Small Radio Telescope for Observing the Neutral Hydrogen Line of the Milky Way

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Abstract

Small radio telescopes make it possible to observe the hydrogen emission line of 21 cm at 1420 MHz and to demonstrate the presence of dark matter by measuring the galactic rotation curve of the Milky Way. This paper presents the design, integration and analysis of data carried out to assemble a radio telescope using (COTS, Commercial off-the-shelf). The design uses inexpensive and commercially available materials. The receiver system consists of low-noise amplifiers, band-pass filters, and a software-defined radio USB receiver that provides digitized samples for spectral processing on a computer. The experimental results obtained through several tests carried out to adjust the software settings are presented, to finally estimate the velocity dispersion of the neutral hydrogen of the arms of the Milky Way and compare the results with other observations.

Keywords
Neutral hydrogen, Radio telescope, Milky Way, SDR, COTS

1. Introduction

The industry and the global market create new challenges and requirements for new generations, highly developed human resources in STEM (Science, Technology, Engineering, and Mathematics) where critical thinking and teamwork skills are required (Zervoudi, 2020; OECD, 2022). STEM outreach programs are used to attract students to help them develop new skills with hands-on experiences. In Paraguay, interviews with teachers and students in high school and engineering careers point to the fact that there is a general deficit in the training students receive in mathematics and basic sciences (Molinas et. al. 2018). A few decades ago, robotics, math, physics, and programming olympiads were used as a mechanism to attract high school students to STEM careers (Mauch, 2001; Nugent et. al. 2016; Kurita et. al. 2020). Low-cost radio telescopes are another alternative to inspire students of all ages to pursue (STEM) careers. Technological advances in open hardware and software (COTS, Commercial off-the-shelf) now allow radio amateurs and university and college professors to build their low-cost radio telescopes.

These 1420 MHz photons come from the transition between the two energy levels allowed for the hydrogen atom and are emitted randomly and sporadically, but since the Milky Way contains large amounts of hydrogen, this results in an observable RF power peak at the indicated frequency. When the antenna points to a hydrogen cloud or to the arms of the Milky Way, a peak is observed, which disappears when it points to empty space. In this way, it is also possible to measure the rotation speed of our galaxy by observing the frequency shift due to the Doppler effect.

Small (1-3 m) radio telescopes for 21 cm hydrogen line observations are widely used for education and outreach. Ewen and Purcell (1951) used a pyramidal horn to detect the 21 cm line for the first time at Harvard University. Pyramidal or conical horn radio telescopes of 1 to 3 meters, or parabolic antennas in amateur radio astronomy, are generally used for these observations. These telescopes can be recycled or manufactured with easily available materials, which makes their use in the amateur field proliferate. In addition, other necessary components (filters, amplifiers, coaxial cables) can be acquired at relatively low prices and the software used is generally open source and maintained by the community, thus providing a complete detection system at a reasonable low price.

The design presented in this paper was realized with a conical antenna, a device that combines a band-pass filter, a Low Noise Amplifier (LNA) and a Software Defined Radio (or SDR). The processing was performed with the free software SDR# and Octave.

1.1 Objectives

- Design a system for observing the spectral line of the contained hydrogen found in the arms of the Milky Way
- Build the system with low-cost materials and free software
- Obtain results comparable with other measurements made with similar radio telescopes
- Identify extensions and future upgrades to the system

2. Literature Review

The large optical telescopes located in Hawaii, Chile, Canary Islands etc, and even the Hubble telescope itself from space, have generated many images of our galactic and extragalactic environment in the visible, infrared, and ultraviolet spectrum. However, radio astronomy that studies celestial bodies at radio wavelengths between 30 meters and 1 mm (about 10 MHz and 300 GHz in frequency) is still not very widespread at the undergraduate and graduate level even though with this technique, one can study celestial bodies, black holes, the Milky Way, galaxy clusters, as well as our Sun from the observation of the neutral hydrogen line of λ =21 cm, or 1420 MHz. Radio telescopes make it possible to observe a specific range of frequencies by averaging the received energy over a given period and then plotting the spectrum in search of the characteristic frequency peaks. Two low-cost horn-antenna radio telescopes were built at Harvard University, with the objective of teaching students about radio astronomy (Patel et. al., 2014). One telescope was built with aluminum-foil covered cardboard, and aluminum sheet metal; the results obtained with these telescopes served as inspiration to start the project presented in this paper.

3. Methods

Our galaxy is of the barred spiral type whose thickness is approximately 0.6 kpc (kiloparsecs), where stars and gasses orbit at approximately 220 km/s [9]. To capture the radiation emitted by the neutral hydrogen found in the interstellar medium of the Milky Way requires the integration of the antenna with a system of amplifiers and filters detailed below.

3.1. Requirements

Table 1 summarizes the minimum system requirements for observing the 21 cm line.

Table 1. Elements of the radio telescope to be designed

Elements	Requirements
Antenna	Gain between 15 dB to 20 dB and ±15° aperture.
LNA	Greater than 30 dB and bandwidth greater than 2 Mhz.
Filter	Band-Pass 1,420 Ghz,
SDR	Sampling rate of 1Msps (it is not necessary to include a smart-tee system).

Software	FFT sampling system, with moving window and automatic data logging.

4.2. Design

The block diagram of the radio telescope is shown in Figure 1.

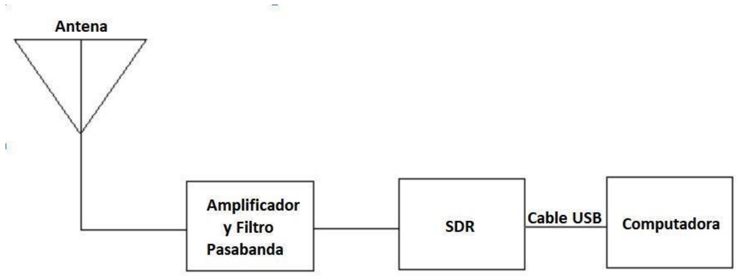
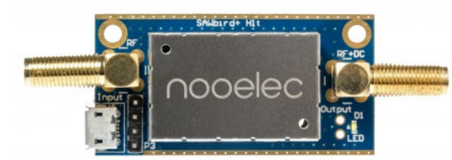


Figura 1: Block diagram used in this experiment.

A conical antenna was used for this project due to its availability and ease of installation. An LNA with a minimum gain of 30 dB at the measured frequency of 1420 MHz is required, together with a band-pass filter to eliminate unwanted signals close to the desired observation frequency, with a bandwidth equal to or less than 200 MHz. The filter used was the Nooelec SAWbird + H1 with a gain of 40 dB.

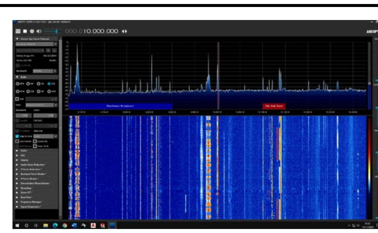
The SDR to be used must be compatible with the LNAs and filters used, and its stable bandwidth must reach 1420 MHz to ensure that the radiation is captured without distortion. The NESDR Smart v4 model from Nooelec was chosen for this work. The elements used are shown in Figure 2.

(a)



(b)

(c)



(d)

Figure 2: Elements to be used (a) Antenna, (b) Filter and LNA, (c) SDR, (d) SDR#

4.3. Characterization of RF Antennas.

For the characterization of the system, a spectrum analyzer and a signal generator provided by the Propagation and Antennas Laboratory of CITEC were used. The procedure consisted of generating a periodic signal of 1420 MHz (the one we want to measure), in order to measure the antenna gain, which is 17 dBi at this frequency, with a standing wave ratio (SWR) of 1.52. It was also verified that the antenna has an aperture of ±12.5° in the E-plane, and ±15° in the H-plane. These data were considered adequate for use in the rest of the project.

Figure 3: Conical antenna used (Model 1.5G-H1D).

Tests were performed to measure the loss and reflection coefficient with a Vector Network Analyzer (VNA), the values obtained for the return loss and impedance were 3.63 dB and 75 ohms respectively.

4.4. Integration of electromagnetic spectrum measurement systems.

To measure the frequency spectrum, the antenna, amplifier, filter and a variable power supply were integrated, following the design used as a reference in (Mauch, 2001). The SDR was then configured to receive the desired frequency through the SDR# program. For data saving and signal visualization, the IF Average plugin was used, which allows sampling and then averaging the measured spectrum from 6 to 7 minutes (which is the average transit time of the Milky Way arm as seen from the earth). The spectrum was determined from the Fast Fourier Transform (FFT) using 1024 points obtained with 1 Mbps sampling.

4.5. Antenna positioning

For these measurements, it is not necessary to use an automatic positioning system, so the antenna can be pointed at a fixed location in the sky. Consequently, the rotation of the earth will define the position of the center or arm of the galaxy, which will be crossed once per day. The positioning can be determined through the Stellarium application. Figure 4 shows the final setup used in the laboratory already pointing in the desired direction.

Figure 4. Complete system in operation.

5. Data Collection

5.1. 1420 MHz frequency measurement

Figure 5 shows the results of the June 22 measurements at 1:00 am pointing to galactic coordinates long./lat. +55°52’01.9’’/-8°57’52.1’’. Likewise, Figure 6 shows the four measurements used for the estimation of rotational velocities in the following subsection.

As can be seen in Figures 5, there is an excess in the average received signal strength near the 1420 MHz frequency at the time when the antenna points to the galactic plane. This pattern was obtained every day that the measurements were made.

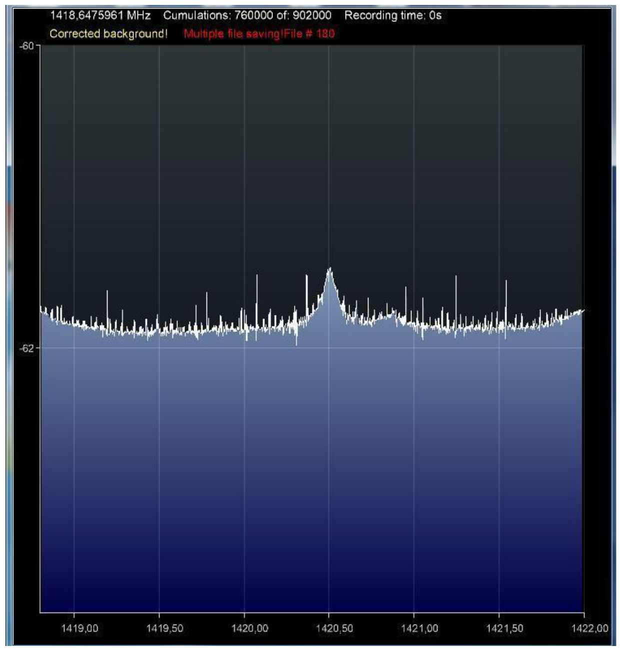


Figure 5: Spectrum measured and averaged with the SDR# program.

Table 3. Date, time and place of test pointing

Test	Date	Time	Longitude (°)
1	22/06/2021	02:02:26 AM	60,550
2	29/06/2021	1:00:47 AM	57,349
3	30/06/2021	12:11:35 AM	60,467
4	15/06/2021	12:32:23 AM	65,683

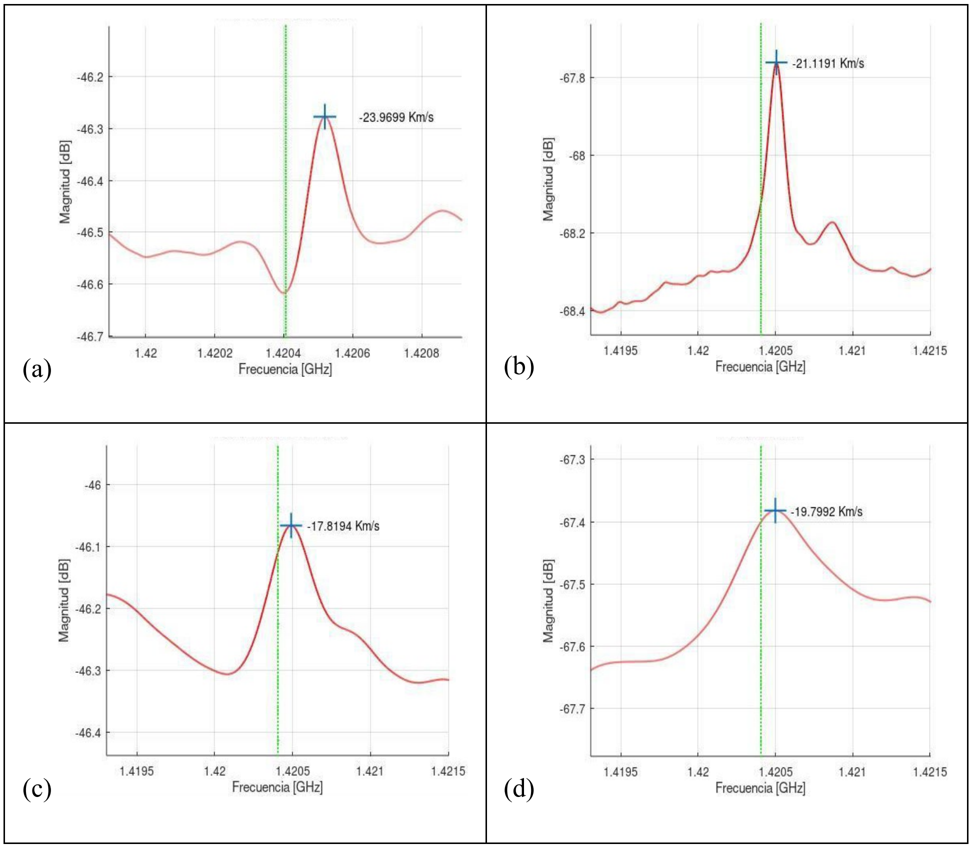


Figure 6: Measured spectrum results, a) 6/15 test, b) 6/21 test, c) 6/28 test, d) 6/29 test.

6. Results and Discussion

6.1. Rotational speed estimation

The measurements were made over several days and the results were taken at the times when the antenna points to the center of the Milky Way (which occurred around 01:00 h local time), and to the outer arm (around 11:00 h local time). Then the velocity of the pointed region with respect to the Earth was calculated with the Doppler shift equation. In all cases it was verified that when pointing at the center of the galaxy, its velocity is negative with respect to the Earth, so it approaches the Earth. On the other hand, when pointing to the outer arm, a positive velocity was obtained, so it is concluded that this region is moving away from the Earth.

In order to obtain the relative velocity of the gas cloud to the galactic center ($V_{r/gc}$) from the estimated velocity values, the scheme shown in Figure 6 and the following equations were used (Hyperphysics, 2021; physicsopenlab, 2020):

$$d = R_0 \, sen(\theta_l),$$

$$V_{r/gc} = V_{obs} + V_{sun} \, sen(\theta_l),$$

where θ_l is the galactic longitude (approximately 60 degrees), d the distance from the observed point to the center of the galaxy (approximately 7.6 Kpc), and V_{sun} the rotation speed of the solar system relative to the galactic center (approximately 220 km/s).

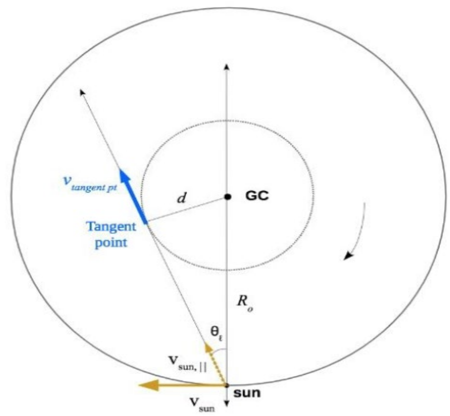


Figure 6: Relative velocity of an object to the Milky Way Source (Clements, 1985).

The results of the estimations are summarized in Table 4, taking into account the direction in galactic coordinates being pointed to calculate the distance from the observed point to the center of the galaxy.

Table 4: Test results and comparison of results.

Test	V_{obs} [Km/s]	Rel. Speed (Values for Comparison) [Km/s] [13]	Absolute Difference	Distance to GC [Kpc]	Rel. Speed. to GC [Km/s]
1	21,120	30,663	9,543	7,402	212,693
2	17,820	37,517	19,697	7,157	203,054
3	19,800	30,663	10,863	7,396	211,215
4	23,970	18,577	5,393	7,746	224,453

7. Conclusion

A complete system for observing the spectral line of the contained hydrogen found in the arms of the Milky Way was designed and built with low-cost materials and free software. The results are comparable with other measurements made with similar radio telescopes. This system proved to be a very effective tool to verify physics concepts and motivate engineering, astronomy, and physics students.

This work can be extended by building a specialized antenna and a mobile base to keep the antenna pointed at a specific known point and thus compare with measurements made by other radio telescopes. Radio astronomy is currently advancing with the use of interferometry, especially VLBI (Very-long-baseline interferometry). The next step for developing radio astronomy in Paraguay could be the restoration of the old ground station in Areguá to convert it into a radio telescope and thus collaborate with research groups in the area.

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Biographies

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Jorge Molina has a PhD from the Centro Brasilero de Pesquisas Físicas (CBPF), did his PhD thesis at the DZero experiment at Fermilab, with postdoctoral studies at the Universidad Estadual de Rio de Janeiro (UERJ) and CIEMAT in Madrid, where he collaborated with the CMS experiment at CERN. From 2009 to 2015 he worked at FIUNA as director of the Mechanics and Energy Laboratory. He is currently Director of Research at FIUNA, and continues to collaborate with the Fermilab Laboratories, with UNICAMP in Campinas and represents Paraguay in the LAGO and LAS4FRI collaborations.