Lab 2: The Big Horn and the 21-cm Line

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Abstract

The purpose of this lab was to experimentally investigate the 21-cm line of atomic Hydrogen in the Milky Way using the Big Horn telescope on the roof of Campbell Hall. This lab included exercises to help gain familiarity moving from large amounts of raw signal data to final spectra, including velocities relative to various reference frames. We were able to measure HI spectra from the horn pointing off the Galactic plane, as well as pointing at the Cassiopeia constellation, in which the main star, Cas A, is a supernova remnant and the brightest extrasolar radio source in the sky at frequencies above 1 GHz. These laboratory skills will be useful for future work in this lab, as well as in research and future careers.

1 Introduction

Neutral hydrogen (HI) is a primordial universal element; abundant and ubiquitous in low-density regions of the ISM as well as in our own galaxy, in which it moves in nearly circular orbits around the galactic center. It is detectable in the 21 cm (1420.405751 MHz) hyperfine line, well within the radio frequency range. The 1420 MHz HI line is an extremely useful tool, and studying its properties has inspired many investigations into the origins of our galaxy, gas in the ISM of external galaxies, as well as the large-scale distribution of galaxies in the universe. Cassiopeia A is a supernova remnant that is the strongest radio source in the sky outside the solar system, and was found among the earliest discrete radio sources by radio astronomers in 1947. We are motivated in this lab to use our learned observing skills to repeat their original measurement with modern technology.

2 Measure a 21-cm line power spectrum from atomic Hydrogen in the Milky Way

2.1 Experiment and Data: The Receiving System

For our initial calibration data, we pointed the horn at zenith to reduce interference and thermal noise, and for our experiment we pointed the horn at the spiral arms of the Milky Way galaxy and at Cass A. Our signal, the 21-cm line, was collected from the horn at 1420.4 MHz and was received through the following double heterodyne system and as illustrated Figure 1.

The first mixer was a DSB, with an LO of 1230.0 MHz. The difference frequency from that stage was 190.4 MHz and the sum frequency was 2650.4. We used a 20 MHz-wide bandpass filter centered at 190 MHz to obliterate the sum frequency, so we were left with a replica of the 21-cm line that is centered at 190.4 instead of 1420.4 MHz.

The second mixer was an SSB, with an LO of 190.0MHz, so the output frequencies were positive and negative centered at zero (the baseband). In the absence of a Doppler shift, we would have been left with the line centered at 0.4 MHz. However, the line is shifted and broadened by galactic rotation and the Earth's orbital velocity, so it covered a range of frequencies of 1420.2+=0.5 MHz. We used a low pass filter with a cutoff frequency of 2MHz to eliminate aliasing, and sampled the complex signal at a voltage of 50mV, at a sampling rate of 16000, with a divisor of 8. We wanted 10,000 spectra per measurement to average them to reduce the noise, so we took 10 samples of 1000 blocks each per measurement.

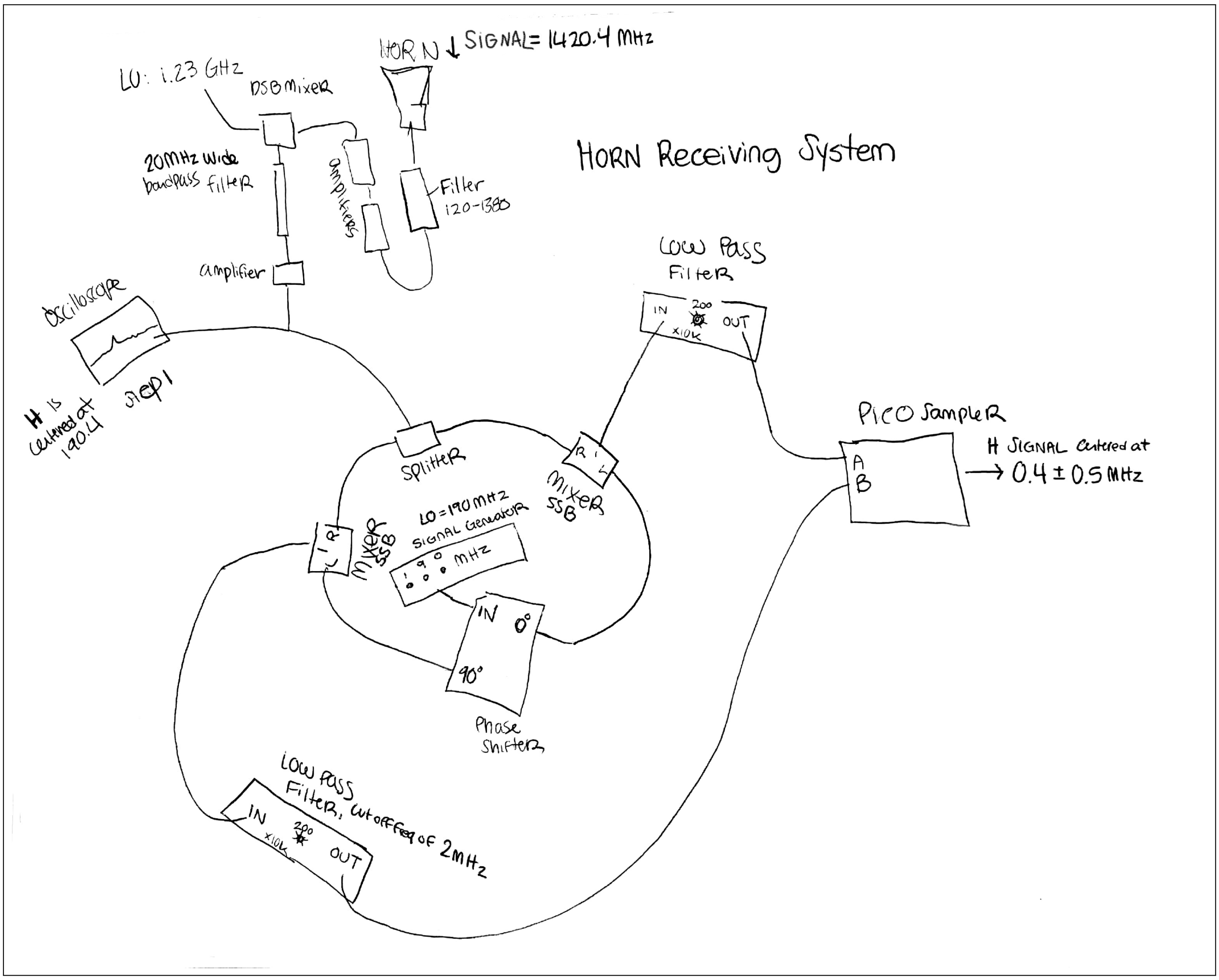

Figure 1: Block diagram of telescope electronics. The 21-cm neutral hydrogen line was measured from the horn telescope on the roof of Campbell Hall at 1420.4 MHz, and was filtered through a double heterodyne system to optimally output a 0.4MHz signal that we could analyze. This diagram is taken from a page in the author's lab notebook.

2.2 Data reduction and manipulation

To reduce our data and understand our detected signal we took two main data measurement sets: a long integration to measure the line's shape and a short integration to calibrate the line's intensity. This process is detailed for our data from the horn pointing at zenith, and is then applied to our data for the horn pointing at Cass A.

2.3 Line Shape

To see the weak hydrogen line shape in our spectrum, we needed to correct for other dominating shapes caused by frequency-limiting filters acting on the system temperature.

We did this by obtaining two spectra: one with the line present and one with the line not present ("online" and "offline"). First we measured the line roughly in the upper half of the baseband spectrum by changing the second LO's frequency (usually 190MHz) to 191 MHz, then we measured with the line centered roughly in the lower half by changing the LO frequency to 189 MHz.

2.3.1 Combine data using mean and median

Using a home brewed python module, averagespectrum.py (see Appendix I), we combined the 10,000 signals collected to make a single power spectrum for each measurement. To accomplish this task there were two functions we had the option of using, numpy's mean function which would average of the power spectra, or numpy's median function, which would take the medians. In the top half of Figure 2, we show the comparison between the effects of mean and median on the offline spectrum at this step in the reduction process.

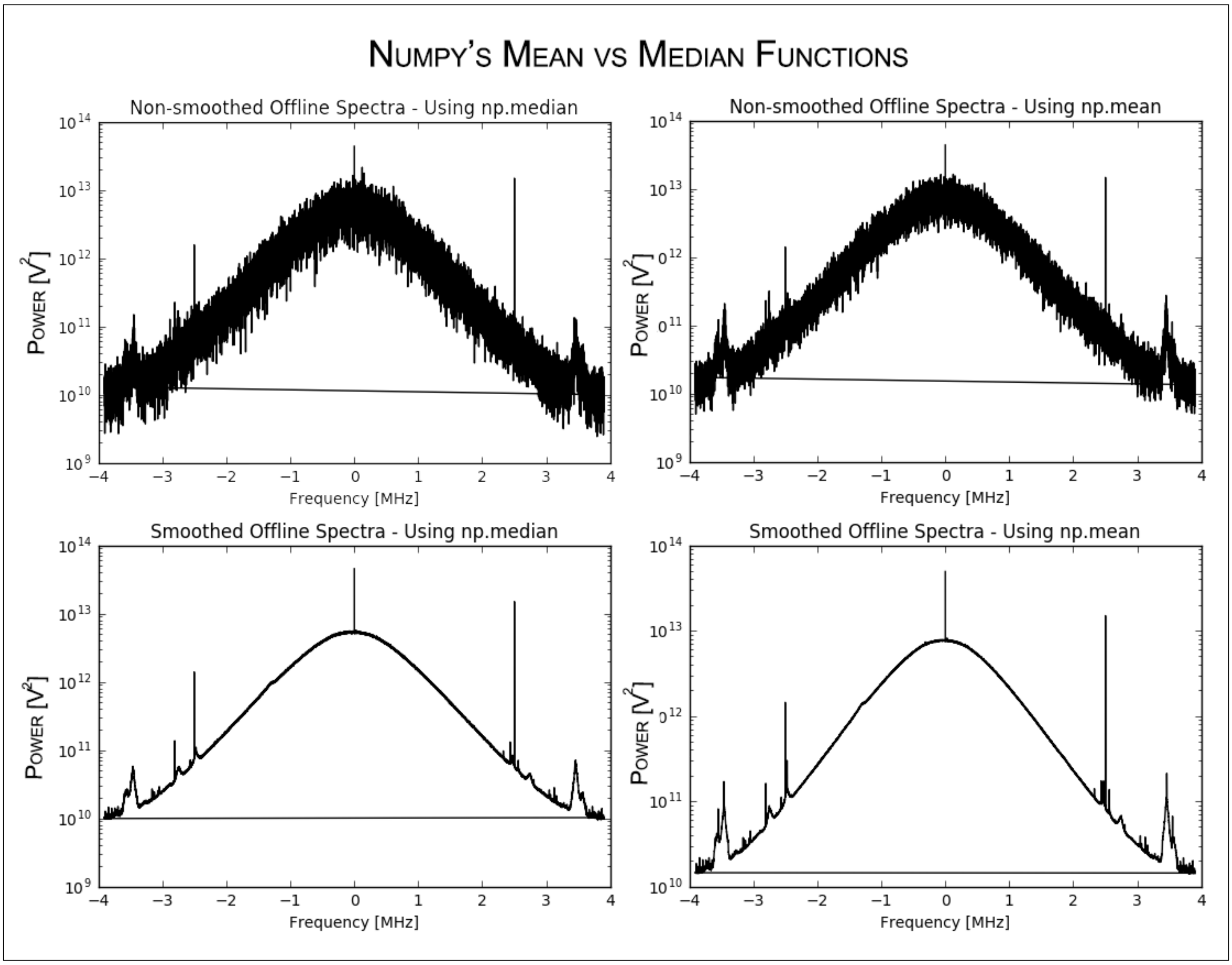

Figure 2: Comparison of data reduction effects of Numpy's mean and median functions, before and after smoothing channels. The top two plots are a result of taking the power spectrum of the complex data, then either averaging or medianing the results. The bottom two plots are a result of filing the complex data into 1000 channels, then taking the power spectrum of each channel and averaging or medianing the results to smooth the spectrum. The spectra using the mean function produces less noise, so we use the mean in the analysis of our data moving forward.

We knew in advance that taking the average would lead to a less noisy result, but taking the median would handle the time-variable interference better. What we found is that the averaging function provided a spectrum with comparatively less noise than the medianing function, which we can see because the thickness of the fuzzy signal is smaller in the graph of the non-smoothed spectrum using the mean.

Although we combined all 10,000 spectra, from the fuzziness of the line we know our spectrum still contained a lot of noise, so we needed to further reduce by averaging over many channels. Since we took 10 samples of 1000 blocks each per measurement, we decided to smooth over 1000 channels. The data compromise is that smoothing degrades the spectral resolution, but since the HI line is never narrower than about 1 km/s, it was fine to degrade the frequency resolution to a few kHz. The bottom half of Figure 2 shows the spectral differences between using the averaging or medianing function to smooth the channels. The differences between the mean and median function in the smoothed spectrum are less drastic than in the non-smoothed spectrum: from the graphs we can see that the smoothed median spectrum has endpoints around 10^{10}, a little lower than in the smoothed mean spectrum with endpoints that are a little higher than 10^{10}, although the spectra both peak at the same height. It may be a product of the vertical scale, but the smoothed median plot also looks a little wider than the smoothed mean plot.

Based on these results, we decided to use Numpy's mean function for our data analysis going forward.

2.3.2 Line shape is the ratio of online to offline

The instrumental bandpass, determined mainly by a smooth low pass baseband filter, currently dominates the shape of our spectrum. It has a gradual falloff to zero at the upper edge as the frequency increases, we we don't need to worry about aliasing.

To remove the instrumental bandpass and get the shape of the HI line, sline, we took the ratio of the smoothed online to the smoothed offline spectrum:

$$sline = \frac{online}{offline} \tag{1}$$

The shape of the line (sline) is plotted in Figure 3. In the top plot, the HI line is visible at the local minimum around -1.5 MHz and at the local maximum around 0.5 MHz– these are the same line which should be centered halfway between the two peaks, around -0.5 as corrected for in the bottom plot of Figure 3. Since it is a ratio of two power spectra, sline does not have units.

2.4 Line Intensity

2.4.1 Calculate Gain

To get the the line intensity we had to remove the instrumental contribution to the spectrum, which we did by taking second pair of measurements at short integration: one with the horn looking at a known blackbody, "sCal" (three of our group members standing in front of the horn to fill the aperture), and one looking at the cold sky at zenith, "sCold". By standing in front of the telescope, we are introducing a known temperature (Tcal = 300 Kelvin) into our spectra that we can then compare to the open sky off the Galactic plane (Tsky = 10 Kelvin) and see how much that known temperature difference changes the measured values in our spectra. This calibration, Equation 2, is called the gain (G), which we calculated as 123.367 Kelvin.

$$G = \frac{(Tcal - Tsky)}{\sum(sCal - sCold)} * \sum(sCold) \tag{2}$$

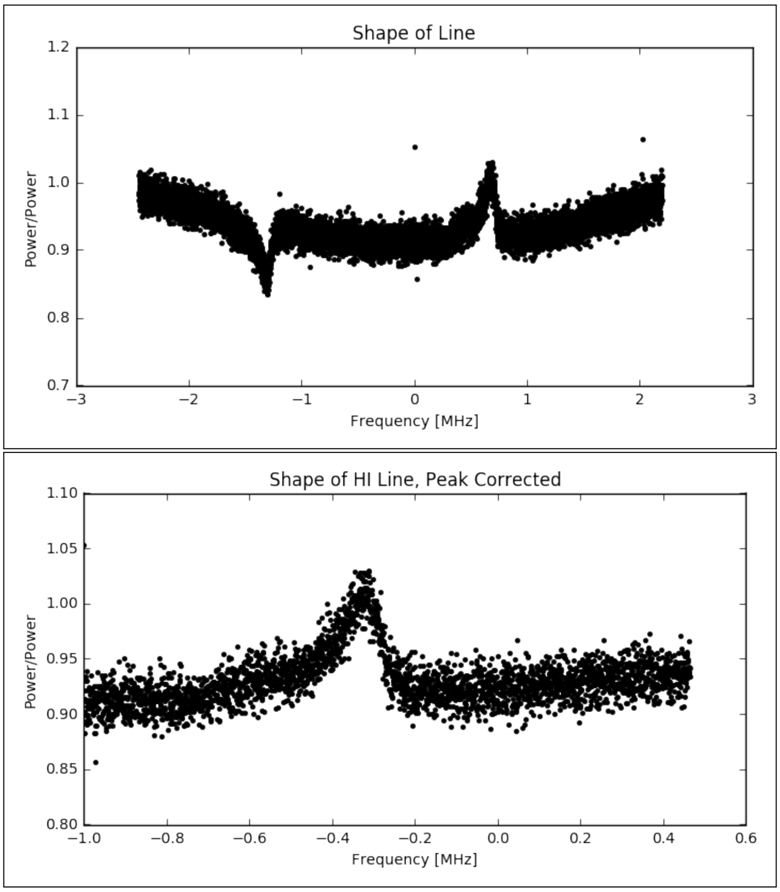

Figure 3: The shape of the HI line can be seen by taking ratio of the smoothed online to the smoothed offline spectrum, Equation 1, to remove the effects of low pass baseband filter. The HI line taken in our offline spectrum is the local minimum around -1.42 MHz, the HI line taken in our online spectrum is the local maximum around 0.58 MHz. If we recall that our online and offline spectra were offset from our second LO's frequency by 1 MHz on each side, and we apply that back, then the HI line would center around -0.42. In the absence of Doppler shift, we would expect a line centered at 0.4 MHz, however Galactic rotation and the Earth's orbital velocity shift the line within a small range of frequencies, so our -0.5MHz measurement is reasonable.

2.4.2 Intensity is the line shape multiplied by gain

To get intensity, we would like to convert the measured units of sline, which are digital numbers from the system, into physically meaningful units like Kelvin. To get the line intensity in temperature units (Tline), we just need to multiply the shape spectrum (sline) by the gain (G):

$$Tline = sline * G \tag{3}$$

Figure 4 is a plot of the final calibrated spectrum in Kelvin versus the frequency in MHz. The top plot plots the spectrum against the filtered frequency we gather from the receiving system, the bottom plot is the spectrum against the R.F. frequency, which is the original signal from the sky. We get the R.F. frequency by taking our signal frequencies and adding back in the LOs (1230.0 and 190.0). From the Temperature vs RF Frequency plot we can confirm that our original signal peaks around 1419.7 MHz, which fits within our expected range of 1420.2 ± 0.5.

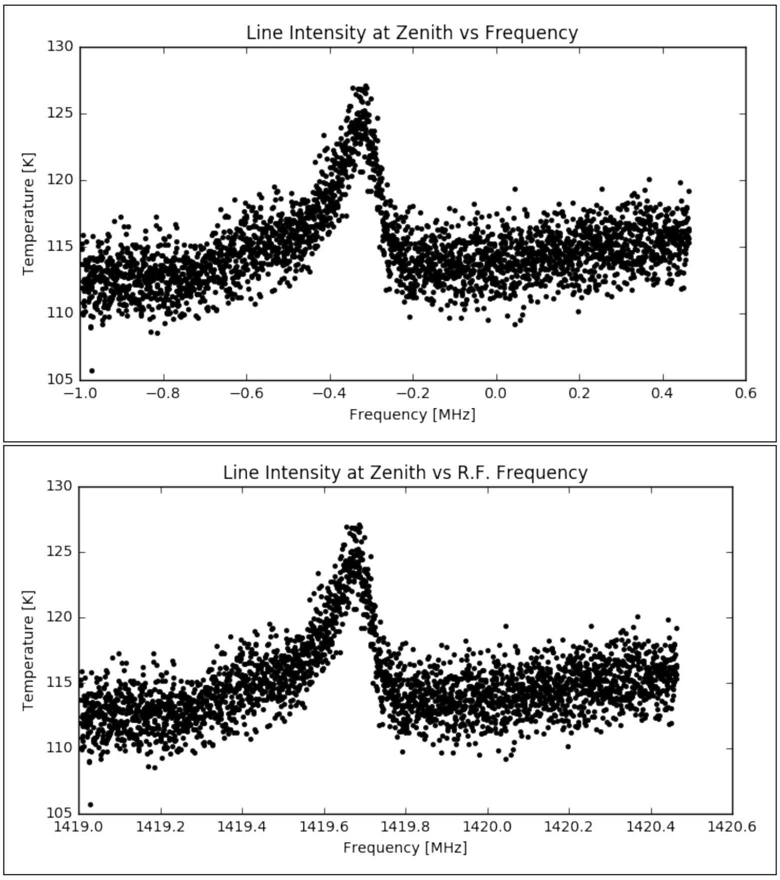

Figure 4: HI line intensity plotted against the frequency outputted from our receiver and the frequency originally outputted from the horn pointing at zenith. The temperature of the HI line in the sky peaks around 127 Kelvin, at a frequency of 1419.7MHZ.

2.5 Produce spectra with velocities relative to various reference frames

2.5.1 Doppler Velocity

The observed center frequency of the HI line can be used to measure the radial velocity of the galaxy which it is being emitted from. This is called the Doppler velocity. By astronomical convention, a positive velocity would indicate motion away from the observer, in the understanding that the Universe as a whole is expanding positively. The equation for Doppler velocity is as follows in Equation 4, where c is the speed of light, $\Delta\nu$ is the frequency offset from the line frequency ν_0 (1420.4058 MHz), LO1 is 1230.0 MHz, and LO2 is 190.0 MHz.

$$\frac{v}{c} \approx \frac{\Delta\nu}{\nu_0} \tag{4}$$

$$\nu_{RF} = receivedsignal + LO1 + LO2 \tag{5}$$

$$\Delta\nu = \nu_0 - \nu_{RF} \tag{6}$$

$$\nu_{Doppler} = -\frac{c * \Delta\nu}{\nu_0} \tag{7}$$

Our final Doppler velocity spectrum as calculated in Equation 7, is plotted in Figure 5, "Line Intensity at Zenith vs Velocity". This graph plots HI spectral line in the reference frame of the observer, which peaked at -151.6 km/s. In the frame of the observer, we know that this observation was moving towards us.

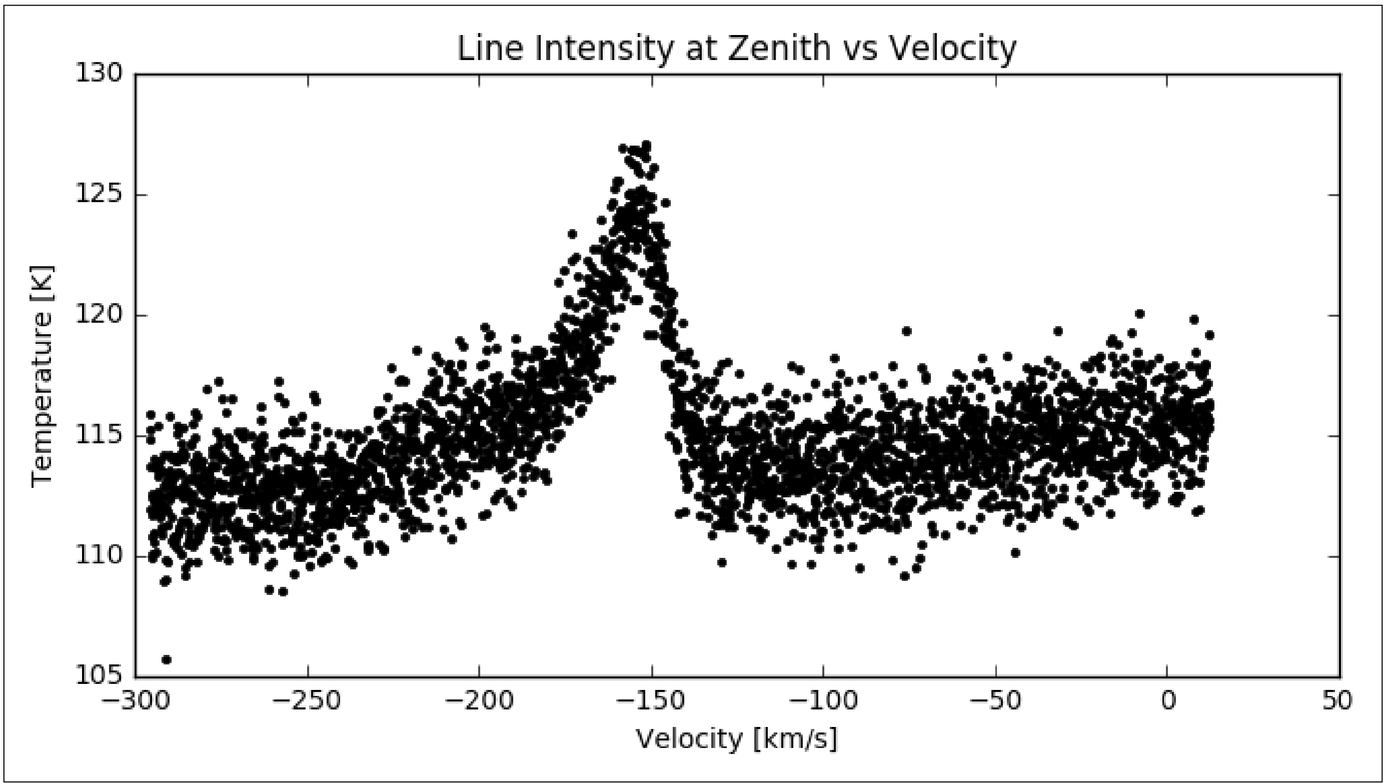

Figure 5: Temperature vs Velocity spectrum of HI atoms somewhere in the sky. The temperature at the line peak is 127 Kelvin and the observed velocity of the line peak is -151.6 km/s. Because the velocity value is negative, it means that the cloud of hydrogen atoms in the sky above telescope pointing at zenith on the day of our observation was moving towards us observers on the roof of Campbell Hall.

2.5.2 Reference Frame

However, a Doppler velocity on its own only tells us about the relative motion between the observer to the HI atoms, in which there are many rotating systems that one would need to correct for, including the the rotation of the observatory around the center of the Earth, the orbit of the Earth around the barycenter of the solar system, and the peculiar velocity of our Sun with respect to other stars in the neighborhood. These calculations include special relativistic treatment of velocity, general relativistic effects from the influence of the gravitational fields of all bodies in the solar system, and the proper motion of the target source, and thus is beyond the scope of this lab report, but will be left as an exercise to the reader, see (Wright & Eastman, 2014).

2.6 Use rotation matrices to convert among spherical coordinate systems

Finally, after all of our calibration measurements with the Big Horn pointed at zenith, were we finally able to observe the HI spectral line of a known radio source. We were initially instructed to point the horn to the Galactic coordinates (l, b) = (120 , 0), which we assume is a location within the Galactic plane along a spiral arm of the Milky Way galaxy. In order to point the horn we needed to convert from Galactic coordinates to altitude and azimuth. This involves three separate coordinate transformations: Galactic longitude and latitude to equatorial right ascension and declination [(l, b) $\rightarrow$ (α, δ)]; to hour angle and declination [$(\alpha, \delta) \rightarrow (ha,\delta)$]; to azimuth and altitude [$(ha, \delta) \rightarrow (az, alt)$].

However, our observational team neglected to notice that the coordinates given were in Galactic coordinates, and missed a step in this process. Assuming that the (120, 0) coordinate was an RA and DEC value, we used the get-altaz function in the coord module provided in the ugradio GitHub, which is used to convert RA and DEC coordinates into AZ, ALT coordinates, which we could use to point the horn. Using this understanding and the time of the observation, we calculated that altitude would be 23.8 degrees above the horizon, and azimuth would be 110.2 degrees from North. While we were pointing the Big Horn telescope to this location, it was interesting to note that our compasses that should have been pointing North were pointing North-East of what should have been North, so it is possible there is some large current in that direction on the Campbell Hall 7th floor, which we considered would be the main source of error before we realized we had neglected the third coordinate transformation and we were pointing the telescope to a completely different part of the sky.

While we were disappointed with our initial Galactic measurements, we were still interested in observing an astronomical radio source, so we took several spectra of the Cassiopeia constellation, which has a central supernova that is a large emitter of radio signals, so we knew we would be able to get spectral measurements of its HI line. For this observation we pointed the telescope using StarTracker, a constellation app.

The plots in Figure 6 are of our resulting spectrum of the Cass A HI spectral line versus both the R.F. frequency and the observed velocity. The multiple peaks come from HI clouds having different velocities. The peaks are usually represented as Gaussians with appropriate central intensities, velocities, and widths.

3 Discussion and Conclusion

Cassiopeia A was originally discovered by radio astronomers in 1947, and has been inspiring generations of astronomers ever since. In this investigation we measured the 1420 MHz HI spectral line for the first time as novice radio astronomers, an inspiring moment that built confidence in our technical abilities, connected our theoretical understandings of astrophysics and atomic chemistry to our hands-on experimentation. The completion of this lab could have been more complete with a more thorough understanding of coordinate transformations among reference frames, as well as an exploration of statistical analysis. It was challenging to understand the connection between the observations and the measurements using the coaxial cable and waveguides. Even so, this lab was very fulfilling for the author and has imparted a permanent state of awe for the profound and complex nature of the Universe.

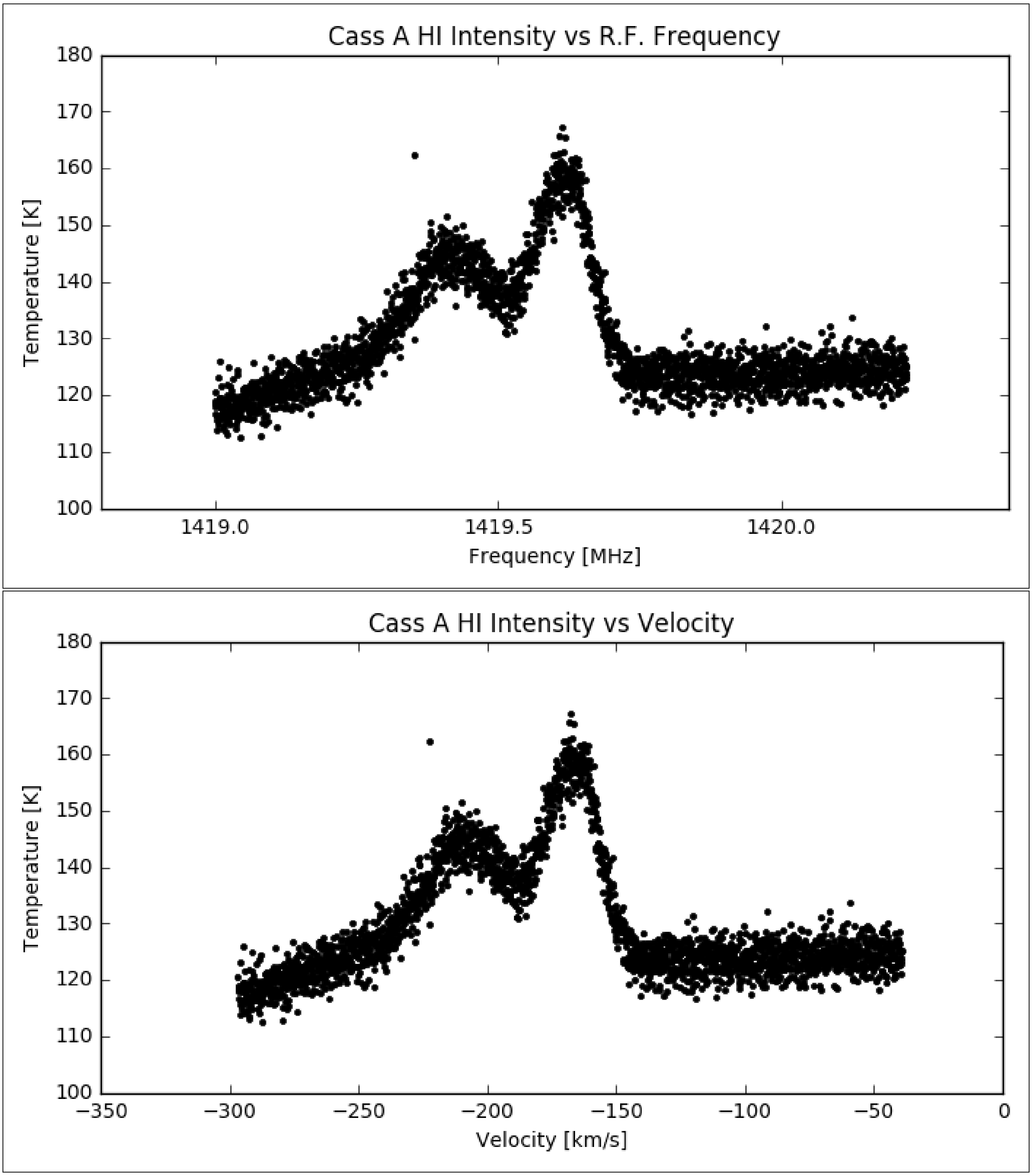

Figure 6: This plot shows the Cass A spectral HI spectrum plotted as a function of frequency and as a function of the observed velocity. The multiple peaks come from different HI clouds having different velocities, for example, the peak on the left is a cloud with peak velocity -210 $\pm$ 30 km/s, and the peak on the right has a peak velocity of -170 $\pm$ 20 km/s in the observing frame. This means that the cloud with the peak on the left is moving closer to us observers faster than the cloud on the right.

4 Appendix

4.1 Modules

4.1.1 averagespectrum.py

""" INPUT: (array) OUTPUT: (power spectrum, frequency spectrum)""" —– This module will take an input data array with 'Vsamp = 62.5 / 8 ', 'nsamples = 16000' and 'nblocks = 1000'. It will first make data complex; with the understanding that the first half is real, second half is imaginary Then it will seperate this long file into 1000 nblocks arrays Then it will take the power spectrum of each array, using Numpy's Fast Fourier Transform function and squaring the result The power spectrum is calculated using Numpy's mean function, it will average the arrays of power spectra into a single spectrum The frequency is calculated using Numpy's Fast Fourier Transform Frequency function, using the length of the average spectrum with intervals of 1./Vsamp. If you take many measurements of the same source, run this module for each measurement, then average the results.

References

[1] Parsons, A. (2019). Astronomy With The 21-CM Line; Some Microwave Electronics. [online] AstroBaki. [Accessed 12 March. 2019].