Radio Lab

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Introduction

The purpose of this lab is to measure the neutral hydrogen in our Galaxy. We do this by taking measurements of the Galactic plane at various Galactic longitudes and measuring the HI line. The parameters of interest for the HI line are the observed central velocity of the signal, the width of the signal, and the amplitude of the signal. To measure these parameters, we fit a Gaussian to our HI data. We also determine the velocity of our observatory in the direction of the signal at the time of observation and the observed velocity in the local standard of rest. As we increase Galactic longitude away from the Galactic center, we expect to see an increase in the centroid velocities.

Procedure

We used the provided laptop to carry out calibration observations. We connected the LNA to the RTL-SDR dongle using a long coax cable. The SDR was connected to the laptop via a USB cable (we attached the 50-ohm resistor to the other end of the SDR for some parts of the calibration), and at the other end of the setup, we attached the 50-ohm resistor to the LNA. We removed the LNA from the system completely when using the bunny-ear dipole to calibrate the NOAA radio signal, just connecting the bunny-ear dipole to the SDR with a coax cable. For observing on the sky, our setup consisted of the radio dish, the mounting structure, tripod, and feed. On the laptop end, we connected the SDR to the laptop via USB as before. We connected the LNA to the telescope via the big-to-little adapter, then linked the LNA to the SDR with a coax cable.

We started by taking basic calibration data on November 12, 2020. First, we took five one-second darks with the 50-ohm resistor off of the SDR. We then took the same number of darks with the 50-ohm resistor on. Next, we took one 300-second dark with both the 50-ohm resistor on and off. We increased the timeout factor by steps of one until we reached a timeout factor of seven. Calibration data with the resistor off was also taken in the same way. We then attached the LNA to the SDR dongle with the coax cable and took the same calibration measurements both with and without the 50-ohm resistor attached.

Next, we take frequency calibrations of our antenna. We attached the dipole antenna to the RTL-SDR and used the python script on the computer to take frequency calibration measurements. We repeated this process ten times and found a frequency correction of 3.

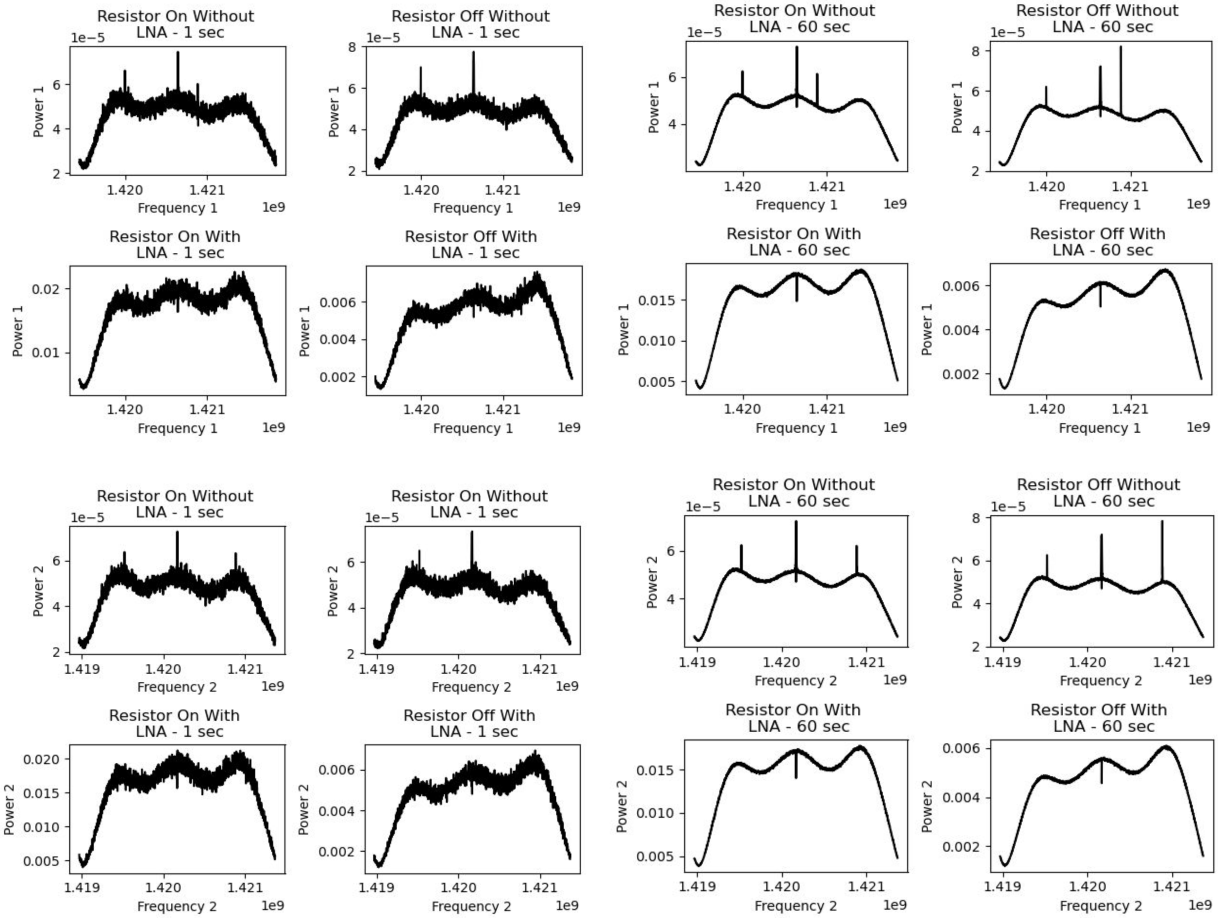

Figure 1 — Calibration data plotted both with LNA on and off. The top eight plots are the frequency and power 1 calibrations. The bottom eight plots are the frequency and power 2 calibrations.

It is clear that the one-second exposures are noisier than the 60-second exposures. This is evident by looking at the first two columns in Figure 1 which resemble the one-second exposures. For both exposures, the curve at the higher end of the frequency is lower without the LNA. Comparing Power 1 to Power 2, it is clear that the lines between the two spectra appear at different frequencies.

We also plotted the frequency switching data. In Figures 2 and 3, we show the frequency switching spectra for each observing configuration (with and without the LNA, and with and without the resistor in the system). The spectra averaged over 60 seconds show a lot less noise than the 1-second scans. The resistor also removes some of the vertical scatter from the spectra. When the LNA is not included in the system (Figure 2), two bright lines (one positive, one negative) dominate the spectra. When the LNA is included in the system (Figure 3), the overall shape of the spectrum bandpass is a lot more visible.

The frequency-switched spectra differ from the non-frequency-switched spectra primarily by the shape of their bandpasses. Especially without the LNA in the system, the frequency-switched bandpass is quite flat, whereas the non-frequency-switched spectra show much more of the bumpy bandpass structure inherent from the telescope.

When we set up our telescope outside, we followed the procedure described in section 1.6 of the lab handout. Our observations were taken using the parameters described in section 2.2 of the lab handout. Our observing log is shown in Table 1.

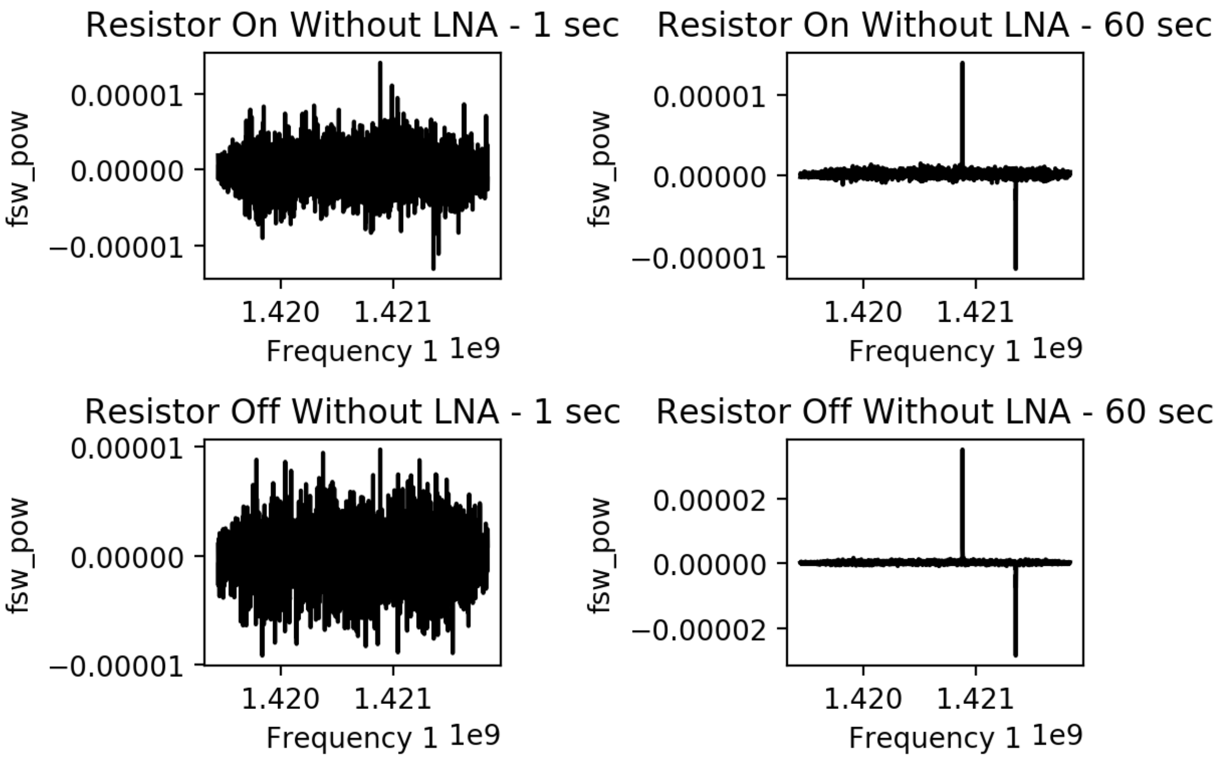

Figure 2 — Frequency switching spectra for the calibration scans without the LNA in the system. The spectra on the left are for the 1-second scans, and the spectra on the right are for the 60-second scans. The spectra on top are for the scans with the resistor in the system, and the spectra on the bottom are for the scans without the resistor.

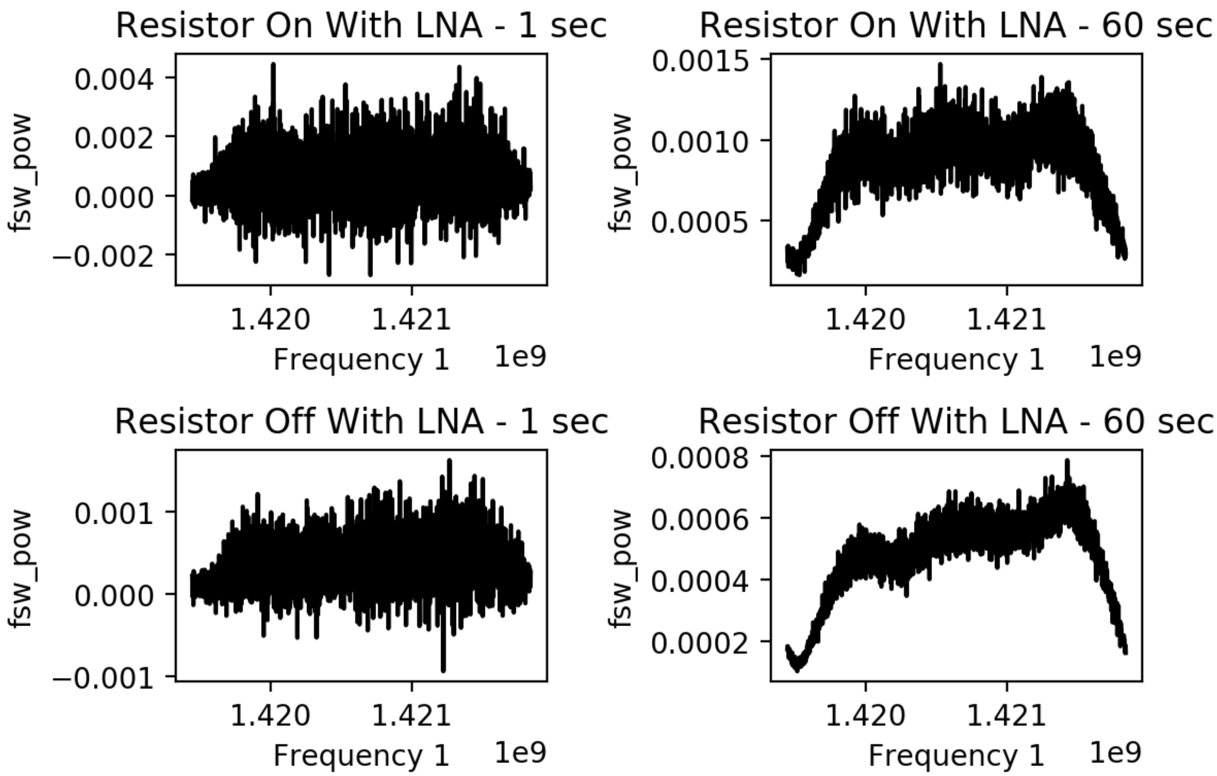

Figure 3 — Frequency switching spectra for the calibration scans with the LNA in the system. The spectra on the left are for the 1-second scans, and the spectra on the right are for the 60-second scans. The spectra on top are for the scans with the resistor in the system, and the spectra on the bottom are for the scans without the resistor.

Observing Log

Name	Observation time (Nov. 13)	Altitude	Azimuth	Galactic longitude (approx)	Galactic latitude (approx)	Integration time (s)
Science_loc1	1:37 PM ET	27°	163°	–1°	–1°	60
Science_loc2	1:46 PM ET	44°	143°	+23°	0°	60
Science_loc3	1:52 PM ET	49°	139°	+28°	+1°	60

Table 1 — Observing log for our observations of the Milky Way. The "name" column refers to the filename ending for each location along the Galaxy. The time of the observation on November 13 was recorded, along with the altitude and azimuth of the pointing as measured by Francisco using the Sky Portal app. Each observation was 60 seconds. The galactic longitude and latitude were approximated using Stellarium (method described on this site: https://www.astroleague.org/content/converting-altaz-coordinates-equatorial).

Data Analysis

Gain Calibration

Using a Jupyter Notebook provided to us by Nick Barth, we report a gain measurement of 4.4626444×10^{15} Hz^{-1} J^{-1}. This value was obtained by taking the Sun's location and determining how close the telescope was pointed towards it. Knowing that the temperature of the Sun is T=5500K and the beam size is 9.2 degrees, we have a filling factor of 0.005. The expected noise of the Sun is 29 K. The following equation is then used to calculate the system temperature.

$$T_{sys,sun} = T_{rec} + T_{CMB} + T_{sun}$$

Where T_{rec} is the receiver temperature, T_{CMB} is the temperature of the Cosmic microwave background, and T_{sun} is the temperature of the Sun. Two observations were taken; one at 29K and one at 0K. This is used to determine the gain of the system. Gain is given by the following equation and we find that the value for gain as stated above.

$$G = \frac{P_{sys,sun,v} - P_{sys,no\ sun,\ V}}{T_{Sun}K_B}$$

This acts as our calibration that we will use to convert our measurements from relative amplitude to intensity measurements. We converted to brightness temperature using code from Nick's notebook. This was done by finding the system temperature, T_{sys} , specifying the power of the antenna when observing away from the Sun,

$$T_{sys} = \frac{P_{sys,no\ sun,\ V}}{GK_B}$$

which produces a value of 94.66 K. Then the system temperature with the Sun, which gives a value of 123.74 K. Using $T_{sun} = T_{A,Sun} - T_{sys}$ to find an inferred solar contribution of 29.09 K. To convert to system temperature, multiply the power-per-frequency by 1/GK_B. Finally, to get the spectrum in brightness temperature units, the observed power-per-channel is divided by the gain times the Boltzman constant as shown in the following equation.

$$T_B = \frac{P_V}{GK_B} = \frac{P}{G\Delta K_B}$$

Fitting the Neutral Hydrogen Signal

For each spectra we determine the observed centroid frequency, its width, its amplitude, the uncertainty of each of these parameters, the velocity of our observatory at the time of the observation, and the observed velocity of the in the local standard of rest.

The data analyzed is the frequency switched science data. We measure the centroid velocity of the signal by fitting a Gaussian to the HI peak as shown below. To accomplish this, we cut around our original data where the signal peaks, to avoid complicated fitting methods. For the first science scan, we find an amplitude of 12, a mean value of 1.4, and a sigma of 5×10^(-5). We estimated the standard deviation in the signal level by eye in a flat area of the baseline for each of the science scans. We used those values as our uncertainties on the amplitudes of the signals. We use the sigma value from our Gaussian fit as the uncertainty in our centroid frequencies. Our power versus frequency (for power 1 and power 2, the two components to the frequency-switching data) and frequency-switched spectra are shown in Figures 4, 5, and 6.

The Gaussian fitting to the first science scan went relatively well. This is shown in Figure 7. However, the Gaussian fits for scans 2 and 3 are not Gaussian as shown in Figure 8 and 9. This is most likely due to the poor baseline. For the first science scan, the baseline was relatively close to the zero y-value. However, for the second and third science scan, the baseline had a higher y-value on the lower end of x-axis. This led to poor fitting of science scans 2 and 3.

Conversion from Signal Frequency to Radial Velocity

We converted our centroid frequencies to our centroid velocities as follows:

$$v = (\upsilon_{HI} - \upsilon_{centroid}) / \upsilon_{HI} \times c$$

Here, v represents our centroid velocity, υ_{HI} represents the rest frequency of the neutral hydrogen line (1.420405752 GHz), $\upsilon_{centroid}$ represents our centroid frequency as measured by our Gaussian fitting, and c is the speed of light. Our converted values for the centroid velocities are shown in Table 2. However, these velocities may not correspond to the Galactic component of the HI signal, as in each scan, a "local cloud" component may dominate the signal that we see (Adam Ginsburg, personal correspondence).

Scan (G. long.)	**Amplitude (K)**	**Centroid frequency (GHz)**	**Sigma (GHz)**	**Centroid velocity (m/s)**	**Barycentric velocity (m/s)**	**LSR velocity (km/s)**
1 (–1°)	12 ± 2	1.42033	5×10^(-5)	15321	–1970	8.6
2 (+23°)	13 ± 3	1.42030	–9×10^(-5)	22051	1197	16
3 (+28°)	14 ± 2	1.4203	0.0001	22996	2263	18

Table 2 — Amplitude, centroid frequency, and sigma of the HI line for the 3 science scans. Also included are the centroid velocities derived from our centroid frequencies, as well as the derived barycentric and LSR velocities.

Barycentric Velocity and LSR Velocity

Using code from Adam Ginsburg, we used our measured velocities as well as our observing directions to convert the observed velocities to velocities in the local standard of rest (LSR) frame. For each pointing, we calculated the Earth's velocity in that direction, and added that velocity to our line of sight velocity to calculate the barycentric velocity (velocity with respect to the center of the Solar System) corresponding to each observation. Then, we transform the barycentric velocities to velocities with respect to the local standard of rest, which represent the signal velocities with respect to the Sun's neighborhood in the Galaxy. These values are shown in Table 2.

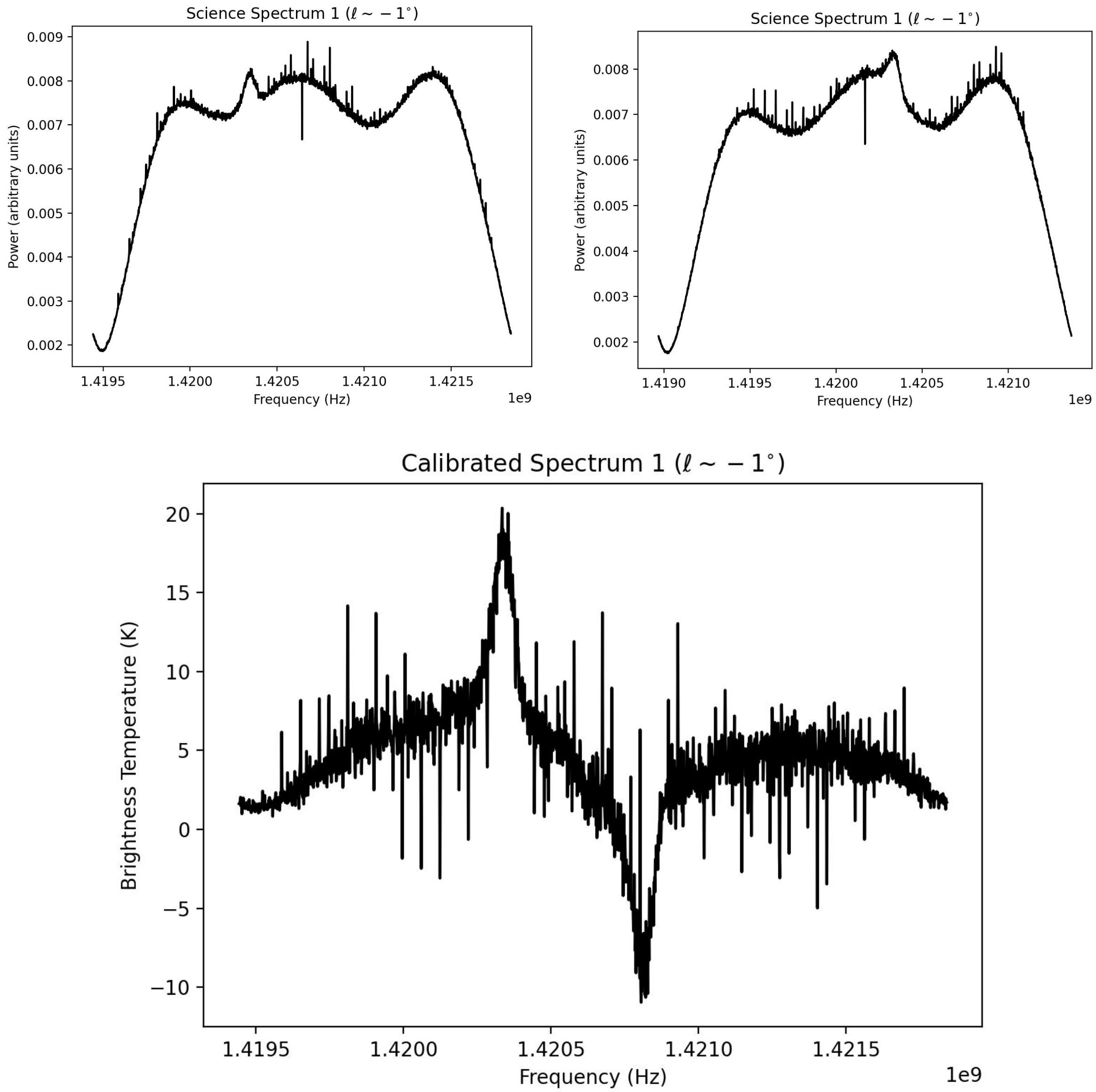

Figure 4 — Power versus frequency (left; power1 vs. freq1) and frequency switching (right) spectra for science scan 1 (at –1° Galactic longitude).

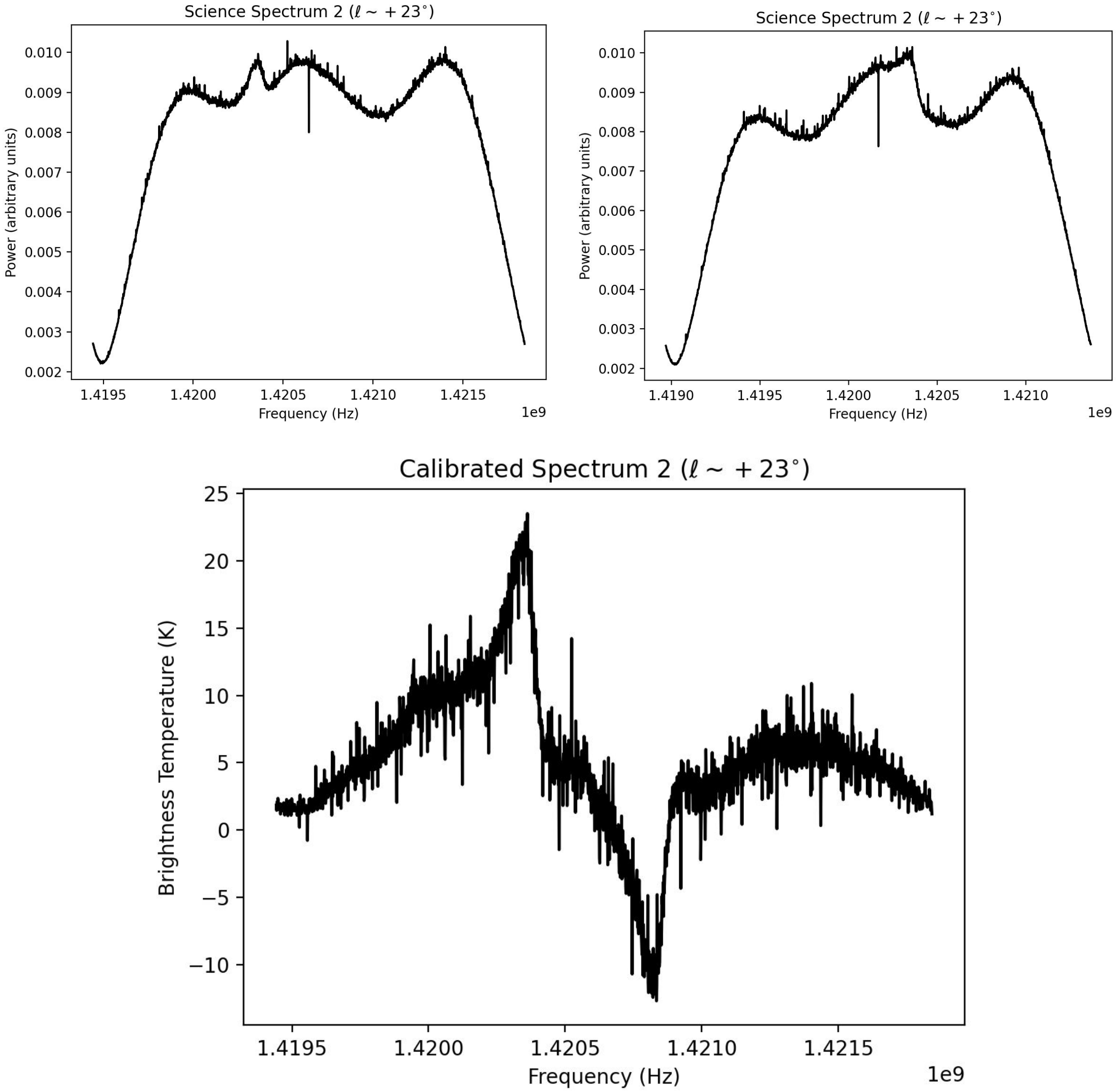

Figure 5 — Power versus frequency (left; power1 vs. freq1) and frequency switching (right) spectra for science scan 2 (at +23° Galactic longitude).

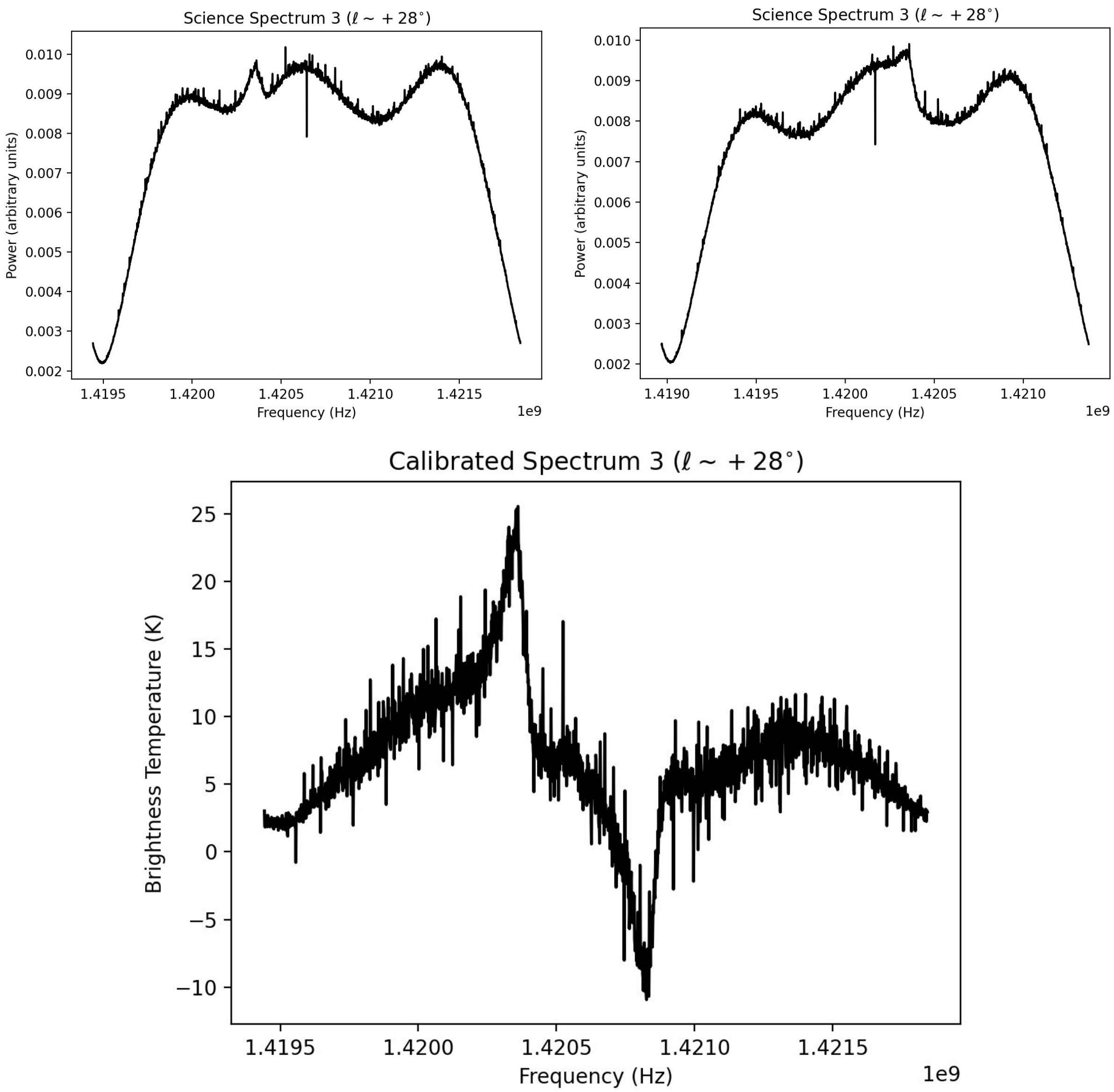

Figure 6 — Power versus frequency (left; power1 vs. freq1) and frequency switching (right) spectra for science scan 3 (at +28° Galactic longitude).

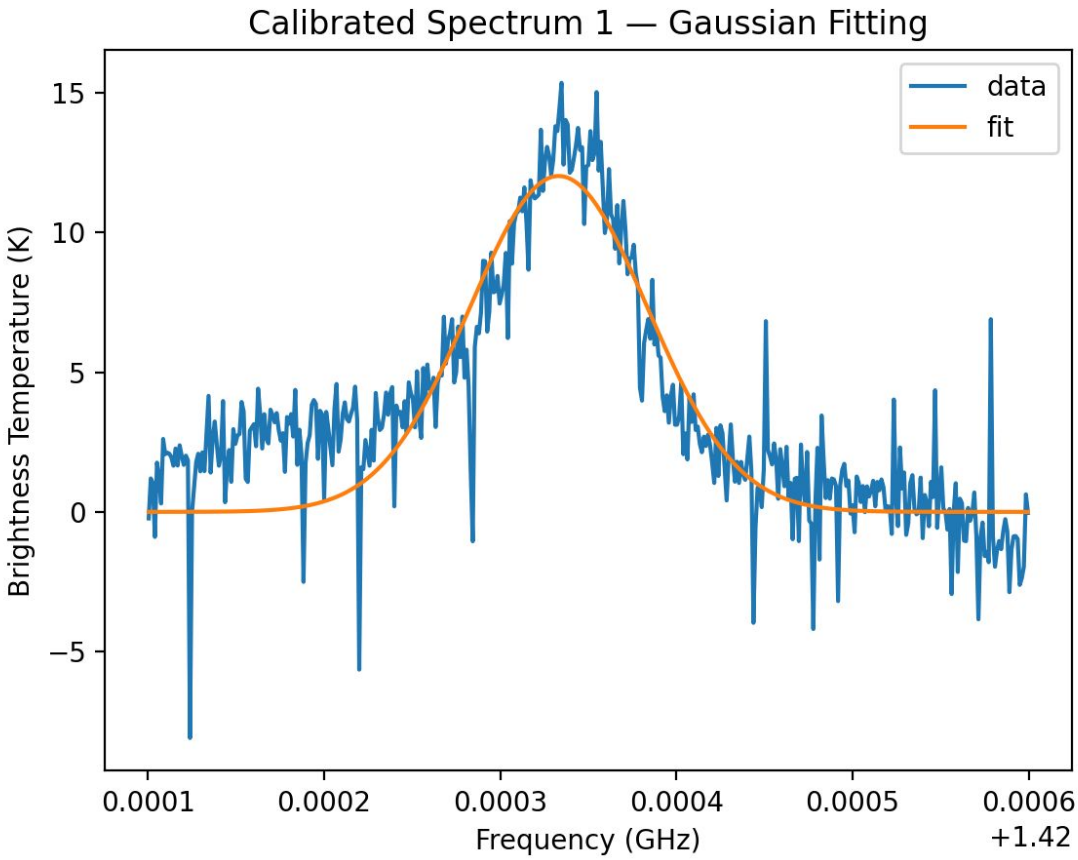

Figure 7 — Gaussian fit for our first science scan. Note the change in scale on the x-axis (GHz, versus Hz in previous plots). This scaling allowed the fit to converge successfully.

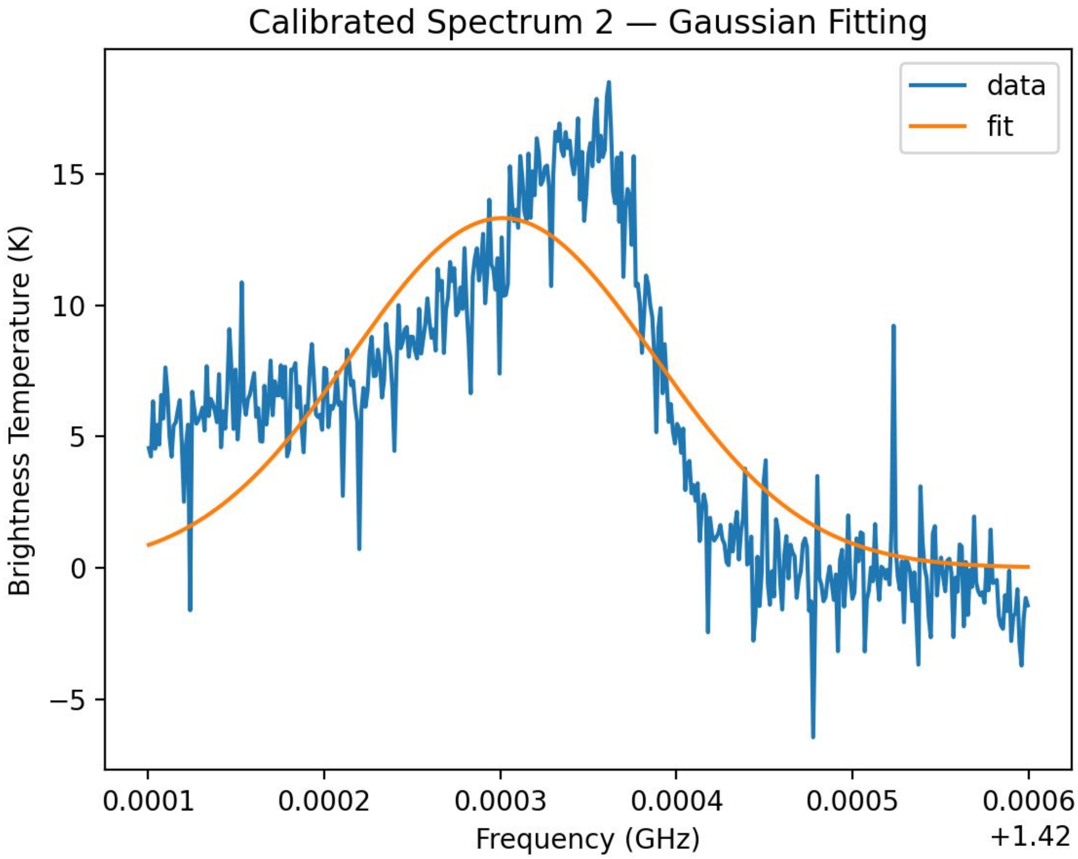

Figure 8 — Gaussian fit for our second science scan. Note the change in scale on the x-axis (GHz, versus Hz in previous plots). This scaling allowed the fit to converge successfully. Due to a shift in baseline level on either side of the peak, the fit is not a good fit.

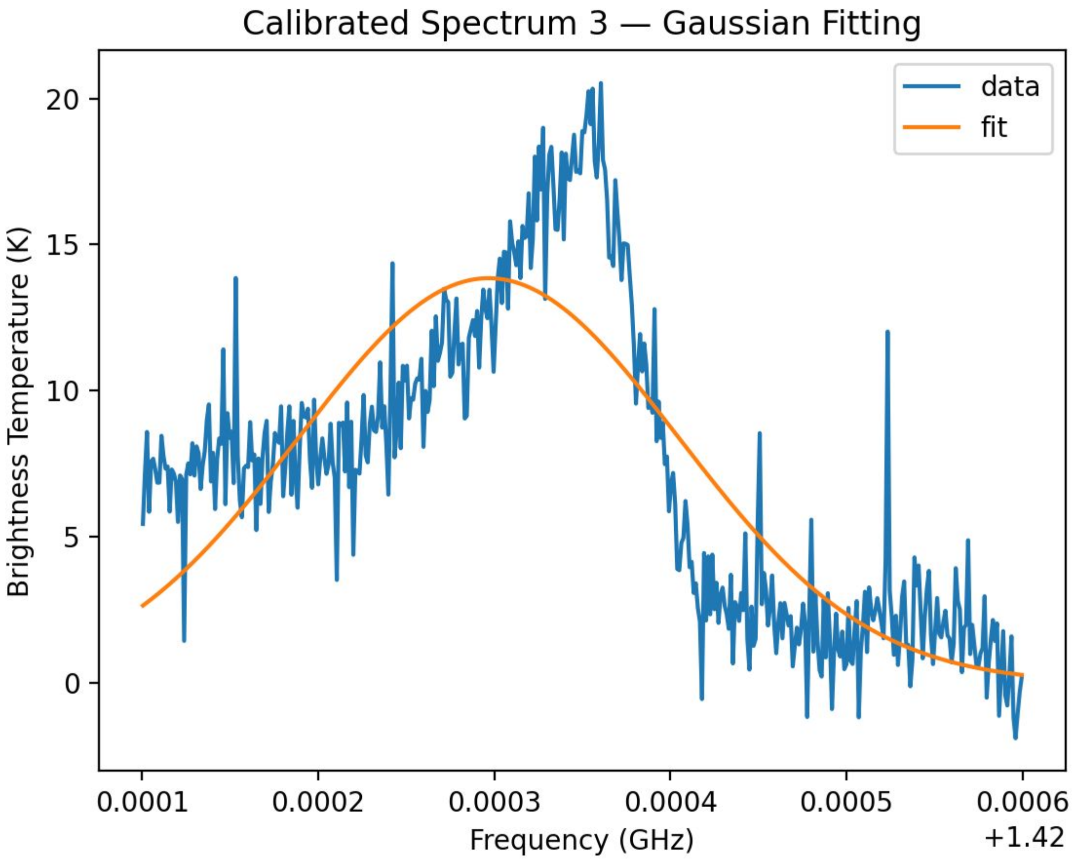

Figure 9 — Gaussian fit for our third science scan. Note the change in scale on the x-axis (GHz, versus Hz in previous plots). This scaling allowed the fit to converge successfully. Due to a shift in baseline level on either side of the peak, the fit is not a good fit.

Data

The data Francisco collected have been submitted with this writeup along with a README file and our observing log.

Conclusions

In this lab we attempted to measure the neutral hydrogen in the Milky Way Galaxy. We first calibrated our radio telescope by taking basic calibration measurements as well as frequency calibrations. Our observations were taken November 13th outside the Bryant Space Science Center.

Using solar data, we find a gain of 4.4626444×10^{15} Hz^{-1} J^{-1}. This allowed us to convert our relative amplitude measurements to intensity measurements in brightness temperatures. We then measured the centroid velocity and amplitude of our frequency switched science data by fitting a Gaussian to the HI line. We measure for Galactic longitudes at -1, +23 , and +28 degrees respectively for science scans 1,2, and 3 respectively. We find an amplitude of 12, 13, and 14 K. The centroid frequencies were found to be 1.42033, 142030, and 1.4203 GHz. These two parameters were similar which is not something we would expect while measuring at different Galactic longitudes. However, the three centroid velocities, barycentric velocities, and LSR velocities did vary somewhat. We find the centroid velocities to be 15321, 22051, and 22998 m/s; the barycentric velocity to be -1970, 1197, and 2263 m/s; and the local standard of rest velocities to be 8.6, 16, and 18 km/s.

One problem with our data could be that the HI signal we think we are observing is not the bulk of what we are actually observing. In each direction on the sky, there is some local HI cloud component in the signal that we observe. This signal from the local clouds would be difficult to separate from the signal from the Galactic arm that we wish to measure. The results we would hope to see would be a steady increase in radial velocity as we increase Galactic longitude away from the Galactic Center. In our centroid velocities, we do see this behavior. So, despite our lack of accounting for any local cloud component, we can still recover the general behavior of the Galactic rotation curve close to the Galactic Center.