Radio Astronomical Instrumentation
And
Analysis Techniques

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BY

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The programs executed in the following writeup can be found at
https://github.com/VinayBharambe/

QR.png

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Abstract

Radio astronomy is a branch of Astrophysics which makes observations of astronomical sources at Radio wavelengths. It is a young branch of astronomy if compared with optical astronomy but still around 90 years old. First Radio observation of an astronomical source was done by Karl Jansky at Bell laboratories in 1932. Since, then this subject has flourished and is a workhorse in current Astronomy and Astrophysics research. Unlike other parts of electromagnetic spectrum the Earth's atmosphere is transparent to a big band of Radio frequencies. This makes ground based observations possible and more effective. Also, due to longer wavelengths Radio observations do not face problems due to intergalactic medium and cosmological observations are also possible at low radio frequencies.

Part 1: Design, simulations and fabrication of Pyramidal Horn antenna for 1.4 GHz observations

Unlike Optical and Infrared astronomy the receiver for the Radio astronomy is an Antenna. An Antenna is an electric device which can both transmit and receive electromagnetic signals. The structure of an Antenna can vary a lot depending on frequency range. One of the most prominently observed frequency range in low frequency Radio astronomy is 1.4 GHz. It is one of the longest wavelength observed in Astronomy. We aimed to Design a Radio telescope for frequency centered at 1.4GHz with 20dB antenna gain. We designed the waveguide, flarings and probe of the antenna. We optimized the size of the flarings (and hence overall antenna) with iteration program. We simulated the design over HFSS simulations to study its radiation pattern and simulated gain. We fabricated 4 of such antennas. We designed and fabricated probe for these antennas. We designed the electronic receiver chain for the antenna and tested the software backend to modify observation conditions such as gain, frequency range, bandwidth, etc and to store the observations in a file. In the end we propose a concept to design a two element interferometer.

Part 2: Search for FRBs in uGMRT and SRT observations

Fast Radio Bursts are Radio astronomical transients that are highly energetic in nature and lasts for millisecond duration. Since, it's first discovery in 2007 (Lorimer et al., 2007) many efforts have been made to detect, localize and follow up FRBs. While most of the FRBs are observed as one of events some of them have been found to be repeating in nature. With latest results from CHIME the number has raised to 50 (Andersen, B. C. et al., 2023). FRB 20180916 is one of such interesting repeater which has observed periodicity of 16.35 ± 0.15 days (Pilia M. 2021).

In this document we present general procedure of analyze of Radio astronomical data with the example of FRB dataset. We also present work on the FRB search pipelines and effort to improvise SPANDAK pipeline. We present drawbacks and shortcomings of earlier pipelines and how SPANDAK helps improve the detection of FRBs.

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Part I

Design, Simulations and Fabrication of Pyramidal Horn antenna for 1.4 GHz

1. Basic structure of a Radio Telescope

1.1 Introduction

A Radio telescope is an instrument which collects the radio signals from astronomical sources. Radio telescope can be a single dish or array of multiple antenna elements. Every Radio telescope consists of several components.

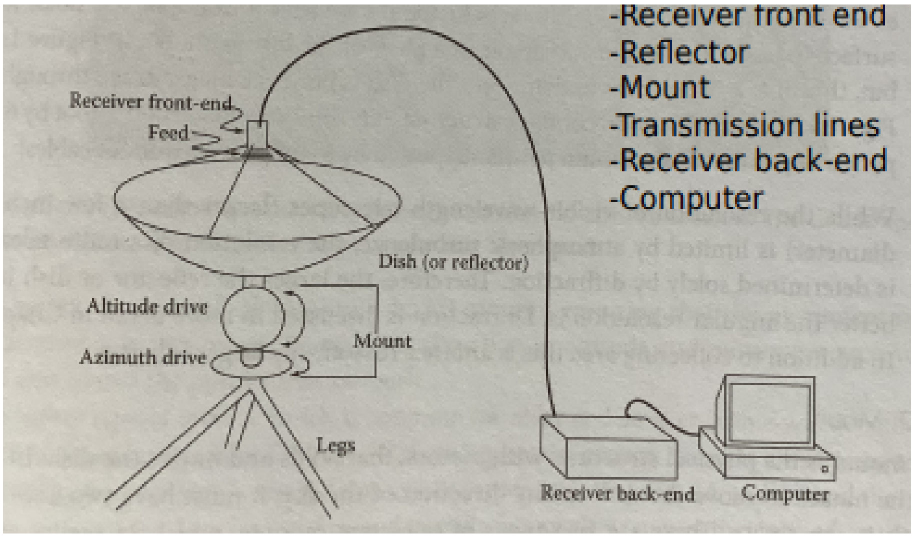

Fig. 1. Degree Distribution

1. Dish or Reflector : It is a structure which collects the radio waves from the sky. The Dish is pointed in the direction of the source. The collected radio waves are then reflected back to the feed which points in direction of the reflector, The pointing of dish needs to be precise in order to receive maximum waves and reflect them to the feed.

2. Feed : A feed is the electric instrument which converts the electromagnetic waves into electric signals. The feeds can be of various shapes. It can be a monopole, dipole, microstrip antenna or as in case of 1.4 GHz, a Horn antenna. Below picture shows feeds from GMRT, Pune (Ananthakrishnan S., 2005). The feed in the 1 GHz to 1.4 GHz is a Corrugated Horn antenna.

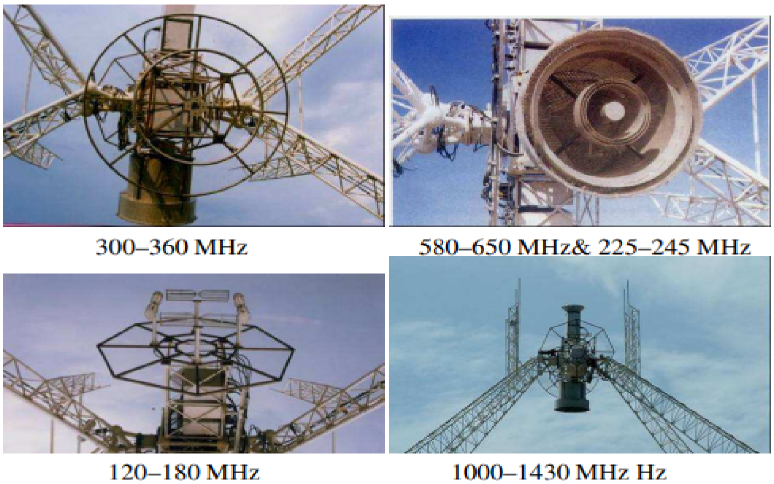

Fig. 2. Degree Distribution

3. Receiver front end : The biggest challenge in observing astronomical signals is they are extremely weak. Before the electric signal is transmitted to back end it needs to be amplified. This needs to be done just after the antenna stage since even a small resistance can introduce enough noise to bury the signal in noise. This is done with Low Noise Amplifiers. Also, after the amplification sometimes a filters are also used to reject known high RFI (Radio frequency interference) channels. Using cooling systems for Front end electronics can remarkably reduce thermal noise in the system.

4. Mount : Like most optical telescopes, due to enormous size of the telescope it is only feasible to have an Alt-Az mount system. The size of fully steerable single dish radio telescope ranges from 10 m (South Pole Telescope) to the biggest 100 m (Green Bank Telescope). Servo motor systems are used for smooth movement of the telescope.

5. Transmission lines : The amplified signal is then transferred to the receiver back end with coaxial cables or optical fiber network. The distance between the two can be few kilometers.
6. Receiver back end : The Receiver back end forms the signal processing units and software back end.
7. Computing facility and storage systems : It includes real time tracking of the observations and monitoring of Antennas. The real time monitoring is very important for transient events such as FRBs.

1.2 1.4 GHz Radio Band

The 1.4 GHz frequency range is very interesting band in Radio astronomy. It is one of the longest wavelengths probed in Radio astronomy. The most important source of emission in 1.4 GHz range is 21 cm Neutral Hydrogen line. There exists many active and energetic sources at 21 cm which are possible to be observed by A small scale Horn Antenna. For example, 3C 461 (SNR-Cassiopeia A), 3C 405 (D Galaxy-Cygnus A), 3C 144 (SNR-Crab Nebula), 3C 145 (Emission Nebula-OrionA) etc. With interferometry techniques and using multiple antennas Pulsar observations from strong sources can also be tried.

1.3 Pyramidal Horn Antenna

An **Antenna** is an electric device which can both receive and transmit electromagnetic radiation. The size, shape and structure of an Antenna can vary a lot depending on its desired gain, frequency range and desired source of observation. The simplest antenna is a monopole antenna which is basically a copper wire which receives electromagnetic waves and downconverts them into electric signals. Few examples of the Antenna type are Long dipole, Helical antenna, Micro strip antenna, Reflector antenna, etc. A Pyramidal Horn antenna has 3 main components - Waveguide, Flarings and Probe.

1.3.1 Waveguide

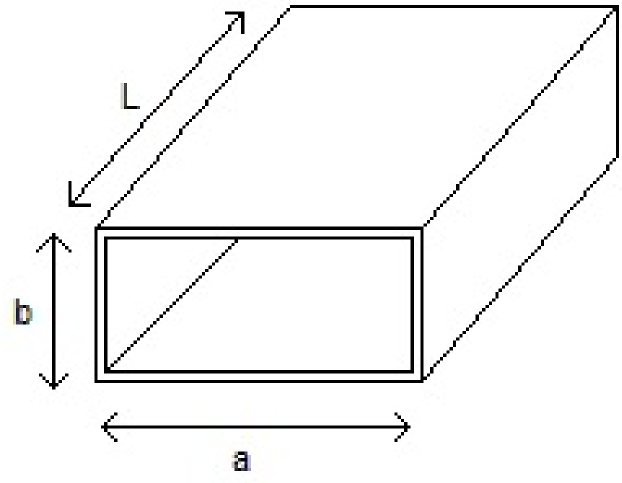

Fig. 3. Rectangular Waveguide

Waveguide is the part of the horn antenna where EM waves are transported from the antenna to the probe or feed. It does not have any gain but is just a high pass filter with very low losses to transport the wave to the electronics. Being a high pass filter it has a cutoff frequency.

We are going to operate our apparatus at 1420405751 Hz or 1420 MHz and we are going to receive red or blue shifted frequencies and **the high pass filter have factor of 1.25 times above cutoff frequency where the transfer function is maximum and the transfer is constant.** Also, there is a fraction after which the gain is not

So, we for our application choose $f_c = 850$ MHz

$\therefore f_{low} = f_c * 1.25 = 1062.5$ MHz

$\therefore f_{high} = f_c * 1.89 = 1606.5$ MHz

Hence, the Horn antenna will function best in the range of about 1.1 GHz to 1.6 GHz. A closest commercial match to this Waveguide is **WR650**. It can be checked on Pasterneck.

The Waveguide have various modes of operation. We will be operating the Waveguide in TE_{10} mode. TE_{10} mode has the lowest attenuation of all modes in a rectangular waveguide and its Electric field is vertically polarized.

Below figure shows that in TE_{10} mode, the variation in E field is in one plane hence there is no variation in H field in perpendicular plane. Hence, a E-field varies sinusoidally along a and uniform along b. The variation along a is $\frac{\lambda}{2}$.

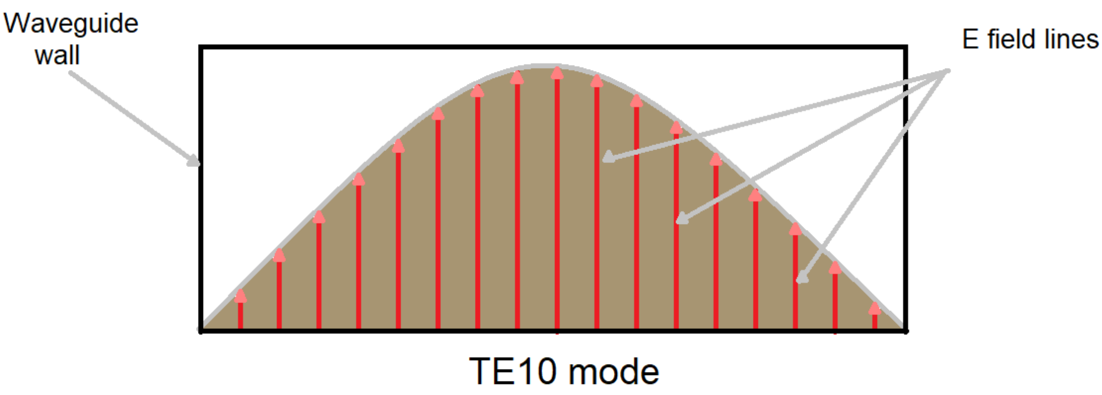

Fig. 4. TE10 mode

The cutoff frequency of a waveguide is given as

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

Since, We are operating in TE_{10} mode, $m = 1$, $n = 0$ and let's use 'c'.

$$\therefore f_c = \frac{c}{2}\sqrt{\left(\frac{1}{a}\right)^2+\left(\frac{0}{b}\right)^2}$$

$$\therefore\ 850\,M = \frac{c}{2a}$$

$$\therefore\ a = \frac{c}{2\times 850M}$$

$$\therefore\ a = 17.64\ cm\ \approx 6.94\text{''}\ \approx\ 7\text{''}$$

Since, we have no dependence on b. 'b' can conveniently be chosen as half of a.

$\therefore b = 8.82\ cm \approx\ 3.46" \approx\ 3"$

$\Rightarrow$ The design that we have decided to build is also almost the same and is perfect just the f_c will be 847 MHz

So, $a = 17.7\ cm$ and $b = 8.3\ cm$. Now, Onwards I will be using these values and $f_\mathrm{c} = 847.4$ MHz or near to it.

The length of the Waveguide can be designed according to the wavelength of operating frequency. Here 1420405751 Hz

$$\lambda_\mathrm{g} = \frac{\lambda}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}}$$

Where,

$f_\mathrm{c} = 847.45$ MHz
$f = 1420405751$ Hz
$\lambda = 21.10cm$

$\Rightarrow \lambda_\mathrm{g} = 26.31$ cm

The Waveguide is air-filled waveguide hence, it has impedance of 377Ω
Further studies of impedance of waveguide with probe distance can be carried out later.

1.3.2 Flarings

To start with,

We have,

$a = 17.7$ cm

$b = 8.3$ cm

We choose desired gain of the horn to be 20dB in order to have good directivity and under control sidelobe shapes.

Let us start with Gain ,

$G_0(dB) = 20 = 10.\log_{10}(G_0)$

$\Rightarrow G_0 = 20 = 10^2 = 100$

Now, we have ,

$$\left(\sqrt{2\chi} - \frac{b}{\chi}\right)^2 (2\chi - 1) = \left(\frac{G_0}{2\pi}\sqrt{\frac{3}{2\pi}}\frac{1}{\sqrt{2\pi}} - \frac{a}{\lambda}\right)^2 \left(\frac{G_0}{6\pi^3}\frac{1}{\chi} - 1\right)$$

Let, the initial guess be

$$\chi_o = \frac{G_0}{2\pi\sqrt{2\pi}} = \frac{100}{2\pi\sqrt{2\pi}} = 6.34936$$

$a = 17.7\ cm = \frac{17.7}{21.20} = 0.8386\lambda$

$b = 8.3\ cm = \frac{8.3}{21.10} = 0.3932\lambda$ and G_0 = 100

On doing iterations from MATLAB program from Balanis book.

For χ_i = 6.0298

$$\Rightarrow \rho_e = \chi_i \lambda = 127.39\ cm$$

$$\Rightarrow \rho_h = \frac{{G_0}^2}{8\pi^3}\left(\frac{1}{\chi_i}\right)\lambda = 141.25\ cm$$

$$\Rightarrow a_1 = \sqrt{3\lambda\rho_2} \approx \sqrt{3\lambda\rho_h} = \frac{G_0}{2\pi}\sqrt{\frac{3}{2\pi\chi_i}}\lambda = 94.62\ cm$$

$$\Rightarrow b_1 = \sqrt{2\lambda\rho_1} \approx \sqrt{2\lambda\rho_e} = \sqrt{2\chi_i\lambda} = 73.37\ cm$$

$$\Rightarrow P_e = (b_1 - b)\left[\left(\frac{\rho_e}{b_1}\right)^2 - \frac{1}{4}\right]^{\frac{1}{2}} = 108.19\ cm$$

$$\Rightarrow P_h = (a_1 - a)\left[\left(\frac{\rho_h}{a_1}\right)^2 - \frac{1}{4}\right]^{\frac{1}{2}} = 108.19\ cm$$

$$\Rightarrow \psi_E = 16.735\ Deg$$

$$\Rightarrow \psi_H = 19.568\ Deg$$

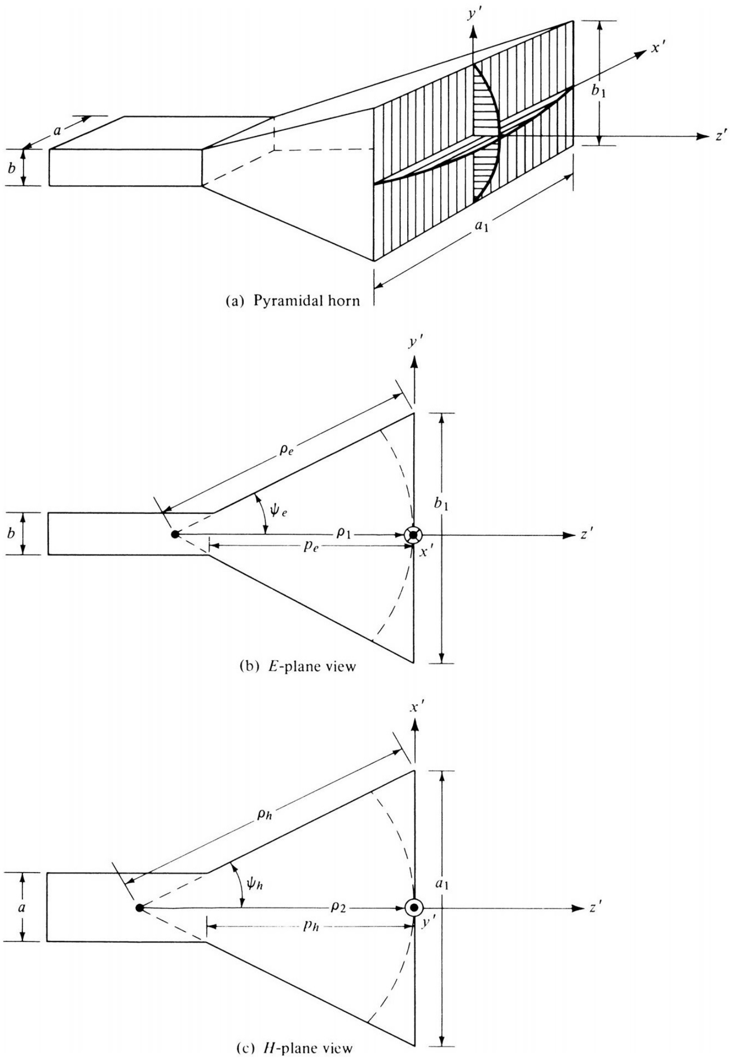

Fig. 5. Antenna theory by C. Balanis fig no. 13.16

a_1 and b_1 : Waveguide dimensions,

a_1 and b_1 : Flaring aperture dimensions,

P_e and P_h : the base height

ρ_e and ρ_h : slant height

ψ_E and ψ_H : E and H plane flare angles

1.3.3 Probe Parameters

(1) Probe length

The probe is nothing but a monopole antenna.

For $\lambda = 21.10$ cm, We should use $\frac{\lambda}{4}$ length probe.

$$l = \frac{\lambda}{4} = \frac{21.10}{4} \approx 5.3\ cm$$

(2) Probe Distance

Probe distance is dependent on λ_{g}

We have calculated λ_{g} in 1.3.1 and should ideally be

$$d = \frac{\lambda_g}{4} = \frac{26.3}{4} = 6.6\ cm$$

(3) Probe Radius

The efficiency of the horn will be dependent on the radius of monopole probe.

With increase in radius,bandwidth of monopole increases .

The ideal radius, as of now I can simulate with HFSS.

Also, different combinations of probe distance,radius can be tried and observed.

1.4 Fabrication and actual dimensions :

We had chosen a good margin in desired gain to compensate for the fabrication uncertainties and errors. In fabrication had to change a_1 by 1.4 cm and the final aperture width turned out to be 93.2 cm. We lost about 0.1 dB gain in this manipulation. With the simulations on the latest design the Total Gain = 20.19 dB.

All the other dimensions were very precise and error was within range of mm's for length dimensions and 1°for Flaring angles,

Fig. 6. Side View

Fig. 7. Four Horn Antennas

2. Simulations of Pyramidal Horn on HFSS

We performed simulations of the Pyramidal Horn antenna to study its Gain characterstics, Radiation pattern, Impedance-Admittance parameters etc. Here, we present the Simulation results of the Fabricated design. I have divided the study in two parts

2.1 Modern solution simulations

We studied Scattering parameter, Admittance parameter and Impedance paramter of the Horn antenna. We also studied VSWR and Passivity of the antenna.

2.1.1 S - Parameter

Scattering parameter forms elements of Scattering matrix which is one of the matrix solved to get antenna characteristics. It is closely related to VSWR of the Antenna. S parameter values help study linear characteristics of the Horn antenna. Below is the simulated S(1,1) - parameter characteristics for the 1.42 GHz Horn antenna. The graph shows S(1,1) Return loss of the system.

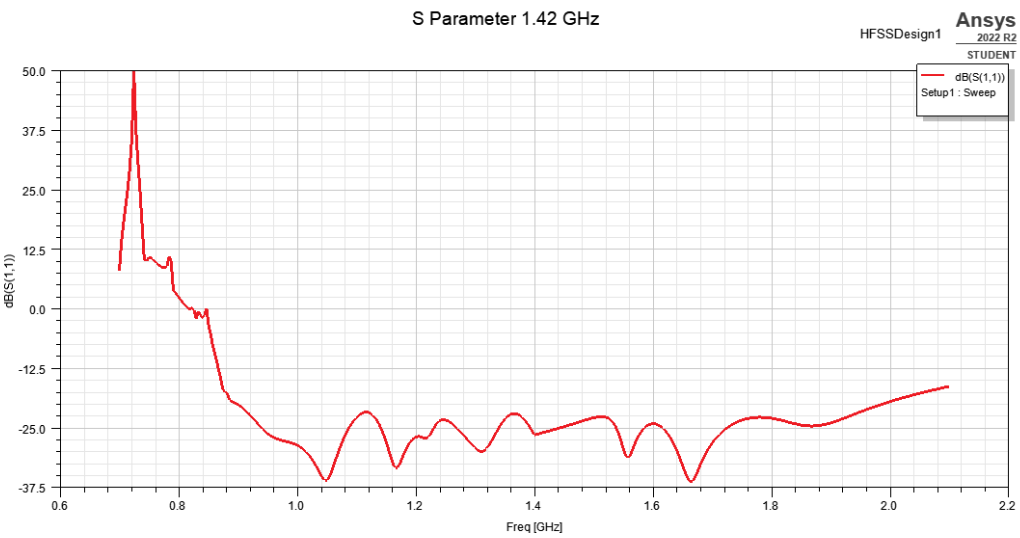

Fig. 8. S parameter

2.1.2 Y - Parameter

It is also known as Admittance parameter or elements which forms elements of Admittance matrix. Y parameters are also called as short circuit impedance because they are calculated in Short circuit conditions. It is difficult to measure Y and Z parameters reliably but still we can simulate there results in HFSS.

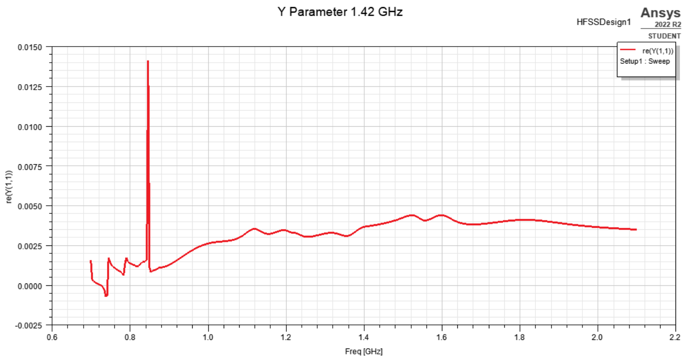

Fig. 9. Y parameter

2.1.3 Z - Parameter

They are similar to the Y parameters and describes behaviour of linear electric circuits. They are also known as Impedance parameters. It is difficult to measure Z parameters reliably but still we can simulate there results in HFSS.

Fig. 10. Z parameter

2.1.4 VSWR

VSWR (Voltage Standing Wave Radio) is a measure of how well the antenna impedance matches with the transmission line connected to it. It is given as

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$$

Where Γ is another antenna parameter which is known as Reflection coefficient. VSWR is the ratio of the peak amplitude of a standing wave to the minimum amplitude of a standing wave.

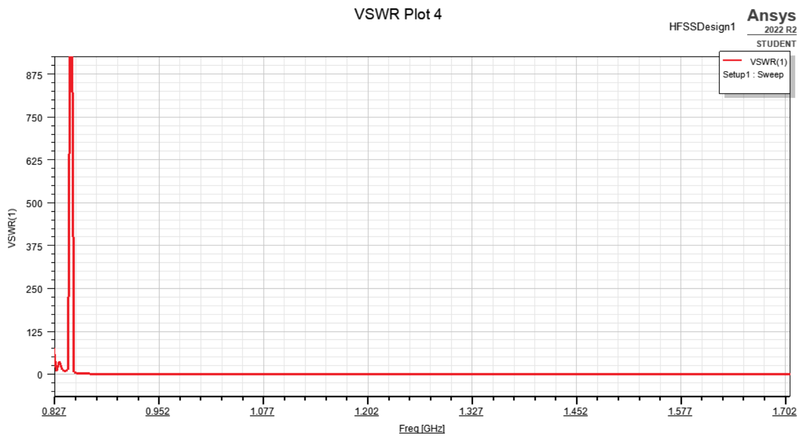

Fig. 11. Z parameter

2.2 Far field simulations

This includes 2D and 3D simulations of Gain, Realized Gain, Directivity of the antenna.

2.2.1 Gain (Total)

Gain represents the input power on the collecting area of the antenna. A better gain reflects to a good antenna. Amplifiers can be used to improve the signal quality but a bare minimum gain is required till the signal is fed to the electronic circuit. Fig 12 shows a 3D Polar plot of total Gain of the Antenna. The Azimuthal angle is Phi and Altitude angle is Theta.

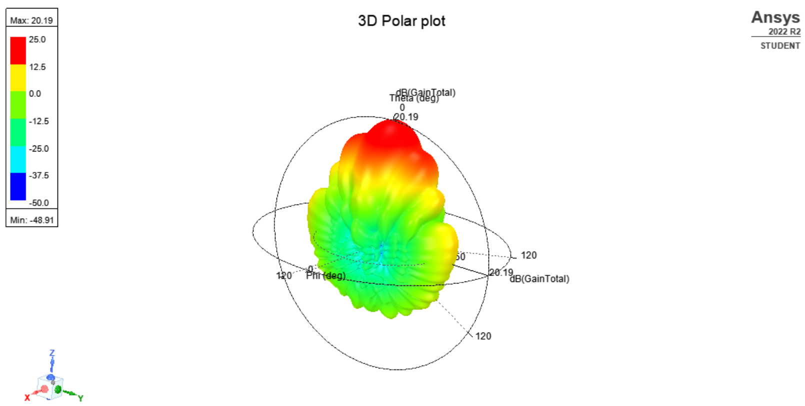

Fig. 12. 3D Gain plot.png

Fig. 13. Front view