Design and Implementation of a Software Defined Radio-Based Radio Telescope for Hydrogen Line Observation at 1.42 GHz

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Abstract—This paper describes the design and implementation processes of a radio telescope suitable for the detection of the hydrogen line, proposing a receiver system based on Software Defined Radio (SDR). The design and fabrication of the antenna are presented, as well as the results of its characterization (electrical, radiation), both with simulations and measurements in an anechoic chamber. The functionality of the instrument is demonstrated by the satisfactory observations of the hydrogen line emitted by our Galaxy. This is an affordable project that allows the development and application of the skills of telecommunications students since it includes many of the fundamental aspects of electronics applied in this field.

Index Terms—Communication system, horn antenna, hydrogen line, radio astronomy, radio telescope, software-defined radio (SDR).

I. INTRODUCTION

The hydrogen line is a spectral line resulting from a transition that a neutral hydrogen atom undergoes between two specific energy levels [1], from one with a higher energy to another with a lower one. The atom radiates this energetic excess, generating a spectral line of a specific frequency, depending on the associated transition energy, which in this case is 1420.405 MHz. (λ=21.12 cm) [2]. By studying the properties of this line (shape and frequency displacement, mainly) we can obtain diverse information about the region in which it is generated. Neutral hydrogen moves in the form of clouds in the interior of the Milky Way. (Fig. 1), mainly by the interstellar medium of its disk, accumulating in spiral arms [3]. Despite the low density of these clouds (1 atom per cm³ on average) and the low emission frequency of this spectral line in a hydrogen atom, its observation is possible, given the large number of existing hydrogen clouds due to the large size of the disk of the galaxy.

Radio telescopes are used to measure electromagnetic radiation from sources outside the solar system, such as the hydrogen line. A radio telescope consists of a high-gain antenna (usually parabolic) and a radio receiver to capture and record the radio waves picked up by the antenna. These instruments are extraordinarily expensive due, on the one hand, to the large size of the antennas used (tens of meters in diameter) and the complexity of the radio receiver systems.

The recent emergence of software-defined radio (SDR) systems has allowed the design of many of the modules that make up a radio frequency instrument to be reformulated.

The concept of software-defined radio can be defined as a digital radio in which various system functionalities, conventionally implemented in hardware (modulators, demodulators, mixers, etc.), can be reconfigured by software. This allows for simpler signal processing, giving the system greater flexibility. In addition, system performance can be improved without the need to replace the hardware, thus reducing the cost of the system. [4] [5]. A wide variety of SDR devices are already available on the market today, which can be used as radio spectrum scanners, receivers of live radio signals, or even transmitters. Additionally, system performance can be improved without the need to replace hardware, thus reducing the cost of the system.

The main objective of this paper is to present the design and construction of a radio telescope capable of receiving the 1.42 GHz neutral hydrogen spectral line from our Milky Way galaxy. It is intended to implement a functional instrument, as well as to present a feasible project from an academic point of view.

This manuscript is an extension of a paper presented at the TAAE 2022 conference [6], chosen by JENUI2022 as one of the best of the congress for submission to IEEE-RITA. In the present version of the paper, a new simulation section has been added and some descriptions have been reformulated in order to make the text more understandable, as well as the subject matter.

II. RADIO TELESCOPE DESIGN

The proposed radio telescope is composed of an antenna, suitably designed for the reception of the frequency of interest, a filtering and amplification stage with a good signal-to-noise ratio, and an SDR module as a receiving device that, with the corresponding software, allows a correct transformation and processing of the received signal. A simplified diagram of the complete system of the proposed radio telescope can be seen in Fig. 2.

A. Antena

The use of a rectangular horn as the antenna has been considered, since these offer sufficient gain for our purpose while
allowing an affordable fabrication with limited resources. A horn antenna consists of a waveguide, its corresponding driver element, and the horn itself.

1) Waveguide: The rectangular waveguide has a cutoff frequency of \( f_c \):

\[
f_c = \frac{k_c}{2\pi\sqrt{\mu\varepsilon}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2
\]

where \( \varepsilon \) is the dielectric permittivity of the medium that fills the waveguide, \( \mu \) is the magnetic permeability and \( a \) and \( b \) refer to the lengths of the longest and shortest sides of the rectangular section of the waveguide, respectively. Assuming only the dominant mode is propagating TE\(_{10} \) \((m = 1, n = 0)\), which also has the lowest attenuation [7], the cutoff frequency of the waveguide is:

\[
f_c = f_{c\ (TE_{10})} = \frac{c}{2a}
\]

where \( c \) is the speed of light in the vacuum. We will take the usual convention that \( b = \frac{a}{2} \). Thus, the cutoff frequency of the following mode corresponds to \( 2f_c \). To ensure the correct propagation of the dominant mode only, in practice, margins of 0.25 over \( f_c \) and margins of 0.1 below \( 2f_c \) are respected [8]. Consequently, the frequency range of interest \((f)\) is centered within the interval:

\[
1.25f_c < f < 1.9f_c
\]

In our case, the frequency of interest (1420.4 MHz), due to the Doppler effect produced by the relative motion of the hydrogen clouds with respect to the Earth, may suffer a frequency shift of ±2 MHz, so a reception range from 1418.4 MHz to 1422.4 MHz must be considered. All in all, the dimensions of Table I.

2) Exciter post: An exciter post is used as a transition element between the waveguide and the coaxial power cable [9] consisting of a vertical monopole (half dipole) on a ground plane, which in this case corresponds to the metallic conducting plane. In Fig. 3 a schematic of the longitudinal section of the waveguide together with the pole is shown. This element must be located at a distance of \( d = \frac{\lambda_g}{4} = 6.84 \) cm of the rear wall [8] of the waveguide, where \( \lambda_g \) is the wavelength of the guide. The length of the exciter pole is \( l = \frac{\lambda}{4} = 5.25 \) cm, where \( \lambda \) corresponds to the wavelength of the plane wave in the medium filling the waveguide. The length of the waveguide under consideration is \( h = 25 \) cm. [10].

3) Horn: The horn is a gradual transition of the waveguide that improves the directivity and matching of the antenna [11]. Following the design process for a pyramid-shaped horn described in [12, cap. 13] and using the Matlab program [13], for three possible gains (13 dBi, 18 dBi and 23 dBi) and one wavelength \( \lambda = 21.12 \) cm, three possible horn dimensions are obtained (Tabla II and Fig. 4). Looking for a trade-off between size and gain, the horn design was chosen with gain \( G_0 = 18 \) dBi.

B. Receiving system

The receiving system consists of a low noise amplifier (LNA), specific for 1.42 GHz applications, a coaxial cable and an SDR module which, in this case, is connected to a usual laptop computer through the USB port. Several SMA-type connectors are also used to interconnect some of the elements.

1) LNA: The SAWbird + H1m module (from Nooelec) is used, which is connected to the antenna output via an SMA (male-male) connector. It consists of two LNAs and a SAW filter (surface acoustic wave) of high performance. It has

---

**TABLE I**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>16.36 cm</td>
</tr>
<tr>
<td>( b )</td>
<td>8.32 cm</td>
</tr>
</tbody>
</table>

---
Fig. 4. Diagram of the pyramidal horn. (a) 3D view. (b) Lateral view (E-Plane). (c) Zenit view (H-Plane).

### TABLE II

**DIMENSIONS OF THE HORN ANTENNA**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>G₀ = 13 dBi</td>
<td>132.19 cm</td>
</tr>
<tr>
<td>G₀ = 18 dBi</td>
<td>75.45 cm</td>
</tr>
<tr>
<td>G₀ = 23 dBi</td>
<td>43.8 cm</td>
</tr>
<tr>
<td>a₁'</td>
<td>31.61 cm</td>
</tr>
<tr>
<td>a₁</td>
<td>58.02 cm</td>
</tr>
<tr>
<td>a₁''</td>
<td>104.72 cm</td>
</tr>
<tr>
<td>b₁'</td>
<td>23.65 cm</td>
</tr>
<tr>
<td>b₁</td>
<td>79.68 cm</td>
</tr>
<tr>
<td>b₁''</td>
<td>259.79 cm</td>
</tr>
<tr>
<td>ρₑ'</td>
<td>12.96 cm</td>
</tr>
<tr>
<td>ρₑ</td>
<td>63.57 cm</td>
</tr>
<tr>
<td>ρₑ''</td>
<td>234.07 cm</td>
</tr>
<tr>
<td>ψₑ</td>
<td>41.93º</td>
</tr>
<tr>
<td>ψₑ'</td>
<td>21.35º</td>
</tr>
<tr>
<td>ψₑ''</td>
<td>11.64º</td>
</tr>
<tr>
<td>ρₑ'</td>
<td>30.27 cm</td>
</tr>
<tr>
<td>ρₑ</td>
<td>89.85 cm</td>
</tr>
<tr>
<td>ρₑ''</td>
<td>275.79 cm</td>
</tr>
<tr>
<td>ψₑ</td>
<td>46.33º</td>
</tr>
<tr>
<td>ψₑ'</td>
<td>24.83º</td>
</tr>
<tr>
<td>ψₑ''</td>
<td>13.87º</td>
</tr>
</tbody>
</table>

### TABLE III

**ATTRIBUTES FOR THE MATLAB “HORN” FUNCTION**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name (Matlab)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a₁</td>
<td>FlareWidth</td>
<td>0.7545</td>
</tr>
<tr>
<td>b₁</td>
<td>FlareHeight</td>
<td>0.5802</td>
</tr>
<tr>
<td>Pₑ,h</td>
<td>FlareLength</td>
<td>0.6357</td>
</tr>
<tr>
<td>a</td>
<td>Width</td>
<td>0.1636</td>
</tr>
<tr>
<td>b</td>
<td>Height</td>
<td>0.0832</td>
</tr>
<tr>
<td>h</td>
<td>Length</td>
<td>0.25</td>
</tr>
<tr>
<td>l</td>
<td>FeedHeight</td>
<td>0.0525</td>
</tr>
<tr>
<td>−</td>
<td>FeedWidth</td>
<td>8e-4</td>
</tr>
<tr>
<td>−</td>
<td>FeedOffset</td>
<td>[-0.0566]</td>
</tr>
</tbody>
</table>

a passband gain of 40 dB and a maximum noise figure of $F = 0.9$ dB. Detailed specifications can be found at [14].

2) **Coaxial Cable:** The LNA and the SDR **dongle** are connected via a 2.6 mm outer diameter, 3 meter length RG174/U coaxial cable. Approximate cable losses of 3 dB are assumed.

3) **SDR:** The **dongle** RTLSDR Blog V3 has been used, which is a wideband SDR receiver based on the RTL2832U chipset, with the R820T2 tuner. The technical characteristics of the tuner and the SDR receiver can be seen in [15] and [16], respectively. It is a device with a good price-performance ratio and adequate performance for the purpose of this project.

4) **Analysis of the receiving system:** Assuming total connector losses of 0.5 dB [17] and a gain of 18 dB, the total (minimum) gain up to the SDR can be calculated as follows:

\[
G = G_{\text{ant}} + G_{\text{LNA}} + L_{\text{cable}} + L_{\text{connect}} \\
\text{= 18 dB + 40 dB - 3 dB - 0.5 dB} \\
\text{= 54.5 dB (4)}
\]

### III. SIMULATIONS

To evaluate the designed horn antenna, a series of simulations are performed, using the functions provided by the Matlab **Antenna Toolbox**.

First, the horn antenna is created using the function `horn(Name, Value)` [18], specifying the pairs of arguments `Name, Value` shown in Table III, which correspond to the antenna dimensions obtained from the design process described in Section II-A. Once this object has been created, it can be displayed in 3D with the `show(object)` function. The parameters described in the following paragraphs are also obtained.

#### A. Radiation Pattern

Using the function `pattern(object, frequency, azimuth, elevation)` [19] the radiation pattern is represented in spherical coordinates, of E-plane (azimut: 0º) and H-plane (elevation: 0º), as it is shown in the following Fig. 5. It is also possible to visualize the radiation pattern in 3D. The directivity obtained is 18.13 dB.

Moreover, in Fig. 6 normalized diagrams in Cartesian coordinates, obtained from the Matlab program [20], are shown. Assuming a narrow main lobe and negligible secondary lobes, it is possible to calculate the approximate directivity by knowing the half-power beamwidth (HPBW), of two perpendicular planes [12, Chap. 2]. From Fig. 6, 3 dB beamwidths of 19.5º in the E-plane and 21.5º in the H-plane are observed, giving an approximate directivity of 19.9 dBi, where $\Omega_e$ is the equivalent solid beam angle:

\[
D \approx \frac{4\pi}{\Omega_e} = \frac{4\pi (180/\pi)^2}{19.5 \cdot 21.5} = 98.4 \rightarrow D \approx 19.9 \text{ dBi (5)}
\]

#### B. Return Loss $S_{11}$

The calculation of the parameter $S_{11}$ is performed by the function `s = sparameters (object, frequencies)` [21] and the function `refplot(s)` [22].
Fig. 5. Numerical calculation of the radiation pattern. (a) E-Plane. (b) H-Plane.

Fig. 6. Numerical computation of radiation pattern in Cartesian coordinates.

is used to plot the data. The resulting plot is shown in Fig. 7, having a reflection coefficient of -13.5 dB at 1.42 GHz.

IV. IMPLEMENTATION

The following paragraphs describe the construction and assembly process of the parts of the system that require it and provide a list of the main materials used.

A. Antena

The antenna is made of aluminum sheets assembled by using aluminum angles, screws, nuts, and washers. It is made up of five pieces (four sides and bottom), obtained with the dimensions considered in section II-A, which have been adequately bent to form the waveguide-horn assembly. Finally, the driver element has been inserted after drilling a hole of the correct dimensions in the roof of the waveguide and the mouth of the horn has been reinforced with PVC angles so that the aluminum plates do not bow. Fig. 8 shows the antenna during the assembly process and Fig. 9 shows the finished horn antenna, to which a small platform has been added under the SMA connector where to place the LNA module and a base has been built on which to place the antenna to keep it stable in a vertical position.

B. Materials and budget

Table IV shows the approximate budget for the main materials and devices used for the construction and implementation of the radio telescope.

V. ANTENNA CHARACTERIZATION

The antenna has been suitably characterized, both electrically (parameter $S_{11}$) and in radiation (pattern and gain).

A. Return Loss $S_{11}$

The parameter $S_{11}$ was measured in the anechoic chamber using the small and portable vector network
Fig. 8. Horn antenna assembling.

Fig. 9. Finished antenna, resting on the base.

Fig. 10. Return Loss $S_{11}$ measured inside anechoic chamber.

B. Radiation Pattern

The H- and E-plane radiation patterns have also been measured in the anechoic chamber. Fig. 11 shows the horn antenna attached to the Orbit positioner, oriented for the corresponding measurement of the $E$-plane radiation pattern. For the measurement of the $H$-plane, both antennas (transmitting and receiving) are rotated 90° about their axis to maintain polarization matching. Fig. 12 and Fig. 13 show, respectively, the radiation patterns of the $E$ and $H$ planes resulting from the measurements, compared with those obtained in simulation (Fig. 6). It is observed that the main lobe in one of the planes is wider than in the simulation, therefore, the real directivity is lower than that resulting from the simulation.

### TABLE IV

<table>
<thead>
<tr>
<th>Materials</th>
<th>Units</th>
<th>Price/u</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum sheet (1000x2000x1 mm)</td>
<td>1</td>
<td>29.81€</td>
<td>29.81€</td>
</tr>
<tr>
<td>Aluminum angle (2.6 m) (15x15x1.3 mm)</td>
<td>2</td>
<td>3.85€</td>
<td>7.70€</td>
</tr>
<tr>
<td>Angle PVC (2.6 m) (20x20x1 mm)</td>
<td>2</td>
<td>3.60€</td>
<td>7.20€</td>
</tr>
<tr>
<td>SMA connector antenna (50Ω) (Female-Male)</td>
<td>1</td>
<td>7.08€</td>
<td>7.08€</td>
</tr>
<tr>
<td>SMA connector straight (50Ω) (Male-Male)</td>
<td>1</td>
<td>12.09€</td>
<td>12.09€</td>
</tr>
<tr>
<td>Matched load RF (50Ω) (Male)</td>
<td>1</td>
<td>3.47€</td>
<td>3.47€</td>
</tr>
<tr>
<td>Nooelec SAWbird+H1 + SMA straight (M-M)</td>
<td>1</td>
<td>51.95€</td>
<td>51.95€</td>
</tr>
<tr>
<td>RTL-SDR Blog V3 + Coaxial Cable (3m)</td>
<td>1</td>
<td>34.95€</td>
<td>34.95€</td>
</tr>
<tr>
<td>Screws (3mm)</td>
<td>-</td>
<td>-</td>
<td>6.90€</td>
</tr>
<tr>
<td>Aluminum tape</td>
<td>-</td>
<td>-</td>
<td>4.22€</td>
</tr>
<tr>
<td>Antenna support materials</td>
<td>-</td>
<td>-</td>
<td>10.36€</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>175.73€</strong></td>
</tr>
</tbody>
</table>
If, from the measured normalized diagrams, we calculate the approximate directivity as done in section III-A (Eq. 5), we have:

$$D \approx \frac{4\pi}{\Omega_e} = \frac{4\pi (180/\pi)^2}{17 \cdot 38} = 63.86 \rightarrow D \approx 18.05 \text{ dBi } (6)$$

Assuming an antenna efficiency of 100%, the gain is equal to the directivity.

VI. RESULTS

Once the design and construction process of the radio telescope was completed, the observation consisted of keeping the horn antenna pointed at the zenith in continuous reception mode for approximately one full day. The SDRSharp software was used to record the measurements [24]. This software is compatible with the RTL2832U chipset of the RTL-SDR Blog V3. In addition, the IF Average [25] plugin has been installed to average many samples over time to extract the peak of the hydrogen line from the noise floor. In parallel, we have used the program Stellarium [26] to visually associate the intensity of the observed hydrogen line with the celestial region from which it originates. For this purpose, we have made use of the tools Chronolapse [27] and the Time-Lapse Tool [28] tools to capture snapshots of the sky-spectrum state automatically and periodically, and then form a fast-speed animation with them. In [25] we explain the configuration procedure of the programs SDRSharp and Stellarium for the observation and we show how to calibrate the application IF Average.

The animation of sky-spectrum snapshots obtained during a full day can be seen in [29]. Of these, it has been observed that when the Milky Way disk passes through the part of the sky towards which the radio telescope is pointing, the spectral line of hydrogen is received with more power. When it points outward from the disk of the galaxy, the intensity of the line decreases and becomes almost negligible. This is consistent with the main location of the hydrogen clouds in the arms of our galaxy.

Fig. 14 shows the image of the hydrogen line received at an instant when the radio telescope is pointed towards a region of the Milky Way disk, namely towards an approximate galactic longitude of 165°, in the direction of the constellation Auriga. The frequency at which the peak of the hydrogen line is observed (1420.529 MHz) is slightly higher than expected (1420.405 MHz), i.e., it is blue-shifted. This means that the distance between the hydrogen cloud and us is decreasing either because the cloud is getting closer to us or vice versa.

This line shift in the spectrum is proportional to the relative radial velocity between emitter and observer (Doppler effect)
and is expressed in Eq. 7, where \( v_r \) is the radial velocity, \( f_r \) the emitted frequency, \( f_o \) the observed frequency and \( c \) the vacuum speed of light (\( 3 \times 10^8 \text{ m/s} \)),

\[
v_r = c \frac{f_e - f_o}{f_o} \quad (7)
\]

Therefore, the relative radial velocity, in this situation, is:

\[
v_{r_1} = 3 \times 10^8 \frac{1420.406 - 1420.529}{1420.529} \approx -25.98 \text{ km/s} \quad (8)
\]

The negative velocity indicates the approach between the emitter and the observer; however, this approach does not have to be in the direction of the line of sight between them. By looking at the direction in which one is observing within the galaxy (Fig. 1), it is understood that the emitting hydrogen cloud must be in an orbit (around the galactic center) slightly outside our own (Sun), probably in the same arm of Orion. It is assumed that the translational velocity of objects around the galactic center (in the disk) generally decreases as the radius of the orbit increases [30]. Therefore, it is considered that we are the ones that catch up with the hydrogen cloud since we are moving at a higher speed than it (each one moving along its own orbit). This would agree with the curvature drawn by the arms of the Milky Way dragged by its rotation, which would be clockwise (from the view shown in Fig. 1).

However, radial velocity calculations are considered an approximation, since the Earth’s motion, both rotation and translation around the Sun, is not taken into account.

**VII. PEDAGOGICAL ASPECTS**

From the pedagogical point of view, a project such as the one described above is in itself a teaching experience that brings together a good part of the many aspects of electronics, from its fundamentals (both analog and digital, and its conversion), to its application in telecommunications and communication systems, developing for this purpose a functional electronic instrument. communication systems, developing a functional electronic instrument for it.

In addition to the basic competencies required for the students of the Degree in Telecommunications Electronics Engineering, the development of this work allows the assessment of many of the general competencies and some of the specific ones. That is why both the overall design process of the instrument and its use itself can be considered in the design of the contents of some of the subjects of the degree, such as:

- **Graphic expression** (horn antenna design).
- **Physics II** (electromagnetic waves).
- **Fundamentals of communications**.
- **Electronic telecommunication systems** (waveguides, SDR).
- **Circuits high-frequency subsystems** (amplifiers RF).

**VIII. CONCLUSION**

The feasibility of building a low-cost radio telescope consisting of an aluminum horn antenna, an amplifier, and an SDR module connected to a PC has been demonstrated. The functionality of the instrument has been demonstrated by measuring the hydrogen line (1.42 GHz) that comes from the Milky Way.

**REFERENCES**


