



Observations of the 21 cm HI line from the milky way galaxy using pyramidal horn radio telescope

KAUSTAV BHATTACHARJEE^{1,2,*} , HIMANSHU GROVER^{1,3} and P ARUMUGAM¹

¹ Indian Institute of Technology Roorkee, Roorkee 247667, India.

²Raman Research Institute, Bengaluru 560080, India.

³National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune 411007, India.

*Corresponding author. E-mail: kaustav_b@ph.iitr.ac.in

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Abstract. We present the design, implementation, and operation of a pyramidal horn radio telescope built for detecting the Galactic 21 cm neutral hydrogen line emission. The system employs a Software-Defined Radio (SDR) based pipeline to obtain drift-scan observations, which were calibrated and processed to generate HI sky maps, a Galactic rotation curve and spiral arm features. This demonstrates that this low-cost system is effective both for educational purposes and scientific exploration of Galactic structure at radio frequencies.

Keywords. Radio telescope—21 cm line—Neutral hydrogen—Pyramidal horn antenna—SDR—Galactic rotation curve—Spiral arms.

1. Introduction

The hyperfine transition line of neutral hydrogen (HI) provides a powerful tool for probing the structure and dynamics of the Milky Way and other galaxies. Spin-spin coupling between the electron and proton of neutral hydrogen atom breaks the spin degeneracy of its 1s ground state and produces two hyperfine levels with an energy gap ΔE given by:

$$\Delta E = \frac{4g_p \hbar^4}{3m_p m_e^2 c^2 a_0^4} = 5.874 \mu\text{eV}, \quad (1)$$

where all symbols have their usual physical meaning (see [Griffiths & Schroeter 2018](#)). The frequency ν of the photon emitted in a transition from the triplet state to the singlet state, using Planck's formula relating energy and frequency, is

$$\nu = \frac{\Delta E}{h} = 1420.405 \text{ MHz}. \quad (2)$$

Dutch astronomer Hendrik van de Hulst predicted the existence of this radio spectral line in 1944 ([van de Hulst 1945](#)). Ever since its first detection in March of 1951 by Harold Ewen and Edward Purcell ([Ewen & Purcell 1951](#)) using a horn antenna at the Lyman

Laboratory of Harvard University, the 21 cm hydrogen line has become a cornerstone of astrophysical research. It enabled astronomers to measure line-of-sight motions of atomic hydrogen by measuring the Doppler shifts in the line's detected frequency. Additionally, because of its long wavelength, this spectral line allowed astronomers to probe the stellar structure of the Galaxy through the extensive clouds of dust in the Galactic plane, which absorb all optical light within merely a few thousand light years ([Binney & Merrifield 1998](#)). This emission line is thus a key observational feature in radio astronomy, providing critical insights into Galactic rotation curves and spiral arm structures ([van de Hulst et al. 1954](#)), and the distribution of interstellar matter.

In recent years, there has been a growing interest in developing accessible and low-cost radio telescope systems to enable student and amateur participation in observational radio astronomy; some of these include instruments such as the BHARAT dual-mode conical horn telescope demonstrated by [Mhaske et al. \(2022\)](#), the 91cm x 81cm aperture pyramidal horn telescope made by [Langston \(2017\)](#), and the 70 cm x 60 cm aperture pyramidal horn designed by [Pandian et al. \(2022\)](#).

The system presented by Pandian *et al.* (2022) employs a pyramidal horn with a wide beam of approximately 30° full-width at half-maximum (FWHM) and 1.953 kHz spectral resolution. While this design is well-suited for detecting large-scale Galactic HI emission, the large beam limits the angular resolution and results in significant spatial blending of emission from different Galactic structures. As a result, the reported spectra focus on integrated emission rather than resolving individual HI components along the line of sight. Additionally, because the instrument operates without a dedicated pointing mechanism, observations were targeted toward specific regions rather than a comprehensive sky survey. Given these design considerations, the data were not intended to constrain the Galactic rotation curve or map spiral arm structures, serving instead a different observational scope.

The pyramidal horn antenna presented by Langston (2017) achieves a substantially narrower beam of approximately 13° FWHM and includes a rudimentary mechanical locking mechanism using a hook and chain, enabling the detection of multiple spectral peaks associated with different Galactic arms; however, the observations were carried out over a relatively short timespan of about one month, and a significant fraction of the data had to be discarded due to adverse weather conditions and radio-frequency interference, resulting in a sky map with incomplete coverage in which the Galactic plane nevertheless remains clearly visible as a continuous high emission band spanning the full sky. Additionally, the study does not proceed to calculate a Galactic rotation curve or to attempt a derivation of the spiral arm structure.

In contrast, the dual-mode conical horn demonstrated by Mhaske *et al.* (2022) had a beamwidth of approximately 16.5° FWHM and reduced far-field sidelobes, enabling the estimation of the Galactic rotation curve and spiral arm structure, although a full-sky HI intensity map was not presented and the horn geometry is comparatively complex to fabricate for an amateur radio astronomer.

We present the design and implementation of a pyramidal horn radio telescope tailored for detecting the 21 cm HI line, developed as part of the activities of the Radio Telescope Project¹ of the Physics and Astronomy Club² at IIT Roorkee. The instrument employs a mechanically simple and easily constructed pyramidal horn with $\sim 20^\circ$ FWHM and a stable locking and pointing mechanism. The system was operated over an



Figure 1. Pyramidal horn radio telescope. The horn antenna is mounted on a support stand with an elevation locking mechanism. The signal processing electronics are housed in the plastic box, with AC power and USB cables connected.

extended observing period spanning several months, producing a full-sky map of Galactic HI emission with complete coverage. The achieved angular resolution and spectral fidelity allow the resolution of multiple HI velocity components and enable quantitative derivations of the Galactic rotation curve and spiral arm structure.

The telescope system described here uses a pyramidal horn antenna optimised for operation at 1.42 GHz, combined with a low-noise receiver chain and Software-Defined Radio (SDR) backend. The complete setup is shown in Figure 1. The primary goal was to make a functional platform capable of detecting Galactic HI emission with sufficient sensitivity and resolution to allow the study of the Milky Way's rotation curve. The outline of the paper is as follows: Section 2.1 discusses the construction of the horn and waveguide. Section 2.2 describes the analogue electronic components and the SDR used in the setup. Section 2.3 then presents the electromagnetic simulations and the characterisation of the antenna performance. Section 2.4 discusses the GNU Radio flowgraph design. The observational strategy is presented in Section 3, covering the scanning and calibration procedures. Section 4

¹<https://iitr.ac.in/rtp>.

²<https://paac.iitr.ac.in/>.

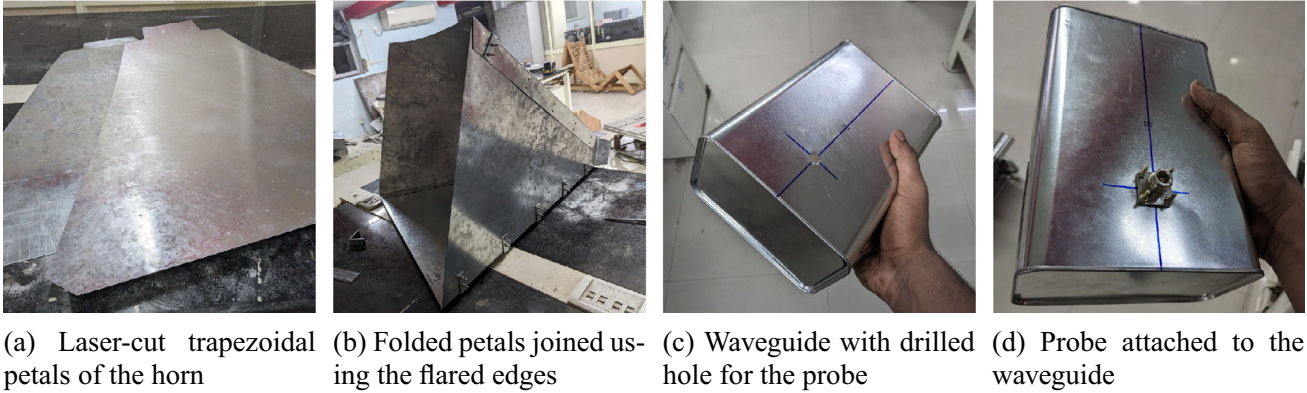


Figure 2. Major steps of construction of the feedhorn assembly. The four petals and the waveguide enclosure were mechanically fastened by drilling and riveting owing to the unavailability of welding equipment, with any remaining gaps sealed by lining the entire internal surface using aluminium tape.

Table 1. Approximate breakdown of the setup cost (in INR).

Component	Quantity	Cost
Stainless Steel sheets	1	Rs. 4,500
Aluminium tape rolls	10–15	Rs. 160
Support stand	1	Rs. 13,800
Nooelec SAWbird + H1 LNA	1	Rs. 6,000
Wideband Amplifier	1	Rs. 22,000
Bandpass Filter	1	Rs. 7,000
USB Power Supply	1	Rs. 200
DC-DC step-up converter	1	Rs. 60
Cables, connectors and rivets	–	Rs. 500
HackRF One SDR	1	Rs. 15,000
Total		~ Rs. 74,220 (approximately \$775 USD)

outlines the data analysis methodology and presents the results of the observations, which include the processed Galactic maps, the derived velocity curve, and the identification of spiral arms. Finally, Section 5 concludes the paper and outlines directions for future work.

2. Design, construction and performance of the antenna

2.1 Construction of horn and waveguide

The feedhorn was constructed following the pyramidal design of the Digital Signal Processing in Radio Astronomy (DSPIRA) project ([West Virginia University Research Experience for Teachers 2020](#)). The aperture dimensions were 75 cm × 60 cm, sufficiently large

to allow passage through most doorways. The fabrication process is summarised in Figure 2. A breakdown of the costs involved in constructing and assembling the setup is provided in Table 1. It should be noted that the overall cost of the setup could be reduced with alternative component choices. For example, a less expensive support stand could be fabricated or sourced, the use of two amplifiers is not strictly required, a lower-cost SDR (like the RTL-SDR Blog V4, the Nooelec NESDR or the Airspy R2) could be substituted for the HackRF One, and the Raspberry Pi could be replaced by an existing desktop or laptop computer. With such substitutions, the total cost could plausibly be reduced to approximately half of that listed in Table 1.

The horn body was fabricated from 1 mm thick stainless steel sheets, which were laser-cut into trapezoidal petals with flared strips along the edges to allow assembly, as seen in Figure 2a. The flares were bent to right angles relative to the petals by hammering them gently, after which the petals were aligned, drilled, and riveted together to form the horn structure, as seen in Figure 2b. A schematic of the dimensions of the horn is shown in Figure 3.

At the narrow end of the horn, a stainless steel enclosure was similarly riveted to house the waveguide. A commercially available F-style 1-gallon rectangular paint thinner can was used as the waveguide, chosen for its suitable dimensions of $16.8 \times 10.2 \times 24.1 \text{ cm}^3$.

The longer side of the aperture is $a = 16.8 \text{ cm}$, which translates to the maximum (cutoff) wavelength of the electric field that can propagate parallel to the long sides $\lambda_c = 2a = 33.6 \text{ cm}$, effectively acting as a high-pass filter with cutoff frequency $\nu_c = c/\lambda_c = 892 \text{ MHz}$. To minimise group velocity dispersion near ν_c , and to avoid higher order modes ($2\nu_c, 3\nu_c, \dots$) that propagate at very different group velocities, waveguides are

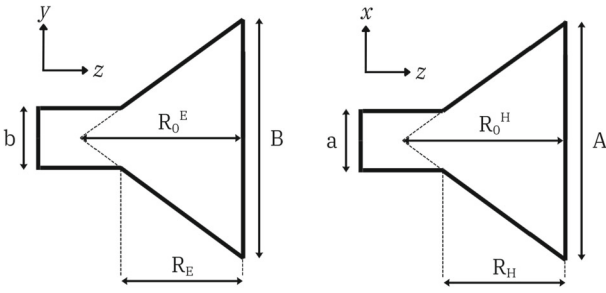


Figure 3. Schematic illustrating the horn geometry. A and B are the dimensions of the aperture of the horn; a and b are the dimensions of the aperture of the waveguide; $R_E (= R_H)$ is the axial length of the horn, and R_0^E and R_0^H are the distances from the virtual apex to the aperture plane in the E-plane and H-plane, respectively.

limited in practice to $\sim 1.25\nu_c$ to $1.9\nu_c$, constraining our observation band to 1115 MHz to 1695 MHz, a band that contains the desired 1420 MHz line quite well in its centre. The shorter side of the aperture is $b = 10.2$ cm, cuts off electric fields that propagate parallel to the shorter sides with frequencies less than $\nu_{c,b} = c/2b = 1469$ MHz, a value greater than the frequency of the most blue shifted hydrogen line frequencies we observe. Taken together, the aperture dimensions of the paint thinner can enforce dominant TE₁₀-mode propagation with minimal group velocity dispersion and suppressed higher-order modal excitation.

The top portion of the can, including the handle and spout, was removed, and a feed port was prepared by drilling a hole in the sidewall 5.25 cm from the closed end, as seen in Figure 2c. This value was adopted from the DSPIRA horn antenna construction guide³. The probe should ideally be located at a backshort distance of a quarter of the guide wavelength,

$$\lambda_w = \frac{c}{\nu} \left[1 - \left(\frac{\nu_c}{\nu} \right)^2 \right]^{-1/2}, \quad (3)$$

which evaluates to 6.78 cm away from the closed end for $\nu = 1420.4$ MHz and $\nu_c = 892$ MHz. In the present implementation, the probe was positioned closer to the closed end than this ideal value. Although this differs from the ideal location, the configuration still provided satisfactory coupling and system performance for the intended application.

An N-type female 4-hole panel mount connector, seen in Figure 2d, was screwed to the waveguide wall, with a 5.25 cm copper wire soldered to its central conductor and extending inside as the probe. The location

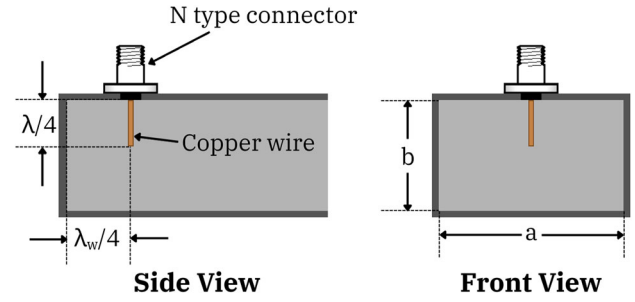


Figure 4. Schematic illustrating the waveguide geometry and the placement of the probe within the waveguide.



Figure 5. Support structure used to mount and orient the feedhorn assembly. Left: the support stand without the feedhorn, showing the square base, the vertical supports, and the horizontal axle that allows rotation in the elevation plane. Right: the elevation locking mechanism, consisting of a threaded locking screw engaging with a perforated steel plate fixed to one of the vertical supports. The array of holes in the plate, spaced at 5° intervals along a semicircular arc, allows the feedhorn elevation to be held securely at discrete angles during observations.

of the probe within the waveguide is illustrated using front and side views in Figure 4. The can was snugly fitted into the aforementioned enclosure, allowing easy removal, reinsertion, or replacement as required.

The interior surfaces of both the horn and the waveguide were lined with aluminium foil tape to improve conductivity. Care was taken to ensure smooth, continuous coverage without gaps. A support stand was manufactured to hold and orient the feedhorn assembly, shown in Figure 5. It was constructed using heavy metal tube welded into a large square base for stability. Two vertical columns were fixed to the base, supporting a horizontal axle that allowed rotation of the mounted feedhorn in the elevation plane. An inner frame, composed of angled iron brackets, was welded to the axle. The feedhorn assembly was fixed in this inner frame by using cables. One end of the axle was equipped with a manual locking mechanism to secure the desired elevation angle. This locking mechanism comprised a steel

³https://www.urail.org/dspira-lessons/FilesUploaded/Horn&Can_Assembly_2021.pdf.

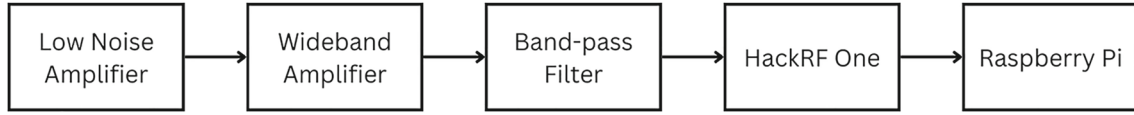


Figure 6. Block diagram of the RF signal chain, showing the major components. The incoming 21 cm signal from the feed passes sequentially through an LNA, a wideband gain stage, and a 1420 MHz band-pass filter before being digitized by the HackRF One SDR. The digitized samples are transferred over USB to a Raspberry Pi, where the GNU Radio observation software performs spectrum acquisition and storage.



Figure 7. Image of the RF signal chain, in a plastic watertight box next to the waveguide, into which the right-angle SMA connector extends. The two amplifiers are seen connected to the dual-port USB phone charger which powers them. The digital signal (white cable) from the HackRF One and the AC power (red and black wires) extend away from the frontend box to a secure room 10 m away, where the Raspberry Pi is.

bar ending in a cylindrical knob with a threaded hole. A locking screw passed through this knob and could be tightened into a perforated steel plate fixed to the outer frame. The plate has an array of holes spaced 5° apart distributed along a semicircular arc, corresponding to different elevation angles. By aligning the screw with the desired hole and tightening it, the feedhorn's elevation could be fixed securely, preventing any unintended motion during observation. The azimuthal orientation of the frame was set using the magnetometer of a mobile phone. The inclinometer was used to verify that the two positions corresponding to northern and southern zenith were aligned with the local horizontal. Based on this, no independent astronomical pointing calibration was performed, as the expected pointing error from this procedure is much smaller than the angular scale set by the feedhorn's beamwidth.

2.2 The radio frequency signal chain

The radio frequency (RF) front-end of the pyramidal horn telescope was designed to receive and amplify weak signals at the neutral hydrogen (HI) line frequency of 1.42 GHz. It consists of a low-noise amplifier (LNA), a wideband amplifier, and a band-pass filter. The conditioned RF signal was then digitised using a HackRF One SDR and subsequently processed and stored on a Raspberry Pi 5 single-board computer. The block diagram and image of the RF signal chain are shown in Figures 6 and 7.

2.2.1 Low-noise amplifier (LNA) The LNA used in the system was the Nooelec SAWbird + H1, a compact, self-contained module specifically designed for hydrogen line observations near 1.42 GHz. It features

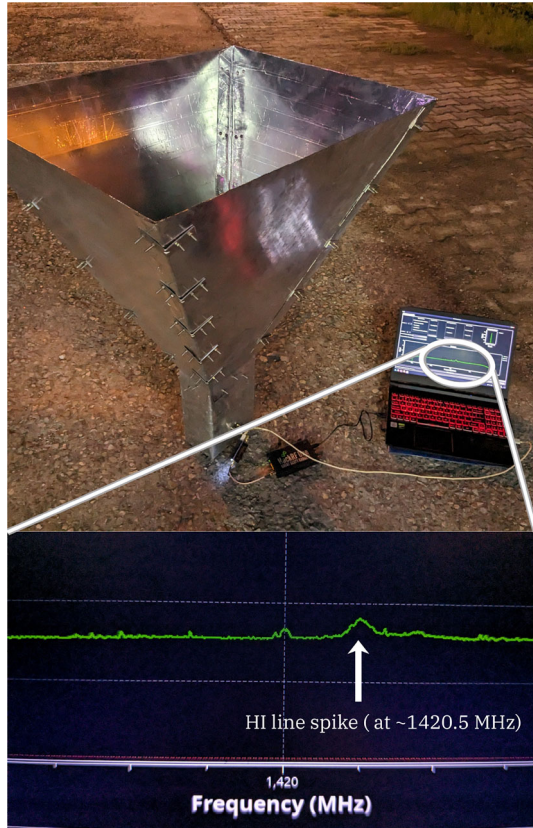


Figure 8. First light of the telescope on 7 August 2023. The horn antenna is oriented upright roughly toward the zenith, and the LNA and the SDR are connected to its probe. The laptop shows a live power spectrum in which the 21 cm HI line from the transiting Galactic plane is visible as a noticeable feature.

a sharp band-pass filter with high out-of-band rejection and provides a typical gain of ~ 40 dB within a 65 MHz bandwidth centred at the target frequency. The module exhibits a low noise figure of ~ 0.8 dB and operates with a nominal current draw of 120 mA. The LNA was powered from one port of a dual-USB phone charger via a micro-USB cable. The LNA was connected to the probe using an N-to-SMA adapter and a right-angle SMA connector. The LNA alone provides sufficient gain for the detection of the HI line without necessarily requiring any of the subsequent amplification and filtering stages. This is demonstrated in Figure 8, where the telescope achieved first light using only the LNA and the SDR. In the photograph, the horn antenna, LNA, SDR, and a laptop displaying the spectrum with the HI line spike visible are shown during the first light test, conducted immediately after the horn was initially assembled, as the Galactic plane transited the local zenith.

2.2.2 Wideband amplifier Following the LNA, the signal was further amplified using the Mini-Circuits ZX60-1614LN-S wideband amplifier. This component offers a noise figure of ~ 0.5 dB, a gain of ~ 14 dB, and a third-order intercept point (IP3) of +30 dBm at 1420 MHz. It operates over the frequency range of 1217–1620 MHz using a DC supply voltage between 11 V and 13 V, with a typical operating current of 42 mA (maximum 50 mA). The second port of the aforementioned dual-USB phone charger powered the wideband amplifier, with the 5 V and ground lines extracted from the USB connection and soldered to an XL6009 DC–DC step-up converter, whose output was adjusted to 13 V using the onboard potentiometer and then connected to the amplifier.

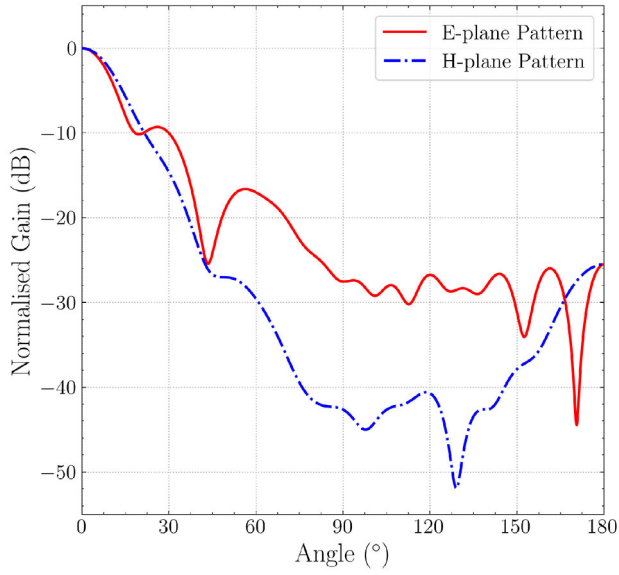
2.2.3 Band-pass filter A Mini-Circuits ZX75BP-1500-S+ lumped-element LC band-pass filter was employed to isolate the desired frequency band. This filter passes signals in the 1350 MHz to 1650 MHz range, attenuating out-of-band noise and interference while preserving the integrity of the hydrogen line signal.

2.2.4 Software-defined radio receiver Signal digitization was performed using the HackRF One, a versatile software-defined radio capable of both transmission and reception over a wide frequency range from 1 MHz to 6 GHz. This open-source, half-duplex transceiver supports a sampling rate of up to 20 million samples per second and provides 8-bit quadrature sampling (8-bit I and 8-bit Q). It is operated as a USB peripheral and is compatible with GNU Radio⁴ for signal processing and analysis.

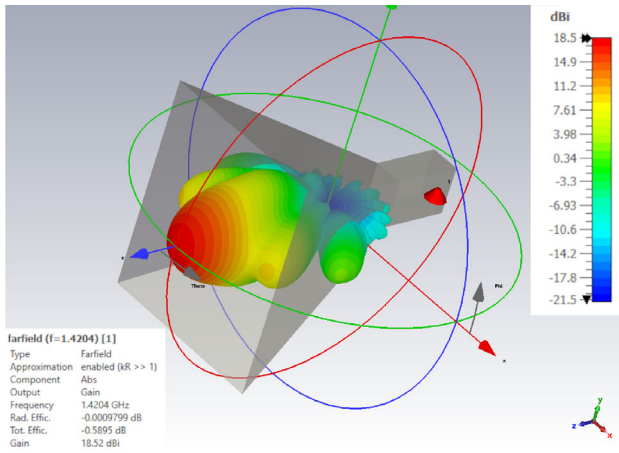
2.3 Simulation of antenna performance

Electromagnetic (EM) simulations of the antenna were performed in CST Studio Suite (Dassault Systèmes Simulia Corp.), a commercial EM analysis software package. The radiation pattern of the horn antenna was computed in the far-field (Fraunhofer) radiation zone. Figure 9 shows the simulated two-dimensional and three-dimensional radiation patterns. The radiation pattern was analysed to determine the FWHM of the main lobe, which was 18.1° in the E-plane and 21.3° in the H-plane. The simulated maximum gain is 18.5 dBi, which was used to normalise the radiation patterns shown in Figure 9a.

⁴<https://www.gnuradio.org/>.



(a) Normalised radiation patterns in the E-plane and H-plane.



(b) Three-dimensional simulated radiation pattern of the horn antenna.

Figure 9. Simulated radiation characteristics of the horn antenna at 1420 MHz. The FWHM of the main lobe is 18.1° in the E-plane and 21.3° in the H-plane. The worst sidelobe level is -9.3 dB in E-plane (red curve in Figure 9a).

The effective aperture area A_e for a gain (G) of 18.5 dBi and wavelength (λ) is calculated as:

$$A_e = \frac{\lambda^2 G}{4\pi} = 0.251 \text{ m}^2. \quad (4)$$

The aperture efficiency η is then obtained as:

$$\eta = \frac{A_e}{A_{\text{phys}}} = 55.8\%, \quad (5)$$

where A_{phys} is the physical aperture area of the horn. The total noise figure of the receiver chain, NF_{total} , is calculated using the Friis formula (Kraus 1966):

$$NF_{\text{total}} = NF_1 + \sum_{i=2}^n \frac{NF_i - 1}{\prod_{j=1}^{i-1} G_j}, \quad (6)$$

where NF_i and G_j are the noise figure and gain of the i -th and j -th stages respectively, and n is the total number of stages.

For the present setup, the first-stage LNA contributes approximately 0.8 dB to the receiver noise figure, while the contribution from the second stage, after accounting for the gain of the first stage through the Friis formula, is only ~ 0.00004 dB. Consequently, the overall receiver noise figure is effectively $NF_{\text{total}} \approx 0.8$ dB. The corresponding equivalent noise temperature T_{noise} is related to the noise figure NF by

$$T_{\text{noise}} = T_{\text{ref}} \left(10^{NF/10} - 1 \right), \quad (7)$$

where $T_{\text{ref}} = 300$ K is the standard reference temperature, customarily taken to be the room temperature. Using this relation, the total noise figure corresponds to an equivalent receiver noise temperature of approximately 60.68 K. As expected, the overall receiver noise figure is dominated by the first amplifying stage, since the contribution of all subsequent stages is suppressed by the gain of the LNA.

2.4 Software architecture

2.4.1 GNU radio flowgraph design The software spectrometer was implemented using a custom GNU Radio flowgraph, as shown in Figure 10, that performed a series of signal processing steps tailored for hydrogen line observations. The modular structure of the flowgraph allows real-time visualisation of system temperature, gain, and signal spectrum, as well as user control over integration time, frequency settings, and output modes.

2.4.2 Fourier transform pipeline The HackRF SDR receives the RF signal centred around the 21 cm hydrogen line. The receiver frequency was set to 1419.5 MHz within GNU Radio. A stream-to-vector block segmented the incoming data stream into vectors of length 4096. To reduce spectral leakage and improve channel isolation, a polyphase filter bank was implemented. The total filter length is $4 \times 4096 = 16384$ samples. This filter is partitioned into four polyphase components, each corresponding to a contiguous segment of length 4096.

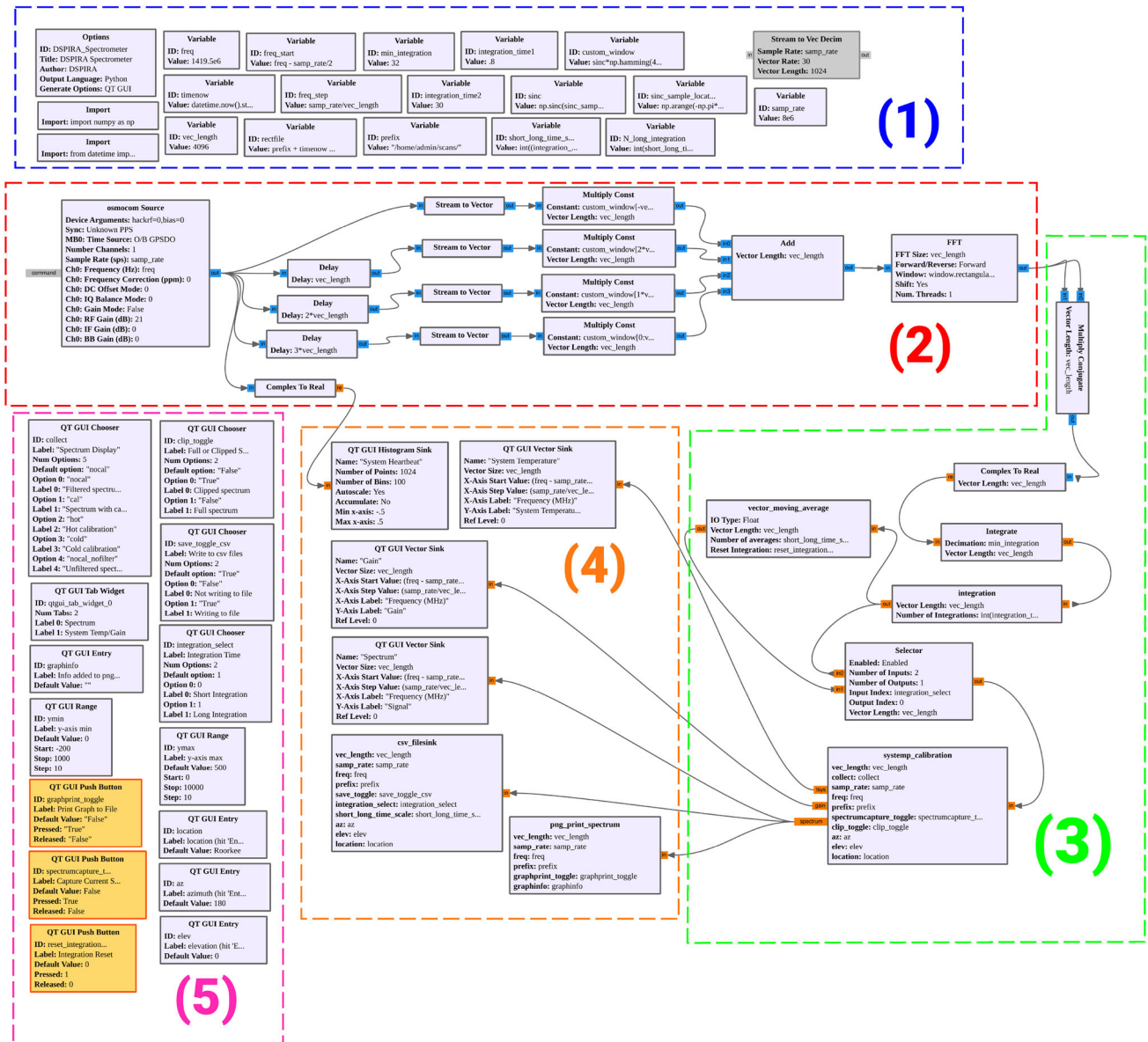


Figure 10. GNU Radio Flowchart. The blocks in the blue box (1) define usage options, imports, and variables. The blocks in the red box (2) show the RTL-SDR source, polyphase filter, and FFT calculation block. Following that, the blocks in the green box (3) perform integration, averaging, and file output. The blocks in the orange box (4) include all QT GUI display modules, while those in the pink box (5) manage the options for the GUI modules.

The input stream is split into four branches with relative delays of 0, 4096, 8192, and 12288 samples. Each branch is converted into vectors of length 4096 and multiplied element-wise by the corresponding segment of a prototype filter constructed as a sinc function tapered by a Hamming window. The weighted outputs from all branches are then summed element-wise to form a single filtered vector, which is passed to a 4096-point Fast Fourier Transform (FFT) to obtain the frequency spectrum. Each FFT operates on 4096 samples at a

sampling rate of 8 MHz, corresponding to $512 \mu\text{s}$ per spectrum.

The FFT output was multiplied by its complex conjugate to get the power spectral density (PSD). The resulting real-valued PSD was averaged over 16 consecutive spectra (8.192 ms). Further accumulation yields a total integration time of 30 s used in this work, with optional additional smoothing via a moving average. The integration time is user-configurable within the pipeline. The final output was visualised in real-time

using QT GUI sinks and was saved continuously for post-processing as well.

2.4.3 Data logging and storage format The processed spectra were timestamped using the system time from the Raspberry Pi and stored in CSV files using the Python `csv_filesink` block within the GNU Radio environment. Each file name includes the acquisition time, allowing for easy temporal referencing.

Calibration periods were identified by recording the start and end times of the hot-load measurements, during which the antenna was pointed toward the ground for more than an hour between successive drift scans. The time ranges corresponding to each fixed elevation setting were also recorded, allowing the sky data from each drift scan to be associated with the correct antenna elevation during later analysis.

The system was designed for unattended operation. When data logging is enabled, new files are automatically created after each integration interval. This one-file-per-integration approach follows the native behaviour of the GNU Radio pipeline and was retained to minimise additional custom blocks and software complexity. Additionally, writing each integration to a separate file ensures that data already written to disk remain intact in the event of power interruptions or system failures. This automation ensures continuous data acquisition over long observation sessions.

3. Observational strategy

3.1 Scanning

The antenna was aligned along the local meridian (North–South direction), allowing the centre of the beam to sweep across the sky from the northern to the southern horizon through the zenith when movement was not locked. At discrete elevation angles ranging from near the Celestial North Pole down to the southern horizon, the antenna was fixed, and the sky was allowed to drift past the beam over a full 24-hour period. This resulted in a series of drift scans at different declinations, enabling coverage of the entire visible sky over time. The observations analysed in this work were acquired between January and May 2025.

3.2 Calibration

Between each change in elevation, i.e., after each complete drift scan, the antenna was manually pointed toward the ground for more than an hour. This position

served as the hot load, assumed to have a brightness temperature of approximately 300 K. For cold load calibration, each drift scan was examined to identify regions with the highest Galactic latitude, i.e., areas farthest from the Galactic plane, where the contribution from neutral hydrogen is minimal. These regions predominantly contain only atmospheric emission, cosmic microwave background (CMB), and receiver noise, and are therefore used to define the cold load reference, assumed to have a brightness temperature of approximately 10 K, consistent with the single-dish HI experiment reported by [Saje & Vidmar \(2017\)](#).

The peak brightness of the HI line in the collected spectra is significantly less than the peak brightness in the spectra obtained from radio telescopes with better spatial resolution, such as in the HI4PI all-sky database of Galactic HI ([HI4PI Collaboration et al. 2016](#)), which is based on the Effelsberg-Bonn HI Survey (EBHIS) ([Winkel, B. et al. 2016](#)) and the Galactic All-Sky Survey (GASS) ([McClure-Griffiths et al. 2009](#)). This is because the temperature detected at an antenna T_A is

$$T_A = \frac{\int_0^{2\pi} \int_0^\pi G(\theta, \phi) T_b(\theta, \phi) \sin(\theta) d\theta d\phi}{\int_0^{2\pi} \int_0^\pi G(\theta, \phi) \sin(\theta) d\theta d\phi}, \quad (8)$$

where $G(\theta, \phi)$ is the antenna gain pattern, and $T_b(\theta, \phi)$ is the brightness temperature of the sky. In plain words, the temperature T_A is the weighted average of the temperature of the sky (and the ground) weighted by the beam pattern of the antenna. A beam pattern with a smaller spread will be truer to the actual nature of the sky, and conversely, a beam pattern with a larger spread will show a smudged view of the sky. The Effelsberg 100-m Radio Telescope, which was used in EBHIS, and the Murriyang, the 64-m CSIRO Parkes Radio Telescope, which was used in GASS, have enormously better beam patterns and sensitivities than our humble horn antenna, and observe a multitude of narrowly separated peaks in the HI line spectrum near the Galactic plane, where we can only resolve a few widely separated peaks.

We convoluted the spectra from the HI4PI database with the simulated beam pattern we discussed in Section 2.3. The peak brightness temperatures of the resulting beam-convolved spectra were compared with the peak temperatures measured in our crudely calibrated observations. This comparison was performed in 5° bins in Equatorial coordinates. From the mean of the ratio of the HI4PI-based peak temperatures to the observed peak temperatures, we derived a calibration factor for each declination drift scan. These factors were subsequently applied as multiplicative corrections to the corresponding observed spectra.

A systematic frequency drift was observed in the spectra, presumably instrumental in origin. The HackRF One SDR was tested by capturing the digitized spectrum using a APSIN3000 AnaPico signal generator. A frequency sweep confirmed a 26.35 ppm mean drift observed across the band. This corresponds to a correction in line-of-sight velocity of 7.90 km/s.

Since this offset is systematic rather than random, it was incorporated as a correction to the line-of-sight velocities prior to converting them into velocities in the Local Standard of Rest frame. Consequently, the derived Galactic rotation curve and the spiral arm structure are based on the corrected velocities and are not systematically biased by the SDR clock drift.

The authors' best guess is that the drift is produced by the 25 MHz X1 crystal oscillator onboard the HackRF One that is used to generate the clock signal for both the local oscillator and ADC/DAC (see the device's block diagram in [Lichtman, 2024](#)), unfortunate as the above specified part is rated to have a frequency stability of less than 20 ppm.

4. Data analysis and results

4.1 RFI detection and mitigation

Radio-frequency interference (RFI) appears in the spectra as narrow high-amplitude spikes at specific frequencies across the observing band. In particular, a comb-like pattern of interference with an approximately 1 MHz spacing was observed consistently, likely originating from internally generated electronic noise within the receiver system or associated digital electronics. To suppress these contaminating features, we first applied a threshold-based flagging method. After flagging, we fit a sum of narrow Gaussian functions plus a smooth baseline to the affected regions. Each Gaussian was centred at a detected RFI spike, and its parameters (amplitude, width, and centre frequency) were optimised to model the shape of the interference. The fitted RFI model was then subtracted from the raw spectrum.

This multi-Gaussian approach was implemented using Python and enabled restoration of underlying Galactic signals while removing narrowband interference. The RFI mitigation was applied only for Galactic longitudes between 0° and 270° , because beyond this range the Doppler-shifted HI emission overlaps with a persistent RFI features near 1420.0 MHz, preventing reliable separation of the astronomical signal from the interference.

4.2 Galactic mapping

Following RFI mitigation, we averaged all calibrated spectra corresponding to each sky position, binned in Equatorial coordinates. Averaging multiple observations enhanced the signal-to-noise ratio and reduced random noise.

For each region, we fit the averaged spectrum using a sum of Gaussian profiles plus a constant baseline. The value of the sum of Gaussian profiles at the position of the Gaussian with the highest amplitude was used as the HI signal strength at that location. The result was a map of neutral hydrogen intensity across the observed sky regions. The number of Gaussian components was determined iteratively by increasing their number until the relative change in the residual variance between successive fits satisfied $\epsilon < 0.05$, where

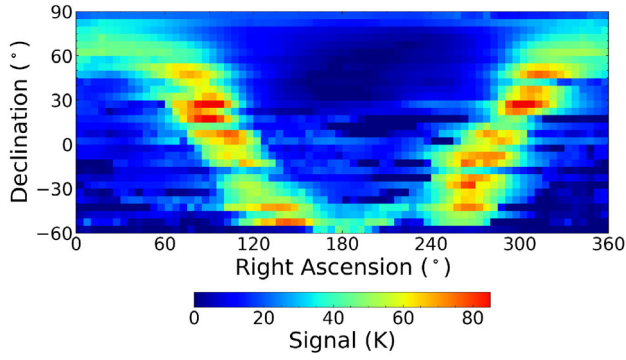
$$\epsilon = \frac{|\sigma_n^2 - \sigma_{n-1}^2|}{\sigma_{n-1}^2},$$

and σ_n^2 is the variance of the residuals for a fit with n Gaussian components. This criterion was used to approximate convergence of the model. The value of the summed Gaussian model at the position of the Gaussian component with the highest amplitude was used as the HI signal strength at that location. The result was a map of neutral hydrogen intensity across the observed sky regions.

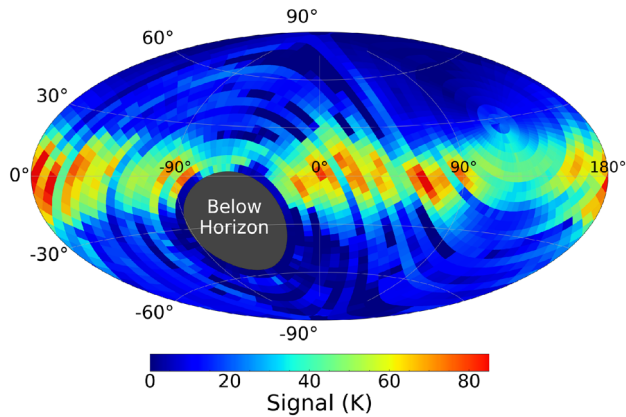
The decomposition of an HI spectrum into Gaussian components is not unique because Gaussian basis functions are not orthogonal, and different combinations of components can reproduce the observed spectral profile. Therefore, the fitted Gaussian components should not necessarily be interpreted as distinct physical structures or individual clouds but instead as a convenient representation of the observed spectral profile ([Haud & Kalberla 2007](#); [Roy et al. 2013](#)). This non-uniqueness is particularly relevant when multiple velocity components overlap along the line of sight, leading to degeneracies in the Gaussian decomposition.

After calibrating and processing the spectral data, the sky maps in Figure 11 were generated to visualise the intensity of the 21 cm line signal at different points in the sky.

Figure 11a was created using Equatorial coordinates and extends to a minimum declination of approximately -60° , corresponding to the southernmost sky visible from the observing site at Roorkee, India ($\varphi \sim 29.86^\circ$ N). Figure 11b used Galactic coordinates projected with an Aitoff projection and includes a grey region around the southern celestial pole that remains permanently



(a) Heatmap in Equatorial coordinate system.



(b) Heatmap in Galactic coordinate system.

Figure 11. All-sky maps of the calibrated HI line intensity derived from our observations, shown in two different coordinate systems. Figure (a) presents the sky map in Equatorial coordinates (right ascension and declination). Figure (b) shows the same data transformed into Galactic coordinates and displayed using an Aitoff projection. A distinct, continuous band of relatively stronger emission corresponding to the Galactic plane is visible across the maps.

below the horizon. These maps trace the structure of the Galactic plane, where the HI signal is strongest, and show a decrease in intensity at higher Galactic latitudes, as expected.

4.3 Doppler velocity calculation

The observed frequency shift of the HI 21-cm line was converted into a Doppler velocity using the radio definition:

$$v = c \frac{\Delta f}{f_0}, \quad (9)$$

where $f_0 = 1420.4058$ MHz is the rest frequency, $\Delta f = f_0 - f_{\text{obs}}$, and c is the speed of light. This yields the line-of-sight velocity relative to the observer's frame on Earth.

To convert the observed radial velocities to the Local Standard of Rest (LSR) frame, Python routines based on the Astropy astronomy library Astropy (Astropy Collaboration *et al.* 2013, 2018, 2022) were used. This implementation was verified against PyAstronomy (Czesla *et al.* 2019) correction routines and an adaptation of the velocity correction calculator developed by F. Ghigo⁵, originally intended for the Green Bank Telescope, with the backend adjusted for the geographic coordinates of the present observing site. The correction was applied in two stages:

1. The barycentric velocity of Earth at the time of observation was calculated using the geographic location of the telescope and the observation time.
2. The solar peculiar motion with respect to the LSR was calculated by adopting the values $(U, V, W) = (11.1, 12.24, 7.25)$ km/s, following the determination by Schönrich *et al.* (2010), where, U is directed radially inwards toward the Galactic Centre, V is along the direction of Galactic rotation, and W points vertically upwards toward the North Galactic Pole.

Both the barycentric and solar peculiar velocities were projected onto the line of sight (LOS) towards the target source by taking the dot product of each velocity vector with the unit vector along the LOS. The sum of these two projections was taken as the velocity correction required, and was computed individually for each observation using the target's coordinates and the time of observation. Figure 12 presents the 21 cm HI line spectrum obtained by averaging all spectra within a 5° bin centred at $(\ell, b) = (82.5^\circ, 0^\circ)$, which is roughly the direction of the Cygnus constellation. The residuals show some of the spurs discussed in Section ?? that could not be removed because they lie within the frequency range where the 21 cm HI line is strong. The Gaussian profiles fitted to the spectrum and the beam-convolved HI4PI spectrum at that region are also shown.

4.4 Velocity-radius curve estimation

To estimate the Galactic rotation curve, we employed the tangent-point method within the inner Galaxy range $0^\circ < \ell < 90^\circ$. For a given Galactic longitude ℓ , the tangent point is the location along the line of sight that is closest to the Galactic Centre, where the line is tangent

⁵<https://www.gb.nrao.edu/~fghigo/gbt/setups/radvelcalc.html>.

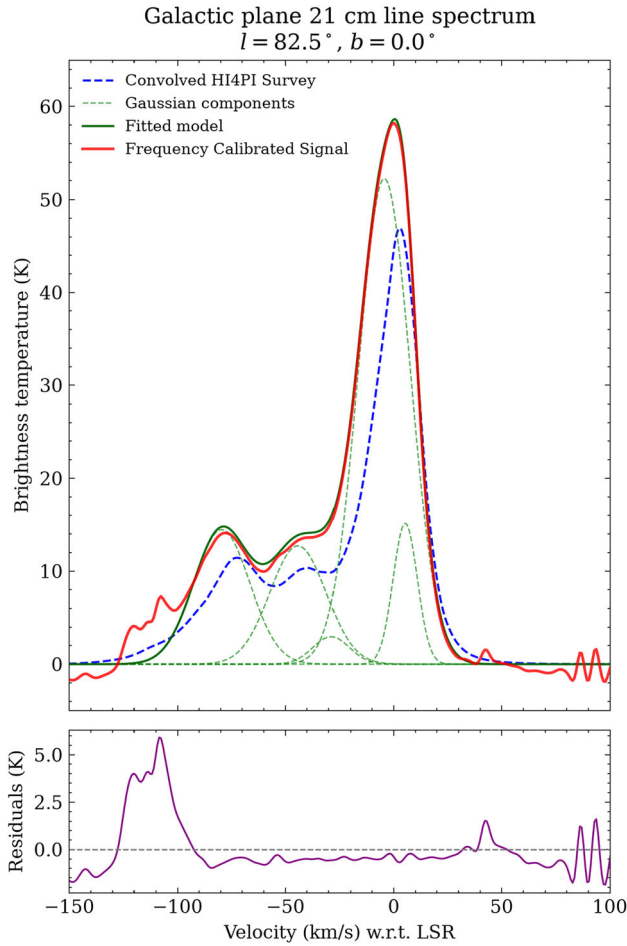


Figure 12. 21 cm HI line spectrum at Galactic longitude $\ell = 82.5^\circ$ and latitude $b = 0^\circ$, approximately in the direction of the Cygnus constellation. The observed line profile is compared with the data from the HI4PI survey convolved with the simulated antenna beam.

to a circular orbit (the assumption that orbits are circular is maintained throughout this study).

From Figure 13, it is clear that from the perspective of an observer in the LSR frame, orbiting the Galactic Centre with velocity V_0 at a distance R_0 away from it, a target that is orbiting the Galactic Centre with velocity $V(R)$ at a distance R away from it, in the Galactic plane at a Galactic longitude ℓ , moves away with velocity V_{obs} :

$$V_{\text{obs}} = V(R) \sin(\theta + \ell) - V_0 \sin \ell. \quad (10)$$

Clearly, along a particular line-of-sight, the maximum line-of-sight velocity V_{max} is observed from the clouds of hydrogen that move satisfying $\sin(\theta + \ell) = 1$, i.e. are on the tangent point for that the Galactic longitude of that line-of-sight, under a not-too-unreasonable assumption that $V(R)$ is not heavily varying with R . Thus, from the spectra from the Galactic plane, for each

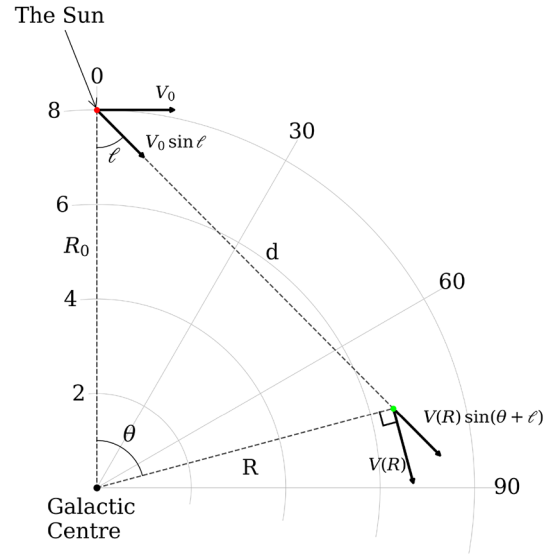


Figure 13. Schematic view of geometry of Galactic rotation and line of sight velocities in the Galactic plane. The observer in the LSR frame, orbiting the Galactic Centre with velocity V_0 at radius R_0 , and the target is orbiting the Galactic Centre with velocity $V(R)$ at radius R .

longitude ℓ , we can calculate the corresponding Galactocentric radius and rotation velocity by selecting the most red-shifted Gaussian component using:

$$R = R_0 \sin \ell, \quad V(R) = V_{\text{max}} + V_0 \sin \ell \quad (11)$$

where V_{max} is the observed velocity of the most red-shifted Gaussian component. Due to the geometric limitation of the tangent-point method being applicable only when the line-of-sight is tangential to an orbit, the rotation curve derived from this method ends at a maximum Galactocentric radius R_0 .

The uncertainty in $V(R)$ was estimated using a Markov Chain Monte Carlo (MCMC) analysis of the Gaussian fits, implemented with the Python package *emcee* (Foreman-Mackey *et al.* 2013). For each fitted Gaussian component, posterior distributions of the amplitude, central velocity, and width were sampled, and the parameter uncertainties were taken from the 16th and 84th percentiles of the marginalized posterior distributions, corresponding to an approximate 1σ interval. The uncertainty in R was derived from the Galactic longitude bin width and propagated through the geometric relations used to compute the Galactocentric radius. These calculations were implemented in Python by binning the data in Galactic longitude, extracting V_{max} from the Gaussian fits, and computing the rotation curve point-by-point.

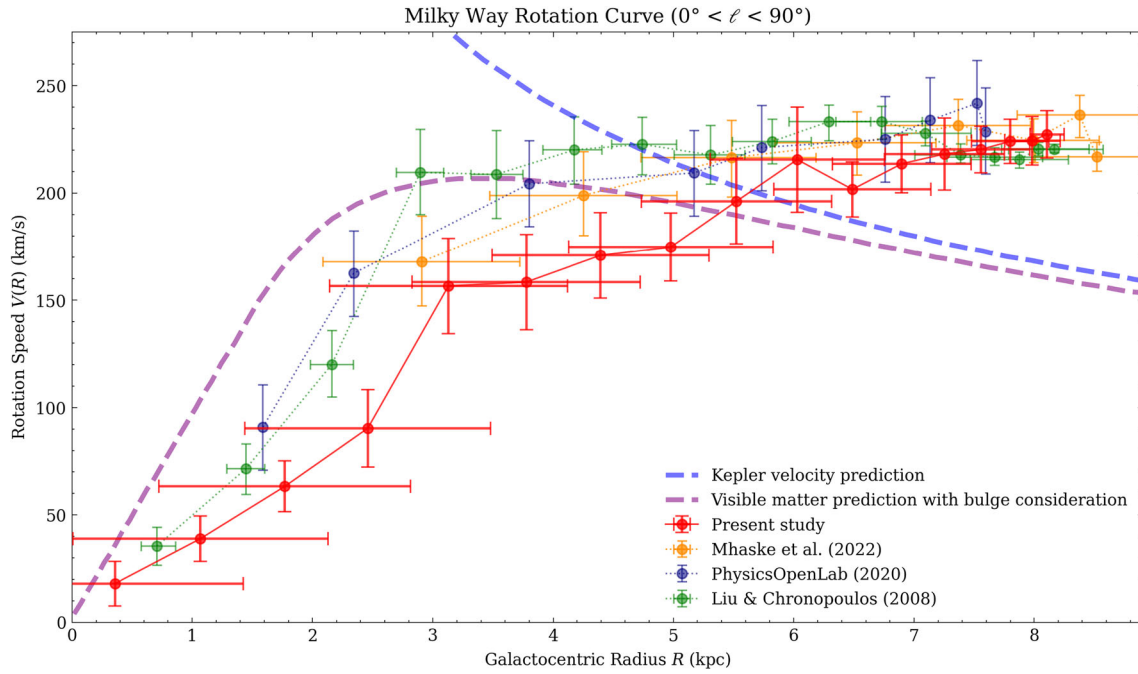


Figure 14. The Velocity-Radius rotation curve for the Milky Way galaxy. The measured rotation curve is consistent with results from similar analyses in the literature and shows a clear deviation from the Keplerian prediction at large Galactocentric radii.

A couple of previous studies have attempted to extend the Galactic rotation curve beyond R_0 using an alternative approach based on a so-called “velocity-vector method” and the application of Oort constants (Pandian *et al.* 2022, Makhijani *et al.* 2024). However, such a method is not used in the present work because the Oort constants are defined through a first-order Taylor expansion of the Galactic angular velocity about the Solar neighbourhood and are strictly valid only for tracers located at distances much smaller than R_0 ($d \ll R_0$). This assumption does not support inferring the rotation curve at Galactocentric radii much larger than R_0 . We therefore restrict our analysis to radii $R \leq R_0$, where the tangent-point method is applicable. The rotation curve can be and has been extended to $R > R_0$ using other sources like stars and masers, and more sophisticated methods, including VLBI and spectroscopy (Sofue 2020).

The resulting rotation curve, shown in Figure 14, is consistent with the general trend reported in the literature (Liu & Chronopoulos 2008, Mhaske *et al.* 2022, Physicsopenlab 2020). The curve rises steeply near the Galactic Centre, reflecting the increasing enclosed mass at small radii, and then gradually flattens at larger distances from the centre. This deviates from the Keplerian and visible matter predictions, according to which the velocity of circularly orbiting matter should decrease as

$V \propto 1/\sqrt{R}$ (Liu & Chronopoulos 2008). This flatness supports the presence of a halo of dark matter, which is invisible in optical and radio frequencies, but provides the additional gravitational force needed to maintain higher-than-expected rotation speeds at large distances (Corbelli & Salucci 2000).

4.5 Spiral arm structure

To infer the large-scale spiral structure of the Milky Way, we make use of the measured line-of-sight velocities of all the Gaussian components, not just the most red-shifted one. Using the law of sines and Figure 13, we get:

$$\frac{R_0}{\sin(\theta + \ell)} = \frac{R}{\sin \ell} = \frac{d}{\sin \theta}, \quad (12)$$

which, using Eq. (10), can be simplified to:

$$\theta = \pi - \left(\ell + \sin^{-1} \left(\frac{R_0}{R} \sin \ell \right) \right), \quad (13)$$

$$R = \frac{V(R) R_0 \sin \ell}{V_0 \sin \ell + V_{\text{obs}}}. \quad (14)$$

For each Gaussian component at each Galactic longitude, the corresponding Galactocentric coordinate (R, θ) was determined under the assumption of a flat

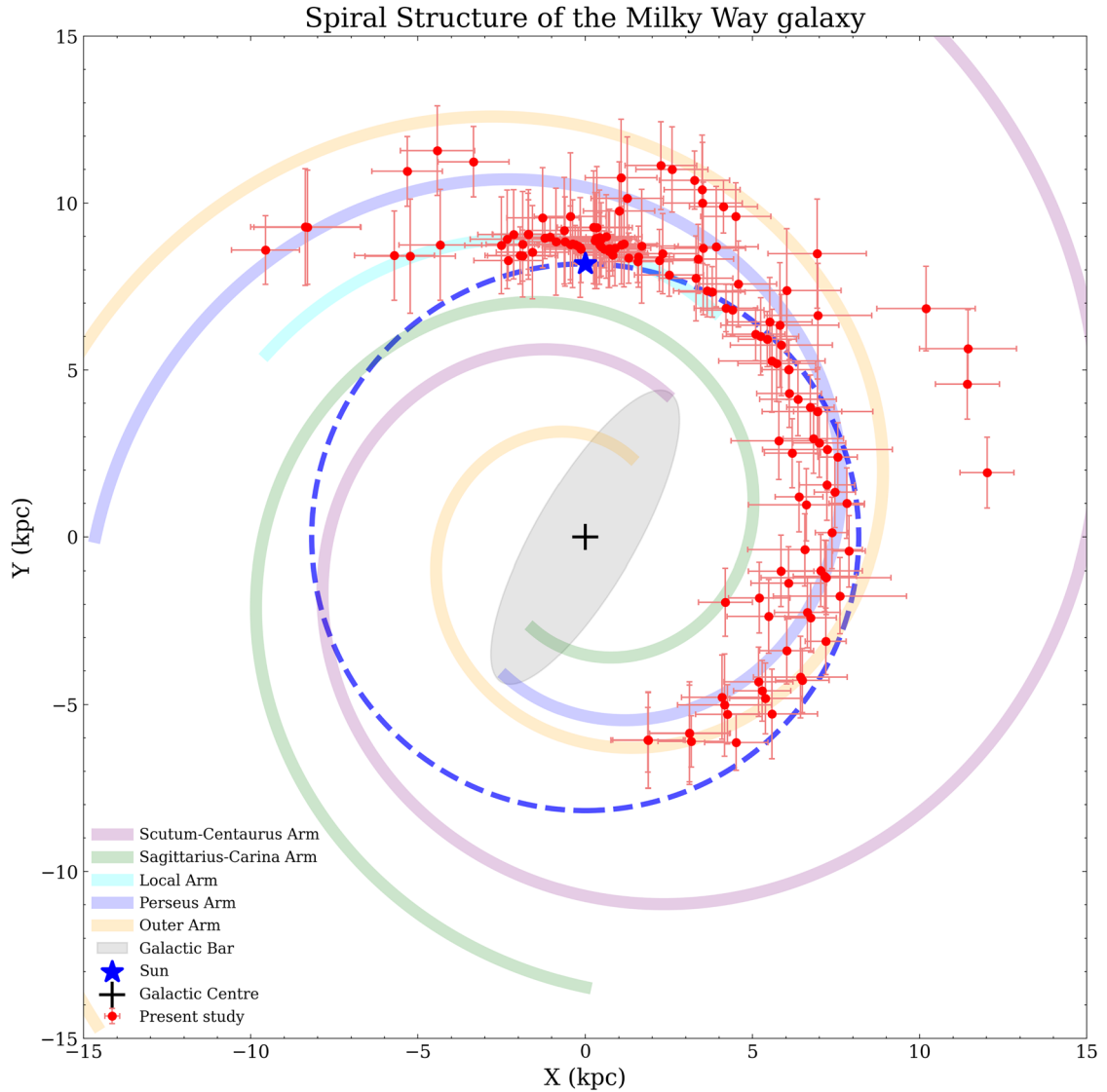


Figure 15. The structure of the Milky Way galaxy obtained using our hydrogen line observations. The Sun and its orbit around the Galactic Centre are shown in blue. Red points correspond to individual detected spectral peaks. Spiral arm loci from the literature, shown as thick coloured curves, are overlaid for comparison.

Galactic rotation curve with constant circular velocity $V(R) = V_0$.

These polar coordinates were then converted into Cartesian coordinates in the Galactic plane via

$$x = R \cos \theta, \quad y = R \sin \theta, \quad (15)$$

allowing every detected HI component to be plotted as an individual tracer point producing a two-dimensional map of neutral hydrogen structure within the Milky Way disk from the distribution of observed spectral peaks.

Figure 15 shows the distribution of hydrogen by mapping the spiral arm tracers of HI in the Galactic plane. The Sun, the solar circle ($R = R_0$) and Galactic Centre are marked for reference. The schematic trajectories of

the major Milky Way spiral arms (Denyshchenko *et al.* 2023) and the Galactic bar (Wegg *et al.* 2015) overlaid for context. The spiral nature of the galaxy can be seen clearly, and the tracer positions are consistent with the locations of the spiral arms up to the Outer Arm.

Some tracers near Galactic longitude $\sim 75^\circ$, possibly associated with the Scutum-Centaurus arm, appear significantly closer to the Sun than expected. This discrepancy may arise from the assumption of a constant circular velocity. From Eq. (14), underestimating the true circular velocity $V(R)$ at the location of the cloud infers a smaller Galactocentric radius R , thereby shifting the reconstructed arm position closer to the observer.

5. Conclusion

The construction and working of the pyramidal horn radio telescope to detect the HI line is presented in this work. Our pyramidal horn radio telescope successfully detected the Galactic 21 cm HI line and produced spectra suitable for mapping the hydrogen distribution and deriving the Milky Way rotation curve and the spiral arm structure. Despite limitations imposed by the sensitivity, beamwidth, and RFI contamination, the results reproduce the expected rotation curve and reveal large-scale Galactic structure, demonstrating the effectiveness of this low-cost design and methodology.

Future work in the Radio Telescope Project of the Physics and Astronomy Club will focus on advancing the observational and instrumental capabilities. Efforts are underway to construct a 5-meter radio dish, which in its initial stage will operate in a fixed zenith mode for hydrogen-line observations. This dish will subsequently be motorised to enable full-sky scanning and upgraded with higher-sensitivity feeds and backends, ultimately enabling pulsar observations and timing studies (Grover *et al.* 2024).

All data products and analysis codes used in this study are publicly available on Github⁶.

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