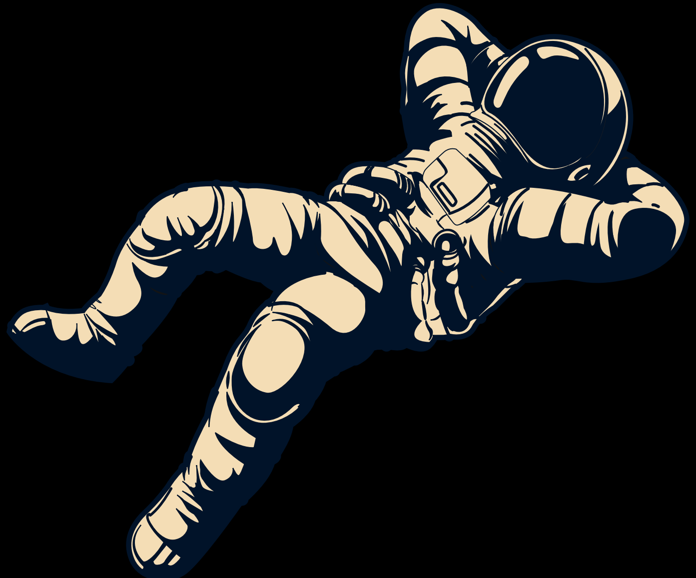
CosmoCode

A brainstorming avenue for Astronomical Signal Processing



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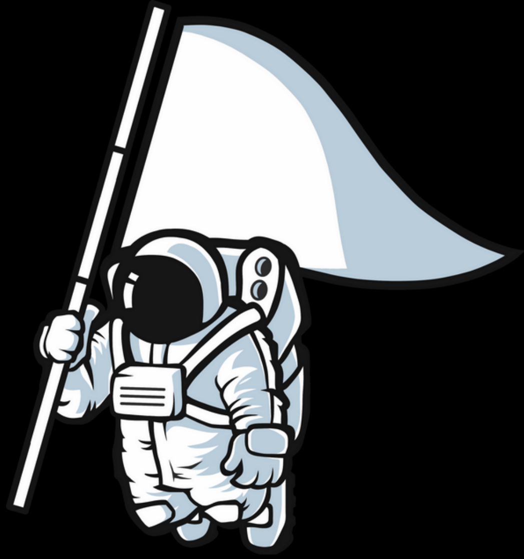
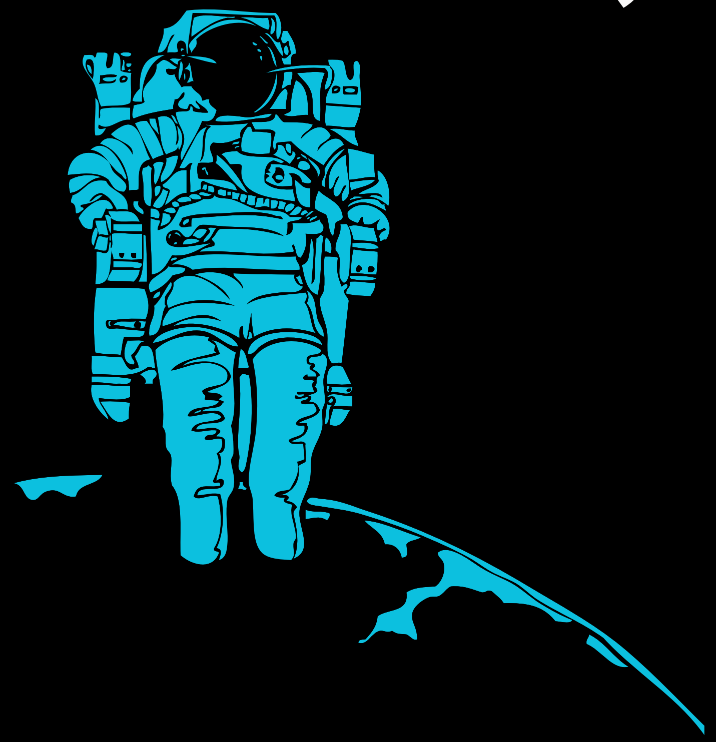
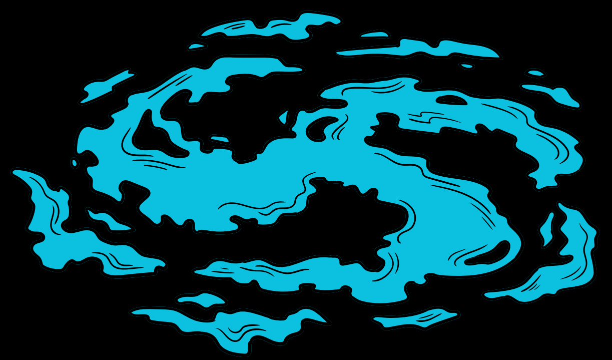
ACKNOWLEDGEMENT



We would like to express our gratitude to our mentors who gave us this oppurtunity and People from SSA Lab for helping us during lab visits, which was beneficial and we did indeed learn many new things.





CONTENTS:

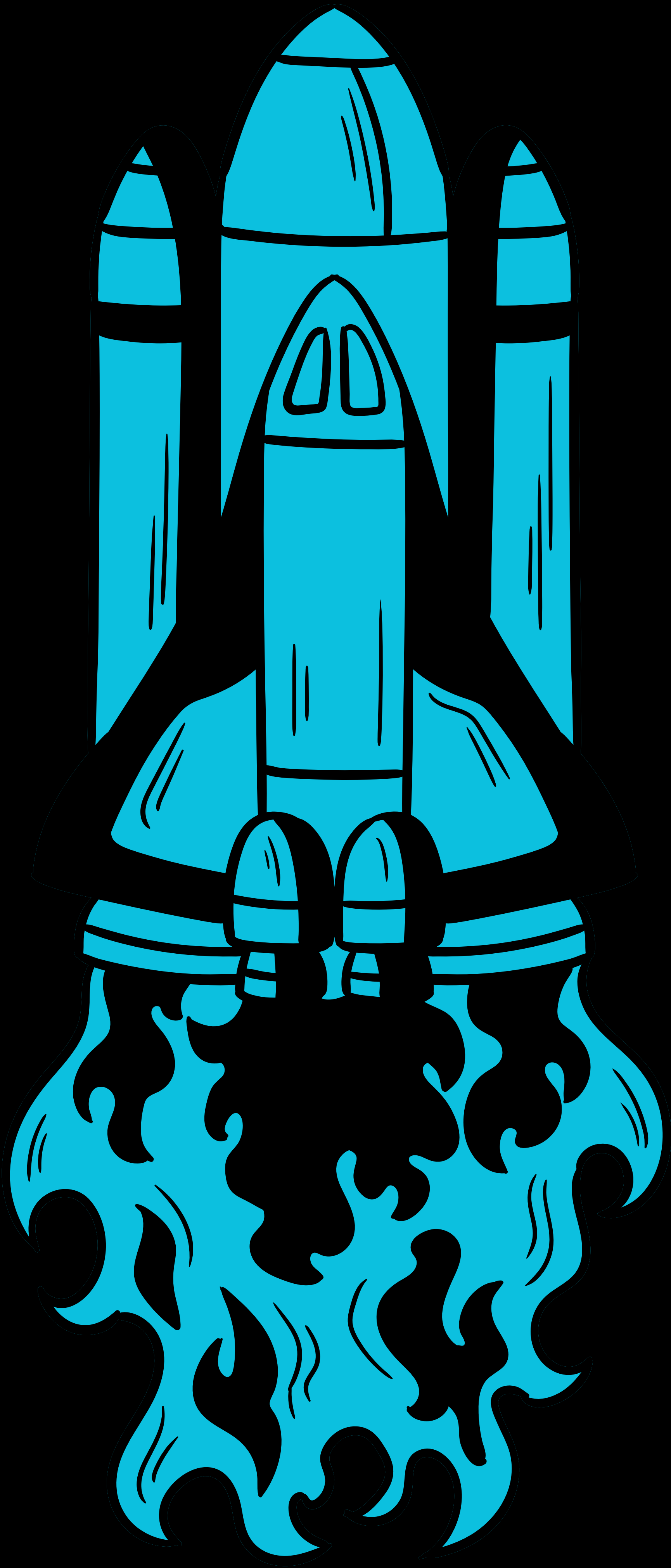
Computational Astronomy

Horn Antenna

Signal Processing

WEEK 1

- Basics of python
- Numpy, Pandas
- Horn Antenna introduction
- Matplotlib, Subplots

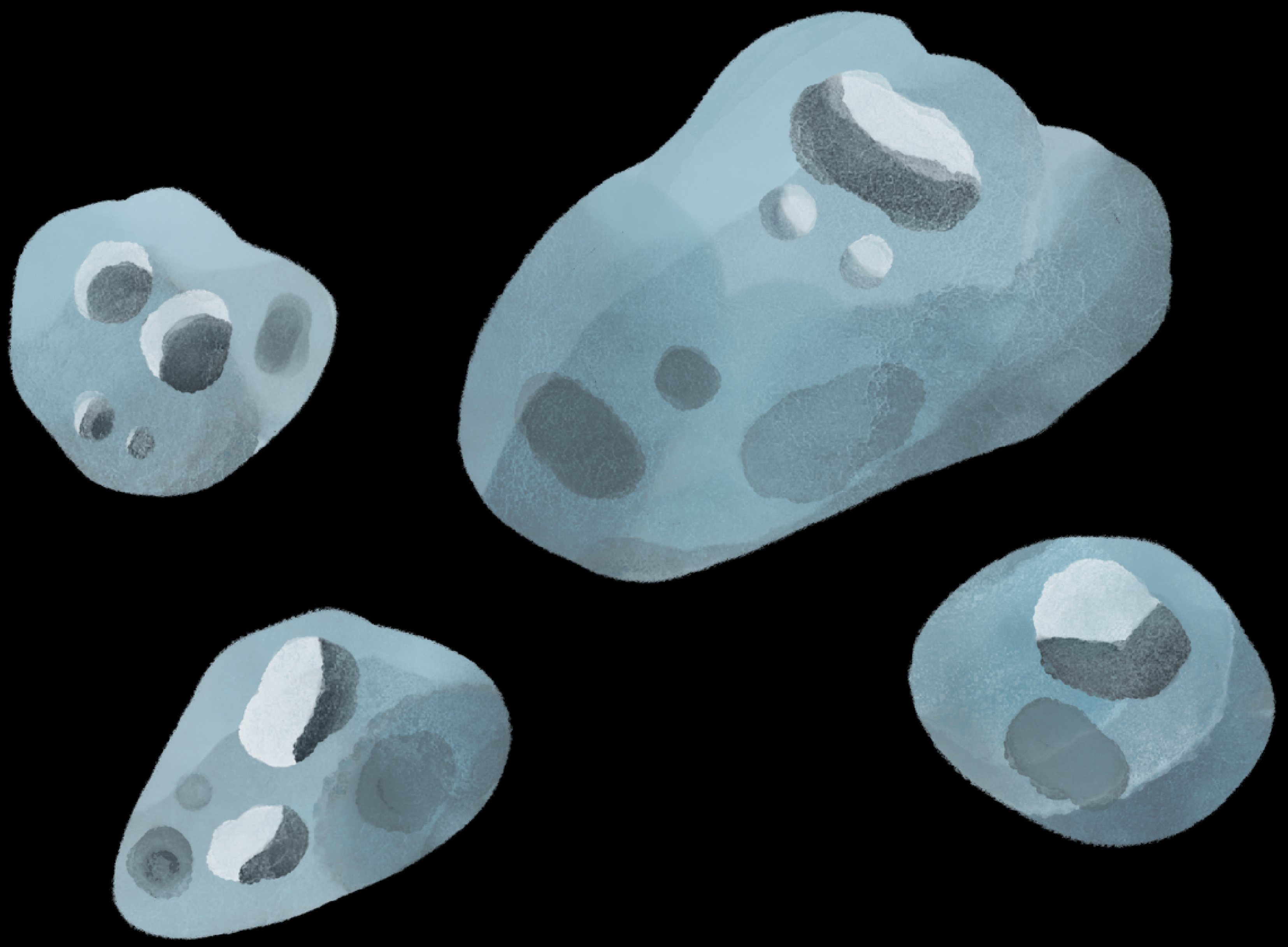


WEEK 2

- Signal processing
- Fourier's Transform theory

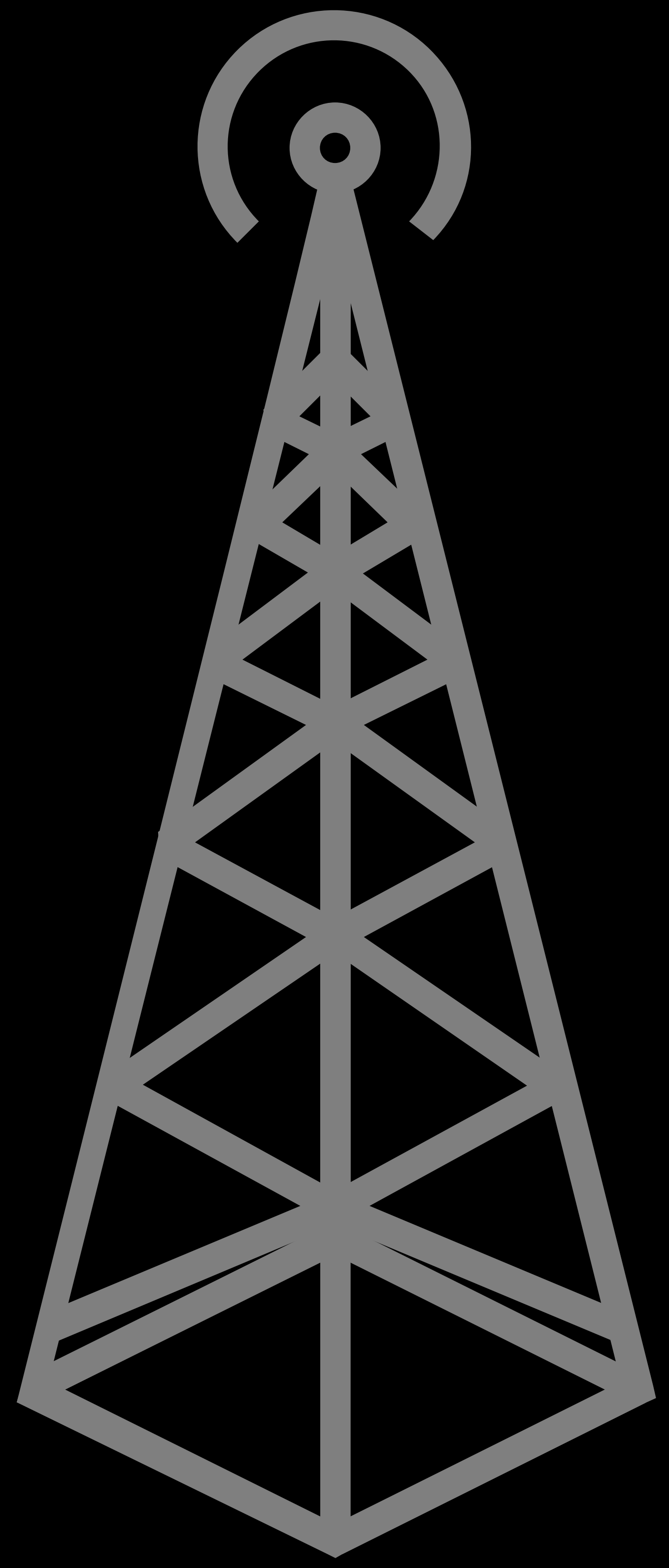
WEEK 3

- Fourier transform
- Visualising radio signals
- Signal processing: Part 2



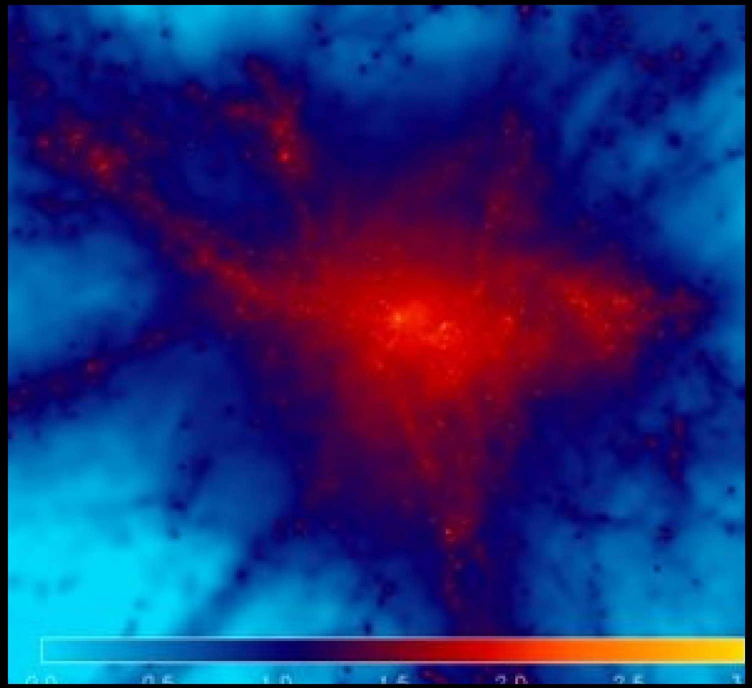
WEEK 4

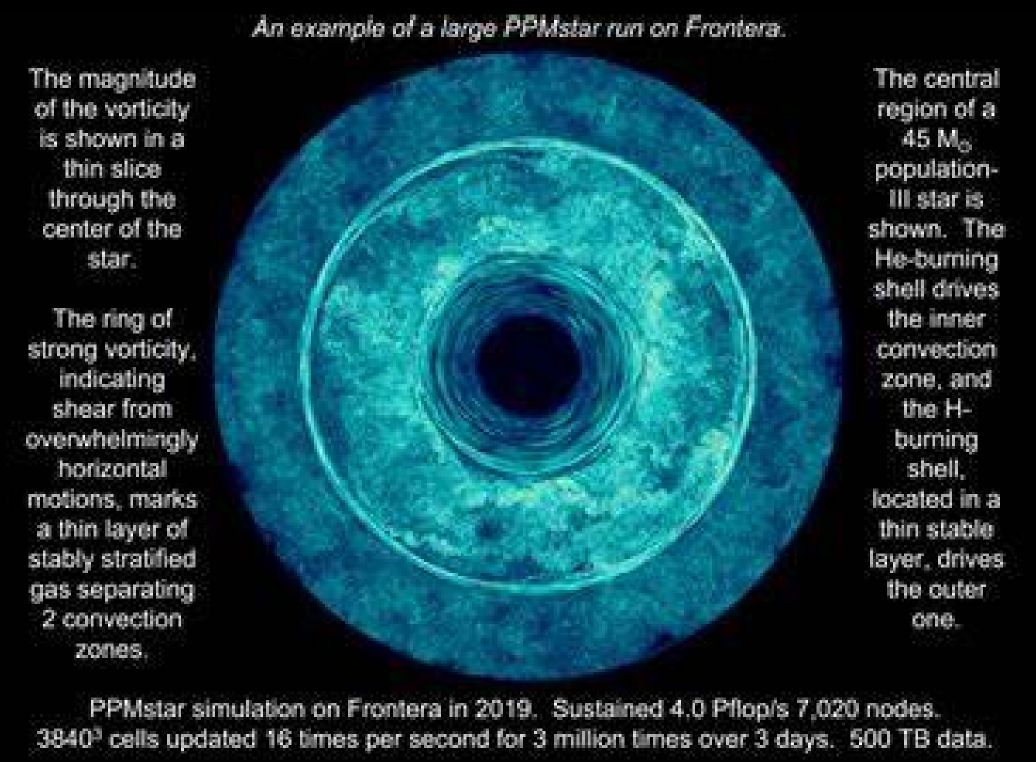
- SSA lab visits
- Horn Antenna testing

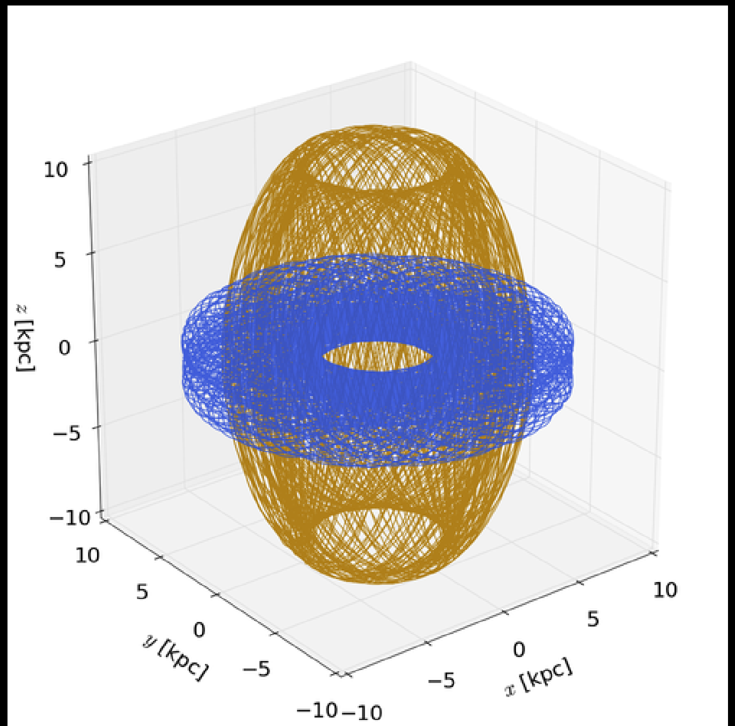


Computational Astronomy

Computational astronomy is a field of study that combines astronomy, computer science, mathematics, and statistics to analyze and interpret astronomical data, simulate astrophysical phenomena, and develop computational models of the universe. It involves using advanced computational techniques to process large datasets, perform complex calculations, and make predictions about the properties and behavior of celestial objects.



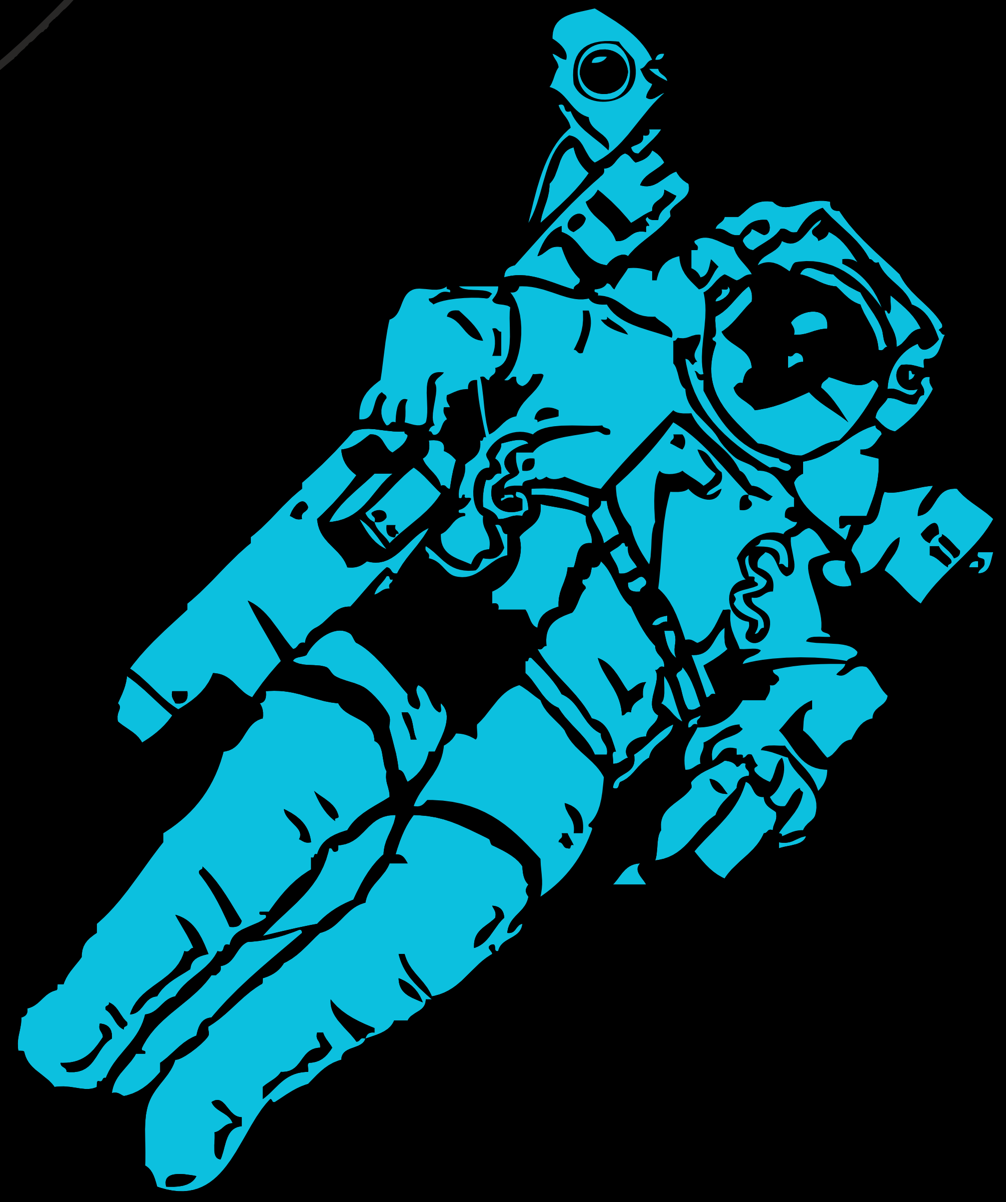




Uses of Computational astronomy

Computational astronomy has proved to be highly succesful in various subfields of astronomy and astrophysics.

- Data Analysis
- Modeling and Simulation
- Cosmological Studies
- Gravitational Wave Astronomy
- Exoplanet Studies
- Astrostatistics
- Machine Learning and Artificial Intelligence



Tools of Computational astronomy

- Programming Languages: Python, MATLAB, R, C++
- Data Analysis Software: Astropy,IRAF, TOPCAT
- Numerical Simulation Software: GADGET, RADMC-3D,Hyperion
- Statistical Analysis Tools:Python libraries,R, Stan,emcee
- High-Performance Computing (HPC) Facilities: supercomputers , cluster systems etc.

WEEK 1

Horn Antenna

It is used for transmiting and receiving waves . It converts electrical energy into EM waves and vice versa .

Types of Horn Antenna:

-sectoral
-pyramidal
-rectangular
-conical
-scalar feed

Advantages:

-simple design and adjustment.
-low interference & light weight.
-moderate to high gain that enhances signal strength.
-low standing wave ratio.
-moderate directivity.

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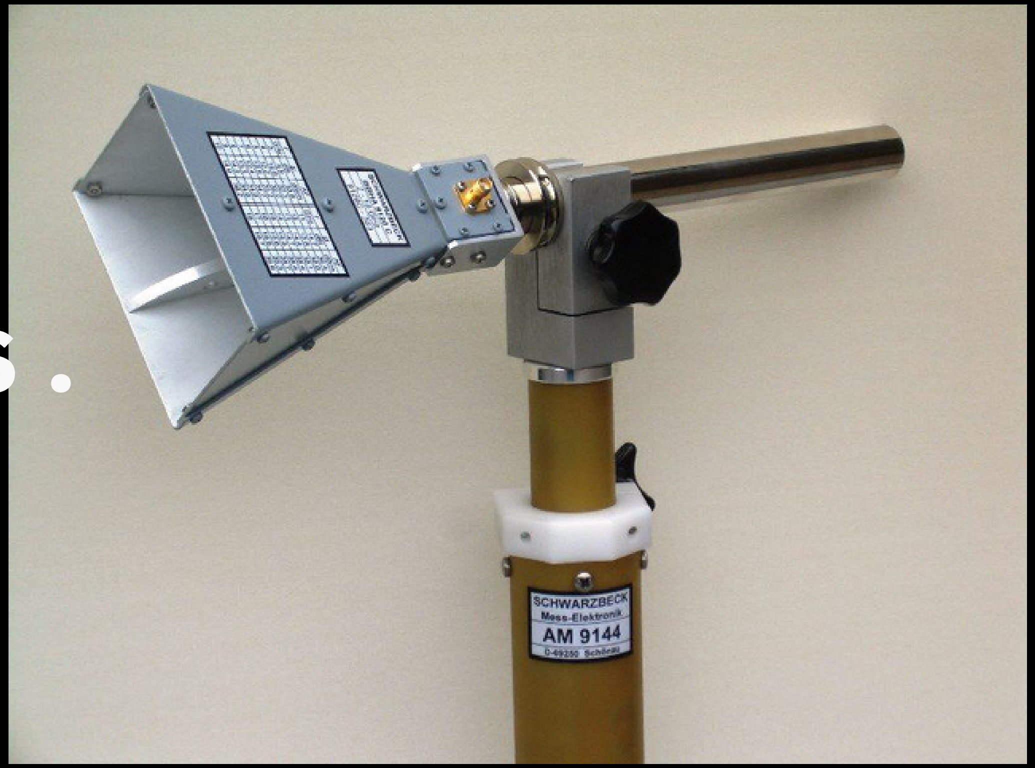

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Functioning of Horn Antenna :

-The flared metal waveguide in the antenna helps EM waves as they travel towards wider opening.

-As the waves reach the horn they radiate into free space as a directional beam. Flared shape helps to improve directivity & efficiency.

-Extended aperture to radiate all the energy in forward direction.

-For receiving the waves ,Horn Antenna performs reverse process.

-EM waves enter the wider opening of the horn from the source. The waves travel & converge to narrow throat . The converging shape of antenna helps to increase the sensitivity of antenna .

-It is used in radar system ,radio astronomy ,satellite communication, and wireless communication.

Design of a Pyramidal Horn Antenna

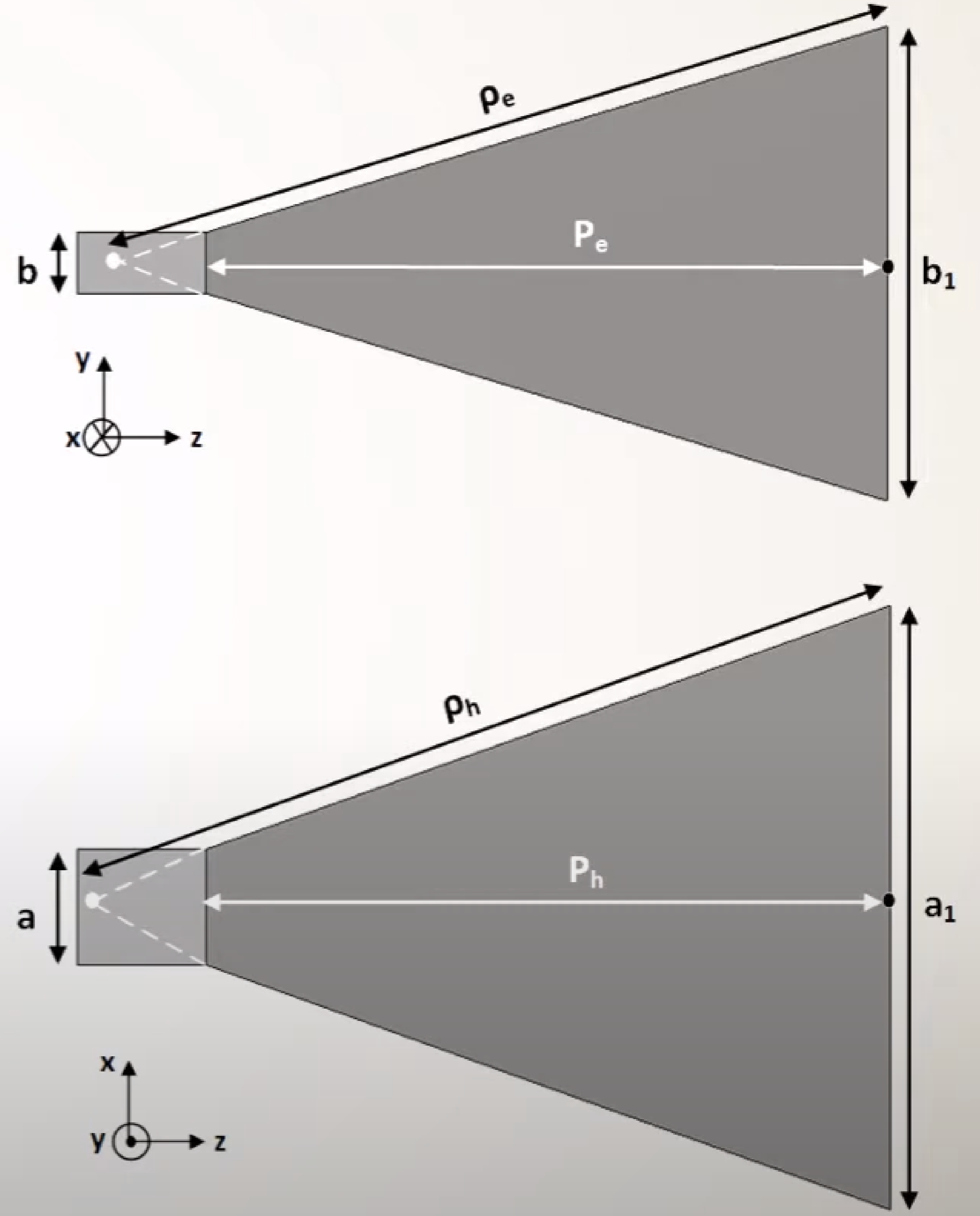
Dimensions of P_e and P_h :

$$P_e = (b_1 - b)\left[\left(\frac{\rho_e}{b_1}\right)^2 - \frac{1}{4}\right]^{1/2}, \qquad P_h = (a_1 - a)\left[\left(\frac{\rho_h}{a_1}\right)^2 - \frac{1}{4}\right]^{1/2}$$

For pyramidal horn ➡ $P_e = P_h$

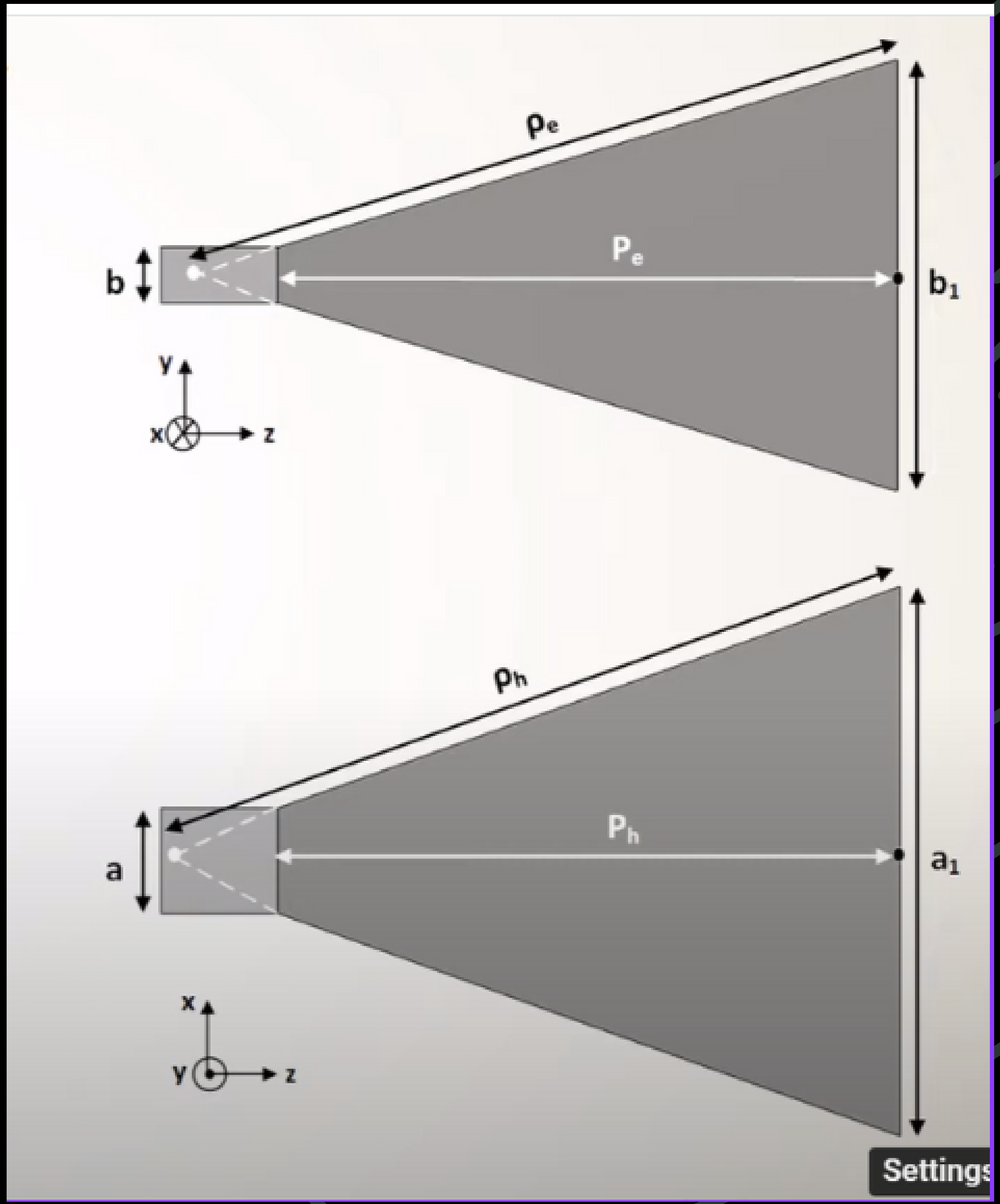
Gain Relation:

$$G_0 = \frac{1}{2}\frac{4\pi}{\lambda^2}(a_1 b_1) \simeq \frac{2\pi}{\lambda^2}\sqrt{3\lambda\rho_h}\sqrt{2\lambda\rho_e}$$



Constantine A. Balanis, Antenna Theory: Analysis and Design, 4th Edition

Design:



fr: design frequency

Go: desired gain

a,b: dimensions of waveguide

a1,b1: dimensions of horn aperture

Pe: distance between horn aperture &waveguide(E -plane).

Ph: distance between horn aperture & waveguide (H-plane)

★ Python

- Scientific library like NumPy, SciPy and Pandas provide powerful tools for data manipulation, analysis and visualization.

- It includes Matplotlib and Plotly which facilitate the creation of high-quality plots and visualisations of astronomical data.

Continue.......

- NumPy provides tools for signal processing tasks like ***filtering, noise reduction, convolution, and Fourier analysis.***
-

Pandas plays a vital role in preparing data for machine learning applications in computational astronomy.

WEEK2

Signal Processing

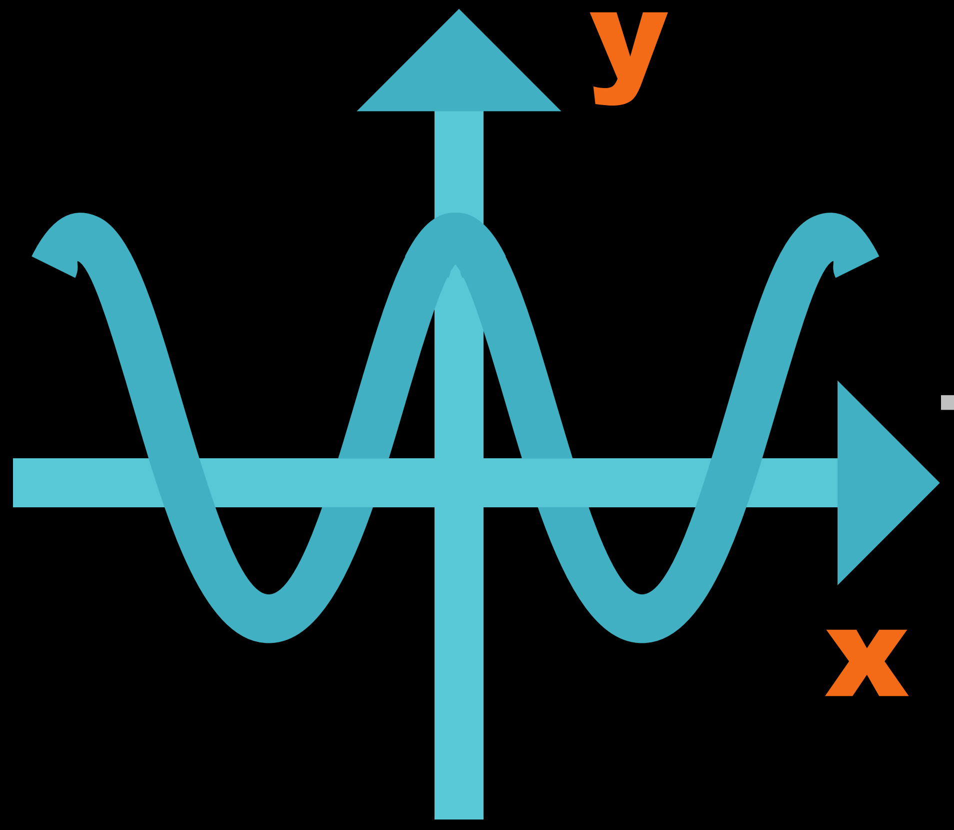
What are signals?

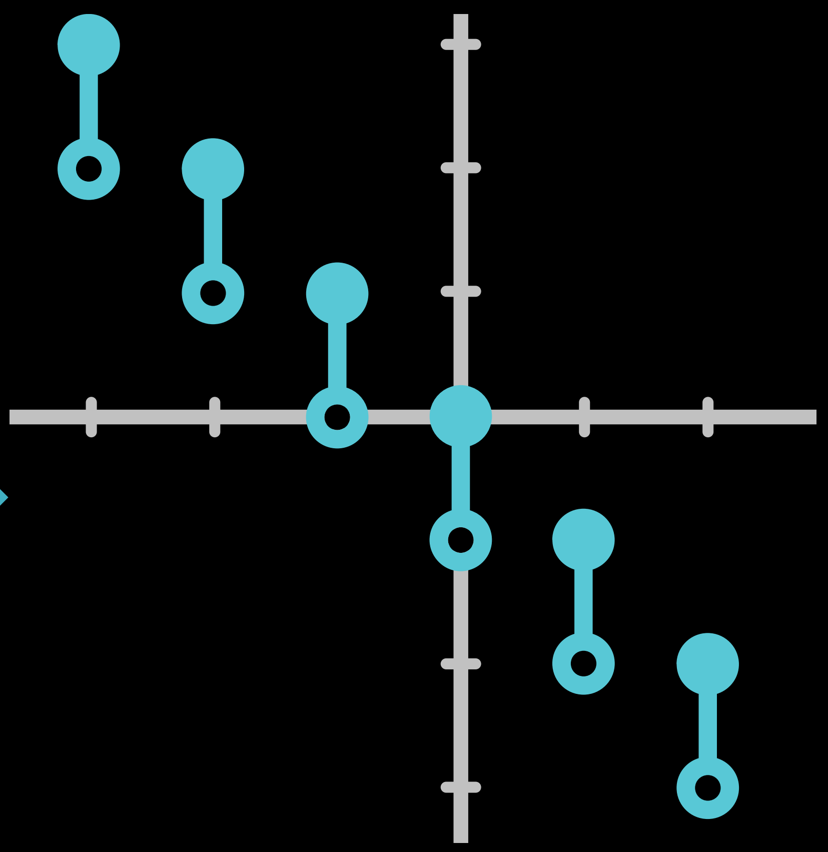
A signal is a time-varying quantity that carries some information. There are two types of signals: continuos/discrete and analog/digital.

What is processing?

It refers to the manipulation, analysis, and transformation of signals to extract useful information, enhance their quality, or achieve specific objectives.

TYPES OF SIGNALS AND SYSTEMS





CONTINOUS

DISCRETE

LINEAR

NON-LINEAR

METHODS FOR SIGNAL PROCESSING

FOURIER TRANSFORM

deals with continuous time signals and converts them from time domain to frequency domain.
provides information about the amplitude and phsase of each frequency and components

LAPLACE TRANSFORM

extends the concept of fourier transform to include complex exponential functions.
utilized for analyzing and characterizing the behavior of linear time - invariant system

Z -TRANSFORM

similar to laplace transform but specifically designed for descrete - time signal
transform a descrete - time signal or system from the time domain to the z-domain

BASIC STEPS OF SIGNAL PROCESSING

- **Digitization & Sampling**

Digitalizing radio signals by an analog-to-digital converter and then determining the resolution of the signal by the sampling rate.

- **Noise Filtering**

incoming signals contain disturbance due to radio frequency interference and noise. We isolate the target signal by Bandpass filtering and spectral analysis

- **Fourier Transform**

It decomposes the signal into its frequency components to reveal information about its composition and origin.

- **Beamforming**

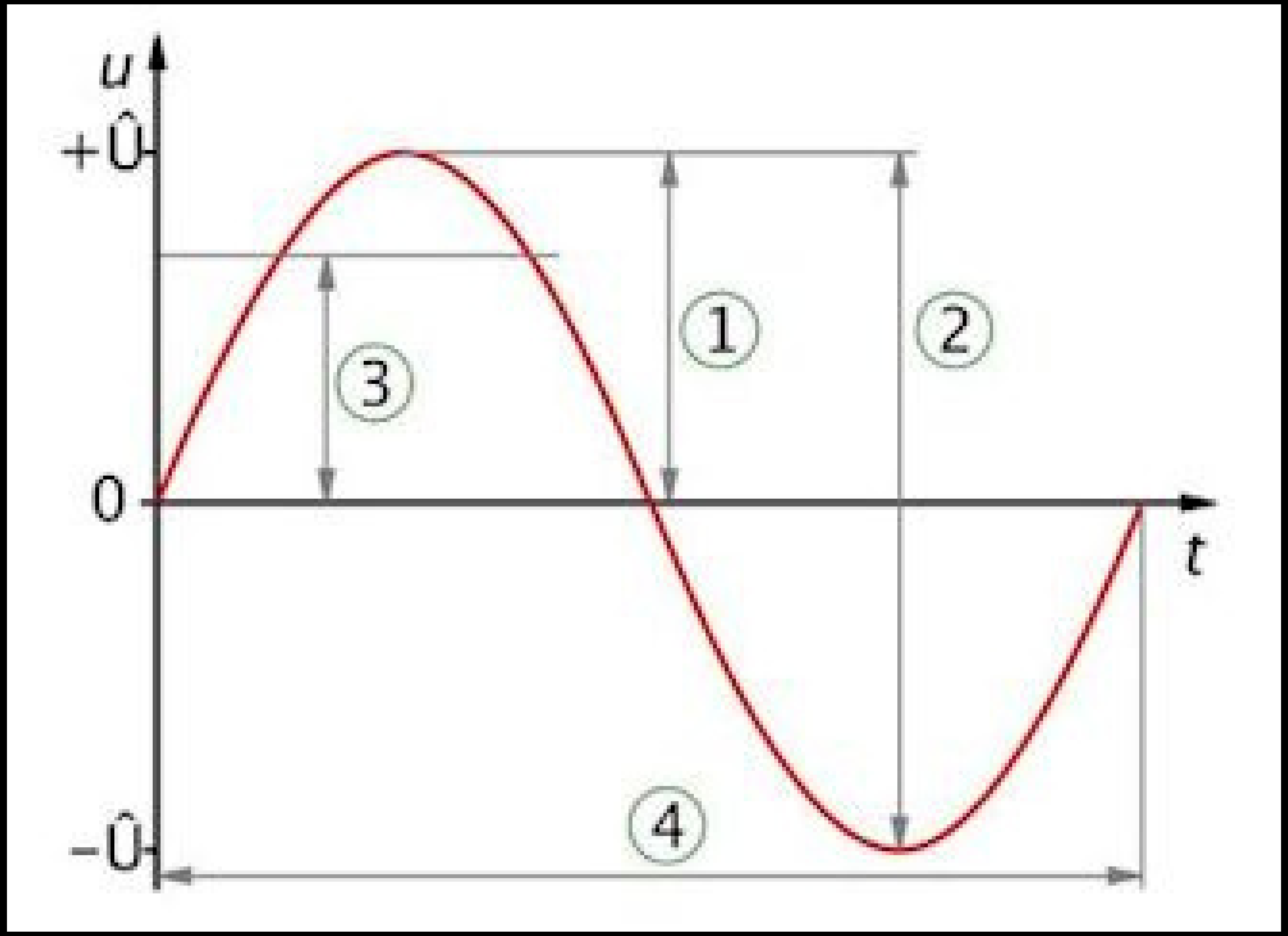
Beamforming is a spatial filtering technique that combines the signals from individual antennas to optimize the reception of radio signals.

Fourier's Transform Theory

Fourier transform is a mathematical framework that deals with the representation and analysis of signals or functions in terms of their frequency components.

The mathematical formula for the Fourier transform of a functio f(t) is:

$$F(\omega) = \int[f(t) * e^{(-i\omega t)}]\, dt$$



Fourier Transform

Mathematical transform that expresses a function of time as a function of frequency

Bandwidth

- **Band:** The range or interval of radio frequencies used to transmit a signal .All bands are identified by their lower and upper limits.

- **Radio Spectrum:** Electromagnetic waves in the frequency Range (3Hz to 3000 GHz) are called Radio Waves.

- **Bandwidth:** Bandwidth is the range of frequencies that a signal occupies .A higher bandwidth means a higher data rate and more information.
  Difference between Upper and Lower Frequency limits.
  Frequency range over which a signalis tranmitted /recieved.

Signal Corrections

- **Pre -Processing :** Pre- processsing techniques include filtering ,noise reduction , and signal conditioning.The goal is to remove unwanted components amd enhance the signal of interest.

- **Importance:** Signal corrections are necessary to improve the quaity and acccuracy of the signal.They correct for errors introduced by the tranmission of the measurement process.

- **Post - Processing :** Post - processing technique include equalization error correction.The goal is to correct for distortions introduced by the transmission of measurement process.

Devices used in signal processing

Analog Devices : Analog devices such as amplifiers and filters, are used to process signals in their original analog form.

Digital Devices: Digital Devices such as microcontrollers and digital signal processors (DSPs) are used to process signals in their digital form.

Software: Software tools such as MATLABs and Pyton,are used for simulation ,modelling and algorithm development for signal processing.

Filters

- **Low - pass :** It passes signals of lower frequencies but don't allow high frequency signal to pass
- **High - pass:** It passes signals of higher frequencies but don't allow low frequency signal to pass .
- **Band - pass :** It passes signals of certain band of frequencies but don't allow other frequency signal to pass.
- **Band - stop:** It rejects signals of certain band of frequencies.

Introduction to RTL-SDR:

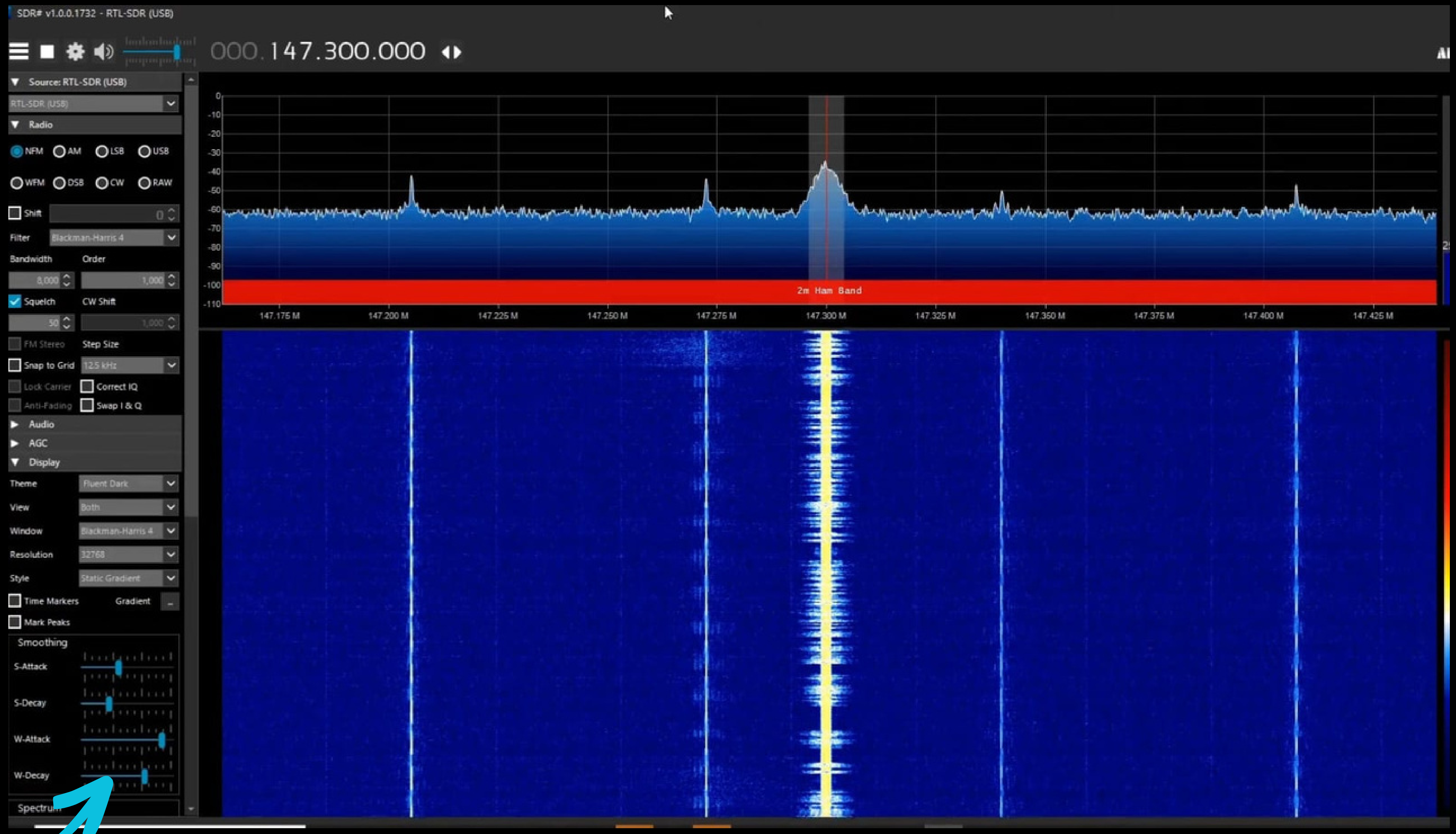
What's RTL-SDR and it's applications?

- RTL-SDR is a USB Device that's used as a computer based radio.
- Depending on the device it can receive frequency from 500kHz to 1.75 GHz.

Applications:

Used as a part of Interferometry to study radio signals from various telescopes.

Listening to music radio,airband and ham radio.



Components of RTL-SDR:

- SDR, USB connector at one end of the device & antenna connects through a CMX connector
- Dipole base
- Antennas(Wideband telescopic antennas are preferred)
- Extension cable
- Tripod mount/Suction cup Antenna mount

WEEK 3

Usefulness of Fourier Transform in Signal Processing

- The Fourier transform is extensively used in signal processing for analyzing and manipulating signals.
- By decomposing a signal into its constituent frequencies, it enables the identification of specific frequency components, filtering out noise, and extracting useful information.
- It plays a crucial role in applications such as audio and image compression , equalization , filtering , and modulation / demodulation techniques.

Properties of Fourier Transform

1. Homogenity (Linearity) :

$x_1(t) \rightleftharpoons X_1(j\omega) \longrightarrow \alpha x_1(t) \rightleftharpoons \alpha X_1(j\omega)$ → ①

$x_2(t) \rightleftharpoons X_2(j\omega) \longrightarrow \beta x_2(t) \rightleftharpoons \beta X_2(j)$ → ②

α, β are scaler

Adding eq.1 & 2

$$\alpha x_1(t) + \beta x_2(t) \rightleftharpoons \alpha X_1(t) + \beta X_2(t)$$

2. Time Reversal :

$$x(t) \rightleftharpoons X(j\omega)$$

$$x(-t) \rightleftharpoons X(-j\omega)$$

3. Time Scaling:

$$x(t) \rightleftharpoons X(j\omega)$$

$$x(at) \rightleftharpoons \frac{1}{|a|} X\left(j\frac{\omega}{a}\right)$$

a<1 :compression

a>1 :dilation

Properties of *F*ourier Transform

4. Time shifting

$x(t) \rightleftharpoons X(t+t_0)$

$x(t+t_0) \rightleftharpoons X(j\omega) \cdot (e)^{\omega t_0}$

5. Frequency Shifting

$x(t) \rightleftharpoons X(j\omega)$

$e^{\pm j\omega_0 t} \cdot x(t) \rightleftharpoons X[j(\omega \mp \omega_0)]$

4. Convolution:

$x_1(t) \rightleftharpoons X_1(j\omega)$

$x_2(t) \rightleftharpoons X_2(j\omega)$

$\hookrightarrow x_1(t) \cdot x_2(t) \rightleftharpoons X_1(j\omega) \cdot X_2(j\omega)$

7. Multiplication in frequency :

$x_1(t) \rightleftharpoons X_1(j\omega)$

$x_2(t) \rightleftharpoons X_2(j\omega)$

$\hookrightarrow x_1(t) \cdot x_2(t) \rightleftharpoons \frac{1}{2\pi} X_1(j\omega) \cdot X_2(j\omega)$

VISUALISING SWAN DATA :

- SWAN data plays a crucial role in advancing our understanding of the solar wind, the heliosphere, and their interactions.

- **Dataset used for Fourier Transform Analysis :**
  ch07_SUN_20210414_121708_000.mbr
  ch03_SUN_20210414_121708_000.swn

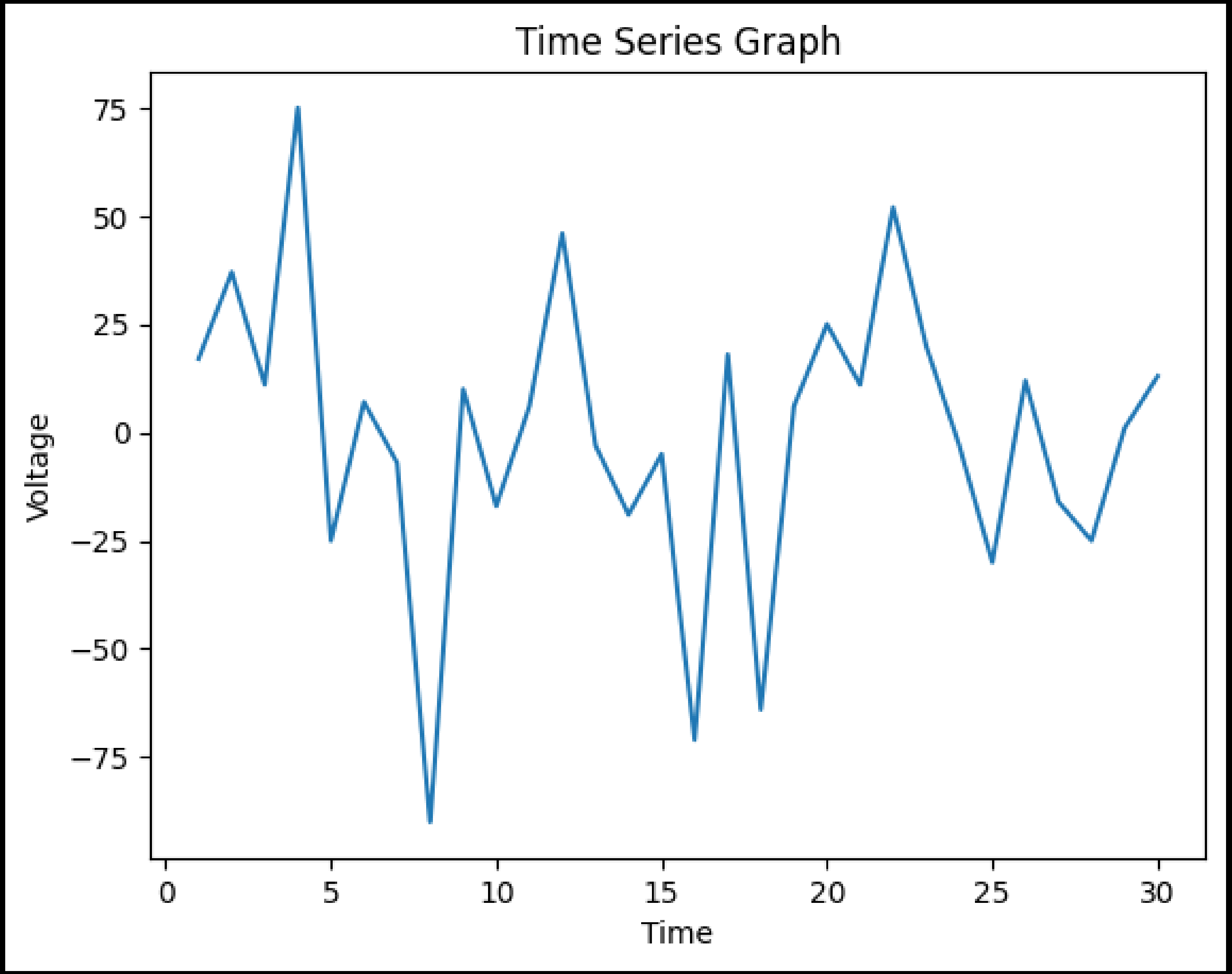
- Types of SWAN datasets:

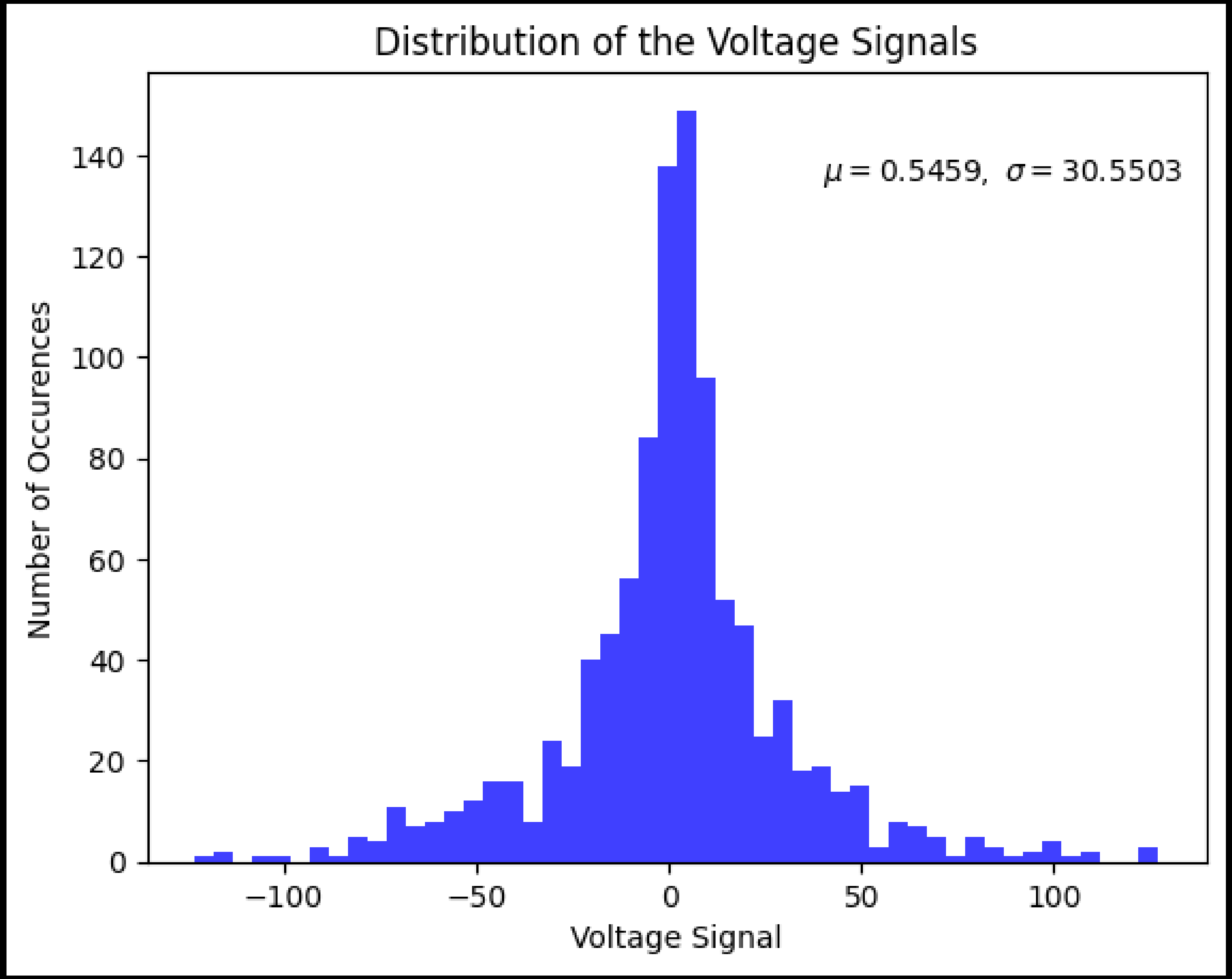
1. Single tiled data (covered)
2. Double tiled data (Interferometry and cross correlation)

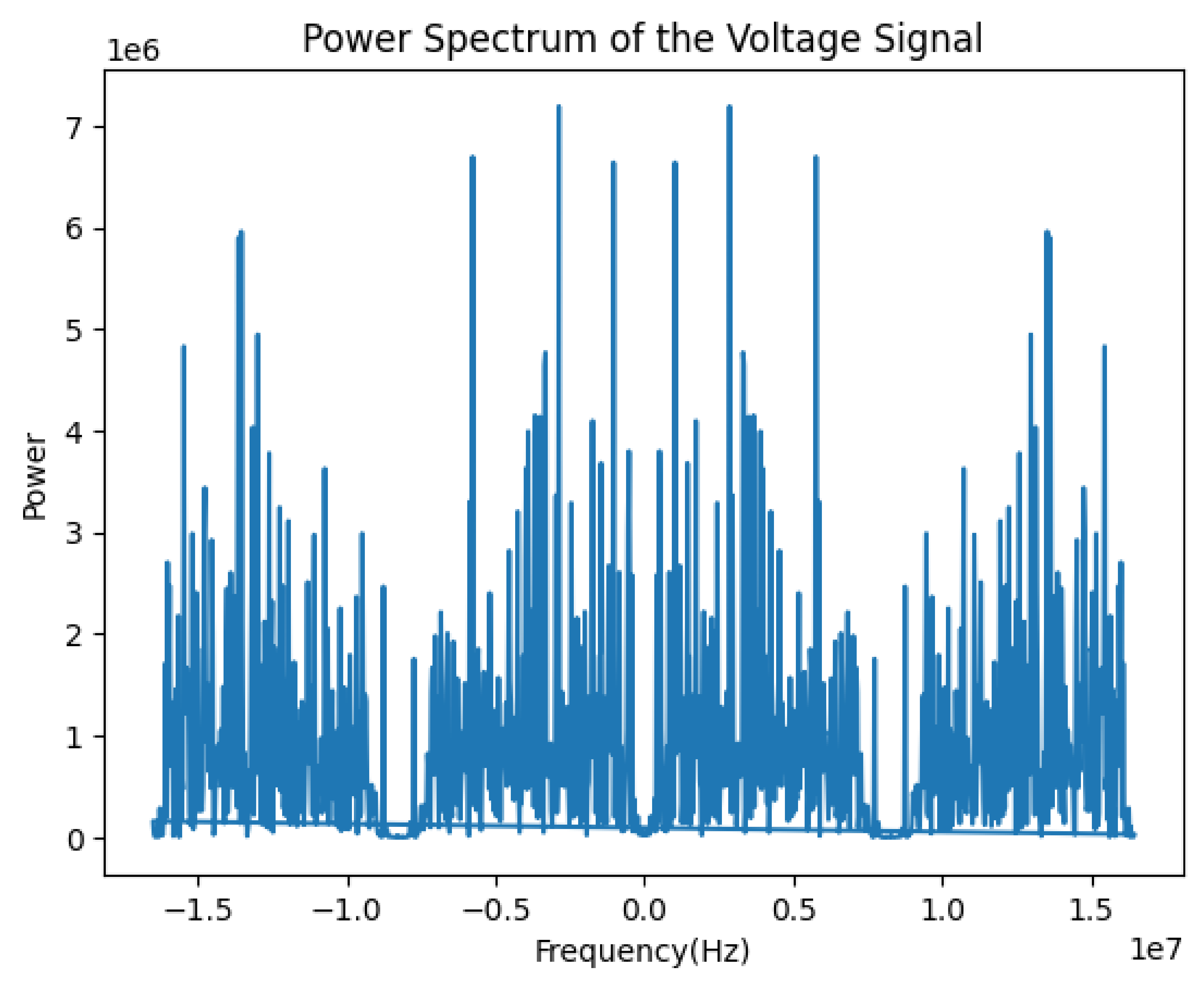
VISUALISING SWAN DATA : Code

- Plotted Time Series Graph of observed Voltages in .swn file
- Plotted frequency distribution of Voltages
- Applied Fast Fourier Transform (FFT) on the data with specified swan bandwidth and sampling rate
- Plotted Power Spectral Density graph (Power of the signal vs. Frequency)

VISUALISING SWAN DATA :



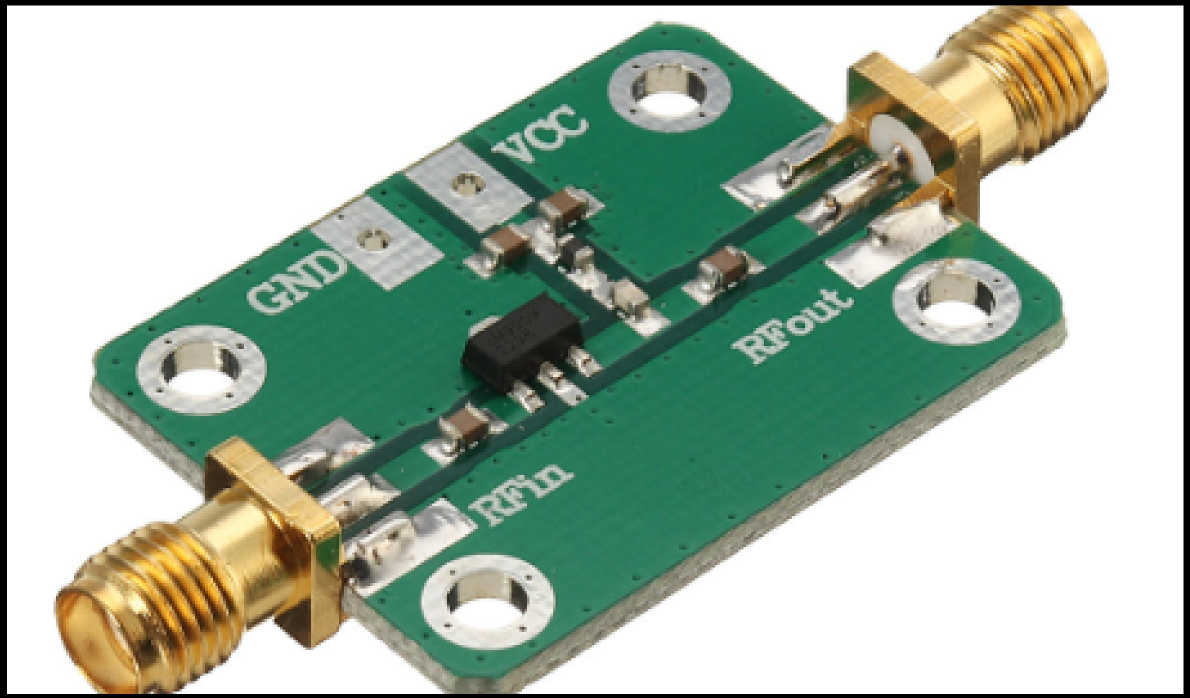




Power Spectrum of the Voltage Signal
1e6
7
6
5
4
3
2
1
0
Power
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
Frequency(Hz)
1e7

VISIT TO SSA LAB :

- Low noise amplifier

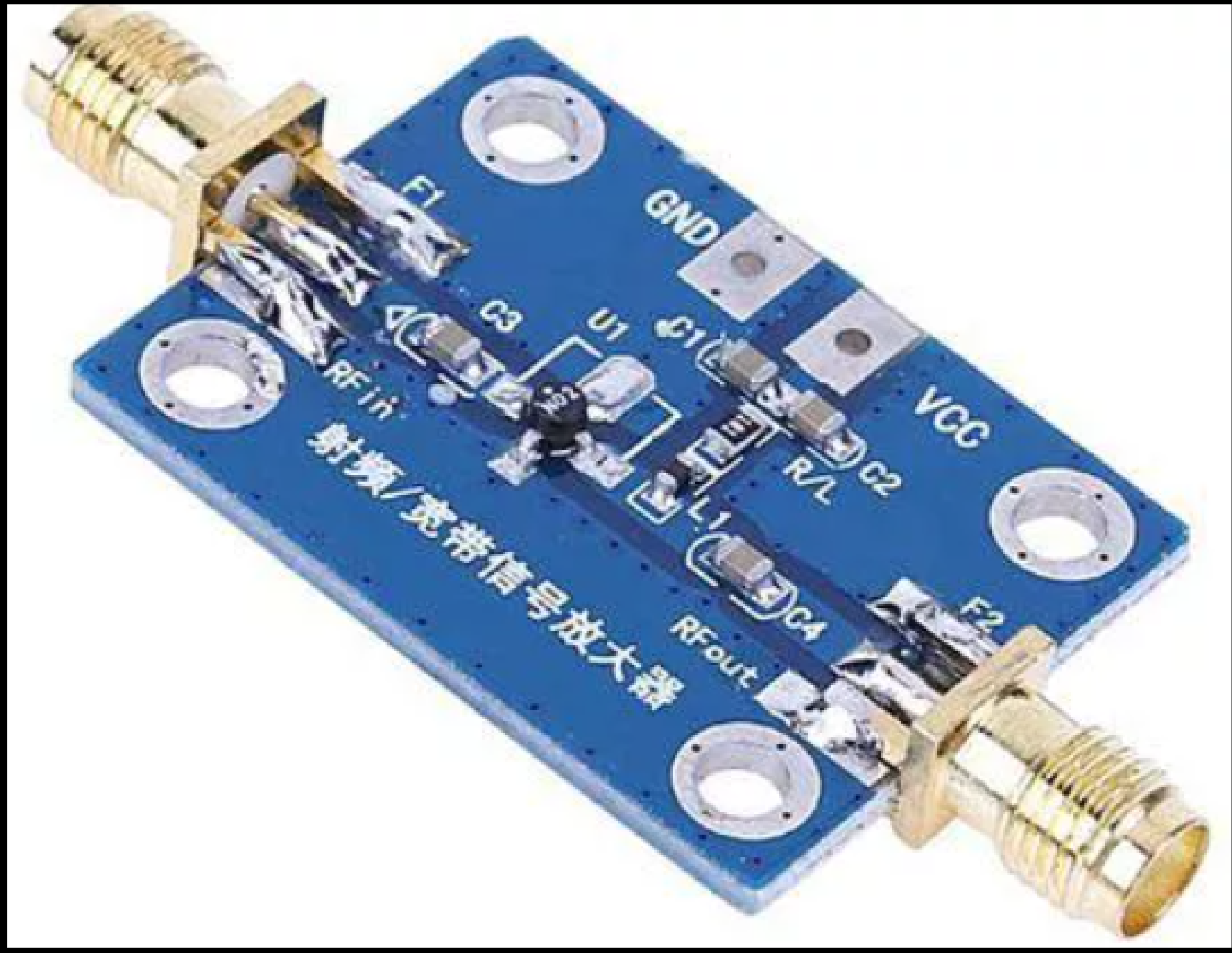


- Local oscillator and its function

- The Nyquist sampling theorem

Low noise amplifier :

A low-noise amplifier (LNA) is an electronic component that amplifies a very low-power signal without significantly degrading its signal to noise ratio (SNR). Any electronic amplifier will increase the power of both the signal and the noise present at its input, but the amplifier will also introduce some additional noise. LNAs are designed to minimize that additional noise, by choosing special components, operating points, and circuit topologies.



Design considerations

Low noise amplifiers are the building blocks of communication systems and instruments. The most important LNA specifications or attributes are:

- **Gain**
- **Noise Figure**
- **Linearity**
- **Maximum RF Input**

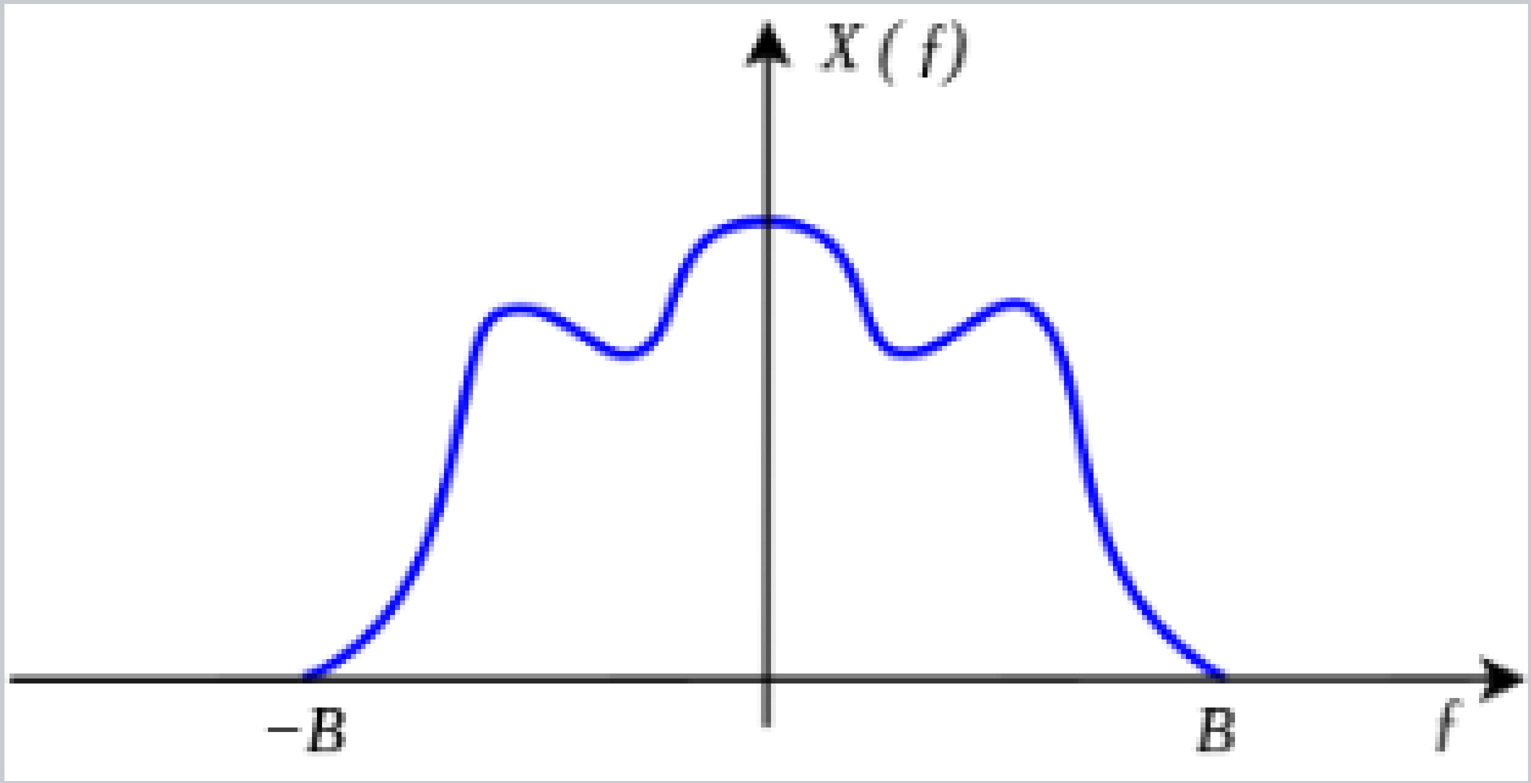
Low noise amplifiers are used in communications receivers such as in radio telescopes, cellular telephones, GPS receivers, wireless LANs (WiFi), and satellite communications.

Local Oscillator

- A local oscillator (LO) is an electronic oscillator used with a mixer to change the frequency of a signal.
- The primary function of a local oscillator is to generate a stable and controllable oscillating signal at a specific frequency
- Local oscillators are used in the superheterodyne receiver. They are also used in many other communications circuits such as modems, cable television set top boxes, frequency division multiplexing systems, microwave relay systems, atomic clocks, radio telescopes, and military electronic countermeasure systems

The Nyquist Sampling Theorem

The Nyquist–Shannon sampling theorem is an essential principle for digital signal processing linking the frequency range of a signal and the sample rate required to avoid a type of distortion called aliasing. The theorem states that the sample rate must be at least twice the bandwidth of the signal to avoid aliasing distortion



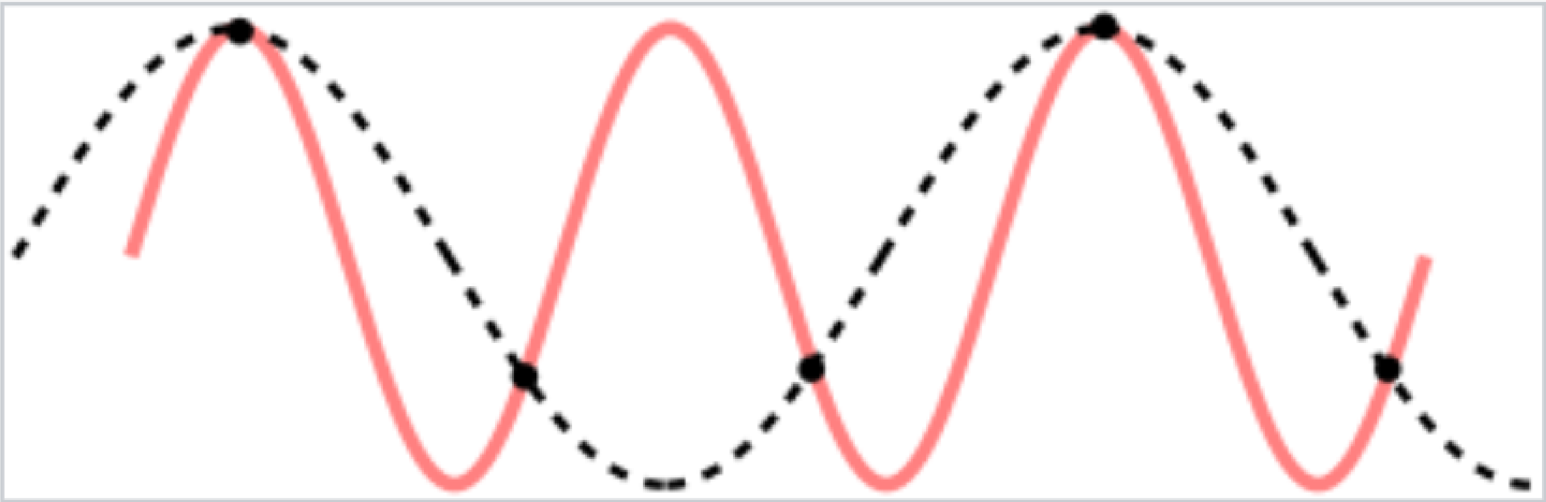
Example of magnitude of the Fourier transform of a bandlimited function

Mathematically

$$Fs \geq 2 * Fmax$$

The Nyquist–Shannon sampling theorem is a theorem in the field of signal prossing which serves as a fundamental bridge between continuous-time signals and discrete-time signals. It establishes a sufficient condition for a sample rate that permits a discrete sequence of samples to capture all the information from a continuous-time signal of finite bandwidth.

Theorem — If a function x(t) contains no frequencies higher than *B* hertz, then it can be completely determined from its ordinates at a sequence of points spaced less than 1/(2B) seconds apart.



The samples of two sine waves can be identical when at least one of them is at a frequency above half the sample rate.

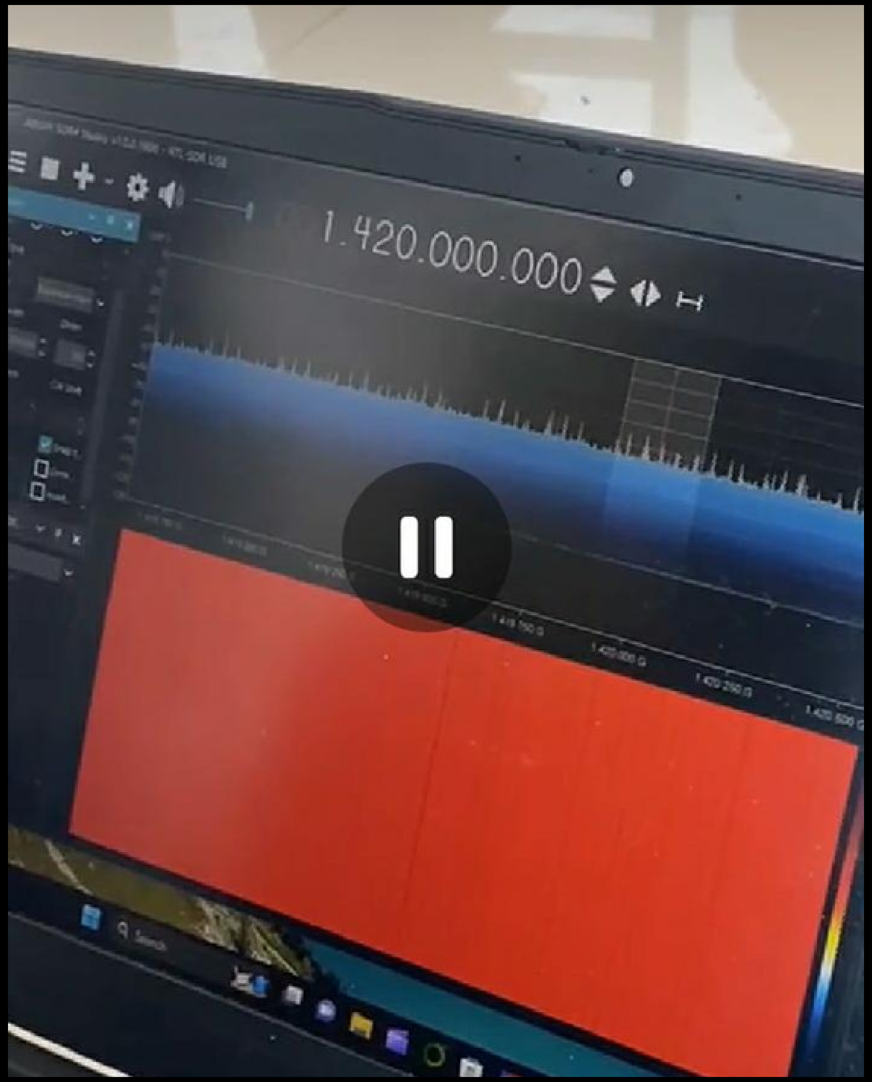
WEEK 4

SSA lab visits

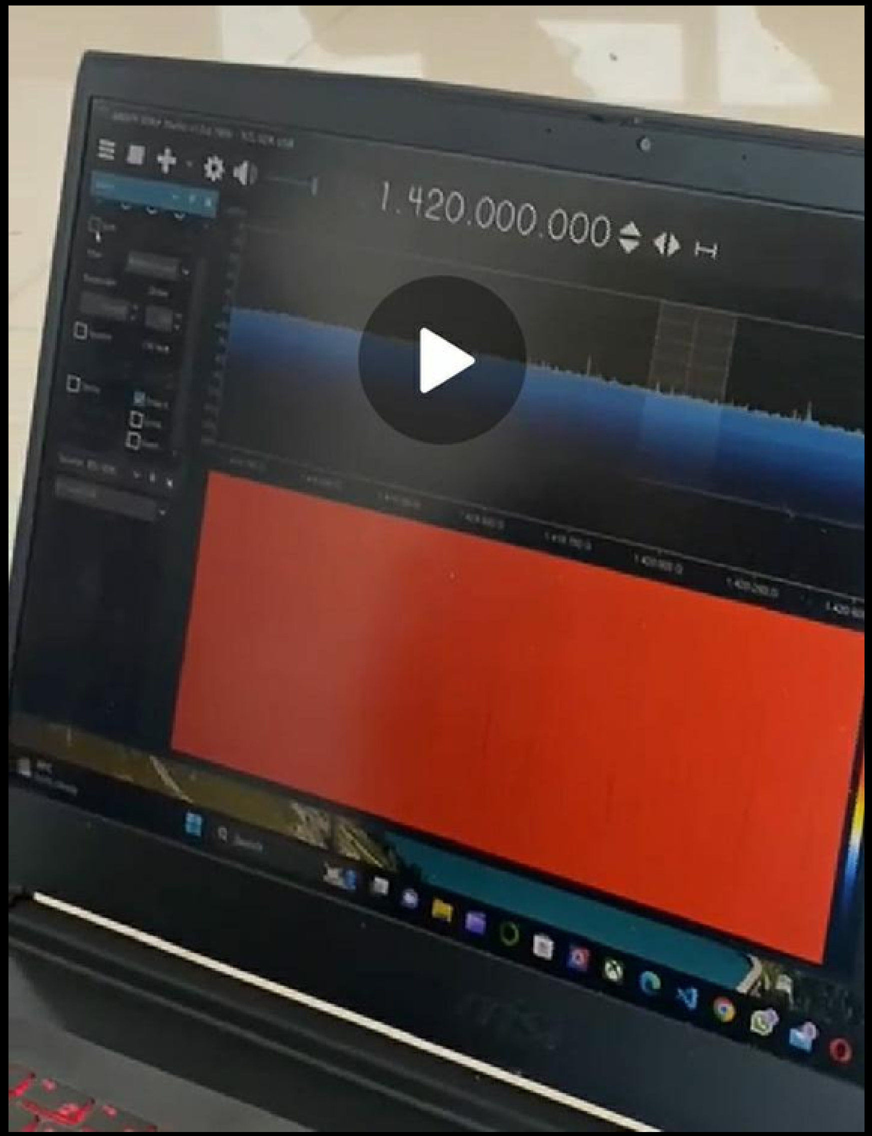
Horn antenna Testing

Small horn antenna

small horn antenna was used to collect and plot signal from atmosphere and walls



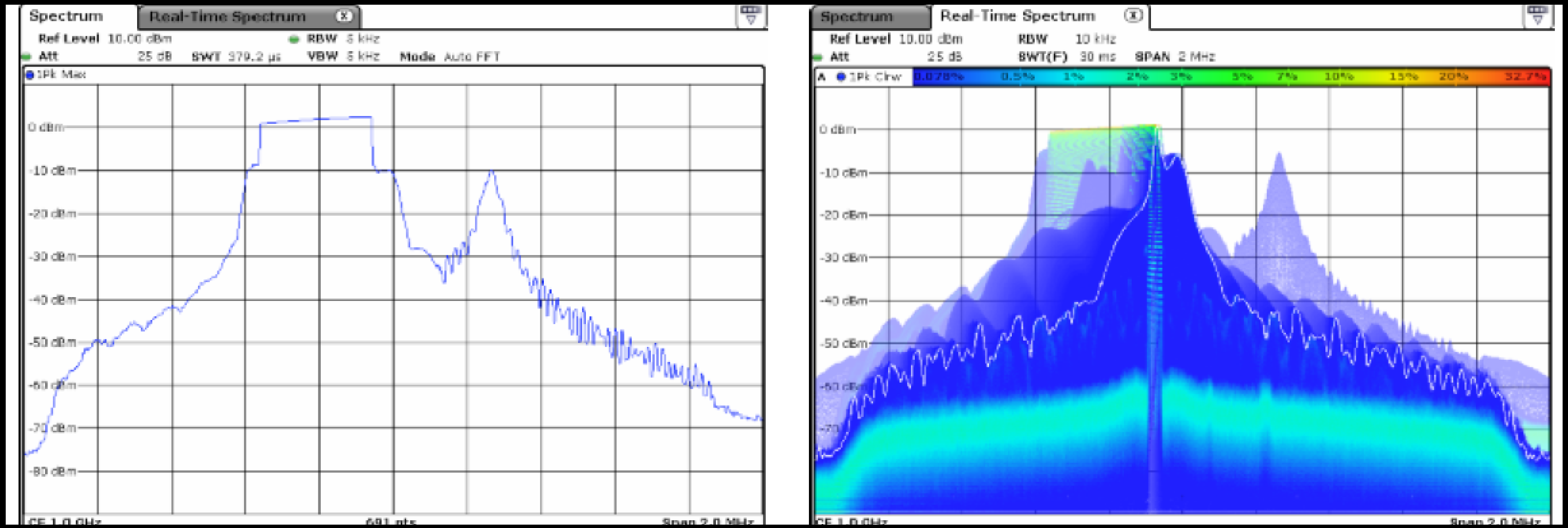
radiation from atmosphere

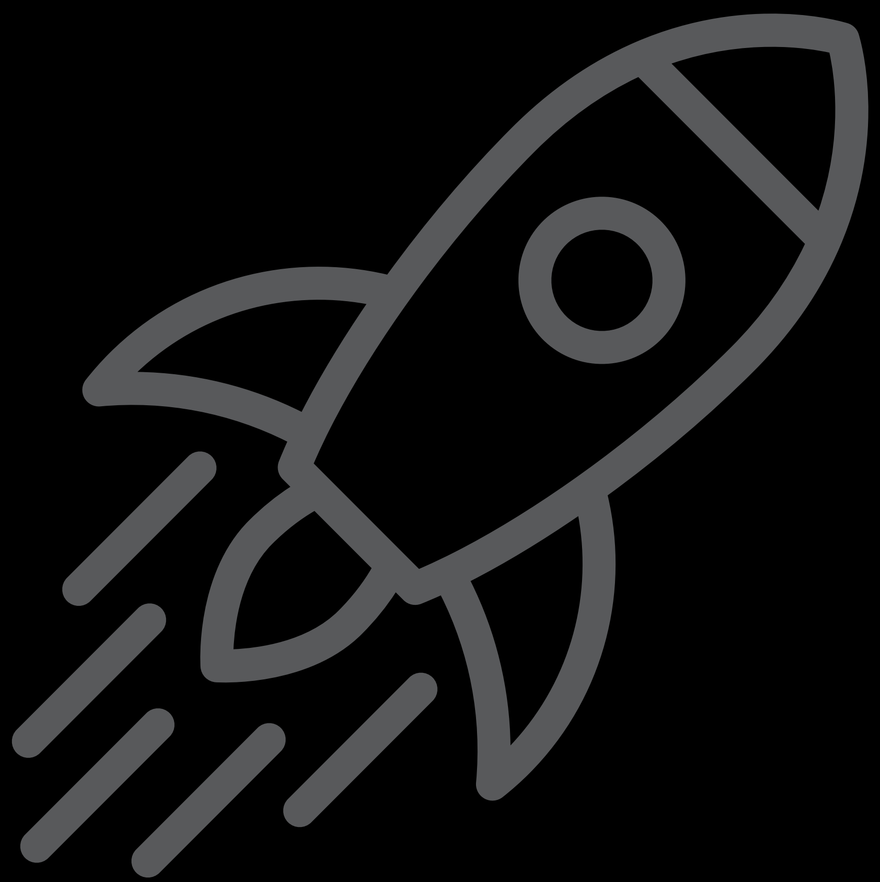


radiation from walls

SPECTRUM ANALYZER

Spectrum Analyzer measures the magnitude of an input signal versus frequency within the full frequency range of the instrument. The primary use is to measure the power of the spectrum of known and unknown signals. The input signal that most common spectrum analyzers measure is electrical.





Thank you!