AST3003S Observational Project

Measuring the Rotational Velocity of the Galactic Plane Using HI Gas 1.4 GHz Emission

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September 2024

1. Introduction

In this project you will be using the Tony Fairall Teaching Observatory's (TFTO) sister radio telescope located in Tallarook Australia to take spectra at various points along the galactic plane. You will be responsible for determining the visibility of your selected coordinates and planning your observations accordingly.

After obtaining your data through multiple acquisitions, you will need to stack your data into one single spectrum. At this point, you will use calibration data taken from a source of known brightness to determine a brightness temperature scaling factor for the telescope. Using this information, you will then determine the brightness temperature of your spectra.

Next, you will use a provided Python script which utilizes Astropy to correct your observed frequency using the local standard of rest (LSR) velocity. At this point you will change your frequency plot to one of radial velocity.

Finally, using your calibrated spectra with an HI profile obtained from the Leiden/Argentine/Bonn (LAB) survey, you will determine the maximum rotational velocity at your chosen galactic coordinates, together with the distance of that velocity from the galactic center. This information will then be shared with your peers, to create a more complete plot of the galactic rotation curve.

2. Method

2.1. Planning Your Observations

You will be expected to choose three galactic longitude coordinates to observe with your groups. Once you have selected your coordinates from the spreadsheet (at least one per column available), enter your group number in the space provided on the linked spreadsheet (4.1).

Observations will be done remotely from UCT in RW James in the meeting room outside Frahn Library together with your groups. Observations will be possible from Monday the 16th until Friday the 20th of September from 10:00 until 14:00. You will need to make an appointment to observe. To make an appointment, first check the time schedule (4.2) to see available times, then email me (bret.yotti@uct.ac.za) to schedule your appointment. You should plan approximately 60 to 75 minutes for your observations. On the day of your observation, make sure you check the weather conditions. While the radio telescope can function day or night and in clouds or rain, it is not able to function in winds greater than 50 kph. There are many websites available to check these conditions, but I would recommend the site Windy (4.3).

2.2. Using the TFTT Radio Telescope

After connecting to the remote computer, you will open the software. You should be familiar with the layout and sections of the software from the user manual. For this project, we will be using the tabs "OnOff" and "Environmental Data".

Figure 1: RadioUniversePRO wind sensor control panel

The first thing to do is connect the software to the weather station, mount and receiver. Make sure that you connect the weather station first, as the telescope is programmed to automatically stow should the wind speeds reach a certain level. This is done in the Environmental Data tab (Figure 1). After connecting you will be able to see useful wind data such as current/max speed and direction, as well as a plot of these over time.

The mount control panel is found on the left side of the software. After clicking connect, you will see the Actual Antenna Coordinates populate (Figure 2). If the telescope was stowed, this will read an altitude of 270° and an elevation of 90°.

Figure 2: RadioUniversePRO mount control panel

The receiver controls are found on the right side of the screen (Figure 3). First click "Connect to Backend", then wait a moment until the receiver connects. When it's ready, you will be able to click "Start Acquisitions".

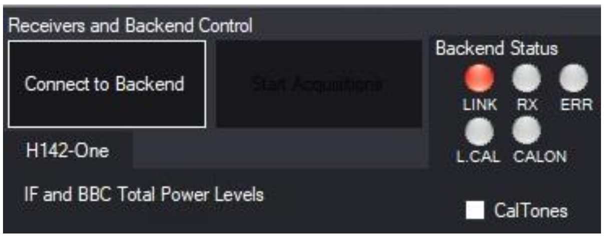


Figure 3: RadioUniversePRO receiver control panel

At this point, you should be able to see both the power spectrum and the FFT waterfall on the IF Monitor tab (Figure 4). For this project, we will only be using the left polarization data. This will be important to remember later when using your data.

Now that you've connected the devices you should be ready to point the telescope and acquire your data. The last thing you'll need to do, is to click on the flashing orange "UNPARK" button on the mount control panel.

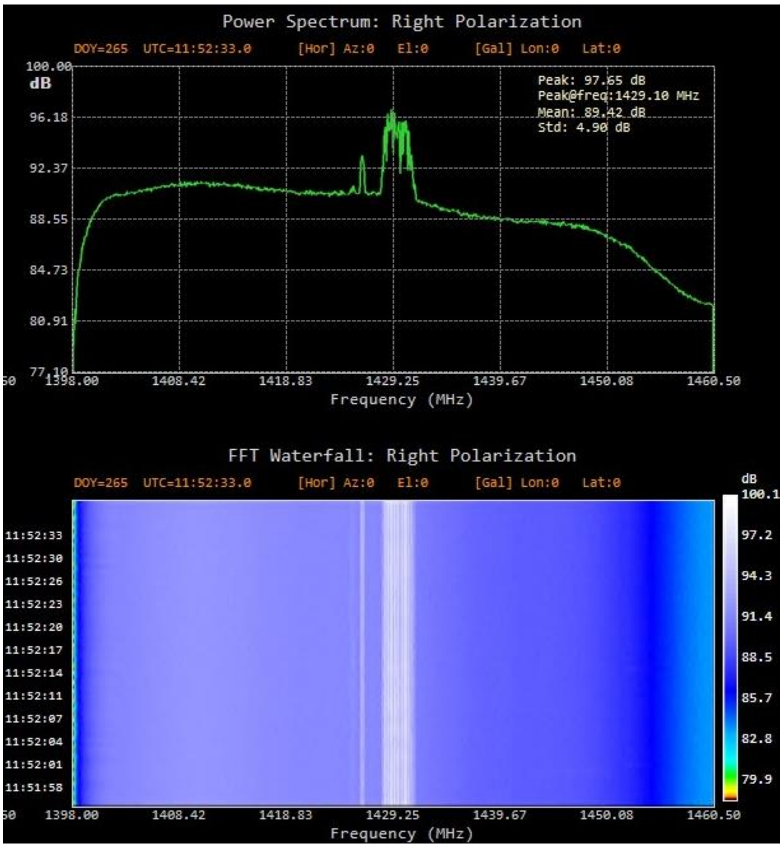


Figure 4: RadioUniversePRO right polarization IF monitor

There are multiple ways of pointing the telescope, but for this project we are going to be using the command window found on the bottom of the screen. The left side of the screen is where you can enter commands, and the right gives a running update on the telescope and what the mount is doing

(Figure 5). The command we need for our purposes is `source=gal,330,0` which will tell the telescope to point to a source at galactic coordinates $l = 330, b = 0$. After entering the command in the left window, the right will read "`antenna slewing…`" and you will be able to see the actual antennal coordinates (Figure 2) changing as the telescope moves. When the telescope is finished, you will see this change first to "`approximating to target`" and then finally "`antenna acquired!`".

NOTE: It sometime happens that the telescope gets stuck on the "`approximating to target`" step. If you see this message repeating for over a minute, reenter your command to point the telescope.

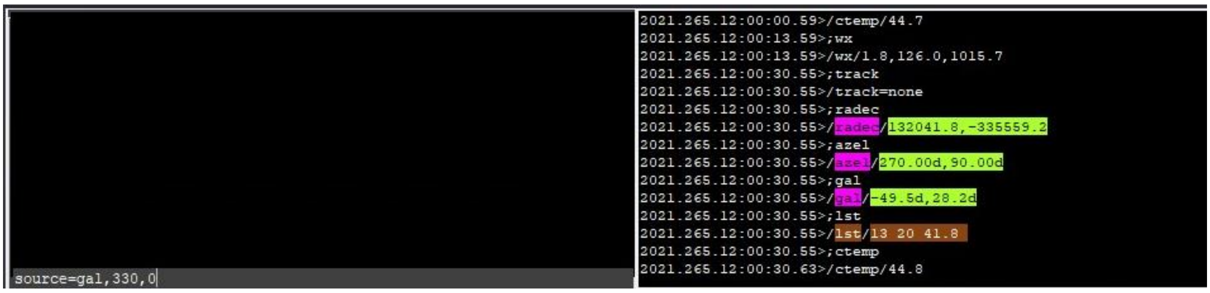


Figure 5: RadioUniversePRO command input and log windows

Before starting your acquisitions, you'll want to adjust the digital gain (Figure 6) to a level that increases the total power while not clipping any parts of your spectrum (Figure 4). After this final adjustment, you're ready to acquire your data.

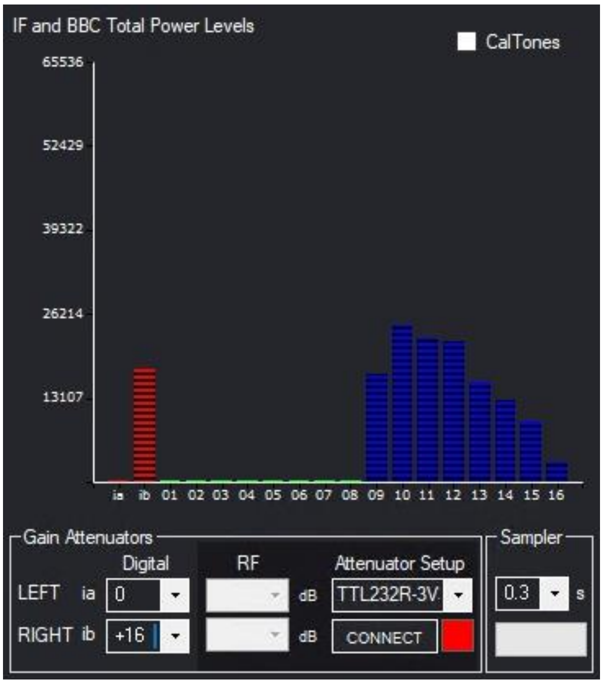


Figure 6: RadioUniversePRO power levels and gain control window

For data acquisition we will be using the tab OnOff. You enter your OnOff parameters in the section on the top left the screen (Figure 7). You will want to use the maximum number of repetitions, 10, and the maximum acquisition time, 10 seconds.

Normally when using this feature, the telescope will acquire an “on” spectrum, and then move a certain number of beam widths away from the target and take an “off” spectrum which it will then use to create a new calibrated spectrum. However, for this project we want to maximize our time on target. This means we will set the distance to 0, which will allow us to use both on and off spectra when stacking our data.

Finally, make sure you have the box “Save FITS Spectra” ticked. When ready, hit the “Confirm setup” button followed by “Start OnOff”. You will now see the phase bar filling up during each acquisition, and the overall bar filling after each acquisition. When the status at the bottom reads “Ready!”, the process has been completed. Your data will automatically be saved in the “RadioUniversePRO Data” directory in a folder with the acquisition date. Remember to repeat this process at least 3 times to get a total on target time of 600 seconds.

If you have another target which is currently visible, you can now enter a new pointing command into the bottom window (Figure 5). If you are finished with your observing, then click on the “PARK” button on the mount control panel and wait until the status window reads “`antenna acquired!`”, and actual antenna coordinates again show 270° azimuth and 90° elevation. Finally make sure you disconnect the mount, stop and disconnect the receiver, and disconnect the weather station. After this, make sure you go back to the web browser and turn off the power all three devices (**Error! Reference source not found.**).

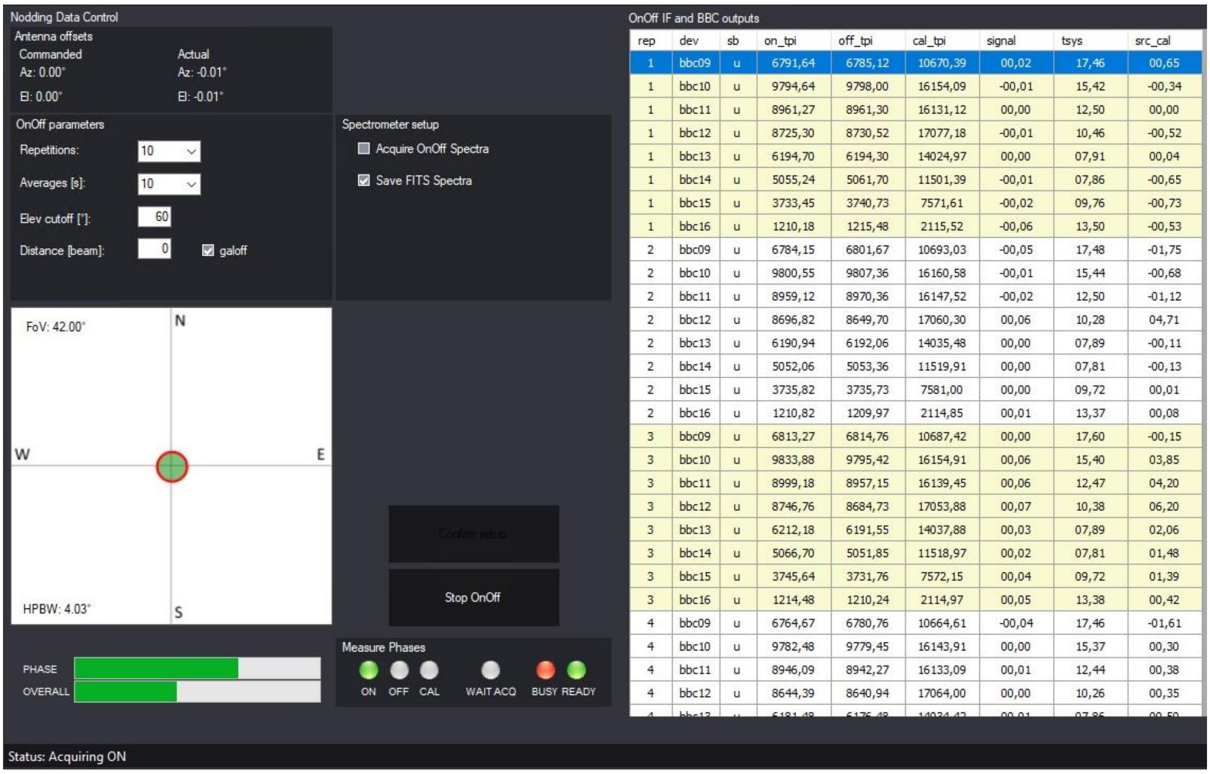


Figure 7: RadioUniversePRO OnOff acquisition window

2.3. Extracting the Spectra from the Data

To get an idea of the structure of your FITS table data, there are multiple software packages available. One of these, is the free NASA software fv (4.4) available for all operating systems. Using this, after opening your file, you will be able to view the FITS header (Figure 8) of your data where you will find important details needed in your project such as beam width, observed frequency, bandwidth and location details.

Additionally, you can also use the "All" feature (Figure 9) to see the full structure of the file. For this project, we'll be interested in the columns "LEFT_POL" and "STATUS". This is where our spectral data is found.

You will notice that there are many rows containing useful information. The column marked status will tell you whether that data was collected when the telescope was pointed on the target, off the target, or whether it was a calibration image. Because we set up our telescope in the previous section to not move between the on and off phases, we will be interested in both of these when combining our collected spectra, while ignoring the calibration rows.

An additional thing you may notice is the option "Plot" in the "RIGHT_POL" column. Clicking on this will give you a preview of the data with the ADU readings on the y-axis, and the channel on the x-axis.

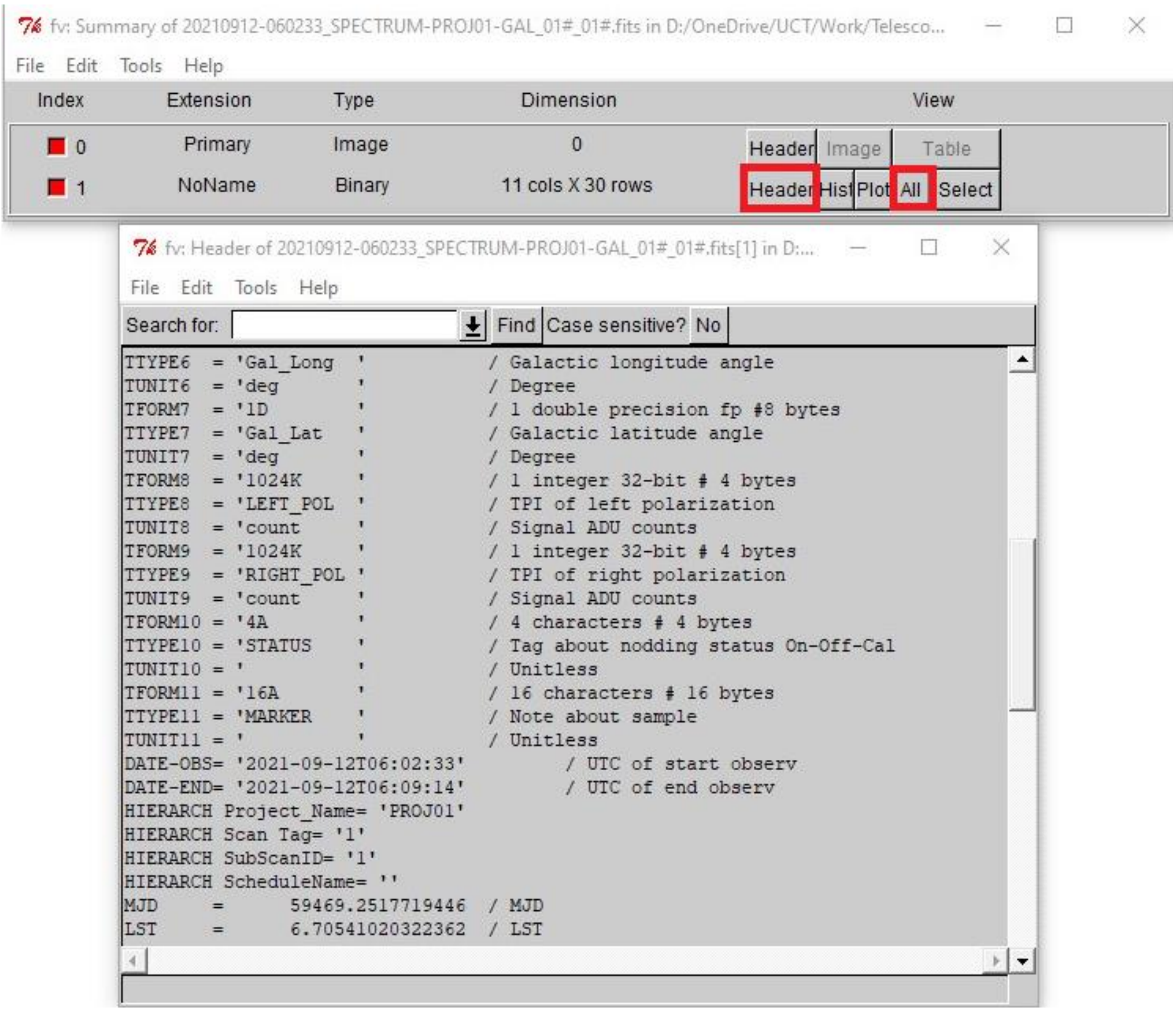
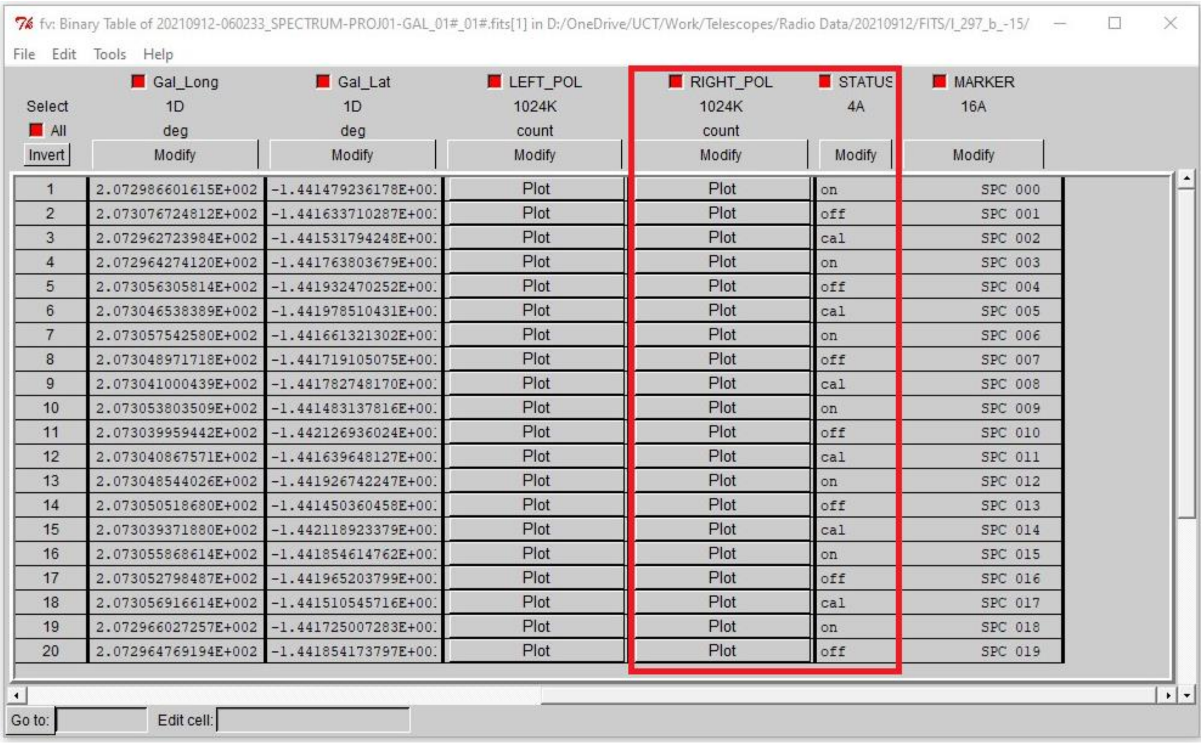


Figure 8: fv displayed FITS header



fv: Binary Table of 20210912-060233_SPECTRUM-PROJ01-GAL_01#_01#.fits[1] in D:/OneDrive/UCT/Work/Telescopes/Radio Data/20210912/FITS/l_297_b_-15/

File Edit Tools Help

Select	Gal_Long	Gal_Lat	LEFT_POL	RIGHT_POL	STATUS	MARKER
	1D	1D	1024K	1024K	4A	16A
All	deg	deg	count	count		
Invert	Modify	Modify	Modify	Modify	Modify	Modify
1	2.072986601615E+002	-1.441479236178E+00	Plot	Plot	on	SPC 000
2	2.073076724812E+002	-1.441633710287E+00	Plot	Plot	off	SPC 001
3	2.072962723984E+002	-1.441531794248E+00	Plot	Plot	cal	SPC 002
4	2.072964274120E+002	-1.441763803679E+00	Plot	Plot	on	SPC 003
5	2.073056305814E+002	-1.441932470252E+00	Plot	Plot	off	SPC 004
6	2.073046538389E+002	-1.441978510431E+00	Plot	Plot	cal	SPC 005
7	2.073057542580E+002	-1.441661321302E+00	Plot	Plot	on	SPC 006
8	2.073048971718E+002	-1.441719105075E+00	Plot	Plot	off	SPC 007
9	2.073041000439E+002	-1.441782748170E+00	Plot	Plot	cal	SPC 008
10	2.073053803509E+002	-1.441483137816E+00	Plot	Plot	on	SPC 009
11	2.073039959442E+002	-1.442126936024E+00	Plot	Plot	off	SPC 010
12	2.073040867571E+002	-1.441639648127E+00	Plot	Plot	cal	SPC 011
13	2.073048544026E+002	-1.441926742247E+00	Plot	Plot	on	SPC 012
14	2.073050518680E+002	-1.441450360458E+00	Plot	Plot	off	SPC 013
15	2.073039371880E+002	-1.442118923379E+00	Plot	Plot	cal	SPC 014
16	2.073055868614E+002	-1.441854614762E+00	Plot	Plot	on	SPC 015
17	2.073052798487E+002	-1.441965203799E+00	Plot	Plot	off	SPC 016
18	2.073056916614E+002	-1.441510545716E+00	Plot	Plot	cal	SPC 017
19	2.072966027257E+002	-1.441725007283E+00	Plot	Plot	on	SPC 018
20	2.072964769194E+002	-1.441854173797E+00	Plot	Plot	off	SPC 019

Go to: Edit cell:

Figure 9: fv displayed FITS table

Now that you've collected your data, have the information from the FITS header and you have an idea of what your data looks like, it's time to extract the spectral data from the FITS file and stack each spectrum to create your final noise-reduced spectrum.

To read the FITS file into Python, you will be using the Python module Astropy. This is pretty straight forward and similar to things you've likely already done in Python, but I will include a few useful bits of code to help you access your data.

```
from astropy.io import fits
```

This imports the required fits module from the astropy package and should be at the top of your code with any other packages you're using.

```
tab=fits.open('filename.fits')[1]
```

This will open the file with the name "filename.fits" and save the data from index 1 (see Figure 8) into an array called "tab".

```
tab.columns
```

This will display the column names from the array we named "tab" (table seen in Figure 9).

```
tab.data[0]['STATUS']
```

This displays the value from the first row, 0, and the column titled "STATUS". If you want to display the values from all rows, you would leave out the `[0]`. You can change the value of the second box to any of the column names to get the data from that column and row.

I'll leave it to you to determine how best to extract all the left polarimetry data from the on and off rows and combine them into one. Remember that the values given are the ADU counts from each channel of the 1024 channel spectrograph. You will need use the information in the FITS header (Figure 8) to convert this into a frequency scale. When you're finished and you zoom in around the 1420.4 MHz HI line, you should see a vast difference between one single spectrum and your combined spectrum (Figure 10).

NOTE: The FITS header shows that the observed frequency is 1429.25 MHz when it is actually 1428.75 MHz. It is essential that you make this correction when creating your frequency scale.

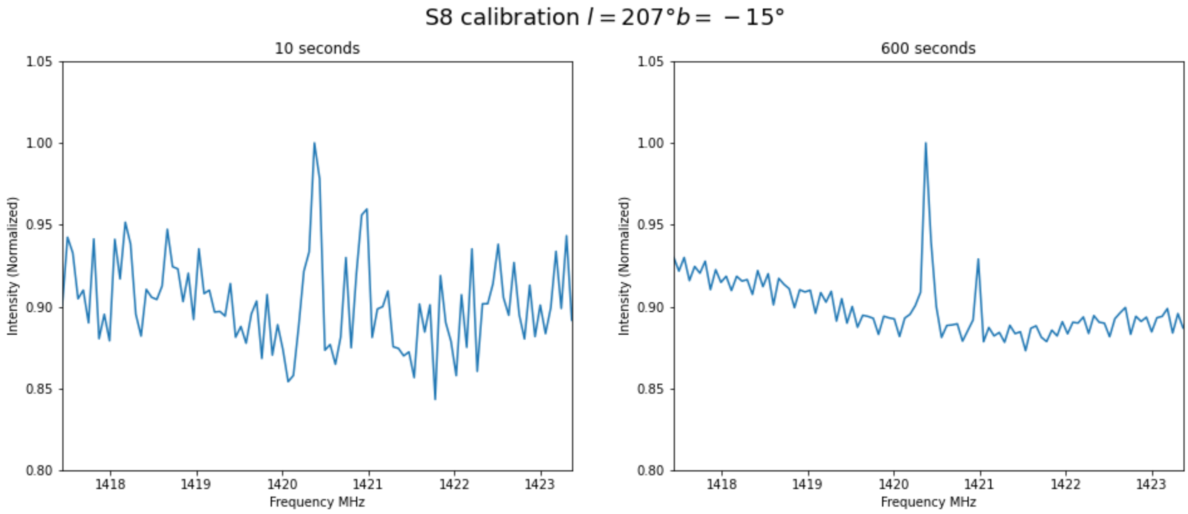


Figure 10: S8 calibration spectra showing 10 second (LEFT) and 600 second acquisitions (RIGHT)

2.4. Determining Brightness Temperature

The next task will be to calibrate our data using a radio source of known brightness temperature. For this, we will be using the IAU S8 calibration point at galactic coordinates $l = 207°, b = -15°$, and the methods used by Kalberla, Mebold, and Reif (Kalberla et al., 1982).

You will be provided with FITS files taken of the calibration point, which you will have to reduce using the methods outlined above in section 2.3. Once you have this, you will compare it to data acquired by the University of Bonn LAB Survey (Kalberla et al., 2005) found at the link below (4.5). You will need to enter the coordinates of the calibration point together with the beam width of the telescope (found in the FITS header), and the website will return the HI profile for that position which can be extracted as an ASCII file and imported into your JupyterLab.

Using these values, you should be able to determine an appropriate scaling factor for your calibration spectrum, which can then be applied to the rest of your data to determine the brightness temperature your chosen points along the galactic plane (Figure 11).

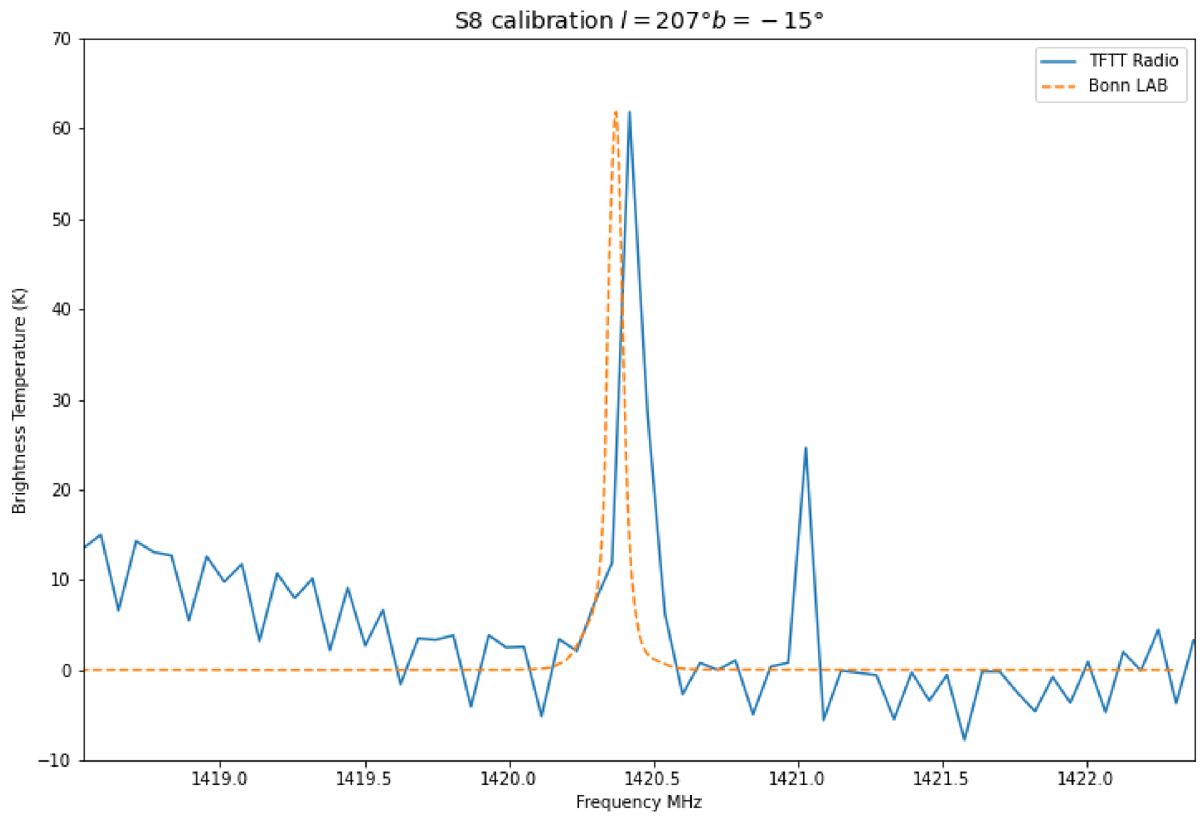


Figure 11: S8 spectrum with University of Bonn LAB survey data

2.5. Correcting for LSR Velocity

You have likely noticed that the peaks in the two plots above (Figure 11) don't line up. The last thing we need to do is to fix this by correcting for the motion of the telescope as it travels through the galaxy causing the incoming light to be slightly doppler shifted. To do this, we will need to find our local standard of rest (LSR) velocity with respect to the direction we are pointing our telescope. This will also be done with the Python package Astropy. We will be using a script written by another radio astronomer Wolfgang Herrman out of Astropeiler Stockert (4.6) (Herrman, 2021).

After copying the script and pasting it into a Jupyter Notebook terminal, you will need to read through the instructions and enter a few parameters. All of these can be found in the FITS header of your data files. Once entered, simply run the script and it will return several values. By looking at the sky frequency of the hydrogen line at rest and comparing it to the rest frequency of the observer, you can determine the correct frequency shift. Applying this shift will correct for the LSR velocity of your telescope.

The last thing to do is to change your frequency scale to a scale of radial velocity. This will help to clearly see which parts of the hydrogen spectrum are redshifted, and which are blueshifted. This is a relatively straight forward procedure, making use of equation 1 below where c is the speed of light, Δf is the difference between the rest frequency and the observed frequency, and f_0 is the observed frequency.

$$v = c\frac{\Delta f}{f_0} \qquad (1)$$

After combining all these steps, you will finish with your spectra having been corrected for the LSR velocity, scaled in both the frequency and velocity frame, and calibrated to the correct brightness temperature (Figure 12). You can now compare your findings with others, such as those found in the University of Bonn LAB survey (4.5).

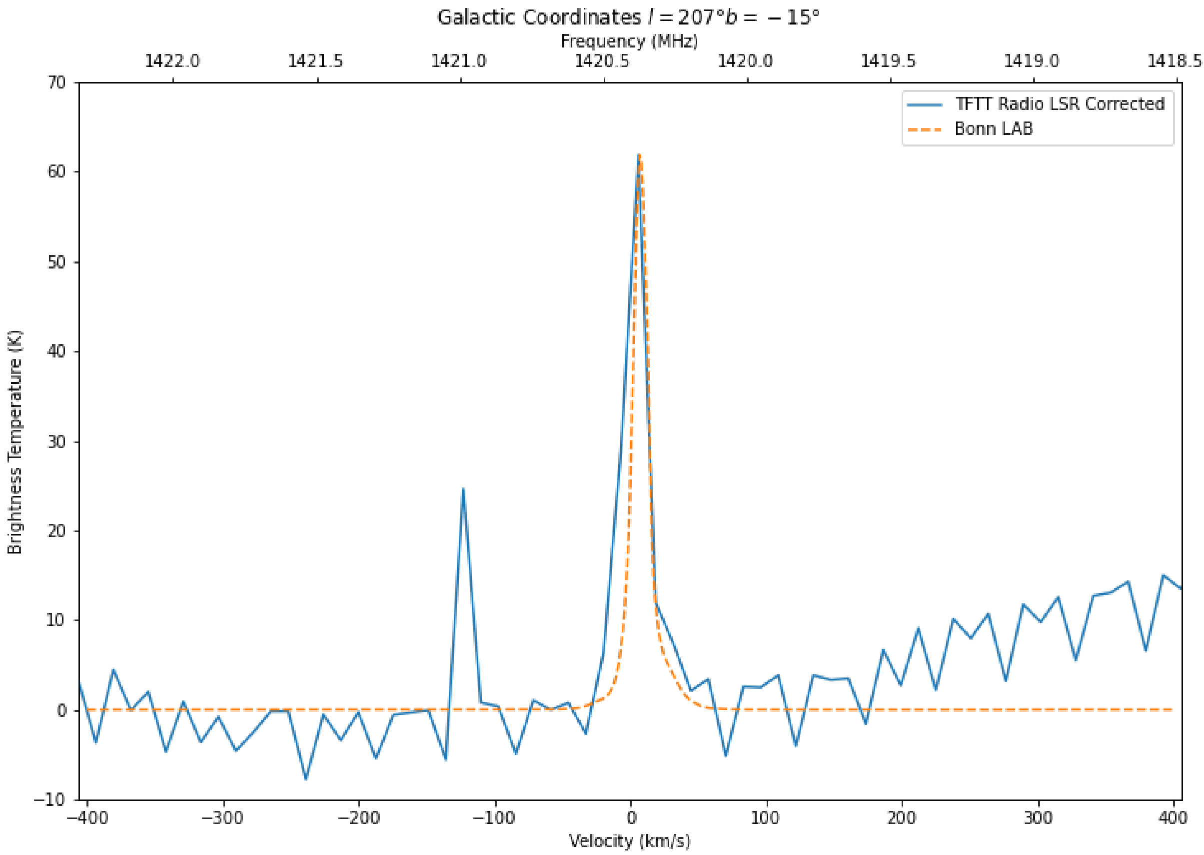


Figure 12: S8 spectrum corrected for LSR velocity

2.6. Determining Rotational Velocity and Distance

Now that we've completed all our calibrations, we can start drawing some conclusions based on our observations. We know for galactic longitudes, l, between 0° and 90°, we expect the velocity of the HI gas to be redshifted within distances less than or equal to that of the Sun's orbit around the galactic center, R_0, as it will be moving away from us and blueshifted for longitudes between 270° and 360°. We also know that the maximum velocity within these longitudes will occur at a distance less than R_0. This is illustrated in the image below (Figure 13). There we see that for the points indicated on the right image, we would expect B, C and D to be redshifted, and A to be blueshifted. We would also expect point C to have the highest redshifted velocity, as it is the point tangent to the closest orbital path around the galactic center. This is verified on the image of the spectra on the left.

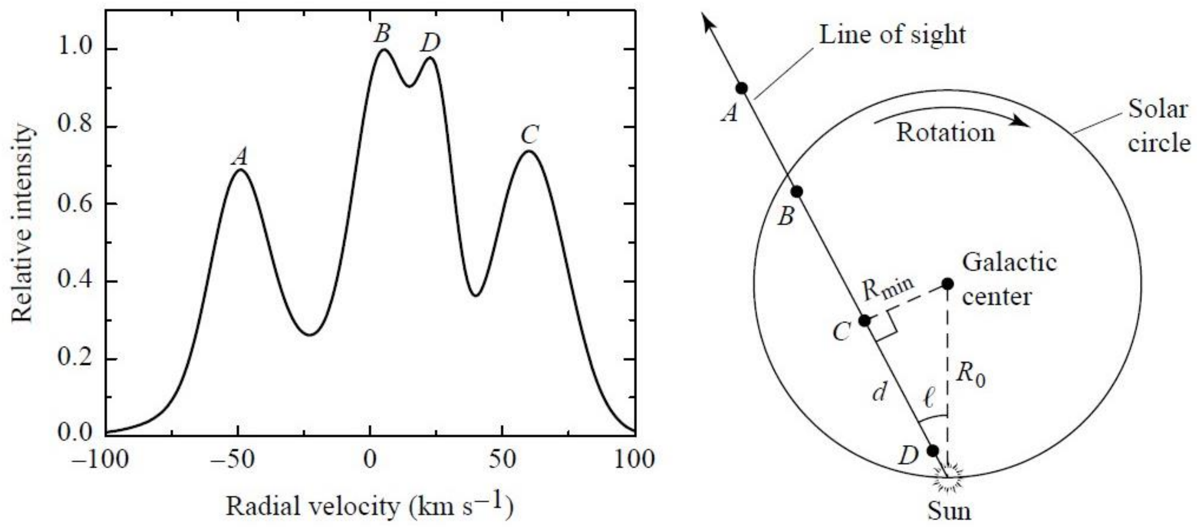


Figure 13: Random HI line profile (LEFT) with observational line of sight example (RIGHT) (Carroll and Ostlie, 2014)

We will use this same method to determine the maximum velocity for our data. As the spectral resolution of our data is on the low side, I would suggest overlaying the data from the University of Bonn LAB survey on top of your own to ensure you are using the correct peak. Using the method outlined above, determine if your maximum velocity should be blueshifted or redshifted, and then determine the velocity of the furthest peak on that side of your data.

An example is given below for the coordinates $l = 310°$, $b = 0°$ (Figure 14).

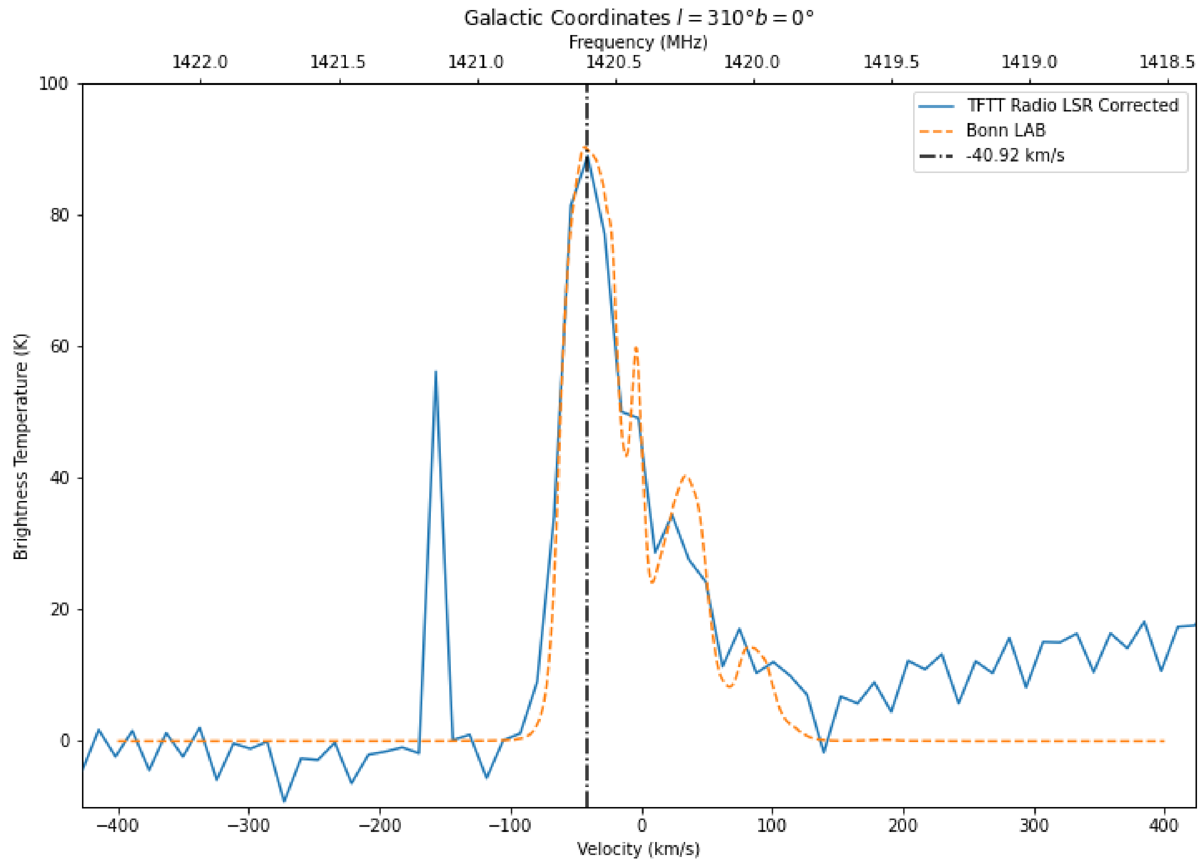


Figure 14: HI line profile of $l = 310°$ showing maximum blueshifted velocity

The last thing to do is determine the distance of this point from the galactic center. This can be done using trigonometry based on the image above (Figure 13). The equation found below is directly from your lecture slides where R_{min} is the distance from the galactic center to the tangential point.

$$R_{min} = R_0 \sin(l) \qquad 2$$

Now that you've finished, please add your values for R_{min} given in kpc where $R_0 = 8.5$ kpc, and the absolute value of v_{max} on the class spreadsheet (4.1) for each of your sets of coordinates.

3. Report Write-up

Your report should have a clearly structured layout. You should have clear explanations of everything you did and why it was done. Explain the overall process, not the specifics of where you clicked on the computer. Someone picking up your report should be able to follow the same steps and get the same results with their own equipment.

Error estimates should be calculated and given on any results quoted in your report. Your results should be compared to those found by other researchers and any differences in obtained values should be discussed.

The hand-in deadline will be October 4th at 16:00. Your report must be submitted in PDF form on Amathuba and will be put through a plagiarism detector. Any plagiarized work will be heavily penalized. Make sure you include references and citations for any source material you use which is not your own.

4. Links

4.1. Group Sign-up for Specific Longitudes

https://docs.google.com/spreadsheets/d/1JcLTG76JRjgf3YgfOmglnmsECClZBBN8tk3pbPS2gWA/edit?gid=0#gid=0

4.2. Observing Time Schedule

https://docs.google.com/spreadsheets/d/1EYgRbfSHKWwFkkm1Wv7RpaZE7mEbhw1UZKmRHSPUOHY/edit?gid=0#gid=0

4.3. Windy Weather Forecast

https://www.windy.com/?-30.933,15.996,8

4.4. fv FITS File Viewer

https://heasarc.gsfc.nasa.gov/ftools/fv/fv_download.html

4.5. University of Bonn HI LAB Data

https://www.astro.uni-bonn.de/hisurvey/euhou/LABprofile/index.php

4.6. LSR Calculator Python Script

https://github.com/Astropeiler/vlsr_calc/find/main

5. References

Kalberla, P., Mebold, U. and Reif, K., 1982. Brightness temperature calibration for 21-cm line observations. *Astronomy and Astrophysics*, 106(2), pp.190-196.

Kalberla, P., Burton, W., Hartmann, D., Arnal, E., Bajaja, E., Morras, R. and Pöppel, W., 2005. The Leiden/Argentine/Bonn (LAB) Survey of Galactic HI. *Astronomy & Astrophysics*, 440(2), pp.775-782.

Herrman, W., 2021. *vlsr_calc*. Astropeiler Stockert.

Carroll, B. and Ostlie, D., 2014. *An Introduction to Modern Astrophysics*. 2nd ed. Essex: Pearson Education Limited, p.1060.