Measuring the 21 cm Line with Cassiopeia

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Abstract

Using the radio telescope on the roof of UC Berkeley's Campbell hall, known as the Big Horn, we measure 21 cm emission from Cassiopeia. We find two peaks of this line corresponding to two spiral arms, and using the Doppler effect, calculate them to be shifted by $\sim 25\,\mathrm{km/\,sec}$ with one moving away and one moving toward us. We also calculate the wavelength both within a waveguide and with a coaxial line, finding that the velocity in coaxial lines remains the speed of light, while in a waveguide it is inversely proportional to frequency.

1 Introduction

The 21 cm line in astronomy refers to the spectral line observed as a result of the hyperfine transition of neutral hydrogen. Due to the spin of the electron relative to the proton, the ground state of hydrogen has two possible configurations: one where the spins are aligned and the other when they are anti-aligned. This transition releases a photon with a frequency of 1420.4 MHz. Although this process is rare, with the sheer amount of hydrogen in the Universe it can still be noticeably observed. I describe our hardware setup used to capture data in §2, our first test measurements and analysis in §3, how we positioned the telescope to a useful place and obtained found the spiral arms in §4, how we corrected for Doppler velocities in §5, as well as our slotted line measurements in §6. I also provide documentation for some frequently used functions in §9.

2 Understanding the Hardware

We first went through and made a diagram of the lengthy processing setup to use as a reference throughout (see Figure 1). The signal comes in at 1420.4 MHz and is very weak, so we amplify it several times. Then, after being mixed by a DSB mixer with an L.O. at 1230 MHz, which brings our target signal down to 190.4 MHz, it is sent through a bandpass filter which only passes frequencies at 190 ± 11 MHz. After being split, it is mixed again by two SSB mixers with L.O. frequencies at 190 MHz. Finally, it goes through a low pass filter set to cut off any frequencies greater than 2 MHz because the only signal we want has been mixed down to 0.4 MHz which we can easily sample.

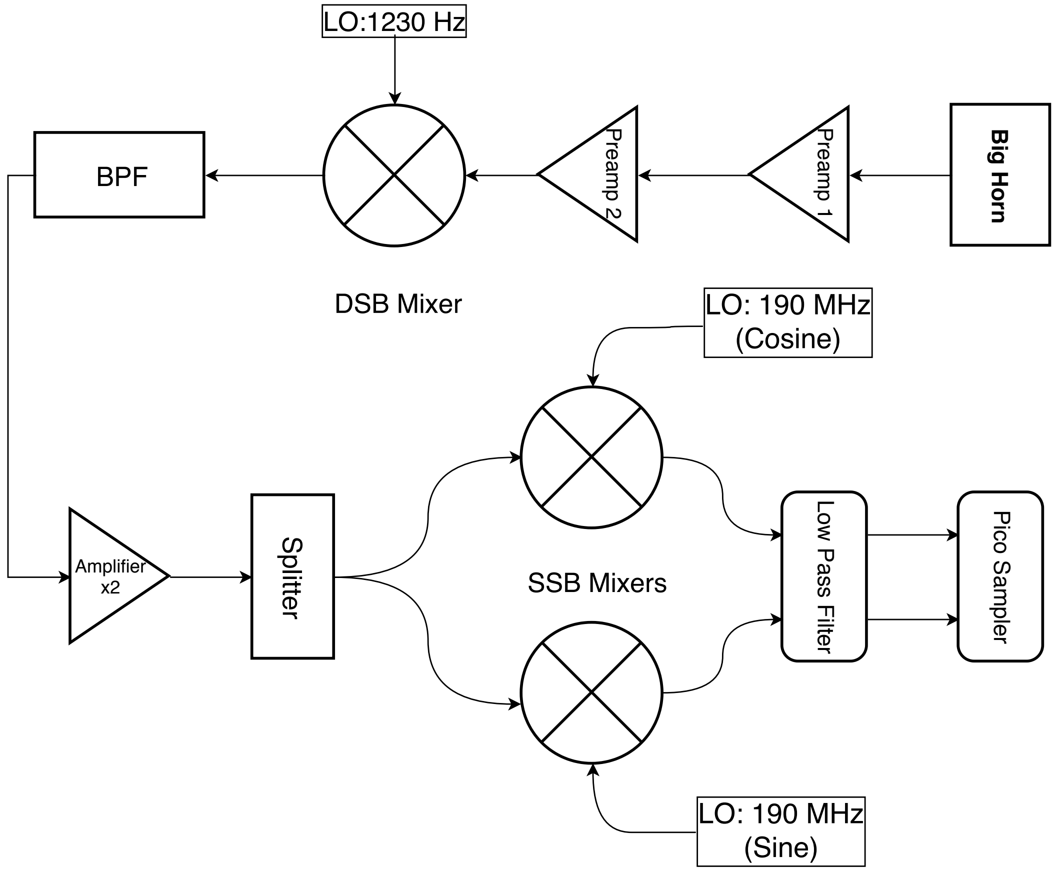

Figure 1: A block diagram showing the Receiving system used to process a signal from the Big Horn on the roof. Incoming signals are amplified, mixed and filtered using a variety of equipment, the goal being to isolate the frequencies we want, which are centered at 1420.4 MHz, then sample them digitally.

For this lab we also used two coaxial slotted line waveguides to measure the wavelength and velocity of a generated signal at various frequencies in the C Band ($\sim$ 3 GHz) as well as the X-Band ($\sim$ 7 GHz). The signal was generated by the HP 83712B synthesizer, fed into the waveguide, then observed using an oscilloscope.

3 Methods I: Our First Measurement

With the telescope at its zenith, we changed the L.O. Frequency by ± 1 MHz. Increasing by 1 MHz puts the 21 cm line in the lower-band and decreasing by 1 MHz puts it in the upper-band. Because the signal was so weak, we took 10,000 blocks of data for each configuration to then average over to obtain the line shape during the analysis phase.

Next, to get the line intensity, we collected another set of data with the horn pointed at the sky, called "cold-sky" then another with the horn pointed at the approximate blackbody that is I♡Radio i.e. three of us stood in front of the telescope.(See Figure 2)

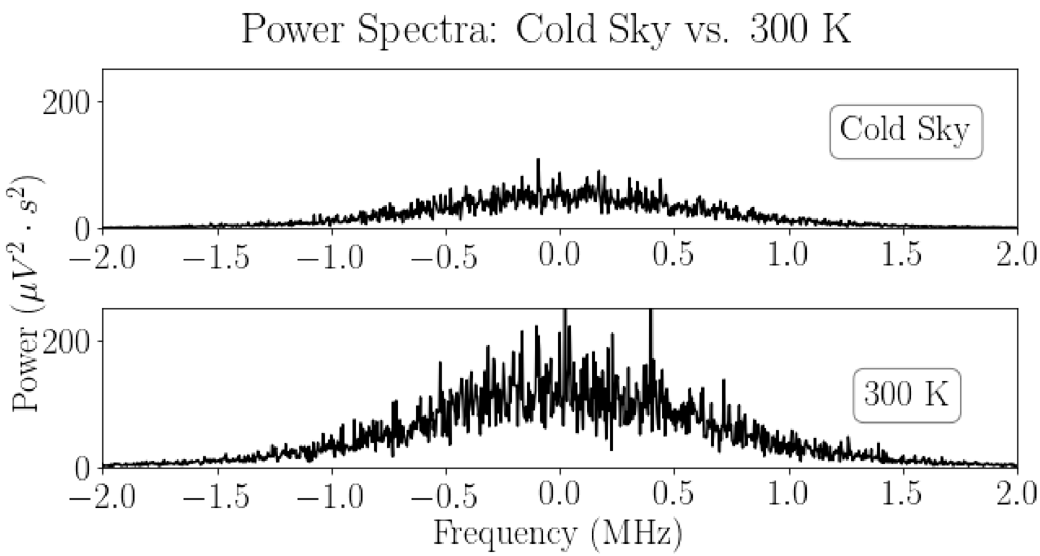

Figure 2: Power spectra for the cold sky measurements and blackbody measurements. As described in later sections we use these to determine the intensity of the line without the instrumental noise.

We saved all these measurements to over 100 different files which, due to their size, became a challenge to handle efficiently when performing calculations.

4 Methods II: A Real 21 cm Line Measurement

Once we confirmed the telescope was properly calibrated we took some real astronomical measurements. The first crucial step was to point the telescope, using the information in the lab alone we found this was more difficult than anticipated. Consequently, with the help of another group and online calculators, we were able to determine that the specified galactic coordinates (120°, 0°) corresponded approximately to the location of Cassiopeia. We could then find Cassiopeia and point the telescope using an application on our phones (Star Walk).

We later learned that this is not entirely a bad idea as Cassiopeia contains a young supernova remnant and is one of the brightest radio sources in the sky[1]. Importantly

[1]arXiv:astro-ph/0603371

for us, it is also in the plane of the galaxy, where we will see the hydrogen spiral arms and thus the 21 cm line we were looking for.

Using the same method described in §3 we collected a total of 10,000 blocks of data with the line in the upper and lower sidebands with a sampling rate of 32.5 MHz but again found this to be too much to handle efficiently. Taking the Nyquist criterion into account we increased our divisor to 5, giving us a a sampling frequency of 12.5 MHz.

4.1 Analysis I: Properly Calibrated Line Shape and Intensity

To obtain the smoothed line shape we started by computing the power spectra of each block, then we averaged over all the blocks with `numpy.mean`. This gave us an averaged spectra for both the upper and lower sidebands which we then patched together to obtain S_{Online} and $S_{Offline}$ shown in Figure 3. Next, we wanted to fully reveal the 21 cm line by removing the instrumental bandpass which comes mostly from the low-pass filter. Using the ratio

$$s_{\text{line}} = \frac{s_{\text{online}}}{s_{\text{offline}}} \tag{1}$$

which does just that, we were left with the line shape we wanted but not the intensity. (See Figure 3)

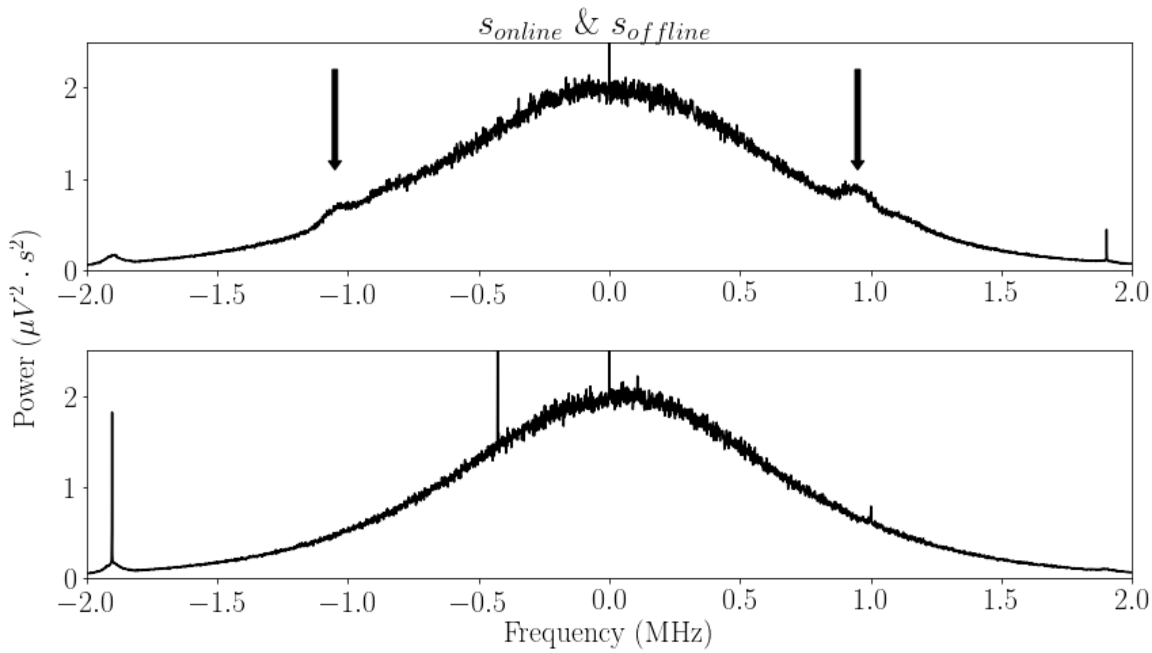

Figure 3: The offline and online spectrum with the correct shape but intensity not yet determined, created by merging the averaged spectra of the signal with the HI line in the upper and lower band. Arrows at ±1 highlight the bumps from the HI line.

Converting to the correct temperature units to get the line *intensity* is done with

$$T_{line} = S_{line} \cdot G(\nu) \tag{2}$$

where

$$G(\nu) = \frac{T_{\text{sys,300K}} - T_{\text{sys,coldsky}}}{\sum(s_{\text{cal}} - s_{\text{cold}})} \sum s_{\text{cold}} \tag{3}$$

Here, $T_{sys,300K} = 300\,\text{K}$ comes from the temperature of the I♡Radio blackbody, and $T_{sys,coldsky} = 2.7\,\text{K}$ comes from the Cosmic Microwave Background. These are the system temperatures which do not come from the HI line and must be removed to find the signal that actually entered the horn.

We have now converted the line to units of brightness temperature, but to remove the extra system temperature we must fit a line to the baseline then subtract it out to bring the baseline down to zero. Finally, we can stack the two images which come from the in-band frequency switching to obtain a properly calibrated spectrum. These final steps are shown in Figures 4 and 5. We are left with a calibrated spectrum for the HI line showing two peaks, corresponding to two separate arms of the galaxy.

5 Doppler Shift

The Doppler effect, a very commonly understood phenomenon, is a shift in the frequency of a signal, light or otherwise, due to relative motion between the emitter and the observer.

With this in mind, we analyzed our data using (`ugradio.doppler`) and calculated that from our reference frame the signal we received is shifted by nearly $25\,\text{km}\,\text{s}^{-1}$.

Because we observed two peaks, we can also examine them individually. With one below and one above zero, they are are moving toward and away from us, respectively. The interpretation of this is that we did in fact observe two separate arms, which due to their rotation about the center of the galaxy, are seen to be moving toward and way from us.[2]

6 Methods III: Slotted Line Measurements

Through the course of this lab, we were also introduced to slotted line coaxial waveguides, and used them to calculate the wavelength of six frequencies in the X-Band (7.5 GHz, 7.75 GHz, 8 GHz, 8.25 GHz, 8.5 GHz and 9 GHz), as well as one in the C-Band (3 GHz).

For each frequency we recorded the the position of the nulls once with the end open and again with the end shorted (A subset of this data is listed in Tables 1 and 2).

[2]I believe that by mapping these HI clouds in our galaxy, astronomers were able to determine our orbital velocity.

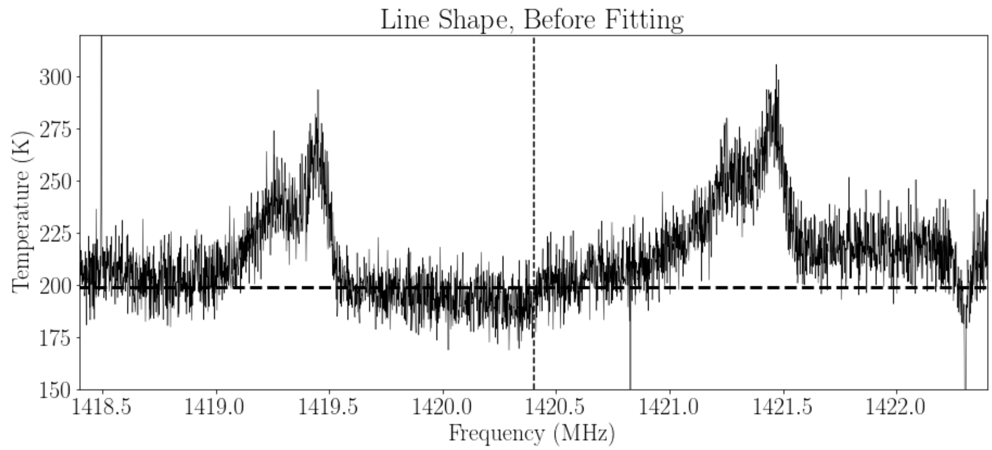

Figure 4: Two images of the 21 cm line shape form as a result of *in-band frequency switching* where we shift the line far enough below the center frequency that it remains visible. Also shown is the approximate fit to the baseline.

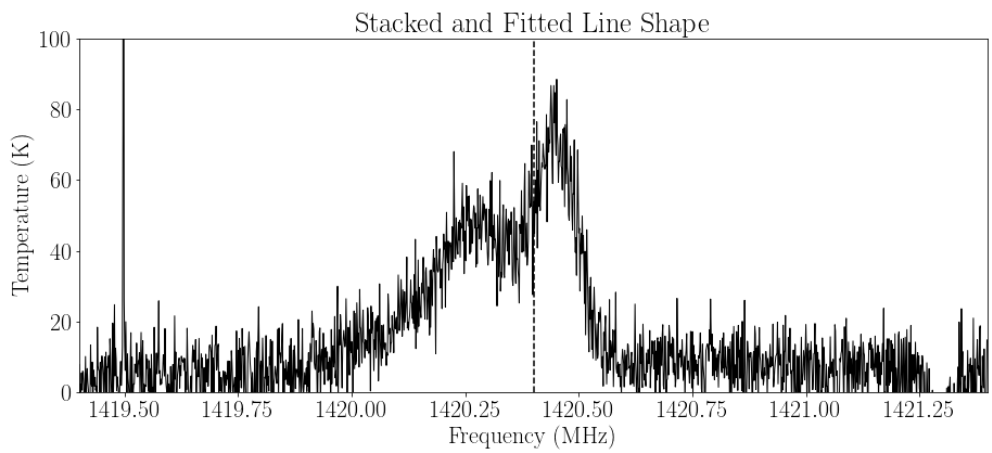

Figure 5: The final calibrated spectrum after stacking and averaging the two images from above and then subtracting the noise temperature.

6.1 Analysis III: Statistical Error

With all measurements there is some uncertainty, here they arise from the imprecise nature of our setup. The slotted line for example can only have so many lines (we assume an uncertainty equal to half the precision), and there is a finite resolution on the oscilloscope making it hard to determine the exact location of nulls.

We first found the wavelength in the slotted line $\lambda_{slotted}$ with a rough calculation where we use the wavelength of each null pair and average over all pairs. Then to calculate the uncertainty in this we use $\sigma/\sqrt{M-1}$ which gives an uncertainty of $\sim$ 0.0167 cm and thus $\lambda_{slotted} = 10 \pm 0.33$ cm for both the open and shorted.

Open/Shorted	Frequency (GHz)	Power (dBm)	Null Position (cm)
Open	3	0	5.5, 10.5, 15.5, 20.5, 25.5, 30.5, 35.5, 40.5, 45.5, 50.5
Shorted	3	0	3, 8, 13, 18, 23, 28, 33, 38, 43, 48

Table 1: The null measurements for the coax slotted line at 3 GHz for the C-band. Note the uniform spacing of 5 cm between each null.

Open/Shorted	Frequency (GHz)	Power (dBm)	Null Position (cm)
Open	7.5	15	8, 12.4, 16.4
Shorted	7.5	15	9, 13.1, 17.5
...	...	...	...
Open	9	20	8, 10.7, 13, 15, 17.9
Shorted	9	20	10, 12.7, 15.2, 17.6

Table 2: The abridged null measurements for the X-band. Only some data points are included to easier see that the signal strength fell with distance and the null spacing did not remain constant unlike the C-Band measurements

Next, we use least squares fitting to solve for $\lambda_{slotted}$ in the equation

$$x_m = A + m\frac{\lambda_{slotted}}{2} \tag{4}$$

and again find that $\lambda_{slotted} = 10$cm (With $A = 0.5\,\text{cm}$.)

Finally, we examine the X-Band waveguide and using the following equation find the wavelength to be 10 cm:

$$\lambda_g = \frac{\nu_p}{f} = \frac{\lambda_{fs}}{[1 - (\lambda_{fs}/2a)^2]^{1/2}}, \tag{5}$$

where λ_g is the guide wavelength and λ_{fs} is the free space wavelength. We observe that through a coaxial line, the wave velocity remains the speed of light, whereas in a waveguide it falls off inversely with frequency.

7 Conclusion

By pointing the Big Horn on the roof of Campbell Hall at Cassiopeia and through careful analysis, we have successfully observed the 21 cm line and found two spiral arms of our galaxy, one moving away from us and the other moving toward us. We have learned how to compensate for the temperature of our receivers, as well as the our own motion through the Universe. We also began to develop the methods for calculating uncertainties in our measurements and used fitting to obtain precise, reproducible results.

8 Acknowledgements

My group I♡Radio was invaluable in the completion of this lab. After all our setbacks we pulled together and helped each other through the software and the hardware.

9 Code Documentation

The majority of my code was done without defining my own functions but here I include functions for operations I used frequently in the coding of this Lab.

```
def scaled(data, volt_range):
"""
Rescales Pico sampler data.

Parameters:
data (array) : data to be rescaled
volt_range (num) : volt range used during
                   ugradio.capture data

Returns:
output (array) : rescaled data
"""

def powerspec(signal, v_samp, nsamples):
"""
Calculates the power spectrum of the input array
using numpy.fft

Parameters:
signal (array) : Array containing signal values
                 from pico
v_samp (num) : sampling frequency
nsamples (num) : number of samples used in
                 ugradio.capture data

Returns:
power (array) : power spectrum
freqs (array) : frequencies
"""
```