A guide to building a horn HI telescope to measure the rotation curve of the Milky Way

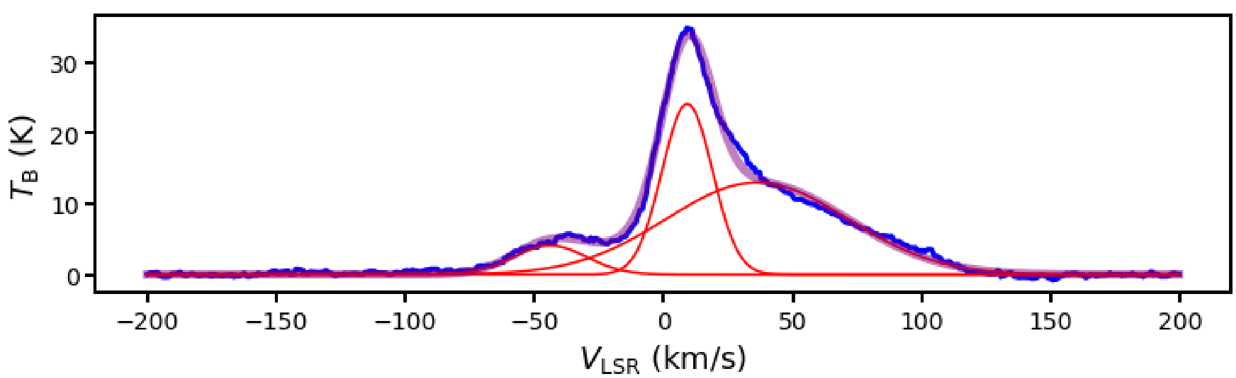

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Table of Contents

Introduction

This (living) document is intended to be a guide for how to build a simple horn radio telescope to detect the HI 21cm line and map the rotation of the Galaxy using off-the-shelf parts readily available at your local hardware store and inexpensive electronics bought online. A parts list is given in the appendix along with places to buy and their 2021 price. The total cost, not including a computer, should be between $300-500 depending on how high end you want to go with the material and, especially, the radio receiver. The first half describes the construction of the horn, stand, and electronic hardware. The second half describes the software used for data acquisition and reduction. Note that these long wavelength radio observations can be carried out from essentially anywhere whether the skies are clear blue or cloudy grey, just as long as it's not raining!

This project was motivated by the Research Experiences for Teachers (RET) program at West Virginia University and follows their design described at https://wvurail.org/dspira-lessons/tour/. We refer to many of their excellent instructions that are available as pdf or web links.

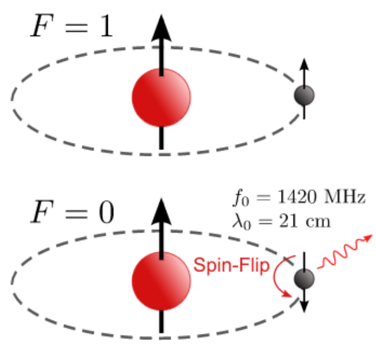
During 2021, we built one telescope with high school students during a summer project as part of our own RET program and two more with University of Hawaii graduate students in a one-semester radio astronomy seminar series. For the latter, we combined the practical work with lectures on radio telescope design. In the following description, I have highlighted areas where there was a good opportunity for a hands-on demonstration of a theoretical result. This work was supported by the National Science Foundation.

Our hope is that this document helps other groups build their own HI telescopes. Please email me at jw@hawaii.edu if you need advice or, indeed, if you successfully built a telescope without any help! I would also be very interested to hear of any improvements to the hardware or software and also of any other applications.

Have fun!

The HI 21cm line

This is a very brief introduction to the physics and history of the 21cm line. You can find much more information on wikipedia or in astronomy textbooks (such as, ehem, my own!).



Hydrogen is the most abundant element in the Universe (90% by number, 76% by mass) and the spin-flip transition of its sole electron produces the 21cm line. This is an extremely low energy line (6μeV) and is therefore easily excited through collisions in the gas. Consequently, wherever there is neutral hydrogen, which astronomers call HI ("H-one"), there is a spectral feature at 21cm.

Figure credit: https://en.wikipedia.org/wiki/Hydrogen_line#/media/File:Hydrogen-SpinFlip.svg

The strength of the line emission directly relates to the number of hydrogen atoms along our line of sight, which we call the telescope "beam". The rest frequency of the HI line is known to extremely high precision from quantum mechanical calculations (which are tested against a host of laboratory measurements and verified through direct observation). Your telescope will measure the spectral profile as it is shifted and broadened in frequency through the Doppler effect. From our measurements of the difference between the observed and rest frequency, we can then determine the motions of the gas. And then by mapping these motions along the plane of the Galaxy, we can measure its rotation.

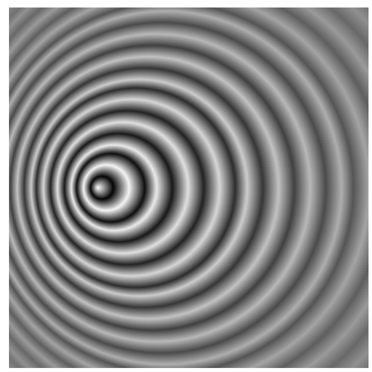
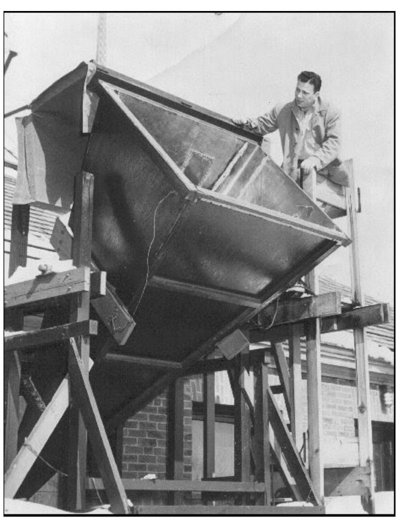


Figure credit: https://upload.wikimedia.org/wikipedia/commons/9/9e/Doppler_effect.svg



The National Radio Astronomy Observatory (NRAO) has a nice webpage on the history of the prediction and subsequent detection of the HI line. In short, van der Hulst published the quantum calculation predicting the existence and frequency of the HI spin-flip transition in 1945. Ewen & Purcell then designed and built a horn antenna and radio receiver to detect the line in 1951. Your telescope is actually quite similar to theirs in the sense of being a horn design feeding a dipole antenna. Amazingly enough, they built their ground-breaking instrument for $500 over an estimated 3.4 months (working on weekends for a year) - numbers that are not too different for this project today! The big difference is that, 70 years later, the signal detection is now greatly simplified by digitization and controlled by software using a device that you can plug into a USB port.

Figure credit: https://www.gb.nrao.edu/fgdocs/HI21cm/images/inspectinghorn.jpg

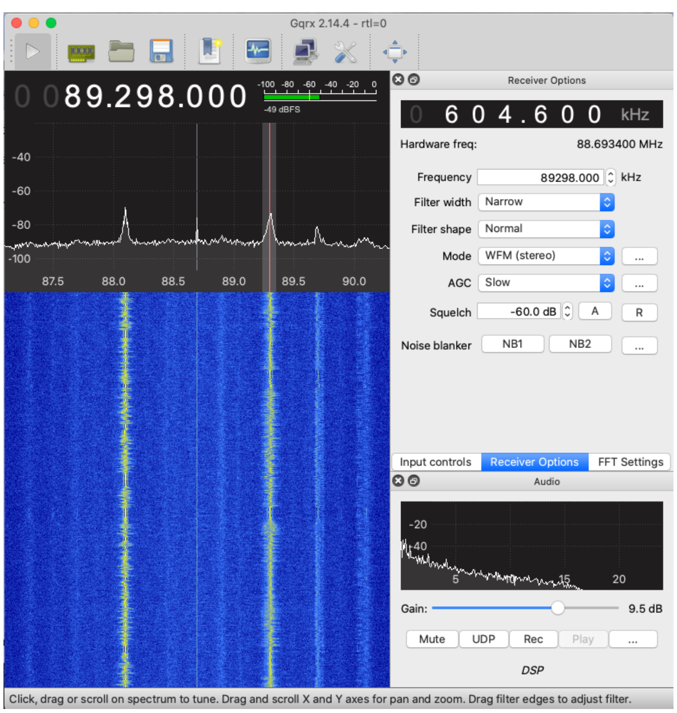
Software defined radio

At the low energy of the 21cm line, the electromagnetic radiation behaves more like a wave than a photon and can be detected through the oscillating current that it creates in an antenna (rather than inducing electrons to jump across a barrier as in CCDs for optical or infrared light). A radio includes multiple components including: an amplifier to increase the signal strength; a filter to select a narrow frequency range; a mixer to combine the incoming signal with a user input; and a demodulator to convert the signal into some user-defined content such as a speaker making sound waves for a traditional radio or a digital signal in our case. The various steps can be done via dedicated electrical circuits (resistors, capacitors, diodes…) but can now also be carried out by software, i.e., mathematical operations on a digitized signal. It is the advent and, increasingly lower costs, of software defined radio (SDR), that make this telescope project feasible.

There are many online resources to learn about SDR and see its many applications, e.g.,
https://en.wikipedia.org/wiki/Software-defined_radio
https://www.rtl-sdr.com/about-rtl-sdr/
https://www.mathworks.com/campaigns/offers/download-rtl-sdr-ebook.html

The technology for SDRs is constantly advancing and prices declining - a benefit of the digital age - and we built the first telescope prototype using a simple, cheap SDR from nooelec:

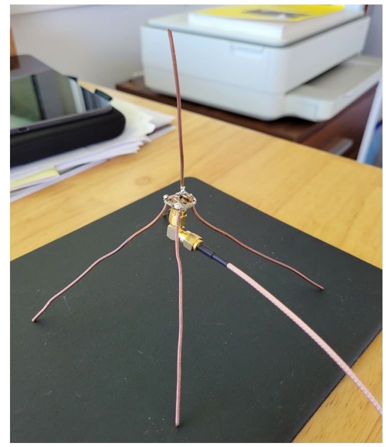
https://www.nooelec.com/store/sdr/sdr-receivers/nesdr-smart-sdr.html



To get started, also buy a basic antenna either from nooelec or amazon (see parts list in the Appendix) and then download a free software package that runs it through a graphical interface; GQRX for mac and linux, CubicSDR for windows. Along with the software, these web pages include instructions for how to set it up so it recognizes your SDR and also give some tips for things to try out. Its a simple plug-and-play exercise and a good introduction to the power of SDR.

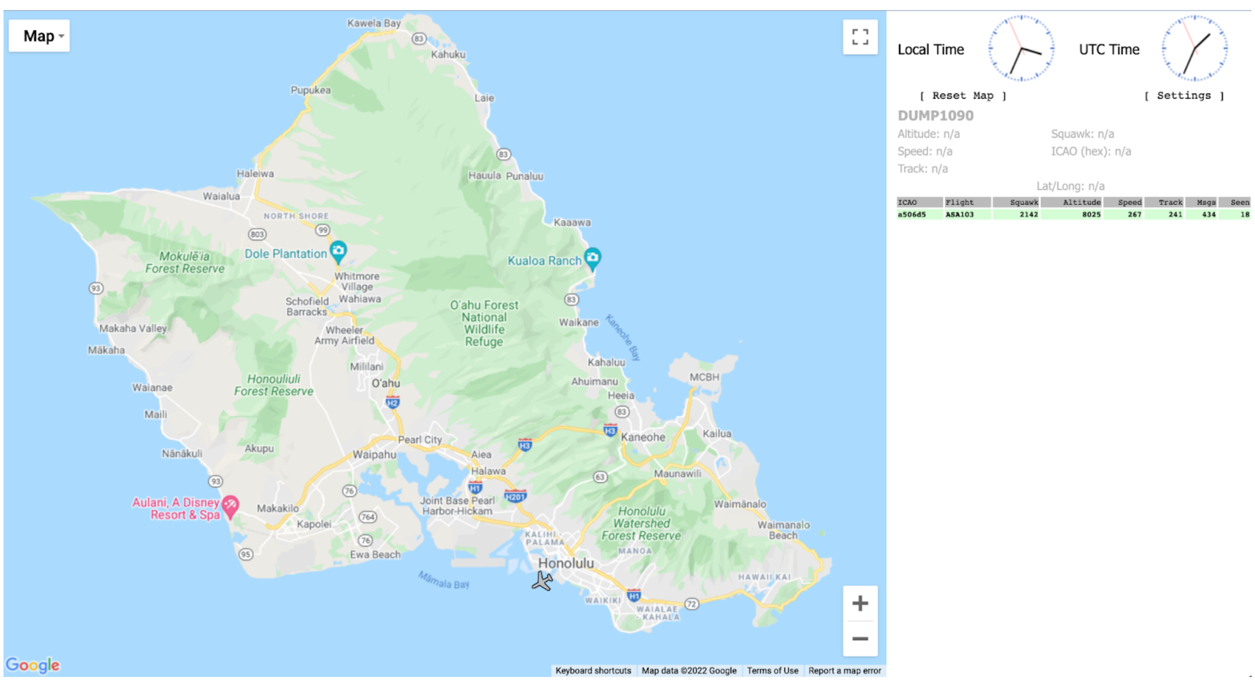
You can listen to FM radio stations but can explore beyond the regular radio dial to hear, e.g., aircraft towers or NOAA weather information. In some cases, you will need to switch between frequency and amplitude modulation for the audio to make sense which gives a chance to learn about the different ways that information can be encoded in a radio wave.

As you scan through the wide frequency range of the SDR, you will also find signals that sound like a series of clicks. The information here is digital and requires different software than GQRX to interpret.



A good side project, if you have the time, is to make an aircraft tracker. Again there are many online resources to delve into, e.g., https://www.rtl-sdr.com/adsb-aircraft-radar-with-rtl-sdr/ This also gives an opportunity to build a dipole antenna and understand how its dimensions relate to the frequency of the observation, and also to think about polarization. For an advanced class, you can go through the theory behind a ground plane antenna and then build one. This helps build intuition for later understanding how the waveguide and quarter-wavelength antenna work in the HI telescope.

For the software, we used the dump1090 program from https://github.com/MalcolmRobb/dump1090
installed on a mac. As shown below – look closely to see the plane – this program nicely interfaces to google maps (but requires that you create an API key). This aspect of the project provides a software challenge which is an equally important skill for the HI project.



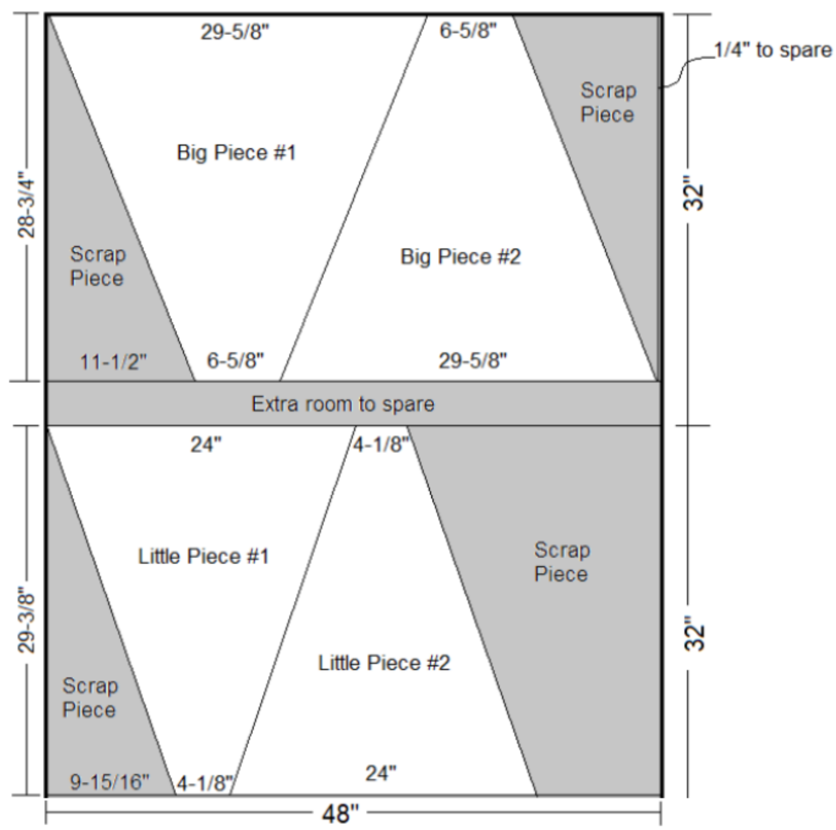
The nooelec SDR is cheap enough that you can feasibly buy several and distribute them to a class so that students can take them home to experiment with. It is also sufficient to detect the HI line using the horn telescope but we found that it was hard to accurately measure the rotation curve of the Galaxy due to its bandwidth which was both narrow (2 MHz) and structured. It is fine if you are on a limited budget and just want to demonstrate that you can detect Hydrogen, but if you progress to the point where you want to do more detailed analysis of the line profiles, then I recommend you get the Airspy R2 SDR at https://v3.airspy.us/product/a-airspy/

This is about five times more expensive than the nooelec but provides a much flatter and wider (10 MHz) bandwidth and substantially greater sensitivity. It makes the HI line detection dramatically clearer and allows the subtle features in the line profiles to be reliably detected which is necessary to measure the rotation curve.

The airspy does not work with the dump1090 program, but there are other aircraft tracker programs for it. My recommendation is to start off with the noospec and let the students begin by playing with something relatively cheap. Then see how far the project progresses (it's fairly involved and requires several weeks of commitment) before investing in the airspy.

Building the horn

So with those very quick introductions to the 21cm line and SDR (both of which you should explore more thoroughly), it's time to build the telescope. We start with the horn, which collects the radiation, and follow the [DSPIRA directions](#) closely.



The horn is built from home insulation board, made of stiff but lightweight foam. A single 4’x8’ board is sufficient to build 1 horn (in fact 1.5 so 2 boards makes 3 horns if you have a big class). I cut the longside of the board into 3 equally sized pieces (32’’) in the Home Depot parking lot so I could fit them in my car. Once transported, the four trapezoidal sides of the horn are cut out following the DSPIRA template to the right.

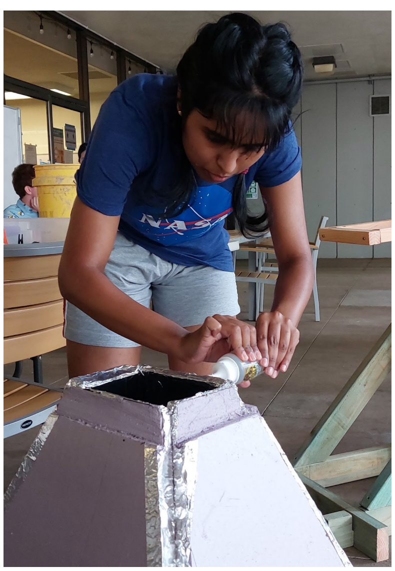
The cutting can be done with a utility knife guided by a straight piece of wood that is used for the next step. Measure twice, cut once! If you are able to find a board that has an aluminized side, then you save a step. In our case, these were not available and we spray-glued on kitchen aluminum foil to each piece. (Be careful that some glues will “eat” the foam so spray very lightly.) Use aluminum tape to go around all four edges of each piece individually and then to join them together into a pyramid-shaped horn.

How accurate do the pieces have to be, and how smooth should the aluminum foil and tape be? This is an opportunity to think about the natural scale of the telescope relating to the wavelength of the observation. In our case, even 1cm errors are a small fraction of the 21cm operating wavelength so we do not need high precision in our construction and certainly the aluminum foil does not need to be so smooth we can see our reflection in it.

“Aluminizing” the reflector.

An advanced class could look at the derivation of the Ruze equation which shows that the aperture efficiency drops to 50% when the surface errors are $\lambda/16$, e.g. Section 3.34 of the NRAO Essential Radio Astronomy book: https://science.nrao.edu/opportunities/courses/era

The horn will not hold its rectangular aperture without some additional support. It also tends to get bumped quite a bit when moving in and out of classrooms so we added a wood frame to the bottom which also provided a way to attach to the cradle and relieved the stress on the waveguide. One team added structural support to the other end of the horn as well though this turned out to be not as critical.



Cutting into the end of the horn and attaching a wooden collar via gorilla glue. This provides structural support and an attachment point for the cradle, thereby relieving stress on the waveguide.

Building the cradle for the horn

The cradle attaches to the horn, provides a frame around the waveguide, and an arm that moves the horn in elevation. Again we follow the DSPIRA directions but modified to use 2’’x1’’ (rather than their suggested 2’’x2’’) wood for the frame to reduce weight.

The cradle which attaches to the horn and pivots in elevation when attached to the stand. The design here has the same dimensions as in the DSPIRA instructions but is made of thinner wood for lightness.

The cradle is attached to the collar on the horn via a “L”-shaped bracket. The black eye hook screw provides an easy way to hand-tighten the L to the cradle so it can be readily taken apart if necessary. The photo shows the waveguide and amplifier connected to the antenna.

Building the stand for the telescope

Here, we follow the DSPIRA directions exactly. This creates a sturdy base that can be taken apart for storage, but it is fairly heavy and not particularly easy for moving the telescope from a classroom to an open area for observing, or for moving in azimuth. However, the use of 2x4's makes this easy and cheap to build.

The high school was able to make use of their on-site woodwork shop and helpful teachers. For my graduate seminar, to save time (and potential accidents), I precut the pieces at home using a miter saw and brought them into class for the students to assemble.

It proved useful for transportation and storage to not fix the cross-struts at the bottom. With reasonable carpentry skills, you can make them fit fairly snugly without being too hard to take apart later. However, if it is too wobbly, it may be wise to screw them together to form a rigid base so that the telescope can be better positioned when doing the observing later.

The cradle and horn are then attached to the stand through the elevation axis, which consists of two long screws with wingnuts. Care needs to be taken here to make sure there is good alignment before drilling. Because the telescope is not well balanced, we elected to use ½ inch screws as the larger wingnuts were easier to hand tighten than the DSPIRA suggested ¼ inch. We also found that adding self-tightening washers helped keep the telescope pointed in a specific direction while also making it easy to move when changing to a new sky position.

Building the waveguide and antenna

The waveguide, as its name implies, guides the radiation that is gathered in the horn to the antenna where it creates an electrical current that can be detected. A waveguide is basically an electrically conducting (i.e. metal) tube that channels the waves in a single direction. In keeping with the off-the-shelf theme of our telescope, we use a rectangular “F-style” can that is typically used to store paint thinner.

You can buy such a can for less than $10 but then need to drain and either store or properly dispose of the paint thinner (but use some to remove the sticky labels if you want to have an aesthetically nice exterior). Remove one end using the smooth edge can opener in the parts list. The easiest is the flat end but you will then need to use aluminum foil to cover the pour hole on the other end (as in the [DSPIRA instructions](#)). I preferred to use pliers to pull the aluminum handle off and then removed that same side with the pour hole for a cleaner look.

The antenna is simply a straight piece of copper wire soldered to an SMA coax connector that attaches to the can. The can acts as a ground plane and the copper wire is therefore one quarter of a wavelength = 5.25 cm. It is also placed that same distance, λ/4, from the closed end of the can on the broad side. For an advanced class, this provides an opportunity to discuss wave propagation in cavities and waveguides, noting that F-style can dimension is almost exactly half the HI wavelength along the side with the antenna.

For the second telescope, we used thinner, 10 gauge, wire than the DSPIRA suggested thick 4 gauge and found a coax connector that could be attached to the can via a nut rather than solder (see parts list). Both of these changes simplified this part of the project.

Soldering the copper wire to the coax connector and then cutting to λ/4 = 52.5 mm, including the connection that sticks inside the waveguide.

Drilling the hole for the connector to connect to the can. The hole is in the middle of the broad side of the can and λ/4 in from the closed end.

The finished antenna looking into the waveguide.

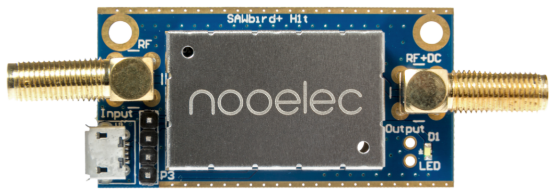
Finally, the can / waveguide is attached, structurally and electrically, to the horn. The dimensions of the horn are such that they should fit the can snugly and the can is then simply taped with aluminum foil from the inside. The can should not intrude into the horn and all four sides of the horn-can edges should be securely covered, leaving no holes.

Looking down the horn to the waveguide, sealed with aluminum foil.

(Note that we again deviate from DSPIRA here in not using aluminum flashing at this step. Because we attach the cradle to the wooden collar around the horn, we avoid mechanical stresses on the waveguide-horn interface - see the previous section for a photo detail.)

Connecting up the electronics

Now that the telescope has been constructed, its time to hook up the electronics and start detecting radio waves! Electrical engineers might want to build their own low noise amplifier (LNA), for which there are designs on the [DSPIRA website] and also the [lightwork memo] series. We took the easy way and just bought one specifically for the HI line from nooelec: https://www.nooelec.com/store/sawbird-h1-barebones.html



For our first telescope in the RET program, we bought one with a case which is undoubtedly easier to handle, but for the second (and third) telescope in the graduate class, we used the “barebones” version. This is slightly cheaper and it turns out we had no problems with static electricity or other issues breaking this component. The LNA is powered by a portable battery through a micro-USB 5V port. The amplifier is connected to the antenna in the waveguide through a short SMA coax cable and the output goes to SDR plugged into the computer. See the parts list in the Appendix for details of each of these components.

The battery and amplifier are fixed to the end of the horn cradle using cable ties. For one design, we used a pegboard to hold them and for another simply attached them to the cradle struts and backing. These attachments can be considered permanent as the battery only needs to be charged occasionally and can be done in situ when not observing. To remove the horn for storage, however, simply unscrew the connection between the antenna and LNA. Remarkably, we found that if you have the airspy, it powers the LNA through the coax (as well as receive the signal) so you do not need a battery.

Make sure that the antenna is connected to the *input* of the amplifier. This is the same side as where the power goes in. This is easy to get wrong and it led to some frantic troubleshooting (two different times!) as we tried to understand why we did not initially see the HI line.

Software

Now that the hardware component of the telescope has now been completed, it's time for the software. We use gnuradio, which is a free, open-source software package, to display and save the spectra that we observe.

The installation and use of this package unfortunately proved to be one of the biggest obstacles in the project for students in both the RET and graduate seminar. There are instructions for installing the package on the gnuradio.org site and you will probably rely on a lot of google searches and thinking carefully to get you through the various steps. As with hardware where we measure twice, cut once, be extra careful before installing or deleting files. If the telescope is a class project, my recommendation is that you dedicate an old laptop to it and, if it runs windows, convert to a linux operating system.

In our case we used mac laptops running OS 10.15 (Catalina), installed macports, and then:

```
> sudo port install gnuradio
```

where > indicates the command line prompt. If there are no errors, then run gnuradio as:

```
> gnuradio-companion
```

If necessary, edit `/opt/local/etc/gnuradio/conf.d/grc.conf` to customize settings

Once installed, gnuradio is simple and powerful. It uses programming blocks written in C++ and python to carry out different signal processing steps which you connect together in a flowgraph. If you have time to explore, it is worth following the tutorials on gnuradio.org or on many other websites. A good (advanced) class exercise is for students to create their homemade version of GQRX that tunes to a specified frequency, creates a waterfall plot, and outputs to audio.

For our HI telescope, we use a customized spectrometer that requires its own block library. We again heavily relied on DSPIRA here but made some small changes. To follow our setup, first download a copy of the github repository that contains all the necessary software:

```
> git clone https://github.com/interstellarmedium/HI_telescope
```

This will create a directory `HI_telescope` that we will repeatedly come back to. To complete the customization of gnuradio, carry out the following (instructions here for a mac, should be very similar for linux):

```
> cd HI_telescope/radio_astro
> mkdir build
> cd build
> cmake ..
> make
> sudo make install
```

Note that you will need to download `cmake` first if you do not have it. This puts the files in `/usr/local/` but the rest of gnuradio is in `/opt/local/` so you need to let gnuradio know by editing `~/.gnuradio/config.conf` to include the line:

```
local_blocks_path=/usr/local/share/gnuradio/grc/blocks
```

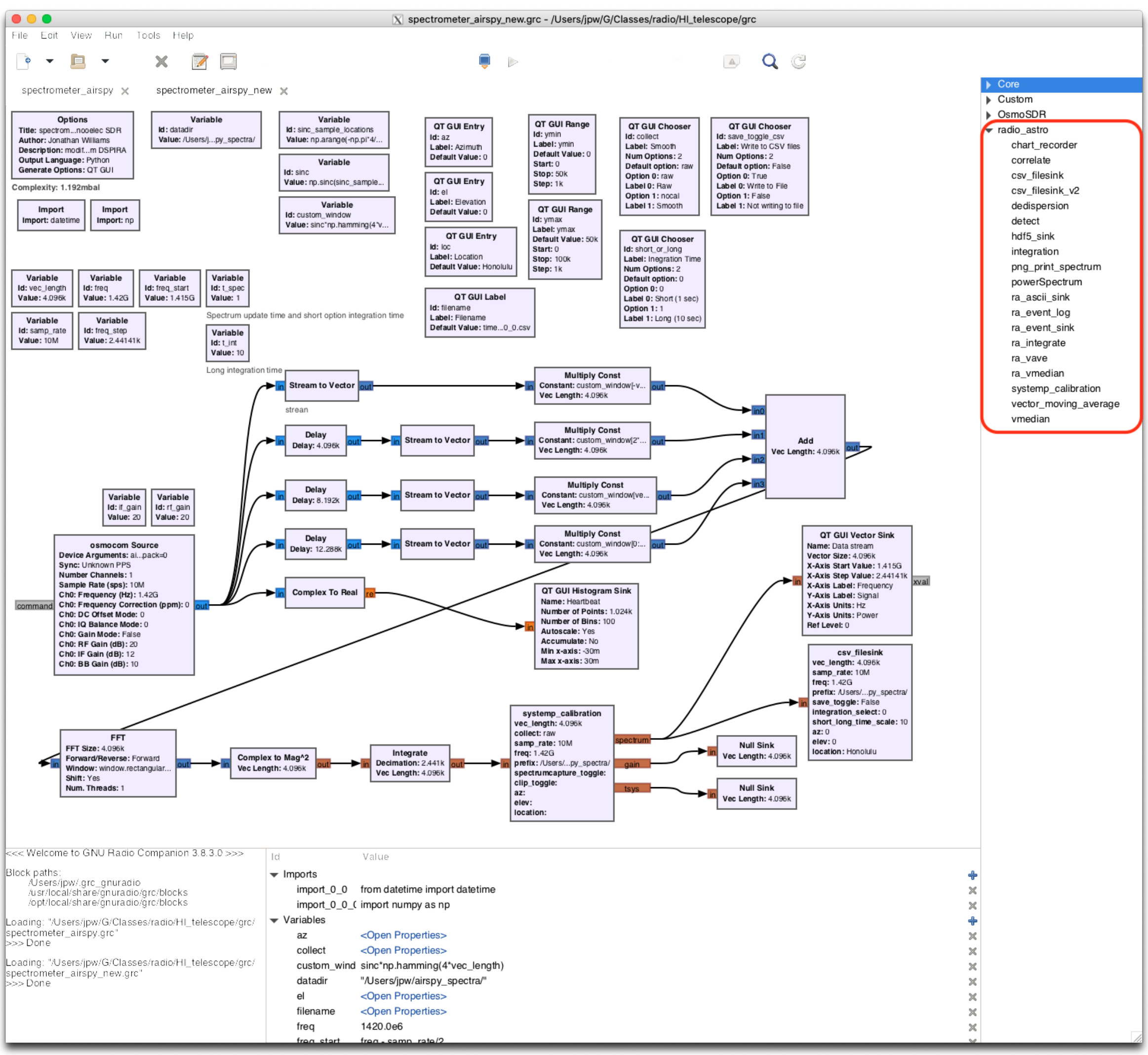
Finally, the computer needs to know where to find the python files that the blocks call. This is defined using the environment variable `$PYTHONPATH` which should be set it in the shell configuration file, e.g., .bashrc, through a line such as:

```
export PYTHONPATH=<path to where you have your python packages>
```

To add the radio_astro package, copy the files over from the repository as follows:

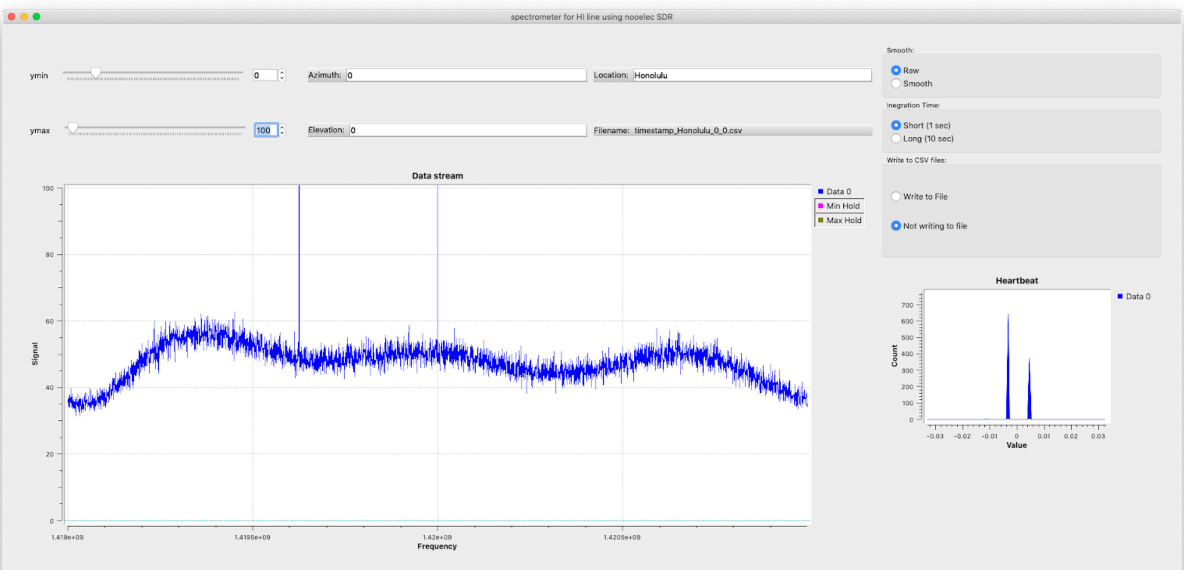
```
> cp -r HI_telescope/radio_astro/python $PYTHONPATH/radio_astro
```

The renaming of the directory in this way is important for the blocks to work properly. If all this worked ok, when you start `gnuradio-companion` from a new terminal window you should see the new block library in the right pane:



This screenshot shows the block diagram for the HI spectrometer. This is based on the DSPIRA version, but modified to allow the azimuth, elevation, and location to be entered into the filename (which we will need later) and removes the calibration option (which we do in software later). There are versions for the nooelec and airspy SDR in `HI_telescope/grc`. Load the appropriate one into gnuradio using "File > Open" from the top banner menu, and then run using the ▷ sign. Note that the SDR should be attached before running the program.

The spectrometer program shows the signal power as a function of frequency. There are options to change the intensity scale (ymin/ymax), and to enter the parameters of the observation (az/el/location). The default shows the "raw" data but the spectrum can be smoothed before display. There are also buttons to choose the integration time (1 or 10 seconds) and to write out the spectrum for later analysis.



The large graph shows that the (nooelec) spectrum rises and then falls off at each end. The decline at the edges is due to the filtering and sampling of the signal but they are well away from the astronomical signal and are simply cropped out later in the analysis. There is a central narrow "spike" which is inherent to the way the SDR works. For an advanced class, you can discuss the details of how the SDR sets the Local Oscillator (LO) equal to the incoming Radio Frequency (RF) and therefore has a zero-Intermediate Frequency (IF) term. The corresponding DC current produces a spike in the output. Note that the upper and lower sideband get mixed together so SDRs include two circuits offset in phase, known as an IQ sampling. For more details, see https://pysdr.org/content/sampling.html. This feature is much narrower than the astronomical signal and is readily removed in the processing steps later on. You may also occasionally see other narrow spikes away from the center (at ~1.4196e+09 Hz in this case) which are typically due to interference such as wifi signals and these are similarly removed without significantly affecting the HI analysis. Note that you can use your cursor in the spectral window to define a rectangle to zoom in on any features (then use <ESC> to go back out).

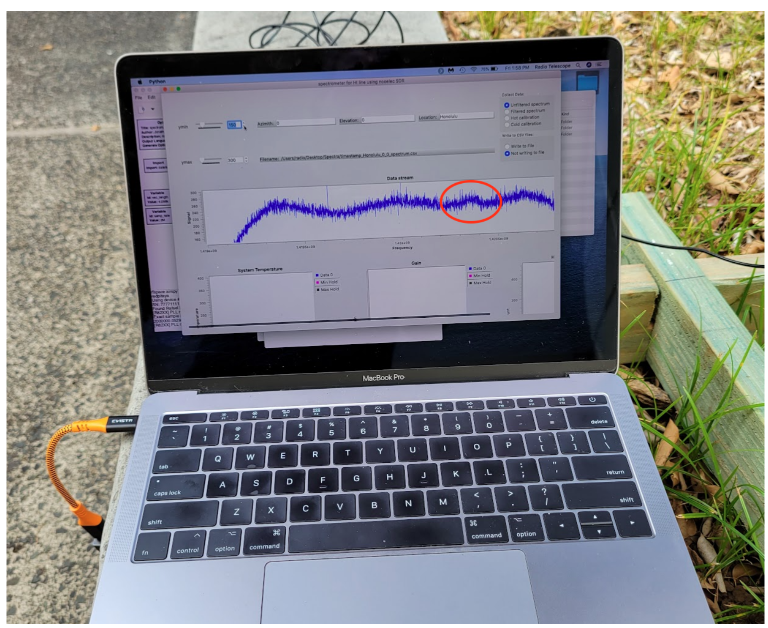
The other output (small right panel) is a “heartbeat” that shows the incoming data stream from the SDR before the spectrum is produced. This should change (slightly) on short timescales and is useful to show that the data are coming as you observe.

The spectrum is obtained by a fast fourier transform of the time sampled data stream from the SDR. If all the software works, you can simply “plug and play” the spectrometer program and go on to data analysis to do the science but studying how the spectrometer works is an excellent hands-on demonstration of digital signal processing. DSPIRA has a very nice set of (non-advanced) exercises using gnuradio to demonstrate some basic elements at https://wvurail.org//dspira-lessons/Simple_Spectrometer There’s also a good description of the polyphase filter and why this is used prior to the FFT block (to reduce spectral leakage) at https://physicsopenlab.org/wp-content/uploads/2020/07/Hydrogen-Line-Project-Documentation.pdf This writeup also includes a lot of handy information about the telescope building and operating process as well.

First light!

An exciting moment for any telescope or instrument builder is *“first light”*, the first observation when you make a detection and show that the system works. In this case, once you have built your telescope, hooked up the electronics, and installed the software, it's go-time.

Set the telescope up to look in the general vicinity of the Galactic Center if you can, or at least somewhere close to the plane in the inner Galaxy. You can use a smartphone app such as Star Walk that shows the Milky Way among the constellations to guide you for this step - it does not have to be very precise. You then connect the SDR to the output of the amplifier and fire up the spectrometer program. If all works well, you should see a slight bump in the spectrum around 1.4204e+09 Hz (highlighted by the red circle in the image here). This is the HI line! If you move away from the Galaxy, for example by pointing to the ground or a building, the overall signal strength may change but the “bump” will go away showing that it is indeed coming from something in the sky.

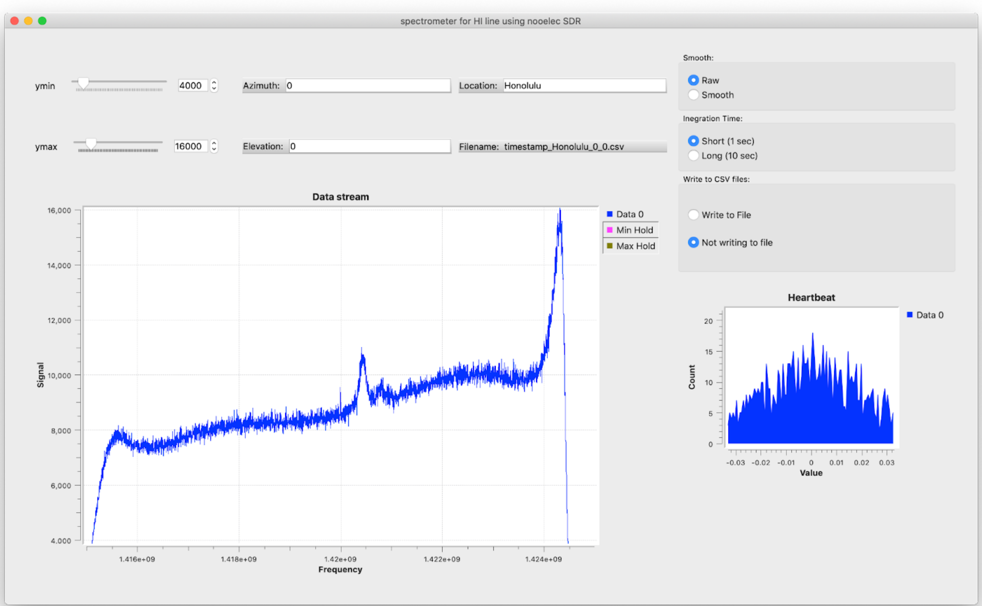


If all goes well, you can now move to the science part of the project. If, however, you do not see an HI line there are several things to look into:

- Double check that the telescope is indeed pointed toward the Galaxy. Make sure it has an unobstructed view with no trees or buildings near the line of sight (within an angular size corresponding to the size of your hand at arm's length)
- Check the connections: the USB to the SDR (in our case shown in the photo, we needed a USB-C converter which sometimes proved problematic); the coax cable to the amplifier; and the amplifier to the antenna
- Is the amplifier powered up? Is it connected the right way (antenna to the input, output to SDR)?
- Is there a short in the antenna? You should be able to see noise spikes if you look at a building with wifi, or sometimes you will see changes in the spectrum if a car drives by. If you point the antenna at the ground and then the sky, the signal strength should noticeably change. If necessary, bypass the amplifier and connect the SDR directly to the antenna and fire up GQRX as a simple direct test.

If you see the line, you can save your first spectrum by clicking on the "Write to file" button. This will write the spectrum as a comma separated values (csv) file in the datadir folder that is specified in the datadir block at the top left of the `spectrometer.grc` file. This will need to be changed to the location on your computer where you want to store data the first time you run the program. We will discuss how to read and analyze these files in the data reduction section.

If you have got to this point with the nooelec SDR, you can play around some more with the telescope and qualitatively see how the HI line varies across the Galaxy. However, quantitative analysis of the line profile requires the more sensitive and stable airspy SDR. As an illustration, the following image shows a screenshot of the spectrometer for an airspy toward a typical location in the Galactic plane showing the much higher signal-to-noise in the line and smoother baseline than the nooelec.



Where am I pointing?

The telescope mount is an alt-az system which we need to convert to sky coordinates, either equatorial (α,δ) or, since we plan to map the Milky Way, galactic (*l*,*b*). This requires knowledge of the time and location on Earth of when the observation takes place and an opportunity for a class to think about, or review, coordinate systems.

Since we use python to reduce and analyze the data, we use this for the coordinate conversion too using the astropy package. I assume that the users know python or can otherwise learn it from other (abundant) sources. To convert from alt-az to *l,b* type at a python prompt either on the command line or, show here, as cells in a jupyter notebook::

```
[1]: from astropy import units as u
     from astropy.time import Time
     from astropy.coordinates import SkyCoord, EarthLocation, AltAz, get_sun
```

```
[2]: here = EarthLocation(lat=21.3036944*u.deg, lon=-157.8116667*u.deg, height=372*u.m)
     now = '2022-01-7 21:00'
```

```
[3]: alt = 45
     az = 45
     c = SkyCoord(alt=alt, az=az, frame='altaz', unit='deg', obstime=Time(now, scale='utc'), location=here)
     gal = c.galactic
     print('l = {0:5.1f}, b = {1:4.1f}'.format(gal.l, gal.b))

     l =  85.2 deg, b =  2.3 deg
```

You will, of course, have to enter your own location (variable "here" above), which you can determine from google maps on your smartphone, and also the time (variable "now"), in the format here and in Universal Time although your time zone can be accounted for in the "scale" parameter. For the reverse, where you want to know where to point the telescope to observe a particular galactic location:

```
[4]: l = 0.0
     b = 0.0
     c = SkyCoord(l, b, frame='galactic', unit='deg')
     altaz = c.transform_to(AltAz(obstime=Time(now, scale='utc'), location=here))
     print('Altitude = {0:4.1f}, Azimuth = {1:5.1f}'.format(altaz.alt, altaz.az))

     Altitude = 39.7 deg, Azimuth = 177.6 deg
```

If you have a particular object in the sky that you want to observe in equatorial coordinates, you can use similar syntax, where the frame would be 'ICRS' rather than 'galactic'. More information is at https://docs.astropy.org/en/stable/coordinates/index.html An example is given along with the above code snippets at `coordinate_conversion.ipynb` in directory `HI_telescope/notebooks` from the github repository that you downloaded for gnuradio.

Lastly, whichever direction we are converting, we need to know the altitude and azimuth of the telescope. This can be most easily determined using a tiltmeter and compass on a smartphone respectively, although a future upgrade would be to add fixed markers to each axis so that the telescope direction could be simply read off without the need for extraneous high tech tools.

An observation run

After you have celebrated first light and figured out how to point the telescope to an astronomical sky position, you are ready to carry out an observing run and start collecting data.

A nighttime high school observing run. Note that, unlike optical starlight, you can study the HI line during the day or at night, through clear or cloudy skies.

A general principle for any observation is that it should be repeatable. That is, someone else could come along and repeat your measurement and get the same result to within a certain level of accuracy. This requires careful documentation of your work, e.g., the time and location of your observation and the pointing direction - these can be entered in the spectrometer program as you take data and need to be updated should you change any of them. It's good practice to keep a log of the observations in a notebook (physical or digital) in addition to changing the az/el on the spectrometer program.

The raw/smooth spectra and short/long integration time options are, to some extent, a personal choice. The raw data will show one or more narrow spikes on the readout but these can be filtered and smoothed later whereas the smooth option applies this processing before writing the data out and is therefore irreversible. The gnuradio spectrum updates at 1 second intervals which allows you to follow the incoming data stream quickly but writing out data at this rate will produce many spectral files which can make subsequent data reduction steps a bit unwieldy. In general, the HI line is strong enough to be seen in seconds but measuring the rotation curve requires total integration times of minutes so I recommend switching to the long integration time setting when you are ready to take science-grade data.

When you have set up the various settings on the spectrometer program and are ready to take data, click on the “Write to file” button and you should soon see files appearing in the datadir folder. Each output csv file is 4096 lines long and each line has the format `frequency, power`. To stay organized it is helpful, though not absolutely necessary, to create new folders for each new location in the datadir folder and move the csv files there after a single observation ends. The examples we use later (and which are included in the github repo) are “hot”, “cold”, “lon10”, “lon20”, etc, which refer to calibration data and specific locations along the Galactic plane.

The power that the telescope measures at each frequency depends on the incoming signal strength of course but also on many parameters of the telescope including the horn, antenna, and electronics. To convert the measurement to physical units requires that we calibrate the

data by looking at different loads of a known signal strength. We begin and end each observing run by carrying out such a calibration, first observing a “hot” load by pointing the telescope to the ground as shown in the figure to the left, and then a “cold” load by pointing the telescope to sky well away from any buildings or trees and offset from the Galactic plane where there is relatively little HI emission (an example location is given in `coordinate_conversion.ipynb`). Save at least 2 minutes worth of data for each hot/cold pair. For the HI spectra that you will analyze later, save at least 5 minutes at each sky location.

Data reduction

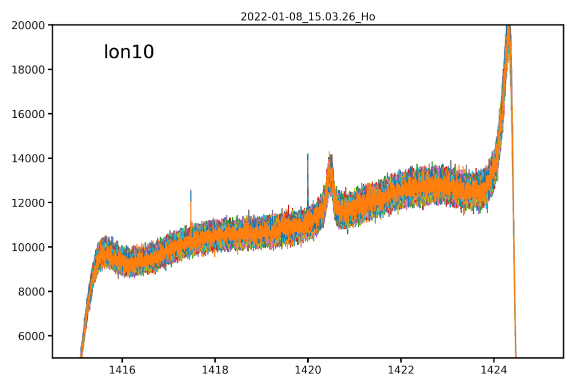
After you have finished an observing run, the next step is to “reduce” the data, whereby you produce a single spectrum at each observed location with units of brightness temperature (equivalent to intensity) as a function of radial velocity. There are 4 basic steps, each with an accompanying jupyter notebook:

1. Inspect the data (`inspect.ipynb`)
2. Determine the calibration (`hotcold.ipynb`)
3. Calibrate the observations (`calibrate.ipynb`)
4. Baseline removal (`baseline.ipynb`)

These notebooks are documented to describe the various steps but they are not simple prescriptions that can be just run as is. Your data will be different from the example used here and you may need to adjust some of the steps here. Consider the notebooks as a roadmap to take you from observation to analysis. In the following figures, we show data taken with the airspy SDR due to its higher quality.

1. Data inspection

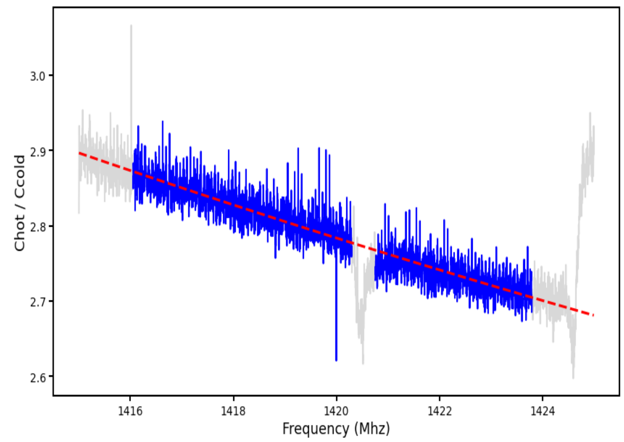
First, we look at each observed spectrum to make sure there are no problems with the data. We want to make sure that there is power at all frequencies and that it is similar from one spectrum to another. If there are any outliers because, e.g. the telescope moved during an integration or there was severe interference, you should identify them and discard them from further analysis. A simple way is to move them to a different folder, e.g., “lon10_discard”.

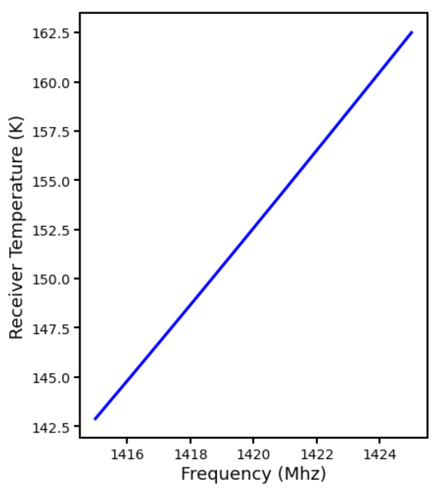


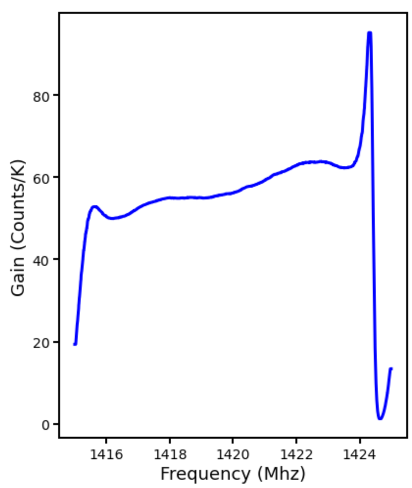
2. Analyzing the hot and cold loads

You should also inspect the hot/cold calibration pairs as well. Once satisfied that they are ok (and discarding bad spectra if necessary), you can determine the scaling between the measured spectral power and the brightness temperature at each frequency. Briefly, at the long 21cm wavelengths of these observations, the thermal (blackbody) emission is in the Rayleigh-Jeans limit and scales linearly with temperature. Thus the power we measure is directly proportional to the temperature of the source. From the ratio of the hot and cold loads we can therefore extrapolate to the equivalent temperature (astrophysically termed "brightness temperature") of the spectral line. The methodology is described in Essential Radio Astronomy section 3.6.6 https://science.nrao.edu/opportunities/courses/era An advanced class can go into the details here that include an offset term (receiver temperature) in addition to the scaling (gain), and also explain why these can be frequency dependent.

A practical issue that the notebook deals with (and why we do not offer a calibration option within our gnuradio spectrometer package) is that there is no truly blank sky without hydrogen emission. Thus the cold load inevitably contains a faint line which can affect the scaling right where it's most important! However, as long as the cold line is narrow, the notebook shows how to manually mask it out and fit a frequency dependent bandpass correction that interpolates across the line.



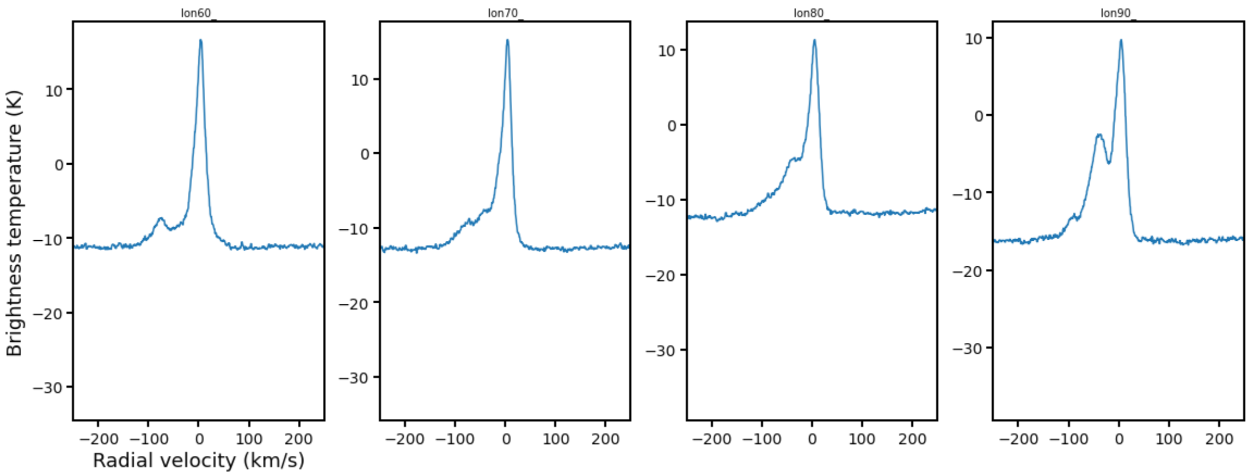




The result is written to a new file `calibration.csv` that contains this gain and receiver temperature values at each frequency that is then applied to the science data.

3. Calibrating the data

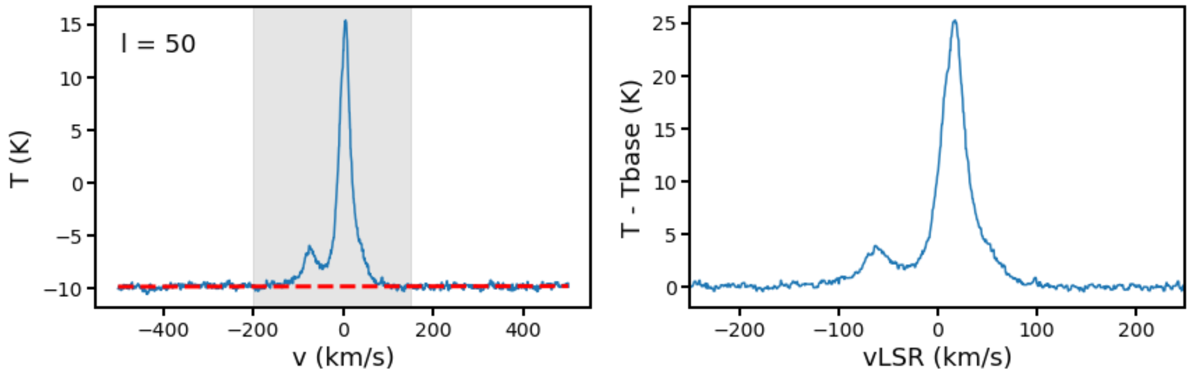
Having inspected the data and determined the gain, the next step is to average all the vetted spectra at a given position (an advanced class can go through the radiometer equation to show that this increases the signal-to-noise ratio by the square root of integration time), and then convert from frequency to radial velocity using the Doppler effect and from power to brightness temperature using the calibration results. You should now have a small set of spectra in a new directory, `calibrated_spectra`, one for each sky location that you observed and, if all went well, they should have quite flat baselines with a very strong HI line and identifiable differences in profile shape from one position to another.



4. Removing a baseline from the spectra

Even after calibration, the brightness temperature away from the HI line may be offset from zero. This is mainly due to observations of different Galactic locations being at a range of elevations and therefore with different paths through the atmosphere. Lower elevations will see greater atmospheric emission and consequently higher power at all frequencies. To remove this effect, mask around the HI line (shown by the gray area in the figure below) and remove a baseline from the data (red dashed line).

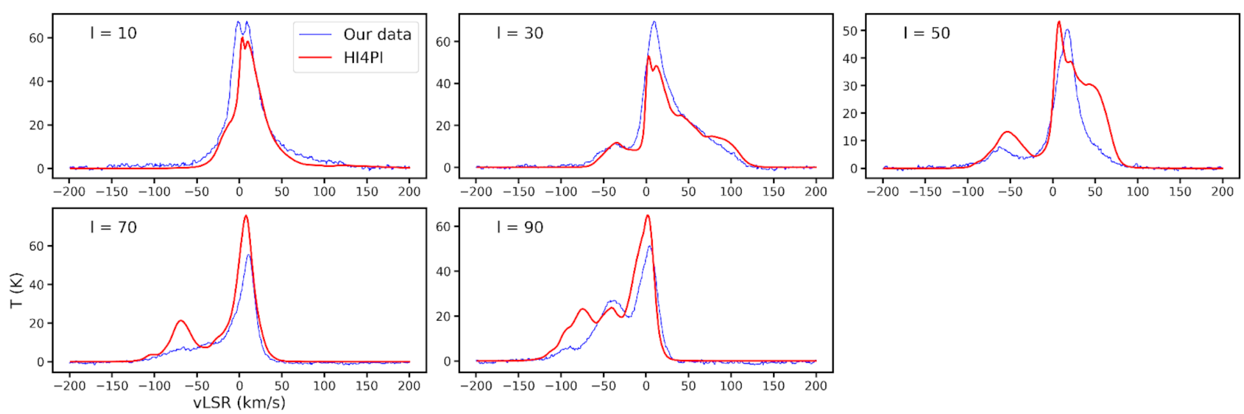
The final step is to remove the Earth's rotational and orbital motion from the velocity (barycentric correction) and then to convert from the Solar System frame of reference to that of the Solar neighborhood in the Galaxy. This is known as the Local Standard of Rest and abbreviated LSR. The two conversions are purely geometric: the barycentric correction depends on your observing location and time as well as the direction that you are pointing; the second depends on the direction you are looking at in the Galactic coordinate system. (These could each be explored in more detail in an advanced class but I suspect by now, the students want to look at the final results!). The overall correction is fairly small compared to the line width but still important. The final spectra, now ready for comparison with other teams or published data, and for analysis to measure the rotation curve, are written out to new directory `reduced_spectra`.



The output of the combined data reduction steps, after summing all the inspected spectra at a given sky location, calibrating, and removing a baseline is a spectrum of brightness temperature in Kelvin as a function of velocity relative to the Local Standard of rest in km/s.

Comparing results with “the professionals”

To make sure that you are on the right track, there is an additional notebook in the github repo, `compare_HI4PI.ipynb`, that compares your HI spectra with those from an all sky survey (i.e. covering 4π steradians) produced from data taken by the 100m telescope in Bonn, Germany and 64m telescope in Parkes, Australia, http://cade.irap.omp.eu/dokuwiki/doku.php?id=hi4pi. The comparison for the example data from our telescope is shown below.

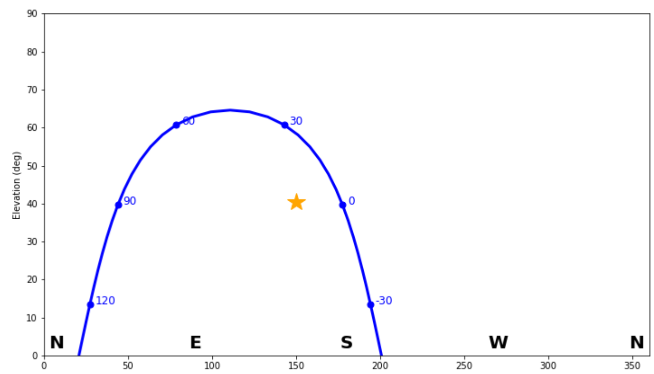


Comparison of spectra taken by our horn HI telescope in blue with the HI4PI survey in red at a series of longitudes spaced by 20 degrees along the Galactic plane. The blue data were multiplied by 2 because the brightness temperature scaling was incorrect but there is reasonable agreement between the profile shapes and the peak velocities showing the barycentric and LSR velocity correction is good.

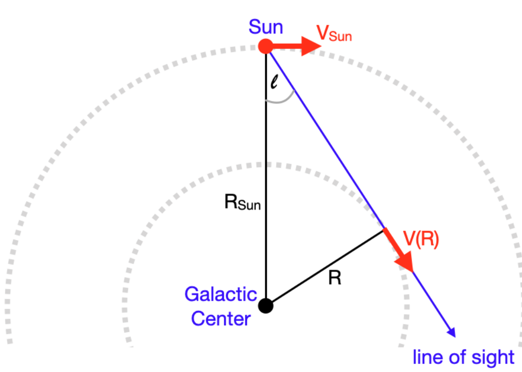
The notebook reads a set of spectra from the HI4PI survey that were created by averaging over 15 degrees in longitude and latitude along the Galactic plane. This is approximately the beam size of the horn telescope, θ ~ λ/D = 21cm/75cm ~ 0.3 radians. As the figure above shows, the agreement may not be perfect (and indeed we found that our brightness temperature was only about one half the HI4PI) but for the next step of measuring the rotation curve of the Milky Way, the most important part is that the velocity scale is the same and that the shape of the lines are similar. If you find good results, you can pat yourself on the back as your sub-$500 telescope is being compared to telescopes that would cost about $100M to build today!

Mapping the rotation curve of the Milky Way

Once you are comfortable with operating the telescope, getting good data that you are able to reduce and that compares favorably with HI4PI survey, then you should be able to carry out your own science project and measure the rotation of the Milky Way. To do this requires sampling the HI emission along the Galactic plane, i.e., in steps of Galactic longitude, l, at zero Galactic latitude, b=0°. As noted above, the resolution of the telescope is about 16 degrees so stepping in 10 degree increments will give you good results. An advanced class can discuss Nyquist sampling which would be 8 degrees.

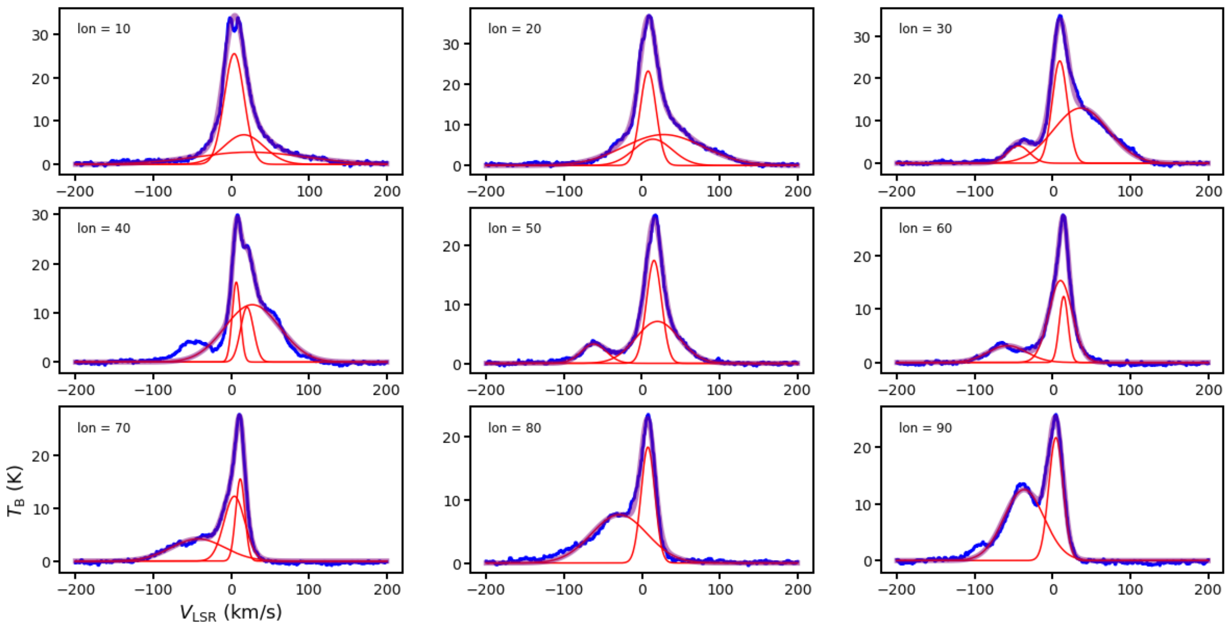


To help plan an observational run, use the notebook `galaxy_azel_plot.ipynb` to produce a plot of the Galactic plane in Azimuth/Elevation, and then use `coordinate_conversion_plot.ipynb` to determine the exact az/el when lining up the telescope at each given longitude point. Take a hot/cold calibration before starting the run, spend at least 5 minutes on each longitude point, and take a second hot/cold measurement at the end to check your calibration results and see if anything changed significantly. Keep good notes and stay organized by moving the set of spectra taken at each position into a clearly labeled directory, e.g., lon10, before moving the telescope to the next spot along the plane.

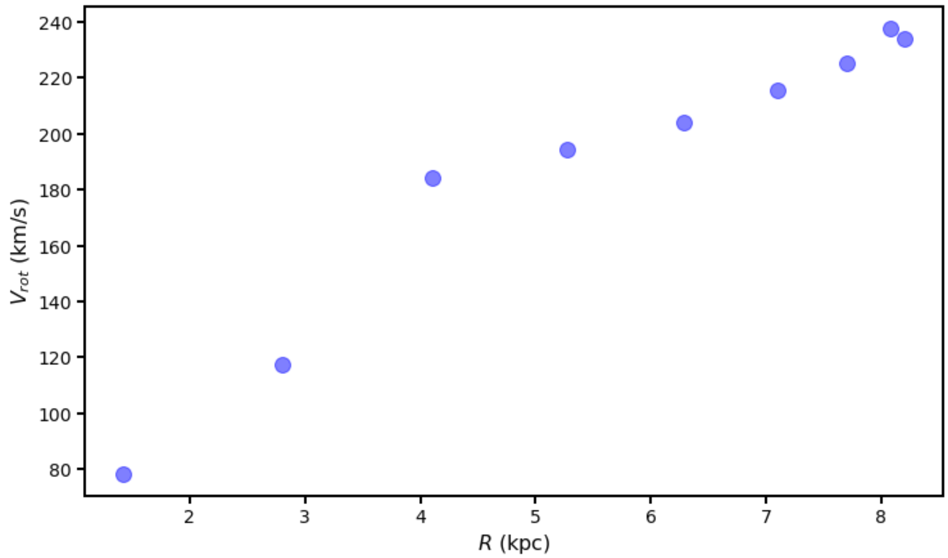


We use the well-known *tangent-point method* to measure the rotation curve. There are many descriptions of this classic procedure in astronomy textbooks. In short, the most extreme radial velocity, positive for 0° < l < 90° and negative for the other side, 270° < l < 360°, occurs when the circular rotational motion projects exactly along the line of sight. This occurs when the line of sight grazes, i.e. is tangential to, a circle with a radius that is readily determined by trigonometry, $R = R_{Sun} \sin(l)$.

Thus we simply need to measure the highest velocity feature in each of our spectra and then apply a couple of analytical steps to convert the longitude to radius and correct for the projection of the Solar motion to the observed radial velocity. This is easier said than done because the highest velocity is not well defined for real (noisy) data. If, however, we think of the hydrogen being in discrete clouds or at least features that produce identifiable velocity components, we can decompose our observed spectra into a series of cloud-like features and measure the velocity of the highest (in absolute sense) feature. This is carried out in the notebook, `rotation_curve.ipynb`, which uses a [publicly accessible code]() to fit multiple gaussians to each spectrum. The algorithm for how this works is published by [Lindner et al. 2015]() and is a good advanced topic. The results are shown for the example data below (and in the cover page to this document).



You need high signal-to-noise data for this to work well as the maximum velocity often depends on quite subtle features in the line profiles. With 5 minute integrations on each longitude point, however, we were able to get good gaussian fits and find that the rotation curve grows from small values near the center to a fairly steady value equal of 220 km/s (and indeed the Sun orbits at this speed). For a test particle of mass m orbiting at speed V at radius R, the centripetal force equals the gravitational force if $mV^2/R = GMm/R^2$ which implies the radial dependence of orbital velocity (the rotation curve) is $V(R) = (GM/R)^{1/2}$. If the mass were concentrated all at the center as in the Solar System, the velocities decrease as the square root of the radius in a manner known as Keplerian rotation. This is clearly *not* the case for the Milky Way and shows that the mass is much more broadly distributed so as to be able to sustain high orbital velocities at large radii. This is perhaps not surprising given that there are stars broadly distributed across the disk, although they are concentrated toward the center.



The Milky Way rotation curve derived from the example data taken by our telescope. The rise of the orbital speed in the inner few kpc followed by a flattening in the outer regions is distinctly different from the Keplerian pattern of orbital motions in the Solar System and shows that the mass is much more broadly distributed in the Milky Way. Further, the total inferred mass required to keep the galaxy bound in this region is about 10^{11} solar masses, which is greater than the total mass of stars and gas, showing that there must be an additional unseen component.

However a greater puzzle arises when we determine the total mass of the inner Galaxy, $M = RV^2/G = 9 \times 10^{10}$ solar masses. This is slightly greater than the estimated mass of stars and gas (baryonic matter) in the Galaxy, see e.g., https://en.wikipedia.org/wiki/Milky_Way, suggesting unseen mass, or *dark matter*. If we were able to extend our measurements of the rotation curve to the outer Galaxy through observations of HI associated with stars with known distance, you would find that the flat rotation curve persists and the discrepancy between the dynamical and total stellar mass grows. This, plus a great number of studies of other galaxies and numerous other lines of investigation, show overwhelming evidence for dark matter. The nature of this matter is a huge topic in astronomy and particle physics. But it all started with HI observations not too dissimilar from what you have done here!

The end?

So you built a radio telescope, detected the HI 21cm line, determined its motion, and then mapped the rotation of the Milky Way… **Congratulations!**

And now what? It may well be that this is as far as you can get in a summer REU or RET program, or a one semester course. Or perhaps that is as far as you want to go… that's ok, its already quite an accomplishment. Indeed, this is as far as we were able to get in 2021. However, I am sure that there is more that can be done. Here's a partial list and I hope to hear from other people about additional possibilities:

Observational projects:

1. Map the intensity distribution in a small part of the Galaxy, showing not just the rotation along the plane but also the scale height of the atomic gas.
2. Observe known HII regions in the outer galaxy and use literature values of their distance to extend the rotation curve to greater Galactocentric radii
3. Detect other astrophysical phenomena (Jupiter continuum, OH 18cm?, pulsars???)

Hardware improvements:

1. Add a circle marked in degrees to a vertical stand leg to quickly show the altitude
2. Put the stand on a movable platform in azimuth
3. Change the design of the mount to something more lightweight and easier to move
4. Automate the pointing using stepper motors

Appendix: Parts and tool list

Item	Store	Cost	Link or description
nooelec SDR	nooelec	$33.95	https://www.nooelec.com/store/sdr/sdr-receivers/nesdr-smart-sdr.html
HI amplifier	nooelec	$44.95	https://www.nooelec.com/store/sawbird-h1.html
FM test antenna	amazon*	$9.69	https://www.amazon.com/gp/product/B08NP4Z2GC/ref=ppx_od_dt_b_asin_title_s00?ie=UTF8&psc=1
airspy R2 SDR	airspy	$169.00	https://v3.airspy.us/product/a-airspy/
SMA coax cable	amazon	$9.99	https://www.amazon.com/gp/product/B07FC8PVZS/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1
SMA extender cables	amazon	$12.99	https://www.amazon.com/gp/product/B07NCLZWHH/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1
SMA cable mount	amazon	$7.99	https://www.amazon.com/gp/product/B078H4F8R6/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1
SMA right angle adapter	amazon	$7.99	https://www.amazon.com/gp/product/B07XHJQDBT/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1
Aluminum foil tape	amazon	$10.44	https://www.amazon.com/gp/product/B01FROBUXE/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1
USB battery	amazon	$29.95	https://www.amazon.com/Wireless-Portable-Charging-External-Compatible/dp/B0915T91JN/ref=pd_lpo_2?pd_rd_i=B0915T91JN&psc=1
Smooth edge can opener	amazon	$23.50	https://www.amazon.com/OXO-Good-Grips-Smooth-Opener/dp/B000079XW2/ref=sr_1_27?keywords=can+opener&qid=1639511127&sr=8-27
Gorilla glue	amazon	$10.99	https://www.amazon.com/Gorilla-Clear-Glue-ounce-Bottle/dp/B07GQ1CT47/ref=sr_1_4?crid=1UIE0PKWI0EU4&keywords=gorilla+glue&qid=1641514693&sprefix=gorilla+glue%2Caps%2C218&sr=8-4
wood	local store	~$40	Two 8’ 2”x4”, two 8’ 1”x2”, plywood
screws	local store	~$15	Exterior grade, 1.25” & 2.5” sizes
Paint thinner can	local store	~$10	F-style gallon size can
Foam insulation board	local store	~$20	8’x4’, aluminized if available
Spray glue and aluminum foil	local store	~$20	If the foam board is not aluminized
Copper wire	local store	~$2	6cm long, fairly stiff e.g. gauge 10

* I have given amazon links here for convenience but you can likely find all these items at other online locations and potentially locally if you prefer

Required tools: tape measure, spirit level, (battery powered) drill, hammer, hand saw, pencils, sharpee, soldering iron, pliers
Optional, but useful: measuring square, miter saw