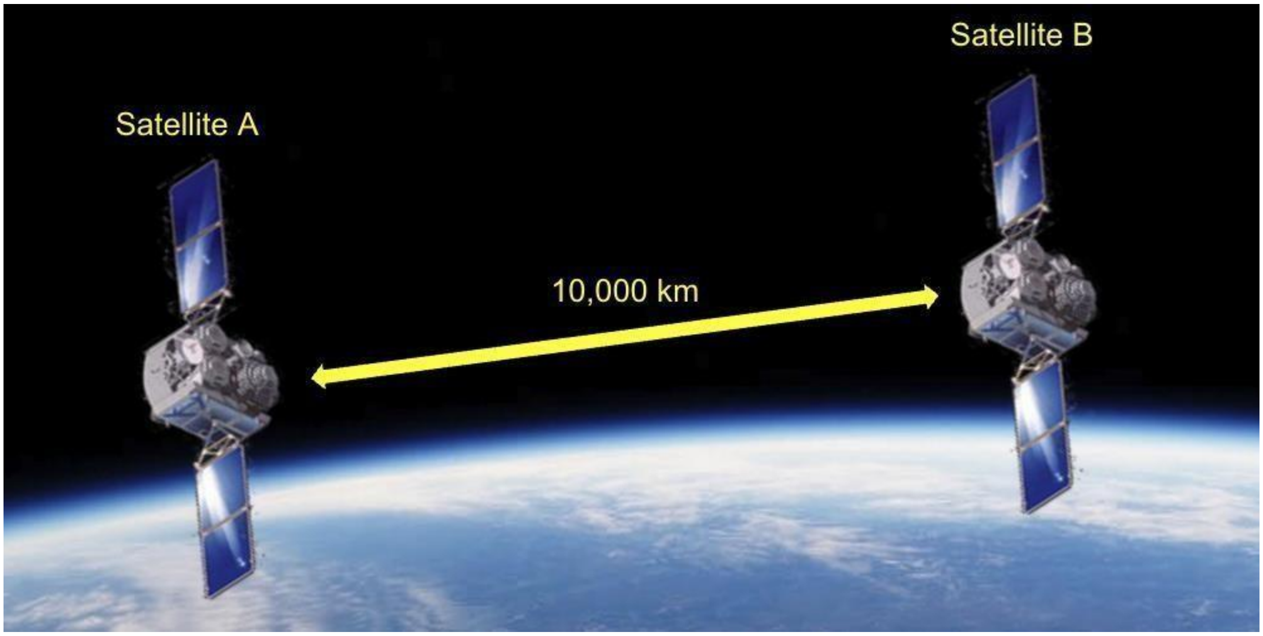
PART A: Terahertz Communication Hardware Design



Imagine two satellites in a low Earth orbit (LEO) that are 10,000 kilometers apart. Each satellite is a 6U CubeSat (i.e., a small satellite with a total volume of 10 cm x 20 cm x 30 cm) and is equipped with a battery, deployed solar panels, a control unit, and a terahertz radio (i.e., front-ends and antenna). The two satellites are well aligned. The operational frequency is 300 GHz. Based on that:

1) Front-end architecture:
   a.

   Electronic: Electronic devices use materials like semiconductors or vacuum tubes to create, modulate, and amplify signals. This method is the traditional approach and includes things like transistors, IMPATT diodes and CMOS technology.

   Photonic: Photonic devices use light to do the same things, with tools like lasers and photoconductive antennas. They're good for quick changes in signals and have less noise, but they usually aren't as powerful as electronic devices.

   Plasmonic: Leverages plasma waves in conducting media and surface plasmon polaritons at interfaces to operate directly at THz frequencies. It's innovative and offers direct THz generation with potentially high efficiencies, especially when employing materials like graphene.

   When it comes to low Earth orbit satellites operating at 300 GHz, using the **electronic approach is a smart choice**. Because electronic technology is well-established and has been around for a while. It offers reliable and scalable solutions for signal generation, amplification, and processing. Electronic devices, like semiconductor components, are tough and have a history of working well in space. Plus, we can tweak them to fit exactly what we need for satellite communication, like making them small and energy efficient. It's also easy to put electronic components into CubeSats (those small satellites) because we already have a lot of experience and designs for it.

   Also, if we combine electronics with photonics – which is using light to do similar things – we get a hybrid solution. This combines the reliability and processing power of electronics with the high bandwidth and great signal transmission of photonics. It makes communication between satellites faster and more efficient, which is important for advanced satellite networks. **So, it's also a pretty cool option to consider.**

b.Electronic-

In a 300 GHz radio communication system, the transmission begins with a Microwave Signal Generator that creates a base signal. This signal is then up-converted by an Electronic Up-converter to the THz range. Following this, an Electronic Modulator modulates the THz signal with the input data provided through a Digital-to-Analog Converter (DAC). To ensure the signal's integrity over distances, a THz Electronic Amplifier boosts its power, and a THz Electronic Filter refines the signal's frequency range. The processed signal is then emitted through a THz Antenna System. At the receiver end, the incoming signal is captured by an equivalent THz Antenna System and passes through another THz Electronic Filter to isolate the desired signal. Another THz Electronic Amplifier strengthens the received signal before it reaches the THz Electronic Demodulator, which extracts the baseband data. An Electronic Down-converter then lowers the frequency of the signal, which is finally transformed into a digital output through an Analog-to-Digital Converter (ADC), completing the reception process.

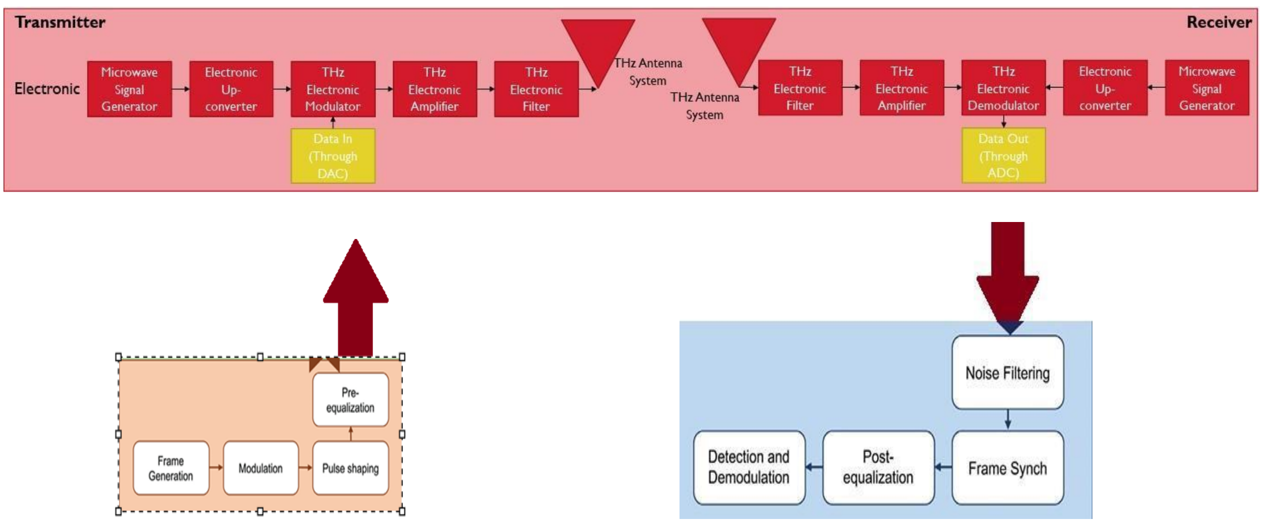


Figure 1: Electronic Block Diagram

At the transmitter, the user-provided data bits are structured in frames, modulated into symbols and shaped into digital signals to be fed to the AWG. At the receiver, the digitized signals captured by the DSO are synchronized, equalized and demodulated to recover the data bits. MATLAB is utilized at both ends, which drastically simplifies the design of the different signal processing blocks.

C. Active components in a system are those that require an external power source to operate. **Passive components** do not require external power to function and cannot introduce energy into the system.

Active: Microwave Signal Generator, Electronic Up-converter, THz Electronic Modulator, THz Electronic Amplifier, THz Electronic Demodulator, Electronic Downconverter.

Passive: THz Antenna System, THz Electronic Filter.

Filters can be placed in one of two categories, passive or active. Passive filters include only passive components—resistors, capacitors, and inductors. In contrast, active filters use active components, such as op-amps, in addition to resistors and capacitors, but not inductors.

d.Superheterodyne Transceiver is a type of radio communication system that converts incoming radio frequency signals to a lower intermediate frequency (IF) for easier processing. This is achieved through a process known as heterodyning, where the incoming signal is mixed with a signal from a local oscillator to produce the IF. The IF signal, which retains the original information from the incoming radio frequency, is then filtered, amplified, and demodulated to retrieve the baseband signal.

In transmission, the process is reversed the baseband signal is modulated into an IF, mixed with a local oscillator signal to reach the desired transmission frequency, amplified, and then sent out through the antenna. The superheterodyne design is known for its selectivity and sensitivity, making it a popular choice for many types of radio receivers and transmitters.

e.

When both the transmitter and receiver share the same antenna for both transmission and reception**, a duplexer or circulator is typically included in the block diagram**.

- **A duplexer** is a tool that lets one antenna be used for both sending and receiving signals, but at different times or frequencies. It makes sure the signals from the transmitter and receiver don't mix up by keeping them apart, allowing both to use the antenna without interference. This is especially useful in systems like radar or radio communication, where the signals going out and coming in are clearly at different frequencies. The device manages this with special filters that guide the signals in the right direction. The smart part about a duplexer is how it smoothly switches the antenna's connection between sending and receiving, ensuring the signals remain clear and uninterrupted. **Duplexers work without needing any extra power, they're considered passive devices.**

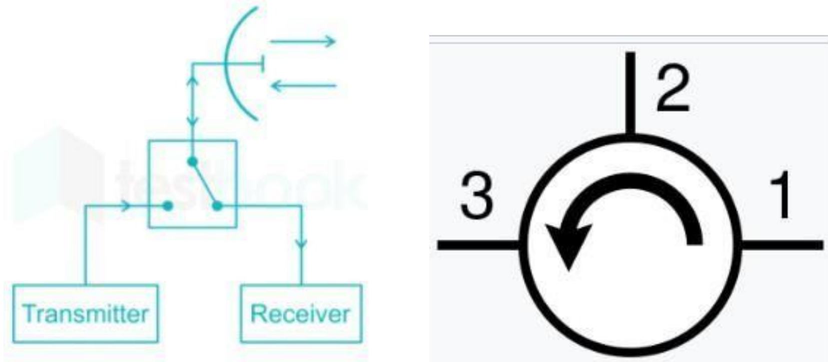


Figure2:TR duplex switching and Circulator switching

- A **circulator** with three connections that makes sure signals only go in one direction, in one port and out the next. When using one antenna for both sending and receiving messages, a circulator helps by sending signals from the transmitter through the antenna and then to the receiver without mixing them up. This keeps the sending and receiving parts from interfering with each other. **Circulators don't require any power to work(passive), they use special materials that naturally allow signals to move in just one direction**. This makes them simple yet effective tools for managing how signals flow in communication systems.

2) Assuming each satellite utilizes a 200-mW transmitter:

a.

- Given a transmit power of 200 mW, the conversion to decibel-milliwatts (dBm) is performed using the below formula is, where 1mW = 0dBm

$$P_{(\mathrm{dBm})} = 10 \cdot \log_{10}(P_{(\mathrm{mW})} \,/\, 1\mathrm{mW})$$

  So we get 23.01dBm.

- Decibels (dB) are used in radio systems because they provide a compact way to represent power levels that span a wide range, simplify calculations by turning multiplication and division into addition and subtraction, and align with human perception by representing changes in signal strength in a logarithmic scale that matches how we perceive intensity changes.

b.

$$\text{FSPL (dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

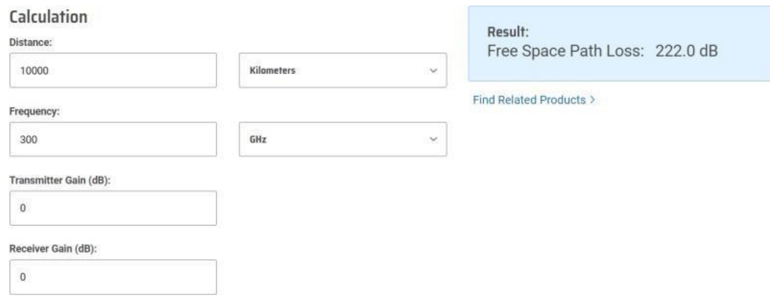


Figure3: FSPL calculation

- c is the speed of light in vacuum.
- d is distance between the transmitter and receiver in meters (m) 10000000 meters.
- f is 300GHz

FSPL formula calculates how much signal is lost while it travels from one satellite to another in free space. The loss is primarily due to the spreading of the wavefront as the electromagnetic wave propagates through space.
To find the received power, we use this below formula considering Antenna gain at Reciever and transmiter is 0dBi.

$$\text{Received Power (dBm)} = \text{Transmit Power (dBm)} - \text{FSPL (dB)}$$

$$\text{Received Power(dBm)} = 23.01\text{dBm} - 222\text{dB} = -199\text{dBm}$$

The Rx power in radio communications is always less than the Tx power due to Free Space Path Loss (FSPL), which reflects signal weakening over distance. As the signal travels, it disperses, reducing its power density, especially over large distances. This fundamental principle ensures that Rx power decreases as the distance between transmitter and receiver increases.

c. Can you think of ways to increase the received power at the receiver? List at least two approaches.

- **Increase the Transmitter's Power**, higher transmit power directly increases the received signal's strength.
- **Use Directional Antennas**,focusing the signal on a specific direction boosts its strength compared to an omnidirectional spread, improving reception.
- **Implement Higher Gain Antennas at the Receiver**, using antennas with higher gain on the receiving end can also improve the received signal strength. Higher gain antennas are more efficient at capturing the incoming signal energy.

d. Either the **transmitter or receiver can benefit from a directional antenna**. At the transmitter, it focuses the emitted energy towards the receiver right from the start. At the receiver, it enhances the reception of the incoming signal. Utilizing directional antennas at both ends is often the most effective strategy. **Using a directional antenna at the transmitter is more beneficial as it efficiently focuses energy towards the receiver, enhancing signal reach and strength.**

e. What is the minimum antenna effective area required to achieve a gain of 15 dBi at 300 GHz?
The effective area of an antenna can be related to its gain and the wavelength.

$$A_e = \frac{G_{\text{linear}} \cdot \lambda^2}{4\pi}$$

We know gain is 15dBi, f = 300GHz we can substitute this value in the formula.

$$A_e = \frac{10^{1.5} \cdot \left(\frac{3 \times 10^8}{300 \times 10^9} \right)^2}{4\pi}$$

Using the formula and substituting the calculated values, the effective area required for an antenna to achieve a gain of 15 dBi at 300 GHz is approximately 2.5 *10^-6 square meters.

f.

A horn antenna is effective for satellite communication due to its directional nature and ability to achieve high gain, such as 15 dBi, making it ideal for high-frequency operations like 300 GHz. Its design allows for efficient transmission and reception of radio waves by focusing the signal in a specific direction, which enhances signal strength and quality. The horn antenna's simplicity, compact design, and excellent performance make it an ideal option for satellites where space is limited and reliable, targeted communication is vital.

PART B: Antenna Design with FEKO

In this section, we will design the antenna using FEKO, a popular electromagnetic solver.

3) I Used the appendix in this document to access the software through the College of Engineering (COE) Virtual Labs (VLABs).

4)
I started a new project in CADFEKO to design an antenna for use at 300 GHz. To create the antenna's shape, I used the construct tab and selected the cuboid to design the waveguide. To design the horn antenna there will be two parts waveguide and flare.
I chose a WR3 standard rectangular waveguide because it works in the frequency range I need, which is from 220 to 330 GHz. The waveguides inside measurements are

- Width: 0.864 millimeters
- Height: 0.432 millimeters

WR3 Specifications

Recommended Frequency Band:	220 to 330 GHz
Cutoff Frequency of Lowest Order Mode:	173.571 GHz
Cutoff Frequency of Upper Mode:	347.143 GHz
Dimension:	0.034 Inches [0.8636 mm] x 0.017 Inches [0.4318 mm]

Figure4:WR3 specification

I established the waveguide structure for the horn antenna by inputting specific dimensions for width and height as per the given values, with the depth defaulting to 1. To achieve the desired directional characteristics of the waveguide, I adeptly adjusted the workplane settings to get the correct structure.

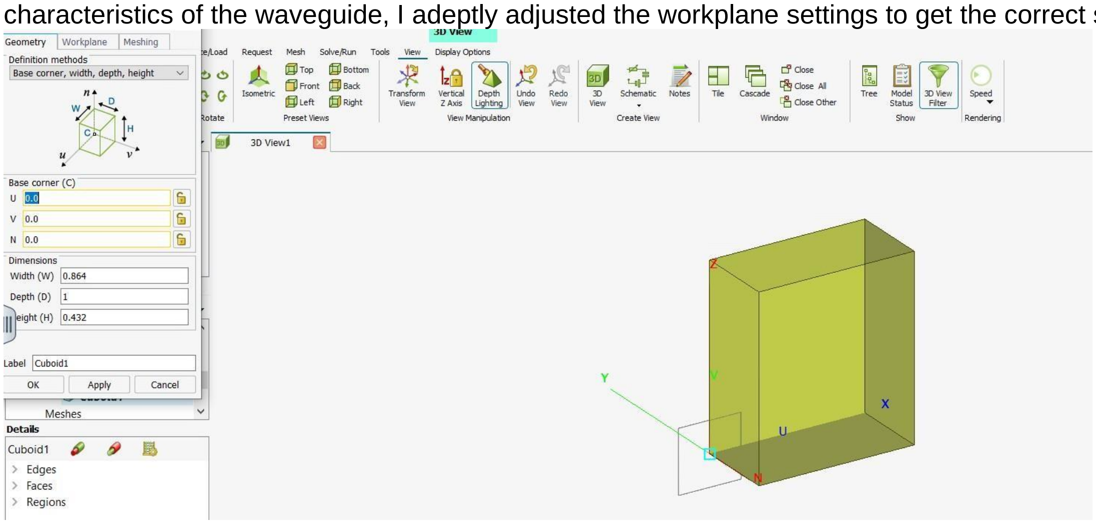


Figure5:horn antenna bottom waveguide design

1. The flare. *Hint:* On one end, the flare is connected to the waveguide, so you know its dimensions. On the other end, the flare needs to have the effective area that you have calculated in Question 2e.

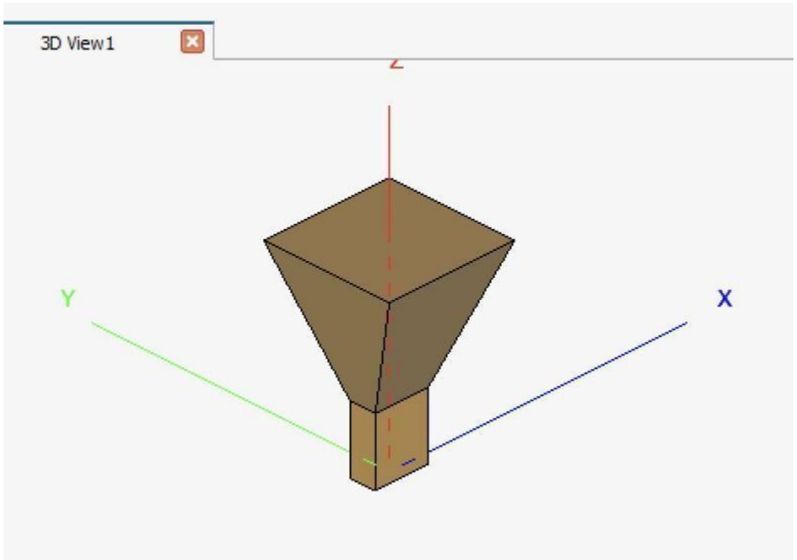


Figure5: horn antenna

In the Feko design process, after setting up the waveguide for the horn antenna, the next step is to model the flare.
To do this, I need to determine the dimensions of the flare mouth, which I consider to be rectangular. Using the effective area (A_eff) of the antenna's aperture from the previous question (measured to be 2.5 x 10^-6 square meters), I can calculate the flare mouth width and depth. The relationship between the width (W) and depth (D) of the flare is given by W = 2D. I performed calculations (which is shown below image)to ensure that I obtain consistent values for both width and depth, and when I multiply them together, I get the effective area value. This confirms that the dimensions are accurate and suitable for the antenna design. I performed two calculations to ensure that I am getting the same width and depth value which is W= 2.2, D=1.1,

RECTANGLE FLARE CALCULATION

$A_{eff} = ax \cdot bx$

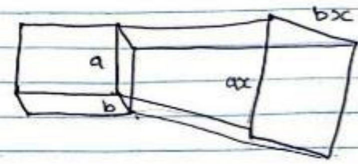
$= abx^2$

$\Rightarrow A = ax,\ B = bx$

we know:

$\Rightarrow a = 0.864 \times 10^{-3} m$

$b = 0.432 \times 10^{-3} m$



$A_{eff} = a \cdot b \cdot x^2 \ \big| \ 2.5 \times 10^{-6} = (0.864 \times 10^{-3}) \cdot (0.432 \times 10^{-3})\, x^2$

$\boxed{x = 2.6 mm}$

$A = a \cdot x = 0.864 \times 2.588 = 2.236 mm$

$B = b \cdot x = 0.432 \times 2.588 = 1.118 mm$

$\boxed{\begin{matrix} W = 2.2 mm \\ D = 1.1 mm \end{matrix}}$

(or) Rectangular formula

$A_{eff} = W \times D$ $\boxed{W = 2D}$

$2.5 \times 10^{-6} = 2D^2$

$D = 1.118 \times 10^{-3} m$

$W = 2.236 \times 10^{-4} m$

D and W From m to mm

$D_{mm} = 1.118 \times 10^{-3} \times 1000$

$= 1.118 mm$

$W_{mm} = 2.236 \times 10^{-3} \times 1000$

$= 2.236 \times 10^{0}$

$= 2.236 mm$

Considering:

$W = 2.2 mm$

$D = 1.1 mm$

The dimensions of the flare's top can be calculated using the method illustrated in the image above. Then, the height of the flare is adjusted iteratively until the desired gain of 15 dBi is reached. I noticed that changing the height made a clear difference in the gain. This is because the flare is the opening at the end of the antenna. When I change the height of this opening, it affects how much electromagnetic energy the antenna can grab and focus. If I make the flare shorter, it captures less energy, so the antenna doesn't work as well, and the gain decreases. But if I make it taller, the flare can capture more energy, so the antenna works better, and the gain goes up. So, adjusting the height of the flare is super important for getting the antenna to perform just right and achieve the desired gain.

After determining the appropriate values for the top width and depth, I input these dimensions into the geometry settings to shape the horn antenna's flare. By carefully manipulating the u, v, and n parameters, I adjusted the position of the flare to ensure it aligns perfectly with the waveguide.

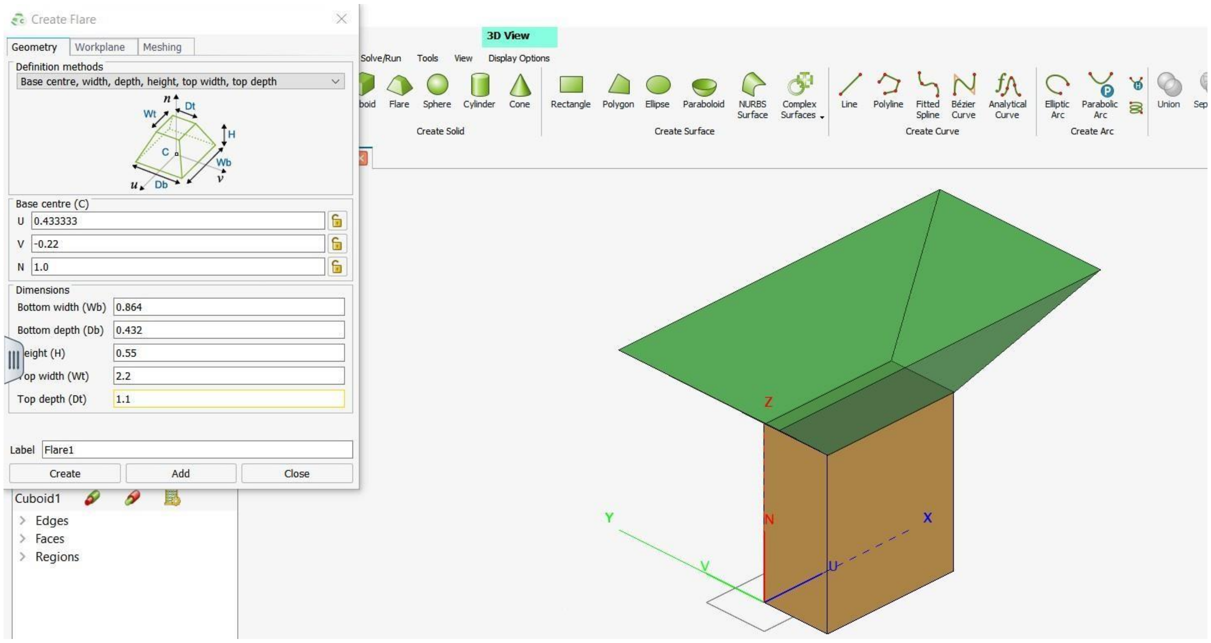


Figure6: Alignment of Horn Antenna Flare with Waveguide

ii. After successful alignment of waveguide and flare, I Used the union feature to merge the waveguide and the flare like in the **figure**

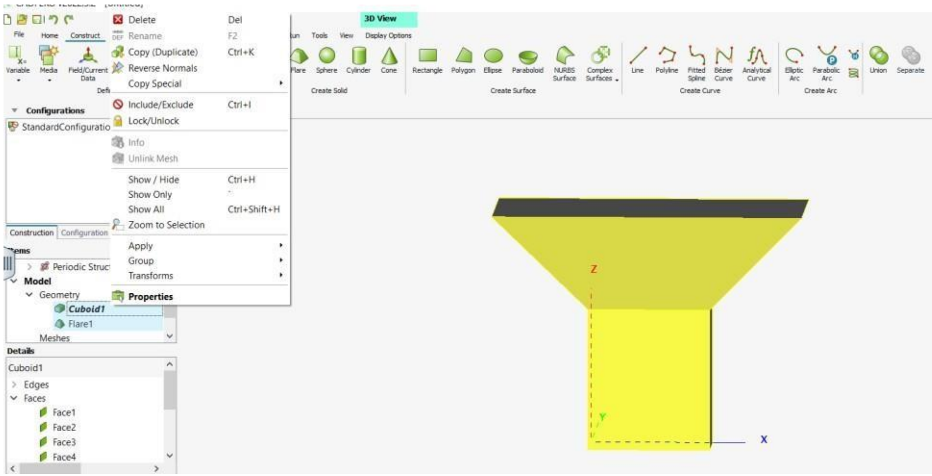


Figure7: Before applying the union.

iii. I modify the model units in millimeter.

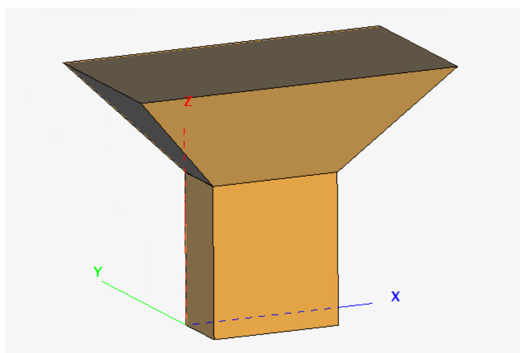


Figure8: perefect horn antenna after applied union

iv.

To ensure the signal could pass through without any blockages.I removed Face 12, which was face of the flare, and Face 13, where the waveguide and the flare meet. I simply clicked on each face and pressed delete. The screenshot I've attached shows the antenna's design with these final changes.

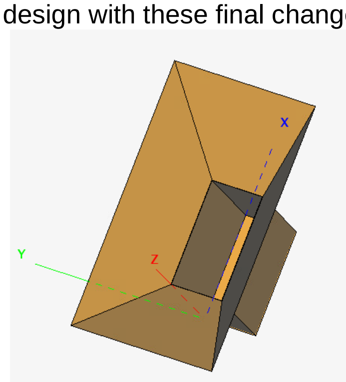


Figure9: removed the blockages.

b.

I adjusted the simulation settings in FEKO to match the operational frequency of the horn antenna to 300 GHz. This frequency was entered in Hertz under the source/load tab, and I specified the simulation to run at a single frequency. Then, I selected the waveguide port face using the waveguide port button to define where the signal will originate within the antenna structure. Finally, I established the actual waveguide source by clicking on the waveguide source button and creating it, which allows the simulation to generate the signal from the chosen port.

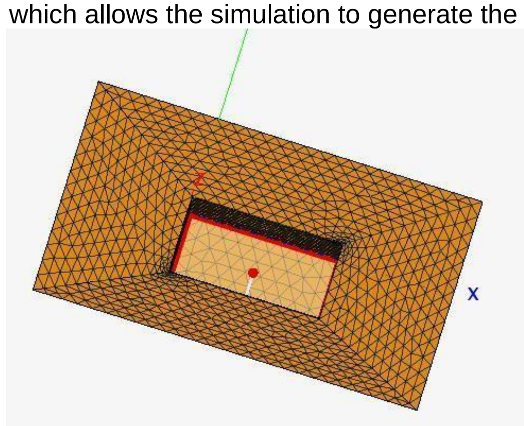


Figure10: Waveguide Port Configuration in FEKO Simulation

c. I went to the mesh tab and utilized the automatic meshing feature. This function automatically generates a mesh over the antenna, which is crucial for the simulation to analyze the electromagnetic behavior accurately.

d. For analyzing the antenna's radiation pattern, I navigated to the request tab and selected the Far Field option. From there, I chose the '3D pattern' to visualize the antenna's radiation properties in three dimensions. After setting this up, I clicked on 'create' to add this request to the simulation.

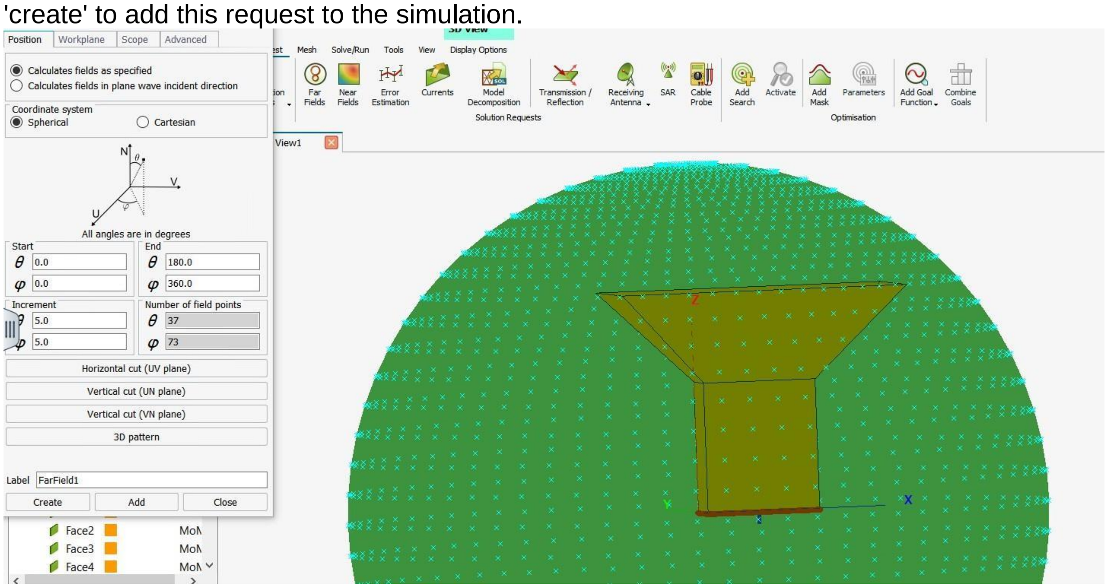


Figure11: setting Up Far Field Radiation Pattern Analysis in FEKO

I saved the antenna model on my computer and started the simulation by clicking the Feko run button. The simulation aims to check how well the antenna works, particularly to see if its radiation pattern, gain, impedance, and efficiency match what I designed it for. The successful run confirms that the antenna should meet its performance goals.

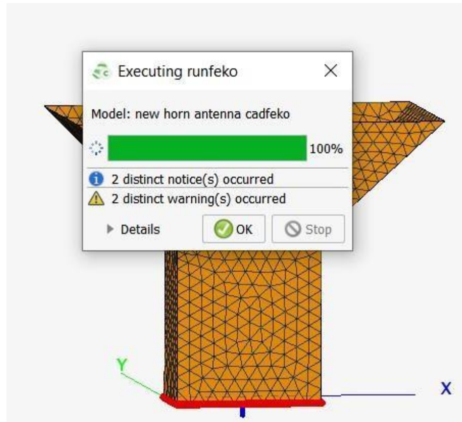


Figure12: Antenna Simulation Execution in FEKO

5) Using POSTFEKO,

a.

In POSTFEKO, I clicked on the Far field button from the Home tab to view the 3D radiation pattern of the antenna. This visual representation allows for a detailed examination of how the antenna radiates energy into space, providing insight into its directional characteristics and efficiency.

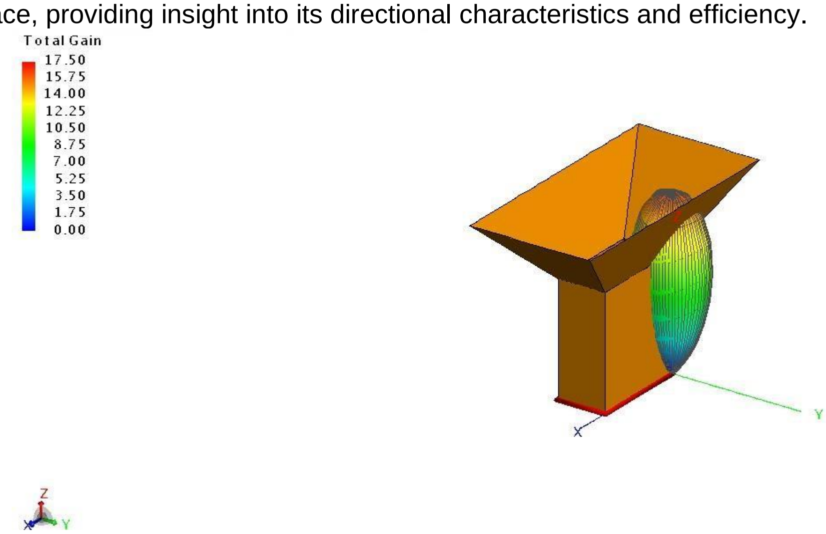


Figure13: 3D Radiation Pattern Visualization in POSTFEKO

I chose the polar plot, cartesian plot option and then added the specified far field data onto the plot area by dragging and dropping it. To ensure accuracy, I enabled the dB option in the Traces panel. Next, I selected "Theta (wrapped)" from the independent axis (Angular) list, which helped me to see the entire radiation pattern in detail.

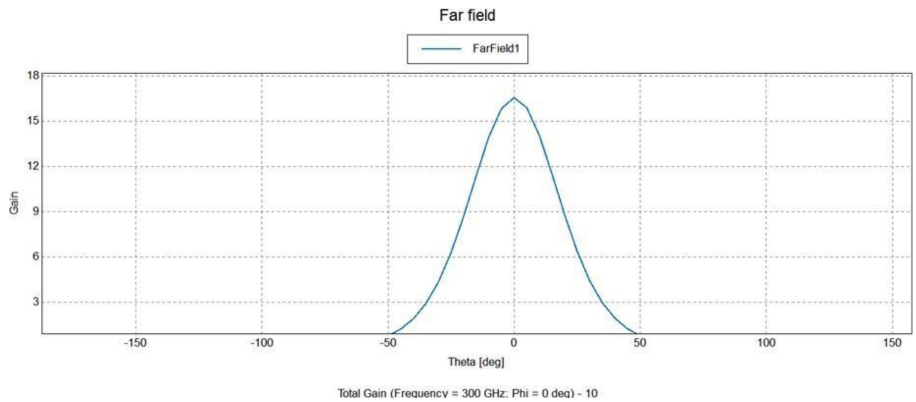


Figure14: Cartesian Radiation Pattern of the Horn Antenna at 300 GHz

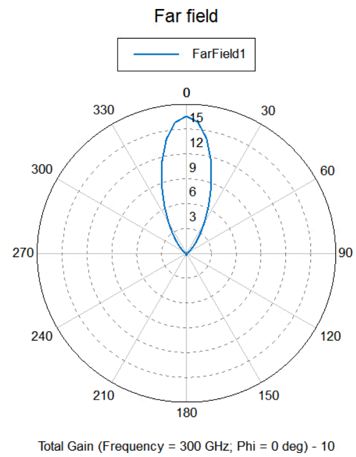


Figure15: Polar Radiation Pattern of the Horn Antenna at 300 GHz

b. The simulation showed that the horn antenna has a gain of 17.50 dBi, which is more than the expected 15 dBi. This means the antenna works better than we thought. The gain went up because we carefully adjusted the antenna's size, especially the height of the flare. Height matters because a taller flare can focus the signal more, making it stronger and increasing the gain. During the simulation, we noticed that changing the flare's height directly affected the gain. A taller flare can concentrate the radiated power into a narrower beam, thus increasing the gain.

Now, if we need to adjust the antenna for even more gain (although it's already higher than what we aimed for), we'd typically make changes like lowering the flare height or making the opening smaller to reduce the gain if needed.

If more gain is required from an antenna, we need to increase Flare Size, Lengthen the Horn, Optimize the Shape.

Increasing the flare height of a horn antenna to get more gain can lead to a few issues. It can make the antenna beam too narrow, which might not be suitable for systems needing wide coverage. The antenna will also be bigger and heavier, which can be a problem for space-limited or weight-sensitive applications. So, when making the antenna taller, it's important to ensure the structure is designed correctly to handle these challenges.

c.

For this type of antenna, increasing the effective area typically requires increasing the length of the antenna as well. Increasing the effective area of the antenna means we're expanding the surface area that can interact with electromagnetic waves. By

lengthening the flare, we widen the aperture through which waves enter or exit the antenna.
This is because the effective area directly influences the antenna's ability to capture and transmit electromagnetic waves efficiently. By increasing the length, the antenna can capture more energy from the surrounding space, thus enhancing its efficiency.

This relates to the efficiency of the antenna because a larger effective area allows for better signal reception and transmission. When the antenna captures more energy, it can convert it into useful signals more effectively, resulting in higher overall efficiency.

SQUARE:

I also designed the flare of the horn antenna's aperture based on the area formula, aiming for an effective area of 2.5×10^−6 square meters.

$\boxed{\text{SQUARE}}$

$$A_{eff} = 2.5\times10^{-6}\, m^2 \;;\; A = \sqrt{A_{eff}(mm^2)}$$

$$A_{eff}(mm^2) = 2.5 \;;\; A = \sqrt{2.5} = 1.581\, mm$$

$$\boxed{A = 1.5\, mm}$$

Four Sides are equal For Flare

I calculated that each side of the square aperture should be 1.5 mm, considering that a square has all sides equal,by keeping the flare height constant at 0.55 mm, I ran a simulation to see if this design would achieve the same gain as Rectangular horn antenna. The result was a confirmed gain of 17.50 dBi. I noticed that changing the height made a clear difference in the gain.

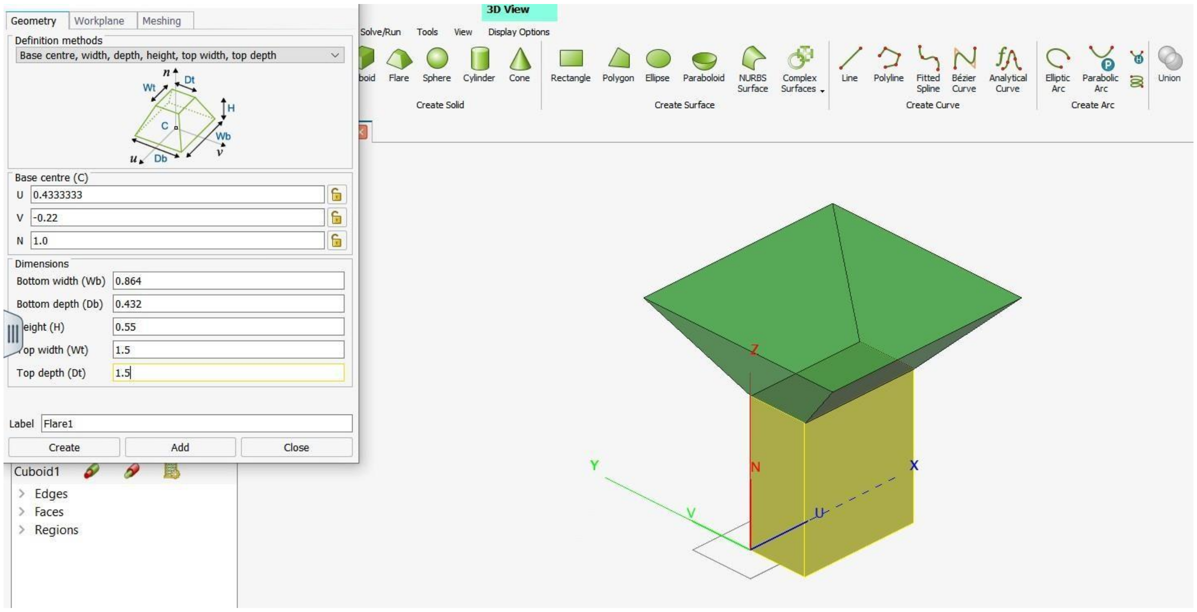


Figure16: Alignment of Horn Antenna Flare with Waveguide for Square

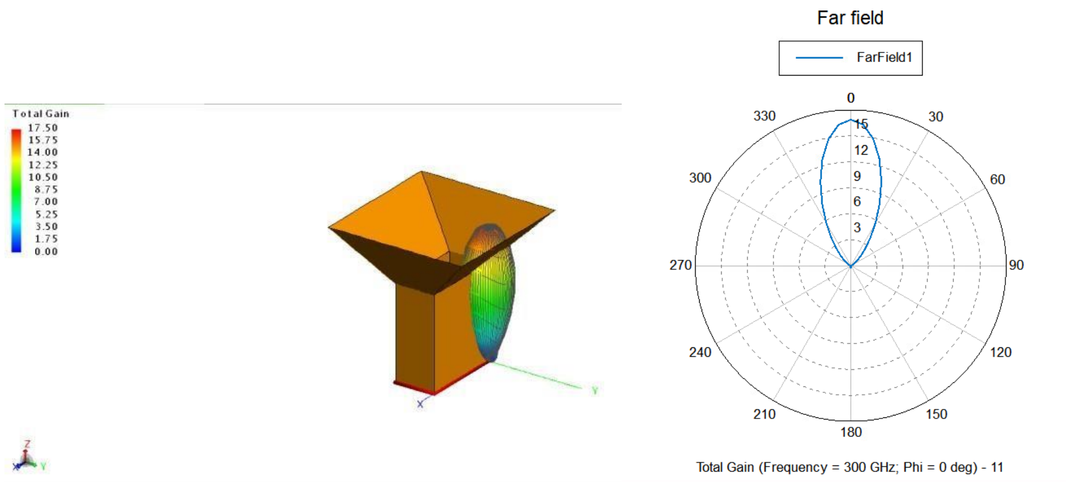


Figure17: 3D Radiation Pattern Visualization and polar Radiation Pattern