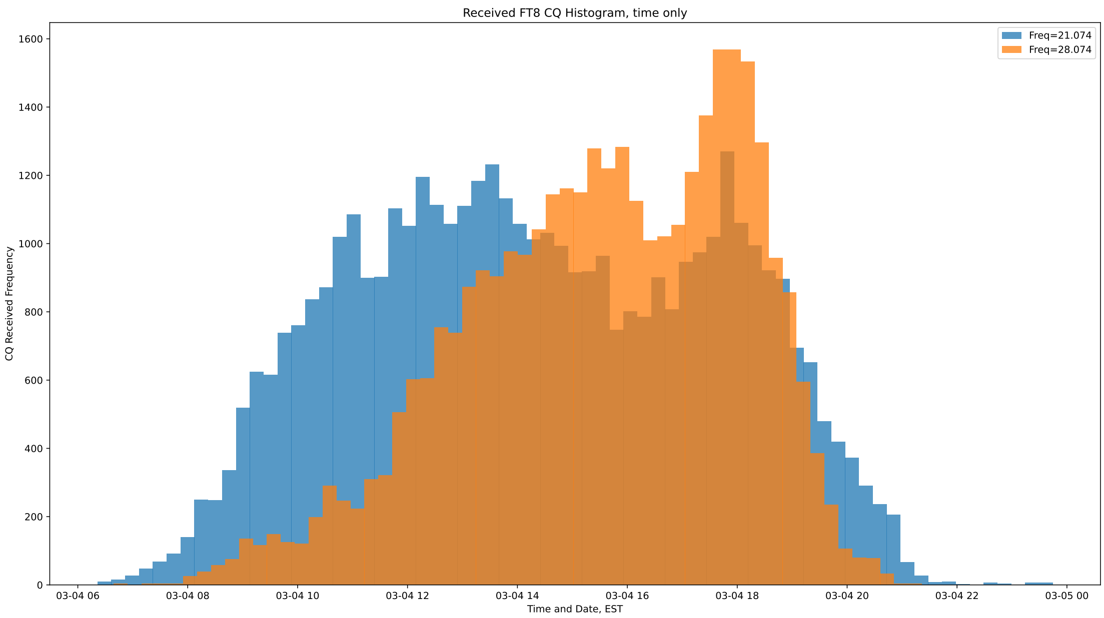

Figure 34: Received FT8 CQ calls plotted over time of day

The signal to noise ratio of CQ calls versus the distance of the call's transmit location (thru FT8's maidenhead location data) is plotted and shown in Figure 35. As we can see, for very close signals the SNR is high, which are signals propagating thru LOS or groundwaves. The SNR quickly drops off before skywaves signal's SNR picks up. The dead zone of sorts in between is no coincidence, as that is the gap between the maximum groundwave propagation distance and nearest skywave hop distance. Past 2000km, the SNR stays consistent with a slow roll-off until 9000km. The gap in signals at around 4500km are regions where nobody lives in. The signal to noise ratio overall is great, but FT8 was designed for weak signals.

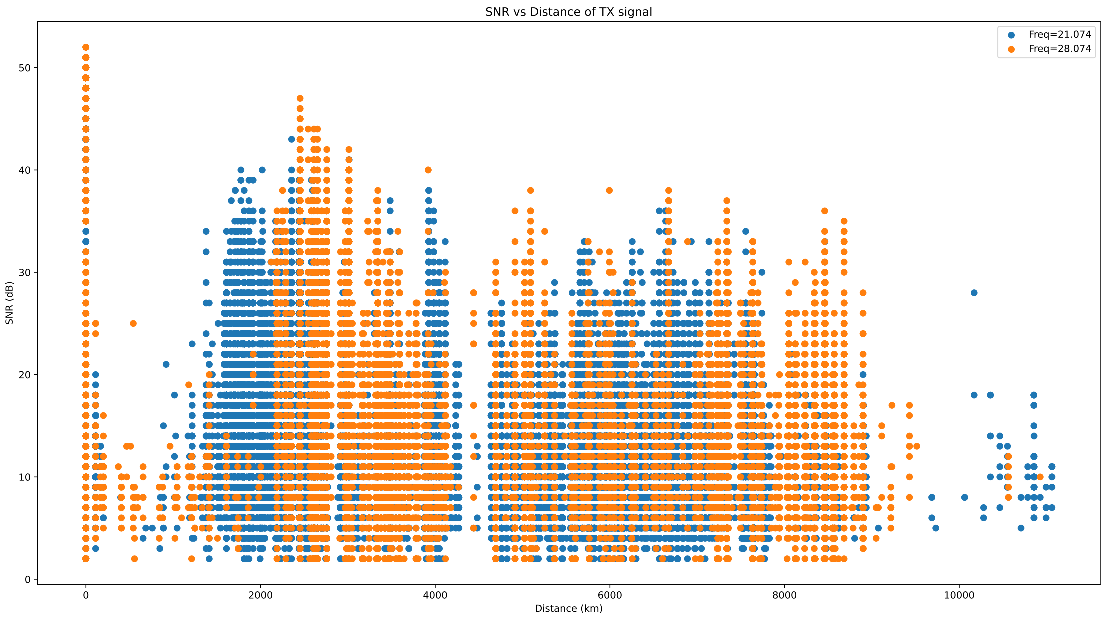

Figure 35: Received FT8 CQ calls's SNR plotted versus distance

The received longitude difference between the signal's transmit location and the home receiver location versus time of day is plotted and shown in Figure 36. As we can see, there is almost a trapezoidal shape to the plots, which confirms that the locations east propagate earlier due to the sun orbiting east to west from earth's point of view.

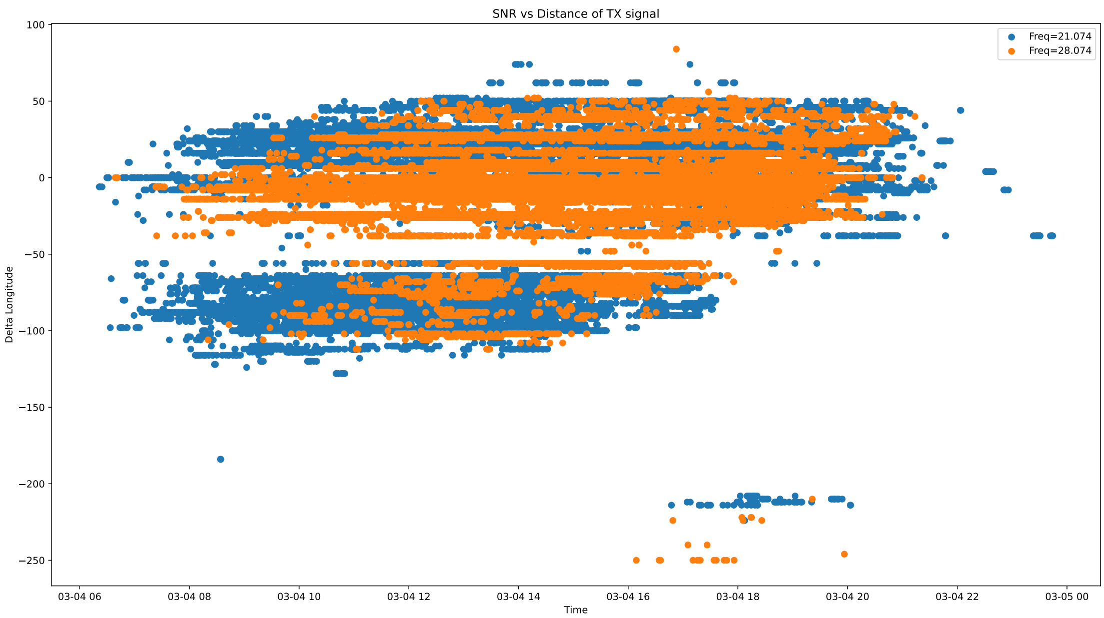

Figure 36: Received FT8 CQ calls's longitude difference versus time of day

A plot of all received CQ call's locations is shown in Figure 37. As we can see, we received FT8 signals from pretty much all over the world. The majority of the locations that wasn't received from is most likely due to a lack of somebody transmitting on FT8 rather than a lack of a usable channel.

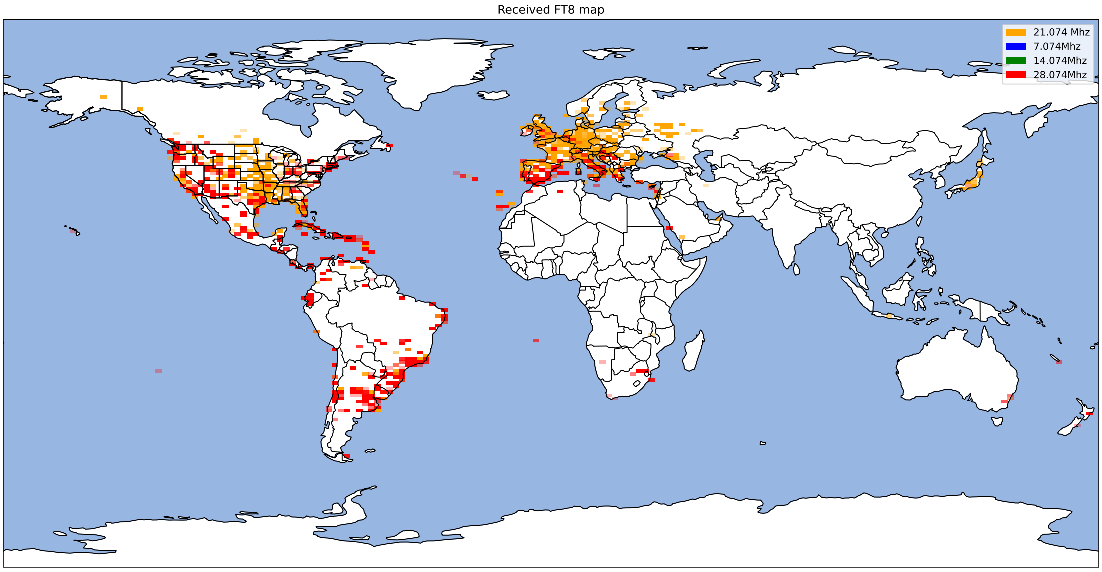

Figure 37: Received FT8 CQ calls's location

7.6 QSOs

When the UNewHaven amateur radio station was partially operational, even without rotation capability we were able to make some confirm contacts (back and forth communication to confirm we heard each other) primarily on FT8. A map of the locations we made confirmed contact with is plotted and shown in Figure 38. All contacts were done in less than an half an hour of cumulative transmission time.

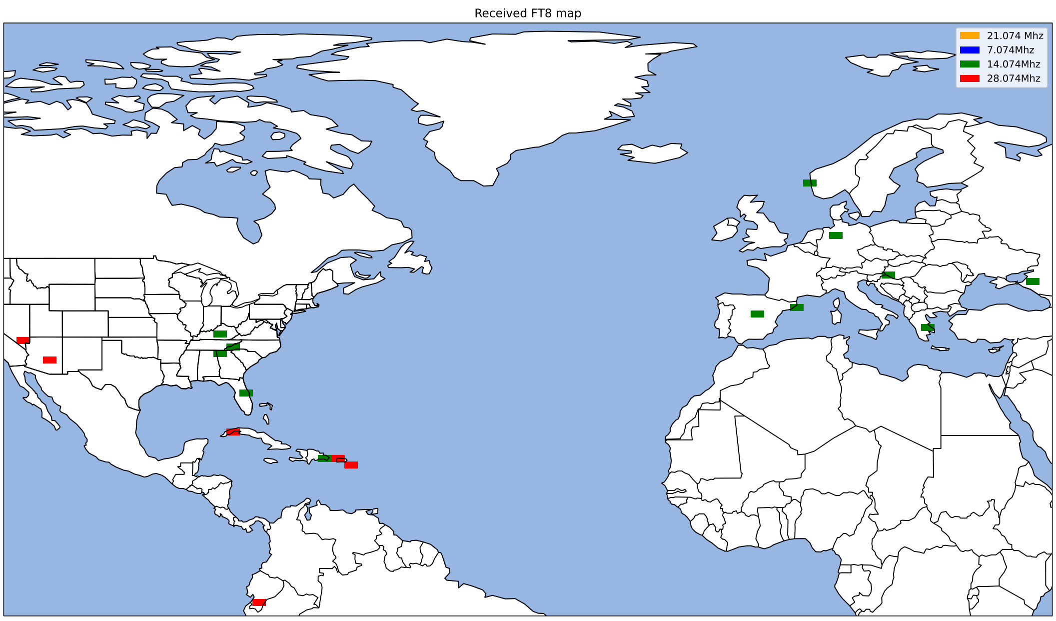

Figure 38: Confirmed Contact's locations on FT8

There are operators that are all over the world that log any received transmission to `pskreporter.com`, a service that logs this data for 24 hours. The data for our transmission was downloaded for a particular day when we were transmitting with about 50W or less of power, and the plot of locations that received our transmission is shown in Figure 39. The transmission time was around 3-5pm EST. This shows that with our setup under 50W all of the dotted locations received our transmission successfully.

If we plot the received signal to noise ratio on the reported receiver's end from our transmission, we can see as shown in Figure 40 that the signal to noise ratio peaked at around 1500km and rolling off from there.

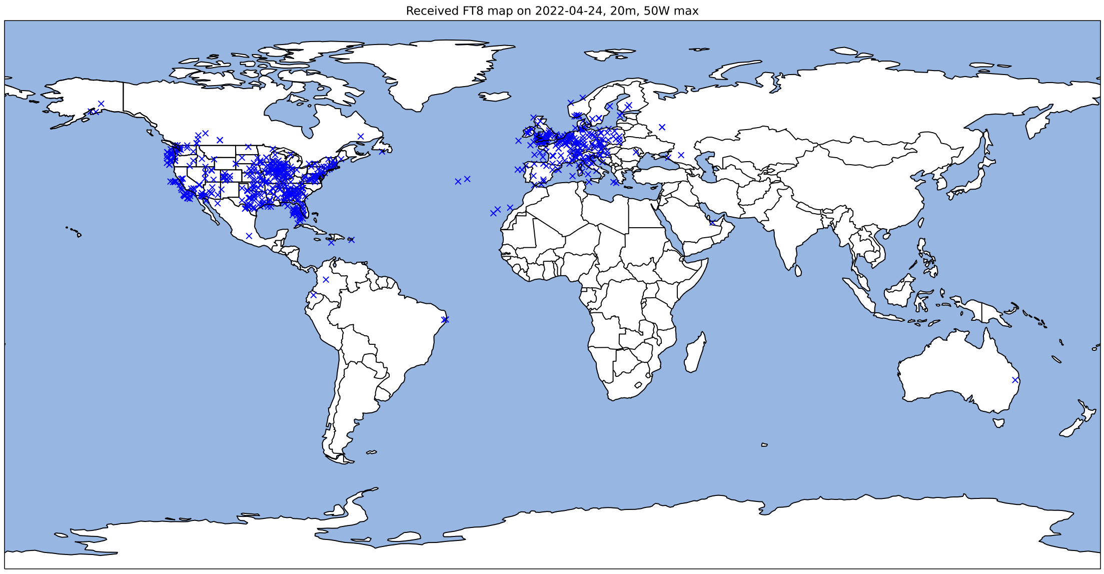

Figure 39: Reported reception location from other stations from our transmission

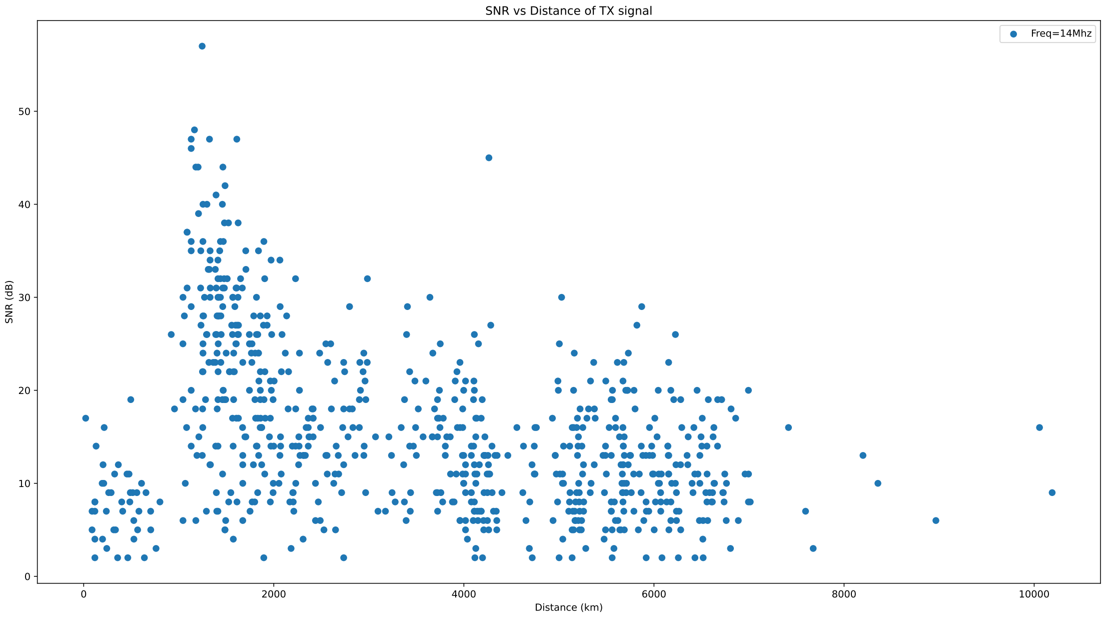

Figure 40: Reported reception SNR from other stations from our transmission

7.7 Beacon Reception

As mentioned in Section 6.5, the International Beacon Project hosts multiple beacons around the world transmitting 24/7, and the signals from these beacons are able to be analyzed with a Windows program by the name of Faros. This was done from April 14th to April 25th, analyzing at 24Mhz from April 14th to April 21th where the frequency was switched to 14Mhz.

If we plot all received signal's SNR vs their location, we can see from graph Figure 41 that the the beacon station closest to the University of New Haven (NYC), propagates thru groundwaves, then the next closes stations are all propagating thru skywaves with a decreasing peak SNR as distance increases. The signals to noise ratio are very variable, anywhere from near 0db to 8db.

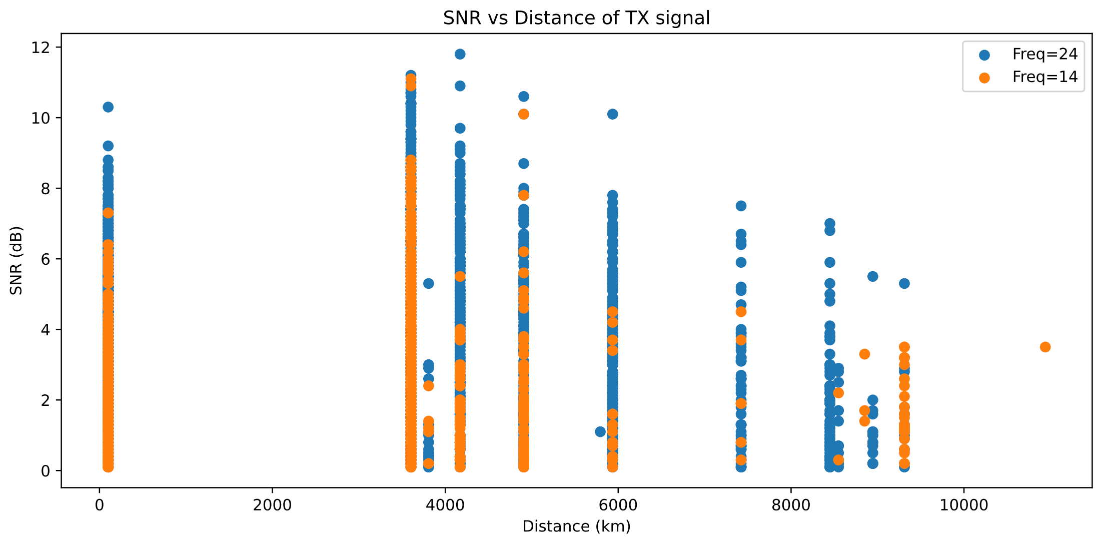

Figure 41: IBP's Beacon's SNR vs Distance

A plot of all received beacon's signals over the course of this experimentation is shown in Figure 42. This graph is a bit of a mess to analyze, so select beacons will be individually analyzed.

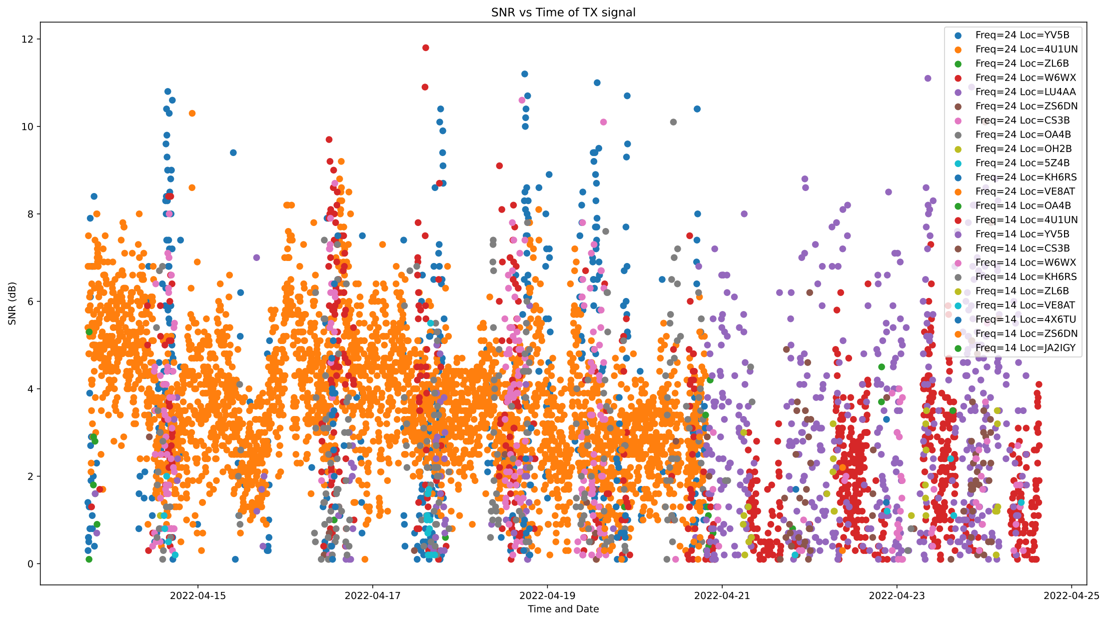

Figure 42: IBP's Beacon's SNR vs Time

If we plot all received signals from station 4U1UN alone (NYC), as we can see in Figure 43 that the signal to noise ratio is continuous from daytime to nighttime on 24Mhz but not on 14Mhz. While this does showcase that the propagation mode for 24Mhz is groundwaves due to it's consistency, for 14 Mhz it surprisingly does not. If we plot all received signals from 4U1UN versus time of day disregarding date, we see that the majority of the received signals were between 8am and 4pm EST as shown in Figure 44. This was a strange finding, as that is not consistent with the physics of groundwave propagation

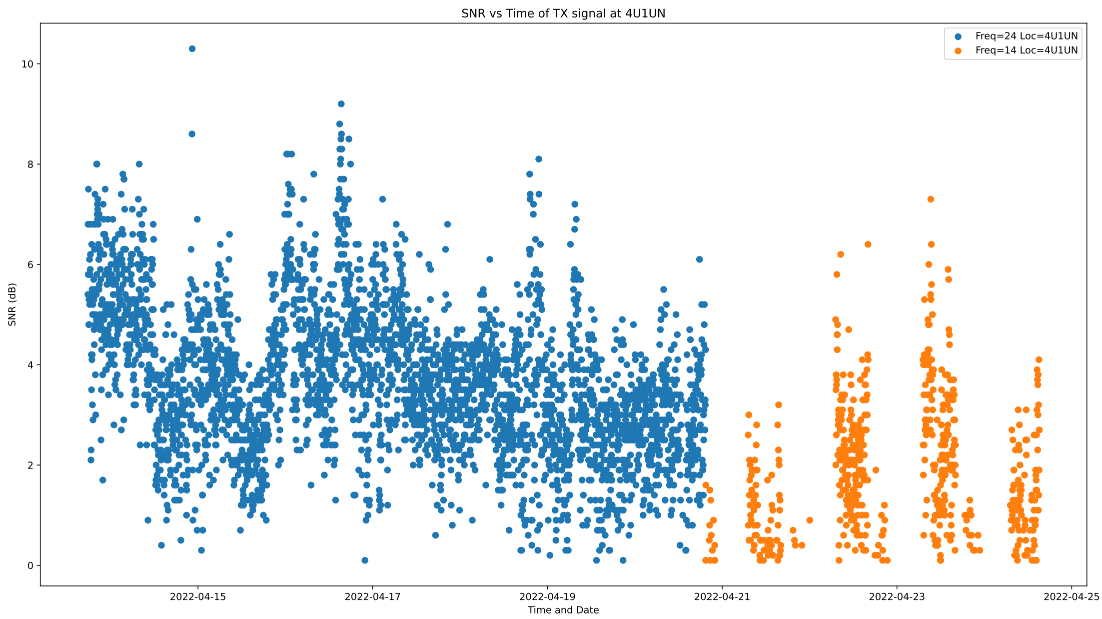

Figure 43: IBP's Beacon's SNR vs Time, station 4U1UN

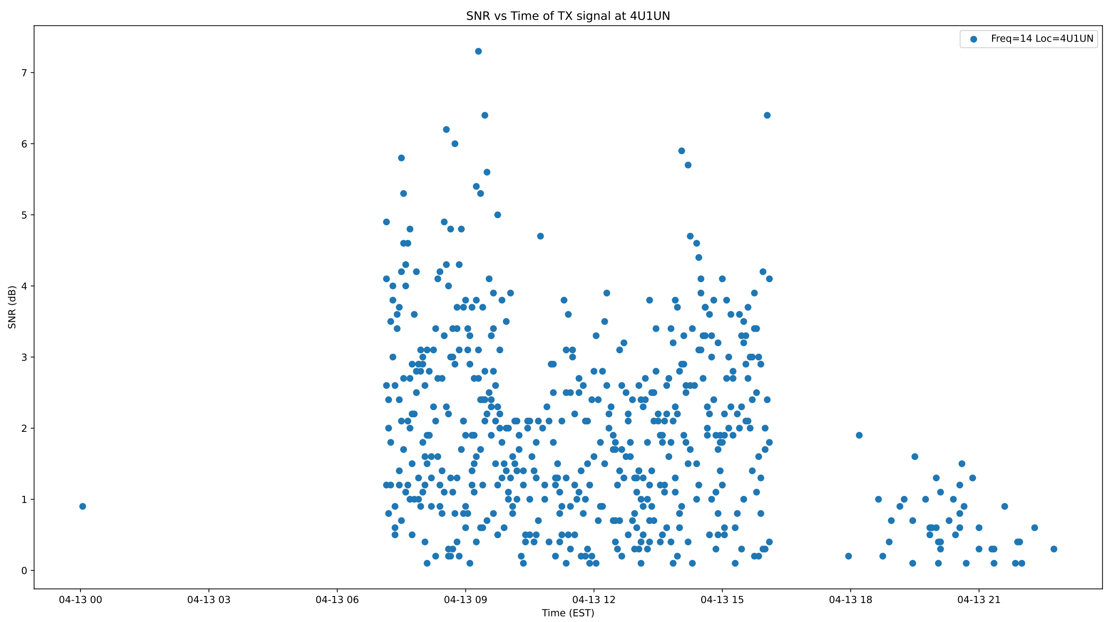

Figure 44: IBP's Beacon's SNR vs Time, station 4U1UN, 14Mhz

If we plot the SNR vs time and date from another beacon with the second most activity, YV5V (Venezuela), shown in Figure 45 we can see that there are times of the day where the signal is most active, further demonstrated in Figure 46 where there is a gap between 1am and 7am EST. For 14Mhz as shown in Figure 47, it is interesting that there is a gap between noon and about 2:30pm. This little gap we cannot determine the cause of it.

Figure 45: IBP's Beacon's SNR vs Time, station YV5V

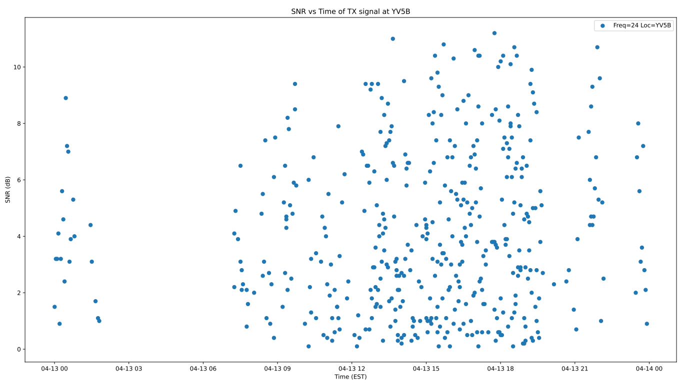

Figure 46: IBP's Beacon's SNR vs Time, station YV5V, 24Mhz

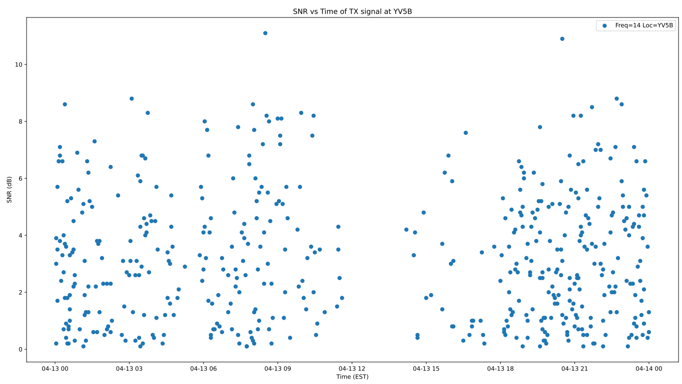

Figure 47: IBP's Beacon's SNR vs Time, station YV5V, 14Mhz

For the station W6WX (California), plotting the received signal's SNR versus time of day as shown in Figure 48 shows another interesting phenomena where 24Mhz signals were prominent between 10am and 10pm as expected, but the 14Mhz signal did not get detected during that time but instead were detected outside of that timeframe except in between 1am and 8am.

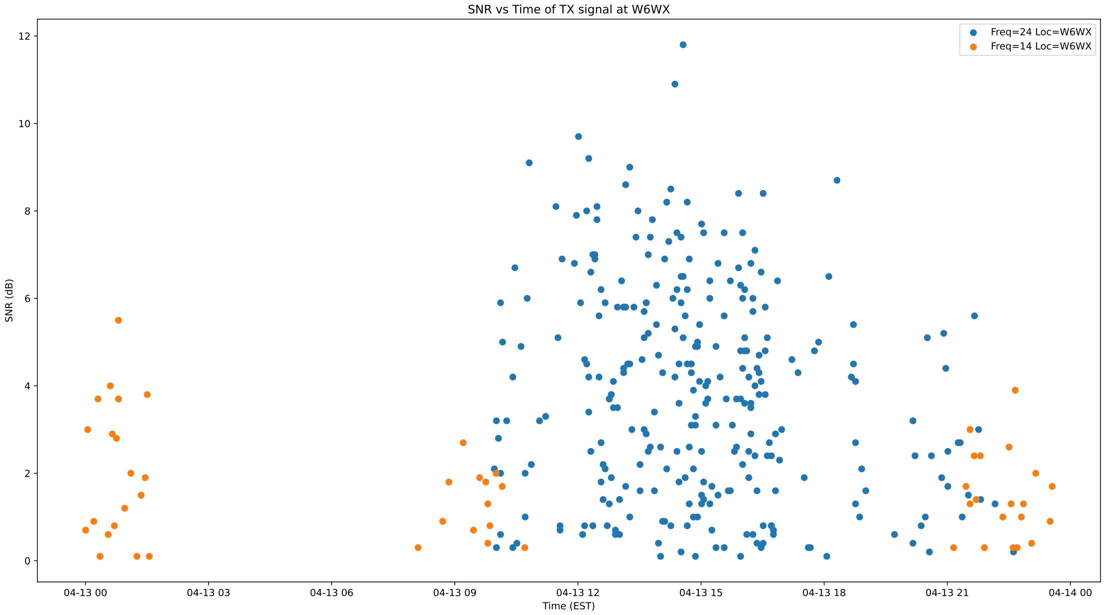

Figure 48: IBP's Beacon's SNR vs Time of Day, station W6WX

The strange behaviour seen in this section cannot be accounted for with rational explanations, so it is concluded that this data, while it does give some insight into propagation conditions, is not enough to make a conclusive analysis.

7.8 Ground Wave Propagation Prediction

Per the ITU-R P.368[15] as mentioned in Section 4.2, we can use the model provided by the ITU to run groundwave propagation path loss predictions. One of those predictions is shown in Figure 49. The parameters for this plot is over dry land ($\sigma = 3x10^{-2}S/m$, $\epsilon = 40$) at all ISM band's center frequencies in the HF spectrum. As we can see, the path loss is higher for higher frequencies as expected.

This mode of propagation can be useful if the variability of skywave propagation conditions are not suited for an end application. For example, if system includes a receiver has a sensitivity of -130dBm and a transmit power of 1W at the base station, thru this predicted path loss one can expect a maximum base-to-mobile distance of 100km on 27Mhz, 140km on 13Mhz, and 220km on 7Mhz which is more than usable for certain applications.

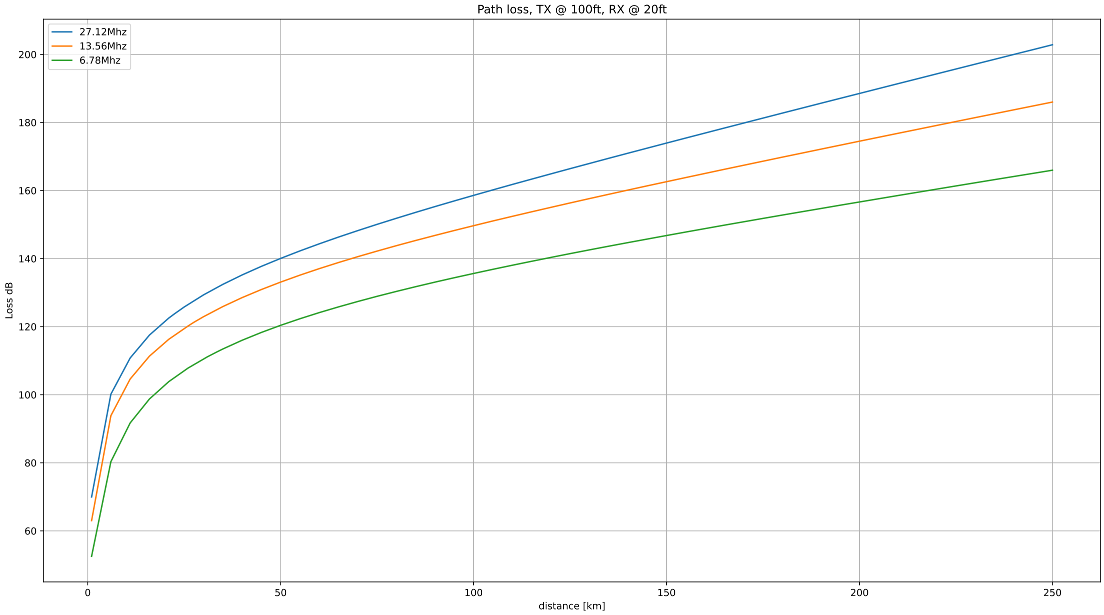

Figure 49: Groundwave Propagation Predicted Path Loss

8 Conclusions and Final Notes

8.1 Band Conclusion

From the data acquired during the course of this project, we can safely conclude that worldwide end-to-end direct communication is possible over the HF band given the right conditions. Groundwave propagation is useful for shorter distances (<150km), anything after that skywave propagation is the only propagation mode that will reach those distances. Skywave propagation is more variable than other modes of propagation due to its dependence on the sun's activity.

8.2 HF Band for Practical Applications

The HF band's modes of propagation (groundwave and skywaves) can have some niche applications. The primary advantage would be a reduction in propagation delay, which was the reason the sponsor was interested in this project. All other communication methods as listed bellow suffer from a higher propagation delay for medium to long distances.

- Line of Sight radio communication at higher frequencies: Suffers from distance, so repeaters will need to be setup for longer distance communication which introduces delays by the repeaters.
- Fiber Optic Cable: Suffers from a lower propagation delay as light in fiber optic cables only travel at 2/3 the speed of light
- Copper Cable: Suffers from distance, so repeaters will need to be setup for longer distance communication which introduces delays by the repeaters.
- Earth-Satellite: Suffers from propagation delay due to each satellite in the chain of communication acting as a modem with its own delay.

Another advantage of HF propitiation modes is the lack of an existing infrastructure, which is useful for emergency communication situations where power might be down at the repeaters.

The biggest disadvantage of using the HF band for an application is the variability in channel conditions. This is more an issue for skywave propagation, as groundwave propagation does not really suffer this variability. Predicting the current and future ionospheric conditions is required for an end-to-end system design using skywave propagation. Ionosondes can measure the critical frequency at its locations as mentioned in Section 4.2. Using them with interpolation in between, we can estimate the critical frequencies for any given HF hop location. The ionosondes can be used with major solar prediction data to predict the feasibility of HF propagation on any given day.

The ITU provides further recommendations on predicting the system reliability and the maximum usable frequency in ITU-R P.533[21], P.842[22], and P.1240[23].

Applications with multiple paths

One potential implementation of HF communication to alleviate any channel issues is with conjunction with other modes of communication. For example with both an HF station and a fiber optic line. If the HF channel is sufficient, data transmitted will arrive at the receiver first, and thus any data from the fiber optic can be discarded. If the channel is poor and data does not arrive, it will arrive later thru the fiber optic channel. This is particularly useful where low propagation communication is desired but is already using a fiber optic line, such as in the case of financial market trading.

8.3 Safety Concerns

The only major safety concern with this project is RF exposure when transmitting. The Federal Communications Commission (FCC) has exposure limits as outlined in 47 C.F.R. 1.1307(b), 1.1310, 2.1091, 2.1093[17][18]. The FCC also provides a guideline for evaluating a station's exposure to say in compliant with federal regulations outlined in [19].

The Bulletin provides a power threshold before a station should be self-evaluated. For the purposes of this project, the only transmissions were on 14Mhz and 28Mhz, each with a threshold of 225W and 50W respectively before the station should be evaluated. No power level above those thresholds were transmitted, so the station was compliant with the bulletin's guidelines.

For the future of the amateur radio station, an evaluation will be self-conducted when the station is fully operational and complete to stay within federal guidelines and regulations.

8.4 Project Costs

The allotted budget for the project was set as $3,000 but based on the cost of equipment after further research some flexibility was granted to exceed the provided budget. The budget includes the equipment to both transmit and receive HF signals, which includes radios, SDRs, antennas, and other miscellaneous components. Due to antenna alignment, rotators and rotator controllers must also be added to this budget.

The cost for this project is around $8000. The Bill of Materials as of that date is shown in Table 3 in the Appendix.

8.5 Future Recommendations

Receiver Setup

The setup described in Section 6.2 was unfortunately not able to be deployed. For future work, the setup should be deployed in multiple locations for a remote reception site.

International Beacon Project Reception

Regarding the International Beacon Project reception, it was concluded that the collected data was not sufficient to make any meaningful analysis due to the inconsistencies in the data versus what we know about HF propagation. It is recommended in the future to create a more robust setup to run this test over a longer period of time. The software used, FAROS, is also somewhat problematic due it's closed algorithm and source code. It is recommended in the future to write a software from scratch that can detect the CW signal codes and output the signal to noise ratio in order to have control of the underlying detection and signal-to-noise calculation algorithms.

9 Team Qualifications

Jamal Bouajjaj, Team Leader | Electrical Engineer

- **Overview:** Jamal is a semi-experienced electrical engineer with personal and professional experience. He has experience with designing circuits in KiCad and Altium Designer, creating Python applications, and embedded firmware. Jamal is also a licensed amateur radio operator under the calls sign KC1GCZ.
- **Main Work Areas:** Project coordinator and top level designer.
- **Other Work Areas:** Python script designing and researching.
- **Public Profiles:**
  - Personal Site: `www.electro707.com`
  - GitHub: `https://github.com/Electro707`
  - LinkedIn: `https://www.linkedin.com/in/jamal-bouajjaj-93755514a/`

Sean Vallie, Team Member | Mechanical Engineering

- **Overview:** Sean has skills in general Mechanical Engineering as well as basic skills in electronics.
- **Main Work Areas:** Mounting systems for antennas, rotators, and controllers for each rotator.
- **Other Work Areas:** Project planning, research, troubleshooting, and documentation.

Mackenzie Myers, Team Member | Electrical Engineering

- **Overview:** Mackenzie has skills in general Electrical Engineering and good work ethic skills. She can research and learn about information she needs to know to completely understand what is going on.
- **Main Work Areas:** HF propagation and waves
- **Other Work Areas:** Documentation, project planning, and research

Thomas Kittelberger, Team Member | Computer Engineering

- **Overview:** Thomas has skills in general Computer Engineering and some basic coding skills.
- **Main Work Areas:** Software design and coding.
- **Other Work Areas:** Research, Project Planning, and Documentation.

10 References

References

[1] N4UFP | HF Radio Wave Propagation
https://nonstopsystems.com/radio/pdf-hell/article-radio-propagation-N4UFP.pdf

[2] Wikipedia | Ionosphere
https://en.wikipedia.org/wiki/Ionosphere

[3] Wikipedia | Reflection Coefficient
https://en.wikipedia.org/wiki/Reflection_coefficient

[4] Wikipedia | Standing Wave Ratio
https://en.wikipedia.org/wiki/Standing_wave_ratio

[5] Dr. Marc Lichtman | PySDR: A Guide to SDR and DSP using Python: Sampling
https://pysdr.org/content/sampling.html

[6] Wikipedia | Software Defined Radio
https://en.wikipedia.org/wiki/Software-defined_radio

[7] Electronics Notes | What Is a Vector Network Analyzer, VNA: The Basics.
www.electronics-notes.com/articles/test-methods/rf-vector-network-analyzer-vna/what-is-a-vna.php.

[8] Wikipedia | Radio Propagation
en.wikipedia.org/wiki/Radio_propagation

[9] Space Weather Prediction Center | Global D-Region Absorption Prediction Documentation
https://www.swpc.noaa.gov/content/global-d-region-absorption-prediction-documentation

[10] Herbert H. Sauer and Daniel C. Wilkinson | Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons
https://www.ngdc.noaa.gov/stp/drap/Sauer_DRAP_Tech_Description.pdf

[11] Steve Franke (K9AN) Bill Somerville (G4WJS), and Joe Taylor(K1JT) | The FT4 and FT8 Communication Protocols
https://physics.princeton.edu/pulsar/k1jt/FT4_FT8_QEX.pdf

[12] EA4FSI radio station | Geometry and operative aspects of the simple modes of ionospheric propagation
https://www.ipellejero.es/hf/propagacion/iono-geo/english.php

[13] http://www.movable-type.co.uk/scripts/latlong.html

[14] http://www.dxatlas.com/Faros/

[15] Internation Telecommunication Union | Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.368-9-200702-I!!PDF-E.pdf

[16] 47 C.F.R. Part 1.1307
https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-1/subpart-I/section-1.1307

[17] Federal Communications Commission | FCC Policy on Human Exposure
https://www.fcc.gov/general/fcc-policy-human-exposure

[18] Federal Communications Commission | Radio Frequency Safety
https://www.fcc.gov/general/radio-frequency-safety-0

[19] Federal Communications Commission | OET Bulletin 65
https://transition.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet65/oet65.pdf

[20] 47 C.F.R. Par 97 https://www.ecfr.gov/current/title-47/chapter-I/subchapter-D/part-97

[21] Internation Telecommunication Union | Method for the prediction of the performance of HF circuits
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.533-14-201908-I!!PDF-E.pdf

[22] Internation Telecommunication Union | Computation of reliability and compatibility of HF radio systems
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.842-5-201309-I!!PDF-E.pdf

[23] Internation Telecommunication Union | ITU-R methods of basic MUF, operational MUF and ray-path prediction
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.1240-2-201507-I!!PDF-E.pdf

11 Appendix

Related libraries used:

- PyNEC Utilities: `https://github.com/Electro707/pyNEC-Utilities`
- NEC2++ Library: `https://github.com/tmolteno/necpp`
- GRWave: `https://github.com/space-physics/grwave`

The raw data collect that are used to generate the graphs shown in this project are scattered as text files that would be too long to fit in this report. If you would like a copy of the raw data, feel free to reach out to `jboua1@unh.newhaven.edu`.

Description	Vendor name	Cost	Quantity	Total	Date Mark Or
LNA (Low Noise Amplifier) for SDR	Amazon	24.95	1	24.95	9/21/2021
Amateur Radio	Amazon	449	1	449	9/21/2021
HF SDR (Software Defined Radio)	AirSpy	169	1	169	9/21/2021
10m Band Antenna	Amazon	99	2	198	9/21/2021
airspy shipping	airspy	15	1	15	9/21/2021
BNC Female to UHF Male PL259 Connector Pack of 2	amazon	6.59	2	13.18	9/22/2021
SMA to BNC 3 Set Adapter 12 Pcs	amazon	11.89	1	11.89	9/22/2021
SMA Cable, 5-Pack 6 inch SMA Male to Male Coaxial Coax Cable RG316	amazon	11.99	1	11.99	9/27/2021
Ancable UHF/PL-259 Male Solder Coax Connector with Reducer Pack of 10	Amazon	29.39	1	29.39	10/7/2021
UHF Female to Female SO239 Socket Surge Protector Bulkhead	amazon	17.99	2	35.98	10/7/2021
UHF Male to Female SO239 Socket Surge Protector Bulkhead	Amazon	17.99	1	17.99	10/7/2021
TRAM Tramflex Coaxial Cable, 500 Feet, Black	Amazon	156.74	2	313.48	
CB Coax Cable 25ft, RG8x Coaxial Cable 25ft, RFAdapter UHF PL259 Male to Male	Amazon	24.99	1	24.99	10/14/2021
RG8x Coaxial Cable, PL259 CB Coax Cable, 10ft RFAdapter UHF Male to Male	Amazon	13.99	1	13.99	10/14/2021
SMA-UHF RF Connectors Kit SMA to UHF PL259 Pack of 4	Amazon	8.89	1	8.89	
RG8x Coaxial Cable, CB Coax Cable, 50ft RFAdapter UHF PL259 Male to Male	Amazon	34.99	1	34.99	10/21/2021
The ARRL Ham Radio License Manual Spiral	amazon	31.3	1	31.3	10/22/2021
The ARRL General Class License Manual	Amazon	29.02	1	29.02	10/22/2021
Pack of 10 UHF Male PL-259 Plug Crimp for RG8X RG-8X LMR240, Eifagur	Amazon	23.99	1	23.99	11/8/2021
SMA Male to SMA Female RF Attenuator, DC to 6.0GHz, 50Ω, 2W, 30dB 3-Pack	Amazon	23	1	23	11/9/2021
150' Length 8 Conductor Rotor Wire - Antenna Rotator Cable	Amazon	162	1	162	11/16/2021
Seismic Audio - Two Pack Speakon Panel Mount Connector - 8 Pole	Amazon	15.85	1	15.85	11/16/2021
Seismic Audio - New Pack of Four Speakon Connector 8 Pole Plug	Amazon	26.33	1	26.33	11/16/2021
Crucial MX500 500GB SATA 2.5 Inch Internal SSD- CT500MX500SSD1	Amazon	54.99	1	54.99	11/18/2021
RCA VH226E Programmable Outdoor Antenna Rotator	Amazon	124.56	2	249.12	
Jameco ADU240100 AC to AC Wall Transformer 24VAC @ 1000 mA	amazon	14.82	2	29.64	
diamond D130J	HRO	124.95	2	249.9	
Yaesu FT-891	HRO	639.95	1	639.95	
yaesu g-1000dxa rotor	hro	579.95	1	579.95	
MFJ MFJ-1848 antenna	hro	749.95	1	749.95	
MFJ freight	hro	29	1	29	
brown direc burry cat6	amazon	129	1	129	
Active Loop Antenna NEW ALA1530LNP NA	Wellbrook Communications	315	3	945	
Wellbrook Shipping	Wellbrook Communications	40	1	40	
HF SDR (Software Defined Radio)	AirSpy	169	2	338	
Airspy shipping	AirSpy	25	1	25	
Libre Computer Board ALL-H3-CC 1Gb	Amazon	30	4	120	12/15/2021
Relay Module	Amazon	10.89	1	10.89	12/15/2021
Compass Module	Amazon	13.69	1	13.69	12/15/2021
100W Attenuator 50db	Amazon	95.8	1	95.8	12/15/2021
rohn 25g wall mount bracket	amazon	175	2	350	1/22/2022
rohn 25G shelf	amazon	85	2	170	
rohn thrust berring	amazon	199	1	199	
rohn 25g thrust bearing plate for top of tower	amazon	230	1	230	
Rohn 25G 10ft Tower Section	DX Engineering	158.99	2	317.98	
DX Engineering Shipping	DX Engineering	129	1	129	
Misc home depot hardware washers / nuts / 1.5" x 10' pipe & supplies	home depot	100	1	100	
UHF to N Connector Kit 4 Set	amazon	12.99	1	12.99	
N Female to N Female 2-Pack N Barrel Connector Coupler Adapter	amazon	8.99	1	8.99	
SignaLink Jumper	HRO	8.95	1	8.95	
SignaLink	HRO	134.95	1	134.95	
Heatsinks for Libre Computer board	Amazon	9.15	1	9.15	
30mm fan	Amazon	9.99	1	9.99	
r pi heat sinks	Amazon	7.79	1	7.79	
RG8X Cable	Amazon	34.99	1	34.99	
UNH Male to BNC Male Connector	Amazon	6.5	3	19.5	
			Grand Total	7727.36	

Table 3: Project BOM