

The Science of Radio Astronomy: An Investigation of Crab Nebula

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Abstract

The science of radio astronomy focuses on the observation and study of celestial objects by reading their radio waves. The 5 meter radio-telescope is able to observe different radio sources using a C-band LNB. This research was essentially focused on Crab Nebula, also known as Taurus A. The study led to interesting observations, which were validated numerically using various scientific computing software. The radio waves emitted by Taurus A are readable by the RTL-SDR, a software defined radio receiver. This device is capable of reading radio frequencies in the range of 0.5 MHz to 1700 MHz.

Keywords

Crab Nebula, Taurus, Radio Astronomy, Galaxy, Radiation, Radio Telescope, RTL, SDR

1. Introduction

Astronomy is the branch of physics that studies celestial objects and the universe as a whole. However, Radio astronomy, according to the National Radio Astronomy Observatory, is the study of celestial objects that give off considerable radio waves. With radio astronomy, studying astronomical phenomena that are often invisible or hidden in other portions of the electromagnetic spectrum is simplified [1]. The study requires the use of a radio telescope, which is an antenna that has the principal purpose of reading radio waves emitted by astronomical objects. In order to collect data, the dish had to be adjusted to look at Taurus A, which is elevated about 34.76 degree above the horizon. In short, data collection is possible because the radio-telescope worked in tandem with the software defined radio receiver, RTL-SDR. On top of that, the universal wave equation theory played an important role because it helped validate the observation.

2. Theory and Background

2.1. What Is Radio Astronomy?

Astronomy studies the formation, evolution, dynamics and other characteristics of objects located beyond the Earth's atmosphere, such as the sun and its planets, comets, stars, galaxies and the universe. This science, imbued with curiosity, aims to answer some of the most fundamental questions: How was the Universe created or was there ever a beginning? What are its limits? How old is it? Will it ever cease to exist? As a science that enlightens us on the place of our planet in the universe, astronomy plays an essential cultural role for humanity. Some very recent discoveries, like black holes and quasars are essential to answer the questions aforementioned about the universe. As for the directly applicable aspects, astronomy has contributed to human progress by laying the essential groundwork such as the invention of our calendar and the time reference system.

Astronomers study the entire electromagnetic spectrum, which extends well beyond the observable region also called optical radiation. Each frequency range provides different information and, as a rule, requires capable telescopes and detectors. Radio astronomers study objects that radiate or absorb energy at various frequencies. In short, some objects of the universe can only be studied through their radio-frequency signature. The radio-frequency observations have played an essential role in complementing previous work carried out in the optic region. As an example, after scientists determined the distribution of Hydrogen in our Galaxy, the Milky Way, it was possible to locate the center of the Galaxy, unambiguously map its spiral arms and establish that the Earth is in an external spiral arm.

2.2. What Is a Radio Galaxy

Radio galaxies are ordinary-looking galaxies, giant elliptical galaxies when observed in the visible domain, but which emit powerfully in the radio domain. Their emissions can be hundreds of times more powerful than those of normal galaxies and sometimes even more. This is the case for Taurus A, M 87, Centaurus A, or even Cygnus A, which is a million times brighter in the radio domain than the Milky Way [2]. The regions of this emission appear at first glance as two lobes placed on either side of the optical component of the galaxies concerned. These lobes correspond in fact to the ends of very narrowed jets of gas expelled from the central regions of these objects and sometimes several thousand light years long. As an example, we can also cite the extreme case of J1420-0545, where the radio source extends over 15 million light years [3].

2.3. The Crab Nebula in Taurus

Also known as Taurus A, M1, Messier 1, or NGC 1952, "It is the remnant of a supernova explosion at a distance of about 6000 light-years, observed almost 1000 years ago, in the year 1054. It contains a neutron star near its center that spins 30 times per second around its axis. In this picture, the green light is pre-

dominantly produced by hydrogen emission from material ejected by the star that exploded. The blue light is predominantly emitted by very high-energy, relativistic, electrons that spiral in a large-scale magnetic field, known as synchrotron emission. It is believed that these electrons are continuously accelerated and ejected by the rapidly spinning neutron star at the center of the nebula and which is the remnant core of the exploded star” [4] (Figure 1).

2.4. Radiation in Radio Astronomy

2.4.1. Why Does a Heated Body Radiate?

At the end of the 19th century, it was discovered that heat makes atoms and molecules of a solid element vibrate. On top of that, atoms of a solid are more or less complex arrangements of electric charges. Maxwell’s theory predicts that oscillating charges emit electromagnetic radiations. This was already confirmed at the time by the experiments conducted by Hertz on simple antennas: The emitted radiation travels at the speed of light. When a body is heated, the resulting molecular and atomic vibrations include oscillating charges. By assuming that Maxwell’s theory is valid at the atomic level, it is safe to deduce that these charges emit electromagnetic radiation as well.

2.4.2. How Is Radiation Absorbed?

Consider a light radiation whose wavelength is in the observable domain of the electromagnetic spectrum: if it encounters a glass surface, it passes through. On the other hand, it is reflected by a shiny metallic surface. However, a black material such as soot absorbs most of it, causing the material to heat up.

Considering the example above, it is only legitimate to deduce that the atoms electrons of the glass do not oscillate in the presence of visible radiation. In fact, the electrons are strongly bonded to atoms and they can only oscillate at certain frequencies in response to an oscillating external electric field. It turns out that these frequencies are not those of visible but opaque to IR and UV.



Figure 1. The Crab nebula in Taurus [4].

In the case of metal, electrons are much more weakly bonded to atoms due to very weak electronegativity. Therefore, the electrons move almost freely, which also explains the good conductivity of metals. They can therefore oscillate with a large amplitude in response to the electric field of a visible wave. Following this oscillation, they emit a radiation which is in fact the same here as the incident radiation: at the macroscopic level, the light is reflected. The incident radiant energy is therefore absorbed then fully reissued.

Soot also has free electrons, but their mean free path or the average distance they can travel before hitting another particle is small, and the resulting collisions cause the material to heat up. Some of the incident radiant energy is transformed into heat [5]. In general, increasing the temperature of a body allows strong energetic radiation. In fact, everybody that has a temperature above absolute zero radiates. Given this evidence, it is safe to state that bodies which absorb the most are also those that emit the most.

2.4.3. Wien's Displacement Law and Black Bodies Radiation

“Stars approximate blackbody radiators and their visible color depends upon the temperature of the radiator. The curves show blue, white, and red stars. The white star is adjusted to 5270 K so that the peak of its blackbody curve is at the peak wavelength of the sun, 550 nm. From the wavelength at the peak, the temperature can be deduced from the Wien displacement law” [6] (Figure 2).

With that being said, using Wien's displacement law allows researchers to make predictions about the color of galaxies, including Crab Nebula, the radio galaxy in investigation. In this experiment, the radio-telescope used detected waves emitted by Taurus A as expected. The goal is to compare published data and numerical approximations to validate our measurements. In the article Crab Nebula, published by New World Encyclopedia, it states that Crab Nebula filaments' temperatures varies roughly between 11,000 K and 18,000, which explain the colors of Taurus A.

Given 4.2 GHz, the maximum frequency readable by the C-band LNB, computing the maximum wavelength is simple:

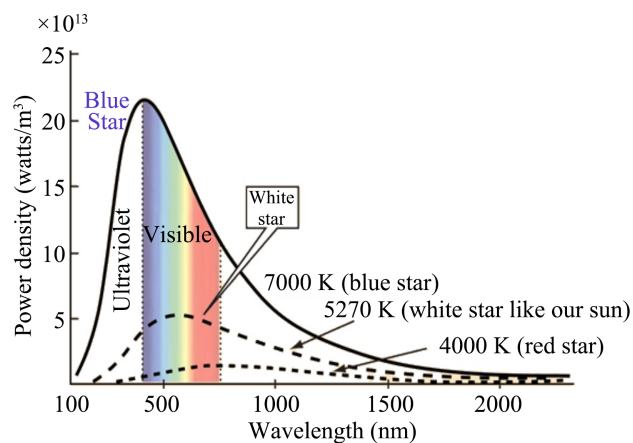


Figure 2. Black body radiation [6].

$$\lambda_{\max} = \frac{c}{\text{freq}} = \frac{3 \times 10^8}{4.2 \times 10^{-9}} = 0.071 \text{ m} \quad (1)$$

Given that purpose of this experiment is to make sense of the data collected and compare the results to published research on Taurus A. The experiment requires a set of equipment, which happen to be relatively cheap and affordable.

3. Experimental Apparatus and Set up, Data Acquisition, and Data

The system required the following devices to work. There are 2 groups: required and optional devices. Each main device has a major impact on the system. On the other hand, the optional devices either simplify or add an extra feature.

3.1. Equipment

3.1.1. Five-Meter Radio Telescope

This is the main Radio Astronomy dish used in this research to capture radio waves emitted by Taurus A. It is 5 Meter long and located at the University of Indianapolis, on top of the science building, Lilly Science Hall. The selection of a 5-meter radio telescope was carefully considered to balance several key factors essential for our research objectives. Firstly, the 5-meter aperture size strikes a balance between sensitivity and cost-effectiveness. While larger dishes offer increased sensitivity, they often come with higher costs and logistical challenges. Conversely, smaller dishes may compromise sensitivity and resolution. The 5-meter dish size was deemed optimal for our study, providing sufficient sensitivity to capture faint radio emissions while remaining within budgetary constraints. The dish is equipped with a C-Band LNB capable of reading large frequencies from 3.7 to 4.2 GHz. Therefore, the system needs a device capable of converting these large frequencies into frequencies readable by the radio receiver (**Figure 3**).

3.1.2. LNB

This is a Low-noise block converter. It has the purpose of converting the high frequencies emitted by celestial radio sources and convert them into lower frequencies readable within the range of our receivers. This device is mounted at the focal point of the parabolic dish in use. The radio receiver used in this experiment reads frequencies in the range 24 MHz to 1.7 GHz. Taurus A emits from low radio frequencies up to 100 MHz. As mentioned earlier, the dish antenna can only read between 3.7 to 4.2 GHz. The C-band LNB has an oscillator frequency of 5.15 GHz. Therefore, the difference between the oscillator frequency and the frequency read by the Radio telescope is the SDR final signal [7]. In our observations, we targeted frequencies within the C-band range, specifically from 3.7 to 4.2 GHz, where significant synchrotron emission from Taurus A is expected (**Figure 4**).

$$\text{SDR}_{\text{sig}} = 5.15 \text{ GHz} - \text{DISH}_{\text{sig}} \quad (2)$$



Figure 3. Radio telescope.



Figure 4. LNB [7].

3.1.3. LNB Power Inserter

The RTL-SDR demands power to work. As it can be seen on **Figure 5**, the power inserter has three ports. The first port is linked to the SDR receiver, the two other are connected respectively to the power supply and the Low Noise Blocker. The power is sent through one of the ports to the dish antenna and receives back the converted signal [7].



Figure 5. LNB power inserter [7].

3.1.4. RTL-SDR

This is a cheap \$25 software define radio device that can be used as a computer based radio scanner for receiving live radio signals in your area (no internet required). Depending on the particular model it could receive frequencies from 500 kHz up to 1.75 GHz. Though the maximum sampling rate is 3.2 MS/s, the device is stable and does not drop samples only when it runs under 2.56 Ms/s. It is said to be Software Defined Radio because the components are not implemented in analogue hardware components, but as software [8] (Figure 6).

3.2. System Setup

3.2.1. Software Installation

The software used to investigate the radio waves emitted by Taurus A is called Rtl-power-fftw.

1) Rtl-power-fftw

The software can easily be installed on a computer running a Linux distribution. First, the system needs a couple of development libraries that can be obtained with the following command:

```
>> sudo apt-get install libfftw3-dev libtclap-dev librtlsdr-dev pkg-config
```

Then, the repository was cloned using the following command:

```
>> git clone https://github.com/AD-Vega/rtl-power-fftw.git
```

Finally, the environment can be built and compiled from the sources by executing the following commands within the folder containing the source files:

```
>> mkdir build
```

```
>> cd build
```

```
>> cmake.
```

```
>> make
```

- **How does it work?**

In simple steps, here is how the software runs and collect data throughout the execution of this command:



Figure 6. RTL-SDR [8].

```
>> rtl_power_fftw -f 1199.0 M: 1201.0 M
-b 256 -t 10.0 -r 2560000 -p 0
-q -g 300 -e 12h -m FileName > FileName.out 2 > & 1 &
```

The software reads the command with these parameters:

- f: Receiver frequency range to scan.
- b: Bins number in the fast Fourier transform spectrum (must be an even number).
- t: Integration time.
- r: Receiver sample rate in Hz.
- p: RTL-SDR correct device given in ppm.
- q: Limit verbosity.
- g: Gain by the receiver in decibel.
- e: Recording duration in unit of time.
- m: File name.

“The program is capable of continuous real-time data acquisition and processing: it uses the RTL-SDR library to access the RTL device and the FFTW library to do the FFT. Data acquisition and Fast Fourier transform are done in separate program threads for maximum efficiency. The resulting power spectrum is written to the standard output.” [9]

a) Rtl-power-fftw software reads the data stream from the connected RTL device.

b) It then performs a Fast Fourier transform on it, converts the frequency-domain data into a power spectrum

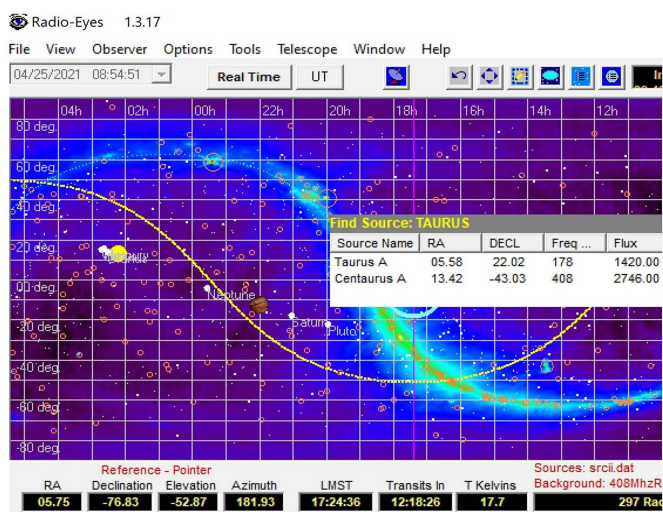
c) Finally, it averages a number of such spectra to gain a better signal-to-noise ratio.

If the range exceeds the device bandwidth, Rtl-power-fftw can perform the measurement in multiple steps, changing the central frequency each time so that the desired frequency range is completely covered [9].

2) Radio Eyes

This software is more than just a visualization program. Though it helps user visualize emissions from the sky at the radio end of the electromagnetic spectrum, it contains tools for planning radio astronomical observations (Figure 7).

Given an appropriate hardware interface, the advanced version even steers radio telescope antennas and trigger data collection via Radio-SkyPipe at the appropriate times. Background and radio source catalog tools allow the user to display a variety of information sets [10]. The idea was to use the find object tool and get information about Taurus A. The observer parameters must also be adjusted in the settings first. In this experiment led in Indianapolis, in the county of Marion, the observer parameters were entered as follows (Figure 8 and Table 1).



Taurus A
3C144
Crab nebula
CTA36
M1

Date Format Used: MMDDYYYY

Calculations for 04/25/2021 08:53:17 UT 04/25/2021 03:53:17 Local Time

Observer Longitude: 86.157 Degrees West Latitude: 39.768 Degrees

Right Ascension: 05:34:30

Declination: 22:00:57

Elevation: -28.16

Azimuth: 356.99

Geo Sub Point > lat 22.02 lng 263.29 West

Object Hour Angle: 11.809

Distance from Beam Center: 162.99 degrees

(With Beam at Azimuth 180.00 Elevation: 45.00)

Time until next Transit: 12:09:28 (HH:MM:SS from view time.)

Next Transit Time: 04/25/2021 21:02:45 UT

Transit Elevation: 72.248 degrees South.

Rise UT: 13:45:17 at Az 60.81deg.

Set UT: 04:24:08 at Az: 299.19deg.

Angular speed: 0.23 deg /minute.

Freq: 178 MHz Flux: 1420 Janskys

Freq 960 MHz Flux: 1030 Janskys

Spectral Index = 0.26

Figure 7. Radio eyes.

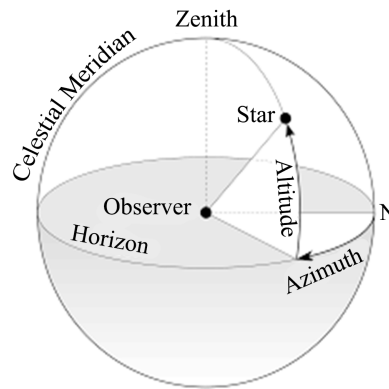


Figure 8. Visual representation of the earth's parallels.

Table 1. Observer parameters.

Latitude	39:46:06.2
Longitude	86:09:25.6
Average elevation	248 m
Time zone	GMT-5
Location Desc.	Indianapolis, USA

Before taking any further step, it is essential to describe how the parabolic dish was adjusted and the theory behind it. Altitude is known as the elevation or how far up is an object above the horizon axis, at 0 degree. On the other hand, declination is known to be as the equivalent of Latitude. The parabolic dish was adjusted to look at Taurus A knowing that it is at about 73.3 degree given the radio telescope location.

3) Python

Python was used through Jupyter Notebook to compute and conduct numerical analysis of the data collected. Python libraries such as panda, numpy, matplotlib, datetime, etc. were effective and efficient because of their usability. In fact, because the experiment requires heavy data manipulation, using Numpy arrays facilitated the work.

3.2.2. Hardware Setup

Though the combination RTL-SDR and the parabolic dish is the piece de resistance of our setup, there are additional devices and software that were of great help. The software-defined radio device is connected to a raspberry pi.

A small single-board computer that keeps the spectroradiometer software running. The radio telescope is used as the main antenna, which is connected to both a low-noise block down-converter and a power supply via coaxial cables. The use of the LNB is necessary simply because the signal received by the dish belongs to the C band spectrum, which goes from 3.4 GHz to 4.2 GHz. This is a problem because our receiver can only read binary data that vary between 950 and 1.75 GHz (**Figure 9**).

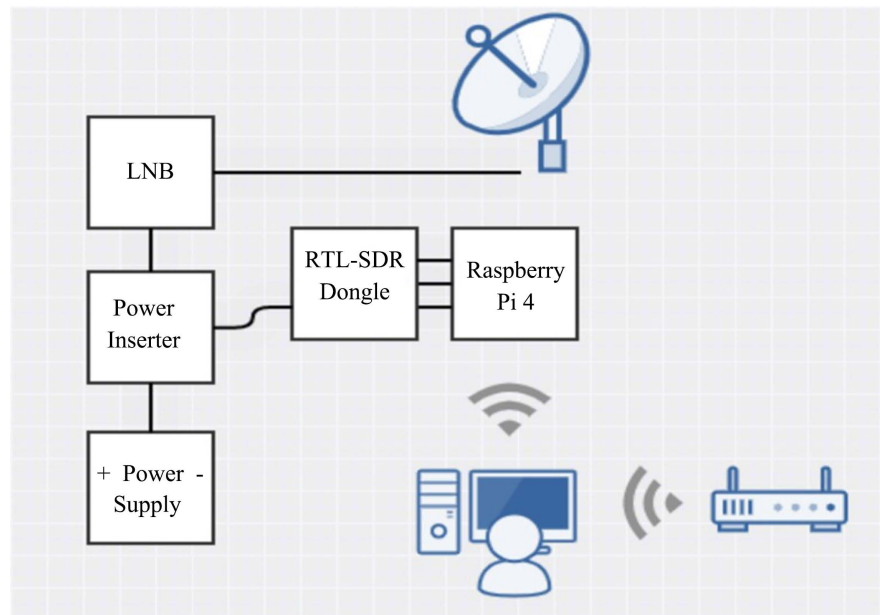


Figure 9. Equipment.

The Rtl-power-fftw is the spectroradiometer software used that provides spectral and continuum modes of the radio waves being read, including the power generated, correlation and differential. The RTL-SDR stayed connected for days and the process was monitored from home using a graphical desktop-sharing system, such as VNC, Teamviewer, or Ssh.

4. Results

The scan stores the data collected by the software, RTL-Power FFTW, in the specified location providing both a .bin and .met file. Bin files are used for different purposes by many applications. They are compressed binary files saved as basic binary format to minimize the overall size of the data collected. By using Python through Jupyter Notebook, the goal was to give these data a meaning. With appropriate commands, the binary data were converted to energies. On the other hand, the .met files generated after each scan bring information about the time, date, and frequency range of our data collected.

This section will not show the entire code and the exhaustive list of commands to run and plot the data collected. However, this section contains snippets of the most relevant commands under Python 3.9.0. The binary file can be read by using the read function. This is a built-in function, which requires no specific library call and has the rb or read only method to allow binary data manipulation.

- *How to Open The Files?*

```
>> file = open('FileName', 'rb')
>> source = file.read()
>> # or file.readlines()
>> f.close()
```

The next step is to split the data store in the variable source into a group of arrays containing different set of data. The idea is to have two major arrays: One containing data radio data and the other times of data collection and the other, the energies. The former requires the use of the `.strip()` function and a data structure such as a dictionary that can properly save data with their keys and corresponding values. The latter is explained in the next lines.

- *How to Get the Times of Data Collections?*

```
>> def Split(filename)
    >> file = open(filename + '.met', 'r')
    >> mets = file.readlines()
    >> file.close()
    >> metDict = {}
    >> for met in mets:
        >> val, key = [x.strip() for x in met.split("#")]
        >> if 'UTC' in val:
            >> metDict[key] = datetime
                .strptime(val, "%Y-%m-%d
                %H:%M:%S %Z")
        >> elif '.' in val:
            >> metDict[key] = float(val)
        >> else:
            >> metDict[key] = int(val)
    >> return metDict
```

In order to build a data frame, the program must read the binary file and the `.timestamp()` is useful because it returns the number of seconds that has passed since the zero moment for the given Timestamp object. This also helps display date times in the plots.

- *How to Get the Times of Data Collections?*

```
def Time():
    >> startTime = metDict['firstAcqTimestamp UTC']
    .timestamp()
    >> endTime = metDict['lastAcqTimestamp UTC'].timestamp()
    >> times = np.linspace(startTime, endTime, len(radioData))
    >> tstamps = np.array([datetime
    .fromtimestamp(x) for x in times])
    >> tseries = pd.Series(tstamps) return pd.DataFrame({'time':tseries,'energy':
    radioData.mean(axis = 1)})
```

5. Analysis & Discussion

The software was run multiple times from March to April and each time, the scan lasted at least four hours. The radio data obtained showed multiple radio sources. However, Radio Eyes predicts that every day, Taurus A can be observed four minutes earlier than the day before. On March 12th, Radio Eyes predicted

that Taurus A would transit at exactly 11:47 pm UTC. This prediction brought a sense of validation in our data since **Figure 10** and **Figure 11** show exactly a bump on the curve around that exact time.

On **Figure 11**, the bumps starts right between 11:37 pm and 11:40 pm UTC. We chose March 14th, 48 hours after in comparison to March 12th to minimize error. The difference in time between the start of the two bumps is approximately eight or nine minutes. The first set of data bump starts at 11:47 pm UTC and at 11:39 pm UTC for the other.

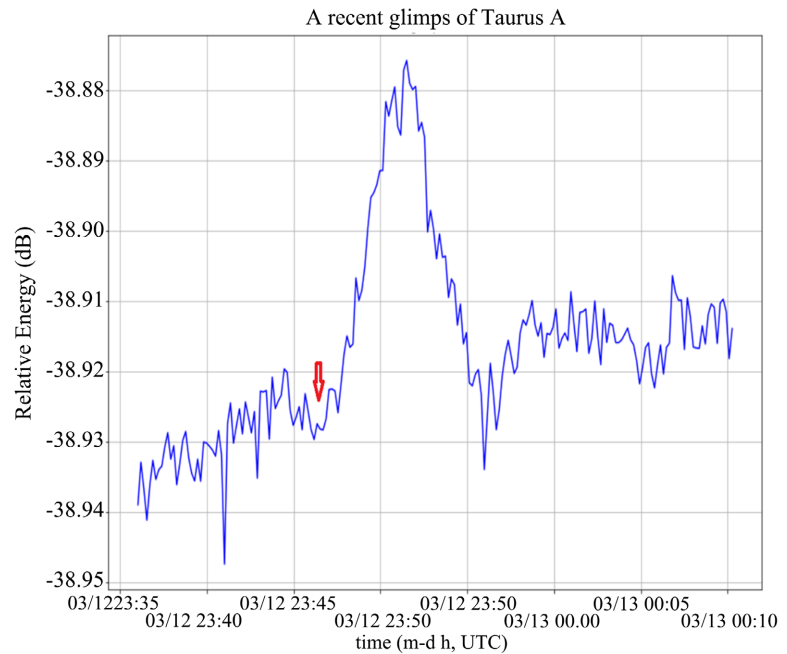


Figure 10. Sample radio data from March 12th, 2021.

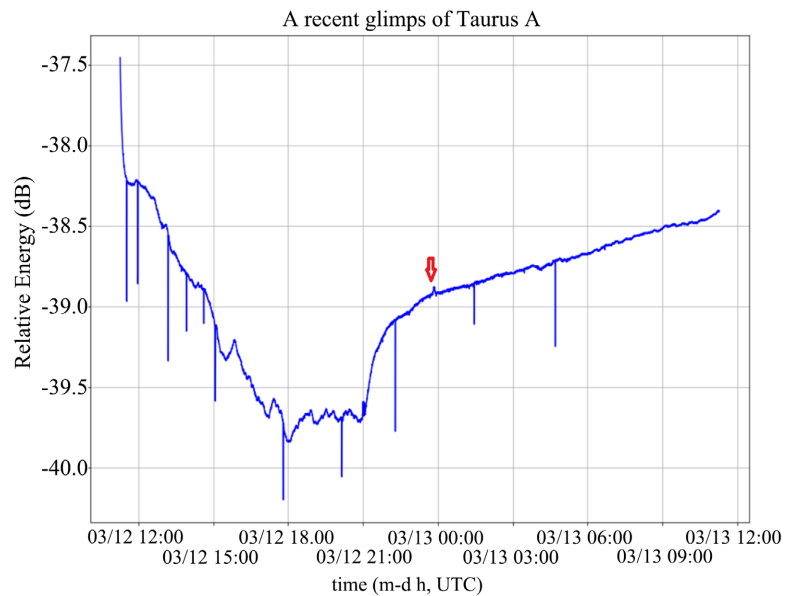


Figure 11. Magnified sample radio data from March 12th, 2021.

- *Sidereal time vs. Solar time to explain the time difference*

As it is shown on **Figure 10**, the scan has a the bump starting right between 11:45 pm and 11:50 pm UTC. This leads to the following conclusion: Radio Eyes predicts Taurus A's transits with acceptable precision. On top of that, the other set of data, after and before March 12th, show exactly what was mentioned earlier: After 24 hours, the radio galaxy transits at about four minutes earlier than the night before.

The time difference can be explained using Earth Rotation and Revolution. In simple terms, because our planet rotates and also revolves around the sun, it creates that time shift. In fact, given that Crab Nebula is stationary, our planet travels approximately 2.6 million km a day from west to east, and it spins on its axis, we can conclude that the point where the radio-telescope reads the radio signals from Taurus A shifts as well.

In other words, the idea of sidereal times is the key to understanding this problem. In fact, the clocks used at home are based on solar time, which is relative to the sun and takes 24 hours to complete a full rotation cycle. However, due to earth revolution, sidereal time is measured based on fixed or stationary stars. As shown on **Figure 12**, while the Earth is rotating on its own axis, it is also revolving around the sun along its orbit. The planet is one degree ahead every day on its orbit. When it completes a full rotation on its own axis, any given point on its surface will not be facing the sun following the same old path. It takes about 4 minutes to complete that extra degree to make it face the sun again [11].

$$t = 24 \frac{\text{hour}}{\text{day}} * 60 \frac{\text{minute}}{\text{hour}} * \frac{1}{365.25} \frac{\text{day}}{\text{degree}} = 3.94 \frac{\text{minute}}{\text{degree}} \quad (3)$$

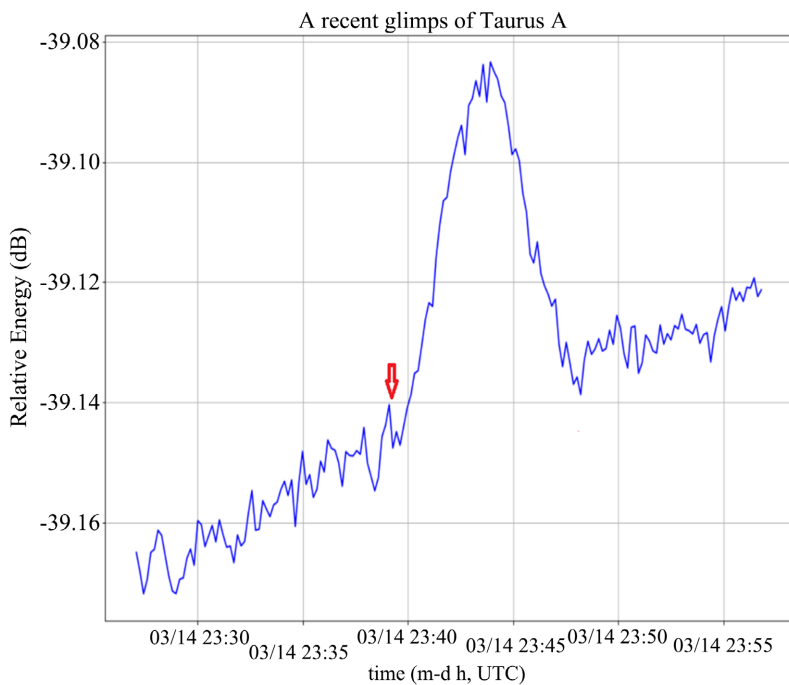


Figure 12. Sample radio data from March 14th, 2021.

- *How to remove noises in our data?*

As it was shown on **Figure 10** and **Figure 11**, the noises are quite important. It would not be wise to deal with each set of data in such a state. However, what if every set of data were combined into one? This is done using a superposition technique. By adding all data together, the result must be free from noises, irregularities, etc.

As it is shown on **Figure 13**, the noise cancelling process required the use of about 10 set of data in order to obtain a graph free of high noises.

The objective of the curve fitting function was a Gaussian peak function plus a linear background signal. After conversion from indexes to unit of time, it was observed that the distance between two indexes in the plots above corresponds to approximately 17.94 sec. Given that, multiplying any index difference by 17.94 should give the difference in time. The objective function is given as:

$$y = m(x - x_0) + e^{-\left(\frac{x-x_0}{w}\right)^2} + b \tag{4}$$

```
>> def objective(x,x0,w,S,m,b):
    >> return m*(x-x0) + b + S*np.exp(-((x-x0)/w)**2)
>> def curve_fitting(xvals,yvals):
    >> x0_0 = 50
    >> S_0 = 1
    >> m_0 = 1
    >> b_0 = -39.25
    >> popt, pcov = curve_fit(objective, xvals, yvals,
    p0 = (x0_0, w_0, S_0, m_0, b_0)) Results:
x0: Peak center: 898.63 sec w: Peak width: 68.16 sec
S: Peak Amplitude: 0.48 dB
m: Slope of the line: 0.00885 dB/sec b: Y-intercept: -328.6 db
```

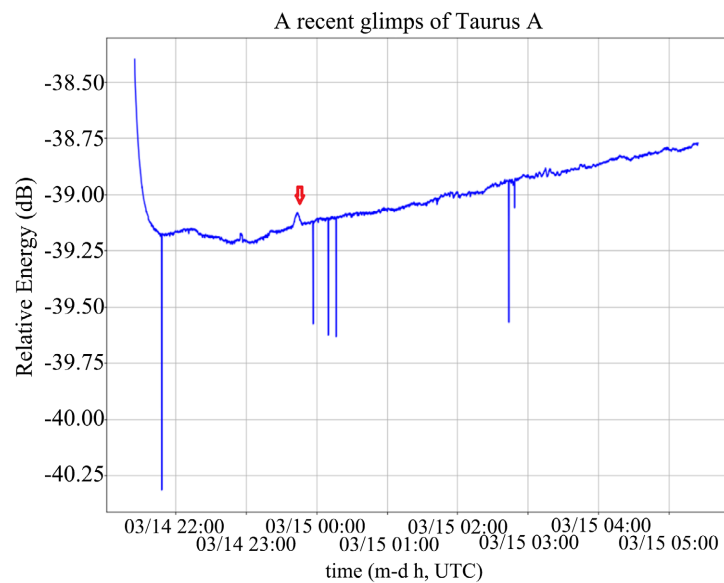


Figure 13. Magnified sample radio data from March 14th, 2021.

• *How to validate the observation?*

It is clear that if the radio waves come from the same source, the overall energy observed should be constant throughout the entire observation time. However, data in **Figure 14** says otherwise. Theoretically, this is explained using the principle of superposition of waves. When the radio telescope enters the path line of the radio galaxy, the electromagnetic waves are in both constructive and destructive interference depending on some factors that will be explained later. Fraunhofer diffraction by a circular aperture can help explain the idea behind the observations. In optics, the equations of this model is used to view diffraction pattern from object source at long distances. Imagine a beam of light trying to pass through a circular aperture of a diameter relatively small. Some of the wavelets spread out as diffracted rays. Each of these wavelets are in either destructive or constructive interference following this phasor amplitude formula: (**Figures 15-17**)

$$y(x, \theta) = \frac{dx}{R} \sqrt{R^2 - (x - R)^2} e^{\frac{2\pi i x \sin(\theta)}{\lambda}} \quad (5)$$

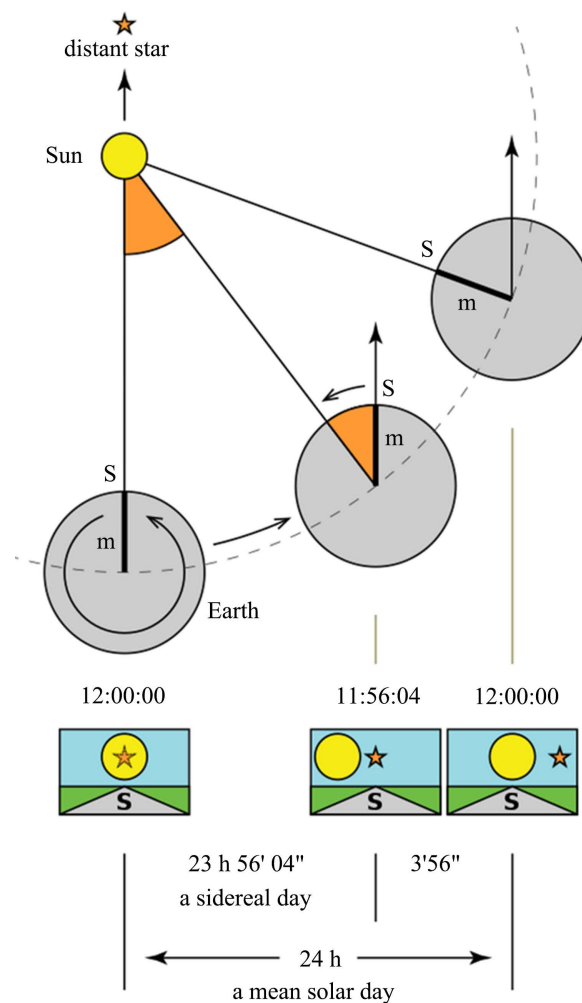


Figure 14. Sidereal vs. solar time [11].

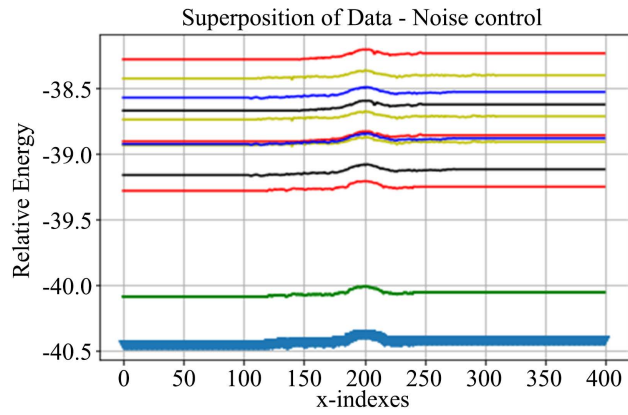


Figure 15. Superposition of data-Noise control.

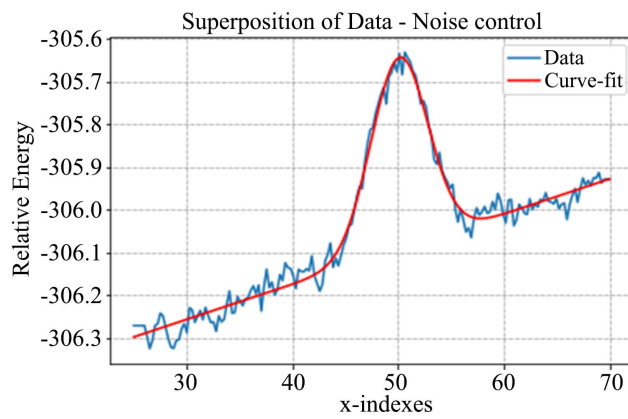


Figure 16. Noise control.

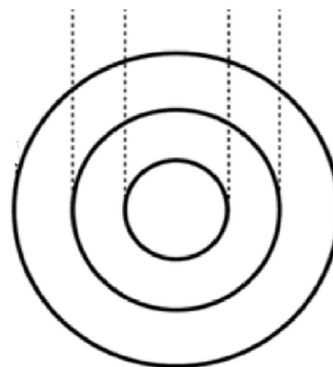
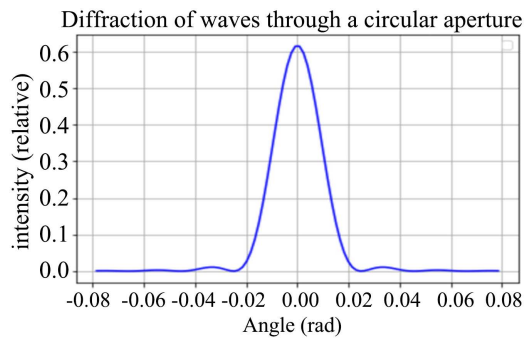


Figure 17. Diffraction of waves through a circular aperture.

6. Conclusion

The spectroradiometer software, RTL-power FFTW saves the data as binary and meta files. After data collection, the goal was to read something meaningful from our data and validate our observation. With the use of modern scientific computing software such as MATLAB and Python through Jupyter Notebook. The analysis of data was necessary to validate the observation with the help of a curve fit approximation.

In conclusion, it was proven both analytically and numerically that the radio galaxy is in the path of the radio telescope about four minutes earlier than the day before. On top of that, the signal obtained followed a Gaussian peak model because of waves constructive and destructive interference.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] (2016) Introduction—Essential Radio Astronomy.
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