

Building your very first Radio Telescope

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Written on December 11th, 2019

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Introduction: What even is radio astronomy?

Radio astronomy is a subfield of astronomy that studies celestial objects at radio frequencies. Unlike traditional telescopes that observe the sky in the visible part of the electromagnetic spectrum (**400-700 nm**), radio telescopes observe the sky in wavelengths **ranging from centimeters to a few meters**.

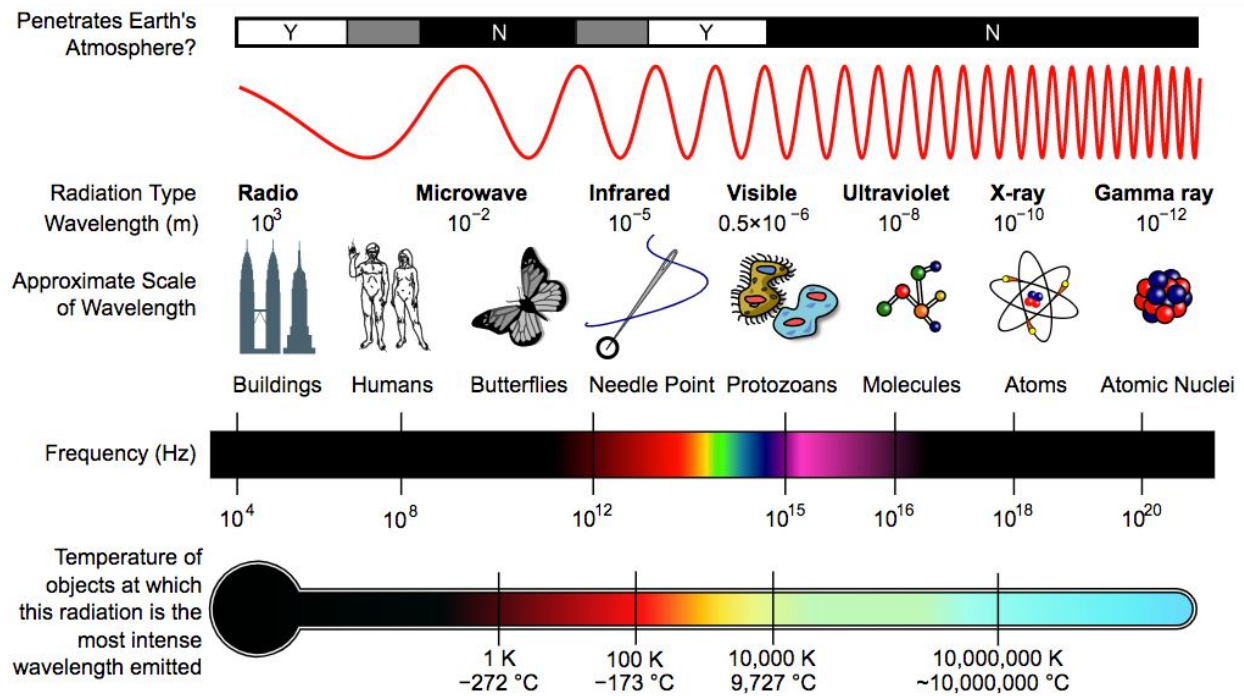


Fig. 1: A diagram of the electromagnetic spectrum, showing various properties across the range of frequencies and wavelengths.

But why should we observe in radio wavelengths?

There are several reasons to observe the sky at radio frequencies. The most common reason radio astronomers point radio telescopes to the sky is **to study sources that produce radio**

emissions: radiation that is invisible to the human eye, but is capable of providing compelling information to astronomers & astrophysicists.

A significant advantage radio astronomers have over IR, UV and high-energy astronomers is the atmospheric window: **our atmosphere is completely transparent to radio waves**, so we don't need to send large radio antennas to space (like we usually have to do with IR/UV/high-energy astronomy satellites) in order to efficiently expose our instruments to the sky.

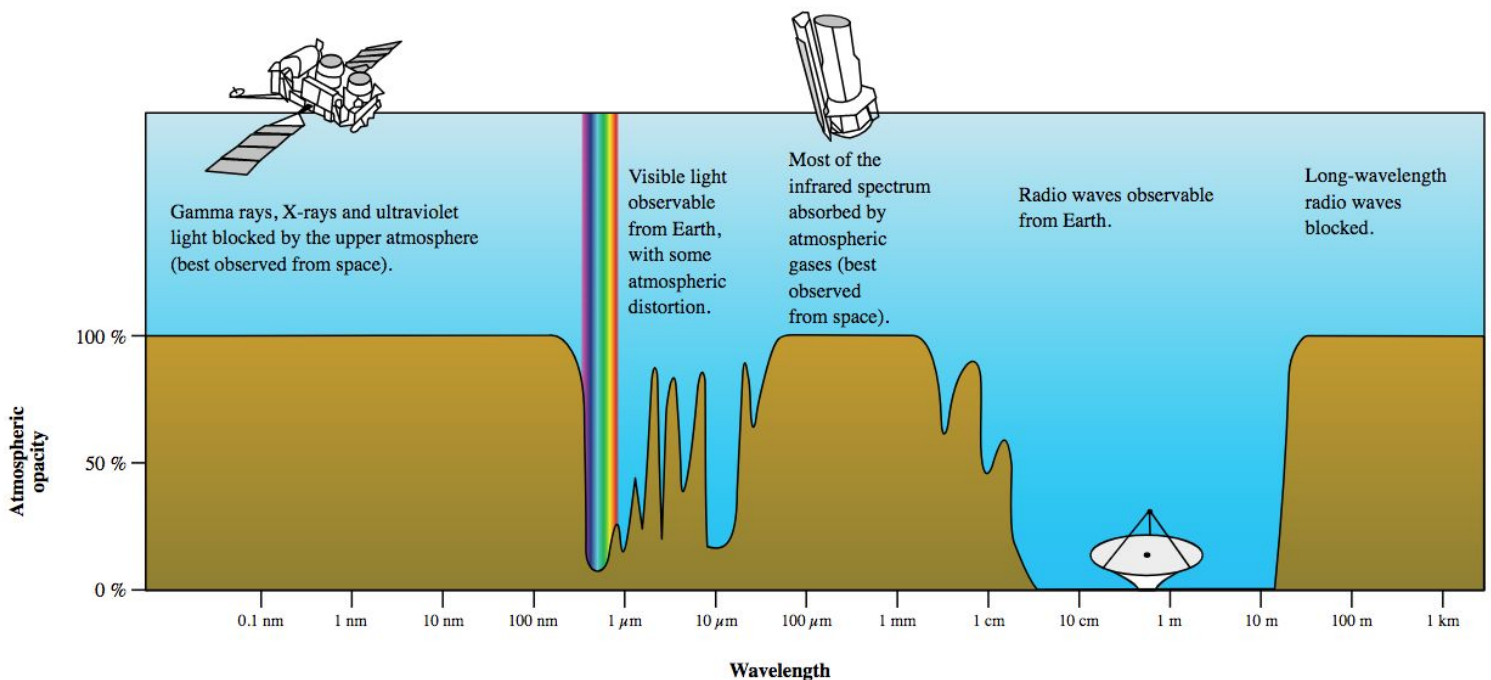


Fig. 2: A diagram showing the amount of absorption of each wavelength of light by the Earth's atmosphere, highlighting the atmospheric windows.

It is also worth noting that radio observations can be carried out **during both daytime and nighttime**, and even under poor weather conditions (e.g. clouds)!

Last but not least, we can utilize the techniques of radio interferometry and aperture synthesis using large arrays of antennas **to achieve extremely high (angular) resolution observations**, which is how the first image of a black hole became possible (the combination of several radio

telescopes around the world allowed the Event Horizon Telescope team to create a virtual telescope the size of the Earth)!



Fig. 3: The Very Large Array (VLA) is one of the most sophisticated radio telescope arrays in the world, consisting of twenty-seven 25-meter radio antennas that can function as a high-resolution radio interferometer.

What will I be able to observe with my radio telescope?

There are plenty of sources in the sky that present radio emissions, including **galaxies, supernova remnants, nebulae, radio galaxies, quasars, pulsars, masers and more**. However, most radio sources in the sky are very “radio-faint” and require very large aperture antennas to be detected. The radio telescope described in this document should be capable of detecting radio emissions from the Sun, the Moon, the 21-cm hydrogen line (intergalactic clouds of neutral hydrogen (e.g. spiral arms)), synchrotron radiation originating in the galactic plane and even Cygnus A (radio galaxy) and Cassiopeia A (supernova remnant) if the aperture of antenna is large enough.

The 21-centimeter hydrogen line

The **hydrogen line** refers to the electromagnetic radiation spectral line that is created by a change in the energy state of neutral hydrogen atoms. This electromagnetic radiation is at the approximate frequency (ν) of 1420.4 MHz, which is equivalent to the wavelength (λ) of approximately 21 cm ($\lambda = \frac{c}{\nu}$). This wavelength falls within the radio region of the electromagnetic spectrum, and it is frequently observed by radio astronomers. The exact mechanism under which hydrogen atoms emit electromagnetic radiation with a wavelength of 21 cm is slightly complicated, but it's not important if you just wish to perform neutral hydrogen observations (if you're interested to learn more about how hydrogen atoms can spontaneously emit radio waves, take a look [here](#) and [here](#)).

The superheterodyne receiver

A superheterodyne receiver is a radio system intended to convert radiofrequency (RF) signals “entering” the antenna into a form that can be conveniently processed and analyzed. This type of radio receiver is adopted by virtually all modern radio devices, including software-defined radios (SDRs) which will be used in our radio telescope. In this section, the block diagram of the superheterodyne receiver is described, with a justification for each component.

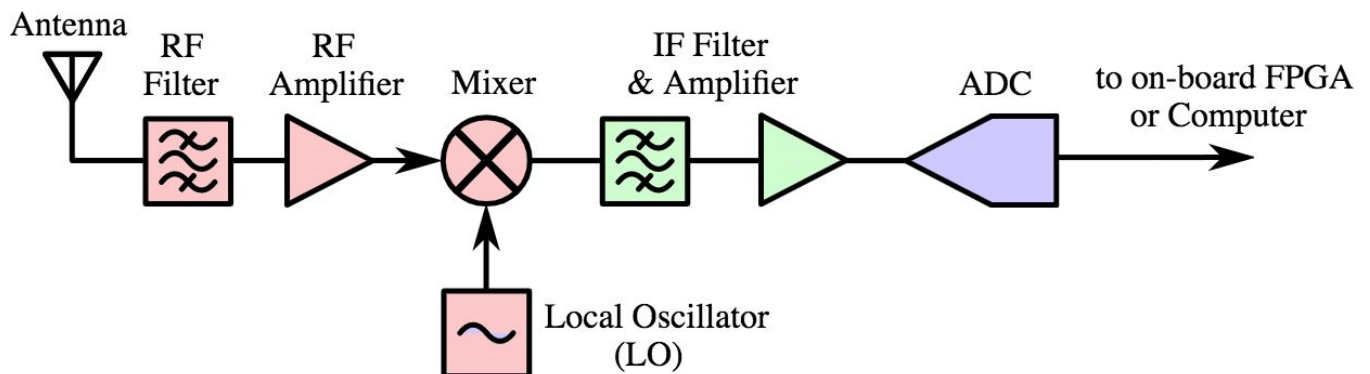


Fig. 4: Block diagram of a typical superheterodyne receiver found in an SDR.

The role of an **antenna** is to convert electromagnetic energy (radio waves) into an alternating current that is easier to process with modern electronics.

An **RF filter** is used to filter out unwanted interference picked up by the antenna before the signal reaches the **RF amplifier**, where it is amplified in order to rise above the noise introduced by components later in the chain.

A **mixer** has two inputs: the output signal of the RF amplifier (f_{RF}) and a signal generated by the **local oscillator (LO)** (f_{LO}). The output frequency of the mixer is the difference between the two input frequencies ($f_{IF} = |f_{LO} - f_{RF}|$). The role of the mixer is to downconvert the RF signal into an intermediate frequency (IF) that is easier to process later on.

Once the signal is downconverted, it goes through one more filtering and amplification stage (**IF filter & amplifier**), before entering the **analog-to-digital converter (ADC)**, where the signal is digitized and forwarded to a computer/FPGA chip (on-board processor) for further digital signal processing.



Fig. 5: A low-cost software-defined radio (RTL-SDR), operating on the superheterodyne principle.

Building our radio telescope

Our radio telescope will consist of a **parabolic antenna** (e.g. satellite TV dish) with a **feedhorn** optimized for 1420 MHz, an appropriate **low-noise amplifier (LNA)** and an **SDR** receiver.

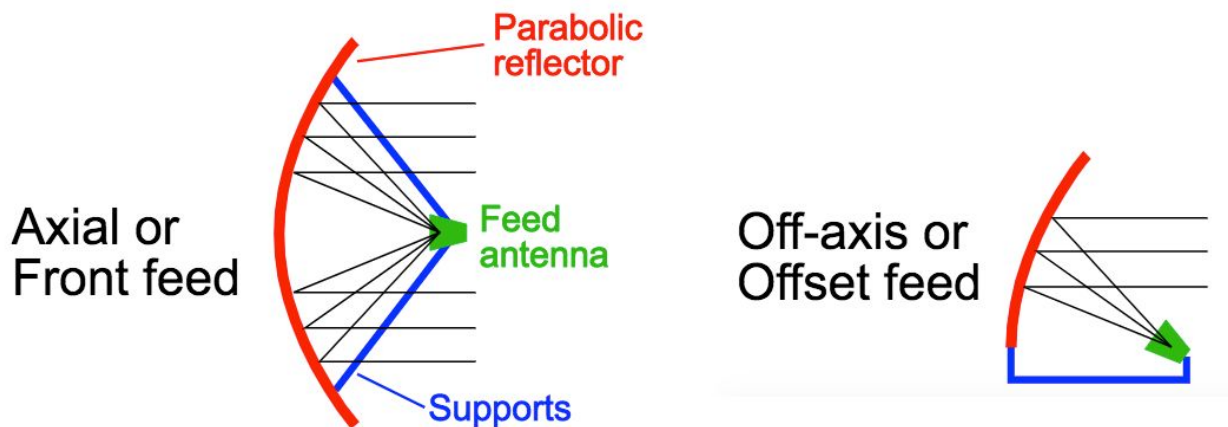


Fig. 6: Most radio telescopes work on the fundamental geometric property of parabolas/paraboloids, which is the ability to concentrate incident radio waves to a particular point called the *focal point* (reflecting (optical) telescopes work in a similar fashion).

Most satellite TV dishes will have an elliptical shape. This indicates that your reflector is an **offset** type of dish, so you'll need to be pointing the antenna approximately **30°** below the apparent "pointing direction" of the dish. If you do not already have a dish, look for one with a diameter of at least 70 cm, although bigger is always better! It is not important if the dish is offset or not. Different types of dish geometries have different advantages and disadvantages, but since they are unimportant for our application, they will not be discussed here.

Once a dish has been obtained, we will need to replace the LNB that was originally used for satellite TV (if present) with a feedhorn optimized for the detection of the 21-cm hydrogen line (1420 MHz). An LNB (low-noise block downconverter) is designed to receive satellite signals ranging from 10.7 to 12.75 GHz (Ku-band), so it will **not** work for detecting the hydrogen line at 1420 MHz.

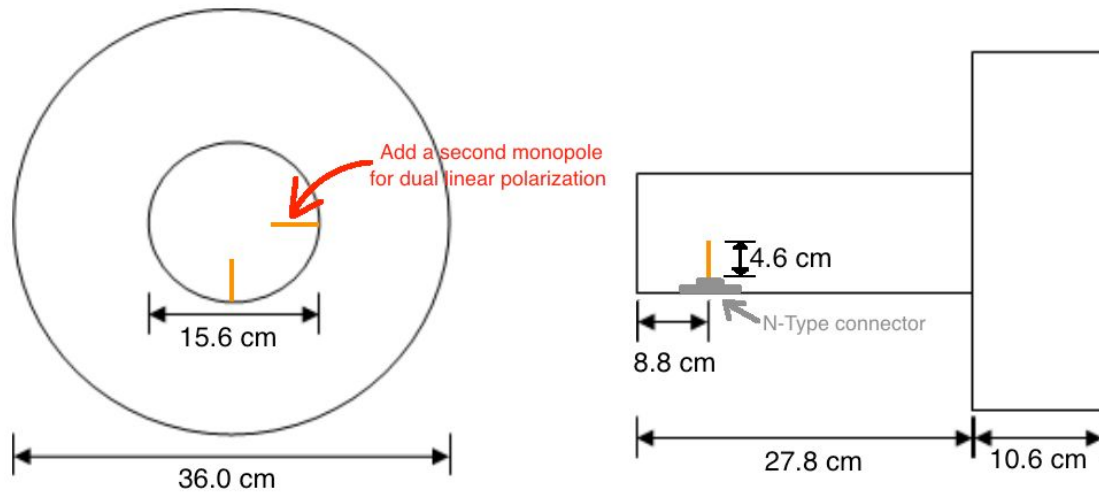


Figure: Top and Side View of the Feed Horn

Fig. 7: A feedhorn with such dimensions should give fine results. It might be preferable (depending on the focal ratio of your dish (f/D)) to not have the outer choke ring at all, so the dimension of your waveguide should be approximately **diameter = 15 cm x height = 18 cm**.

The feedhorn should be made from a conductive metal, such as **aluminum, steel** or **copper**. More importantly, the pin probe should be made of **copper**, have a length of **4.6 cm** and a thickness (diameter) of **2 mm**. The length determines the center frequency the antenna will be sensitive at, while the thickness affects the bandwidth (frequency range) it can effectively operate in. You do not need to add a second monopole (pin probe) to the feedhorn.



Fig. 8: An N-Type connector is needed to solder the copper wire onto and attach it to the feedhorn. You'll also need an N-Type to SMA connector to connect the feedhorn to the LNA.

Once the dish has been obtained and the feedhorn is installed at the focal point, we will need a low-noise amplifier. An LNA's role is to take the extremely faint signals picked up by the antenna and amplify them, bringing the desired signal above the noise floor, ultimately increasing our signal-to-noise ratio (S/N). The key characteristics to look for when searching for an LNA is low noise figure (< **1 dB**) and high gain (> **17 dB**) at 1420 MHz. This will ensure the LNA injects very little noise into the output signal, while the high amplification gain will make sure cable losses etc. are accounted for.

An LNA like the [ZX60-P33ULN+](#) or [ZX60-P162LN+](#) by Mini-Circuits will do, although an SPF5189-based LNA from eBay or Amazon is a much more inexpensive alternative, without a significant difference in quality (i.e. noise figure and gain). The [SAWbird+ H1](#) by Nooelec is another good option, offering a built-in band-pass filter for radiofrequency interference (RFI) mitigation. Just ensure the LNA is powered (directly, or by a [bias tee](#) through the coax cable).

Note: it is important to avoid having a cable run from the feedhorn to the LNA. The desired signal is already extremely weak and even a small loss introduced by the attenuation of a (short) cable can dramatically degrade your S/N.

After the signal has been amplified by the LNA, it is often a good idea to filter out interference by using a low-pass, high-pass, or ideally, a band-pass filter. If your LNA does not have a built-in filter, you can get a hydrogen line filter like [this](#), although it may not be necessary (especially if your telescope is installed in a relatively radio-quiet environment with little RFI).

Once the signal has been amplified (and potentially filtered), it is time to drive it into a radio receiver (i.e. SDR) for digital processing and analysis. While most SDRs will do the job, an RTL-SDR offers one of the most inexpensive and reliable solutions, with rich documentation available online. Of course, you are free to use any SDR of your choice, as long as it's compatible with [GNU Radio Companion](#).

After picking an SDR, connect the RX (SMA) port to the output of the LNA/filter directly, or via a coaxial cable (try to keep the length of the coax less than ~3m to reduce losses). You'll then need to connect the SDR to your computer (e.g. Raspberry Pi 3/4), and you're ready to dive into the software!

VIRGO: A Spectrometer for Radio Astronomy

VIRGO is an easy-to-use **open-source** spectrometer and radiometer based on [Python](#) and [GNU Radio Companion](#) (GRC) that is conveniently applicable to any radio telescope working with a GRC-supported software-defined radio (SDR). In addition to data acquisition, VIRGO also carries out automated analysis of the recorded samples, producing an **averaged spectrum**, a **calibrated spectrum**, a **dynamic spectrum (waterfall)** and a **time series (power vs time)** plot.

To install **VIRGO**, please refer to the official repository and follow the instructions regarding the installation and usage of the application: <https://github.com/OxCoto/VIRGO>

When is the best time to observe the hydrogen line?

The most “ideal” time to observe and detect the 21 cm line would be **when the Milky Way plane is in the telescope’s beam (field of view)**. To check when the galactic plane is directly overhead, you can use a free planetarium software like [Stellarium](#).

Example observation

The following figure is an example 2-minute observation (when the galactic plane is *in the beam*):

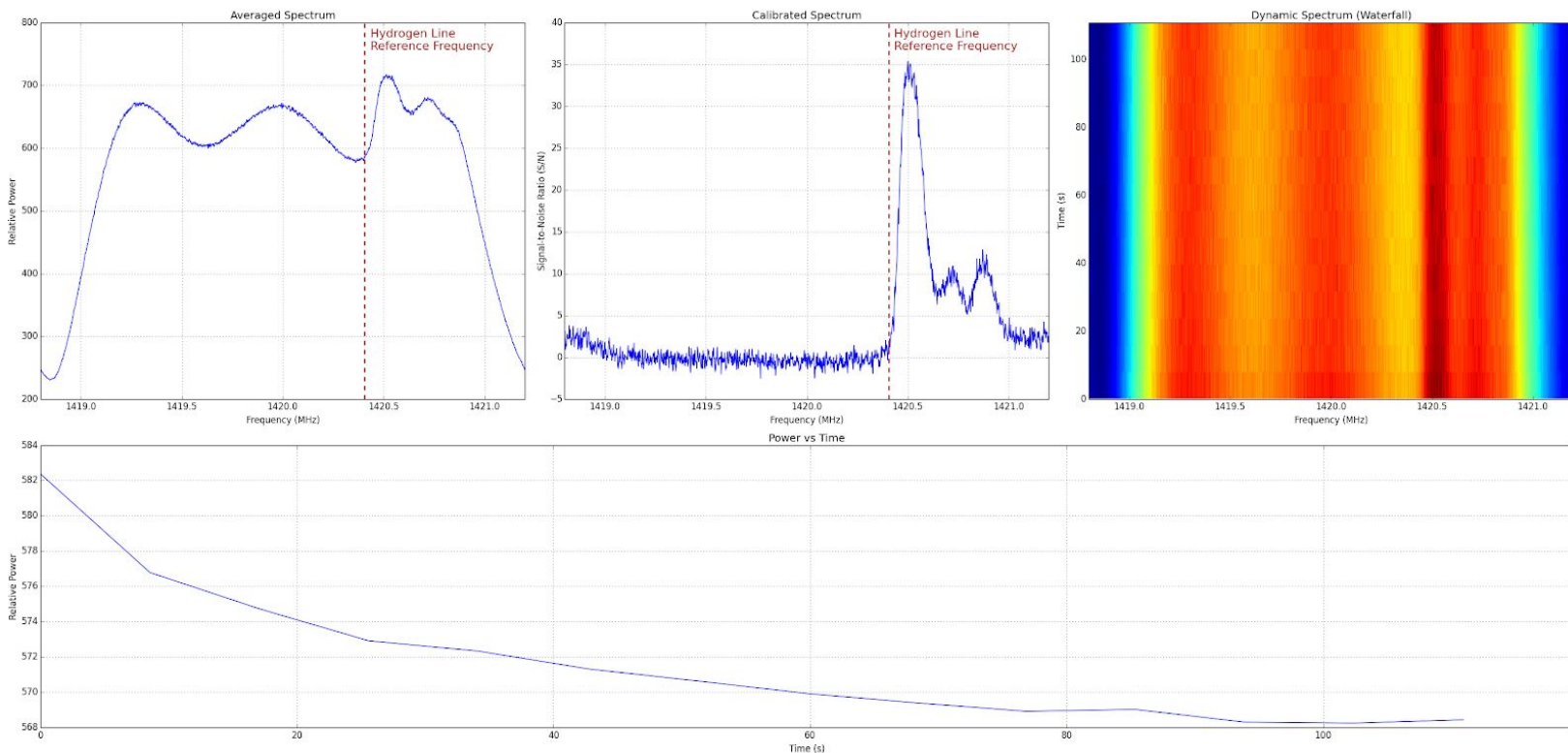


Fig. 9: Example observation. Top left: Averaged Spectrum, top center: Calibrated Spectrum, top right: Dynamic Spectrum (Waterfall), bottom: Time series (Power vs Time plot).

The top left plot is the **averaged spectrum**, showing the average power (intensity) for every frequency. The top center plot is the **calibrated spectrum**, which is identical to the averaged spectrum, with the effects of the receiver removed (so the noise floor becomes flat and the peaks become more distinct). The top right plot shows the **dynamic spectrum (waterfall)** (a Power vs Frequency vs Time graph displayed as a 2D plot with a colormap indicating Power) and the bottom plot shows the average power vs time plot. The **calibrated spectrum** plot is usually sufficient for beginner observers.

We see three curvy bumps in the averaged spectrum. This is due to the receiver's bandpass shape (different sensitivity at each frequency) and **should not be mistaken for radio emissions**

(this is why we should refer to the **calibrated spectrum**: to account for the receiver's instabilities, imperfections, effects etc.).

As you can see, **there are three distinct peaks** on the calibrated spectrum at around 1420.5, 1420.7 and 1420.85 MHz. This is the hydrogen line, and it's **blueshifted** (frequency > 1420.4 MHz), **meaning the source is approaching us!** We've just detected 3 unique spiral arm of our own galaxy, and by conducting another observation (i.e. when the other side of the Milky Way is in the beam), we should expect to see differently Doppler-shifted line(s), potentially indicating more spiral arms, Doppler-shifted (redshifted or blueshifted) to a different degree. From a 2-minute observation with **VIRGO**, we've just proven that beyond any doubt, **we do indeed live in a spiral galaxy!**

Using a few simple Doppler shift equations you are also encouraged to find the velocity of the detected spiral arms relative to Earth.

Conclusion

I hope this document has introduced you to the majesty of the radio sky and guided you regarding the construction of your first radio telescope. If you'd like to learn more about radio astronomy, the following resources are highly recommended:

- Mapping the Galaxy with Radio Astronomy: <https://youtu.be/-UrzmAa62ho>
- Radio Astronomy in Five Minutes: <https://youtu.be/3EcrLNIWdE>
- National Radio Astronomy Observatory (NRAO): <https://public.nrao.edu/radio-astronomy/>
- The Hydrogen 21-cm Line: <http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html>
- What is Radio Astronomy - ATNF: <https://www.atnf.csiro.au/outreach/education/everyone/radio-astronomy/index.html>

If you have any questions, feedback, suggestions or anything else you'd like to contact the author about, feel free to email me at Oxcoto@protonmail.com and I'll be happy to get back to you shortly!