Low cost Radio Telescope for Galactic 21cm Observations

A collaborative effort in Danny's Advanced Radio Astronomy course to map the Galactic 21cm line.

Submitted by: Students of Advanced Radio Astronomy Spring 2021[a]

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April 30, 2021

Figure 1. Horn Antenna on Physics building rooftop, Photo by Katherine Elder

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1. INTRODUCTION

1.1 Radio Astronomy and the 21cm line

The first mention of the hydrogen line was in the 1930s, when there was radio static that changed depending on the day. It was only after many in scientific community suggested that this occurrence was related to the Sun, that radio waves would transmit from the center of our galaxy. The observation of the hydrogen line was the event that sparked the subfield of spectral-line radio astronomy. The concept that the hydrogen line could be observable was predicted by Dutch astronomer H. C. Van De Hulst in 1944 and was first observed by the American physicists Harold Ewen and Edward M. Purcell at Harvard in 1951.[1] Their observations were verified by various astronomers such as Dutch astronomers C.A. Muller and Jan Oort as well as Austrialian astronomers Wilbur Norman Christiansen and Jim Hindman .The spectral line was extensively observed by Wilbur Norman Christiansen and Jim Hindman in 1952 along with H. C. Van De Hulst in 1953.[2] From these observations they authored a paper discussing their detection of hydrogen radiation from a source known as the Magellanic clouds. Within a few years of its first observation in 1954, astronomers John P. Hagen and Edward F. McClain discovered the effects of its absorption . A year later, John P. Hagen and Edward F. McClain collaborated with A. Edward Lillery to author a paper detailing methods of obtaining an absorption profile with a single antenna.[3] These discoveries and accomplishments have aided in our understanding of the hydrogen line and have motivated inspiring astronomers to contribute to the field in the same way.

The hydrogen line, also known as the 21-cm line or HI line, is a spectral line formed by a change in the energy state of neutral hydrogen atoms. At 1420 MHz, the radiation can effortlessly pass through interstellar dust clouds and the Earth's atmosphere without being scattered. Thus we can observe and detect clouds of hydrogen gas throughout the galaxy, and determine their temperature and density. This line has been important for many discoveries over the years, such as the discovery of the milky way's structure, or looking back to the early formation of the universe during the universe's dark ages. Considering the versatility of the emission line and the familiarity the astronomy community has with it as a whole, it's sometimes easy to forget that it has drawbacks. In particular, the emission line is prone to interference from modern electronics and the Earth's atmosphere, which makes especially sensitive observations, such as distant galaxies, much more difficult.

While faint objects and weak signals were unfeasible given the small size of the group's horn, taking a spectrum of the sky was perfectly reasonable given the strength of the signals of the sources. We took several spectra of the sky using the telescope, which are detailed later. We also documented the performance and construction of the radio telescope, and some of the math behind the justification for the telescope.

1.2 Feasibility study of Solar 21cm observations using Horn Antenna

Horn antenna is typically used for 21cm observations from the Galactic centers. But can we use this to make solar observations? To answer that, it is important to understand the hardware we have on hand and the power from the Sun at 1420 MHz. We have to make sure that the power from sun is not high enough to burn our front end RF electronics. This feasibility study is motivated by[4]

Let's start with Plank's equation:

$$P = \int_{\nu_1}^{\nu_2} 2h\nu\eta_{occ}(\nu)\, d\nu \tag{1}$$

We know,

$$\eta_{occ}(\nu) = \frac{1}{e^{h\nu/kT} - 1} \tag{2}$$

and if $h\nu/kT << 1$ then we can Taylor expand leaving,

$$\eta_{occ}(\nu) = -\frac{kT}{h\nu}. \tag{3}$$

Now we can easily solve the following integral by approximating small bandwidth,$\nu_2 - \nu_1 = \Delta\nu$, we arrive at the Rayleigh-Jeans approximation:

$$P = kT \int_{\nu_1}^{\nu_2} 2d\nu = 2kT\Delta\nu. \tag{4}$$

Power should be then divided by two due to the fact that we are using a single dipole which is only sensitive to a single polarization.

$$P = kT\Delta\nu. \tag{5}$$

With $\Delta\nu$=2 MHz, $T_\odot$=5777K, we estimate power to be $P \approx 0.16pW$ Using the integrated solution, and not assuming Rayleigh-Jeans we get $P \approx 0.17pW$, which is only a %6 error. Therefore we can have confidence in our use of the Rayleigh-Jeans approximation.

Using equation for antenna temperature,

$$T_{ant} = \frac{\Omega_\odot}{\Omega_{beam}} T_\odot = \frac{\theta_\odot^2}{\theta_{beam}^2} T_\odot \tag{6}$$

As shown in Figure 2 we used an online protractor to measure this from beam pattern simulations, and estimate $\theta_{beam} = 15°$.

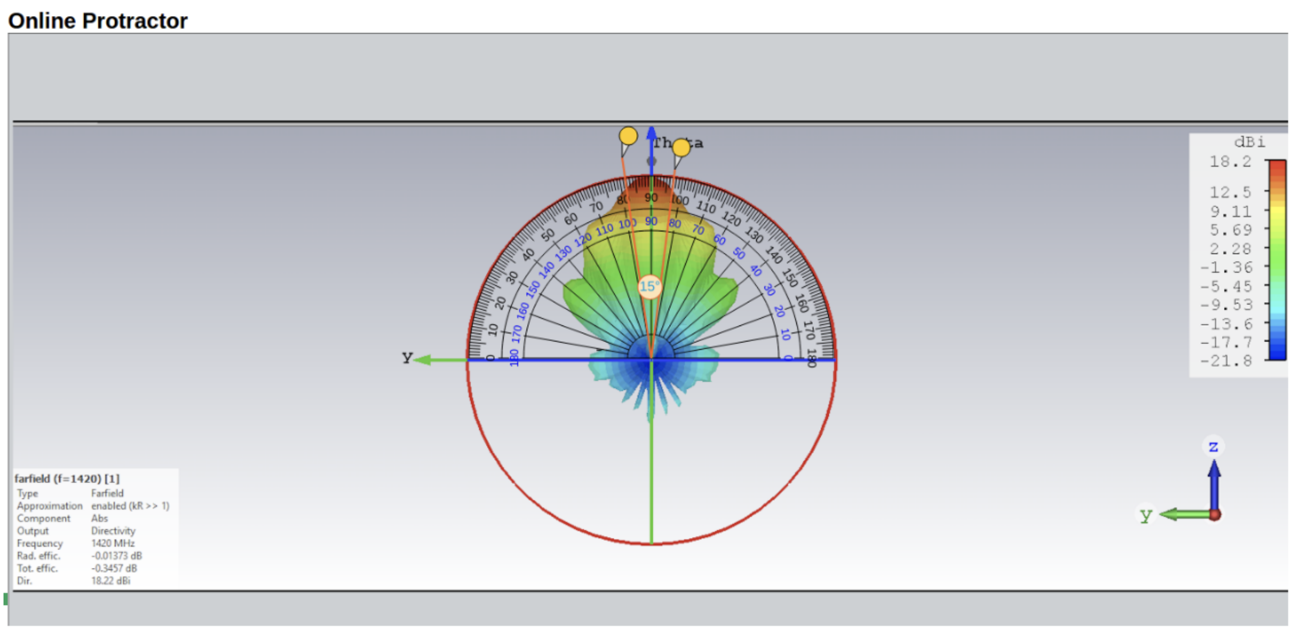

Figure 2. θ_{beam} calculations from beam pattern simulations using an online protractor

For a largest horn dimension 89.7 cm and the diffraction limit,

$$\theta_{beam} \approx 1.2\frac{\lambda}{D} \approx \frac{21\ cm}{89.7\ cm} \approx 16° \tag{7}$$

With this, we have confidence on our simulation results.

Now, for Sun, $\theta_\odot \approx 0.52°$. That gives us $T_{antenna} = 7K$ at 1420 MHz, assuming blackbody approximation. This unfortunately is lower than the expected noise temperature of the amplifier and thus would require substantial integration to observe. There is still hope because it turns out that the sun is much brighter past wavelengths of 1cm than a blackbody.[5] Even during quiet sun time the brightness temperature of the sun at 1.42GHz is greater than 40000K. Given this value we end up with an expected minimum antenna temperature of $\sim 48K$. The radiation spectra of blackbody, quite and active Sun in optical and radio frequency range is given in Figure 3

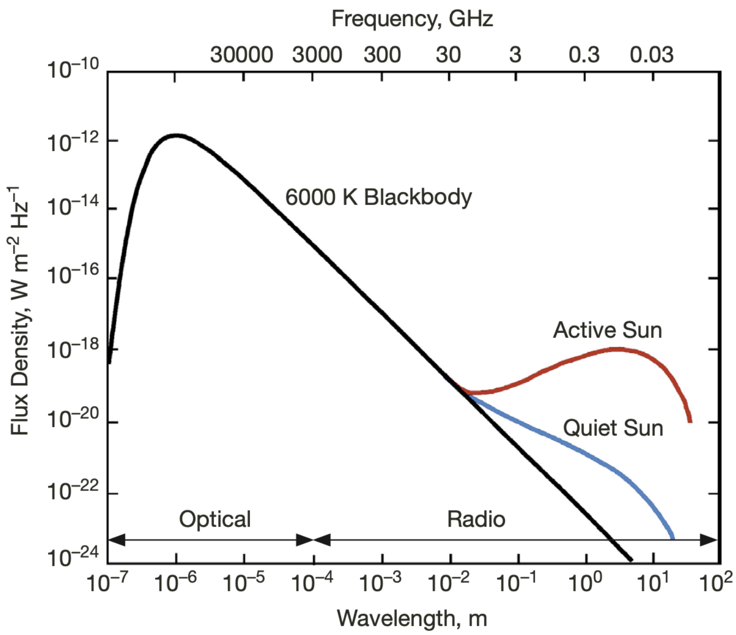

Figure 3. The radiation spectra of blackbody, quite and active Sun in optical and radio frequency range (*From:*[5])

2. RADIO TELESCOPE HARDWARE

2.1 Components of the Measurement Setup

The measurement setup consists of the following components:

- Horn Antenna
- Power Source
- 2 LNAs + 2 batteries
- Bandpass filter
- Pi + Laptop
- SDR
- Coax cables

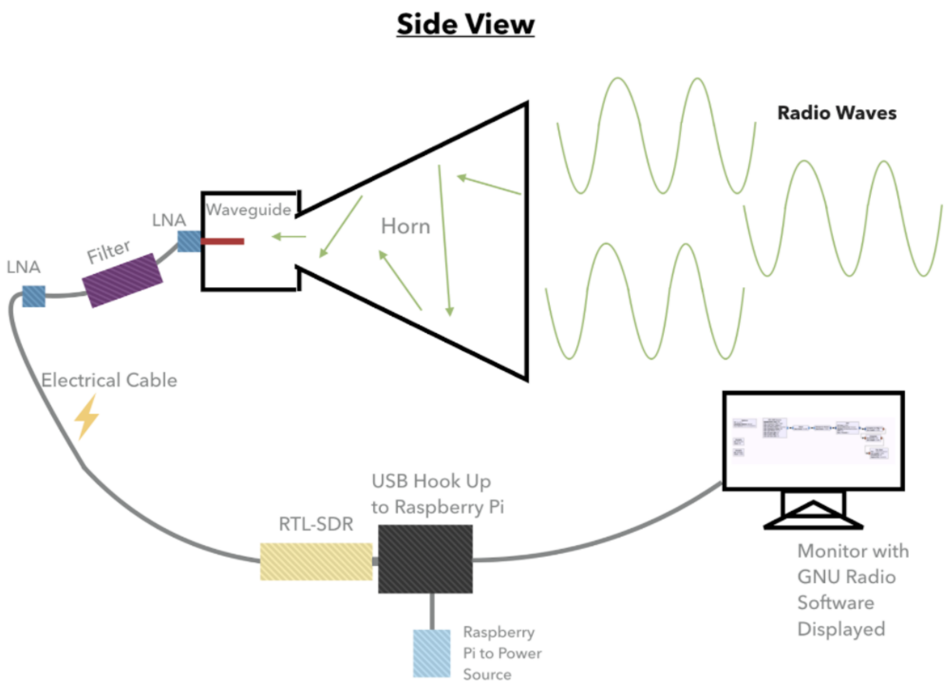

Figure 4. A schematic diagram of the measurement setup

2.2 Dimensions of the Horn

The dimensions of the horn for 21 cm observations is described in the following image:

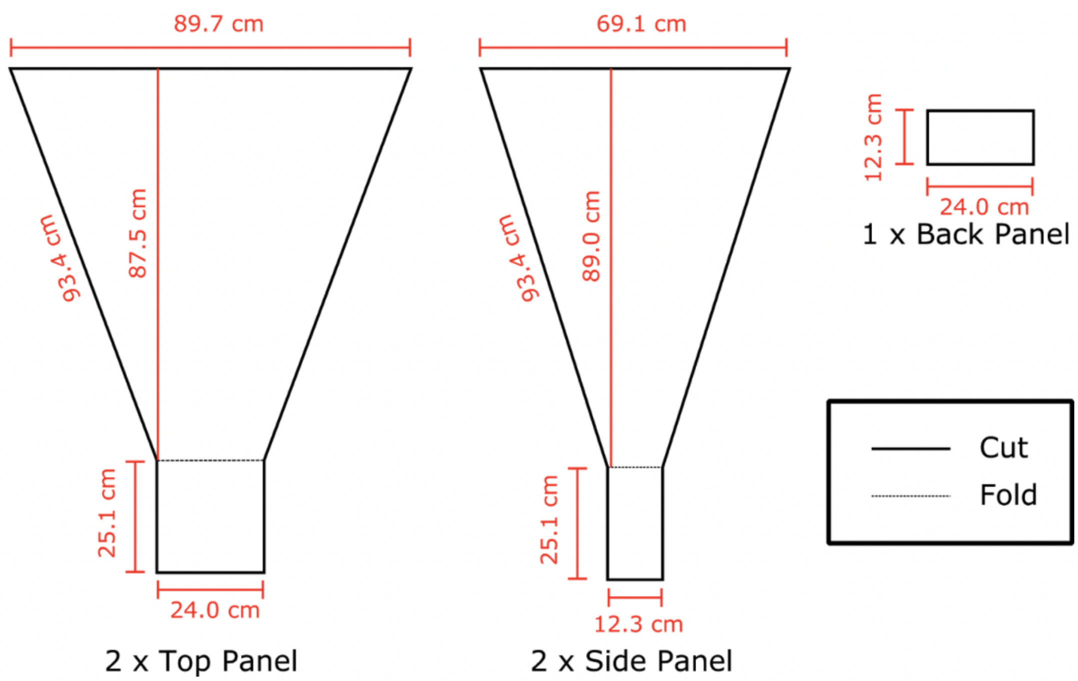

Figure 5. Dimensions of the horn antenna

2.3 Overview of the telescope

The telescope consists of a Horn Antenna that acts as a waveguide. The feed probe collects the signal which is then amplified by a Low-Noise Amplifier (LNA). This LNA amplifies the low-power signal without deteriorating the signal-to-noise ratio. The received signal is then fed into a bandpass filter. This ensures unwanted signals are filtered out. We further have two gain stages to increase the strength of the signal. The data is then recorded using a Software-defined Radio (SDR). The schematic of the analog signal chain is shown in Figure 13.

2.4 Amplifiers

2.4.1 Budget LNAs

Two low cost amplifiers were used in the setup and were aquired from ebay. The vendor provided a plot of the typical gain and noise figure, shown in Figure 6. Unfortunately these amplifiers start to lose performance above 500MHz. From the charts we expected a gain of approximately 27dB and a noise figure of 2.75 dB. This noise figure can be converted to noise temperature using the equation,

$$T = T_0(10^{NF/10} - 1) \approx 295\ K. \tag{8}$$

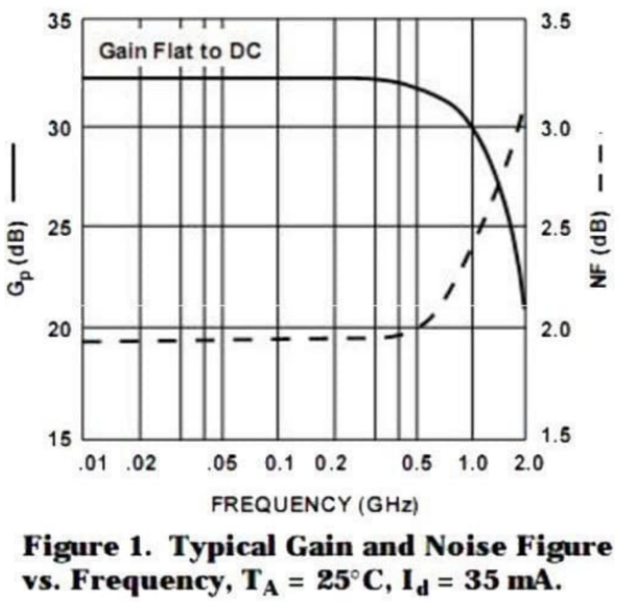

Figure 6. Budget amplifier noise and gain as a function of frequency.

We then set out to verify the gain and noise performance. The measurement setup is shown in Figure 8 with the two amplifiers connected to the fieldfox vector network/spectrum analyzer.

- Gain of LNA 1 at 1.42GHz = 23.54 dB
- Gain of LNA 2 at 1.42GHz = 19.64 dB

To measure the noise we used the fieldfox in spectrum analyzer mode and performed the Y-factor method (The Y-factor method is described in detail in the appendix). By measuring the output power of the chain with two different thermal loads at the system input we can calculate the equivalent noise temperature of the system.

We used a 50 Ω SMA termination as the room temperature 295K thermal load and an HP346C noise source with equivalent noise temperature of 5513K. The noise temperature of the cascaded system is shown in figure 7. We see that the noise is twice as high as expected and this would require longer on-sky integration times, we may also not want to call it an LNA.

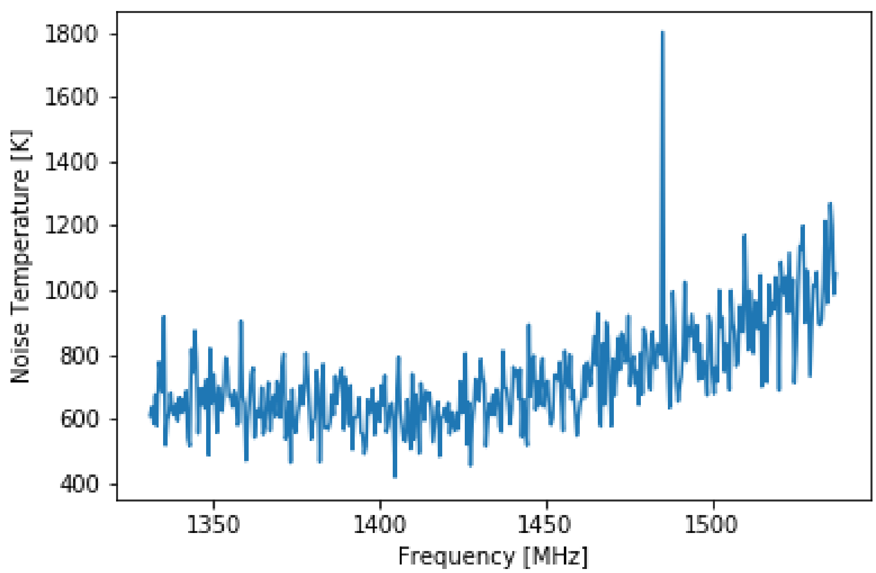

Figure 7. Noise temperature as a function of frequency for the cascaded chain of two budget amplifiers.

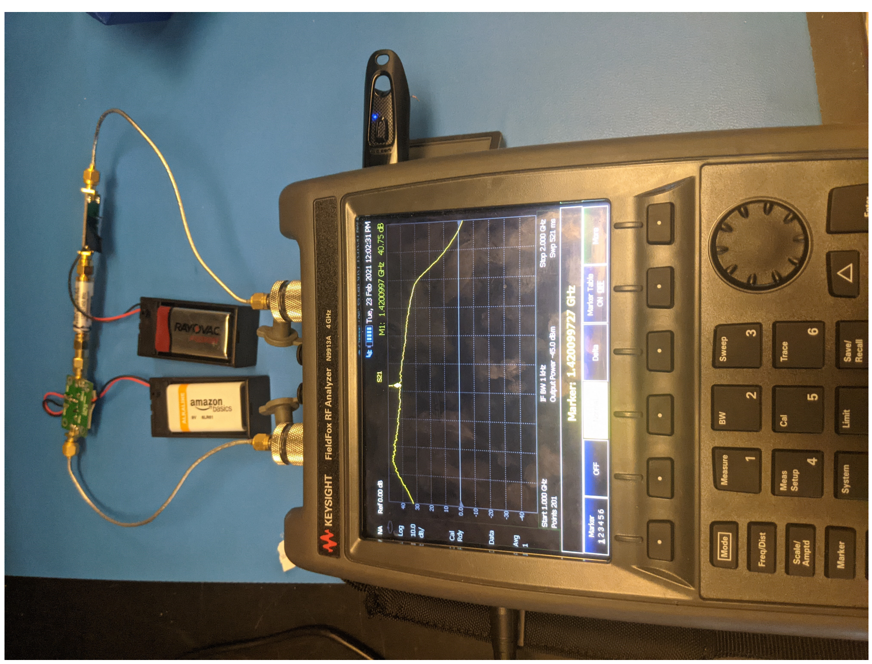

Figure 8. Measurement setup to confirm gain of the budget LNAs

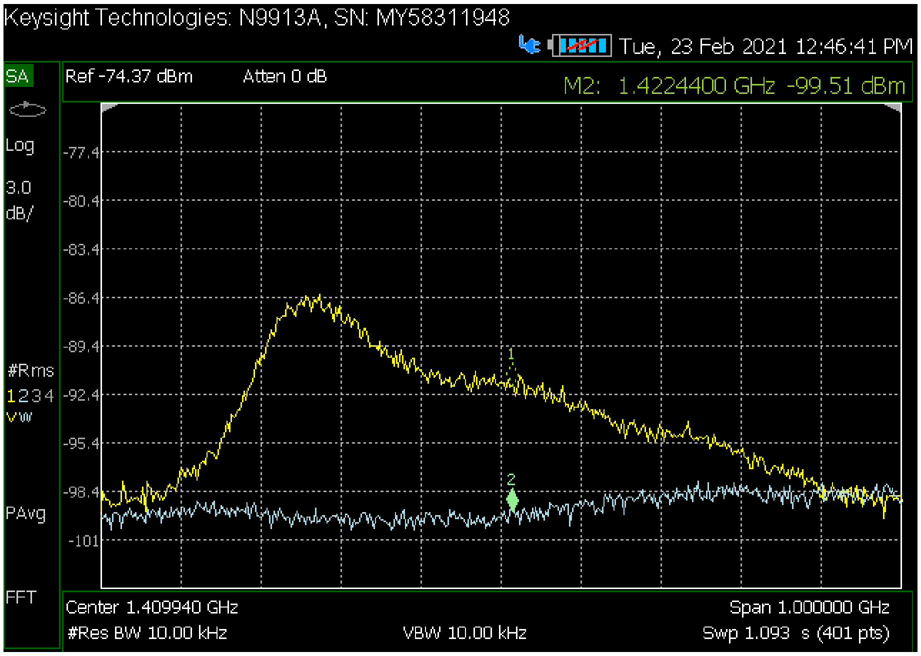

Figure 9. Noise introduced by the Budget LNAs

2.4.2 Expensive LNA ZX60-P162LN+

- Measured gain of LNA on fieldfox at 1.42GHz = 17.75dB
- Cable S21 = -1.46dB
- Actual gain of LNA at 1.42GHz = 19.21dB

Low noise amplifier from Minicircuits to use as front end amplifier. This amplifier has a noise temperature maximum of 71K which is below the budget amplifiers measured noise temperature by a roughly a factor of 10. This factor of 10 means that we can achieve the same signal to noise in 100th of the integration time via the Dicke radiometer equation assuming we are dominated by the LNA noise in the recieve chain.

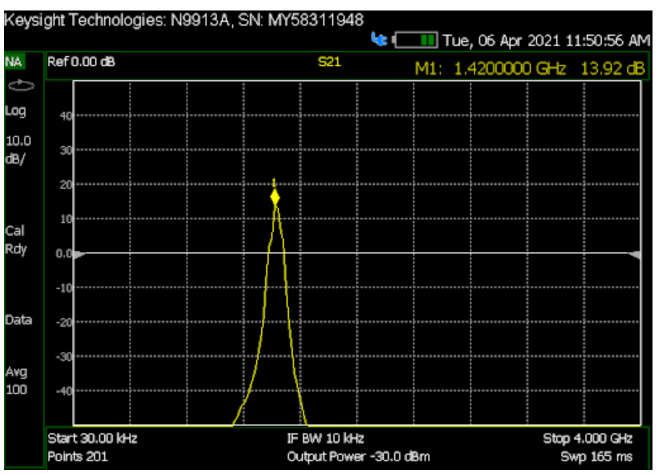

Figure 10. Gain of ZX60 LNA + KL Filter setup at 1.42 GHz

2.5 Filters

2.5.1 Mini-Circuits

Figure 11 shows S-parameters of a mini-circuits band pass filter and two amplifiers in the RF chain. The band-pass filter encompasses 1.42 GHz and a large range around it, allowing this filter to capture other signals, such as phones and other communication devices.

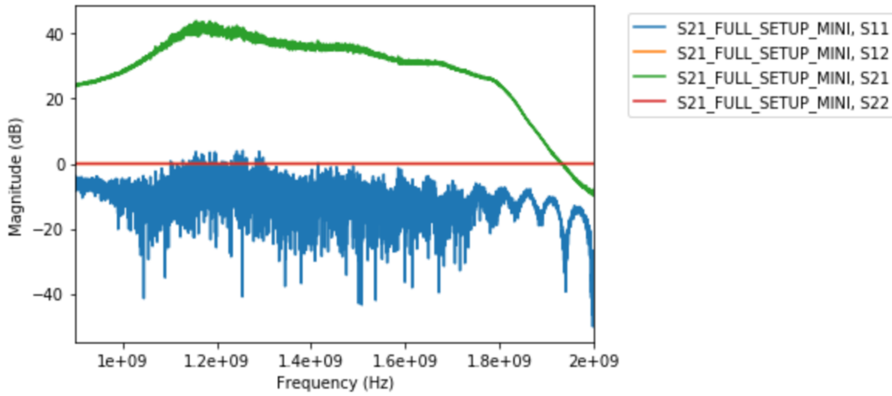

Figure 11. Mini-Circuits filter for around the 21cm line, including 2 amplifiers in the chain.

2.5.2 K&L Filter

The K&L filter is a cavity resonator tuned to 1.42 GHz, as shown in Figure 12. The plot shows that there still is some loss at the resonance peak, but is minimal compared to the rest of the frequency range. The x-limit is set the same for both the K&L filter and Mini-circuits filter to compare the ability to filter frequencies around 1.42 GHz. As can be seen, the K&L filter behaves much better than the Mini-Circuits filter.

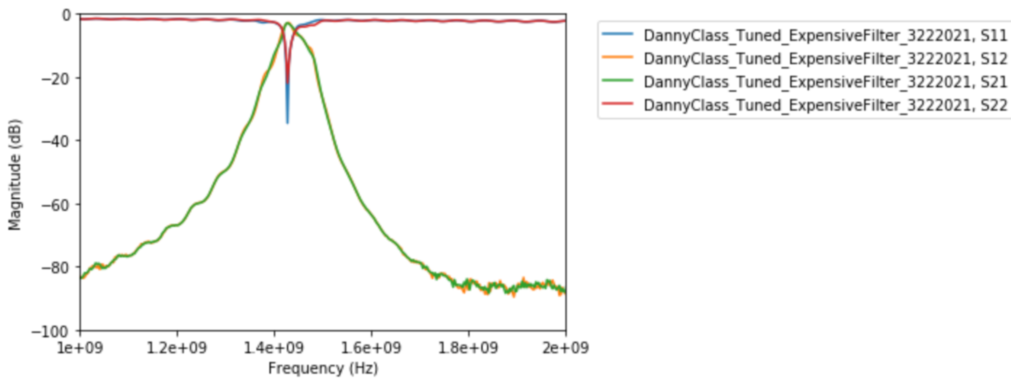

Figure 12. Commercial filter from K&L tuned for the 21cm line using a cavity resonator design

2.6 Gain of the Analog Signal Chain

Block diagram of our final analog signal chain is shown in Figure 13. We have a total of three gain stages.

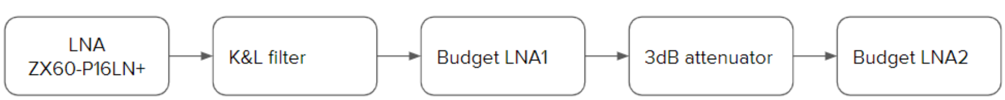

Figure 13. CHART Analog Signal Chain

- Budget LNA1 gain at 1.42GHz = 16.37 dB
- Budget LNA2 gain at 1.42GHz = 19.64 dB
- ZX60-P162LN+ gain at 1.42GHz = 19.21 dB
- Loss due to filter = 3.84 dB
- Total gain = 16.37 + 19.64 +19.21 - 3.84 = 51.38 dB

3. SOFTWARE DEFINED RADIO

We chose to use the RTL-SDR, which is a USB controlled software defined radio reciever. It has one SMA input port and is based on the RTL2832U - realtek chipset which provides the ability to amplify low power RF signals, down-convert, and digitize.

3.1 SDR setup

We installed drivers using this document:

`rtl-sdr4linux_quickstartguidev20.pdf`

We installed the python library pyrtlsdr for controlling the SDR from:

`https://pypi.org/project/pyrtlsdr/`

3.2 Software

A python script was written to configure the RTL-SDR and grab samples and live plot. The script was then modified to save data as hd5 files which would also record the SDR state including center frequency and gain.

`get_spec_v4.py`

Code in appendix.

4. ON-SKY MEASUREMENTS

On April 24, 2021, we took the setup to the roof of PSH for a field test of the system. We set up the horn to point directly up at the sky and took data with various settings. Figure 14 and Figure 15 show a scan from 1300-1500 MHz. Subsequent scans show variation in the spectrum (as shown in Figure 16), so more data is needed to isolate signals from noise.

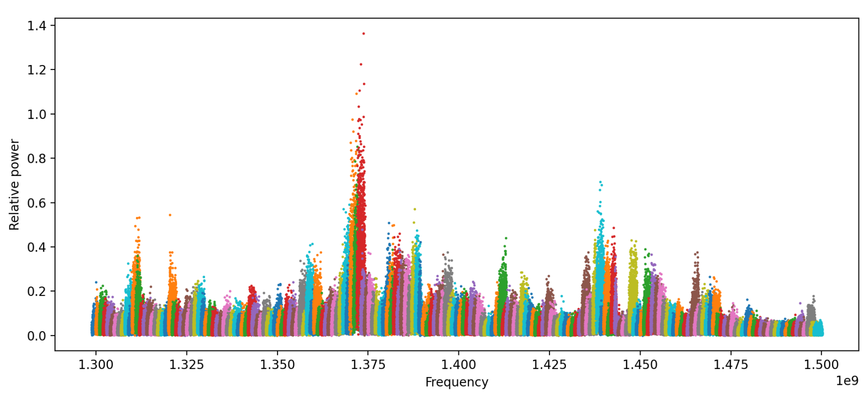

Figure 14. Single integration from 1300-1500 MHz with no averaging, pointed directly up at the sky.

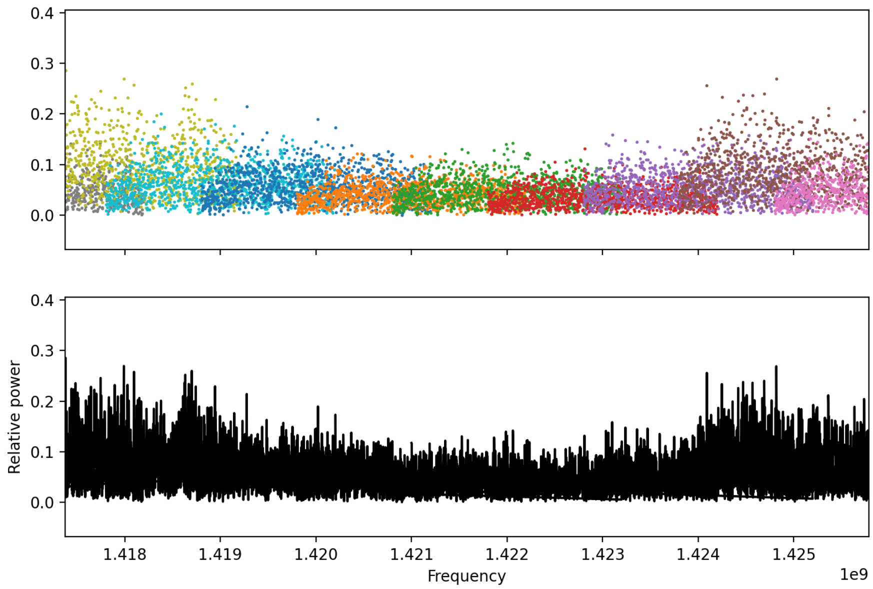

Figure 15. Single integration from 1300-1500 MHz with no averaging, pointed directly up at the sky, zoomed in at 1420 MHz.

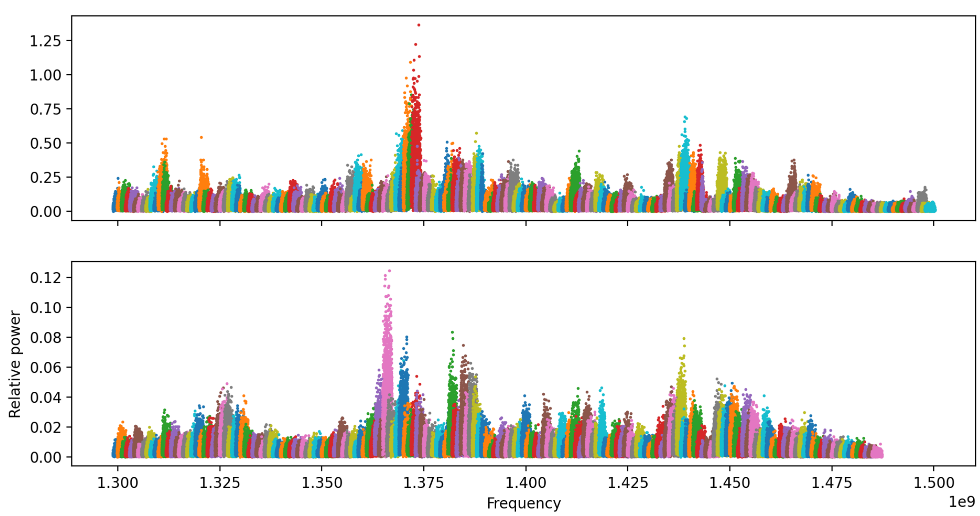

Figure 16. Comparison of two scans. The top scan was shown in previous figures, as a single integration from 1300-1500 MHz with no averaging. The bottom scan is a single integration from 1300-1486 MHz, averaged over 10 tunings.

We also took some datasets at a single tuning with many integrations, to observe the change in the spectrum over time. Figure 17 shows a waterfall plot of one of these datasets.

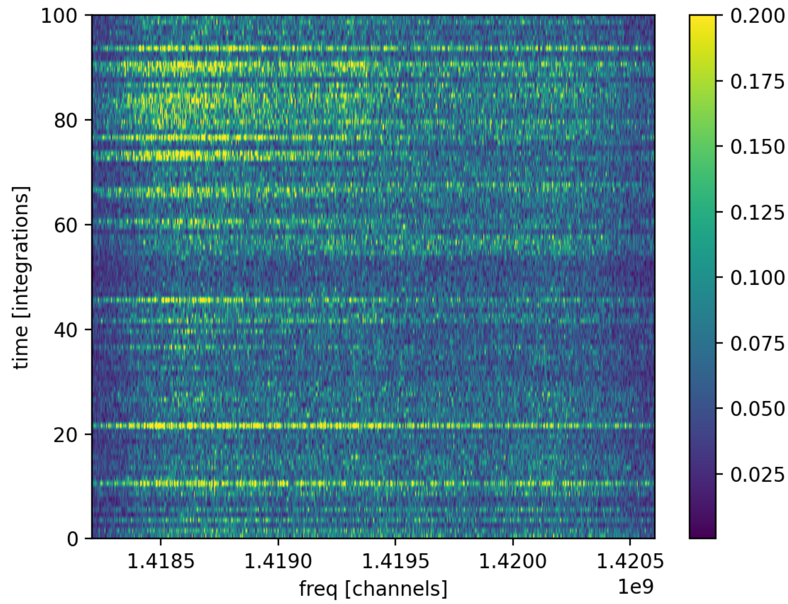

Figure 17. 100 integrations at a center frequency of 1419.405752 MHz, 1 MHz from the 21cm line.

To observe noise levels and to test the effect of the echosorb, we took multiple datasets with and without echosorb on the horn. Figure 18 shows the averaged spectrum over 400 tunings centered at 1420 MHz, with and without the echosorb. There is a noticeable difference between the two, even after median combining to limit the effect of outliers. We are yet to reason the effects we see with the use of echosorb.

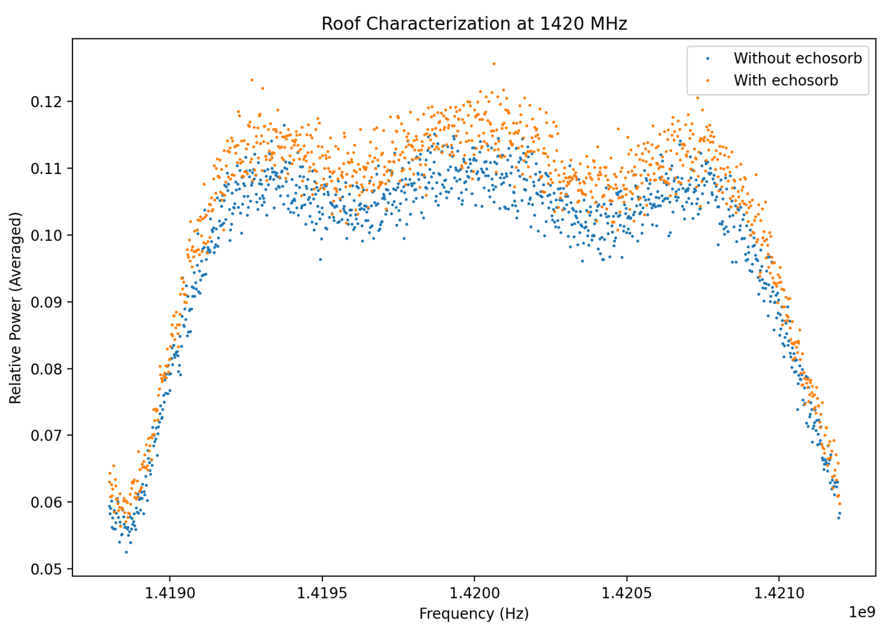

Figure 18. Average of 400 integrations centered at 1420 MHz, with and without the echosorb on the horn.

5. DISCUSSION AND CONCLUSION

We started this course (Advanced Radio Astronomy) at the beginning of Spring 2021 with two goals. The first one being analysis and detection of a flare from Proxima Centuari using archived ALMA data (reports submitted by individual students) and the second one being a group effort to observe the 21cm hydrogen spin-flip signal using a horn antenna designed for L-band at 1420 MHz. We started with a feasibility study of the experiment by calculating the antenna temperature required to successfully observe the 21cm signal from the galactic plane and the sun. We then started setting up RF front end consisting of an LNA, bandpass filters, and additional amplifiers. We performed noise, gain, and Y factor measurements for various combinations of the amplifiers and filters in lab and slowly worked our way up to using the SDR for recording data. This task involved understanding the working of SDR and it's data sampling and then coding in python for averaging and plotting the data.

For many of us, the bench setup and use of network analyser was new and exciting. Although we did start with some of the old electronics which lead to very high noise levels in the signal chain, but with the new components that arrived later in the semester, we were able to achieve gain and noise levels required for this project. The next step was to do the characterization of the antenna and RF front end. For this, we went up the roof and collected data by pointing the horn up in the sky. We recorded data with and without the eccosorb for characterization. We were able to see power difference of about 3dB with and without the eccosorb.

Although we were not able to observe the 21cm from Galactic center by the end of semester, we had a lot to learn from this project. It was especially interesting to work in lab, set-up and record data from the roof. The semi-success of this project could be partly attributed to the logistical limitations to visit and schedule lab visits, caused by restrictions put in place to control the spread of COVID-19. As far as the future scope of the project goes, a few of us plan to complete the project over the summer by recording data overnight, pointing the horn at the Galactic center of the milky way. It would be interesting to see the signal and also verify our calculations for the signal chain set-up.

6. INDIVIDUAL CONTRIBUTIONS

(In no particular order)

1. Sasha Sypkens
   (a) Helped test different filters in readout chain
   (b) Fixed expensive filter
2. Daniel Diab
   (a) Wrote introduction section of the report
   (b) Helped with editing and proofreading the report
3. Anjali Ramesh
   (a) Wrote Radio Telescope Hardware section (with Mru's help)
4. Amy Zhao
   (a) Helped edit and test code to read and record data from the SDR
   (b) Helped with a lab test of the entire signal chain readout before the roof test
   (c) Recorded and plotted data from the roof test
5. Ewan Pringle
   (a) Helped with introduction section of the report
   (b) Extra hands during roof test
   (c) Some editing and proofreading
6. Lindsay Berkhout
   (a) Assisted in many of the lab trips, design, and file writing process.
7. Mrudula Gopalkrishna
   (a) Helped with gain and noise measurements of the analog signal chain
8. Katherine Elder
   (a) Extra hands during roof test
   (b) Moral support
9. Akshatha K Vydula
   (a) Helped with initial setup of signal chain, gain, noise and Y factor measurements
   (b) Helped with roof characterization
   (c) Wrote the memo for feasibility study and parts of this report
10. Adrian Sinclair
    (a) Helped with many parts

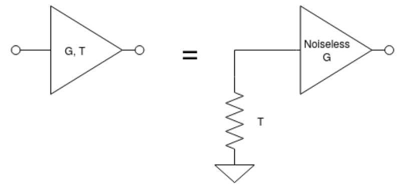

Figure 19.

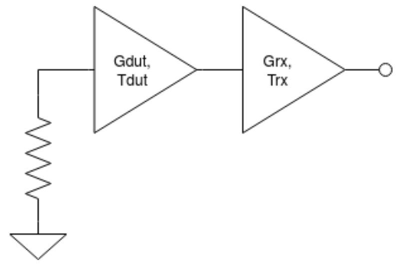

Figure 20.

7. APPENDIX

7.1 Y factor method notes

7.1.1 Y factor I

Starting with the Johnson-Nyquist equation for thermal noise power,

$$P = kTB, \tag{9}$$

Where k is Boltzmann's constant, T is the temperature, and B is the bandwidth. The thermal noise at the input of an amplifier will be amplified by the gain of the amplifier G_{amp}, but also the noise of the amplifier itself will be added to the output signal. This is typically represented by a resistor at some temperature connected to the input of an ideal noiseless amplifier figure 19.

The output power from the amplifier under test when two thermal sources of temperatures, T_h and T_c, are given by,

$$P_c = k(T_c + T_{amp})BG_{amp}, \tag{10}$$

and

$$P_h = k(T_h + T_{amp})BG_{amp}. \tag{11}$$

The Y factor can then be found after the above two output powers P_h and P_c have been measured,

$$Y = \frac{P_h}{P_c} = \frac{T_h + T_{amp}}{T_c + T_{amp}}. \tag{12}$$

Now we solve for T_{amp} to find the equivalent noise temperature of the amplifier.

$$T_{amp} = \frac{T_h - YT_c}{Y - 1} \tag{13}$$

This is the standard Y factor method with no adjustments or corrections.

7.1.2 Y factor II - Remove receiver contribution

Correcting for the receiver system including the spectrum analyzer. We can take four measurements two with the device under test (DUT) and two without the DUT. First we measure the noise temperature via the Y factor method of the system without the DUT. Then we perform the measurement with the DUT in place leaving the four values, $P_{hrx}, P_{crx}, P_{hdut}, P_{cdut}$.

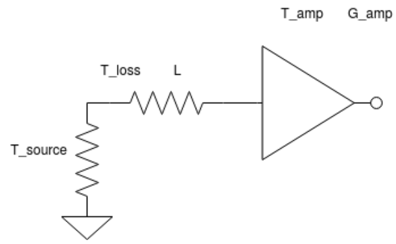

Figure 21.

The noise temperature of the DUT corrected for the receiver system (subscript rx) is then,

$$T_{dut} = T_{sys} - \frac{T_{rx}}{G_{dut}} \tag{14}$$

Where T_{sys} is the noise temperature of the total system including the dut, T_{rx} is the noise temperature of the receiver system when not including the DUT, and G_{dut} is the gain of the DUT determined by,

$$G_{dut} = \frac{P_{hdut} - P_{cdut}}{P_{hrx} - P_{crx}}. \tag{15}$$

7.1.3 Y factor III - Account for insertion loss

If there is loss in between the noise source and DUT then we can correct for this if we know the loss. We can represent the system as two components in between some noise source resistor(Figure 21).

The cascaded microwave noise temperature of the lossy component and amplifier would be,

$$T_{cas} = T_{loss} + T_{amp}L \tag{16}$$

where L is the loss of the component, and T_{amp} is the noise temperature of the amplifier. T_{loss} is the equivalent noise temperature of the lossy component determined by,

$$T_{loss} = T_{physical}(L - 1). \tag{17}$$

Typically $T_{physical}$ is room temperature around 295K. Now we can determine the noise temperature of the amplifier by using both of these equations,

$$T_{amp} = \frac{T_{cas} - T_{loss}}{L} = \frac{T_{cas} - T_{physical}(L-1)}{L} \tag{18}$$

7.2 Tuning the K&L Filter

Figure 22 shows the inside and side of the K&L filter. As can be seen, the inside is a cavity resonator with numerous rods to tune the resonant frequency of the bandpass filter. The center conducting pin of the SMA is soldered to the nearest rod on either end of the cavity, leaving two rods free from direct solder joints. After close inspection, the same side of each rod is connected electrically to ground whereas the other side has a plastic piece to prevent the same connection. The side with the plastic piece of each rod corresponds to screw holes on the outside of the filter, as seen in Figure 22b. There are effectively two layers of screws for each rod. It appears that the top layer (with a hole in the middle so that one can access the lower layer screw) is used to prevent the lower layer screw from coming out. Consequently, the lower layer screw affects the gap between the rod and ground, and is therefore used to tune the filter.

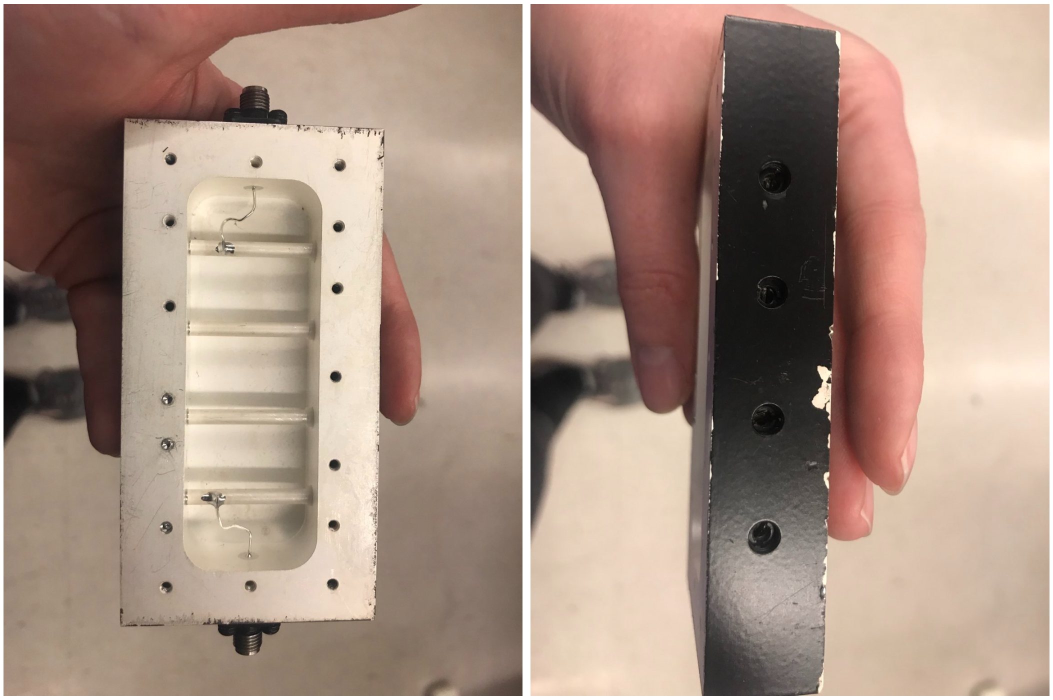

Figure 22. Expensive filter

7.3 Code

```
# 21 cm astro
# 1, 420, 405, 751.7667±0.0009 Hz from wiki
from pylab import *
from rtlsdr import *
import time
import datetime
import argparse
import h5py

parser = argparse.ArgumentParser()
parser.add_argument("--filename")
parser.add_argument("--sample_rate", default=2.4e6, type=float)
parser.add_argument("--sdr_gain", default=496, type=float)
parser.add_argument(’--freq_i’, default=1410., type=float, \\
    help=’Starting frequency, in MHz. Default is 1410.’)
parser.add_argument(’--freq_f’, default=1430., type=float, \\
    help=’Ending frequency, in MHz. Default is 1430.’)
parser.add_argument(’--df’, default=1., type=float, \\
    help=’Frequency tuning step size, in MHz. Default is 1.’)
parser.add_argument(’--int_time’, default=1., type=float, \\
    help=’Integration time, in seconds.’)
parser.add_argument(’--nint’, default=500, type=int, \\
    help=’Number of integrations per file. Default is 500.’)
parser.add_argument(’--navg’,default=100,type=int, \\
    help=’number of spectra to average default is 100’)
args = parser.parse_args()
```

```
filename=args.filename
samp_rate=args.sample_rate
startfreq=args.freq_i
endfreq=args.freq_f
tuningstep=args.df
sdr_gain=args.sdr_gain
inttime=args.int_time
nint=args.nint
navg=args.navg

sdr = RtlSdr()

# configure device
#sdr.sample_rate=samp_rate
#sdr.center_freq=cfreq
#sdr.gain=sdr_gain

plt.ion()

def get_samples():
  samples = sdr.read_samples(256*1024)
  #sdr.close()
  return samples

def plot_psd(color="blue",label="on"):
  # use matplotlib to estimate and plot the PSD
  plt.ion()
  samps = get_samples()
  psd(samps, NFFT=1024, Fs=sdr.sample_rate/1e6, Fc=sdr.center_freq/1e6)
  xlabel('Frequency (MHz)')
  ylabel('Relative power (dB)')
  show()
  return

def live_spectrum(navg=1):
  plt.ion()
  freqs = np.fft.fftfreq(1024,d=1./sdr.sample_rate)
  samps = get_samples()
  X = np.fft.fft(samps,n=1024,norm="ortho")
  plt.semilogy(freqs/1e6,np.abs(X)**2)
  plt.plot(freqs/1e6,np.abs(X)**2)
  plt.ylim(0,1000.0)
  plt.show()

  #for i in range(1000):
  while True:
    plt.clf()
    samps = get_samples()
    X = np.fft.fft(samps,n=1024,norm="ortho")
    if navg>1:
      Xacc = 0
      for i in range(navg):
```

```
        Xacc += X
      Xacc /= navg
      X = Xacc
    plt.semilogy(freqs/1e6,np.abs(X)**2)
    # if avg==True:
    #   Xacc += X
    #   #plt.semilogy(freqs/1e6,np.abs(Xacc)**2/i)
    #   plt.plot(freqs/1e6,np.abs(Xacc)**2/i)
    #   plt.title("Avg # "+str(i))
    # else:
    #   plt.semilogy(freqs/1e6,np.abs(X)**2)
      #plt.plot(freqs/1e6,np.abs(X)**2)
    #psd(samps, NFFT=1024, Fs=sdr.sample_rate/1e6, Fc=sdr.center_freq/1e6)
    plt.ylim(1e-5,1)
    xlabel('Frequency (MHz)')
    ylabel('Relative power')
    plt.pause(0.001)
  plt.show()
  return

def live_timestream():
  plt.ion()
  samps = get_samples()
  plt.plot(samps)
  plt.ylim(-1,1)
  plt.xlim(0,len(samps))
  plt.show()
  for i in range(1000):
    samps = get_samples()
    plt.plot(samps)
    plt.pause(0.1)
  plt.show()

def record_data(navg=navg,filename=filename):
    """
    Purpose:
      Recording nint sweeps across tunings to an hdf5 file
    """
    # initialize hdf5 file
    data_file = filename
    hf = h5py.File(filename, 'w')

    # set metadata
    hf.attrs.create('sample_rate', samp_rate)
    hf.attrs.create('sdr_gain', sdr_gain)
    hf.attrs.create('freq_i', startfreq)
    hf.attrs.create('freq_f', endfreq)
    hf.attrs.create('df', tuningstep)
    hf.attrs.create('int_time', inttime)
    hf.attrs.create('nint', nint)

    for n in range(nint):
```

```
      # create a grouped dataset for each pass
      grp = hf.create_group('nint='+str(n))
      # scan across band
      for c_freq in np.arange(args.freq_i, args.freq_f, args.df):
          sdr.sample_rate=samp_rate
          sdr.center_freq=c_freq*1e6
          sdr.gain=sdr_gain
          frequencies = np.fft.fftfreq(1024,d=1./sdr.sample_rate) + c_freq*1e6
          samps = get_samples()
          Xacc = 0
          for i in range(navg):
            samps = get_samples()
            samples = np.fft.fft(samps,n=1024,norm="ortho")
            Xacc += samples
          samples /= navg
          samp = np.abs(samples)
          data = (samp, frequencies)
          grp.create_dataset(str(c_freq), data = data)
    hf.close()
    plt.show()

print("Running...")
record_data()
#live_spectrum()
print("Done.")
```

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