Data Collection with Low-Cost Horn Radio Telescope

11th November 2023

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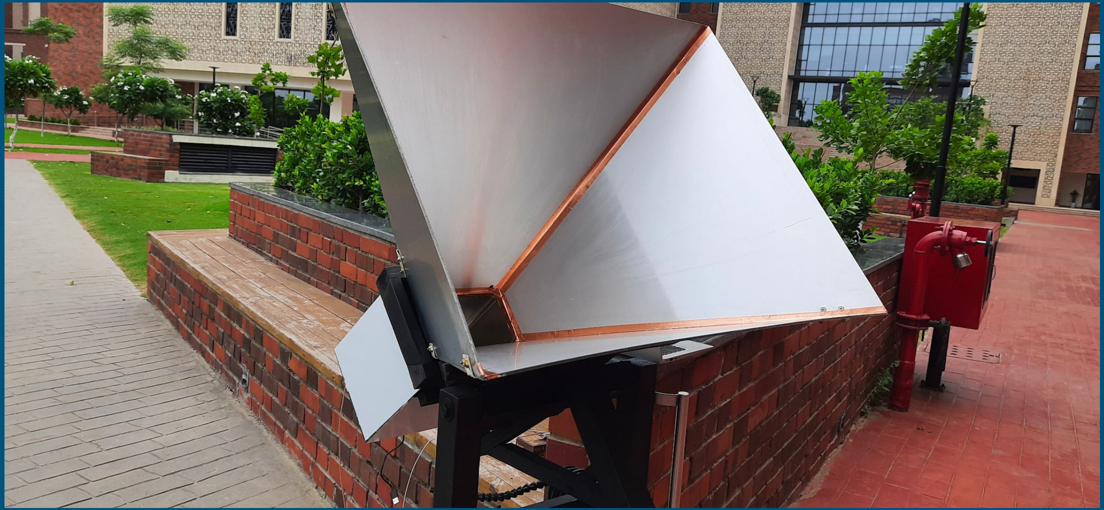
Under the guidance of:
Professor Dipankar Bhattacharya, Philip Cherian

Objective

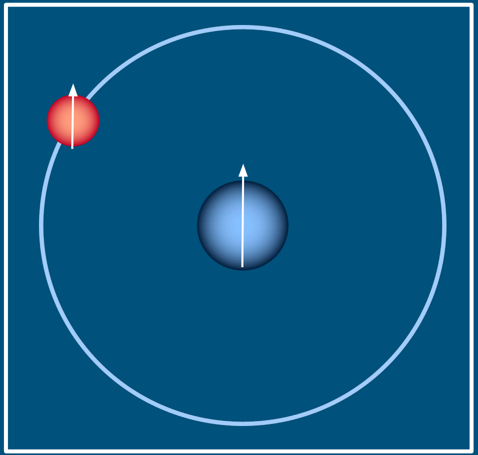
To use a horn antenna to detect the HI line (1420.41 MHz) emitted by hydrogen in our galaxy.



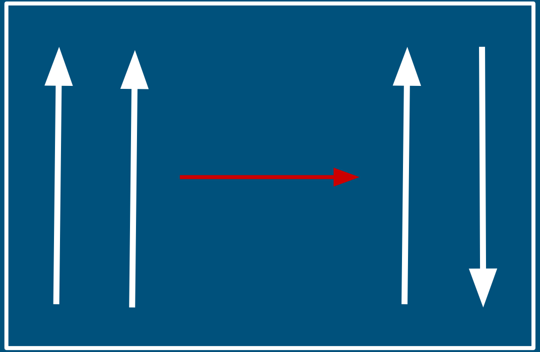
Horn Antenna made by Pradip Chaudhari, under the supervision of Professor Dipankar Bhattacharya

HI (21 cm) Line Emission

- Atomic Hydrogen can undergo 'spin flip' transition releasing radiation at 1420.41 MHz
- Abundance of Hydrogen in the Galactic plane results in strong HI signal
- These radio waves can penetrate clouds of interstellar dust, and can be used to probe the motion of their source

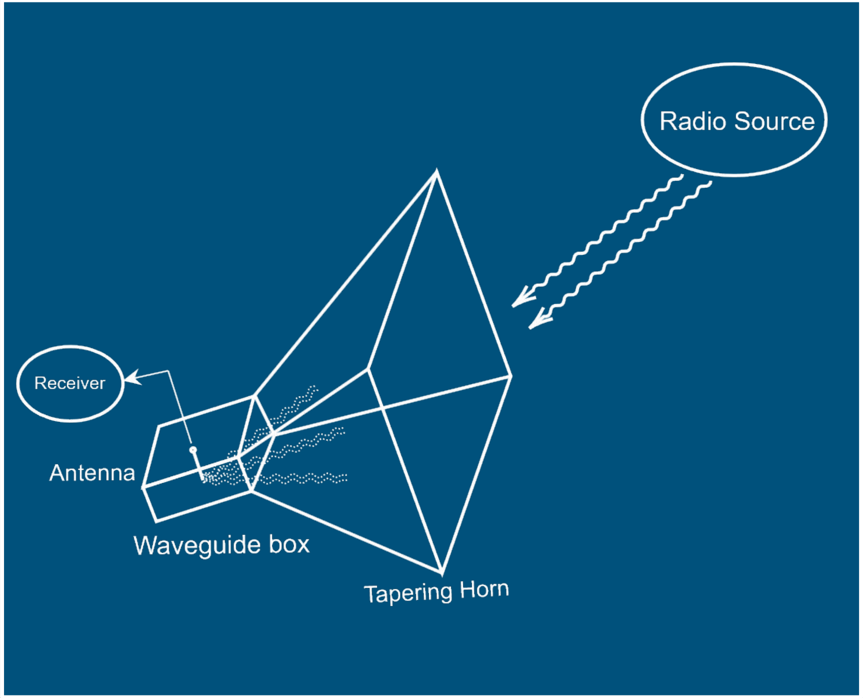


Atomic Hydrogen

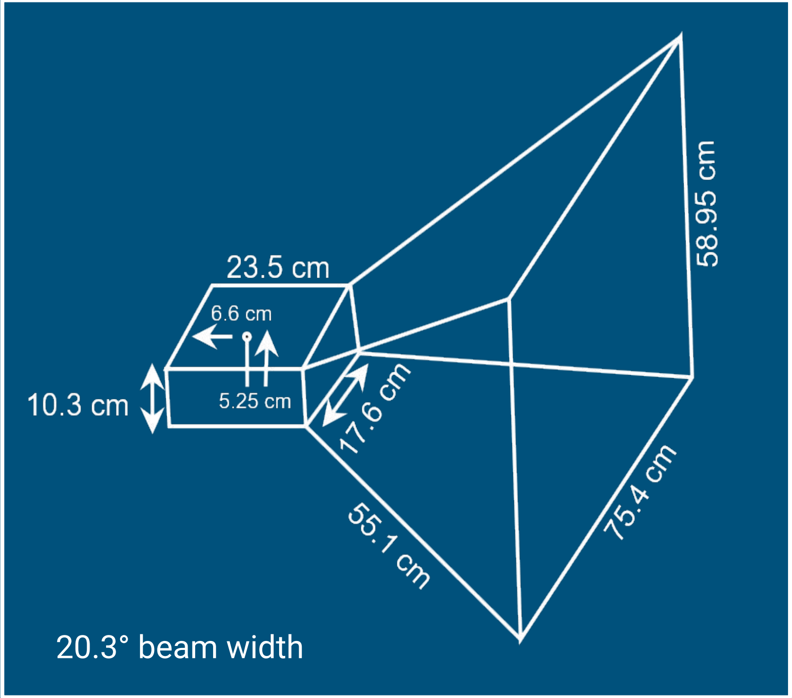


Spin-Flip Transition

Using the Horn Antenna

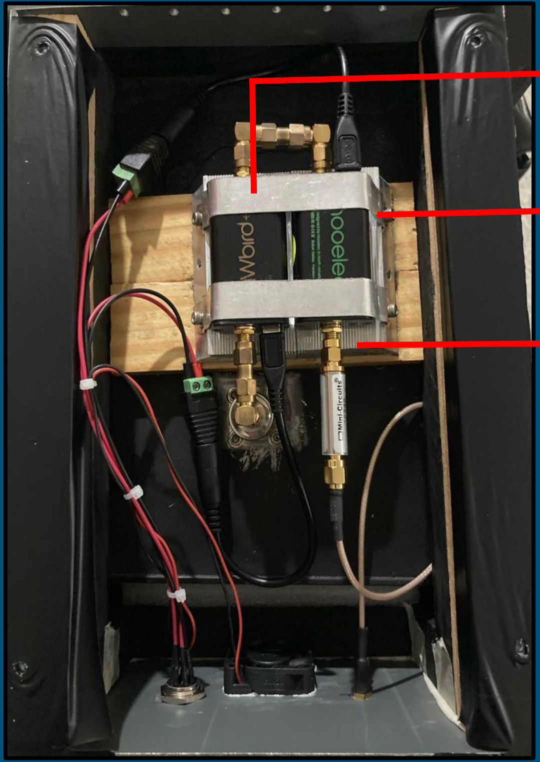


Collection of data using the Horn Antenna



Dimensions of the Horn Antenna

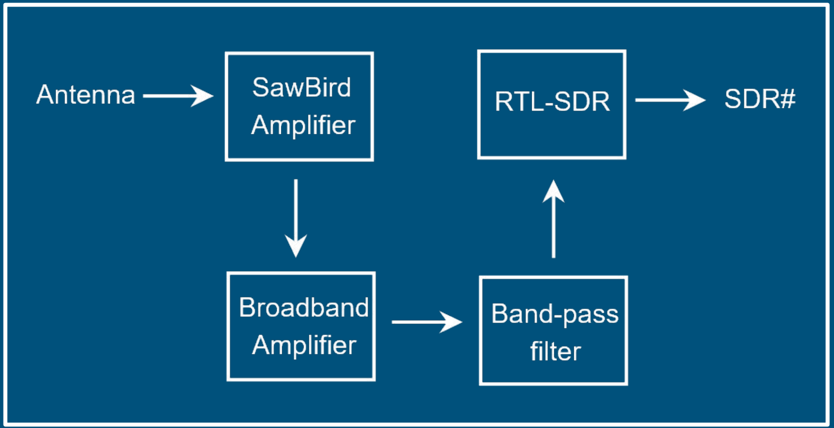
Electronics



SAWBird amplifier: Two LNAs with a SAW filter. Overall gain of 40 dB at 1420 MHz. Bandpass width of 65 MHz

Nooelec LaNA: Broadband low-noise amplifier, gain of 20 dB at 1000 MHz

Minicircuits Bandpass filter: 100 MHz bandpass region centered on 1400 MHz



Software-Defined Radio

Output: USB port which can easily connect to a computer

- RTL-SDR converts analog signal from RF equipment into digital signal which can be processed using software
- This allows flexibility in data processing without changes to equipment

Input: SMA connector which connects it to the RF equipment

Software: SDR# (with IF_Average Plugin)
Converting time-domain to frequency-domain

Divide total signal into chunks

↓

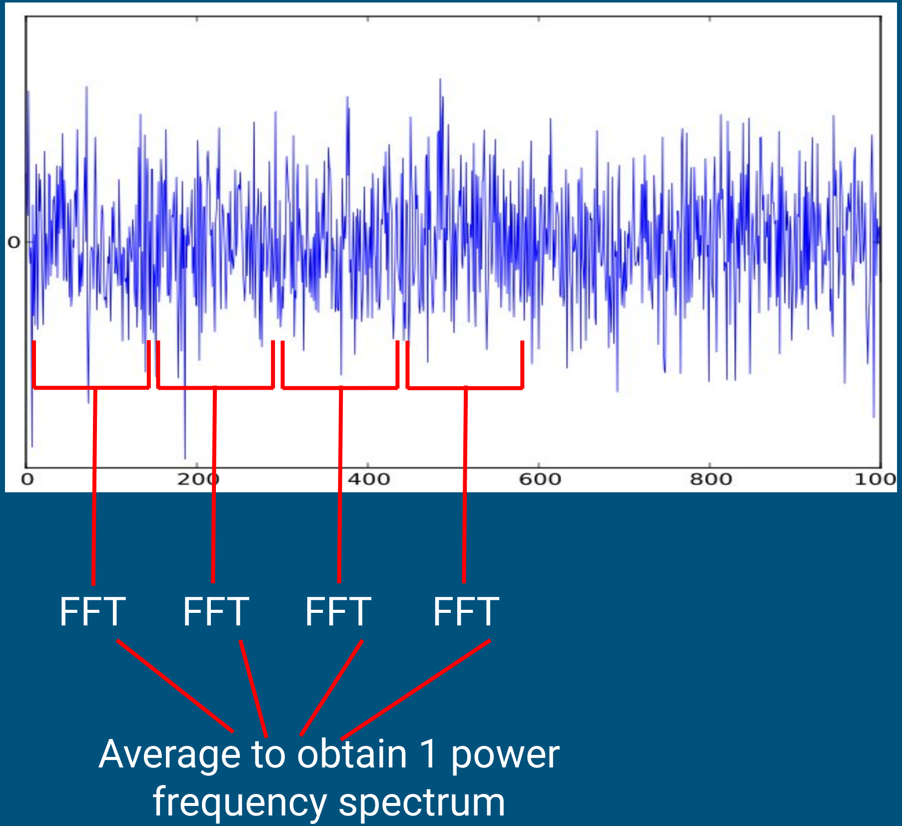
Calculate Fourier Transform of each chunk

↓

Obtain **frequency-power** spectrum of each

↓

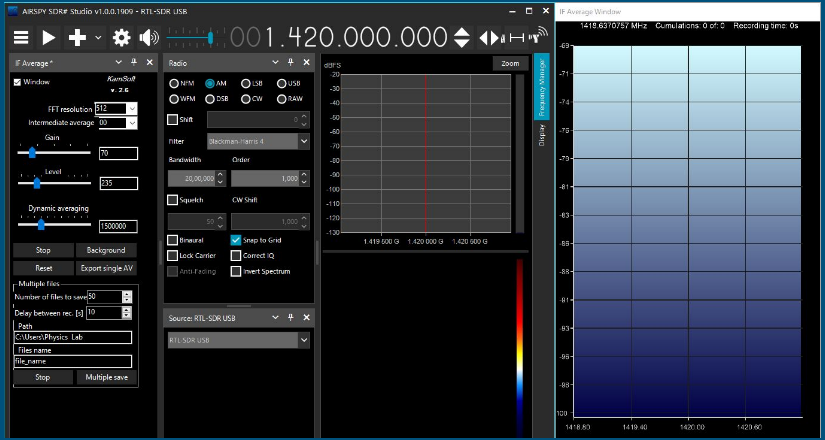
Average over all chunks



Obtaining the Signal

SDR# Settings

1. Length of recording: ~5 mins for one reading
2. Bandwidth of recording: 2 MHz, centered on 1420 MHz
3. No. of bins for FFT: 512



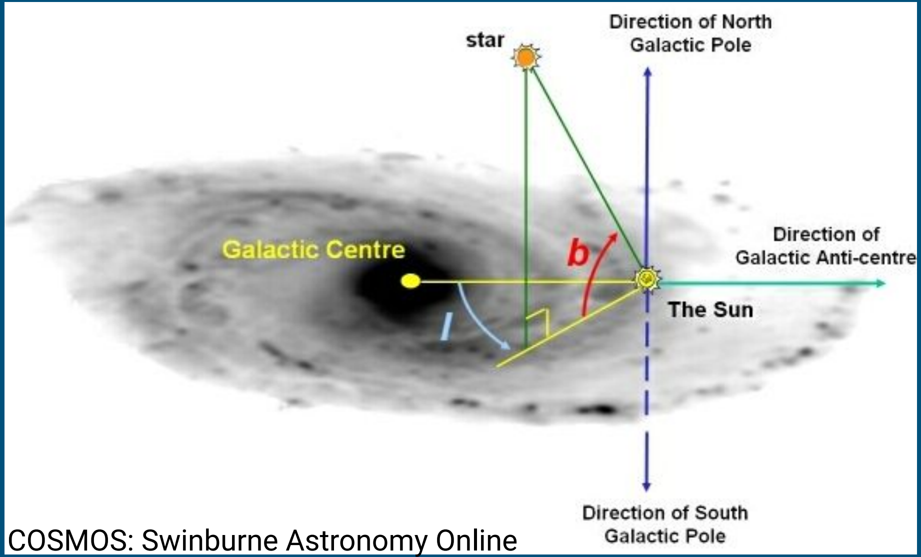
Horn Antenna Coordinates

1. Position of galactic plane estimated using Stellarium
2. Azimuth measured using compass and pre-measured markings
3. Altitude measured using level.

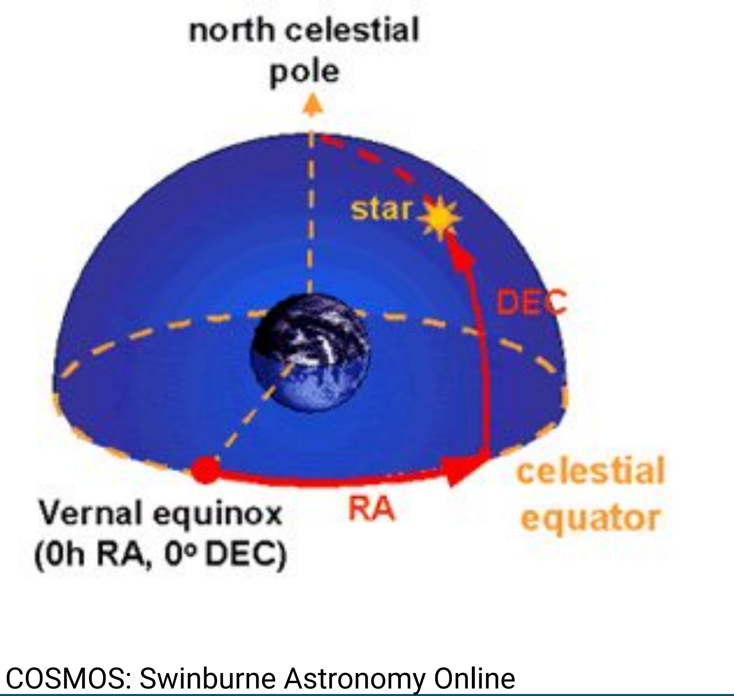
Coordinate systems

Need to find the position of the galactic plane in the sky, at arbitrary time and place.

Convert galactic coordinates to Alt/Az



Galactic coordinates:
Latitude (b) and longitude (ℓ)



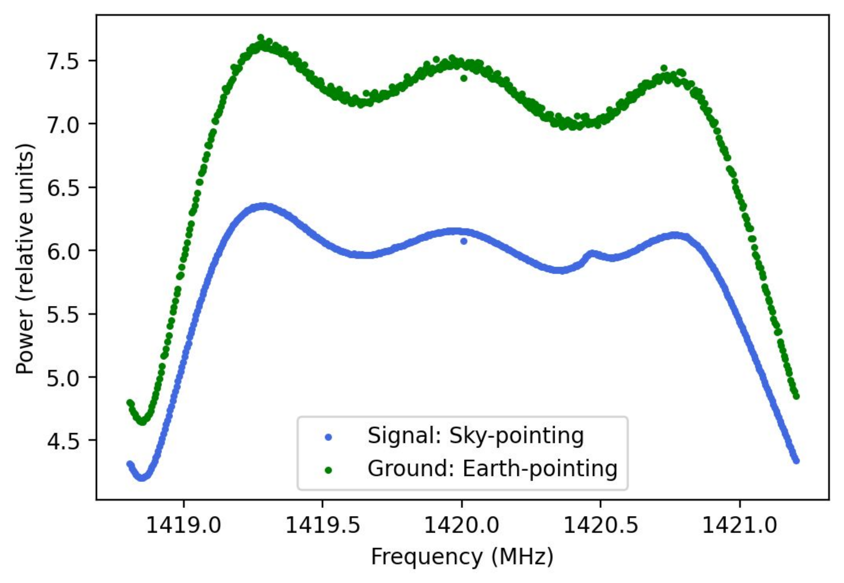
Equatorial coordinates:
Right Ascension and Declination

Signal and background

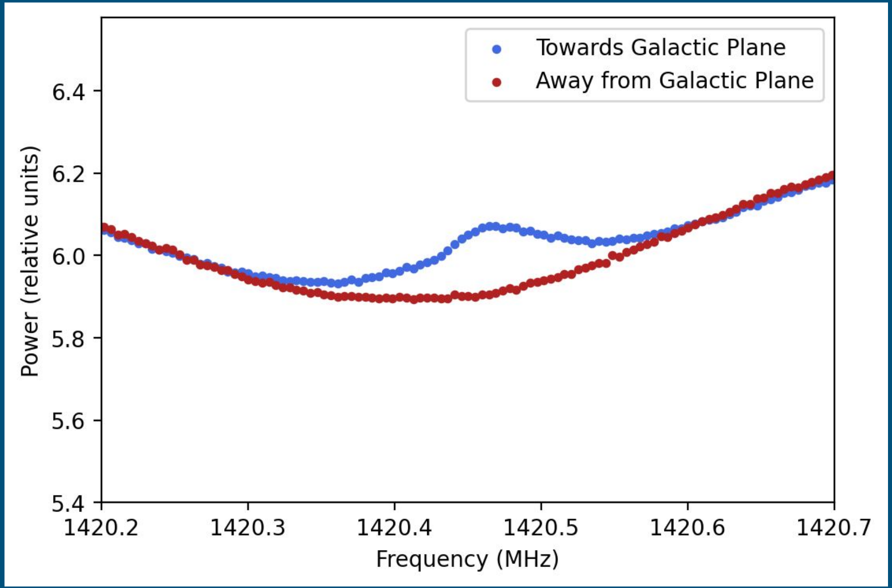
To verify the signal is from galactic hydrogen.

Comparing signals from the ground and the sky

(What is a signal from the ground?)



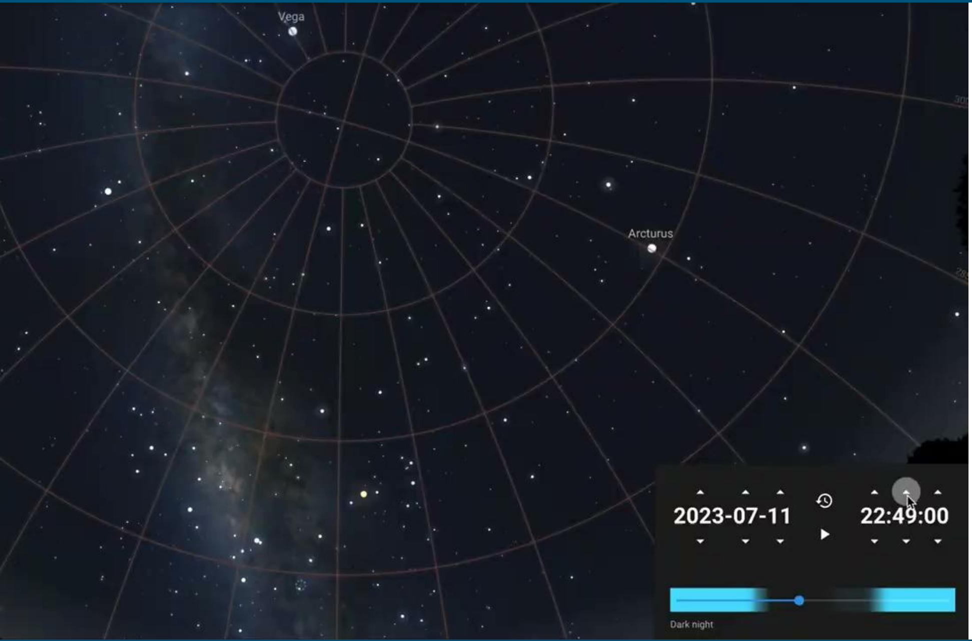
Comparing signals from the galactic plane, and away from it

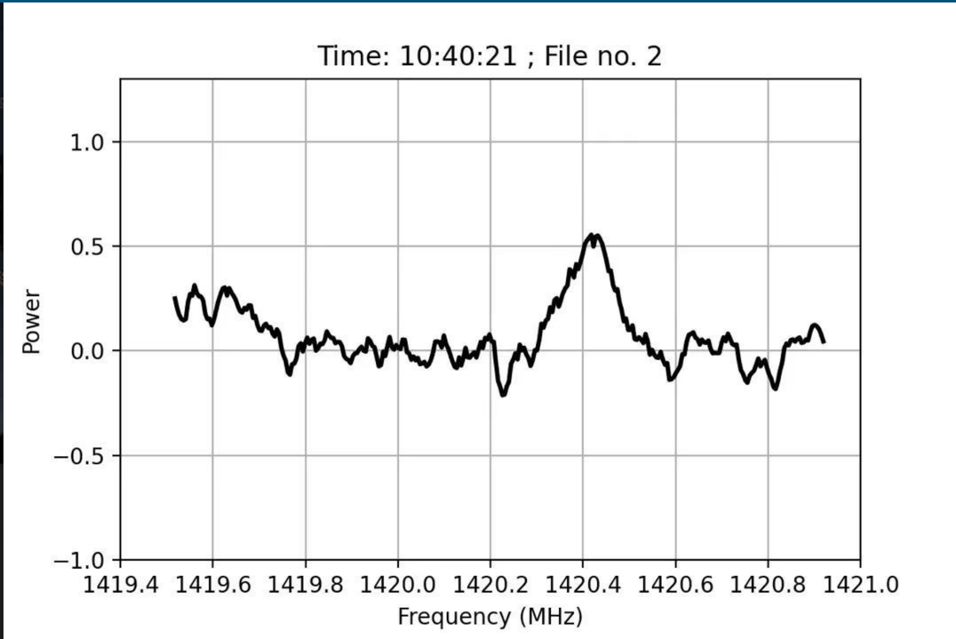


Verifying the signal: Long Exposure Signal

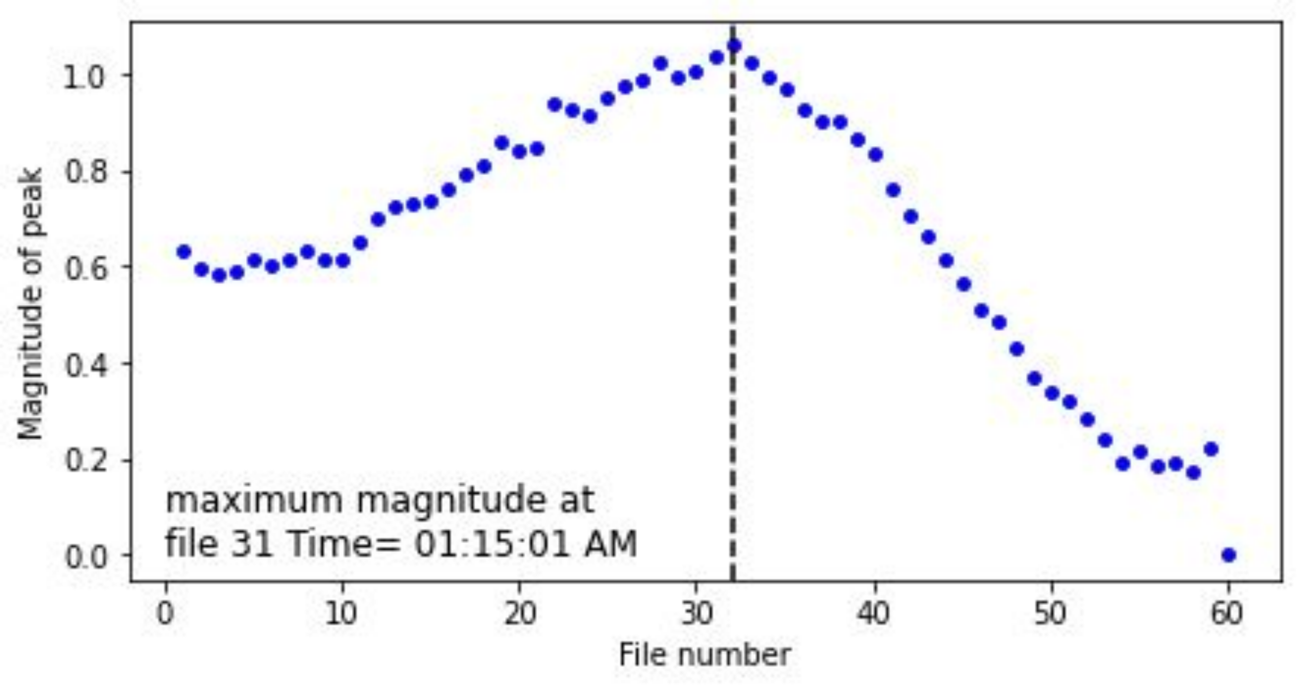
To check whether the strength of the signal varies as the galactic plane passes in and out of view.

- Horn kept fixed from 10:30 PM to 4:00 AM
- Altitude: 73º, Azimuth: 220º
- Total of 60 files recorded: each ~5 minutes





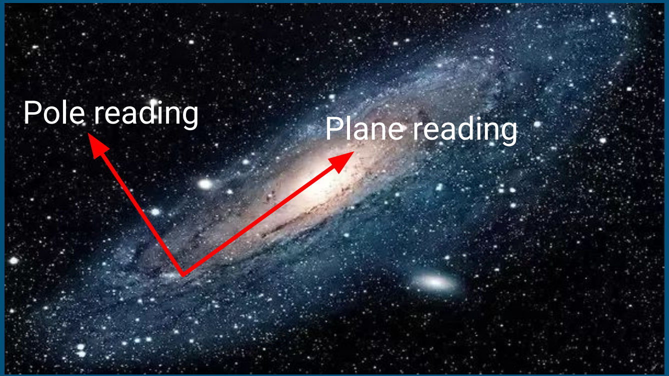
Verifying the signal: Long Exposure Signal

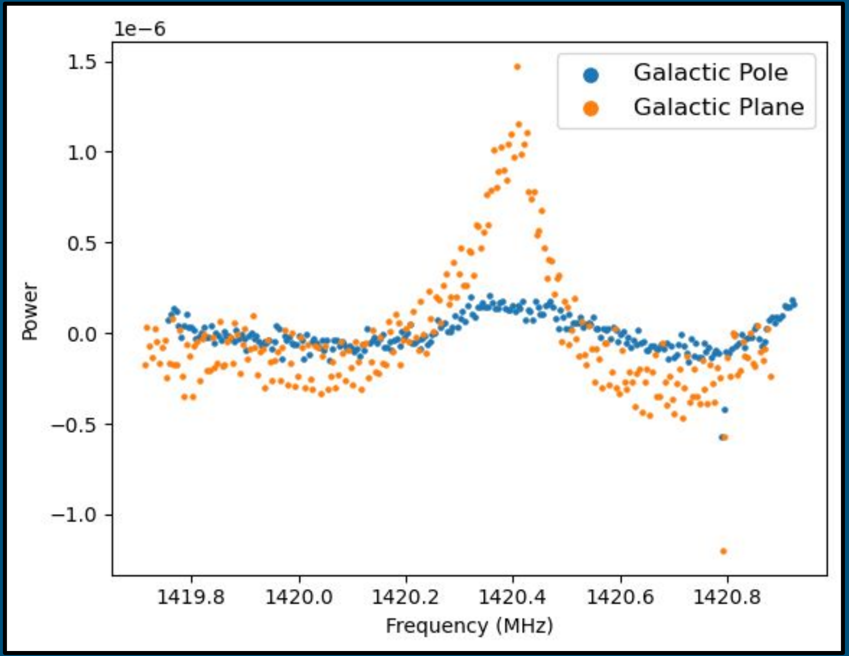


Graph of magnitude of peak
intensity of the signal over time.

Verifying signal- Galactic Pole Reading

- We expect minimum signal at the galactic pole, so we take some readings at the pole as a control.
- Small peak is observed, could be due to:
  - Instrument response at 1420 MHz
  - Signal due to more distant Hydrogen clouds





Signal obtained at the galactic pole vs. galactic plane

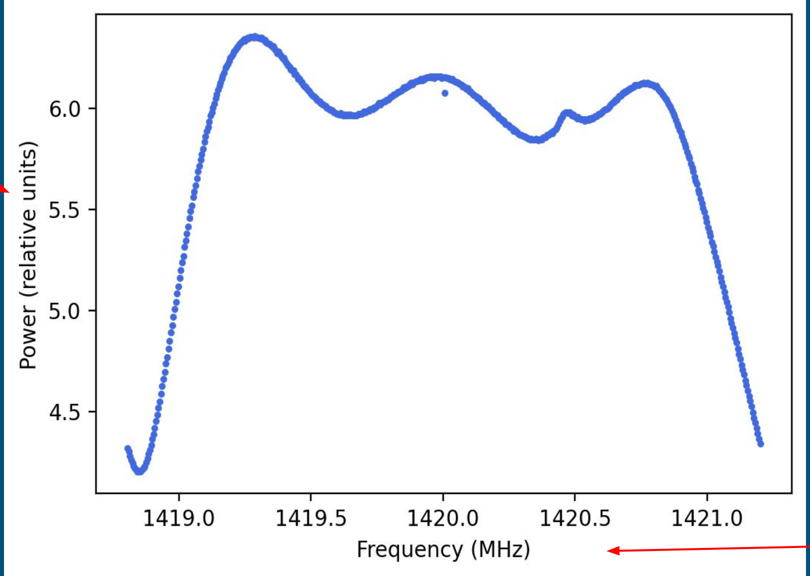
Processing Data

Making sense of the Power Spectrum

Temperature Calibration

$$P_\nu \propto T(\nu)$$

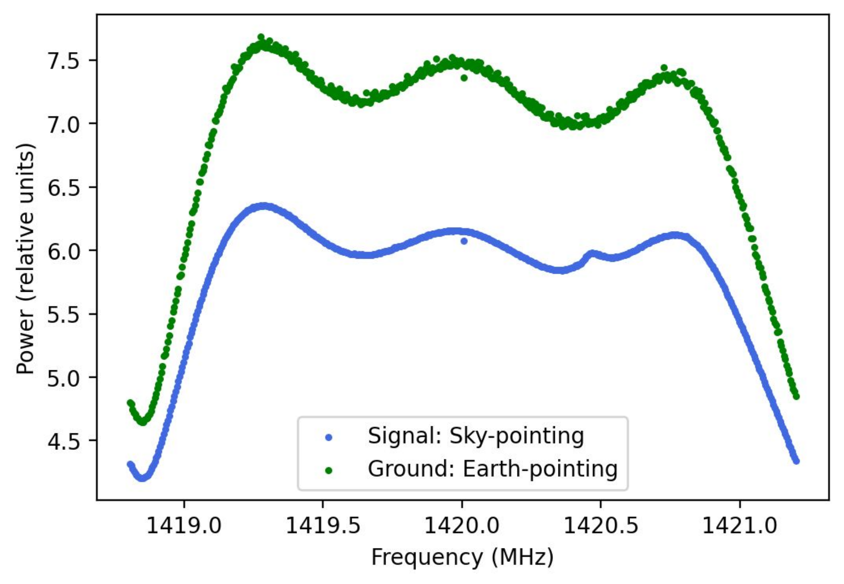
We use this relation to convert power levels to temperatures (brightness temperatures).



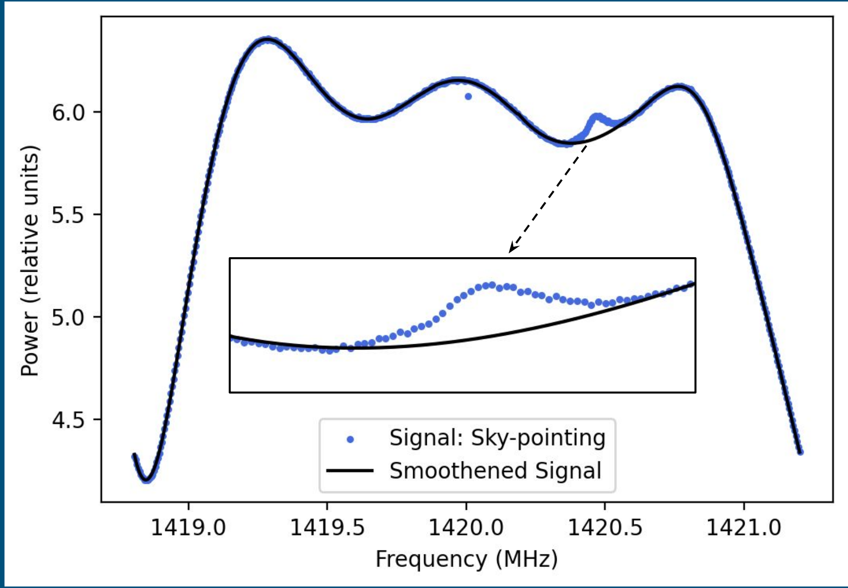
Velocity Conversion & Velocity Correction

We use the doppler effect to convert from frequency to relative velocity. However, to obtain a more meaningful value of velocity, we must correct for the Earth's motion relative to the Galactic plane.

Temperature calibration



'Hot' Calibration (Ground)



'Cold' Calibration (Sky)

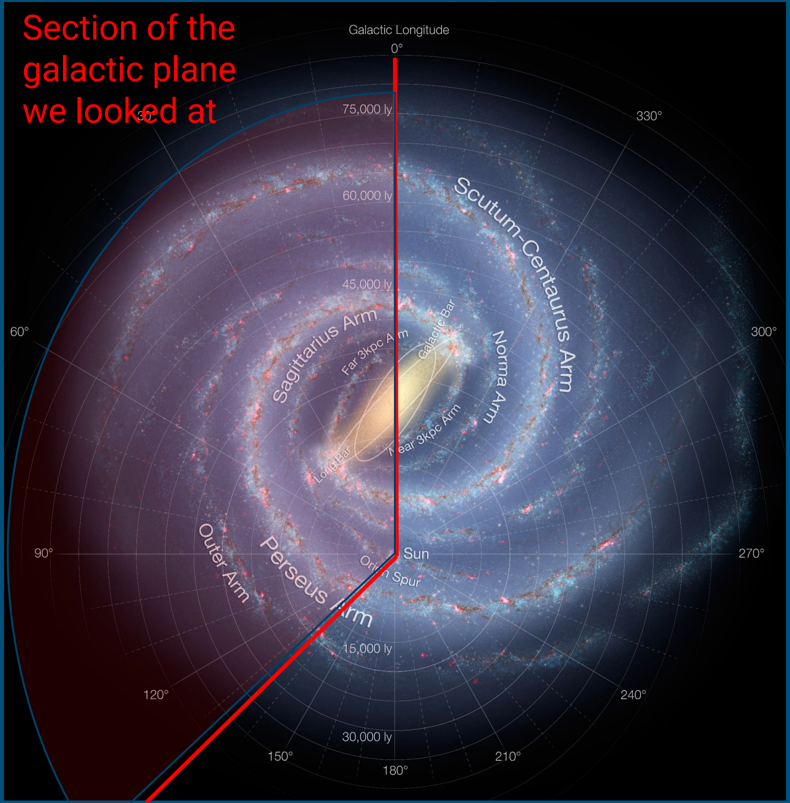
- Use spectra at known temperatures to calibrate temperature axis
- Estimate instrument response as 'receiver temperature'

Velocity Conversion

$$v = \frac{f_0 - f}{f_0} \cdot c$$

where f_0 is the HI emission frequency.

- Doppler shift equation gives the velocity of radio source
- The redshift observed varies for different regions of the galaxy
- Need to account for motion of Earth relative to the galactic plane



Galactic Coordinate System: Wikipedia

Velocity Correction: Local Standard of Rest (LSR)

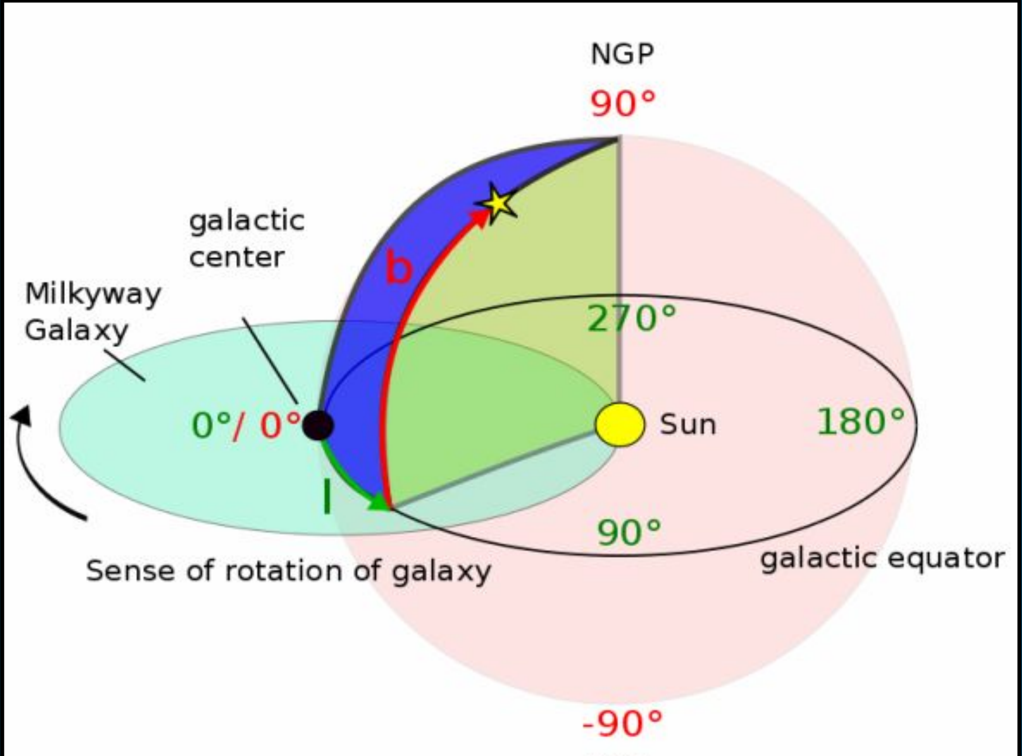
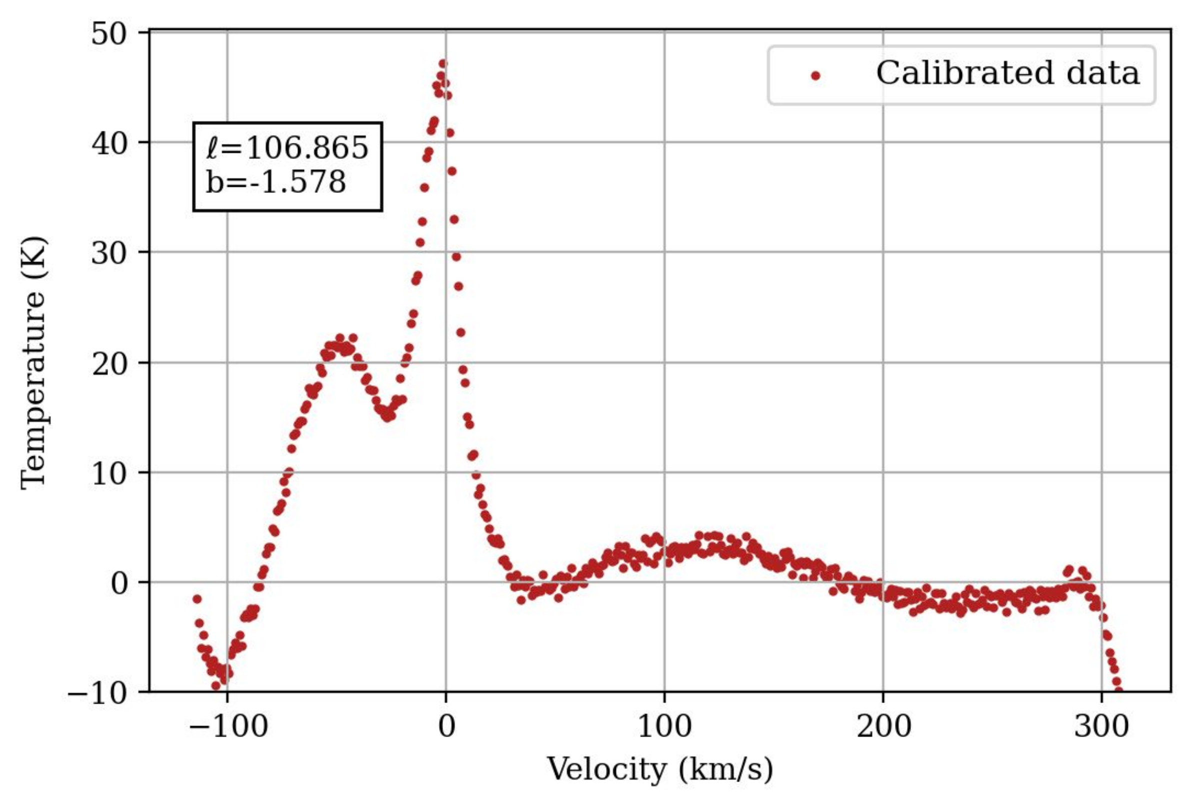


Image: Pierre Auger Observatory

- LSR gives the average motion of matter in the Galaxy
- Need velocities in the LSR frame of reference
- Need to correct for motion of Earth around Sun, and motion of Sun around center of Galaxy

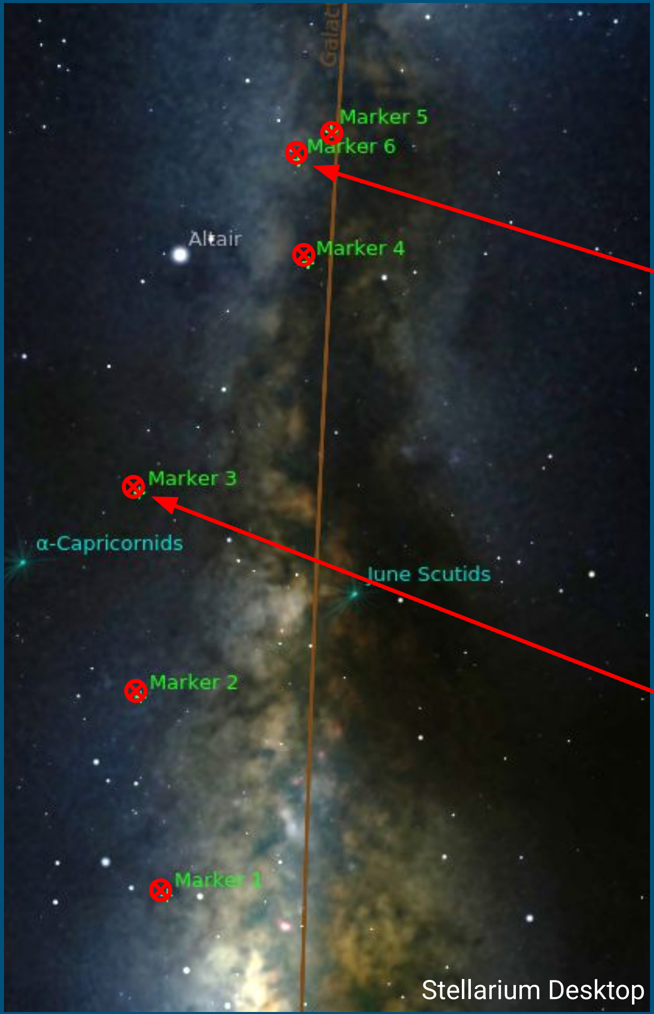
Final Calibrated Graph

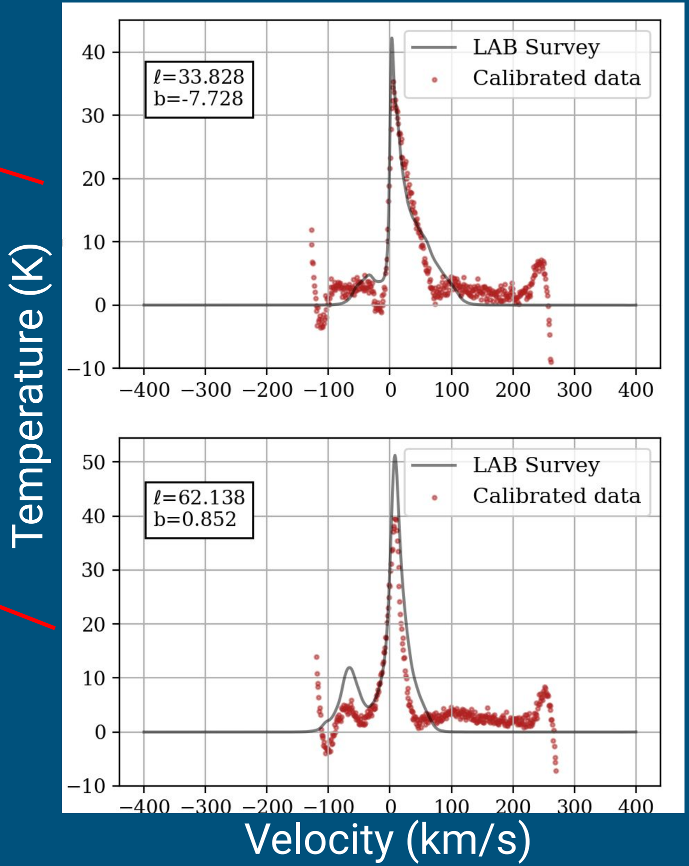


Collecting data for rotation curve

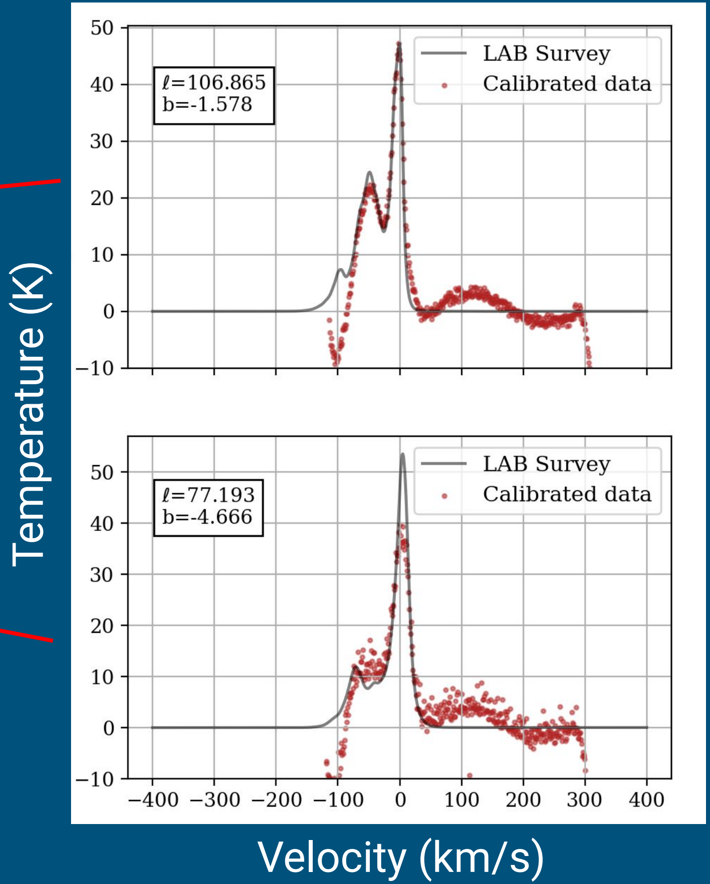
All data taken was compared to the LAB survey of HI emission conducted by *Kalberla et al*.

Measuring H1 along the Galactic Plane- Facing South

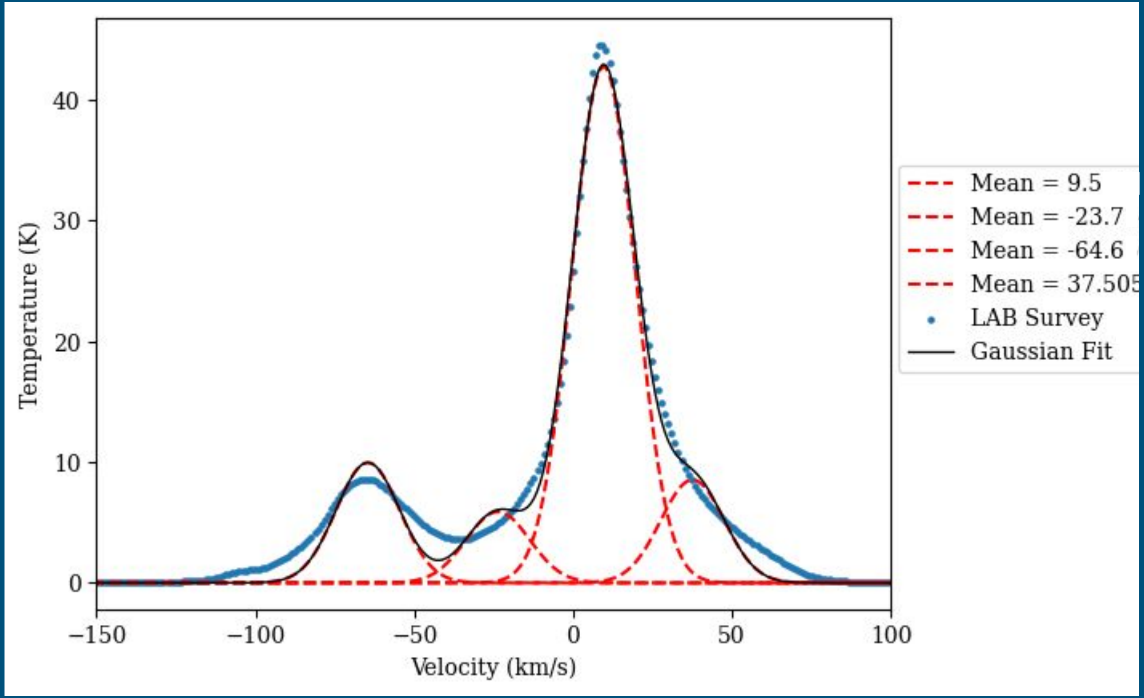




Measuring H1 along the Galactic Plane- Facing North



Gaussian Fitting



- 4 gaussians were summed to curve-fit the overall shape.
- Parameters were fitted using the `astropy` library function *LevMarLSQFitter*: Levenberg-Marquardt least squares algorithm.
- Want to find the mean of each gaussian- obtain velocity of different regions of the galaxy.

Work in progress! Can use this data to obtain the rotation curve of the galaxy

Recap & Conclusion

1. Connect amplifiers and filter components
2. Set recording parameters on software
3. Find Galactic coordinates to observe
4. Calculate corresponding altitude, azimuth
5. Obtain signal from galactic plane
6. Convert frequency to velocity
7. Correct velocity to LSR
8. Convert power to temperature
9. Fit gaussian models to obtain rotation velocities
10. Plot rotation curve!

(Future work)

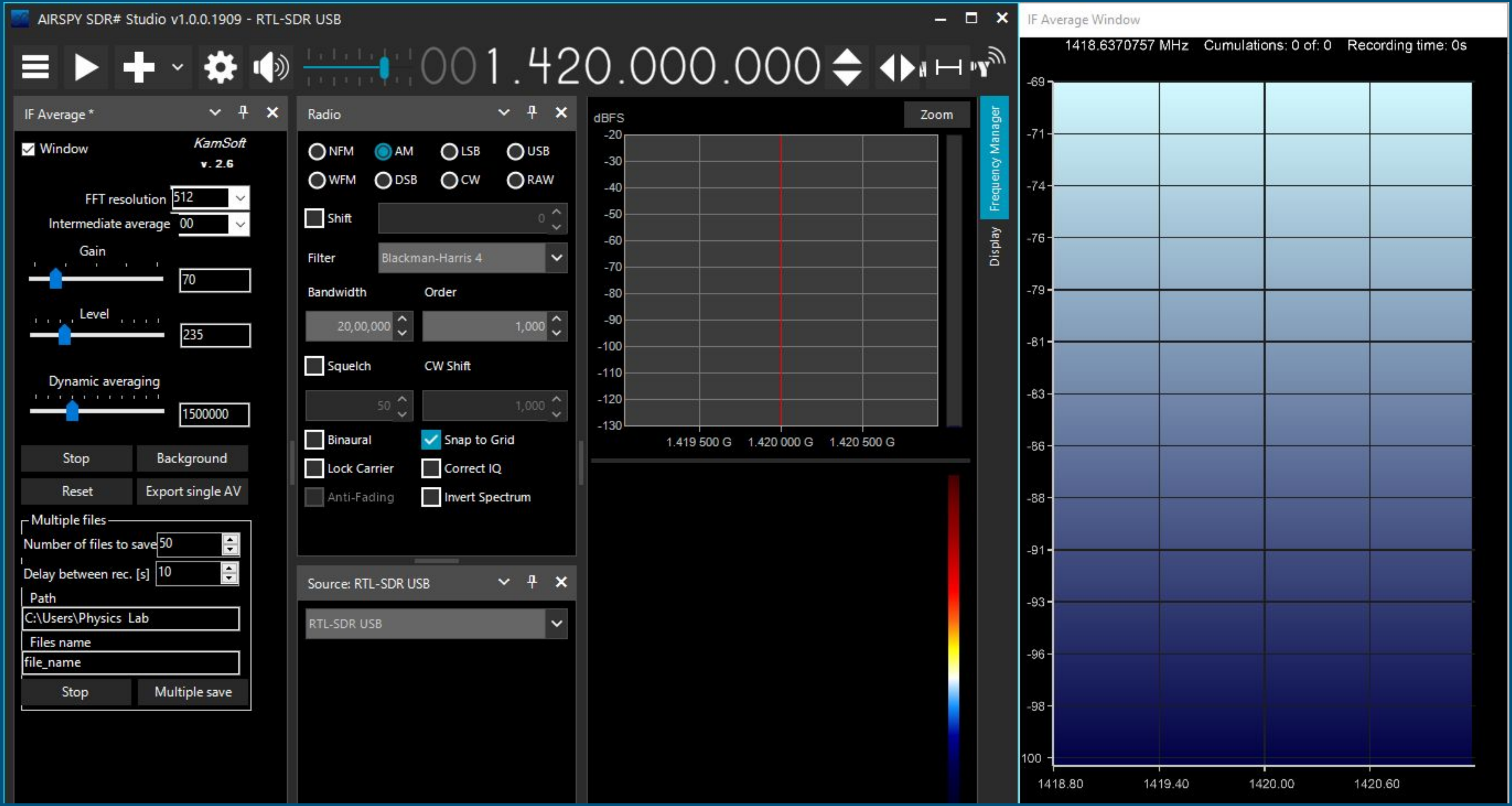
References and Acknowledgements

1. *LightWork Memo 29: Hydrogen Line Project Documentation*, Eric Trumbauer and Sahar Khashayar
2. *HI experiment with horn antenna*, IUCAA
3. *VLSR Correction*, Litster, MIT, 2013.
4. *Leiden Argentine Bonn (LAB) Survey* server, Argelander-Institut für Astronomie in Bonn.

We would like to thank Professor Dipankar Bhattacharya and Philip Cherian, for their invaluable advice and guidance in this project.

We would also like to thank Pradip Chaudhari for the construction of the Horn Antenna and for his assistance with modifications to the Horn, under the supervision of Prof. Bhattacharya.

appendix


AIRSPY SDR# Studio v1.0.0.1909 - RTL-SDR USB
001.420.000.000
IF Average *
Window
KamSoft
v. 2.6
FFT resolution 512
Intermediate average 00
Gain
70
Level
235
Dynamic averaging
1500000
Stop
Background
Reset
Export single AV
Multiple files
Number of files to save 50
Delay between rec. [s] 10
Path
C:\Users\Physics Lab
Files name
file_name
Stop
Multiple save
Radio
NFM AM LSB USB
WFM DSB CW RAW
Shift
Filter Blackman-Harris 4
Bandwidth Order
20,00,000 1,000
Squelch CW Shift
50 1,000
Binaural Snap to Grid
Lock Carrier Correct IQ
Anti-Fading Invert Spectrum
Source: RTL-SDR USB
RTL-SDR USB
dBFS
Zoom
-20 -30 -40 -50 -60 -70 -80 -90 -100 -110 -120 -130
1.419 500 G 1.420 000 G 1.420 500 G
Frequency Manager
Display
IF Average Window
1418.6370757 MHz Cumulations: 0 of: 0 Recording time: 0s
-69 -71 -74 -76 -79 -81 -83 -86 -88 -91 -93 -96 -98 100
1418.80 1419.40 1420.00 1420.60

Obtaining the Signal

Primarily, the app Stellarium was used to roughly determine the region of the galactic plane initially.

Later on, we used Python code and the `astropy` library to convert the desired galactic longitude and latitude into measurable altitude and azimuth coordinates.

Measuring Alt-Az:

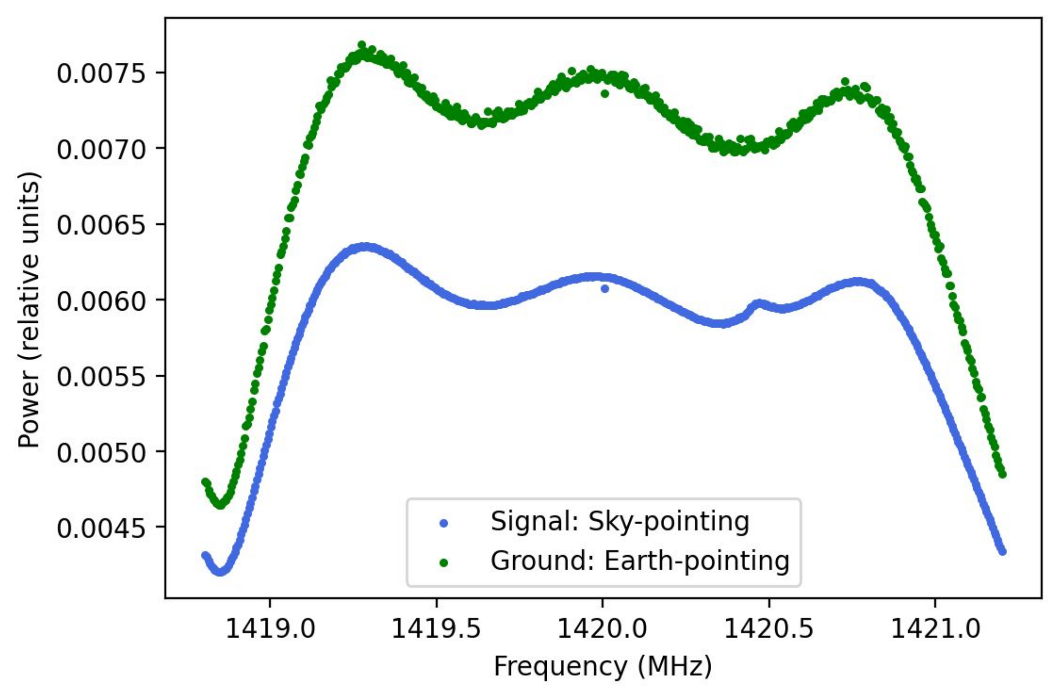
- Azimuth was initially measured using compasses. Then, the azimuth angles were marked in advance for accuracy.
- Altitude measured using mobile app.

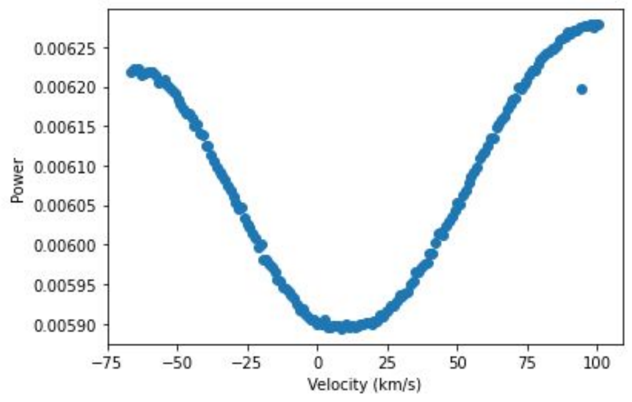
Signal and background

To verify the signal is from galactic hydrogen:

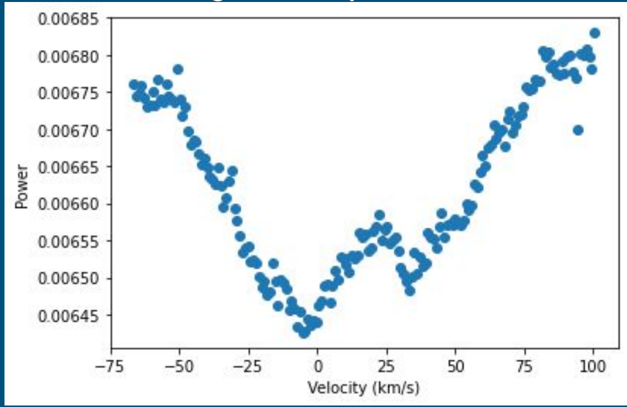
Comparing signals from the ground and the sky

(What is a signal from the ground?)





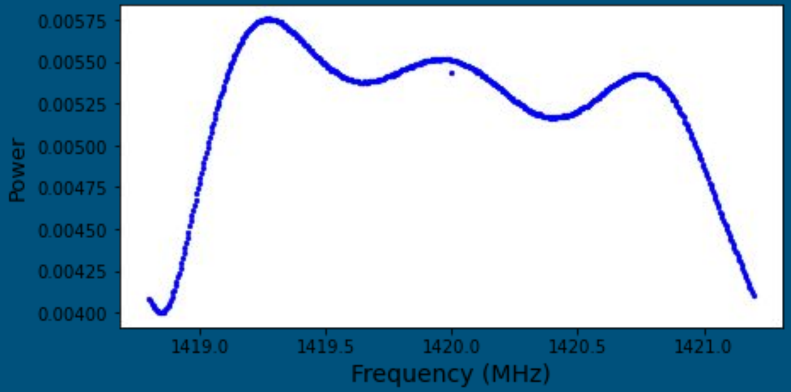
Sky signal away from galactic plane



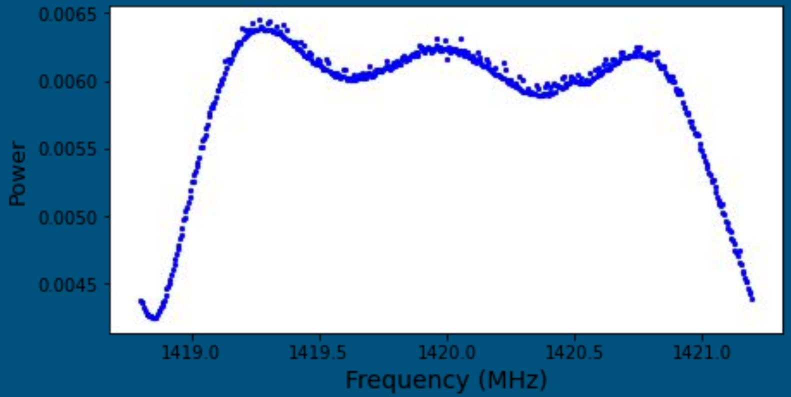
Sky signal towards the galactic plane

Processing data

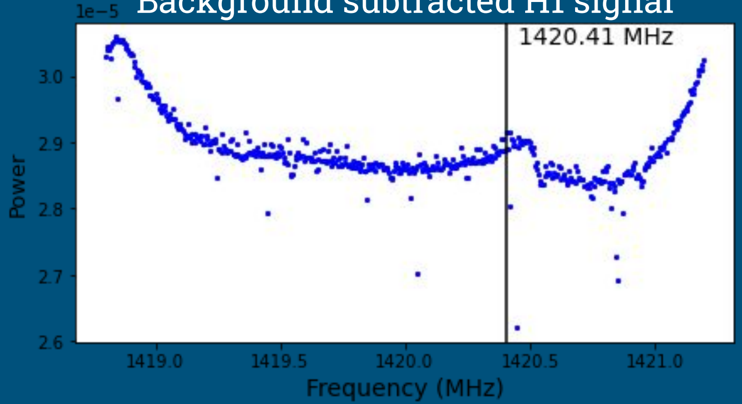
Background signal



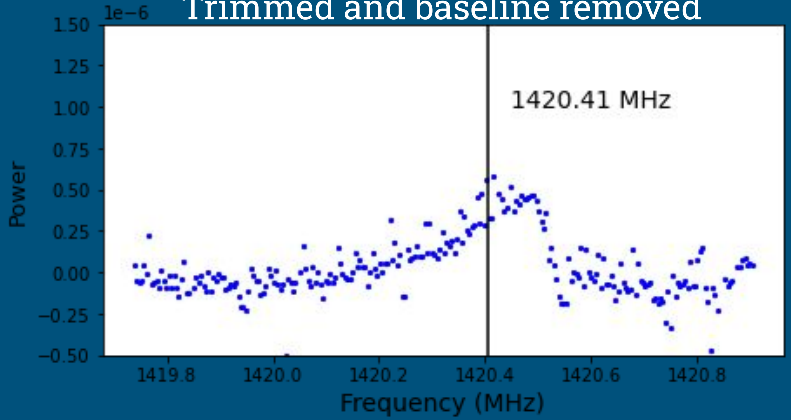
Raw H1 signal



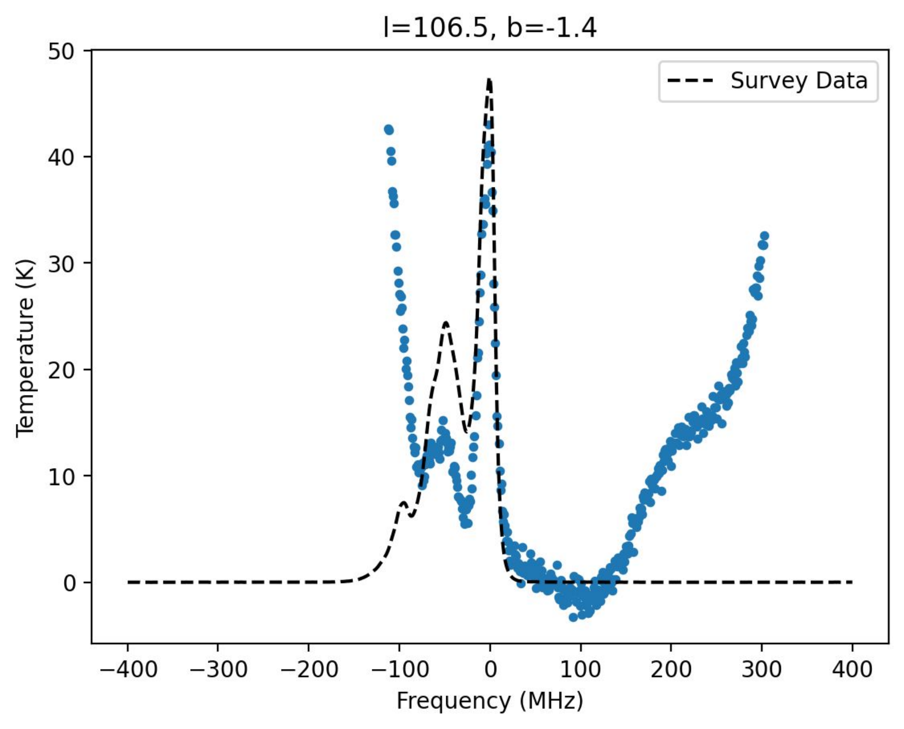
Background subtracted H1 signal

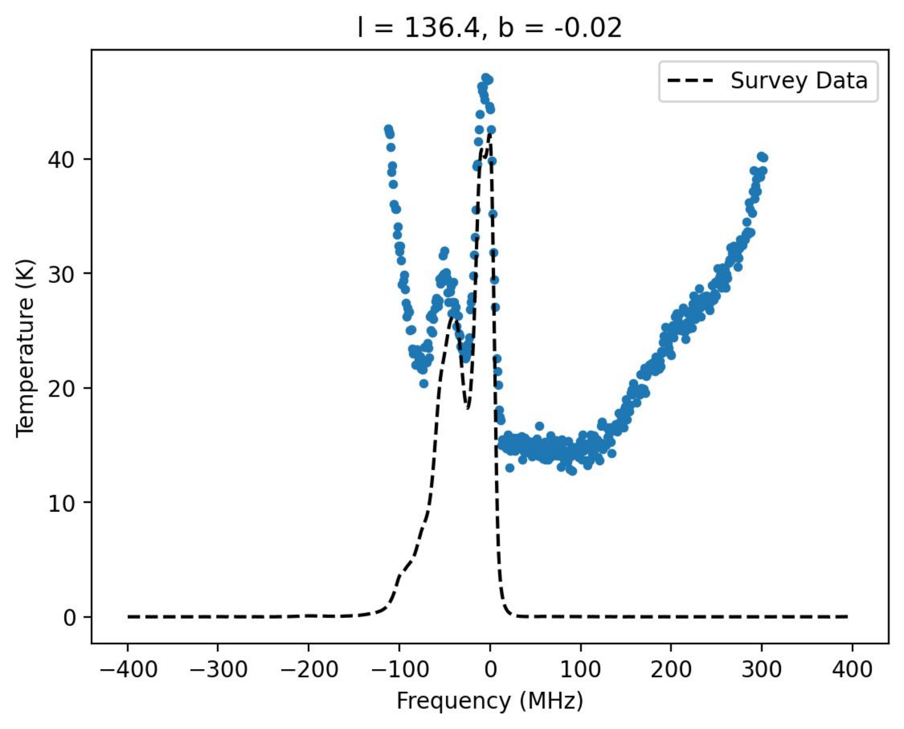


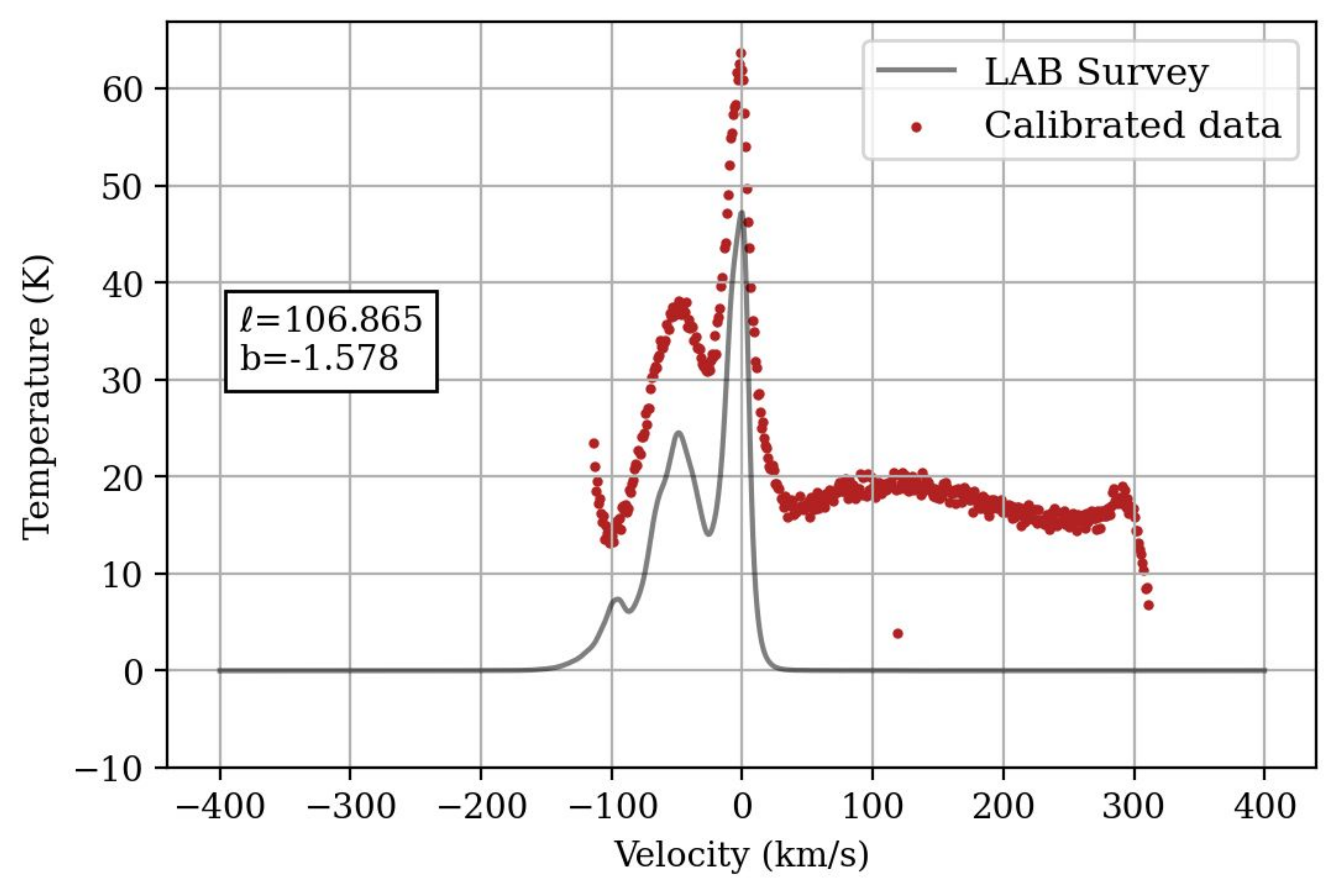
Trimmed and baseline removed



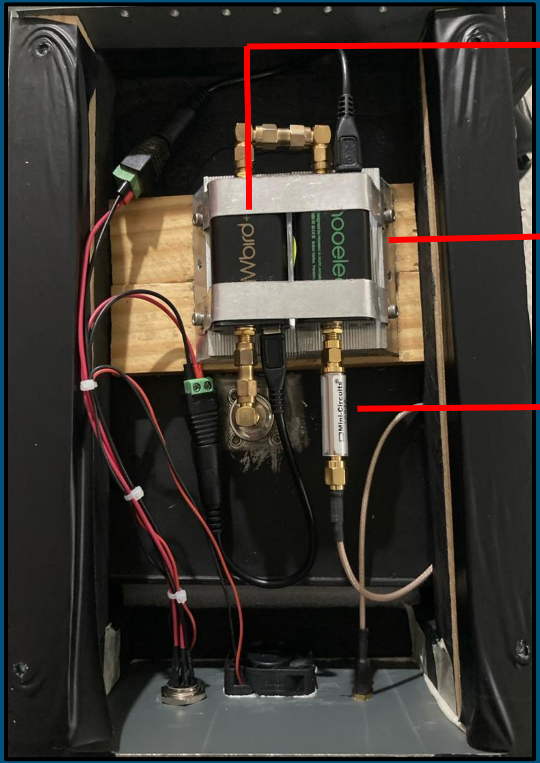
Issues with temperature level






LAB Survey
Calibrated data
ℓ=106.865
b=-1.578
Temperature (K)
Velocity (km/s)
60
50
40
30
20
10
0
−10
−400
−300
−200
−100
0
100
200
300
400

Electronics



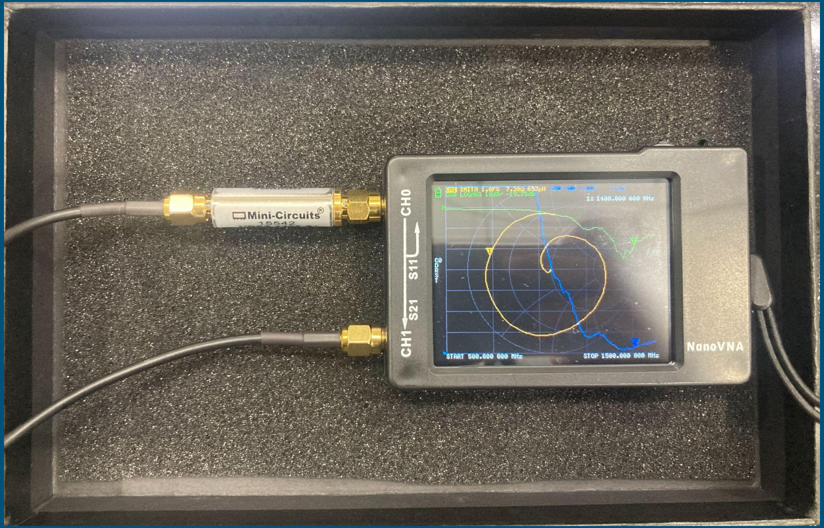
SAWBird amplifier: Two LNAs with a SAW filter. Overall gain of 40 dB at 1420 MHz. Bandpass width of 65 MHz

Nooelec LaNA: Broadband low-noise amplifier, gain of 20 dB at 1000 MHz

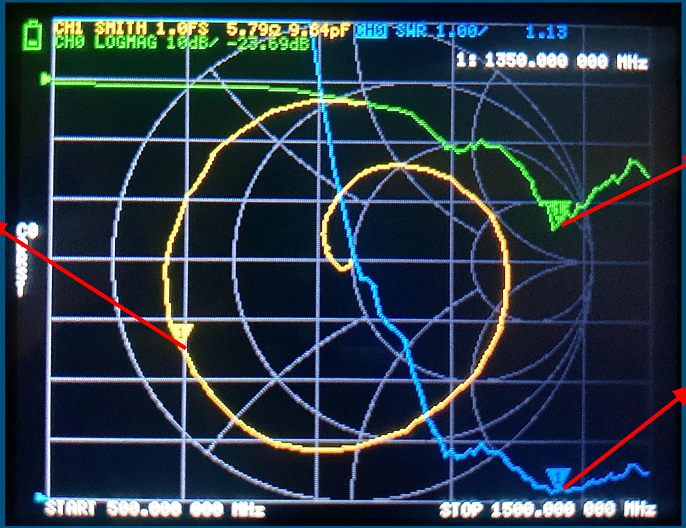
Minicircuits Bandpass filter: 100 MHz bandpass region centered on 1400 MHz

NanoVNA

- Using log-mag mode to measure overall amplification/attenuation
- Using the Smith chart to measure impedance
- Characterization of passive elements like bandpass filter.

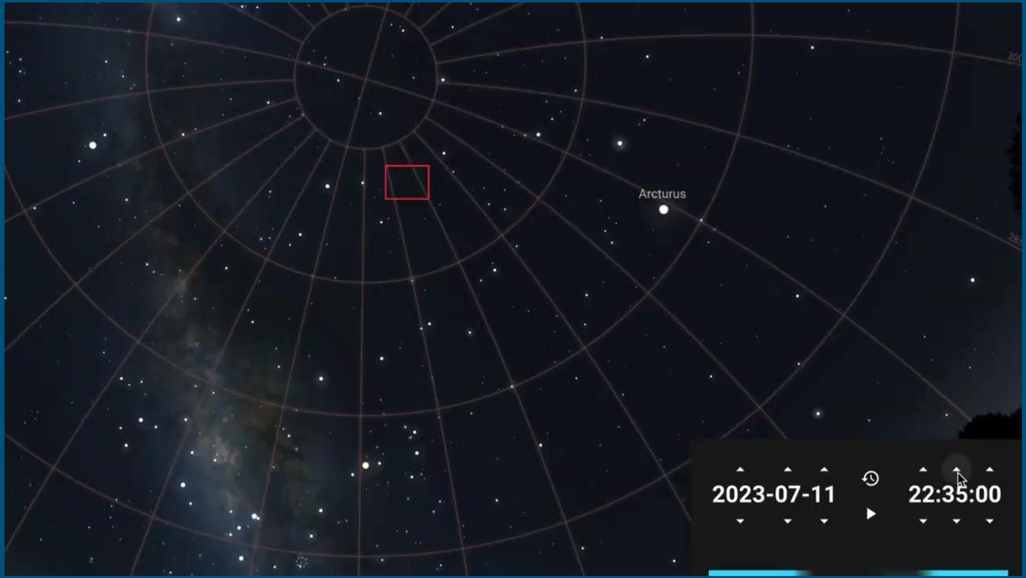


Impedance function



Log-Mag plot

SWR plot


Arcturus
2023-07-11
22:35:00

Verifying the signal: Long Exposure Signal

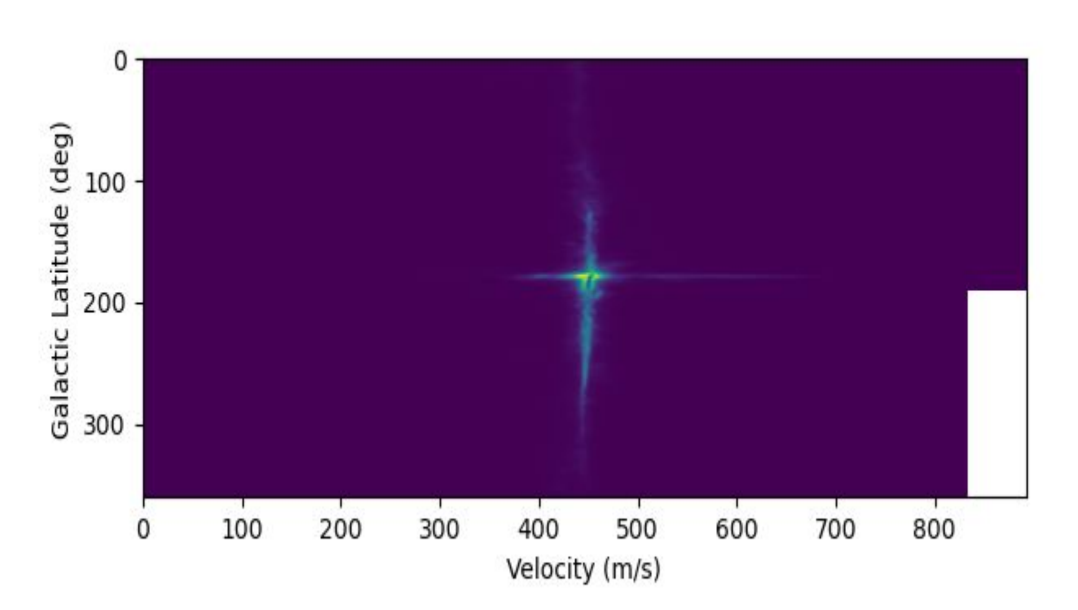
- To check whether the strength of the signal varies as the galactic plane passes in and out of view.
- Horn kept fixed from 10:30 PM to 4:00 AM
- Altitude: 73°, Azimuth: 220°
- Total of 60 files recorded: each ~5 minutes

Automatic background subtraction by SDR#

Plotted values =
Signal – Final file – Fitted Baseline

Verifying signal- LAB Survey

Kalberla, P.M.W., Burton, W.B., Hartmann, Dap, Arnal, E.M., Bajaja, E., Morras, R., & Pöppel, W.G.L. (2005), A&A, 440, 775 (Kalberla et al. (2005))



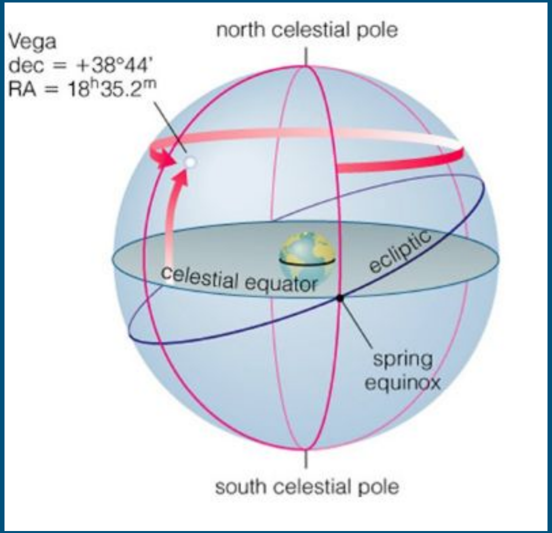
The Leiden/Argentine/Bonn (LAB): Galactic survey of the H1 signal, mapping the strength and position of the 21-cm line across the entire sky. Most sensitive and extensive survey to date. Data is online for free access.

Measurements were taken using radio telescopes that had an effective beam width of approximately 0.6^{o}.

Velocity Correction: Local Standard of Rest (LSR)

Solar Apex (near Vega): (α_s, δ_s)

Radio Source observed: (α, δ)



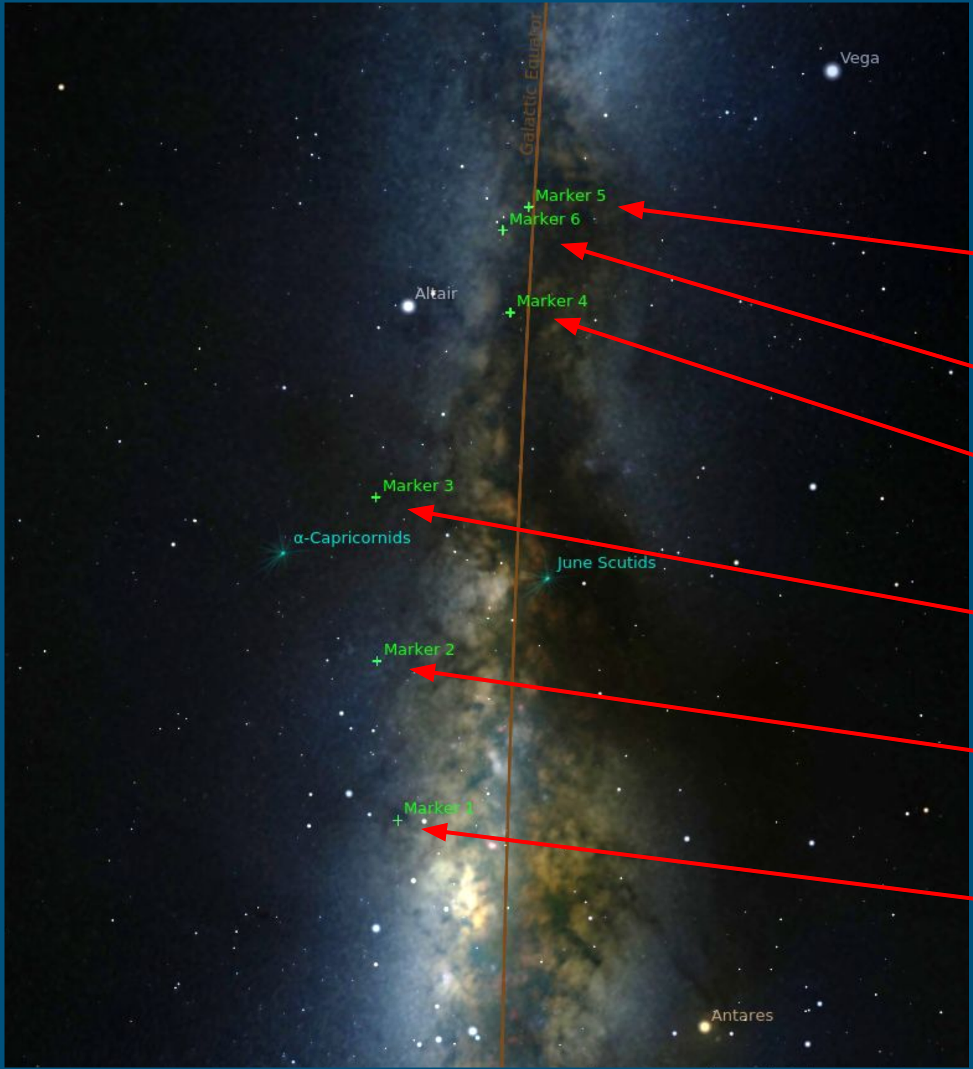
Litster, MIT, 2013.

Motion of the Earth relative to the Sun

$$V_{\mathrm{rE}} = 30.0\,[\cos\beta\sin\lambda_\odot\cos\lambda - \cos\beta\cos\lambda_\odot\sin\lambda]$$

Motion of the Sun relative to the galactic center

$$v_{\mathrm{rs}} = 20.5(\cos\alpha_s\cos\delta_s\cos\alpha\cos\delta + \sin\alpha_s\cos\delta_s\sin\alpha\cos\delta + \sin\delta_s\sin\delta)$$



Measuring H1 along the Galactic Plane- Facing South

Galactic longitude = 79.1,
Latitude = 0.9

Galactic longitude = 62.1,
Latitude = 0.8

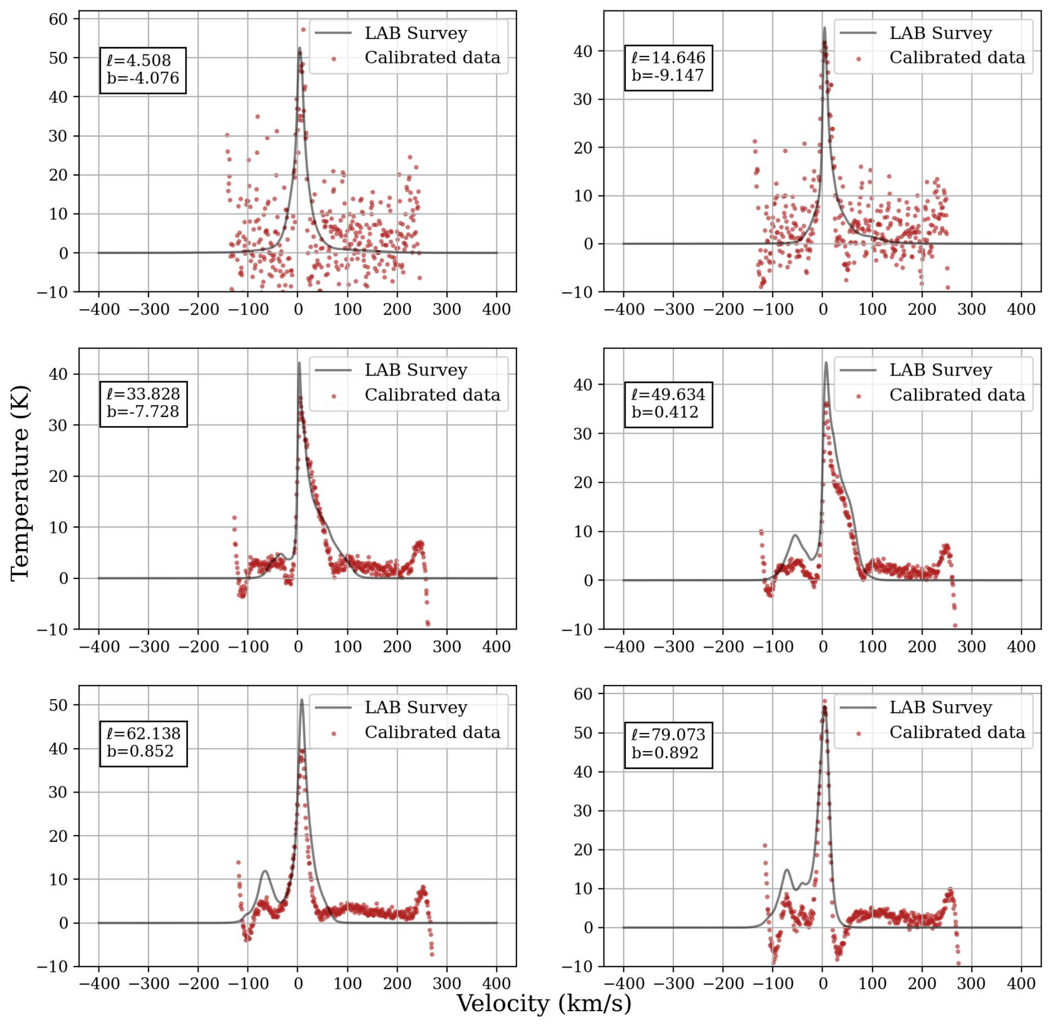
Galactic longitude = 49.6,
Latitude = 0.4

Galactic longitude = 33.8,
Latitude = -7.7

Galactic longitude = 14.6,
Latitude = -9.1

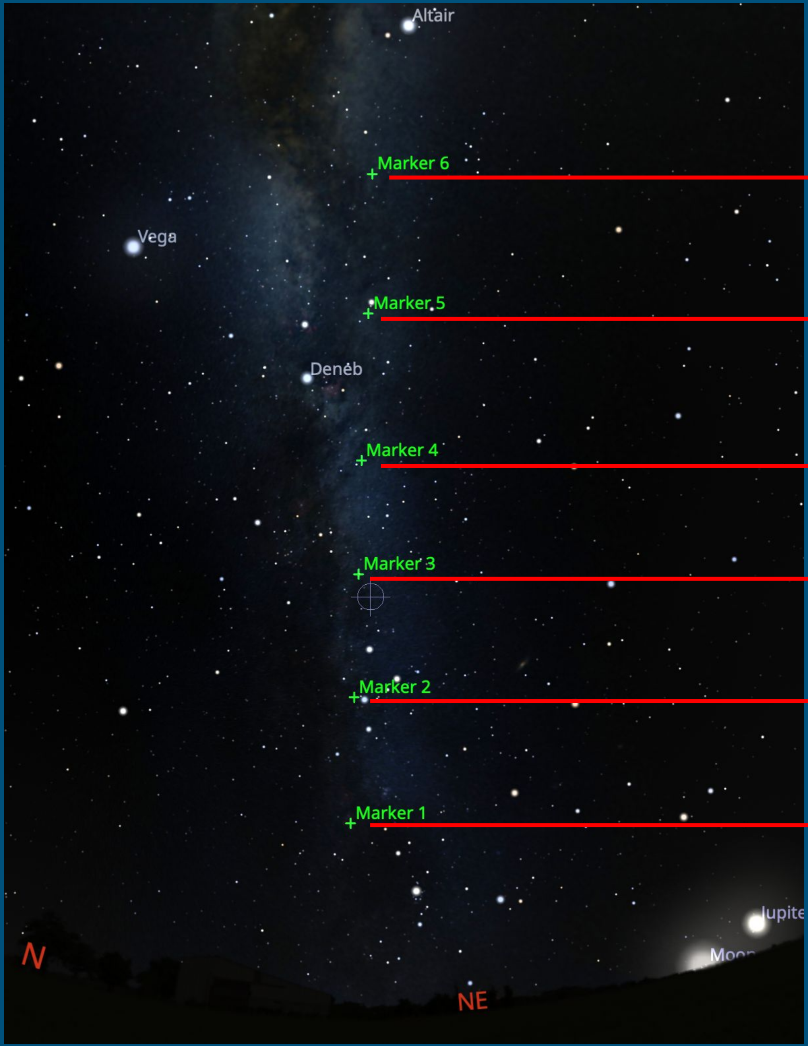
Galactic longitude = 4.5,
Latitude = -4.1

Stellarium Desktop



LAB Survey
Calibrated data
ℓ=4.508
b=-4.076
ℓ=14.646
b=-9.147
ℓ=33.828
b=-7.728
ℓ=49.634
b=0.412
ℓ=62.138
b=0.852
ℓ=79.073
b=0.892
Temperature (K)
Velocity (km/s)

Measuring H1 along the Galactic Plane- Facing North



Galactic longitude = 135.6,
Latitude = -0.4

Galactic longitude = 121.2,
Latitude = -0.7

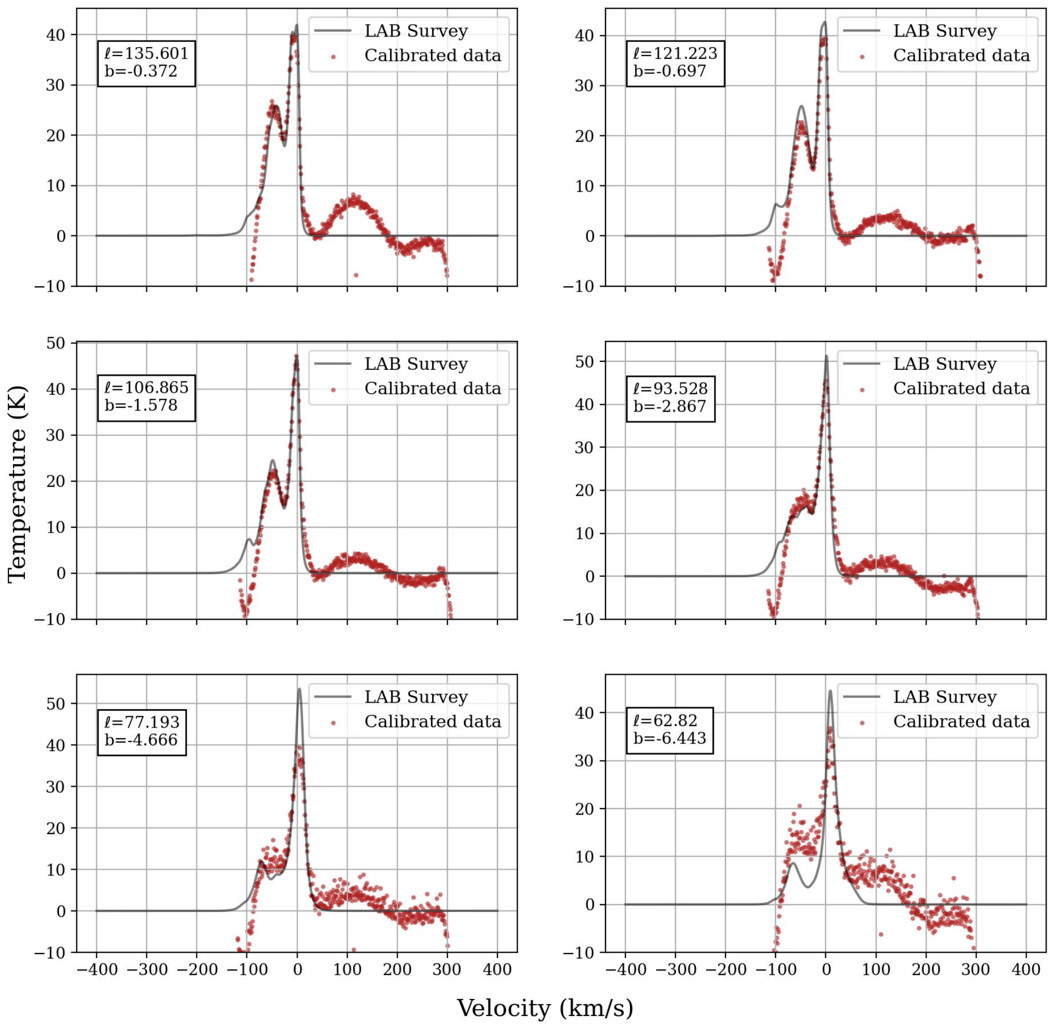
Galactic longitude = 106.9,
Latitude = -1.6

Galactic longitude = 93.5,
Latitude = -2.9

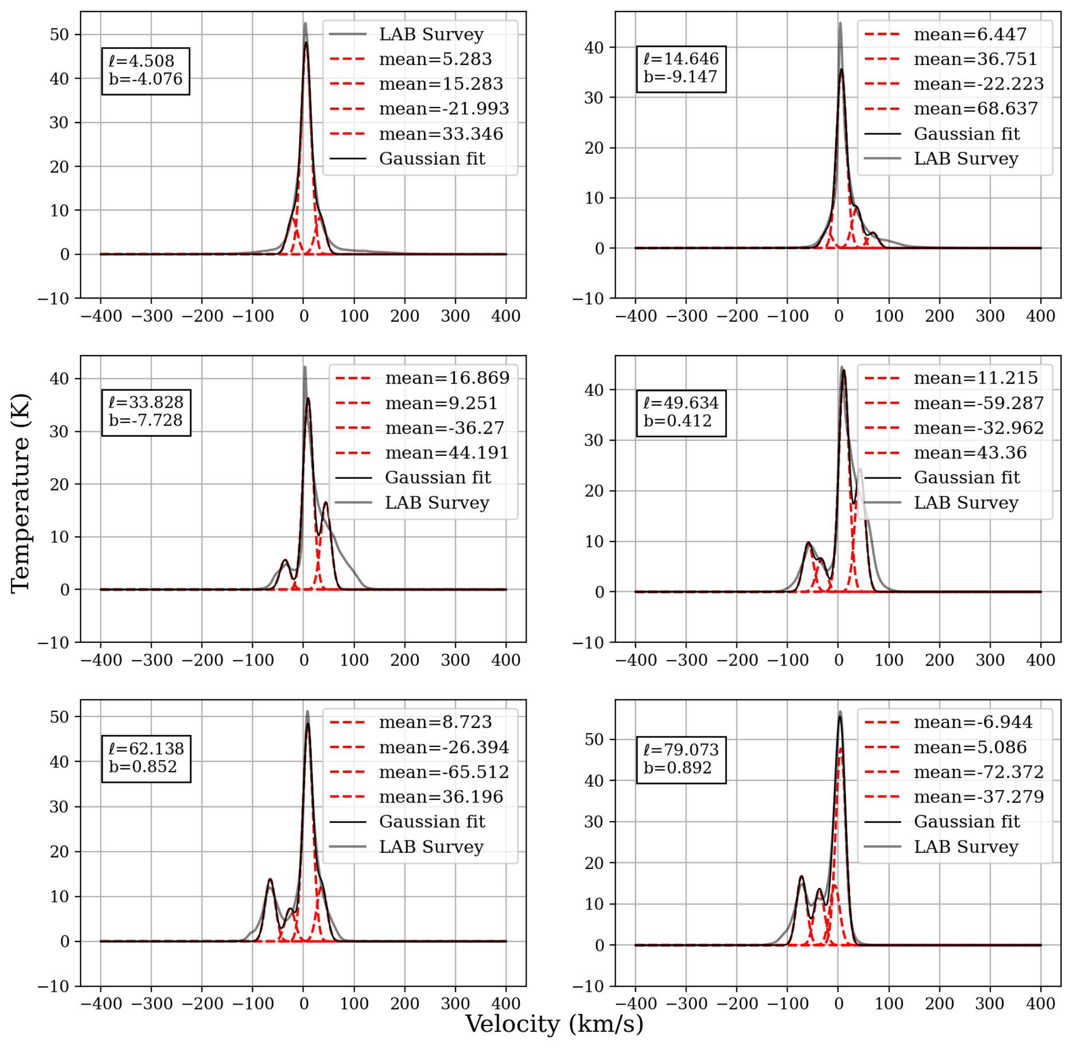
Galactic longitude = 77.2,
Latitude = -4.7

Galactic longitude = 62.8,
Latitude = -6.4

Stellarium Desktop



LAB Survey
Calibrated data
ℓ=135.601
b=-0.372
ℓ=121.223
b=-0.697
ℓ=106.865
b=-1.578
ℓ=93.528
b=-2.867
ℓ=77.193
b=-4.666
ℓ=62.82
b=-6.443
Temperature (K)
Velocity (km/s)



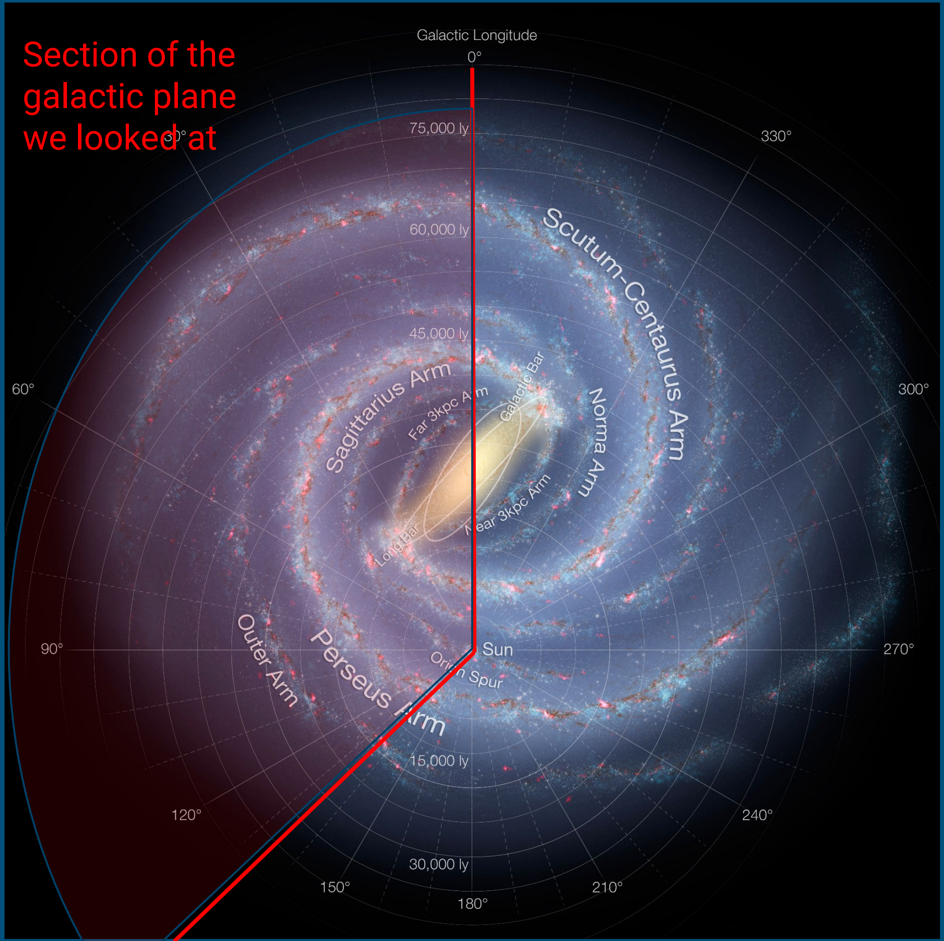
ℓ=4.508
b=-4.076
LAB Survey
mean=5.283
mean=15.283
mean=-21.993
mean=33.346
Gaussian fit
ℓ=14.646
b=-9.147
mean=6.447
mean=36.751
mean=-22.223
mean=68.637
Gaussian fit
LAB Survey
ℓ=33.828
b=-7.728
mean=16.869
mean=9.251
mean=-36.27
mean=44.191
Gaussian fit
LAB Survey
ℓ=49.634
b=0.412
mean=11.215
mean=-59.287
mean=-32.962
mean=43.36
Gaussian fit
LAB Survey
ℓ=62.138
b=0.852
mean=8.723
mean=-26.394
mean=-65.512
mean=36.196
Gaussian fit
LAB Survey
ℓ=79.073
b=0.892
mean=-6.944
mean=5.086
mean=-72.372
mean=-37.279
Gaussian fit
LAB Survey
Temperature (K)
Velocity (km/s)

How we look at the Galactic Plane:

- Pointing in one direction, we are looking across multiple parts of the galaxy.

- Multiple signals overlaid on top of each other.

- If different parts of the galaxy move at different velocities (i.e. what we would see in a rotating galaxy) we would see the same signal at different red/blue shifts.



Galactic Coordinate System: Wikipedia

Thank you.