Creation of an inexpensive spectrometer and interferometer using gnuradio

By Andy Dyck

Abstract.
The ability to observe pulsars and similar phenomena is often hindered by the cost of typical interferometers and prevents the public from having experience with simpler phenomena such as solar fringes. We have developed a working radio interferometer that can be used to observe phenomena such as solar fringe and pulsars very cheaply. The radio antenna utilizes a trapezoidal horn for collection, a Low Noise Amplifier (LNA) attached to the end of the can, and an interferometer program on gnuradio. Solar fringes were observed, A power gaussian was seen for the transit of the sun, and a pulsar was attempted to be detected

Introduction: What is interferometry and beam forming

The ability to conduct research cheaply and efficiently is what allows discoveries to be made without investing large amounts of money and time. Interferometry is a near century old technique that is still giving results in experiments such as the search for pulsars and the Chandragupta experiments on the moon. This paper is explaining a new way to create an interferometer which forgoes the expenses that are normally associated with interferometry. Additionally, this will also allow a practical method to test the effectiveness of citizen scientists and engage students from the high school level as well. Interferometry is a subsection of radio astronomy which uses antennas to add and correlate a signal in order to _________. Beam forming is a subsection of interferometry which analyzes how adding different numbers of horn in certain arrays affects the beam width of the horn.

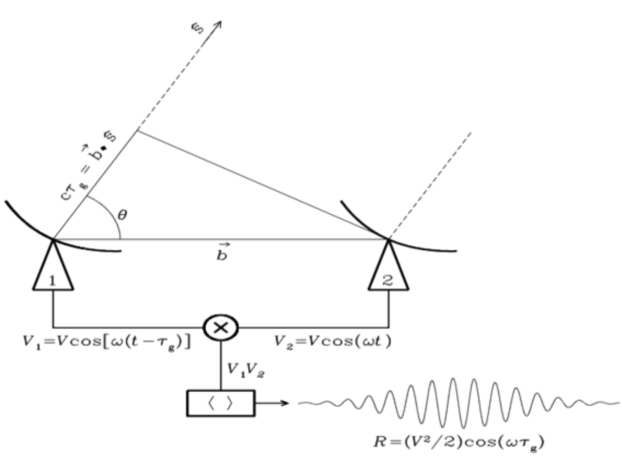

Figure a: This explains the basics of interferometry. There are two horns receiving signals whose output is then correlated and added. The effect of the signal is determined by the baseline and it is assumed that the waves are planar upon detection.

The Spectrometer

One horn was used as a spectrometer to show that the antennas are capable of collecting information. The collecting apparatus that was used is a copper antenna soldered onto a metal can (See figure 2).

Figure 2: The metal can has 23.7cm height, 16.8cm length, and 10.7cm width as measurements. The antenna was soldered about 5.7 from the bottom of the can and is equidistant from the sides. On top of this can, a trapezoidal horn made from foam was taped to the top of the can to create a collecting apparatus. Aluminum tape was used to connect the can to the horn, which was conductive on the inside, and to seal the sides. The horn has 4.6 square meters of collecting area and is 75.9cm from can to collecting width. The antenna was connected to an SMA connection which transferred the voltage the LNA. The horn itself was set inside of a wooden frame, which was used for long term observing to ensure that the horn remained pointed in one direction.

The program used to read the data collected was made using gnuradio. This program was used to clean and correlate the signal. The signal was run through a pfb filter bank before the Fourier transform of it was taken. This was for the purpose of cleaning up the noise. Then it was run through a correlate block which correlates the signal. Two auto correlations and one cross correlation were outputted. Each output is fed to two integrate blocks, which serve to decimate the signal. The three outputs were then run to hdf5 blocks and vector sinks. The sinks are used to verity that data is being received and processed. (picures of gnuradio)

Complications with the setup:
Shorts occurred very often as a result of wires being exposed. Additionally, the limeSDR frequently gave errors stating that it was not able to connect the computer and internal clock in the LimeSDR. Wind caused the horn to experience enough force to move on its stand, which affected the ability to conduct measurements due to a changing angle. Variations on the model that was used can be made, as to limit the effect of wind on the horn.

The Procedure:
The galactic plane was found using StarTracker, an app that was downloaded from my phone. The antenna was then directed toward the centre of the plane and the program run. (see flowgraph)

Results:
The bump that can be attributed to neutral hydrogen was seen at a little more than 1420Mhz, which confirmed that the horn could receive data.

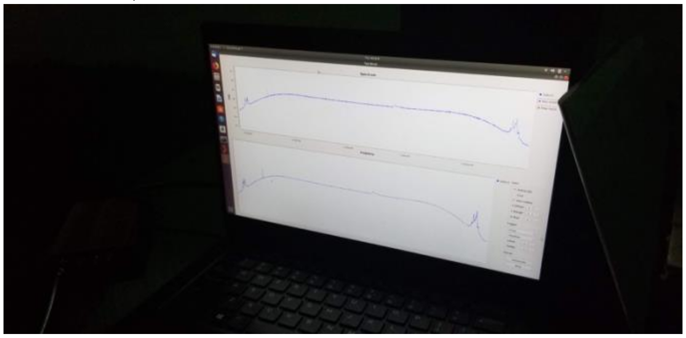

Figure 5: The data received. Note that the spikes at either end are showing the range of the filter.

Problems:
Very little to none

The Interferometer and beam forming:
Two horns were made for the interferometer. From the LNA's both horns had SMA cables leading to biased T's, both powered by one battery pack using a severed USB cable, banana cables and another severed RF cable. From the biased T's, RF cables were attached and led into a limeSDR. This acted as the mixer and clock for the data. A USB cable was attached to the limeSDR and inserted into the USB port on the laptop.

The program used for the interferometer was similar to the spectrometer program. For this, a correlate block was added which outputs two auto and one cross correlation, after which we integrated and send that to hdf5 sinks. (flow graph picture)

The setup for the interferometer:
Using this system, the horns, stands, and equipment were taken outside and placed on flat ground, where there was a clear view of the solar circle from the morning to about 2pm. The horns were mounted on the bases and placed on an east west baseline. The east west baseline orientation gives the most pronounced fringes(see figure 7).

Figure 7: Figure 7 when beam forming, the beam of a single horn is symmetric radially around the horn. However, when we have an interferometer, the beam pattern on the baseline is decreased since we are adding and averaging the beam patterns. Additionally, the beam pattern perpendicular to the baseline remains unchanged. Thus, when wanting to observe the fringes from the sun, one needs to have an east west baseline in order to find the phase difference that comes with beam forming the horns.

The procedure for the interferometer:
The limeSDR battery pack, biased T's and wired were placed in between the horns, with SMA cables running to each horn. The laptop was shaded by a box in the same area. The distance between the horns was 221 inches. The inclination and direction of the antennas were chosen so that the sun would be just outside of the beam. Over three hours of measurements, the sun would cross into the beam and exit it, showing a gaussian in the power vs. time graph for autocorrelations and the cross correlation. When measurements were taken, first a neutral hydrogen signature at 1420Mhz was observed in the auto correlation of the antennas, which denoted real data is being recorded, as opposed to noise generated by the limeSDR.

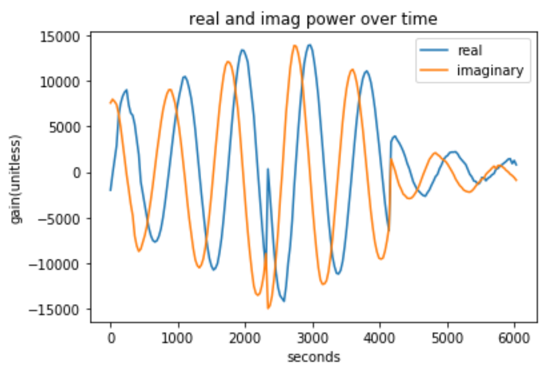

Figure 8a: This is the fringes from the sun as it passed through the beam

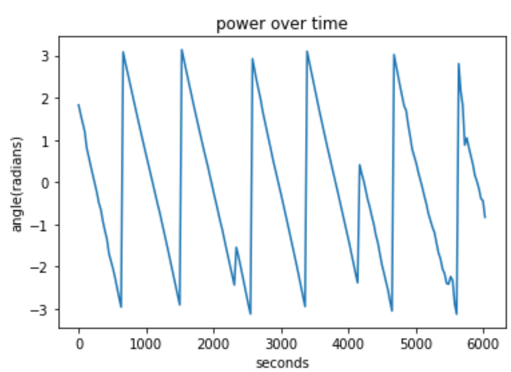

Figure 8b: Here is shown the angle between the fringes over time. As expected there is a periodic angle shift going from 3π to -3π.

Results and Data Calculation:
The data received from this test showed a clear fringe pattern and phase shift between the horns. To prove that the interferometer is working, the distance between the horns can be found using the data, and then compared to the distance that was measured using a measuring tape. The telescope resolution equation of the form $\theta = \frac{\lambda}{D}$, gives us the distance between the horns after rearranging. The θ is found by looking at the fringes that are seen on the data. Looking at the data $t_1 = t(s_2 - s_1)$, where s_1 and s_2 are the samples where the fringe starts and ends, t_1 is the total time that the sun took to move across the fringe, and t is the rate that samples were taken at. The rate at which the sun moves across the sky is $v = 15 \sin d$, where d is the declination of the sun. The fringe width of the interferometer can then be found by $\theta = vt_1$.

The wavelength that we used was 21 cm, which was in to see neutral hydrogen in our correlations to confirm that we were receiving data. It was found that using $\lambda = 21cm$, and our results from our data, the average value for D was found to be

222in, which was one inch difference from our recorded distance with the tape measure. This corroborates our findings that the interferometer works for cross correlations.

In addition to the phase data, the auto correlation and cross correlation power vs time should show a Gaussian as the sun transits through the beam of the horn.

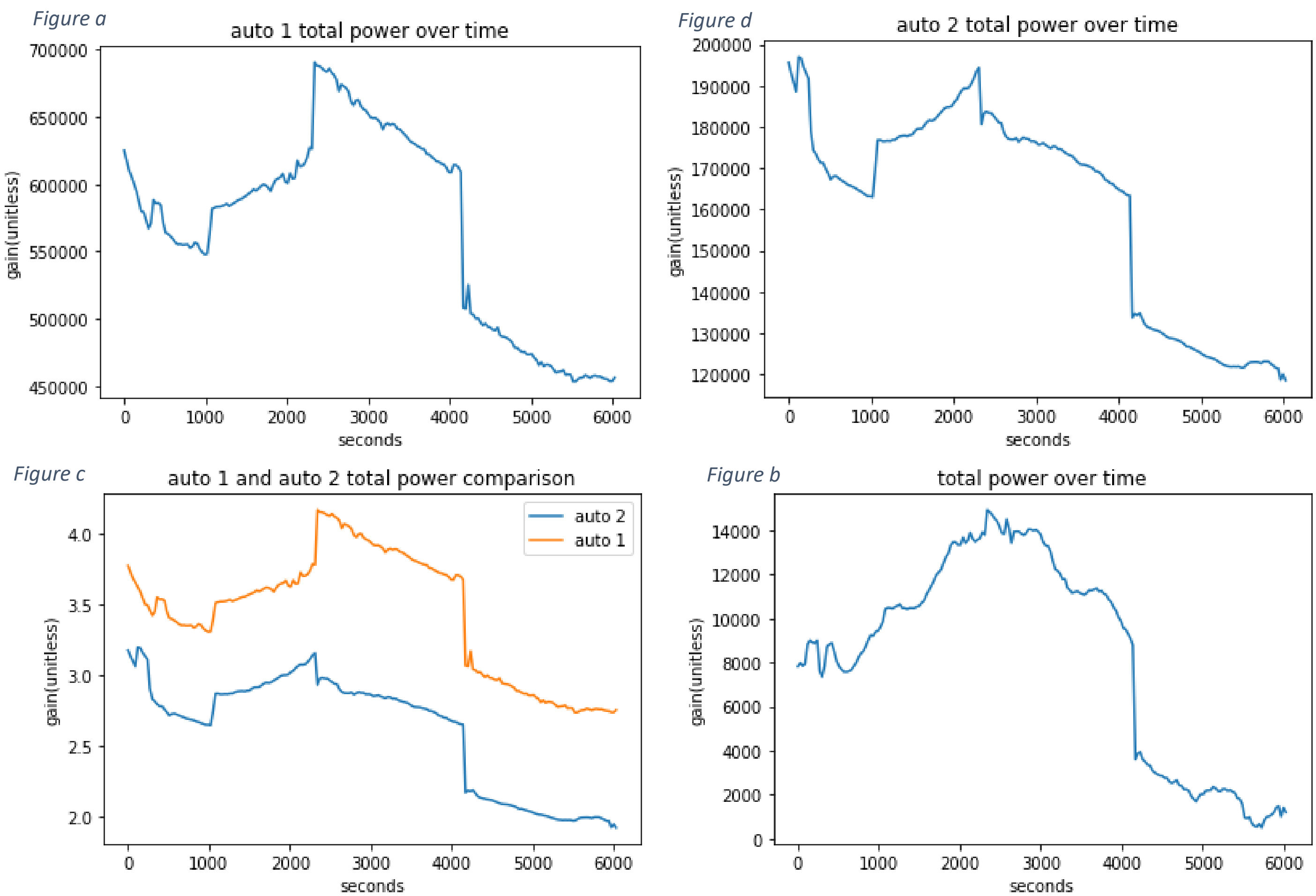

Figure 9a- This shows the total power output for the auto correlation for te second antenna. Figure 9b- This shows the total power over time for the auto correlation for the second antenna. Figure 9c- This shows the total power output comparison between the two antennas. Figure 9d- This shows the total power output of the cross correlation for both antennas.

Problems with the interferometer:
The auto correlations, contrary to expectations, did not fit the prediction that was
made. As the sun passes through the beam, the power will rise and fall, and if the power is time averaged, the result should be a Gaussian

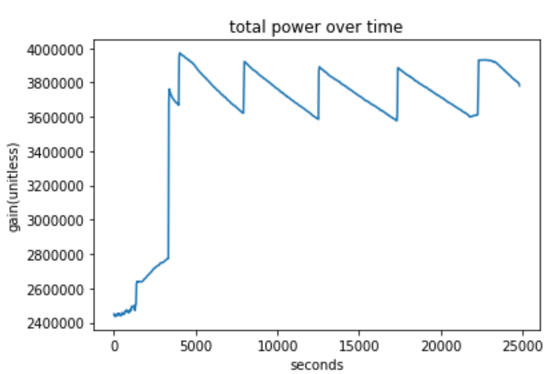

Figure 10- The repeating pattern of rises and falls indicate that the lime was being affected by the air conditioning of the house1

distribution. Even the absolute value of the cross correlation could be barely counted as a Gaussian. While the data looked gaussian in some parts, a significant part data showed spikes of 20 to 60 percent. Additionally, a full Gaussian could never be seen, as the spread looked to always be cut during the middle or first fourth of the Gaussian distribution. The heat that the system was experiencing was thought to be severely affecting the system, so it was taken inside to perform tests in a more controlled environment. The horns were removed from the LNA's. The LNAs were capped with resistors, and the temperature of the room was regulated by a residential air conditioning unit. The experiment ran for four hours. When the data was analyzed, it was found that there was a recurring pattern of spikes and slow descents in the gain. Additionally, there was a massive jump in the beginning. This pattern was believed to be the air conditioning unit of the house, and that the spikes seen in the data were caused by temperature fluctuations outside, discounting the original spike. The sensitivity to temperature of the lime and the LNA's were measured to test this hypothesis. The setup for this was the same, except that the battery was changed and the lid of the LimeSDR was taken off. The first trial heated the FPGA heat sink on the limeSDR. The starting temperature was measured with a voltmeter that could measure temperature.The program ran for a few samples and then the sink was heated with a heat gun. The maximum temperature was measured, and the sink was let to cool. At the end of the experiment, the final temperature was recorded. The same experiment was repeated with the receiver chip. To create controls for these experiments, the temperature of the chips was recorded at the beginning of another experiment and the program was run. No heat was added, and the end temperature was taken. _____(create graphs) Using known final and initial temperatures, which were corroborated with video recording, and the gains at those two temperatures, a percent change in gain per degree temperature was calculated. As so far, only two points were measured and the percent change per degree C was found to be .25%. These results were within range with what was expected from the limeSDR, and so could not contribute completely to the change in gain seen.

LNA testing for solution to interferometer problem:
Another experiment was run to test the LNAs, where since we already knew that they remain stable over long periods of time in lab testing with a Noise Figure analyzer, they were heated with a heat gun to a high temperature and then let cool, with the gains recorded for the two LNAs. For this experiment, we let the lime heat up as to not give us any false signal. Our results show that while the effect that heat had on the LNAs was greater than expected, it was still within reasonable expectation. We concluded that the reason for massive jumps in gain was because the entire system was heating up, which would give us our 30% percent gain jumps that were observed in the data. Additionally, while the lid was off, there were no more observed spikes. It was concluded that the lid being on caused the chips to experience high temperatures for extended periods of time, which combined with the gain increases from the other equipment, caused these high spikes. (give results for setup for the lime experiment, and the rate of change per temp). In the end it was found that having the lid on the lime caused the chip inside to experience high heats which caused the massive spikes and that the LNA and lime were especially sensitive to temperature fluctuations accounting for the 20 to 40 percent temperature variations.

Solution to interferometer problem and an update to the LNA testing:
Another experiment was done on the LNAs to concretely conclude the effect of temperature on gain. This is because the previous LNA experiments were not videotaped and the temperature of the samples could not be surmised. Thus, a similar experiment was conducted. The LNAs were switched (ie not the same ones as last time) and instead of a heat gun, they were heated with a lighter. The data was recorded (see figure___)and the graph showing the gain vs temp was created(Figure___). It was found that for this particular LNA, which can be assumed has a similar reaction to temperature, the gain decreased .32% per degree of Celsius increase.

Starting Temperature (Celsius)	Power
31	223375
32	222939
33	222488
34	222282
35	221910
36	221445
37	
38	220549
39	219928
40	219427
41	218577
42	
43	217592
44	
45	215873
46	215290
47	
48	213800
49	213142
50	211961
51	
52	211004
53	209976
54	209240
55	
56	208197
57	
58	207023
59	
60	
61	204787
62	202027
63	
64	201075
65	200382

Figure 11a: The data was recorded by taking a video of the computer and the thermometer as the LNA was being heated and finding the matching gain with the corresponding temperature, as we knew the approximate sample that each temperature corresponded to.

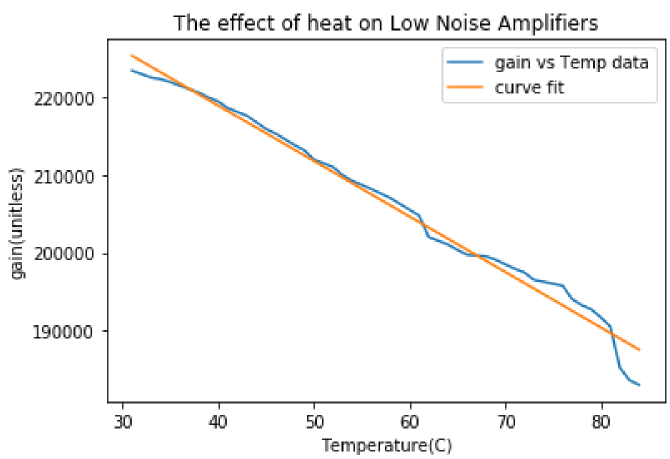

Figure 11b: The data was inserted into python and the data was graphed and a line of best fit was placed, which gave a slope of .32.

Problems discovered:
When doing experimentation for pulsars, the battery that we were using turned off when it was charging and reached full battery. When the data was looked at, there was a massive increase in gain, which didn't make much sense, since it should have gone to zero. It was surmised that the battery experienced a short as this was the only way to account for this spike. This battery I realized was the same battery that we used to do our interferometry experiments. The spikes in both of the experiments were near identical in their behavior, and I did experience the battery turning off sometimes, but did not pay much attention to it. However, while this could account for the spikes that increased the gain, this could not explain why sometimes the jumps would be a decrease in gain.

At this point, I did not believe that the temperature explanation was a good explanation for this. It was a couple of days after this when I was told that if the computer reaches a certain charge level, it will cease functions and turn off. This was corroborated by comparing my file sizes of my pulsar and I found that the time when my computer was in such a position, the file size was nearly half the size when running the same experiment. For example, when I should have recorded for 3 hours minimum, there was only 1 and a half hours of data on the computer
I realized that in other experiments at a later time I had been using magnetic north instead of true north for all of my experiments. This is a massive mistake because the difference between true north and magnetic north is ten degrees in Morgantown and Greenbank. This means that any positions that I looked up in stellarium, in true north coordinates, I was ten degrees off from. This would explain why for all of my scans for the transit of the sun, I kept on only being able to get a partial gaussian of the total power. Additionally, we were not finding pulsars while this gaff was undetected. However, when we corrected it and began using true north, we have discovered a potential pulsar.

Conclusion for Interferometer 1:
The baseline interferometer works and can find the distances between the baseline. Additionally, beam forming is an effective way to detect the fringes of the sun, to finding a pulsar perhaps. The effect of temperature on the gain of the system was not as extreme as first thought, due to sloppy experimentation. However, it is still present and will cause a noticeable change in the gain of recordings. Additionally, there is an unverified oscillation pattern that has been seen in the cross correlation between the horns.

Retesting the interferometer Setup:

On August 1 the interferometer experiment was redone. Using the knowledge that I have learned including the compass, computer turning off, and the battery short circuit, I am attempting to record a gaussian and see the distance between the horns. The horns were set up 175 cm apart and a makeshift table was used to place the equipment on. The lime was left with its lid on and covered by a box. The horns were positioned where the sun would be at 15:00, and placed on an east west baseline. When I went to check the horns at 14:44, one of them was at 57 degrees instead of the 60 that was supposed to be at 15:00. I will then take note that I expect to see something strange at around 1h and 14 minutes from the start time. The gains were set to 8,9,10 for channel 1, and 7,8,10 for channel 2. I was measuring at ten megahertz, and 1420Ghz central frequency
At 15:52, I moved the horn from 50 to sixty, the wind must have blown it down.

Results:
When I received the data, I received a full Gaussian for all correlations. The spike at 6500 seconds was when I moved the horn back to the 60 degrees. You can see when the wind originally moved the horn at the peak. Then the wind moved the horn back to

Figure a

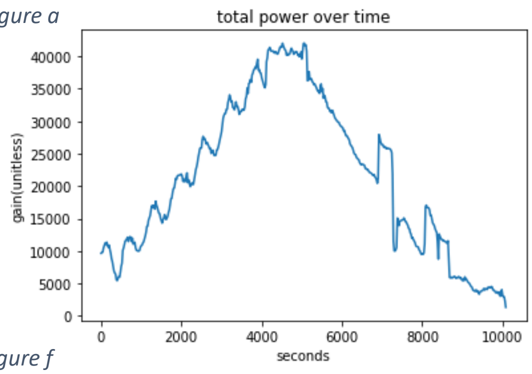

Figure g

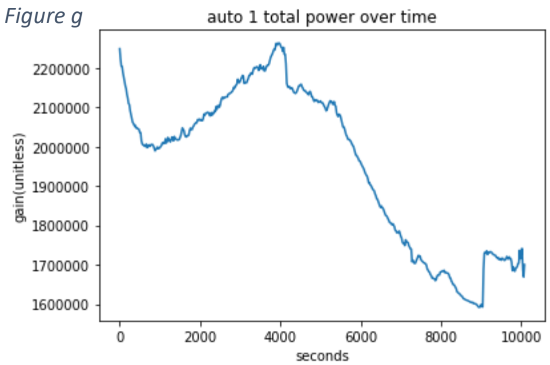

Figure f

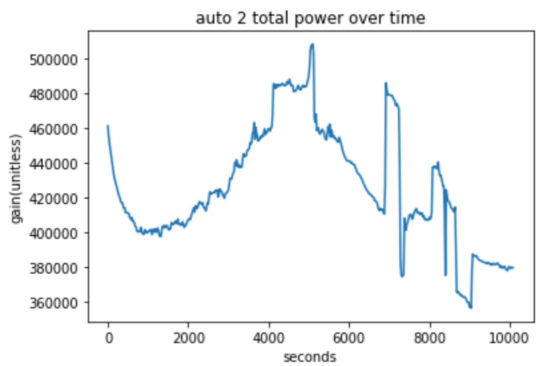

Figure e

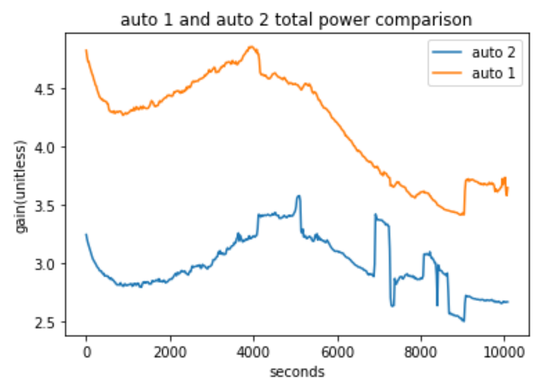

Figure 12a: The cross correlation shows an oscillation in the beginning, which I am unable to explain, however the Gaussian is present. 12b: This is the auto correlation for one of the horns, this is the one that did not move. 12c: The autocorrelation for the other horn, which was the one that moved. 12d: a comparison of the tow horns.

The 52 degrees that I measured when I moved the horn the second time at around 7000 seconds. I moved the horn back to the correct position at 8500 seconds which can also be seen.

The phases were also checked and a nice solar fringe was observed

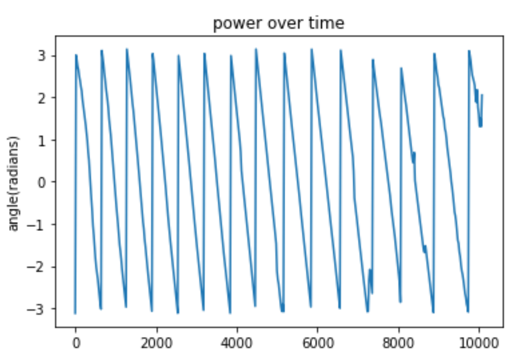

Figure 13a: The constant phase shift from the horns. A very regular phase shift, which is expected.

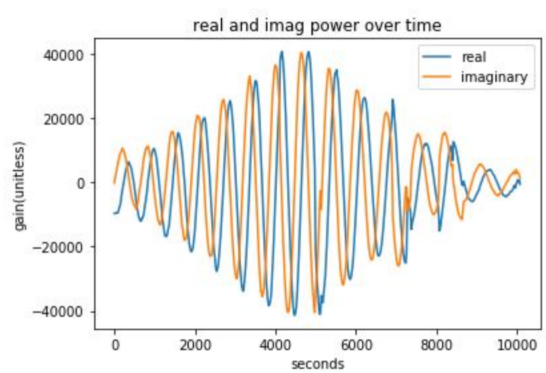

Figure 13b: Close to the entire fringe pattern from. The sun, showing the entrance and exit of the sun from the beam

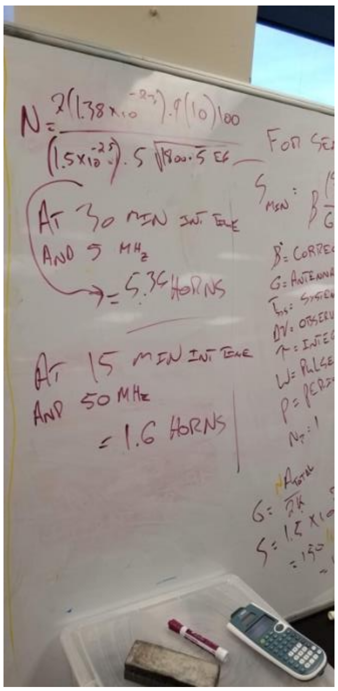

Figure 14a: The reasoning for why we could have 2 horns with those parameters.

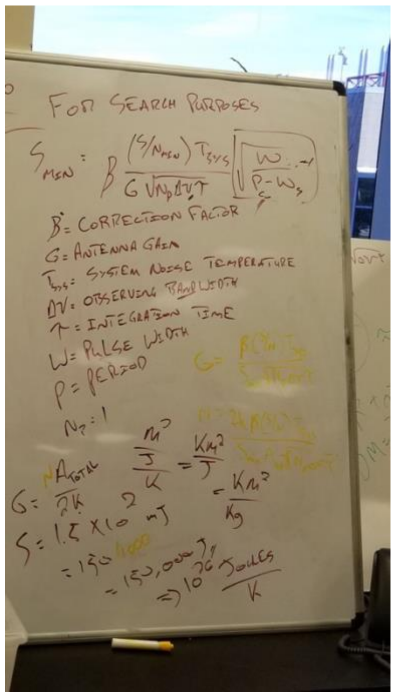

Figure 14b: A description of all the values of the variables

Pulsar detection:
To begin the process for detecting pulsars, calculations needed to be done in order to find the number of horns needed to see the star. The equation that we used was $SS_{min} = \beta \frac{\left(\frac{S}{N_{min}}\right) T_{sys}}{G\sqrt{N_p \Delta\nu\tau}} \sqrt{\frac{W}{P-W}}$. The in depth explanation can be seen in image _.

The setup:
Now knowing the number of horns necessary to observe a pulsar, we took the four horns and used a four horn stand in order to ensure the horns were all planar and were pointed in the same direction.

The horns were then attached to LNAs and an sma cable was sent to a splitter which combined the data from all 4 horns. Then the cables ran to a tee splitter which powered the

system using a battery pack and the signal was again split into two cables so that it could be processed by both the limeSDR and the lime Mini. These were then plugged into the computers using SMA cables. The limes were placed on a metal table which acted as a heat sink to prevent them from overheating. The angle and position of the horns were measured and were recorded. The position of the pulsar we decided to measure, PSR Bo329+54 was found using stellarium. The cables from the horns were positioned such that there would be minimal gain changes caused by the wires overheating.

Pulsar Data:
Andy's computer had the undedispersed data on it, while rhys's computer had the dedispersed data on it.
See his report on the data from the trials, as his computer was the only one able to process the undedispersed data.

Conclusion:
So far we have not been able to confirm that we have found a pulsar