First Experiences With An SDR Radio System

Introduction: As SARA Education Coordinator, I get lots of requests for help, which allows me to see the types of projects that people are interested in. I noticed a tremendous growth in SDR radio experiments and decided it was time that I 'take the plunge'. I found a poster done by Dr. Nimesh Patel (a Harvard researcher/radio astronomer) and his students called "A low-cost 21 cm horn-antenna radio telescope for education and outreach" (https://www.cfa.harvard.edu/~npatel/hornAntennaAASposterPDF2.pdf). Being a retired science teacher, this really appealed to me, so I set out to build this device.

After building the antenna and radio, I tried to detect radio continuum emission from the Sun. I chose the Sun because, when I had a large 10' dish, I used it to adjust my pointing since it is close to a point source. For this device I used SDR# software, which did not integrate (collect data for seconds to minutes before writing the data). I detected nothing! Feeling frustrated, I described my project process on the SARA list-server; several people (including Jim Sky, Ken Redcap, Dr. Nimesh Patel, Dr. Wolfgang Herrmann, Michiel Klaassen, and others) wrote helpful responses. I was reminded that a small horn would find it extremely difficult to detect individual objects like the Sun or Cass. A because of the beam dilution factor. In this case, Dr. Patel explained that the beam dilution factor would be: (Sun's angular size divided by the beam width of the horn)^2 => (0.5/19)^2 = 0.0007 or about 1/1000 – thus the Sun's brightness drops to just a few K. Luckily, we can detect hydrogen clouds. This helped decide my next steps and the projects I could now aim for. I decided I wanted to:

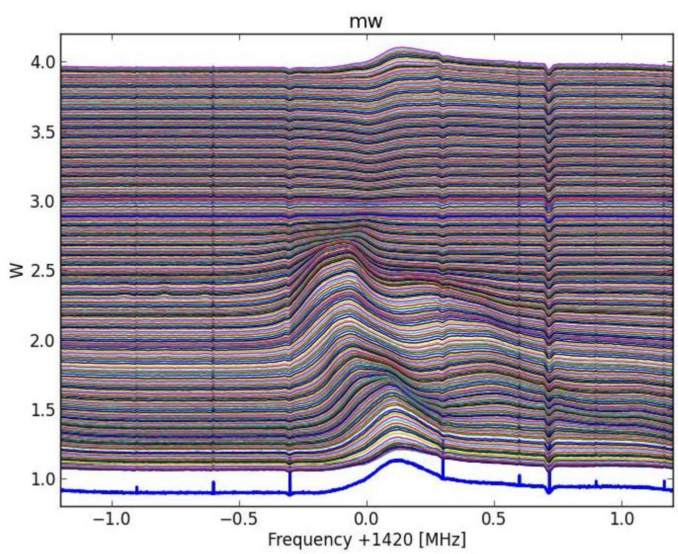
- Detect the 21 cm line from hydrogen and take 24-hour charts near Cygnus A, Cass. A, and Virgo A (figure 1).

After completing this challenge, I found out I could do the rest of the list below with a lot of help and work (see acknowledgements at the end of this article) – thank you all!

- Produce galactic longitude graphs (30-240 degrees by 30 degrees) using a calibrated scale for SDR# set-up for 1.024 and 2.048 MHz bandwidth.
- Calculate and graph V_{LSR} (the local standard of rest velocity) (figure 2).
- Produce a galactic rotation graph (figure 3).
- Lastly, make a galactic arms graphic showing my measurements of the distance to various galactic arms (figure 4).

Here is a preview of some of the results (figures 1-4). Please note, the charts that were done using the Python script do not have vertical axis labels. In those graphs the vertical axis shows relative intensity.

Figure 1: 24 hour scan of Cassiopeia A



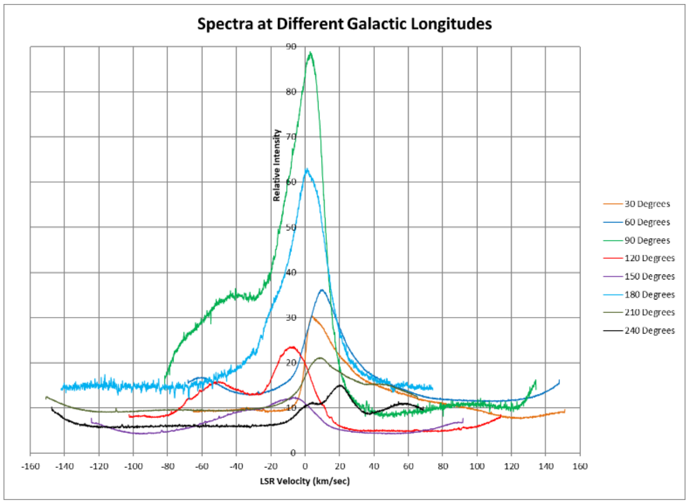


Figure 2: LSR Velocity for Galactic Coordinates

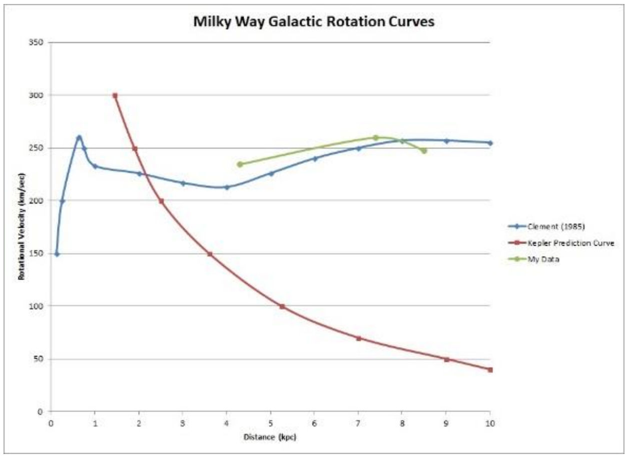


Figure 3: Milky Way Galactic Rotation Curves

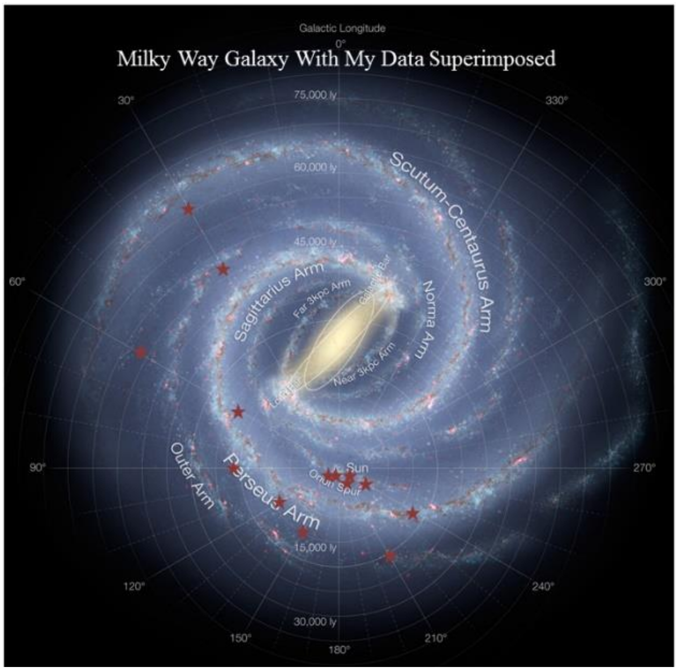


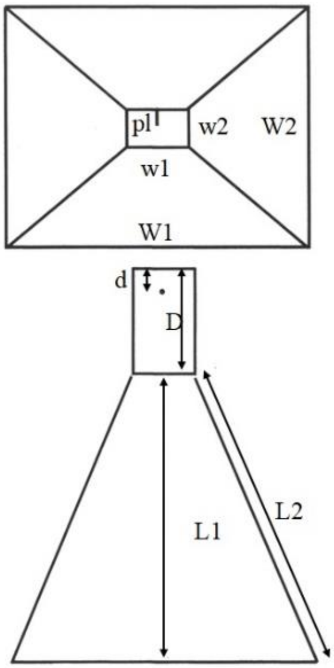
Figure 4: My Galactic Arm Calculations Superposed on Milky Way Graphic

Project Set-Up:
This article is an attempt to share my experiences and help beginners to recreate this project for themselves by providing a step-by-step explanation of what I did. I think such projects are one of the best avenues for learning more about radio astronomy. Being a teacher, providing an opportunity for beginners to build something and do a project that is educational and challenging is important to me. And, since I always seem to have problems with projects like this, it makes me the perfect person to try things out since I run across many of the issues people will encounter along the way.

I hope many people will find some useful information in this article and I would really appreciate hearing from anyone who tries this project. A description of what I did and the issues I encountered follows.

Hardware:
I first discovered that the dimensions given for the sides of the horn had to be adjusted for angle in order to fit together properly. I then had problems with the power supply for the LNAs from Mini-Circuits that were recommended; they require a very narrow range of voltages, so I had to buy a new power supply. Lastly, I had an inverted signal, which turned out to be due to transients on the power supply. I will deal with each of these issues when we get to them.

Horn Antenna
The horn antenna is based on the Harvard poster listed earlier. It has a gain of about 20dB and a beam width of about 19 degrees. I detail the dimensions I used below. I constructed it from aluminum sided foam board - a sheet of Dow Super Tuff-R insulation - cut to size, assembled with the aluminum side in, and held together with some high-quality aluminum tape (make sure it has conductive adhesive). I checked the connection between the pieces of the horn by using a multi-meter to making sure resistance was near zero. For the back end of the horn I bought a 1 gal. rectangular metal can, cut off the end and drilled a hole to mount a surface mount 'N' connector with a brass rod (from a hobby shop) soldered in place to act as the probe (see diagram – figure 5 below). I then cut 4 pieces of aluminum sheeting and drilled 2 holes at each end and screwed it to the can and then to the horn (using fender washers on the insulation to prevent pulling the screw through when tightening).
I constructed a carriage for holding the horn out of 1"x3" pine boards and 2"x4"'s (See figure 6 for details below). The long screws holding the carriage are 3/8" carriage bolts. I put 3/8" T-nuts into the 3" piece of 2"x4" and the side 1"x3" pine of the carriage to allow the bolt to be screwed in, and then used a 3/8" wing nuts to tighten the carriage securely. I also drilled through the horn and placed long machine screws through it and carriage to secure them together. Remember to use fender washers on the inside of the horn to prevent the screws from ripping through the foamboard. If you need any additional information to build this carriage, feel free to contact me.



Horn dimensions:

w1 – 6 5/8”
W1 – 29 5/16”
w2 – 4 1/8”
W2 – 23 1/4”
pl – 2 1/16”
d – 2 5/8”
D – 9 7/8”
L1 – 27 1/2”
L2 – 27 3/4”

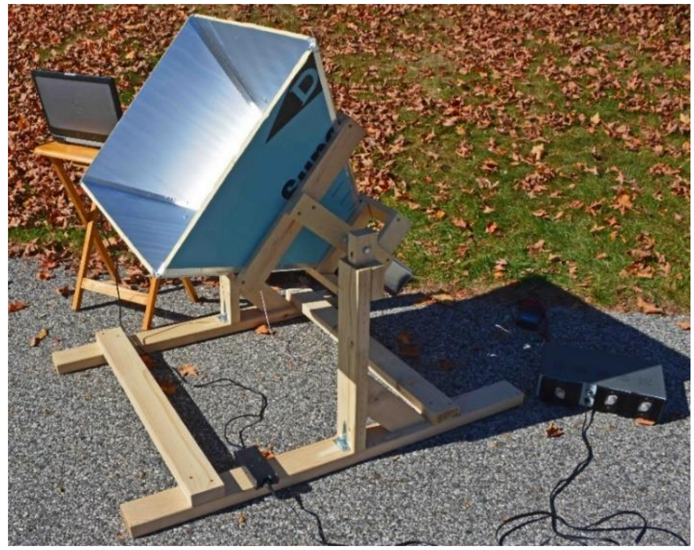


Figure 5: My Horn and Radio Set-up with Dimensions Diagram

Figure 6: Horn with Stand Including Measurements

Power Supply

I bought a decent quality, variable, power supply which could be adjusted to 4.2V, off E-bay for about $30. When I used it the first few times, I got some wild results - inverted signal and intermittent changes in output - as mentioned earlier. After some e-mails from the SARA list-server it was decided it must be rf on the power supply inputs, so I soldered decoupling/bypass capacitors (I used 100pF ceramics) across the power supply inputs on the LNAs – problem solved!

Receiver

The receiver system consists of an ‘N-type’ adapter; two Low Noise Amplifiers (LNAs - I used Mini-Circuits ZX60-P162LN+ (in max condition: 4.2 Volts and 60 mA resulting in 0.252 Watts)); a bandpass filter (I used Mini-Circuits VBF-1445+); an FM trap placed at a distance from the first three components (added because of the FM noise in my area – thanks Jim Sky); and an RTL2832U & R820T2 SDR Tuner (a ‘regular’ tuner would work fine in most areas, but due to high noise levels where I am, I used NooElec NESDR Mini 2+ Al: 0.5PPM TCXO RTL-SDR & ADS-B USB Receiver Set w/Heavy Duty Aluminum Enclosure & Antenna. RTL2832U & R820T2 Tuner. Low-Cost Software Defined Radio). You will also need connectors, power wires and antenna wire to link system together and to the horn. See figure 7 below.

Figure 7: Front-end with LNA's, Bandpass Filter, etc.

Software:
I had a few problems installing and using the necessary software - SDR# and the Harvard Python script ("based on the program by "Roger""). With SDR#, I found that zadag.exe was not in the folder after unzipping, so I had to download a copy. I then had issues trying to use the Harvard Python software, which I was unfamiliar with. I tried taking charts using just SDR# but got nothing. I tried standing in front of the horn to get a large signal but got an inverted signal (the power supply issue discussed above). I finally decided on two pieces of software that seem to work well for me – SDR# and CFRAD2.

SDR#
The issues with Zadag not installing seemed to have been fixed in the new version I used recently. Install the program exactly as they recommend (https://www.rtl-sdr.com/rtl-sdr-quick-start-guide/ - the download is through the Airspy website as described in the link directions). I've found that small deviations can cause big issues! If you have issues feel free to contact me and I'll try to help you with some of the comments I got from people (mostly Michiel and Henk – thanks!) when I had problems.

CFRAD2
I remembered (after being reminded by several people on the list-server) that the data must be integrated (gathered over a period of time). Because I have such a small horn, I needed a long time interval, so I searched for other choices than SDR# and finally found Michiel Klaassen's website: (parac.eu/projects.htm). (Michiel also discusses a number of 'simple' projects he has done over the years which are really interesting and worth checking out). I found that CFRAD2 was specifically designed for these cheap dongle SDRs and had an integration time of 5 minutes before writing a data file.
Michiel's instructions for CFRAD2 can be found at: http://parac.eu/projectmk4.htm.
Two notes: 1) be sure libusb-1.0.dll is copied to c:\windows\syswow64 (for 64 bit machines) or c:\windows\system32 (for 32 bit machines).
2) when Michiel mentions 'Sharp#' he is referring to 'SDR#'.

Python(x,y) and Spyder
Michiel has written a script in Python that analyzes the data, so you need to install python on your computer. Currently Python(x,y) and Spyder are packed together and can be downloaded from: https://python-xy.github.io/downloads.html. Follow the instructions exactly (once again, I tried to shortcut to make things faster and had to re-install!). You will access Python through Spyder (more later under Data Analysis).

Download the zip file from here CFRAD2.zip
1. You need to unzip the CFRAD file to a folder and copy the libusb-1.0.dll to the systems32 folder.
2. Start your Sharp# program, select your RTL usb dongle and select play.
3. You can select any sample rate, AGC settings, etc. for your need.
4. Bring up the task manager by pressing ctrl alt delete.
5. Go to the window "processes" tab in the task manager.
6. Right click SDRsharp.exe and click "end process", and again "end process"
7. Go to your cfrad2 folder and start cfrad2.exe
A raw file is written immediately; you can open it with an editor and check the first two values in the file…

Data Gathering:

As mentioned earlier, I had a lot of guidance along the way before getting to this point. But once I resolved the problems, I had to figure out how to use the equipment and software to gather the data.

Step 1: You will need to establish a baseline for your data. To do so, you can find an area, at your declination and during your observation time, which has very little hydrogen and record data files. If you can't find one, you can create a baseline by pointing the horn toward the ground (I set up in the basement and aimed into the concrete floor once) and recording 10 data files. (See below.)

Step 2: You need to determine what to observe. I used Jim Sky's 'Radio Eyes' program to determine where to point my antenna; it is helpful for finding an object or area of sky, selecting it, and making a tracking table (under 'Tools') using UT (I tried using my local time and it was off – probably an error in my set-up but UT always works!). You can print that out and pick the best set of coordinates for your yard (mine has lots of trees to aim around!). Aim the antenna (azimuth; elevation) to the region of the sky you want to observe. For azimuth, I used a compass adjusted for magnetic declination (the angle between magnetic north and true north at your particular location - you can look your declination up online). For elevation, I used an angle finder (you can get one at Amazon)

Step 3: Run SDR#, select your dongle (RTL-SDR), set-up for your device using the settings icon (the 'gear' at the top) and adjust the frequency at the top where you see the frequency numbers (up – at the top of the number, down – at the bottom of the number). You can try my set-up, but may have to change gain, etc. for your particular device. Then press play. See figure 8 for my SDR# settings.

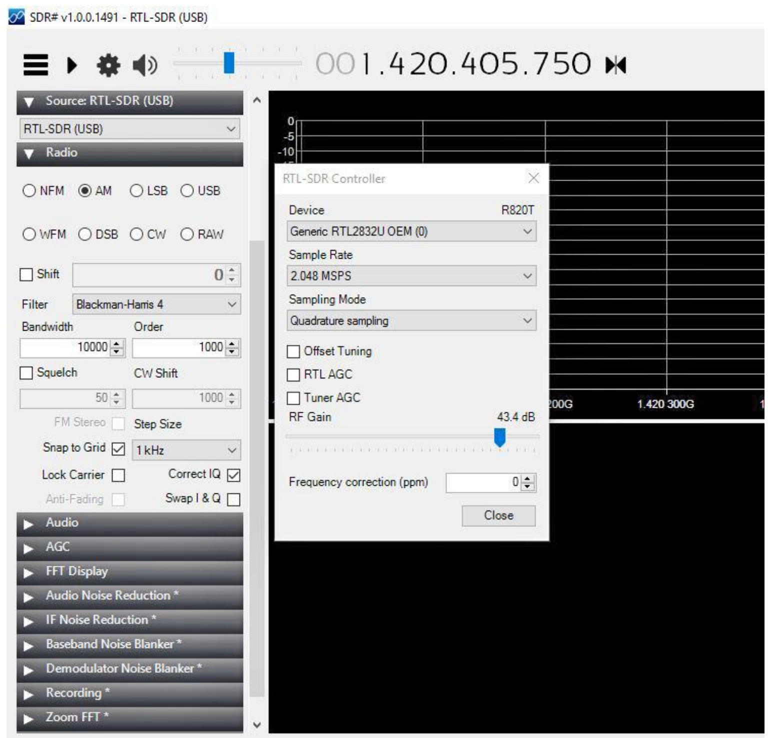


Figure 8: Screenshot of my SDR# Settings

Step 4: Press 'Control' 'Alt' 'Delete' to bring up the 'Task Manager'. Click on the 'Processes' tab. Right click on SDR# and select 'End Process' then 'End Process' again – you must do it this way or it will not work! I found that out when I tried some shortcuts I knew.

Step 5: Open your CFRAD2 folder and start cfrad2.exe. The program runs in the background and the only evidence it is working is the writing of files to the output file in the CFRAD2 folder. Make sure to check that a file is written immediately after starting and every 5 minutes afterwards.

Step 6: Run CFRAD2 for the time you need and exit using 'Task Manager'.

A Short Note About Pass Band Curve Correction: The pass band of these inexpensive SDR radios is pretty poor so a 'baseline' value is divided into the data collected to yield a 'corrected' data set. See the example below (from Michiel's MK-6 experiment file: parac.eu/projectmk6.htm – see figures 9&10 below). The file nrad29 is the data; nrad180 is the baseline value; a/b is nrad29/nrad180; and the final value scales the 'corrected' data.

Point #	nrad 29	nrad180	a/b	c*100-90
1	5.31E+00	5.34E+00	9.94E-01	9.43E+00
2	5.32E+00	5.32E+00	1.00E+00	1.01E+01
3	5.30E+00	5.29E+00	1.00E+00	1.02E+01
4	5.28E+00	5.34E+00	9.89E-01	8.86E+00
5	5.29E+00	5.32E+00	9.94E-01	9.39E+00
6	5.30E+00	5.33E+00	9.95E-01	9.48E+00
7	5.29E+00	5.31E+00	9.97E-01	9.66E+00

Figure 9: Portion of the MK-6 Project Spreadsheet File

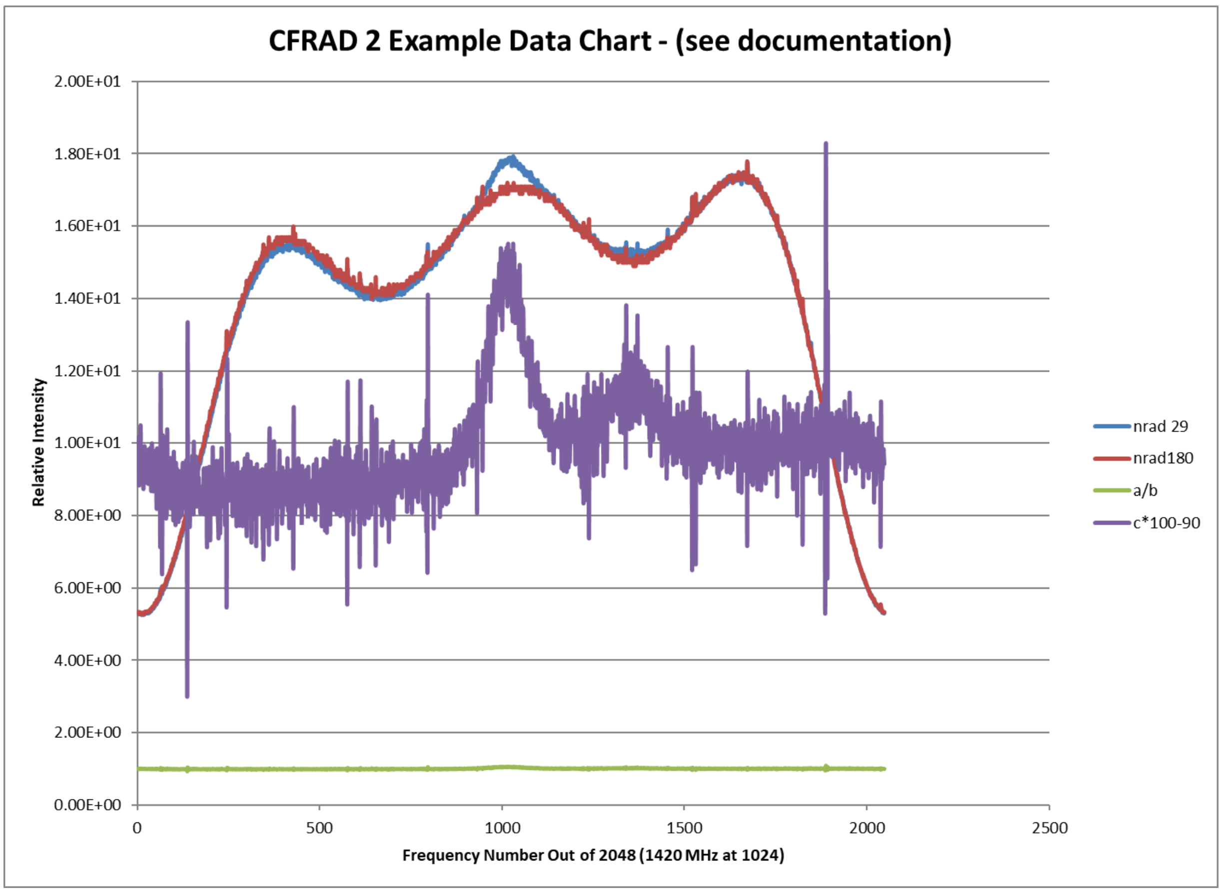


Figure 10: MK-6 Project Chart

I am also including an image of my "concrete" baseline made by pointing the horn into the basement concrete floor and collecting 10 files with CFRAD 2. I used this to 'correct' data when I didn't have a baseline area in my collected data. See figure 11 below.

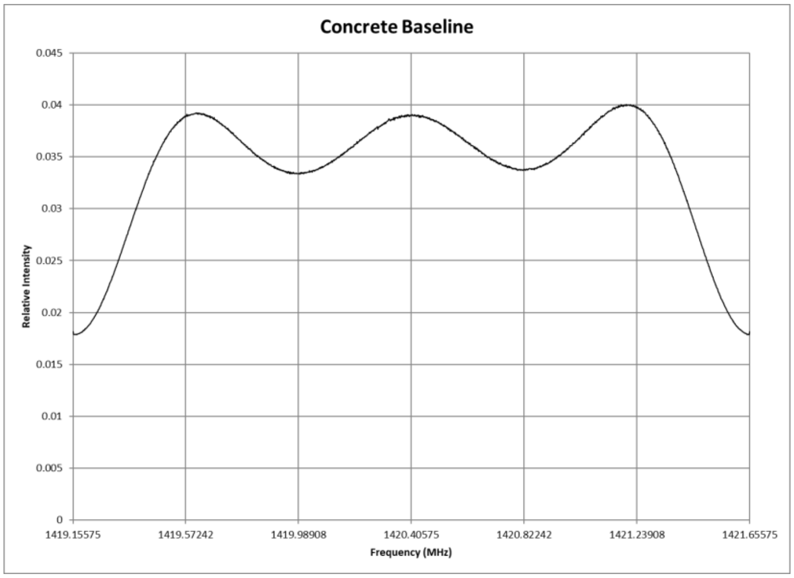


Figure 11: My "Concrete" Baseline

Data Analysis:

So, now that I have the data I need, how do I analyze the data? There are two ways – for longer collections with more than an hour of data you should use the python code; for short data collections you can use Excel. During my first attempt, I aimed the antenna toward the Cassiopeia A region and took 24 hours' worth of data. It was so exciting for me when I saw the first chart appear on the screen! Because of the longer time frame, I needed to run the Python script Michiel had written. I have no experience with Python so I needed some help yet again.

Using Python Code:

Step 1: Copy the python script (you can get this from: http://parac.eu/projectmk6.htm - or you can contact me for my version which eliminates the limit protections on the graphs) into the folder that has the data you wish to analyze.

Step 2: open Spyder and Open your python file from the file folder you copied it into.

Step 3: Scroll down to the *vans=180 # vanaf set*
ms=190 # to set; om zoveel mogelijk een gladde curve te krijgen
this is your band pass correction (your baseline). Figure out from your data where this is in the files and type the beginning and ending 'nrad' file numbers in the vans and ms lines. If you are using your own baseline, you will need to add it to the file and use those numbers.

Step 4: Scroll down to *sets=12 # select een set van 0 tot 288* – if you have less than 12 files or your baseline is near nrad-12 - you should change this number to a spot with good data.

Step 5: Scroll down under "series" to: *vans=0 # bereken de 5 minuten sets vanaf set x*
ms=288 # tot set xx
If you have less than 288 files you need to change the 'ms' number to the number of files you have.

Step 6: Click on Object Inspector (right bottom half of screen). Run the file (tab at the top). Select *Execute in a new dedicated Python console* and run. As graphs are made you can save them and view as JPGs (or other file types) at a later time. When done viewing or saving graphs, click the 'X' and continue to the next graph until the run is complete.

Using Excel:
There are some graphs I wanted to use Excel to create – I'm more familiar with that program and I have more control. I will send copies of my spreadsheets to anyone who is interested, so you can just cut and paste your data into them.

Step 1:
The CFRAD2 files collect 2048 frequencies and your center frequency ends up at about 1024 so you can figure out the beginning of the data and the interval between each point and have Excel fill in the frequency column. In the Galactic Longitude example below, I ended up starting at 1419.89400 MHz since I used 1.024MSPS in SDR# - I should have used 2.048MSPS but mis-read the SDR# instructions. Luckily 1024 MSPS worked out o.k., but if I gather more data, I will use 2.048 MSPS.

Step 2:
Calculate which files you want to show for the Excel graphs based on collection time/region observation time from Radio Eyes.

Step 3:
Open each CFRAD2 file you need (I chose to use 5 to average with the center time at file 3 – i.e.: 2 files either side) and copy each into the spreadsheet (right click and copy).

Step 4:
When finished copying the files use the AVERAGE function to average the 5 points.

Step 5:
Do Steps 2&3 for your baseline files (again, I chose 5 to average)

Step 6:
Divide the Average Data by the Average Baseline to get a corrected data set.

Step 7:
Adjust the data offset so it is in an appropriate scale (in the example below, I chose to multiply the D/B data by 100 and subtract 30; you may need a different scaling factor so just change the formula to suit your needs).

Step 8:
Copy the Frequency and D/B*100-30 column (or whatever scale you chose) as shown above.

Step 9:
Select the data in step 8 and Insert a Scatter graph (without points). See graph.

Below is my first spreadsheet and resulting graph (figures 12 & 13) – plotting the data from each galactic longitude (every 30 degrees from 30-240 degrees). There are more Excel sheets and graphs in the Projects section, as well as more information about this project.

Frequency	Data 1	Data 2	Data 3	Data 4	Data 5	Average Data	Baseline 1	Baseline 2	Baseline 3	Baseline 4	Baseline 5	Av Baseline	Data/Baseline	D/B*100-30	Frequency	D/B*100-30 Val
1419.89400	8.52E-03	8.49E-03	8.47E-03	8.34E-03	8.19E-03	8.40E-03	1.82E-02	1.82E-02	1.82E-02	1.82E-02	1.81E-02	1.82E-02	0.462191574	16.2191574	1419.89400	16.21915739
1419.89450	8.26E-03	8.25E-03	8.19E-03	8.08E-03	7.89E-03	8.13E-03	1.79E-02	1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	0.453796613	15.3796613	1419.89450	15.37966127
1419.89500	8.24E-03	8.27E-03	8.20E-03	8.04E-03	7.89E-03	8.13E-03	1.80E-02	1.79E-02	1.80E-02	1.79E-02	1.78E-02	1.79E-02	0.453641566	15.3641566	1419.89500	15.36415661
1419.89550	8.27E-03	8.24E-03	8.18E-03	8.03E-03	7.92E-03	8.13E-03	1.80E-02	1.79E-02	1.79E-02	1.78E-02	1.79E-02	1.79E-02	0.45366311	15.366311	1419.89550	15.36631096
1419.89600	8.26E-03	8.25E-03	8.21E-03	8.11E-03	7.91E-03	8.15E-03	1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.78E-02	1.79E-02	0.454870571	15.4870571	1419.89600	15.48705714
1419.89650	8.24E-03	8.22E-03	8.20E-03	8.01E-03	7.91E-03	8.12E-03	1.80E-02	1.79E-02	1.79E-02	1.78E-02	1.78E-02	1.79E-02	0.453531358	15.3531358	1419.89650	15.35313575
1419.89700	8.24E-03	8.21E-03	8.18E-03	8.03E-03	7.89E-03	8.11E-03	1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	0.452248743	15.2248743	1419.89700	15.22487434
1419.89750	8.25E-03	8.18E-03	8.17E-03	8.04E-03	7.89E-03	8.11E-03	1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	0.452627765	15.2627765	1419.89750	15.26277651
1419.89800	8.20E-03	8.20E-03	8.19E-03	8.06E-03	7.89E-03	8.11E-03	1.79E-02	1.79E-02	1.80E-02	1.79E-02	1.78E-02	1.79E-02	0.452699667	15.2699667	1419.89800	15.26996668
1419.89850	8.22E-03	8.22E-03	8.16E-03	8.03E-03	7.91E-03	8.11E-03	1.80E-02	1.79E-02	1.80E-02	1.79E-02	1.79E-02	1.79E-02	0.452098839	15.2098839	1419.89850	15.2098839
1419.89900	8.24E-03	8.22E-03	8.17E-03	8.04E-03	7.88E-03	8.11E-03	1.80E-02	1.79E-02	1.78E-02	1.79E-02	1.78E-02	1.79E-02	0.453565386	15.3565386	1419.89900	15.35653859
1419.89950	8.24E-03	8.20E-03	8.14E-03	7.99E-03	7.85E-03	8.08E-03	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.80E-02	1.79E-02	0.450455446	15.0455446	1419.89950	15.0455446
1419.90000	8.24E-03	8.21E-03	8.19E-03	8.04E-03	7.87E-03	8.11E-03	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	0.452932215	15.2932215	1419.90000	15.29322148

Figure 32: Spreadsheet of Data from Galactic Longitude Collection Project

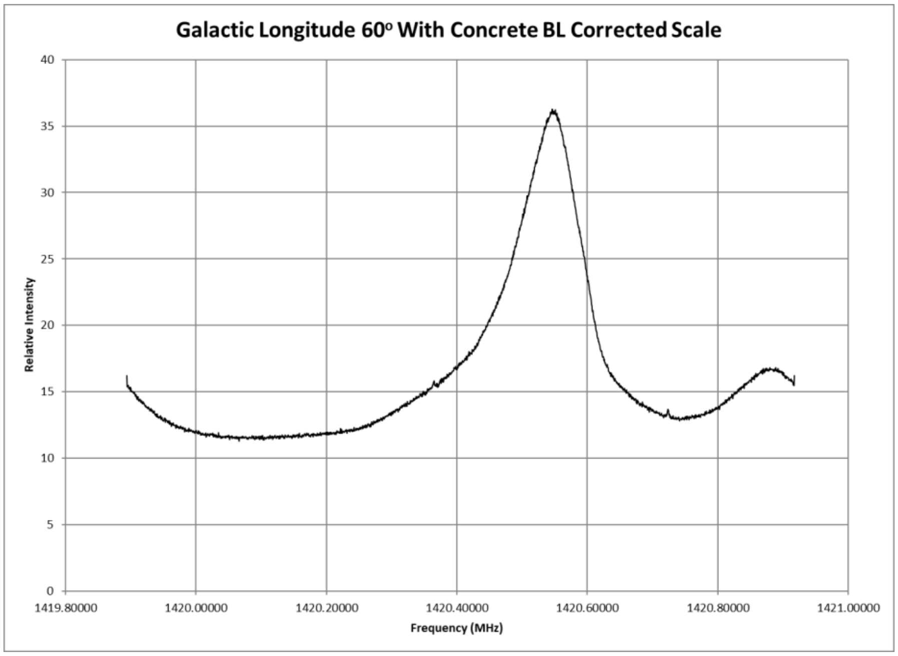


Figure 4: Graph of the Galactic Longitude Data in Figure 12

<u>Projects</u>:
<u>I) Detecting hydrogen and taking 24-hour charts near Cygnus A, Cass. A, and Virgo A </u>(Refer to figures 14-22 below)

This was my first project. I did this to make sure I could detect hydrogen gas clouds and to get a 'feel' for what a 24-hour scan might look like. I just used the technique described above under "Data Gathering" and ran for 24 hours. Below are some of the charts I gathered. The vertical scale is for relative intensity (I didn't calibrate the system). Since I wasn't using these for anything other than my information and interest, I did not run them many times, which would be necessary to get clear charts. On a few occasions, the charts had 'issues' which turned out to be a 'cold' solder connection that was intermittent. Fixing that yielded consistent data. It was interesting for me to see the Doppler shift over the 24-hour period.

Cygnus A Region (figures 14 & 15)

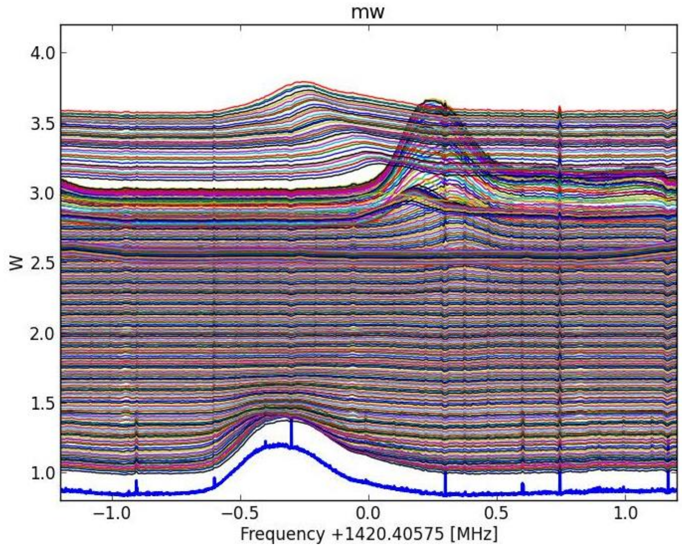


Figure 14: Long Scan at the Altitude of Cygnus A. Data Collected 3/25/18. Start=20UT. Peak of Cygnus A Transit=11UT.

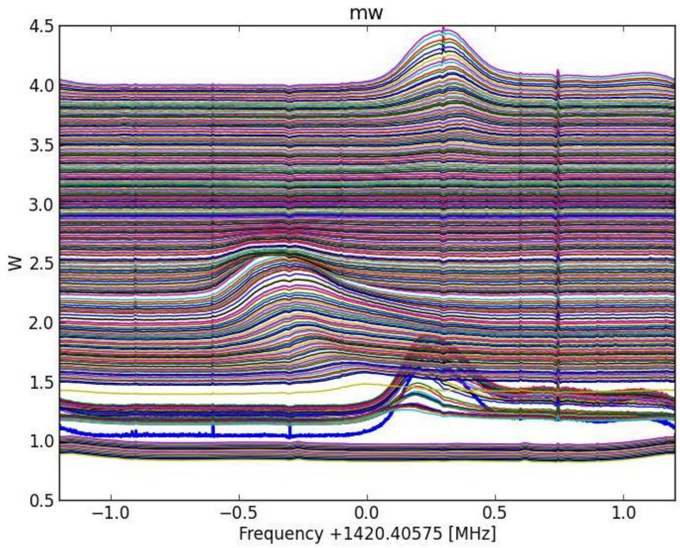


Figure 15: Long Scan at the Altitude of Cygnus A. Data Collected 3/31/18. Start=1012UT. Peak of Cynus A Transit=1030UT.

Virgo A Region (figures 16 - 18)

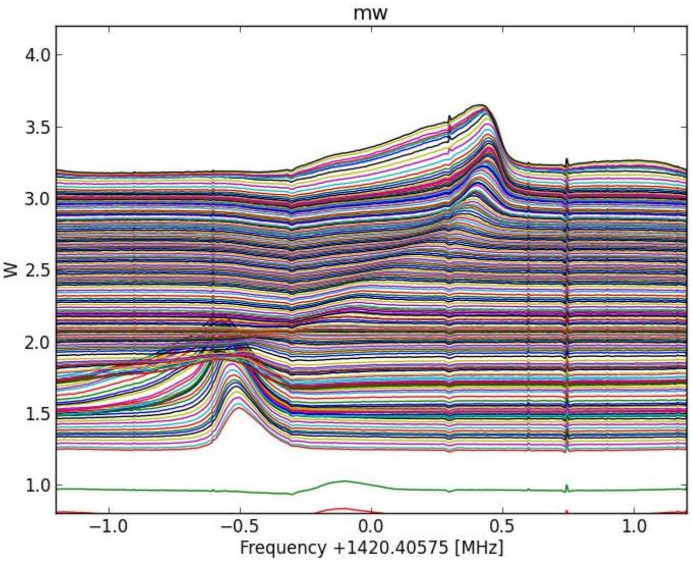


Figure 16: Long Scan at the Altitude of Virgo A. Data Collected 3/26/18. Start=19UT. Peak of Cygnus A Transit=06UT.

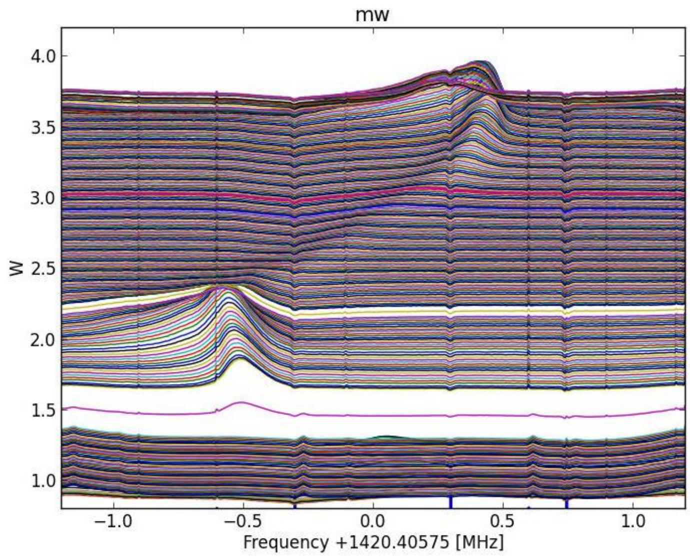


Figure 17: Long Scan at the Altitude of Virgo A. Data Collected 3/28/18. Start=15UT. Peak of Cygnus A Transit=06UT.

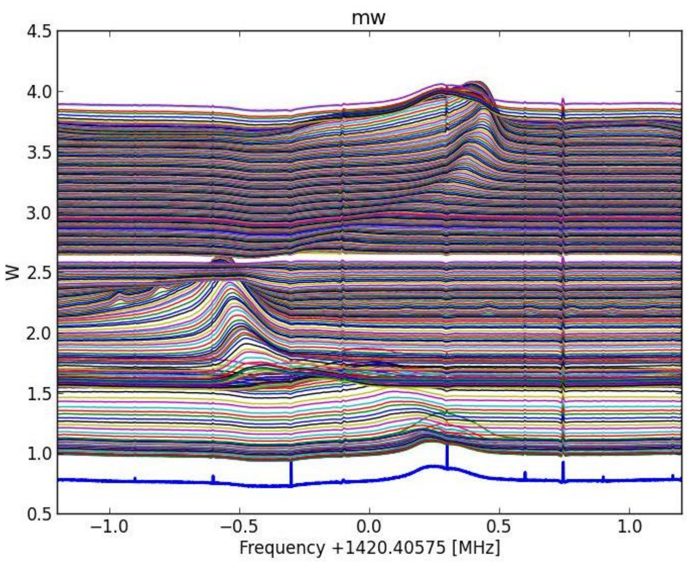


Figure 18: Long Scan at the Altitude of Virgo A. Data Collected 4/02/18. Start=1346UT. Peak of Cygnus A Transit=0530UT.

Cassiopeia A Region (figures 19 - 22)

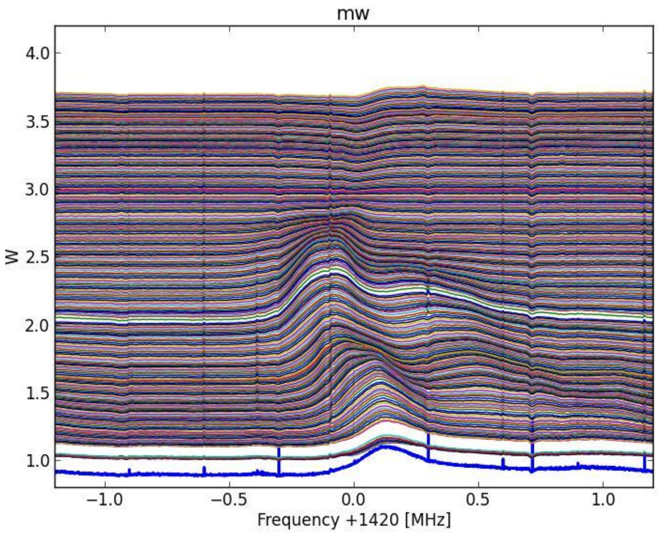


Figure 19: Long Scan at the Altitude of Cassiopeia A. Data Collected 1/18/18. Start=13UT. Peak of Cassiopeia A Transit=18UT.

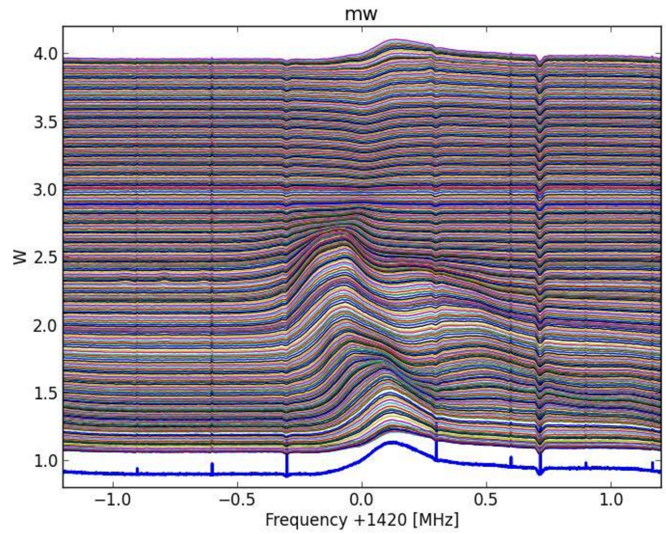


Figure 20: Long Scan at the Altitude of Cassiopeia A. Data Collected 1/20/18. Start=13UT. Peak of Cassiopeia A Transit=18UT.

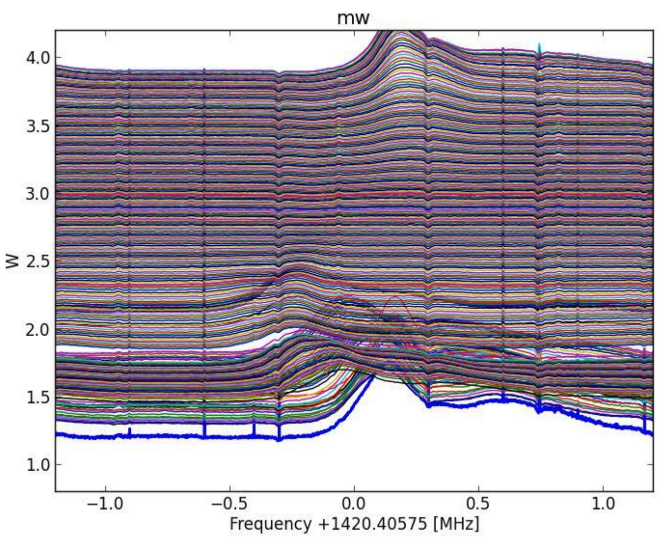


Figure 21: Long Scan at the Altitude of Cassiopeia A. Data Collected 3/27/18. Start=13UT. Peak of Cassiopeia A Transit=1430UT.

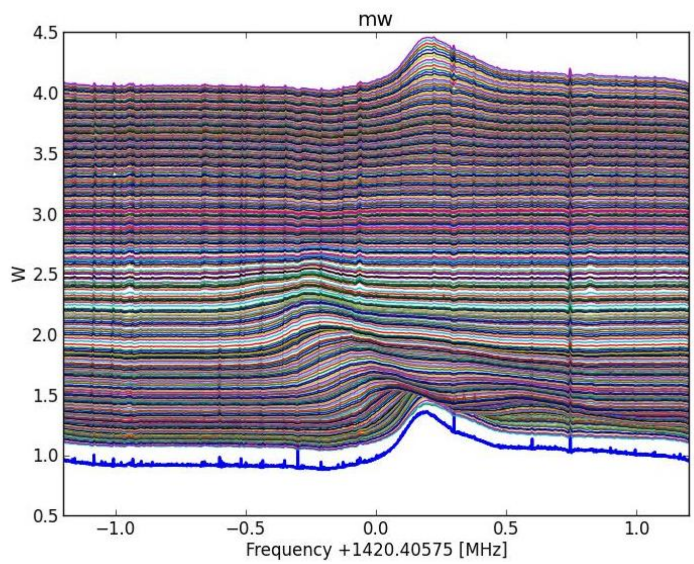


Figure 22: Long Scan at the Altitude of Cassiopeia A. Data Collected 4/01/18. Start=1043UT. Peak of Cassiopeia A Transit=14UT.

II) Galactic Longitude Graphs (30-240 degrees in 30-degree increments)

Having proven that the SDR system was working, I wanted to do more. I decided to try to replicate the project that was done by Dr. Nimesh Patel's students at Harvard (discussed above - https://www.cfa.harvard.edu/~npatel/hornAntennaAASposterPDF2.pdf).

To be sure of what I was collecting, I decided to use a calibrated signal generator and calibrate the scale for SDR# set-up for both 1024 and 2048 MSPS sample rates (I accidentally chose 1024 instead of 2048 so did both for future work). A sample of that graph is shown in figure 23.

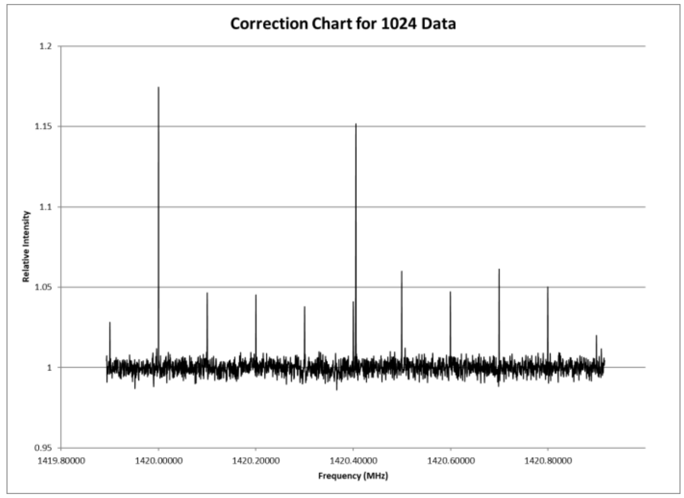


Figure 23: My 1024 MSPS Calibrated Frequency Chart

I first needed to find the galactic coordinate system and determine where I would need to point my horn antenna. Galactic coordinates are chosen so that 0 degrees points toward the center of the galaxy and go counter-clockwise around – see the galactic coordinates picture in figure 24.

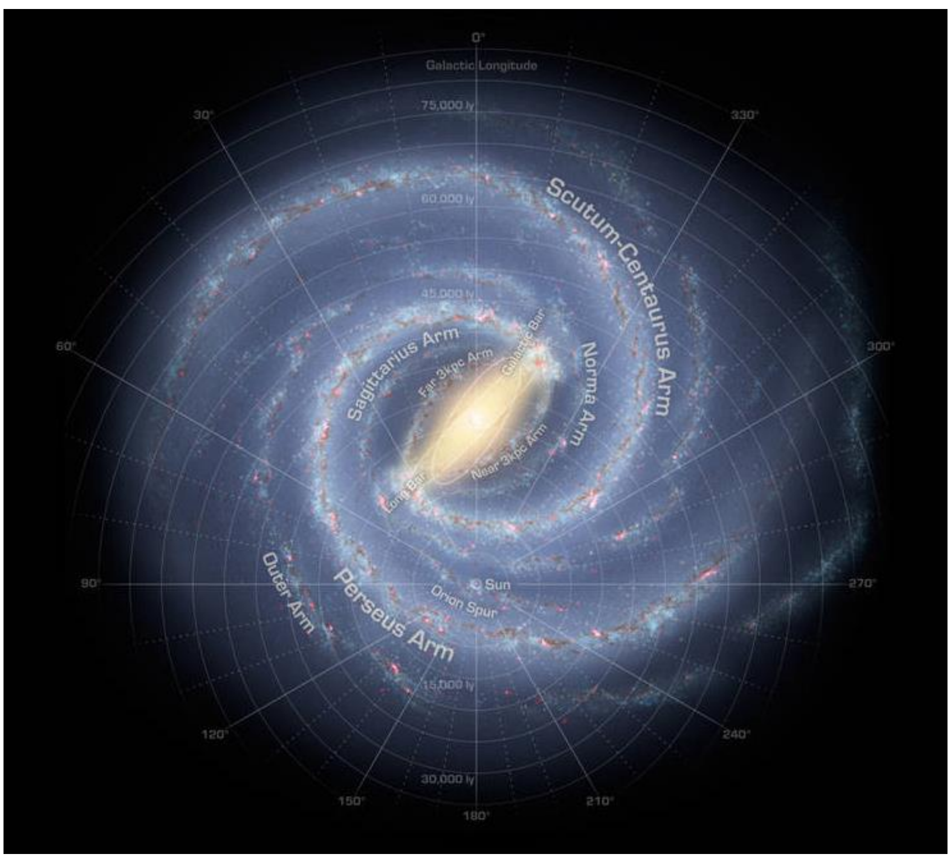


Figure 24: Galactic Coordinates Graphic From: www.nasa.gov/ mission_pages/sunearth/news/gallery/galaxy-location.html

I next needed to find out where in the sky these galactic coordinates are located, using the chart I found (shown in figure 25).

MILKY WAY GALAXY COORDINATES

GALACTIC COORDS		EQUATORIAL COORDS	
l(deg) longitude	b(deg) latitude	RA(HMS) right ascension	DEC(dms) declination
0	0	17h45m37s	-28d56m10s
10	0	18h07m46s	-20d17m24s
20	0	18h27m32s	-11d29m19s
30	0	18h46m05s	-02d36m33s
40	0	19h04m23s	+06d17m14s
50	0	19h23m19s	+15d08m33s
60	0	19h43m54s	+23d53m25s
70	0	20h07m28s	+32d26m33s
80	0	20h35m53s	+40d39m49s
90	0	21h12m01s	+48d19m46s
100	0	22h00m01s	+55d02m59s
110	0	23h04m32s	+60m09m34s
120	0	00h25m48s	+62d43m32s
130	0	01h52m17s	+62d02m01s
140	0	03h07m15s	+58d17m51s
150	0	04h04m28s	+52d25m12s
160	0	04h46m58s	+45d14m46s
170	0	05h19m29s	+37d18m54s
180	0	05h45m37s	+28d56m10s
190	0	06h07m46s	+20d17m24s
200	0	06h27m32s	+11d29m19s
210	0	06h46m05s	+02d36m33s
220	0	07h04m23s	-06d17m14s
230	0	07h23m19s	-15d08m32s
240	0	07h43m54s	-23d53m25s
250	0	08h07m28s	-32d26m33s
260	0	08h35m53s	-40d39m49s
270	0	09h12m01s	-48d19m47s
280	0	10h00m01s	-55d03m00s
290	0	11h04m31s	-60d09m35s
300	0	12h25m48s	-62d43m33s
310	0	13h52m17s	-62d02m02s
320	0	15h07m15s	-58d17m52s
330	0	16h04m28s	-52d25m13s
340	0	16h46m58s	-45d14m47s
350	0	17h19m30s	-37d18m54s

DECs not visible from Espanola, NM or too low in elevation for good S/N measurements

Figure 25: Galactic Coordinates and Equatorial Coordinates
Chart From: www.k5so.com/Radio_astronomy_HI_line.html

I decided to try to observe every 30 degrees starting at 30 degrees and going to 240 degrees (I can't observe below 30 degrees from my home – surrounded by woods). Using Radio Eyes software, I calculated the times and dates I wanted to try for observing these coordinates. I then used Excel to plot the galactic longitude graphs shown below. The technique for doing this was described above under 'Data Analysis: Using Excel'. I include a portion of the spreadsheet and a sample graph, as well as the final composite of all graphs on one chart in figures 26 - 28.

Frequency	Data 1	Data 2	Data 3	Data 4	Data 5	Average Data		Baseline 1	Baseline 2	Baseline 3	Baseline 4	Baseline 5	Av Baseline		Data/Baseline	D/B*100-30		Frequency	D/B*100-30 Val
1419.89400	8.52E-03	8.49E-03	8.47E-03	8.34E-03	8.19E-03	8.40E-03		1.82E-02	1.82E-02	1.82E-02	1.82E-02	1.81E-02	1.82E-02		0.462191574	16.2191574		1419.89400	16.21915739
1419.89450	8.26E-03	8.25E-03	8.19E-03	8.08E-03	7.89E-03	8.13E-03		1.79E-02	1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02		0.453796613	15.3796613		1419.89450	15.37966127
1419.89500	8.24E-03	8.27E-03	8.20E-03	8.04E-03	7.89E-03	8.13E-03		1.80E-02	1.79E-02	1.80E-02	1.79E-02	1.78E-02	1.79E-02		0.453641566	15.3641566		1419.89500	15.36415661
1419.89550	8.27E-03	8.24E-03	8.18E-03	8.03E-03	7.92E-03	8.13E-03		1.80E-02	1.79E-02	1.79E-02	1.78E-02	1.79E-02	1.79E-02		0.45366311	15.366311		1419.89550	15.36631096
1419.89600	8.26E-03	8.25E-03	8.21E-03	8.11E-03	7.91E-03	8.15E-03		1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.78E-02	1.79E-02		0.454870571	15.4870571		1419.89600	15.48705714
1419.89650	8.24E-03	8.22E-03	8.20E-03	8.01E-03	7.91E-03	8.12E-03		1.80E-02	1.79E-02	1.79E-02	1.78E-02	1.78E-02	1.79E-02		0.453531358	15.3531358		1419.89650	15.35313575
1419.89700	8.24E-03	8.21E-03	8.18E-03	8.03E-03	7.89E-03	8.11E-03		1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02		0.452248743	15.2248743		1419.89700	15.22487434
1419.89750	8.25E-03	8.18E-03	8.17E-03	8.04E-03	7.89E-03	8.11E-03		1.80E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02		0.452627765	15.2627765		1419.89750	15.26277651
1419.89800	8.20E-03	8.20E-03	8.19E-03	8.06E-03	7.89E-03	8.11E-03		1.79E-02	1.79E-02	1.80E-02	1.79E-02	1.78E-02	1.79E-02		0.452699667	15.2699667		1419.89800	15.26996668
1419.89850	8.22E-03	8.22E-03	8.16E-03	8.03E-03	7.91E-03	8.11E-03		1.80E-02	1.79E-02	1.80E-02	1.79E-02	1.79E-02	1.79E-02		0.452098839	15.2098839		1419.89850	15.2098839
1419.89900	8.24E-03	8.22E-03	8.17E-03	8.04E-03	7.88E-03	8.11E-03		1.80E-02	1.79E-02	1.78E-02	1.79E-02	1.78E-02	1.79E-02		0.453565386	15.3565386		1419.89900	15.35653859
1419.89950	8.24E-03	8.20E-03	8.14E-03	7.99E-03	7.85E-03	8.08E-03		1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.80E-02	1.79E-02		0.450455446	15.0455446		1419.89950	15.0455446
1419.90000	8.24E-03	8.21E-03	8.19E-03	8.04E-03	7.87E-03	8.11E-03		1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02	1.79E-02		0.452932215	15.2932215		1419.90000	15.29322148

Figure 26: Portion of a Spreadsheet for Galactic Longitude 60 Degrees

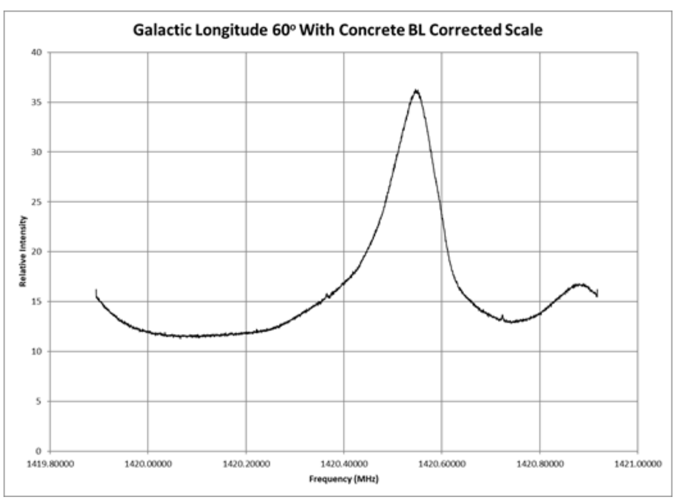


Figure 27: Graph of Data from the Spreadsheet Shown in Figure 25

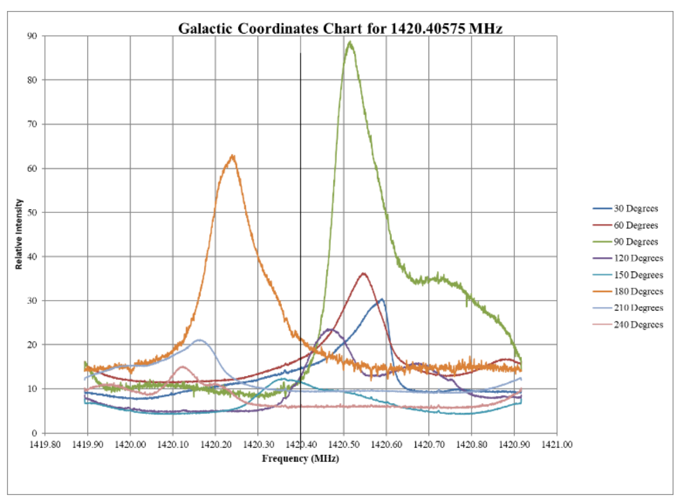


Figure 28: Galactic Coordinates Chart for 30-240 Degrees

III) Calculating and graphing V_{LSR} (Local Standard of Rest Velocity)

The results (figures 26 - 28) are the relative velocities of galactic arms in the galactic coordinate I observed. I then had to convert these to V_{LSR} - Local Standard of Rest Velocity. The V_{LSR} accounts for the motion of the Earth and Sun in our observations. The radial velocity on the spreadsheet is the motion of the object being observed relative to Earth. I was told of a great site that actually calculates the radial velocity as well as the V_{LSR} (http://neutronstar.joataman.net/technical/radial_vel_calc.html). You will need the following data to calculate the values for each observation: the frequency (1420.40575 MHz); UTC; RA; DEC; Latitude; Longitude. Once you have these values you can calculate both radial velocity and V_{LSR}. I also ran a quick check by calculating the V_{LSR} values directly (see final column in spreadsheet below). f_{obs} = 1420.40575 MHz; f_{meas} = the frequency associated with the measured peak from the LSR Velocity graphs below; c = velocity of light (300,000 km/s); and Rad V is the radial velocity from the website. The values are very close. See figure 29 below.

Galactic Coordinate Velocity Calculations - Radial Velocities from: neutronstar.joataman.net/technical/radial_vel_calc.html

Galactic Long.	Date	UT	Radial Velocity	Frequency	VLSR		V=(fobs-fmeas)c/fobs - Rad V km/sec
30	4/22/2018	9:30	-42.82	1420.5895	4.04		4.010666822
30	4/22/2018	9:30	-42.82	1420.7625	-32.48		-32.52818836
60	4/22/2018	10:25	-39.60	1420.5435	10.53		10.50620057
60	4/22/2018	10:25	-39.60	1420.8755	-59.55		-59.61460822
90	4/23/2018	10:00	-26.05	1420.5120	3.63		3.609229115
90	4/23/2018	10:00	-26.05	1420.7300	-42.39		-42.43395256
120	4/23/2018	11:00	-5.48	1420.4650	-7.02		-7.034029882
120	4/23/2018	11:00	-5.48	1420.6695	-50.19		-50.22591361
150	4/23/2018	16:30	16.50	1420.3595	-6.74		-6.731664438
150	4/23/2018	16:30	16.50	1420.4945	-35.23		-35.24464392
180	4/23/2018	20:00	34.12	1420.2340	2.13		2.154846114
210	4/21/2018	21:30	42.91	1420.1570	9.59		9.627804779
210	4/21/2018	21:30	42.91	1419.9920	44.42		44.47700192
240	4/21/2018	22:30	39.60	1420.1175	21.24		21.28049137
240	4/21/2018	22:30	39.60	1420.1940	5.09		5.123136329
240	4/21/2018	22:30	39.60	1419.9440	57.86		57.92495018

Figure 29: Spreadsheet for Calculating the Local Standard of Rest Velocity for Each Galactic Longitude

The graph is quite tricky to make and you need to copy each of the velocities and intensities from your individual graphs onto a single spreadsheet (portion of mine shown below). You highlight the 30-degree data (first two columns) and make a scatter graph. You then select the data and go to Design; Select Data; Add and then select your next set of data (60 Degrees) from the sheet and keep adding data until you have all of your data represented on the chart. I then highlighted each data set and changed the color to align with the original color in the first graphs made. See figures 30 – 31 below.

V=(fobs-fmeas)c/fobs - Radial Velocity km/sec	30 Degrees	V=(fobs-fmeas)c/fobs - Radial Velocity km/sec	60 Degrees	V=(fobs-fmeas)c/fobs - Radial Velocity km/sec	90 Degrees
151.1165202	9.72332149	147.8965202	16.21915739	134.3465202	14.05328041
151.0109166	9.034102629	147.7909166	15.37966127	134.2409166	16.03808942
150.9053129	8.980738475	147.6853129	15.36415661	134.1353129	16.19399308
150.7997093	9.032440188	147.5797093	15.36631096	134.0297093	16.15280743
150.6941057	9.034163875	147.4741057	15.48705714	133.9241057	15.98322758
150.5885021	9.15672343	147.3685021	15.35313575	133.8185021	15.88517026
150.4828984	9.156471078	147.2628984	15.22487434	133.7128984	15.31786906
150.3772948	8.997994576	147.1572948	15.26277651	133.6072948	15.41021376
150.2716912	9.153202842	147.0516912	15.26996668	133.5016912	15.44341227
150.1660876	9.184894522	146.9460876	15.2098839	133.3960876	15.73169515

Figure 30: Spreadsheet for Creating the Local Standard of Rest Velocity Graph for All Galactic Longitudes Recorded

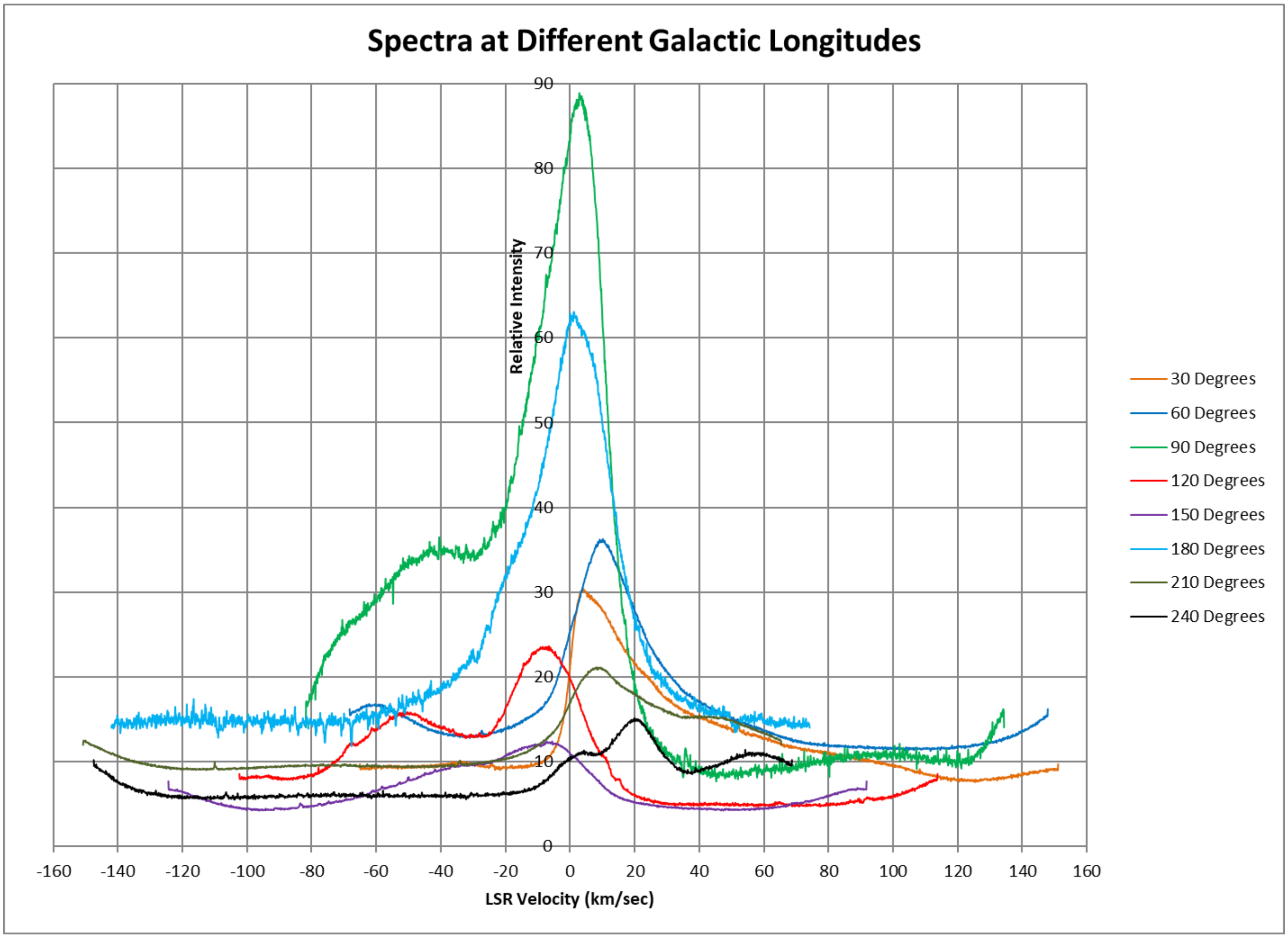


Figure 31: Spectra of LSR Velocity for all Galactic Longitudes Recorded

IV) Galactic Rotation graph

I wanted to try to calculate the galactic rotation graph and show how the galaxy rotates at various distances from the center. This one took a lot of help and thinking to complete. Luckily, J.J. Maintoux is on the SARA list-serve. He sent me to his website, where he has some wonderful information posted online (http://f1ehn.pagesperso-orange.fr/pages_radioastro/Images_Docs/Radioastro_21cm_2012b.pdf), including a great video clip on YouTube (https://www.youtube.com/watch?v=HGwkZY4E64k). Using his material (in French; translate with Google if you need to) I was able to complete the spreadsheet below (figure 32) and make the graph (figure 33). To measure V_{rmax}, the maximum value on the graph is found and measured. I have included an example graph showing the approximate location of the maximum value with an arrow (figure 34). Ro and Vo refer to the Sun's distance from the center of the galaxy and the velocity of the Sun around the galaxy center (8.5 kpc and 220 km/sec respectively). To calculate the distance R, the distance from the center of the galaxy to the Sun was multiplied by the sin of the galactic longitude in radians. The V(R) value is repeated in the spreadsheet for easier chart creation (R and V are next to each other).

As you can see from the graph below (figure 33) the flatness of the curve supports Dr. Vera Rubin's "missing matter" theory which she deduced from the first studies of galactic rotation curves in the 1970's with Dr. W. Kent Ford Jr. – now known as dark matter/dark energy.

Note: The graph can only be done for values of galactic longitude from 0-90 degrees since there is no tangent point in our line of sight for most other values involved. For more details on this, please refer to J.J. Maintoux's materials mentioned above.

My Data Re-calculated Using New Information from J-J. Maintoux					
Galactic Long. (gl)	**Vo*sin(l)**	**Vr_max (measured)**	**V(R) (km/sec) = Vr_max + Vo*sin(l)**	**R (kpc) = Ro*sin(l); where Ro=8.5 kpc - the distance from the galactic center to the Sun**	**V(R) (km/sec)**
30	110	124	234	4.3	234.0
60	191	69	260	7.4	259.5
90	220	27	247	8.5	247.0

Figure 32: Spreadsheet for Calculating Galactic Rotation Velocity at Various Distances

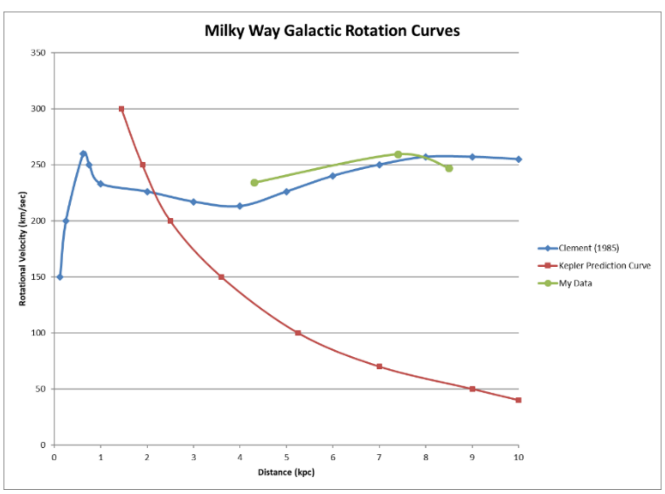


Figure 33: Milky Way Galactic Rotation Curves with my Data Included

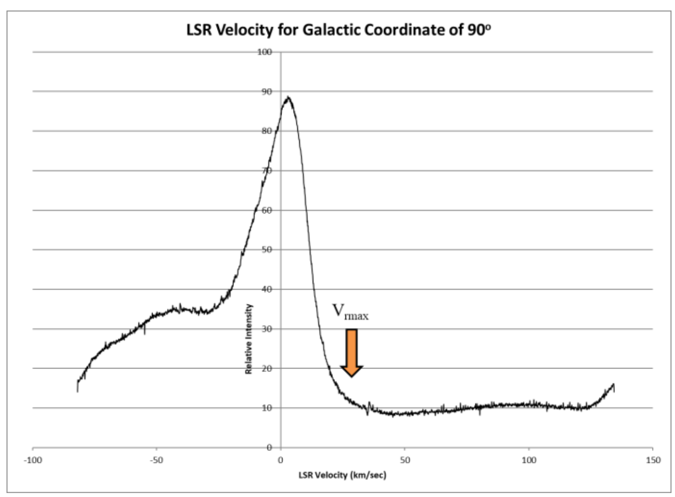


Figure 34: Graph of LSR Velocity Showing the Position of the Maximum Velocity (Vr_max)

V) Galactic Arms Graphic

Once again, I had a lot of help; the information from J.J. Maintoux (mentioned in the last section) again proved useful. Ro and Vo refer to the Sun's distance from the center of the galaxy and the velocity of the Sun around the galaxy center (8.5 kpc and 220 km/sec respectively). To plot the values on the graphic, I needed to convert to light years, thus the last column multiplies by 3,262 to get the correct units. See figures 35 & 36.

Galactic Long. (gl)	**JJM R value = Ro*Vo*sin(l)/(Vo*sin(l)+Vlsr**	**r (dist to H mass)=(R^2-Ro^2*sin^2(l))^0.5 + Ro*cos(l) kpc**	**r (dist to H mass)= r*3.262e+3 ly**
30	8.2	14.37	46,883
30	12.1	18.65	60,833
60	8.1	7.52	24,530
60	12.4	14.18	46,270
90	8.4		
90	10.5	6.21	20,267
120	8.8	0.62	2,015
120	11.5	4.64	15,127
150	9.1	0.63	2,069
150	12.5	4.40	14,351
180			
210	9.3	0.92	3,015
210	14.3	6.25	20,381
240	9.6	1.86	6,067
240	8.7	0.45	1,466
240	12.2	5.49	17,902

Figure 35: Spreadsheet for Calculating the Distance to Galactic Arms for all Galactic Coordinates Recorded

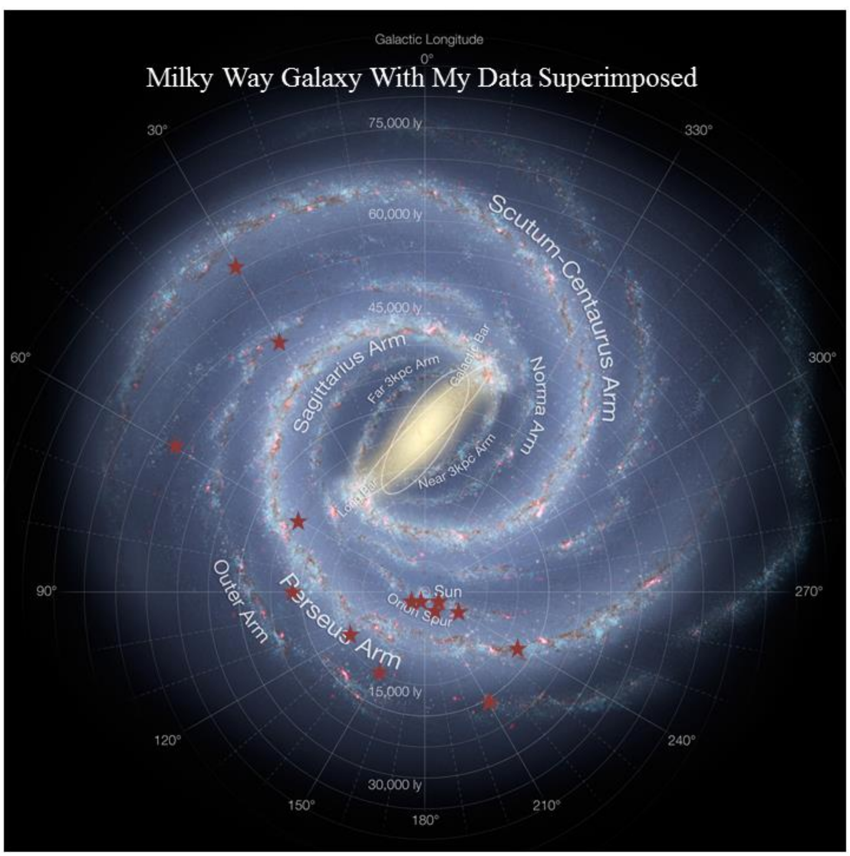


Figure 36: Measured Galactic Arm Distances Superimposed on Milky Way Galaxy Graphic

Conclusions:
I was amazed at how much information could be obtained from such an inexpensive device and with fairly small effort. This project was challenging (mathematically/ conceptually), but yielded a lot, and was well worth the effort. I encourage anyone who has any interest in exploring radio astronomy to give this a try. If you like it, then 'scale-up' to bigger and better receivers and antennas. Please let me know if you try this project, or some project like it, and consider writing it up for the SARA Journal.

Acknowledgements:
I originally started this due to a paper by Dr. Nimesh Patel (a Harvard professor) and his students called "A low-cost 21 cm horn-antenna radio telescope for education and outreach" (https://www.cfa.harvard.edu/~npatel/hornAntennaAASposterPDF2.pdf). Thank you for getting me interested and for all your comments, suggestions and support!
As mentioned earlier, many people helped me along the way. I started this project with no knowledge of SDR radios. Many people on the SARA List-Serve helped me with the problems I encountered along the way, such as the capacitor issue discussed above. These people include (but are not limited to): Jim Sky, Ken Redcap, Dr. Wolfgang Herrmann, Paul Oxley, and Bruce Randall.
I had help with the mathematics of some of the projects from J.J. Maintoux via the SARA List-Serve. As mentioned, he has a lot of interesting material on the web and, though it is in French (easy to translate using Google), it is very useful for understanding these concepts. ((http://f1ehn.pagesperso-orange.fr/pages_radioastro/Images_Docs/Radioastro_21cm_2012b.pdf) and a wonderful video clip on YouTube (https://www.youtube.com/watch?v=HGwkZY4E64k)).
I want to give a special thanks to Michiel Klaassen for the tremendous amount of help he gave me. Without his help, I wouldn't have been able to do this project at all. He helped me understand Python and get things working on my computer (no small feat!!!). He also helped me better understand hydrogen emissions and LSR calculations. His website (http://parac.eu/projects.htm) is a wealth of information for the amateur radio astronomer and experimenter. He does some things in the projects pages I didn't think were possible. I strongly urge you to check them out.
I also want to give a special thank you to my wife who thinks I live in the basement but is still willing to proofread my articles.
Lastly, thank you to those who take the time to read SARA articles. I hope you found something of value in this one.