Astronomy With The 21-CM Line; Some Microwave Electronics

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Abstract

Our team explores Microwave astronomy by recording Hydrogen emission from the spiral arms of our own galaxy using the Big Horn antenna of the roof of New Campbell Hall. Using spherical coordinate transformation we can point to galactic coordinates in the sky using our Local Standard of Rest and collect data to evaluate HI velocities and calculate corresponding intensities using a calibrated signal from our antenna.

Introduction

In a cloud of HI gas that has elements which have been excited to the higher hyper fine state, when the electrons decay to the lower state the resulting photon has a frequency of approximately 1421.4 MHz and a wavelength of approximately 21 cm. These photons penetrate both dust in space and the atmosphere on Earth, allowing us to observe the distribution of gas in the Universe. Because stars and galaxies are largely composed of hydrogen, a radio telescope that observes the HI 21 cm line can create maps of the Universe. The photon frequency is tightly dictated by the hyper fine energy difference, so any observed shift in frequency may be attributed to either the temperature of the HI source, or its motion. We detail the signal chain used to capture data as well as methods to validate and smooth the collected data. We analyze HI signal data collected from zenith, adjusting for the instrumentation temperature and the velocity of the Local Standard of Rest. We repeat this analysis on HI signal data collected at coordinates in the galactic ecliptic.

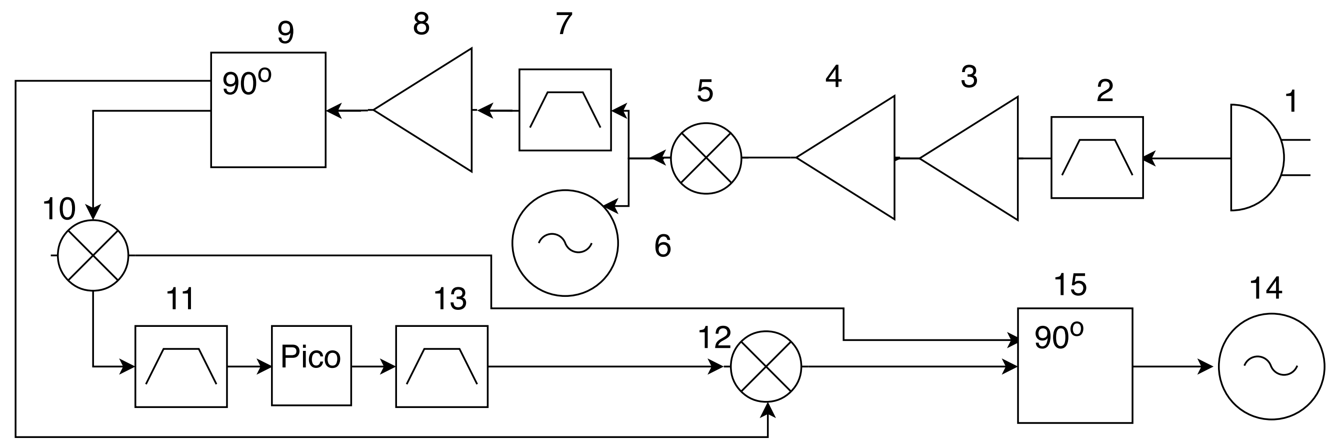

Figure 1: The full horn signal chain from the L-band horn to the PicoScope 2000 digital sampler.

1 Apapratus

Our instrumentation is outlined in figure 1 above. The signal begins at the horn antenna (1) on the roof which collects radio frequencies and passes them to a double sideband mixer. The signal is passed through a KL Microwave Inc 5B120-1380/160 Bandpass Filter (2), a 160 MHz range centered on 1380 MHz. From (2), the filtered signal is amplified in two 20 dBm amplifiers, (3) and (4). The amplified signal is combined (5) in a double sideband mixer with a local osicllator, (6), an Agilent N9310A RF Signal Generator set to 1230 MHz. The signal has been shifted from 1420.4 megaHz to 190.4 megaHz, and is fed into a sideband separating mixer (SSB). The output of (5) is passed into a Telonic 190-22 Bandpass Filter (7), which has a 22 MHz range centered on 190 MHz. This is then amplified in (8), a MiniCircuits Amplifier ZFL-1000LN, and split in the MiniCircuits Splitter ZFSC 2-1 (9). The split signal is sent to a sideband separating mixer composed of two mixers (10) and (12). The second input to the SSB is the output of a local osillator (14), a Keysight 9310A RF Signal Generator set to 190 MHz. The Keysight signal is split in the 90 degree splitter (15). The signal has now been shifted down to 0.4 mHz. The output from the SSB is passed through a variable bandpass filter (13), a Krohn-Hite Model 3202R Filter set to 2 MHz. Finally, the signal from the bandpass filters is collected using a pico Technology PicoSeries 2000 digital sampler.

2 Method

To begin we collected data to ensure that the equipment is working properly and to see that our signal was passing through the band-pass filters. Our emission signal lies at 1420.4 MHZ. Our first LO is set at 1230MHZ. Our second LO is set to 190 MHZ. This should result in mixing our signal down to a signal centered at 0.4MHZ.

$$\nu_{sig} = \nu_{HI} - \nu_{lo_1} - \nu_{lo_2} = 0.4Mhz \tag{1}$$

Since our expected signal is 0.4MHZ, it should not be filtered out of our 2MHZ band pass filter. Before we view signal the we check that our sampling rate is not too low. The pico sampler has a maximum sample rate of 62.5 MHz. This maximum rate can be reduced by adjusting the divisor parameter in the ugradio.pico.capture data() function. By passing an integer into divisor, we divide the maximum rate by that integer. From the resulting value, we must keep the associated Nyquist frequency sufficiently high. We set our divisor to 10. Our Nyquist frequency is equal to our max rate (62.5) divied by twice our divisor (10) which should be greater than our band-pass (2MHZ). We end up with a Nyquist frequency of 3.125 which is greater than 2MHZ.

2.1 Saturation

We adjust the volt range parameter in capture data(). This setting represents the range of amplitudes that the pico sampler will correctly read. Because the sampler has only 256 distinct sample levels [1], setting this value too high results in severely quantized data, while setting this value too low causes the readings to saturate the sampler. The data must also be converted from the raw integers reported by the sampler to millivolts, which we do using our function scale().We increment volt range until saturation is no longer visible. In Figure 2 we show how a setting of 200 mV affects the sampled signal.

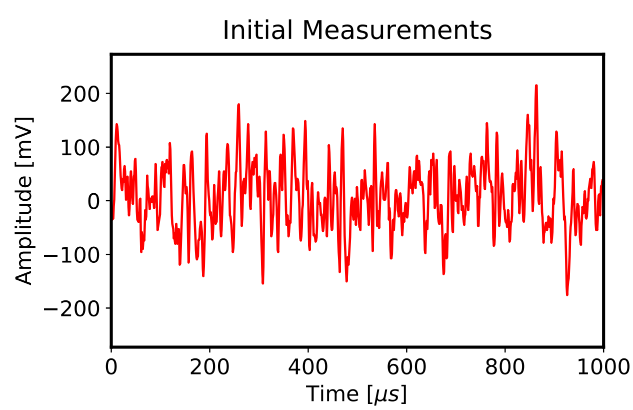

Figure 2: This is a figure of our first set of data collected to validate that we were within our specified voltage range and that we did not saturate the pico sampler.

2.2 Quantization

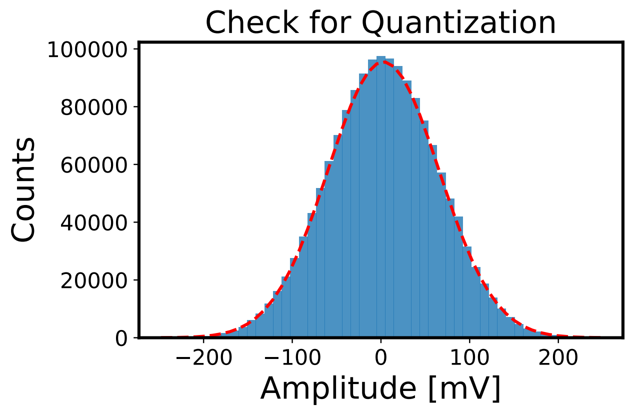

Figure 3: This is a histogram of our initial signal to see if we are in range of the pico sampler bit range

Our pico sampler has a limited number of distinct levels in which it outputs data. If we are using only a small subset of these levels, our data will exhibit severe quantization. We collected in total 99 blocks of data totaling 16,000 samples. From our figure 3 we do not see any quantization. We perform a least squares to a Gaussian distribution on the histogram using curve fit() from scipy.optimize. The fitted line closely matches our histogram, we conclude the noise we collect is mostly Gaussian. We are collecting large amount of data to be able to create a baseline which will allow us to reveal our low amplitude HI signal.

2.3 Noise Reduction

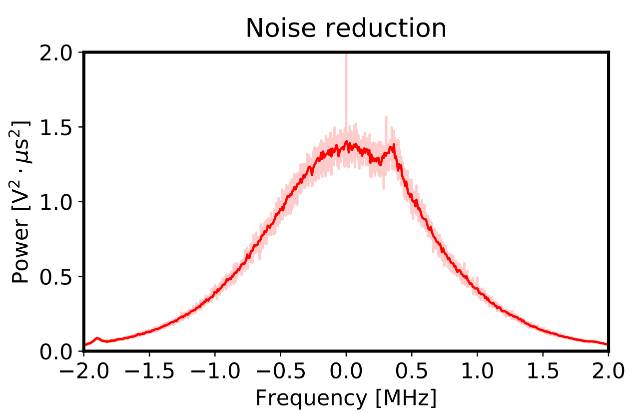

Figure 4: This is a power spectra of 99 data blocks. By breaking blocks of data into smaller chunks, we decrease both frequency resolution and noise.

Our HI signal we aim to view has a width of approximately 10kHz. Each bin in our frequency space has a width determined by the number of elements, and the sample rate. With 16000 elements in our frequency space, the width of each bin is

$$\Delta V = \frac{6.125MHZ}{16000} = 0.38kHZ \tag{2}$$

By decreasing the number of elements, we increase the width of each bin and decrease the resolution. We have our sample rate at a fixed value, and so we change the number of elements in each power spectra. Since our data comes in complex blocks of 16000 samples, the number of elements we change to must be a multiple of 16000. If we divide each block into 25 chunks of 640 elements, we arrive at a bin width of

$$\Delta V = \frac{6.125MHZ}{640} = 9.57kHZ \tag{3}$$

We collect 1000 blocks of data with the horn directed towards zenith. In Figure 4 we compare the effect of changing the number of chunks. With 25 chunks per block, the peak near 0.4 MHz is clearly defined, and the noise is reduced significantly.

3 HI at Zenith

For this section we are pointing the horn straight up to collect two sets of 1000 complex blocks. One set is collected with our dsb LO set to 190.8KHZ which will keep the HI signal in the upper sideband and another SSB LO set at 190.4MHZ which will move the HI signal to the lower sideband. This will give us an online signal and offline signal. By taking the lower sideband portion of the signal and appending it to the upper sideband portion of the signal we produce our offline shape in figure 5. We then take the lower sideband of the signal and append to it to the upper sideband of the signal to produce our online shape, Figure 6.

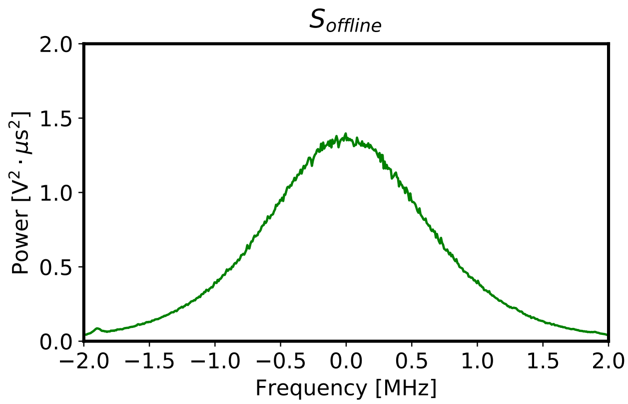

Figure 5: This is a figure of our offline signal by combining the lower sideband and upper sideband of two signals, we can derive the signal shape generated by our instrumentation noise. We use this to reveal the corrected shape of the HI signal.

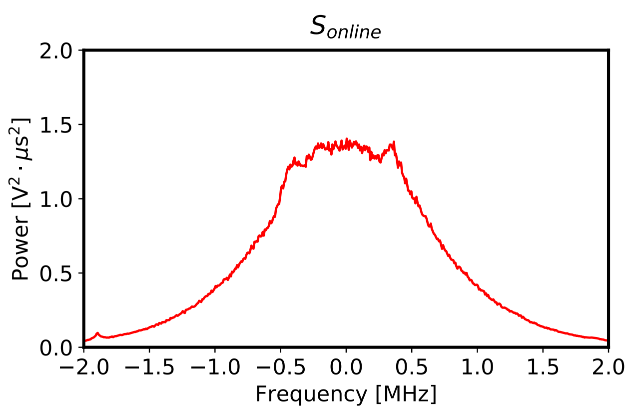

Figure 6: The uncorrected shape of the HI signal

3.1 HI shape

To find the corrected HI signal shape, we divide the uncorrected HI signal shape by the instrumentation shape:

$$HIShape = \frac{S_{online}}{S_{offline}} \tag{4}$$

The resulting shape in Figure 8 represents the relative strength of the HI signal compared to our instrumentation.

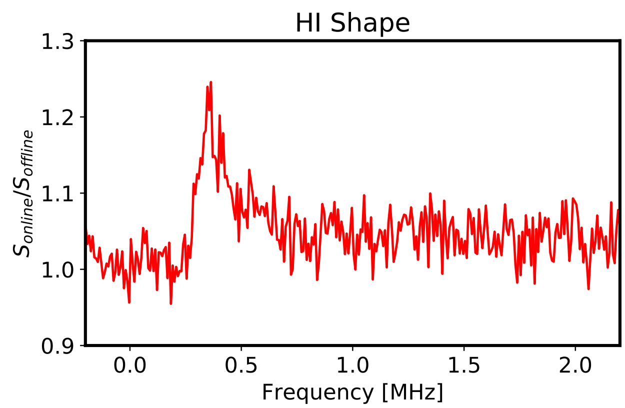

Figure 7: The shape of our HI signal. We divide the two extracted signal shapes, Sonline and Soffline and isolate the upper-sideband. The result is the shape of our HI signal.

3.2 Intensity Calibration

Now we can find the Intensity of our signal. We collect two sets of data each with the LO set to 1230MHZ. For one set we point at the zenith (s cold), and for the other we aim at two human beings (s-cal). Human beings are rather warm, around Tcal = 300 K. To find the intensity of the instrumentation we combine the S cold and S cal spectra.

$$G = \frac{T_{\text{sys,cal}} - T_{\text{sys,cold}}}{\sum(s_{\text{cal}} - s_{\text{cold}})} \sum s_{\text{cold}} \tag{5}$$

Here,$T_{\text{sys,cal}} = 300$ K, because that's the thermal power we injected by standing in front of the horn. Since $T_{\text{sys,cold}} \ll T_{\text{sys,cal}}$, to a first approximation you we neglect it. Then the final, intensity-calibrated spectrum is equation 6:

$$T_{\text{line}} = s_{\text{line}} \times G \tag{6}$$

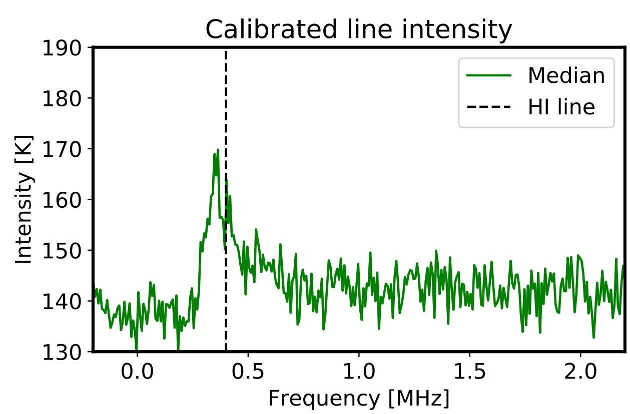

Figure 8: The calibrated shape of the HI signal

3.3 Hydrogen Velocity

Now we need to connect our observed frequency of our HI signal to a velocity. By convention, velocity away from the observer is positive, so

$$\frac{v_{\text{doppler}}}{c} = -\frac{\Delta f}{f_0} \tag{7}$$

Here c is the speed of light and our predicted frequency of the signal is f,0 1420.4MHZ, and f is the frequency difference:

$$v_{\text{doppler}} = -c\frac{f_0 - (1420 + freqs)}{f_0} \tag{8}$$

Next using ugradio.doppler.get projected velocity() we take into account the Earths motion and correct to the Local Standard of Rest (LSR), which takes the celestial coordinates where we are pointing the horn, the Julian date of the observation, and the coordinates of the observatory. we find that the velocity correction to be:

$$v_{\text{corr}} \approx -12.9kms^{-1} \tag{9}$$

When we add this correction to our vdop, we arrive at can plot the intensity of our HI signal versus velocity. We extract the velocity associated with the peak intensity of 179.0 K and find the observed source of hydrogen is moving away from us with a velocity:

$$v_{\text{HI}} \approx -36.8kms^{-1} \tag{10}$$

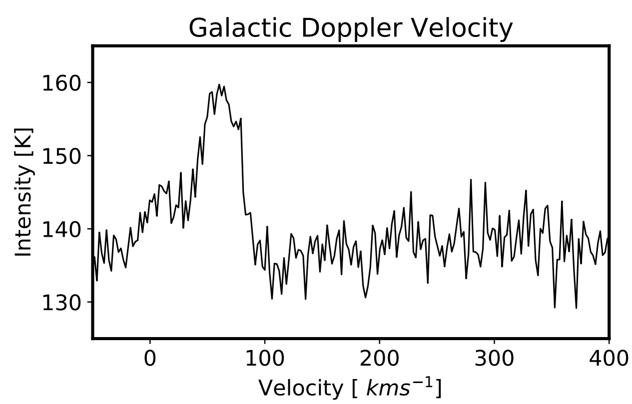

Figure 9: The shape and corrected velocity of the HI signal at zenith

3.4 Hydrogen in the Galactic center.

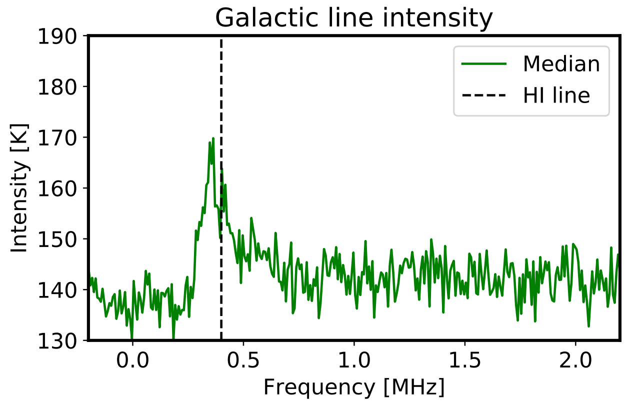

Figure 10: The adjusted Intensity of the galactic HI signal

Before collecting data we needed to know where to point our telescope. We had to convert the galactic coordinates of our galactic arms, (l, b) = (120,0), to local azimuth-altitude coordinates so that we could rotate and tilt the Big Horn. We covert coordinates via spherical rotation matrices located on the UGRADIO Github directory. We point the horn to the galactic coordinates (l, b) = (120,0) and collect 1000 blocks and find the calibrated HI signal shape, Figure 10.

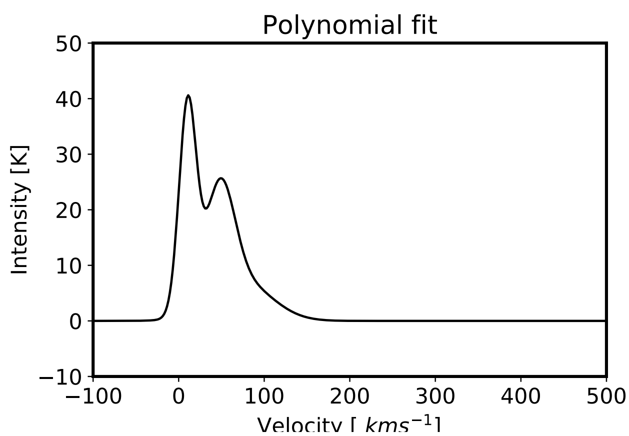

Figure 11: Polynomial fit using a least squares fit to our Galactic data

We perform a quadratic fit on the curved baseline present in the HI signal, using numpy.polyfit() and numpy.polyval(). By subtracting off this quadratic baseline and multiplying the shape by T sys, and T cold, we are able to construct an adjusted calibrated shape for our galactic HI signal with a new velocity correction:

$$v_{\text{corr}} \approx -15.4kms^{-1} \tag{11}$$

The galactic HI signal appears to have multiple peaks. We compute a least squares fit of a polynomial to the adjusted galactic HI signal shape, using ugradio.gauss.guassfit() in figure 12. The fitted polynomial in Figure 12 is the sum of three normal Gaussian distributions. There isn't just one distribution because they each represent portions of the gas cloud moving at different velocities. For each Gaussian we can extract the peak intensity, mean velocity, and a range of velocities 5.

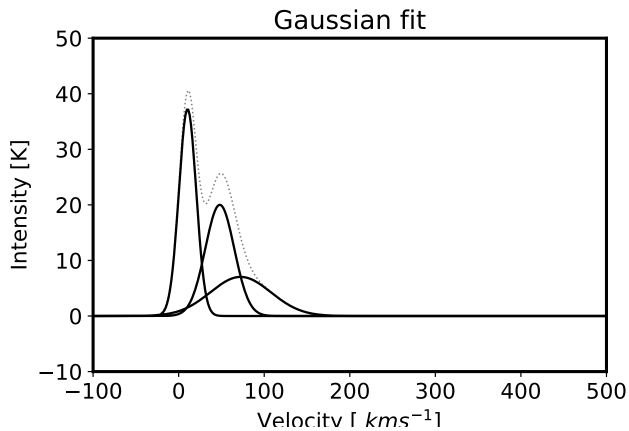

Figure 12: Gaussian distributions (black) and their sum (grey)

Intensity [K]	Mean Velocity [kms$^-$1]	Velocity Range [kms$^-$1]
38	10	0.3 - 20.5
20	50	31 - 65
8	75	37 - 107

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Conclusion

We analyzed HI signal data collected from zenith, adjusting for the instrumentation temperature and the velocity of the Local Standard of Rest. We repeatd this analysis on our HI signal data collected at coordinates in the galactic ecliptic. We were able to calibrate our instrument and create a usable signal. We learned how to manage large sets of data and use that to our advantage when dealing with noise while maintaining proper resolution. We were able to discern HI signal peaks near the frequencies that we knew. This was a real application of forming a hypothesis and testing it with numerical results. The most challenging aspect of this lab was knowing what to look for in the data and extrapolating it in a proper amount of time.

Distribution of Effort

This lab was rough to start with but with discussion with our classmates we were able to tackle it head on. Dr Parsons was able to help with the difficulties and Frank helped us with telescope questions. I guided data collection and provided sanity checks, Matthew helped with coordinate transforms, Oscar determined what would go in plots, and Roman created the code to collect and parse data. Our appropriate code can be viewed under our corresponding branches:

$$http : //github.com/arthurm101/radiolab/blob/Arthur/Lab_2 \tag{12}$$

References

[1] Pico technologies spec sheet. https://www.picotech.com/oscilloscope/2000/picoscope2000-specifications. Accessed: 2018-02-20.