Columbia Radio Astronomy Consortium (CRAC)

Construction & Set-Up of Low-Budget Radio Telescope at Rutherford Observatory, Columbia University

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Preface:

On a Thursday night, I remember expressing boldly to Ben and Tahmid the idea of building a radio telescope on Pupin's Roof. Without second guessing my overambitious idea, they both reassured me that we would all come together as a team and make this project possible. After some intensive research and insightful discussions with Dr. David Schiminovich, we concluded that the project was feasible; and so we embarked on a journey taught us many lessons about the nature of science but also the joy and excitement of transforming an idea to a working project. After endless hours spent on Pupin's rooftop and using our professor's insightful wisdom, we accomplished our very first goal; to receive celestial radio signals.

ad astra per aspera

Abstract

This project aims to demonstrate the feasibility of a cheap radio telescope with the higher performance of a large radio dish but the simplicity and accessibility of a smaller, layman's telescope. The telescope setup is described as well as the partial calibration of the system in order to collect data that can be processed with Python. This is achieved through a proof of concept observation of a solar drift that not only records a noticeable transit of the Sun, but also demonstrates the usefulness of the system by calculating the flux of the Sun and performing Fourier Transforms to pinpoint which frequencies are being emitted.

1. Introduction

Representing the lowest energies of the electromagnetic spectrum, radio astronomy allows observers insights into many of the Universe's diverse phenomena due to the fairly ubiquitous nature of radio waves and their wide range of wavelengths. Radio observation can shed light on exotic topics such as the spin of pulsars, peer through thick shrouds of dust at the center of the Milky Way galaxy, or simply just relay television signals from geostationary satellites orbiting Earth. This wide range of applications makes radio astronomy a very versatile tool to explore and manipulate the physical Universe. Due to the transparency of Earth's atmosphere to these radio wavelengths, many radio telescopes are terrestrial rather than needing to be flown into space to collect high-resolution images. This makes radio astronomy logistically simpler and allows individual telescopes or arrays to remain in service for long periods of time since constant maintenance is possible.

Whereas radio telescopes experience a great many advantages over higher frequencies, they do experience considerable drawbacks, the most notable of which is the large aperture size necessary for a resolution comparable to higher wavelengths. Since resolution decreases as wavelength increases – as dictated by the equation $\theta=\lambda/D$ – and radio wavelengths are very large (> 10 cm), the diameters of these telescopes become absurdly large, to the point where it becomes vastly more efficient to build arrays rather than individual telescopes (radiosky.com). Although radio wavelengths require incredibly large apertures to collect images with resolutions that rival those of higher energy emissions, amateur radio astronomy is still viable even without large and expensive radio dishes.

2. Background

Thanks to the pervasiveness of commercially available radio dishes used for satellite television, amateur radio astronomy at the most basic levels has become economically feasible. NASA recently launched its Radio JOVE Project which is an amateur-level radio astronomy initiative that aims to involve the public – and young people in particular – in radio observation of Jupiter and the Sun, two of the easiest to spot radio sources in the sky (NASA). Participation in this project includes a kit that allows the receiver to construct their own radio telescope out of a commercial satellite dish and some other NASA-manufactured components (such as a receiver and software package).

Other intrepid radio astronomers have managed to fashion their own homemade telescopes without the help of a pre-made NASA package. The vast majority of these homemade telescopes utilize many of the same resources as the Radio JOVE Project kit (i.e. a commercial satellite television dish) but replace some of the more sophisticated components – such as the receiver – with a co-opted satellite finder, which essentially measures the radio flux of the dish's current pointing in order to make locating geostationary telecoms satellites easier.

Many of these individuals have documented their creations and have shared the process of making them on the internet, sometimes in step-by- step form so that other potential radio astronomers can replicate these DIY telescopes (Heatherly, Crowley, & Smith) (NASA). The purpose of this project is to synthesize a coherent design for a radio telescope from the numerous disjointed resources that exist and improve upon existing features. Not only will this project utilize a larger dish to achieve a finer resolution, it will go farther in data analysis methods by not simply measuring the flux of bright radio sources, but extracting the spectra of identifiable sources between 3.4 GHz and 11.7 GHz (Seidle). This is a significant step up from previously constructed amateur radio telescopes since the resolution will be a factor of ~3 times better and the wavelength will extend into both the C and Ku bands (whereas commercial satellite television dishes mainly utilize only the C band), thus increasing resolution further due to shorter wavelength in the Ku band. The spectra that are extracted will be manipulated using a python script to subtract background noise and analyze the data, also a first among the majority of the amateur telescopes described (Falcinelli, 2017).

3. Method

3.1 Hardware

Our project consisted of the following components:

1. Digiwave 1.65 Meter Prime Focus Satellite Dish
2. BSC621 C/Ku Band LNBF
3. Digital satellite signal meter Finder with compass
4. Arduino Uno board with ATmega328P
5. AC to DC Adapter and a Voltmeter
6. Coaxial cables with a cable splitter
7. Resistors with 100Ω and 200Ω resistance

3.2 Software

We utilized the following python program to extract and decode the signal coming from our arduino board. The signal was initially channeled through an arduino program that converts the analog reading to voltage.

```
import serial
serial_port ='/dev/cu.usbmodem1411'
baud_rate = 9600 #In arduino, Serial.begin(baud_rate)
write_to_file_path = "filename.txt"

output_file = open(write_to_file_path, "w+")
ser = serial.Serial(serial_port, baud_rate)
while True:
        line = str(ser.readline())
        line = str(line.decode("utf-8")) #ser.readline returns a binary, convert to string
        print(line)
        output_file.write(line)
```

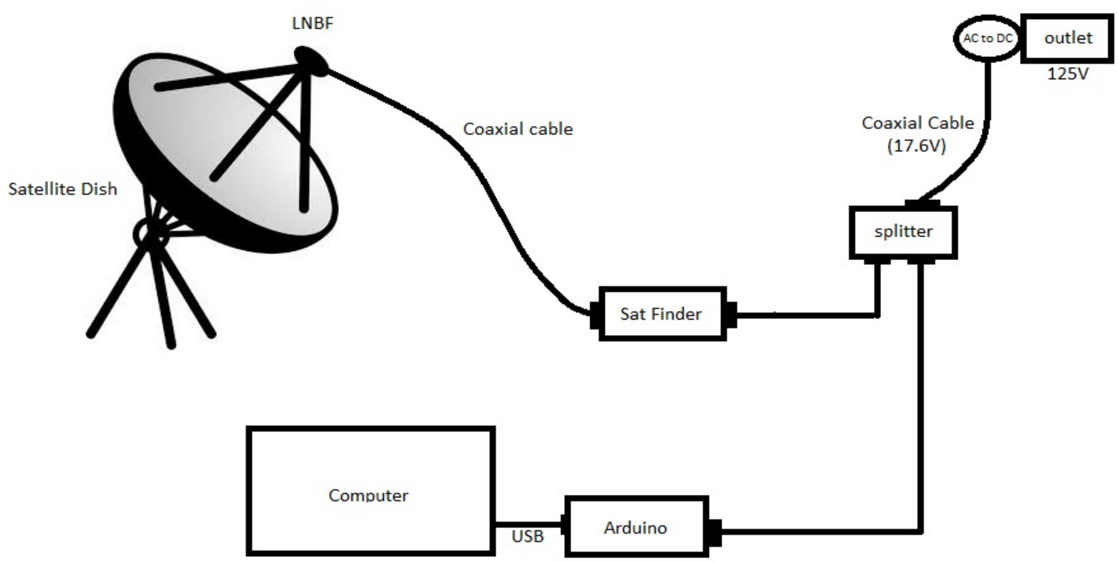
The program opens up a port from python's usb modem development API on the host machine, usually a laptop, where the Arduino board is plugged in.Then it creates a Serial object using the port at a defined rate to read and decode the signal. It continues to write the output to a file while the coaxial cable is feeding data. We can then analyze this file to plot data or for heuristics.

The Arduino pipeline uses the following code block. It initializes a serial communication at 9600 bits per second. Then we run an infinite loop while reading from the analog pin A0 and converting the analog reading (from 0-1023) to a voltage (0-5V).

```
        void setup() {
        Serial.begin(9600); // runs once when reset is pressed
}
void loop() {
        int sensorValue = analogRead(A0);
        float voltage = sensorValue* (5 / 1023.0);
        Serial.println(voltage);
        }
```

3.3 Set up

After acquiring all the components, we set up the satellite dish and moved it to the roof of Pupin. We connected a coaxial cable to an AC/DC adapter (125V-15V) to use with the wall outlet. The LNBF (low-noise block downconverter-feedhorn) was connected to a satellite finder which itself was connected to a splitter.



As proposed, the satellite finder measured the intensity of the radio emissions at the pointing of the dish and the LNBF combined the photon sensing capabilities of a feedhorn with the downconversion capability of an LNB. It collected the information acquired by the satellite dish and sent it to the receiver. For that purpose, we channeled to the Arduino’s A0 input and ran the programs from a usb-connected computer. Because the optimal operating power of an Arduino is between 7-12V, we had to use two resistors with a 100Ω and 200Ω resistance to step down the voltage.

4. Data Analysis

One we correctly understood the proper voltage for our Arduino and created a pipeline where the analog signal was converted to a digital form we utilize the satellite dish to obtain data in 3 distinctive forms: Drift Scan of Sun, Background Sky, LNBF Noise.

4.1 Background Sky

Similar to optical light pollution, radio frequencies also face the interfering factors of pollution "noise" that comes with the cost of living near bustling cities such like New York. Such sources may include, local radio towers, passing airplanes and generally reflection and scattering from the sunlight are some of the possible sources of background noise that contribute to the data. To normalize the background noise, we obtain our "flat" data by pointing the dish at zenith were it is found for it to be relatively "quiet" in radio. We estimate the average Volt of V=1.56 V.

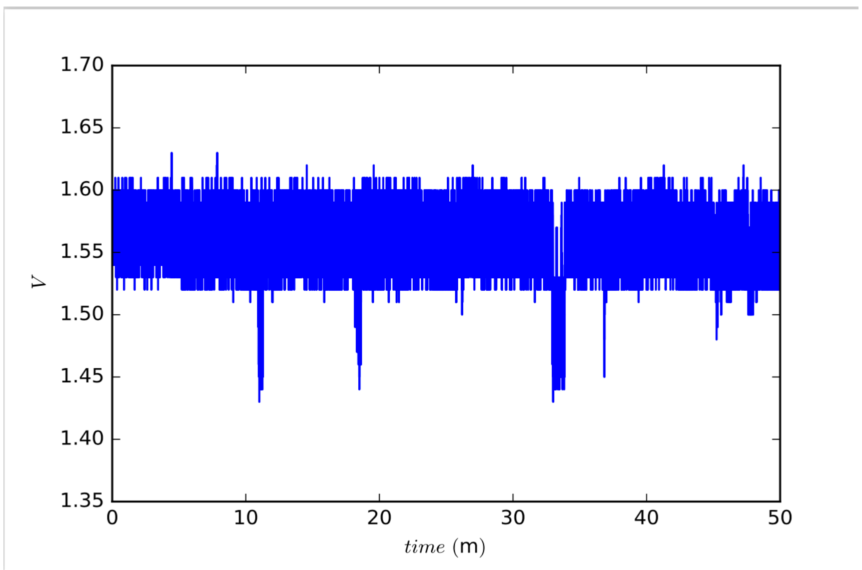


Figure 1. Sky Background Noise.

Such information will be useful later to cross check with the solar drift scan and verify that indeed it is background noise (after the transit) will too be roughly ~1.56 0.1V since we are still relatively close to the sun.

4.2 Solar Drift Scan

By taking advantage of Earth's diurnal motion we are able to detect the radio emission originating by the sun. Since the flux of a black body is directly proportional to the voltage received (see discussion) we are able to demonstrate the transit of the sun by simply allowing the sun to cross the field of the beam width of our satellite dish. Since the sun may be considered roughly as a blackbody, we expect that the presence of the sun in our field of view should result in a higher voltage in comparison to the average sky background.
To first observe the transit, we subtract a 50-minute exposure of the background to the main drift scan. This was done to eliminate any repeating source of noise that may contribute to the final drift scan (see Fig.1).

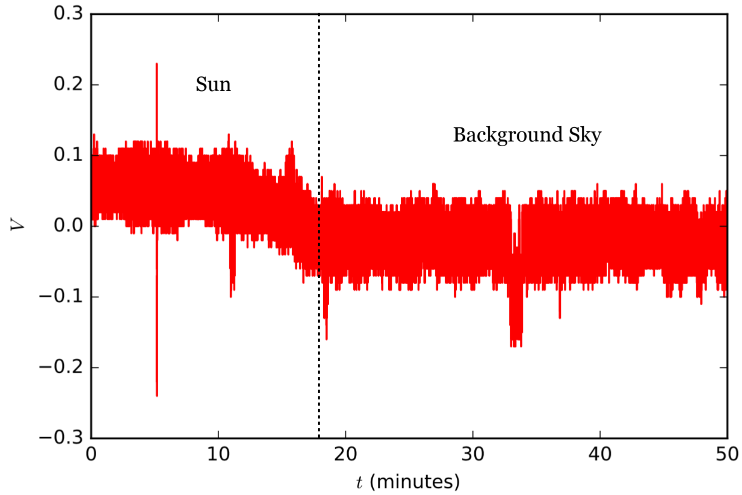


Figure 1. Background Subtracted Solar Drift Scan. When centering the sun at the center of the satellite dish after some time (t~50minutes) we notice that the voltage drops which means that the sun drifted out of the field of view.

First, when plotting the voltage change as a function of time we notice visually a distinctive drop in the voltage -- clear evidence that the sun has crossed the field of view. The shape (half-Gaussian) is due to the fact that the telescope was pointed directly at the sun and was left for it to drift out of the field is why we observe a dip in the voltage.

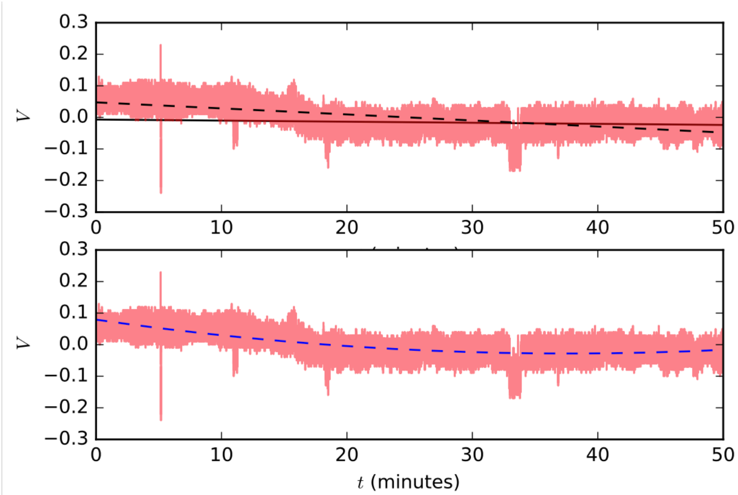


Figure 2. **Linear Regression and Polynomial Fitting to Solar Drift Scan**. One of the evident features of the drift scan is the resulting drop in voltage. To estimate change in voltage we use subtract the intercept of both lines in the top figure. In the bottom figure we fit a 2nd order polynomial to the solar drift scan.

Using a linear regression model in SciPy we plot the best fit line for the entire curve (solid black line) and after the transit (dashed black line, t>20 minutes) to estimate the voltage difference (V). When calculating the linear coefficient (r^2) for both trends and taking their difference we find that the voltage to be V0.054, that is roughly 5 per-cent voltage drop from the average background. Furthermore, we fit a 2nd order polynomial to the curve for a better fit (blue dashed line) which seems also to indicate a changing downward trend. In sum, our first drift scan of the sun is proven by noticing the drop in voltage versus the background.

4.3 LNBF Noise

Like all electronic devices, thermal noise can also contribute to the measuring data and hence may interfere with our measurements. One way to measure the internal noise of the LNBF, we cover the receiver with several layers of thick aluminum foil until we are not able to pick up any external noise – by using the satellite finder. We then take a short exposure of the recorded voltage.

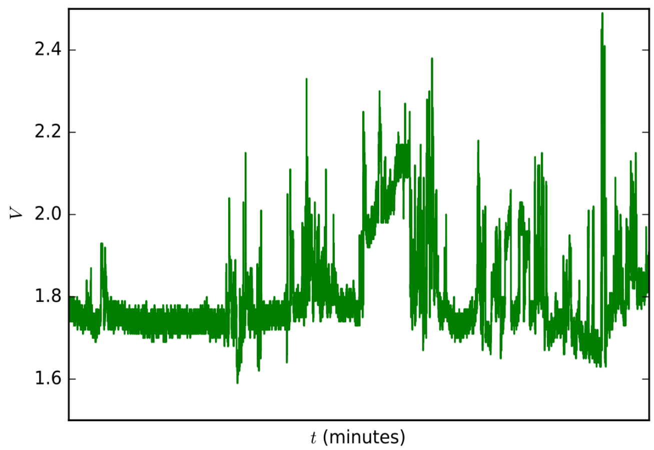


Figure 3. **LNBF Noise**. By blocking the feedhorn with aluminum foil, we attempt to record the inherent noise inside the LNB.

We suspect that this method might not be completely reliable since the average voltage change is much greater than the readout signal. For future calculations, we aim to consider further parameters of the LNBF – such as cooling it and using other material that give us a known value of contamination.

4.3 Features Worthy of Some Discussion

Although voltage as a function of time (section 4.2) may be a useful technique to observe the presence of the sun, we must rely on other techniques to derive other physical parameters of the celestial we choose to observe. A common technique for manipulating the incoming radio wave is the Fourier Transformation. This elaborate mathematical technique used to decompose the incoming wave into its constituent superimposed waves. The plot is the Fourier Transform in frequency space where the relative power of each frequency of wave that contributes to the wave received is plotted. Besides the usefulness of observing the data in a frequency and power space, we expect that the Fourier Transform to reveal dominant emission structures from the incoming wave.

Using the FFT module in Numpy, we apply a Fourier Transform to both LNBF and Sky drift data.

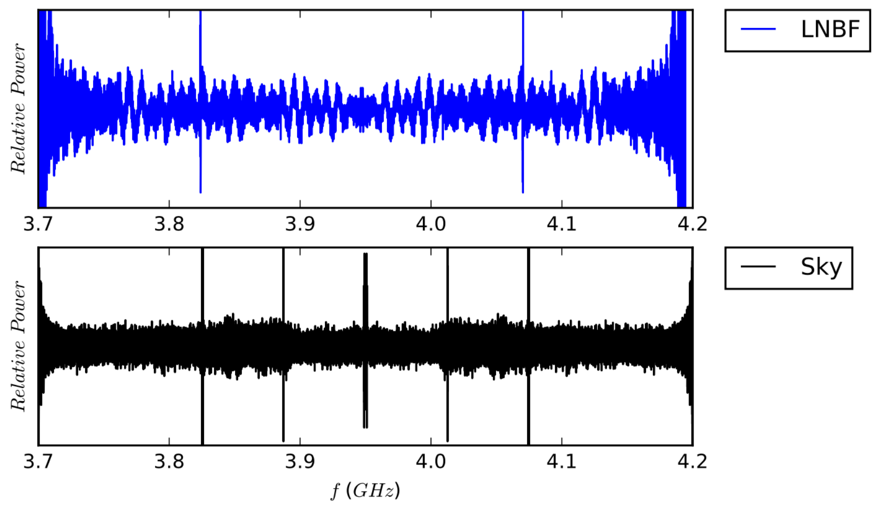


Figure 4**. Fourier Transform of LNB and Sky.** The top diagram represents the Fourier Transform of the LNBF noise with two distinctive symmetrical lines. The bottom diagram is the Fourier Transform of the Solar drift scan, revealing several other new and symmetrical spikes.

We must note that during our calculations, due to time restrains we were not able to estimate quantitate the relative power since we required data from geostationary satellites for calibration. What is rather encouraging about Figure 2, is the presence of two new symmetrical emission lines in the Sky spectrum around ~3.8 and ~4.1 GHz. Although their presence is not completely understood such information will serve as motivation for further analysis – although an educated thought might suggest that these features may have something to do with the presence of the incoming solar radio wave.

5. Discussion

5.1 Drift Scan of Sun

After plotting the background-subtracted data for the solar drift scan and regression lines were fit, the difference in voltage between on-axis solar observation and the region near but outside the solar disk becomes apparent. The change in voltage ΔV=0.054 occurs over a span of 17 minutes. This is approximately half the time required for the Sun to fully transit through the focused effective aperture of the telescope since the data recording began with the Sun centered in the beam of the dish to ensure maximum reading. To make this measurement of a voltage drop useful, it is necessary to calculate the conversion factor between change in voltage and change in radio flux incident upon the dish. Assuming an intensity of $2.85{*}10^{-14}$erg/cm^2/Hz at a frequency of 4 GHz (NRAO) - well within the C band observations discussed in this paper - the equation

$$I = \frac{F}{\Omega}$$

where Ω is the solid angle subtended by the Sun ($6.87 * 10^{-5}$steradians), yields a flux of $1.96 * 10^{-18}$ Hz/cm^2/s/Hz. Thus, dividing the difference in voltage Vby the flux at 4 GHz, a 1 Volt change corresponds to a change in flux of 2.76 $*10^{16}$ ergs/cm^2/s/Hz, which is quite large. This means that the voltage differences created by differences in flux are quite small and therefore very precise measurements of voltage are required for accurate measurements of flux.

It is therefore vital to ensure that the Arduino and the analog to digital conversion process of the source maintains a very high level of voltage sensitivity to ensure the greatest precision in flux calculation. This may be aided by faster data transfer and recording rate within the Arduino and the Python data processing pipeline or simply greater sensitivity of analog input ports.

5.2 Fourier Transform of Solar Data

When the data were Fourier Transformed, numerous spikes were present in the spectrum for both the source data of the Sun and for the background collected from a different region of the sky (Figure 2). Two of the spikes in the Fourier Transforms are located at the same frequency, while the transform for the background observation contains three additional lines. The two lines that the source and background have in common could be due in part to instrumental effects such as sampling frequency or inherent noise within the system. A separate observation was conducted where the LNBF was shrouded in aluminum foil, effectively blocking much of the radio flux from entering the feedhorn and detector itself. However, other possible noise-producing components were not removed from the system, so the results are inconclusive as to whether instrumental noise is the source of these spikes, although this observation did help establish a baseline for instrumental voltage. The additional three frequency spikes present in the background observation could be due to an unknown source such as a satellite or strong radio tower located in the field of view of the background observation, essentially meaning that the "empty sky" chosen for the background was not as empty as originally thought.

Apart from the spikes in the Fourier Transforms, the spectrum of the background observation much closer resembles white noise than the source observation. The background observation exhibits a less well-defined continuum centered on a power of 0 that is more or less constant, exhibiting contributions from most frequencies in the observed band. In contrast, the LNBF power spectrum displays larger gaps between the smaller peaks that define the continuum rather than a fuzzy, flat line. Although it is also centered on a power of 0, the LNBF Fourier Transform appears to show much more vertical variation than the background observation, meaning that there are more frequencies that distinctly contribute to the overall shape of the data, which is to be expected from looking at a real source that could emit various discrete frequencies more than others (as opposed to random variation from true background).

5.3 Beam Width and FWHM

Utilizing the time required for a half transit of the Sun across the beam of the radio dish, it is possible to calculate the beam width of the telescope and the full width half maximum (FWHM). Assuming a gaussian fit of the form

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

where a is the amplitude of the gaussian function, b is the position of the center of the peak, and c is the standard deviation of the function. Half of the FWHM as calculated from half of the full gaussian-shaped transit is 9 minutes, thus the full FWHM is 18 minutes. Converting this value to degrees by assuming a rotation of the Earth (and therefore objects in the sky) of 15 degrees per hour, this yields a beam width of 4.50 degrees.

This value is slightly above the theoretical resolution limit of 3.39 degrees as dictated by the angular resolution equation:

$$\theta = 1.22\frac{\lambda}{D}\frac{180}{\pi}$$

Although this calculated FWHM is 1.11 degrees larger than the theoretical resolution limit, much of the discrepancy can be attributed to the noisy location on top of Pupin roof as well as the limitation of only recording half of the transit rather than observing the Sun drift into the field of view and then out again, providing a full gaussian fit. These issues can be resolved in a handful of ways. The most obvious way to reduce the noise pollution (and thus refine the background subtraction) would be to turn off all cell phones and electronic devices nearby as well as moving to a more radio-quiet location with fewer passing airplanes and radio emission from the city. Additionally, the addition of a finder scope and more accurate pointing system would ensure that the telescope could be positioned in the path of the Sun rather than relying on simply aligning the dish with the Sun itself at its maximum point, resulting in only a half transit.

It is interesting to note that since the Sun is only ~0.5 degrees in diameter, the full disk of the Sun remains fully within the focused beam of the telescope for at least 16 minutes (assuming a movement of 15 degrees/hour). This adequately explains why the peak of the transit appears to be flat for approximately 9 minutes, since the fraction of the Sun's radio emissions collected by the telescope remains relatively the same while it is fully encompassed by the beam width. This time period can be decreased by lowering the beam width by refining the focus of the dish and reducing the noise, both of which determine the ability to determine curvature of the spectrum.

6. Conclusion

6.1 Feasibility of Setup and Advantages

In hindsight, the progress of this project really began to pick up momentum during the last days of our semester. Given the plethora of problems we encountered and the many imperfections to the system set-up, we managed successfully to meet our very first goal as a team – that is to observe the presence of a celestial body emitting radio source. Since the Sun is one of the closest celestial bodies known to emit in radio, our project successfully recorded the suns presence by performing a solar drift scan and estimating the change in voltage.

Even more ambitiously, the goal of the project was not only the scientific demonstration of the presence of radio frequencies but also the feasibility of low-budget radio astronomy operated through simple machinery that is often accessible to undergraduate students. Our methods hope to inspire future students to become more involved with radio astronomy and realize that although it may be an extremely painstaking and technical process, with some knowledge of the basics principles of physics and computer science, radio astronomy could be as easy as looking through an 8-inch Newtonian reflector.

6.2 Future Work

The CRAC (Columbia Radio Astronomy Consotrium) Radio Telescope is certainly a work in progress. There are still many additions to be made and much work to be done in order for much more meaningful science to be obtained with this system. One of the first and most critical steps should be observing targets such as television satellites that have a very well-defined power output and frequency that can be used to calibrate not only the flux calculation but the Fourier Transform analysis. Currently, many assumptions were made using information and values found from numerous papers and scientific sources, however, for this radio telescope to be successful, it is necessary for it to make measurements of these values itself and calibrate off of those. Following in this vein, additional background observations at different times of day (especially at night) should be conducted after the telescope is calibrated to flux and frequency. This would not only ensure that the sources being detected are true sources and not simply background variation, but also help make measurements more precise through a more refined background subtraction. Furthermore, observations should also be made in the K_u band to compare fluxes, background, and frequency lines yielded by a Fourier Transform.

On the hardware side, the addition of a finder scope would be useful to help point the telescope in the correct direction for viewing sources with smaller solid angles than simply the Sun or the Moon. This would also help position the telescope in front of the path of the Sun in order to get a full transit rather than the half transit described in this paper. A finder scope would greatly improve the precision with which objects could be observed and open up the possibility to observe a wider variety of objects that are more difficult to point to with the naked eye. In tandem with this improvement in pointing from a finder scope, the addition of a swiveling mount (which could be possibly motorized and remotely controlled) would aid in this pointing dilemma. If the mount were to be motorized, it would be a simple matter to code a tracking procedure so that the telescope could conduct more than drift scans and would actually get continuous readings for sources as it moves to keep them in its field of view. This would open up the possibility for imaging, which can be accomplished through the slewing of the telescope across an area of sky and recording the intensity of each portion as it moves. This, too, would be made much simpler with the installation of a motorized mount that has the ability to track sources or certain paths across the sky.

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7. References

Falcinelli, F. (2017, 01 22). How to use RAL10KIT and RAL10AP to build a Microwave Radio Telescope. Amateur Radio Astronomy Equipment.

Heatherly, S. A., Crowley, T., & Smith, K. (n.d.). The Itty Bitty Telescope (IBT): Tips for building and using a simple radio telescope.

NASA. (n.d.). The Radio JOVE Project. Retrieved 04 10, 2017, from NASA.gov: <https://radiojove.gsfc.nasa.gov/>

Radiosky.com. (n.d.). Radio Astronomy FAQs. Retrieved 04 10, 2017, from radiosky.com: <http://www.radiosky.com/faq.html>

Seidle, N. (n.d.). Analog to Digital Conversion. Retrieved 04 10, 2017, from Sparkfun: <https://learn.sparkfun.com/tutorials/analog-to- digital-conversion>

Pranshu, Mandal, Agarwal Devansh, Kumar Pratik, Yelikar Anjali, Soni Kanchan, and Krishna Vineeth. "Everyday Radio Telescope." Indian Institute of Science Education and Research Thiruvananthapuram, CET Campus, Trivandrum, 13 Jan. 2016. Web. 10 May2017.