Radio Frequency (RF) Analog #1: Antennas & Transmission Line

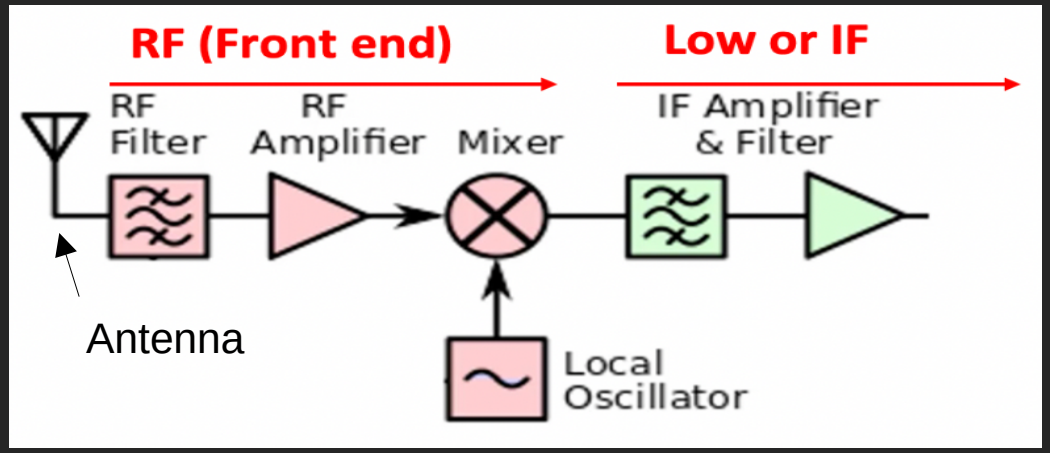
3S24 – Session RA-02a

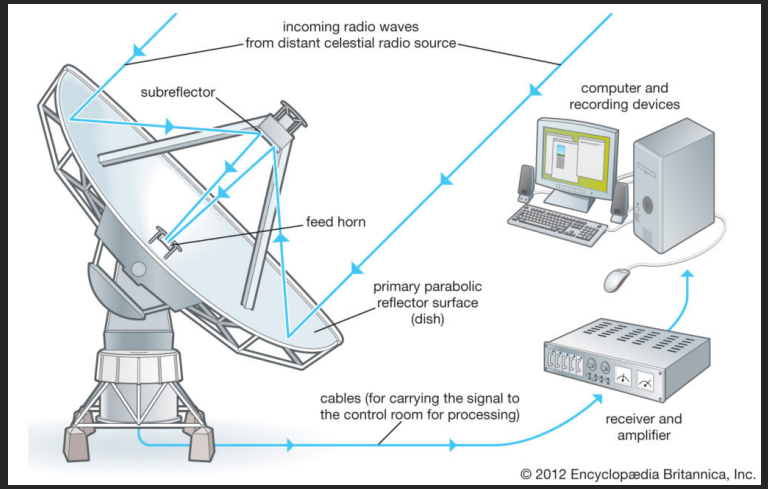
Bang D. Nhan (Nhan Định Bang)
National Radio Astronomy Observatory (NRAO)
Charlottesville, Virginia, USA
Email: bnhan@nrao.edu

Outline

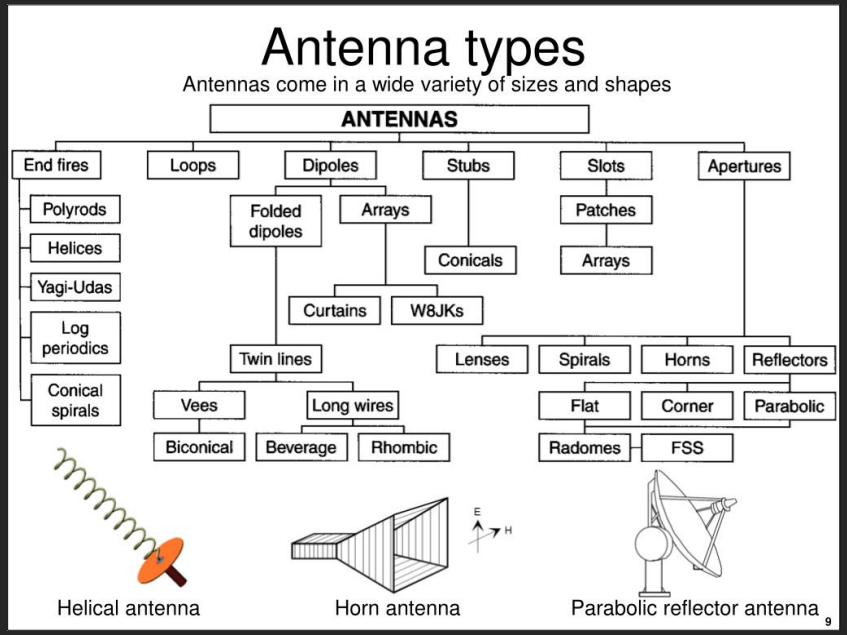
I. Antenna Basics
   i. Maxwell equations
   ii. Beam patterns & examples
II. Transmission Line
III. Impedance measurement
   i. Impedance Mismatch
   ii. Scattering (S-) parameters
   iii. Smith Chart
   iv. Vector Network Analyzer
IV. Antenna Design & Simulation Case Studies
V. Antenna Measurement Methods

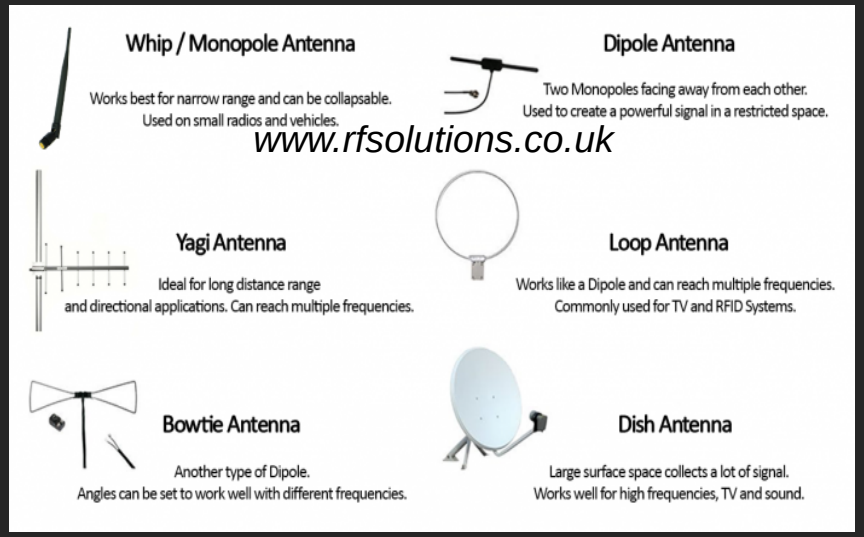
Radio receiver



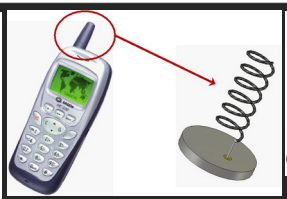


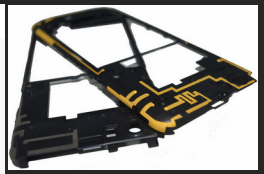
Antenna Types



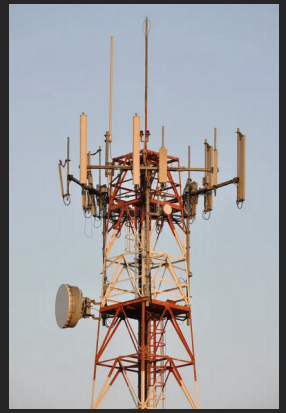


Bluetooth





Smart phone

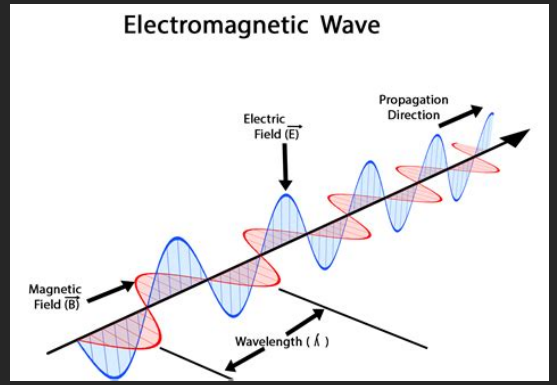


Car shark fin

WIFI router

Maxwell's Equations

Maxwell's Equations	Maxwell's Equations
Differential form	Integral form
div $\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$	$\oint \vec{E} \cdot d\vec{a} = \frac{Q_{enc}}{\varepsilon_0}$
curl $\nabla \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}$	$\oint \vec{E} \cdot d\vec{l} = \boxed{-\int \frac{\partial \vec{B}}{\partial t} \cdot d\vec{a}}$
$\nabla \cdot \vec{B} = 0$	$\oint \vec{B} \cdot d\vec{a} = 0$
$\nabla \times \vec{B} = \mu_0 \vec{J} + \boxed{\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}}$	$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc} + \boxed{\mu_0 \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t}}$

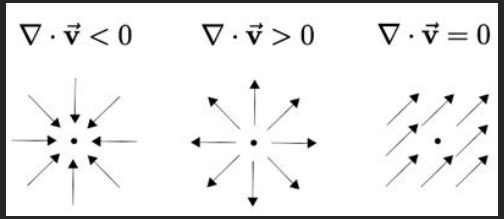


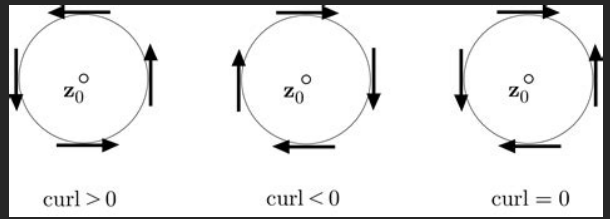
Gauss's law

Gauss's law in magnetism

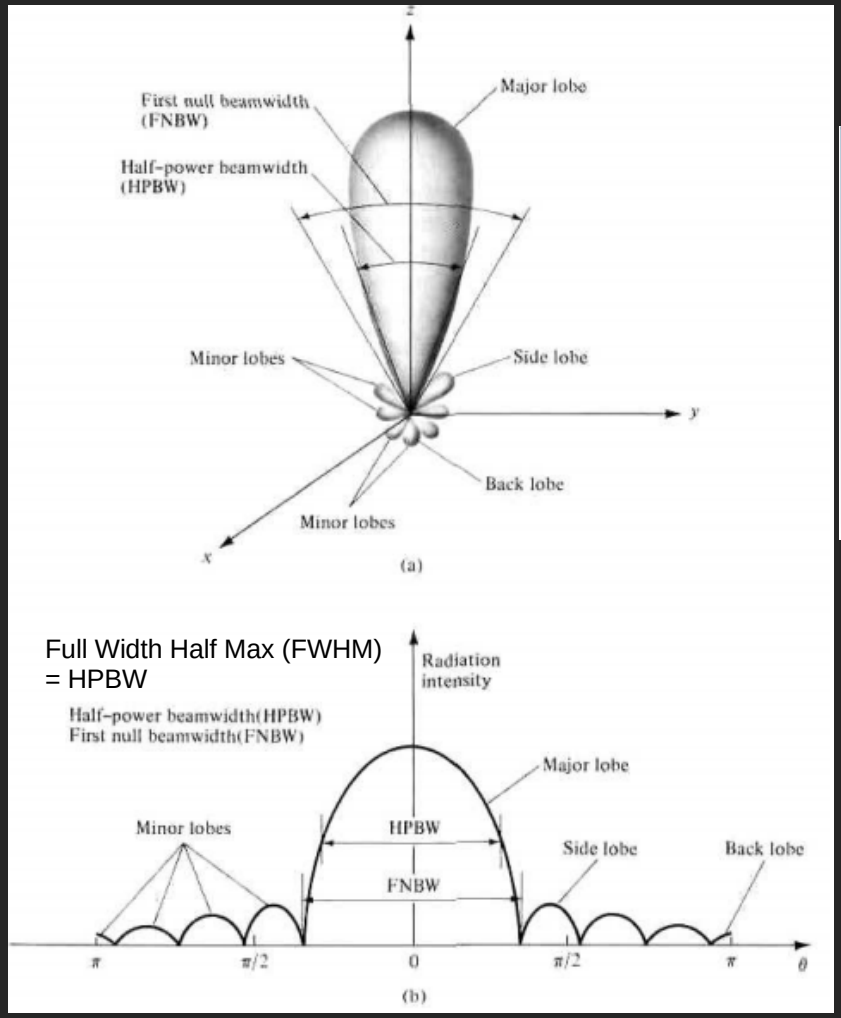
Ampere's law

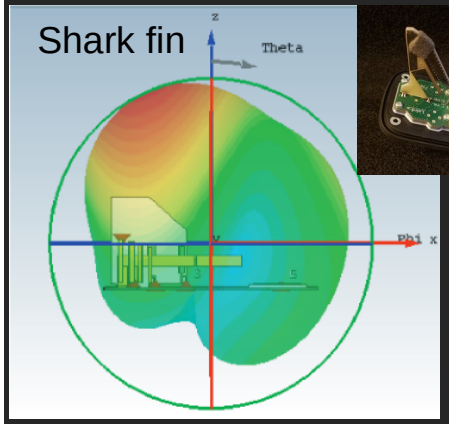
Faraday's law

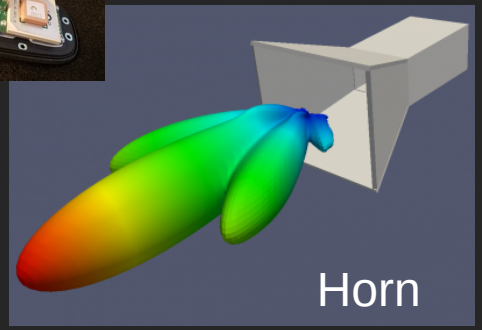




Antenna radiation pattern (or Beam)



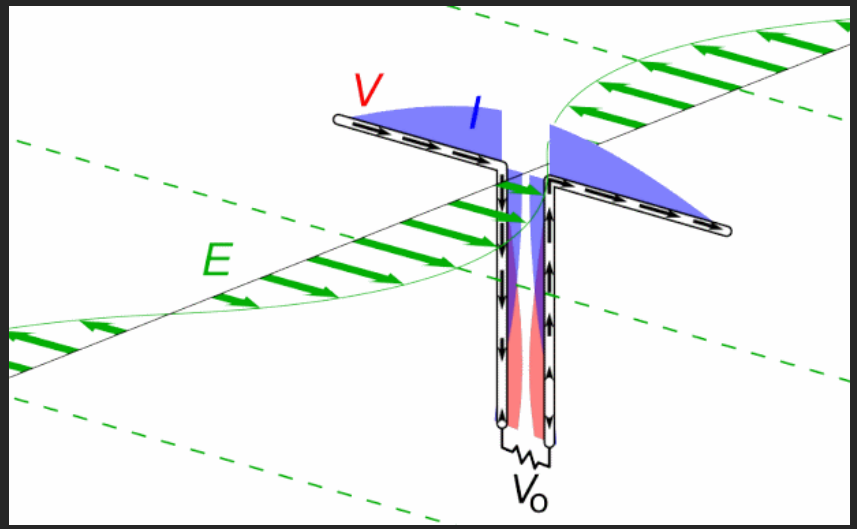


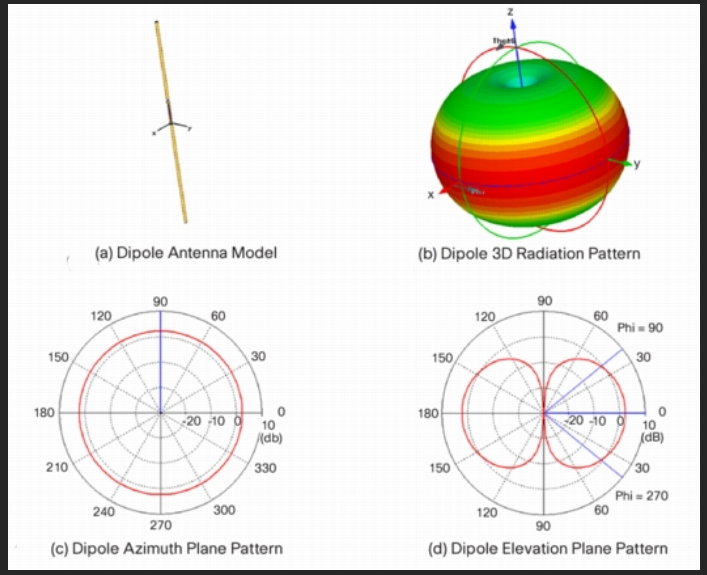


Poynting Vector

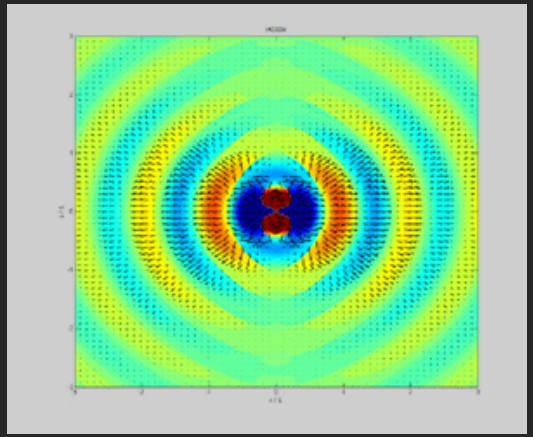
$$\mathbf{S} = \mathbf{E} \times \mathbf{H},$$

Dipole Antennas



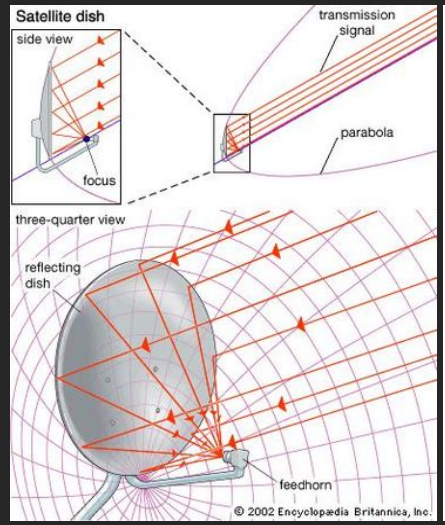


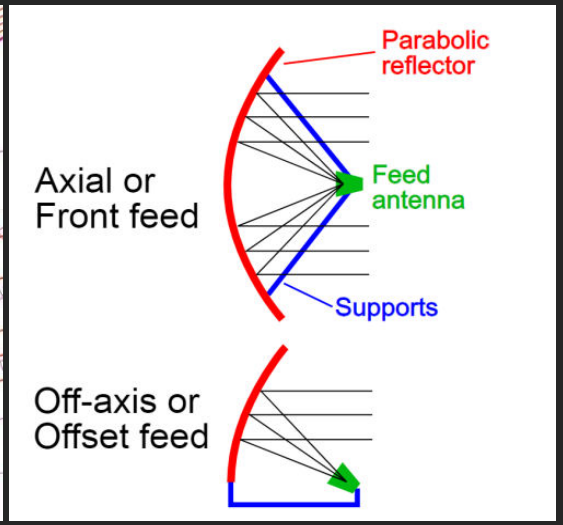
Lesson 1 - Intro to Frequency Characteristics of The Half-Wave Dipole
Lesson 2 - The Current Structure on a Half-wave Dipole
Lesson 3 - Dipole Radiation Pattern Over Frequency

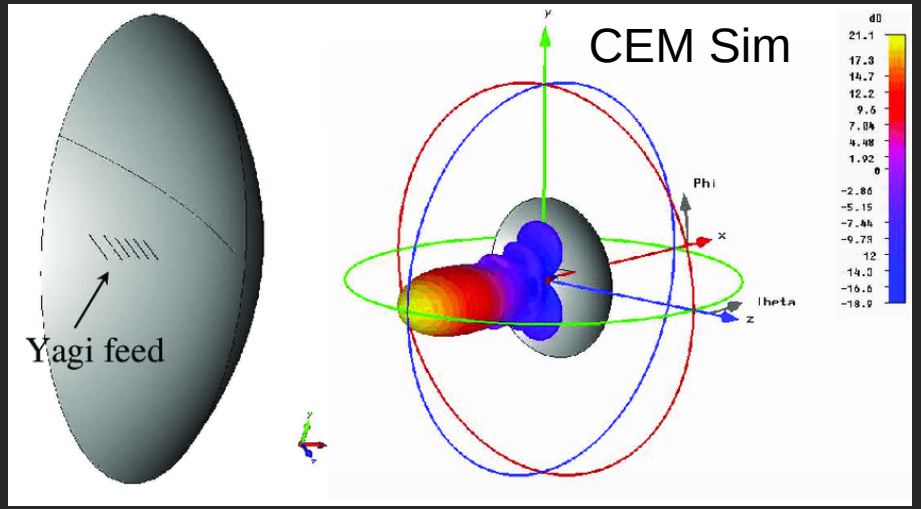


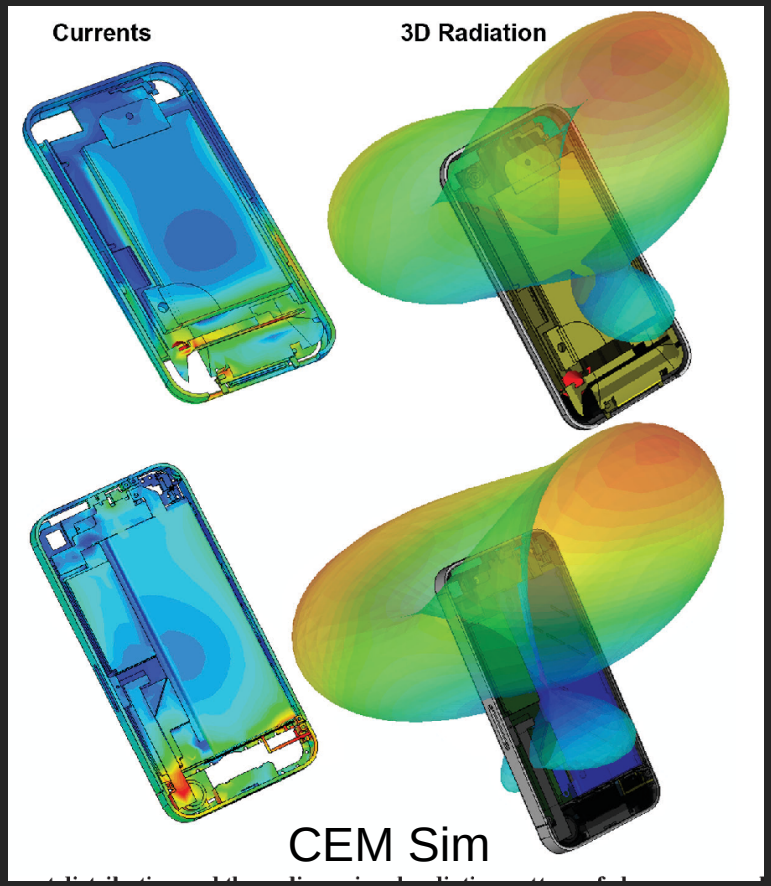
Antenna simulation =
Computational Electromagnetics (CEM)

Parabolic dish antenna









CEM Sim

DOI:10.1109/MAP.2012.6309152

Smart phone

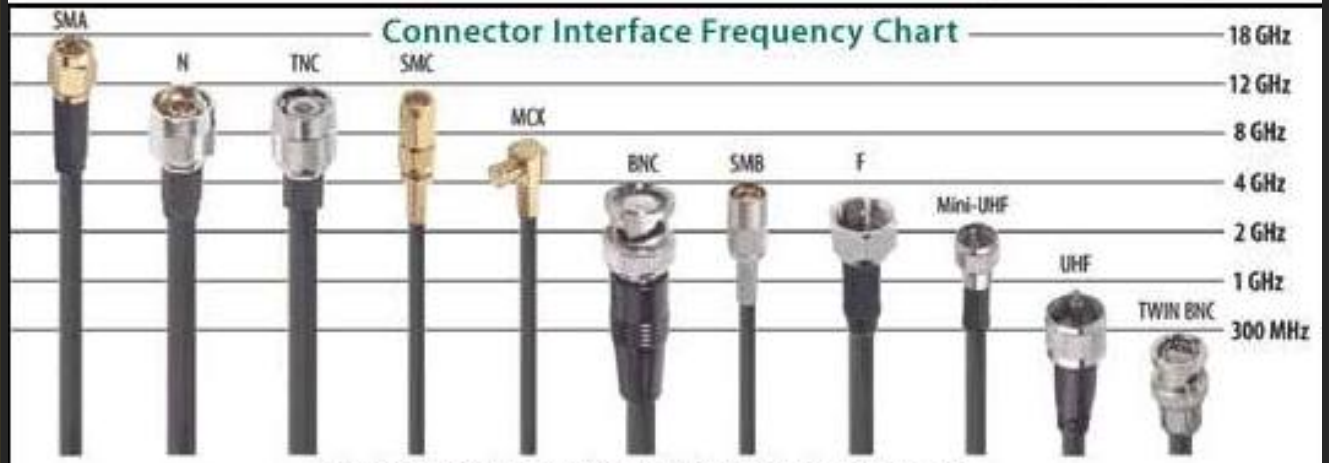
Transmission Line
(Example: Coaxial cable)

RG213/U

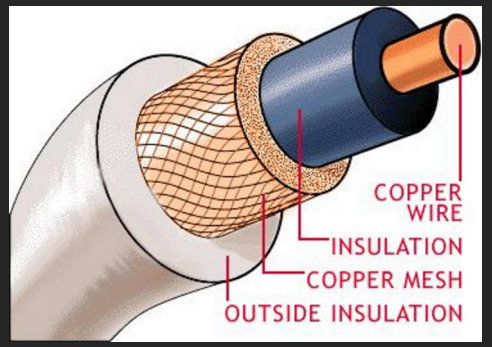
50 Ohm Impedance

- Center Conductor: 13 AWG (7 x .0296) bare copper
- Shielding: Bare copper braids (96% coverage)
- Insulation: Solid polyethylene
- Jacket: Black PVC
- Operating Temperature: -40°C - +80°C

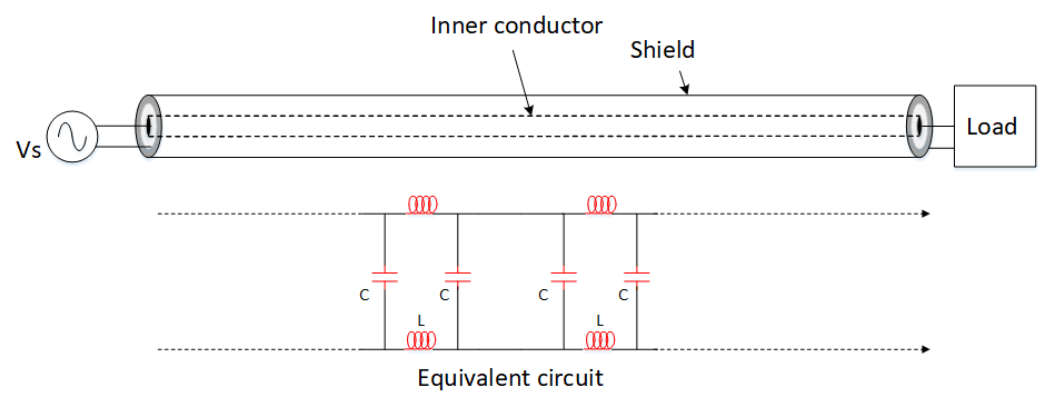
NOMINAL ATTENUATION		
MHz	db/100 ft	db/100m
50	1.3	4.3
100	1.9	6.2
200	2.7	8.9
400	4.1	13.4
1000	8.0	26.2
4000	21.5	70.5



This chart illustrates the upper frequency limit of various interface types only.
Actual frequency limits of cable assemblies are dependent on various other factors.



Coaxial cable impedance



https://www.cdt21.com/design_guide/impedance-and-standing-wave-ratio/

Dielectric constant = Relative permittivity $\varepsilon_r(\omega)$

Material	Dielectric Constant
Vacuum	1.0
Air	1.0006
Dry paper	2.0—2.5
Bakelite	4.5—5.5
Glass	5.0—10.0
Rubber	2.0—3.5
Mica	3.0—7.0
Porcelain	6.0—7.0
Mylar	3.1
Polyethylene	2.25
Polyvinyl chloride	3.2
Teflon(P.T.F.E.)	2.1
Germanium	16.0
Water	80.4
Titanium dioxide (rutile)	173.0

The design formula for characteristic impedance of a single coaxial line is:

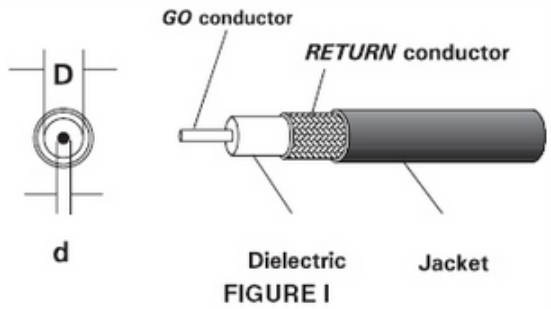


FIGURE I

$$Z_0 = (138 / \sqrt{E}) \times \log_{10} (D / d)$$

where:

Z_0 = Characteristic impedance

E = Dielectric constant (air is 1.0)

D = Inside diameter of the "*return*" (outer) conductor (conductive metal tube or one or more braids), see Figure 1.

d = Outside diameter of the "go" (inner) conductor, see Figure 1.

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Radio Receiver
Antenna types
Maxwell's Eq.
Antenna beam
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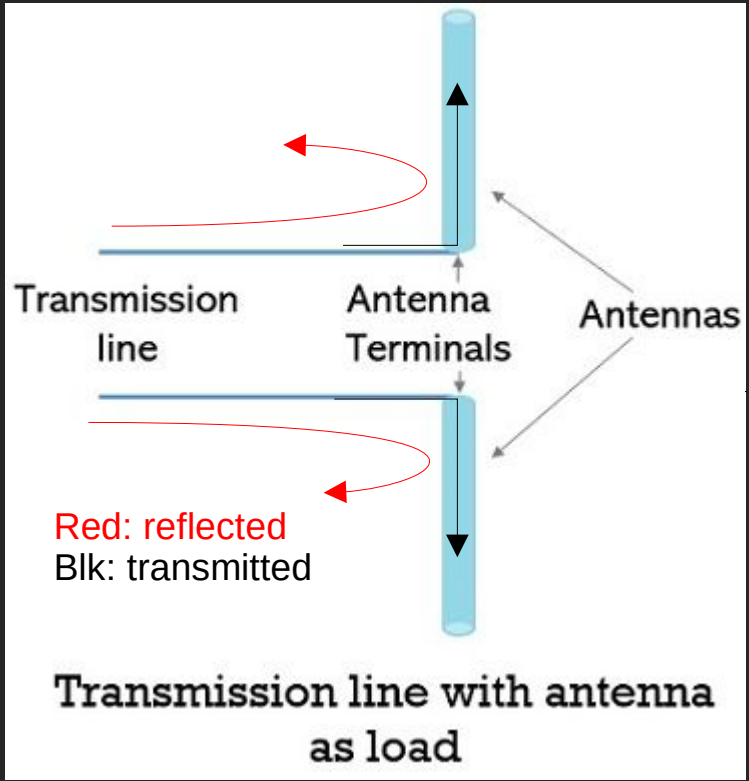
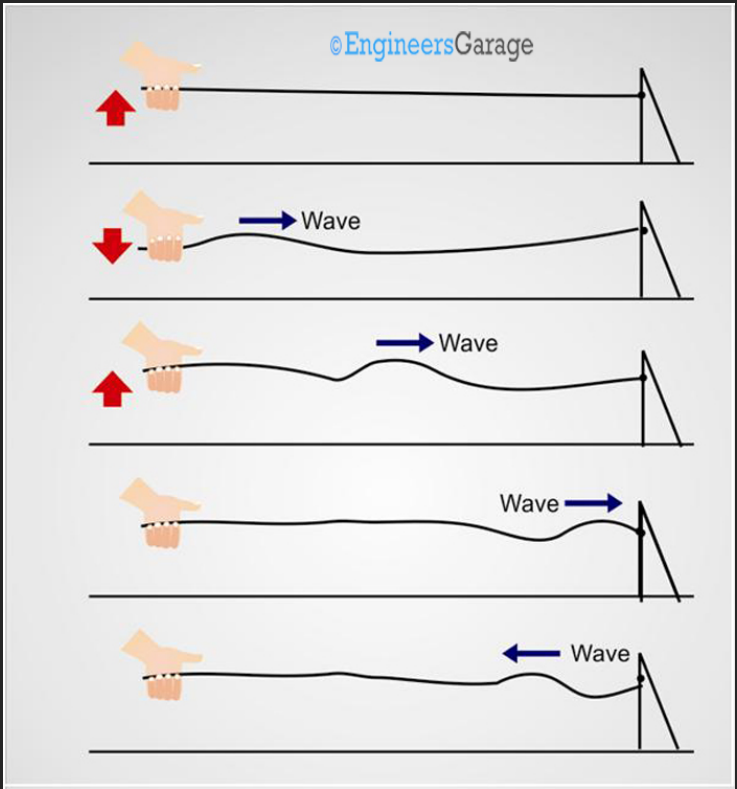
Parabolic Dish
Smart Phone
Transmission Line
Impedance measurement

Impedance Mismatch & Reflection coefficient





Reflection coefficient: $$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

Coaxial cable, typically, $Z_0 = 50$ Ohm or 75 Ohm

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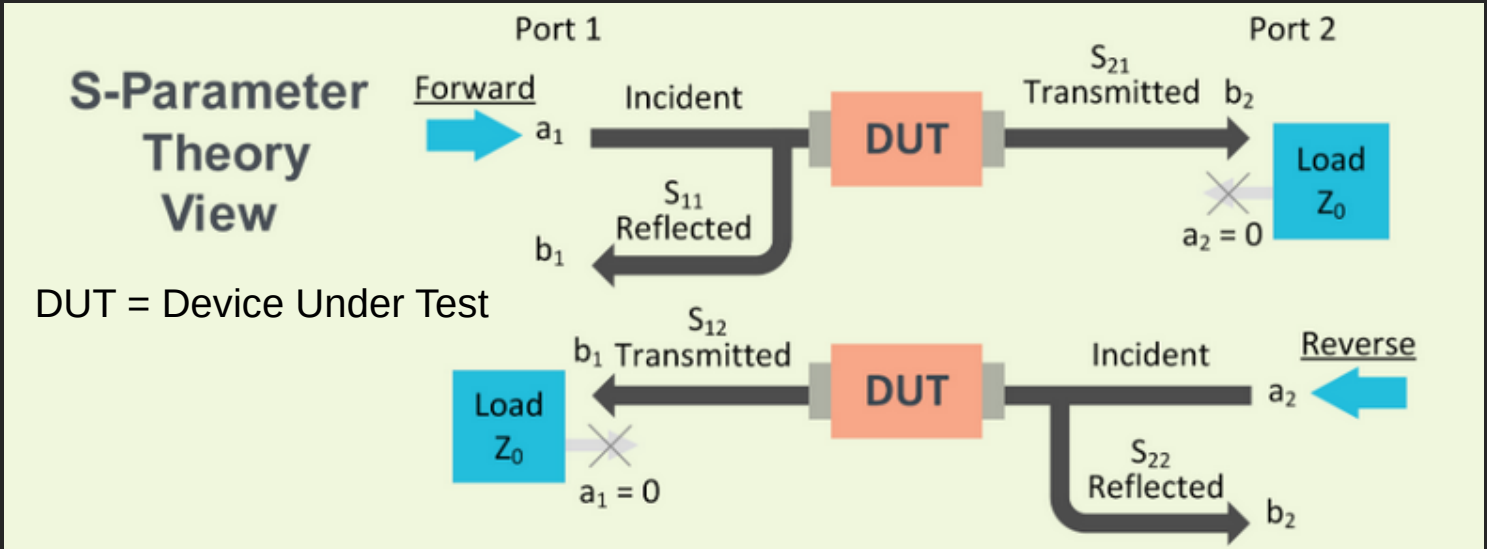
Smart Phone
Transmission Line
Impedance Meas.
S-parameters

Scattering (S-) parameters



	Forward:	Reverse:
Reflection:	$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1}\Big\vert_{a_2=0}$	$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_2}{a_2}\Big\vert_{a_1=0}$
Transmission:	$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1}\Big\vert_{a_2=0}$	$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2}\Big\vert_{a_1=0}$

https://www.tek.com/en/documents/primer/what-vector-network-analyzer-and-how-does-it-work

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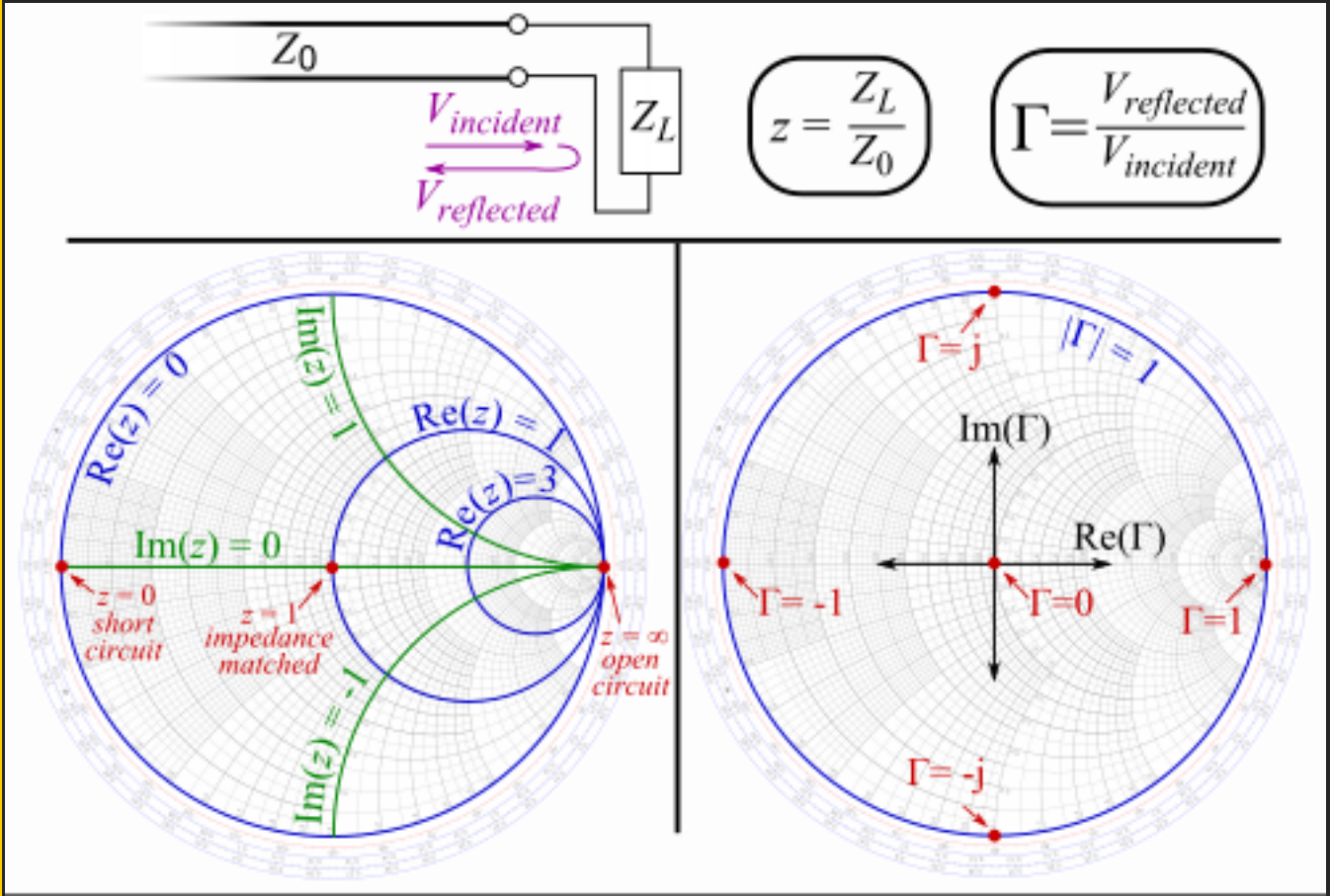
Smith Chart

Smith Chart



Independently proposed by:
- Tōsaku Mizuhashi (1937)
- Amiel R. Volpert (1939)
- Phillip H. Smith (1939)

$$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

Conformal mapping of complex impedance Z

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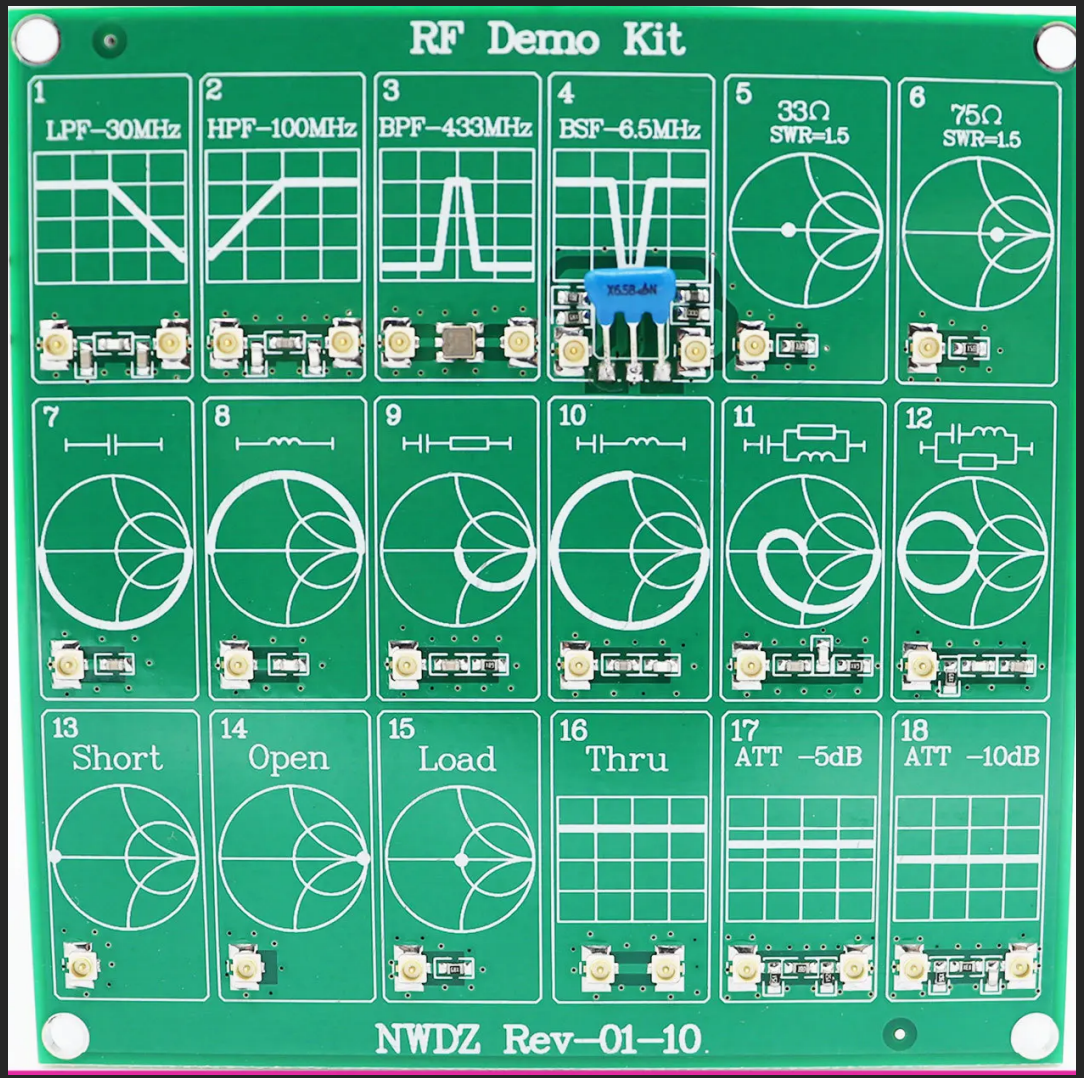

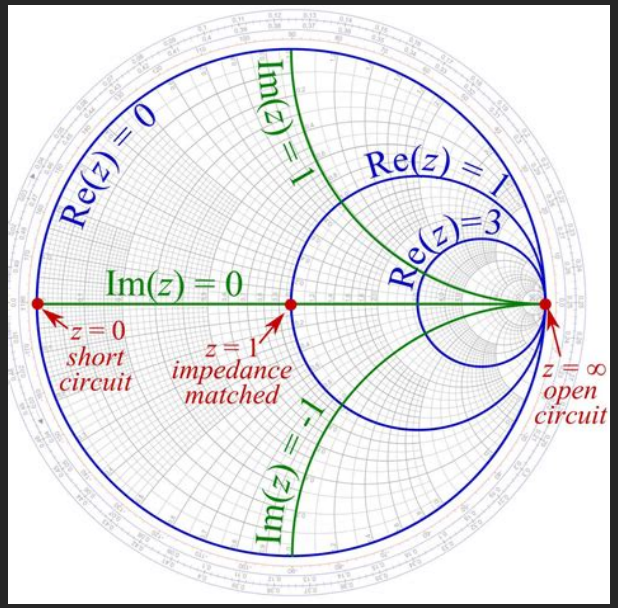

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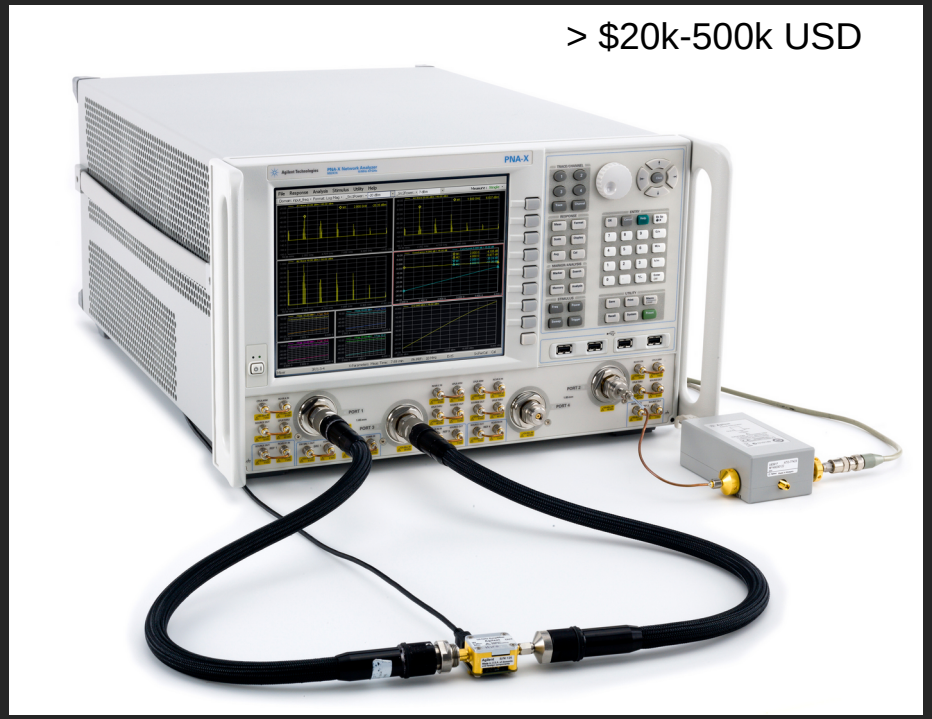
Smith Chart
VNA

Vector Network Analyzer (VNA)



Higher frequency it measures = More expensive !!!

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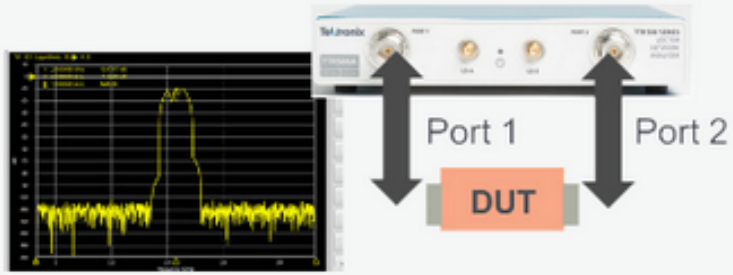
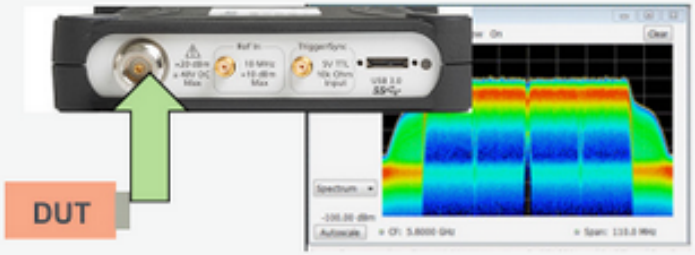
Network Analyzer



- Contains a source and receiver(s)
- Uses known stimulus
- 2 channels or more
- Ratioed measurements
- Offers advanced calibration, more accurate
- Limited to analog and pulsed signals

Spectrum Analyzer



- Contains a receiver
- Measures unknown signals
- Single channel
- No ratioed measurements
- Limited calibration capability, less accuracy
- Works well with digitally modulated signals

Both use FFT to convert voltage to spectrum

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Antenna Design

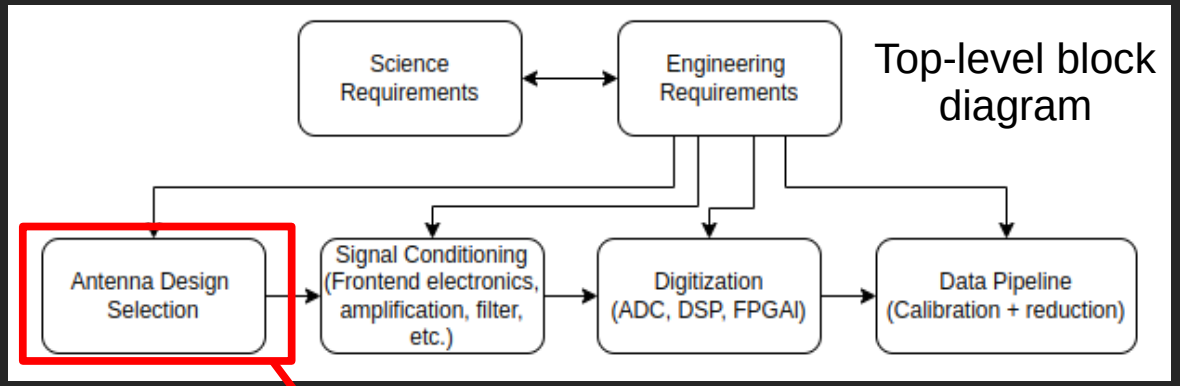
Antenna Design Process

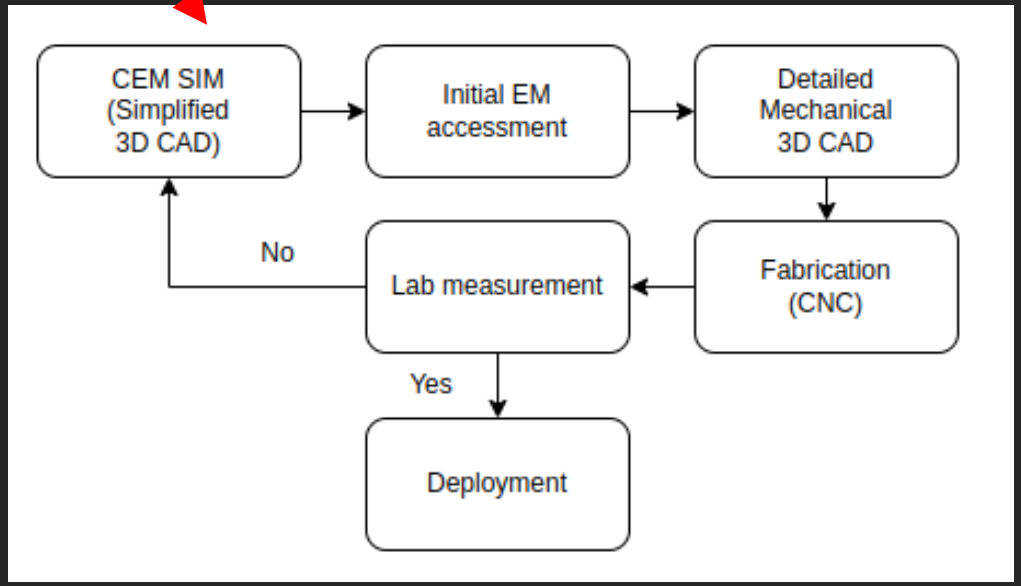
Science requirements:

- Frequency range
- Spatial resolution
- Frequency resolution
- Time resolution (how fast to record the data)
- Integration time (reduce noise)

Engineering requirements:

- Frequency range → bandwidth
- Spatial resolution → Beam shape
- Available technology
- Fabrication material cost
- Fabrication lead time
- Measurement capability/facilities





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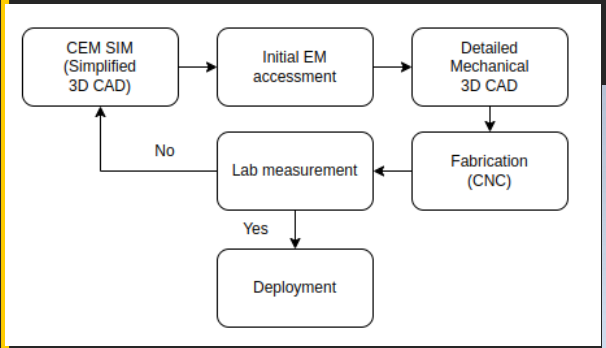
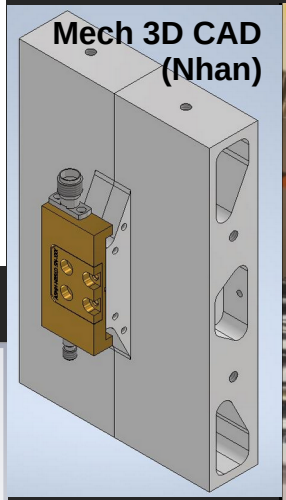
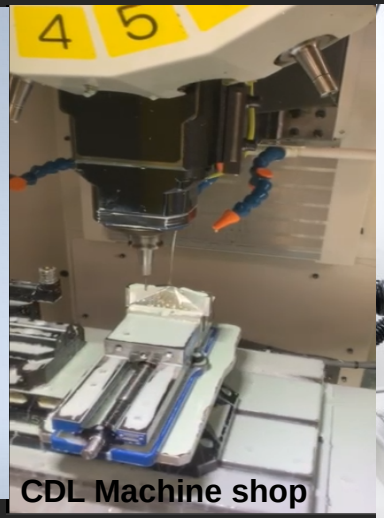
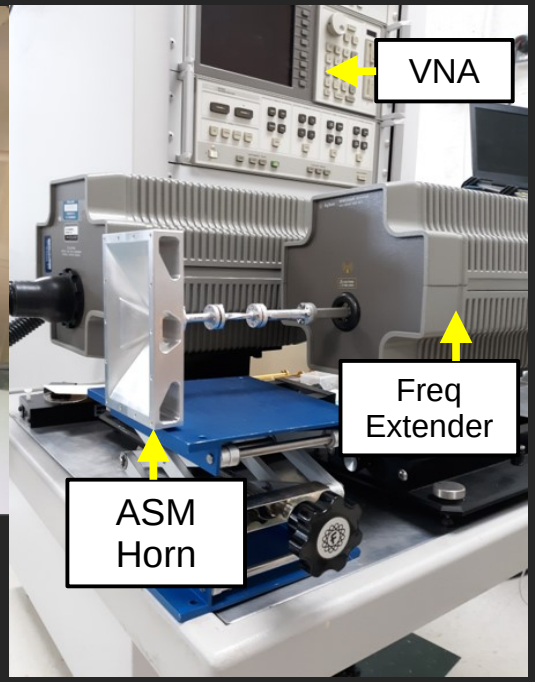
Antenna Design
Dbl ridged horn

Antenna Design Example – Double ridged Horn (16-120 GHz)

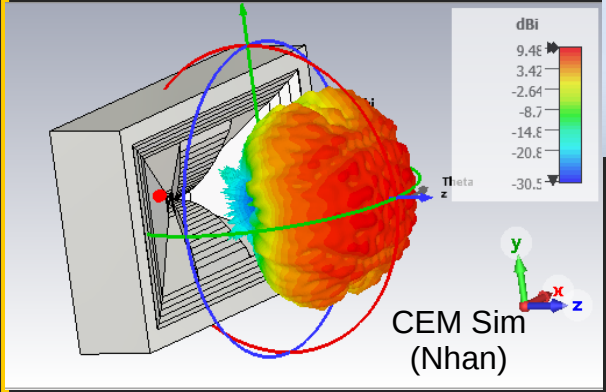








Lab test: Tod Boyd & Kevin Shoemaker



Designed by Bang Nhan (NRAO) Jan 2021
Adapted from Morgan & Boyd (2015) IEEE A&P 63:8

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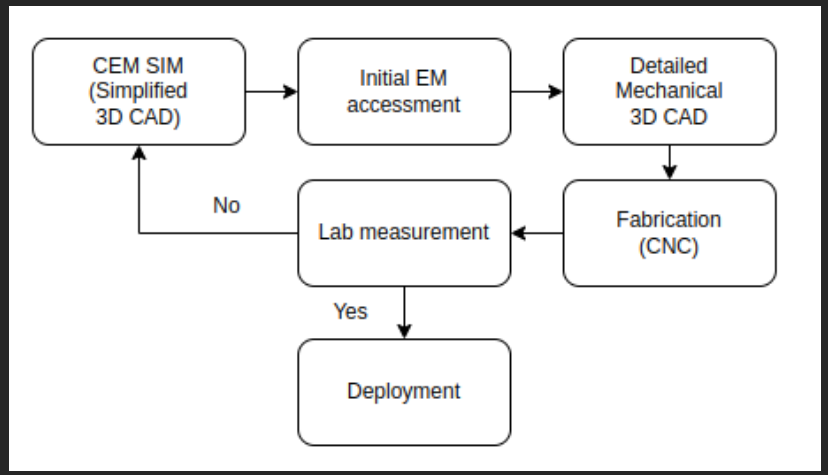
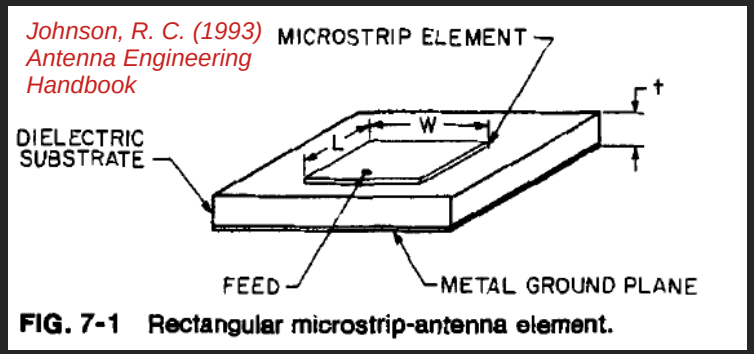
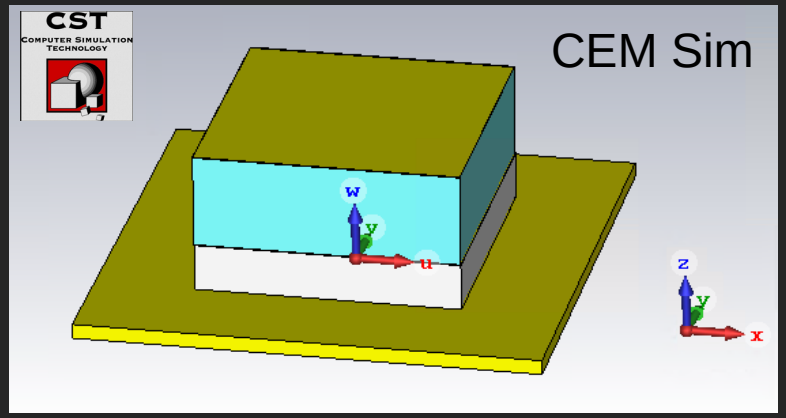
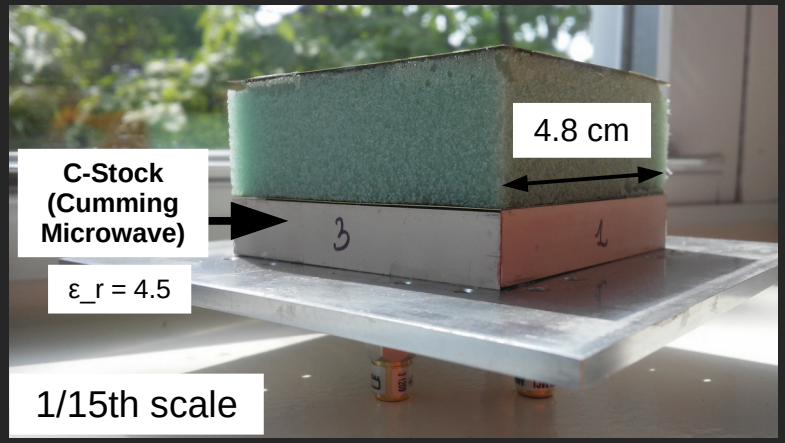
Dbl ridged horn
Patch antenna

Case study: Patch antenna (L-band centered @ ~1.4 GHz)







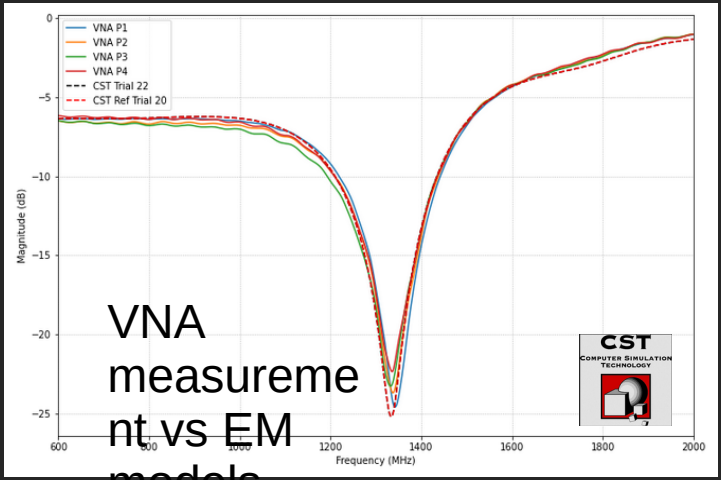


Antenna Basics
Radio Receiver
Antenna types
Maxwell's Eq.
Antenna beam
Dipole Antenna
Parabolic Dish
Smart Phone
Transmission Line
Impedance Meas.
S-parameters
Smith Chart
VNA
Antenna Design
Dbl ridged horn
Patch antenna

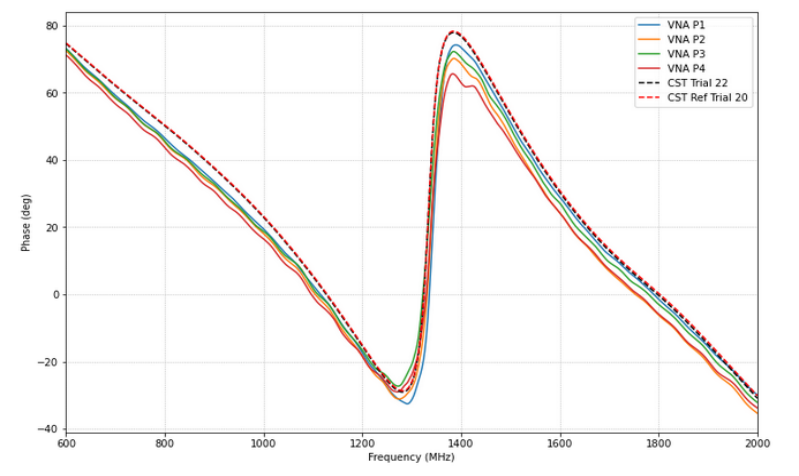
Case study: Patch (L-band)

Vector Network Analyzer (VNA)

Ant's Reflection Coefficient (S11)



VNA measurement vs EM models



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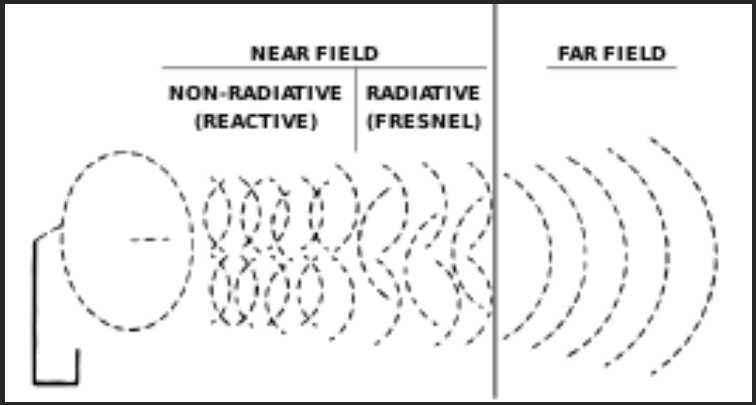
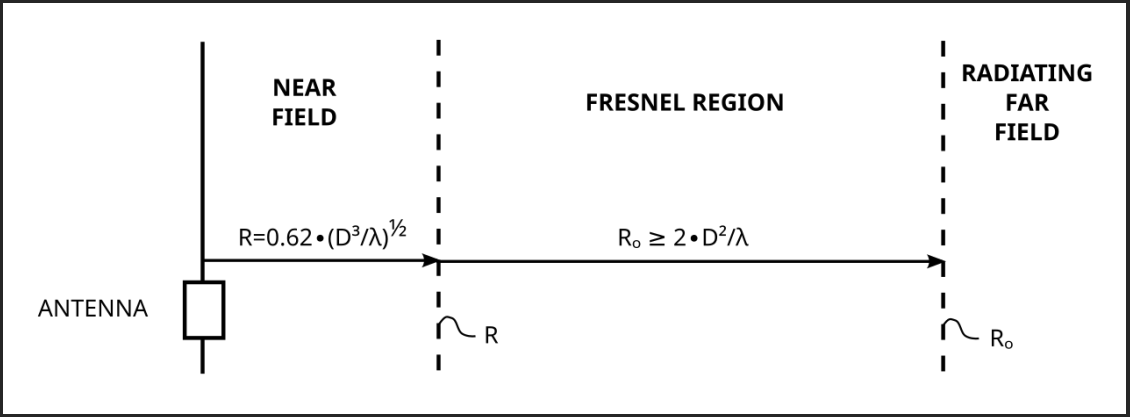
Near & Farfield

Antenna near & far fields





D: largest dimension of the antenna radiating element

Parabolic dish:
D = dish diameter

https://en.wikipedia.org/wiki/Near_and_far_field

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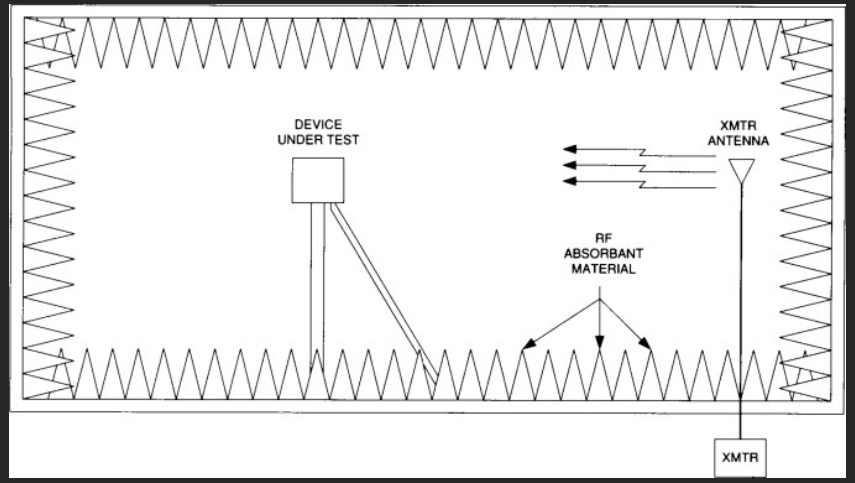
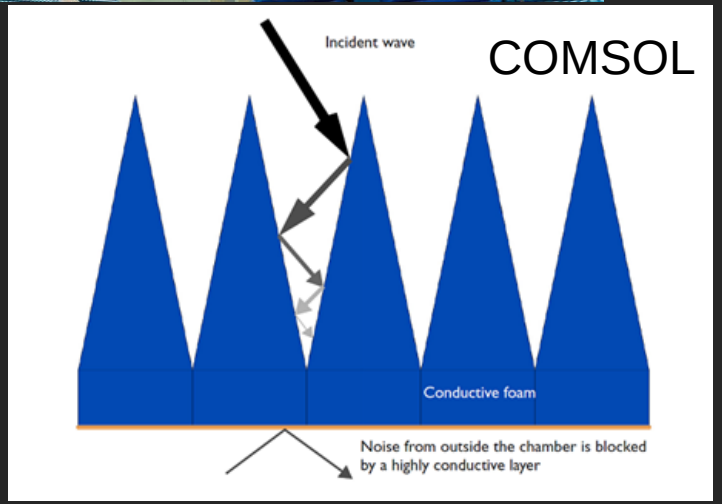
Anechoic Chamber

Conventional Antenna Beam Measurement: Anechoic Chamber





https://www.youtube.com/watch?v=tqdgsMT8vUk

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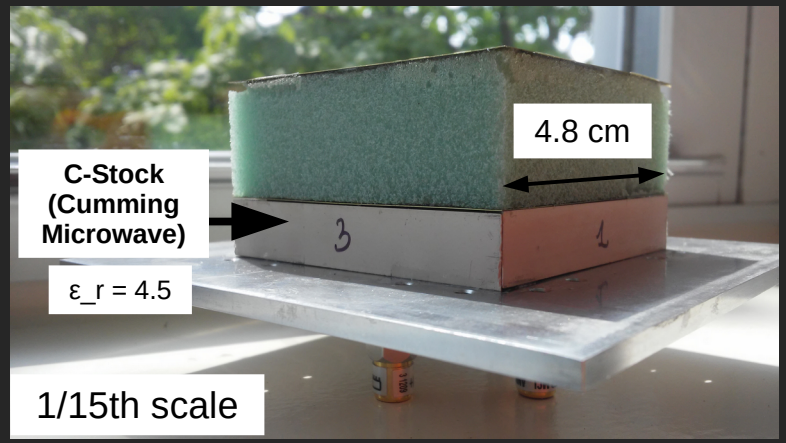
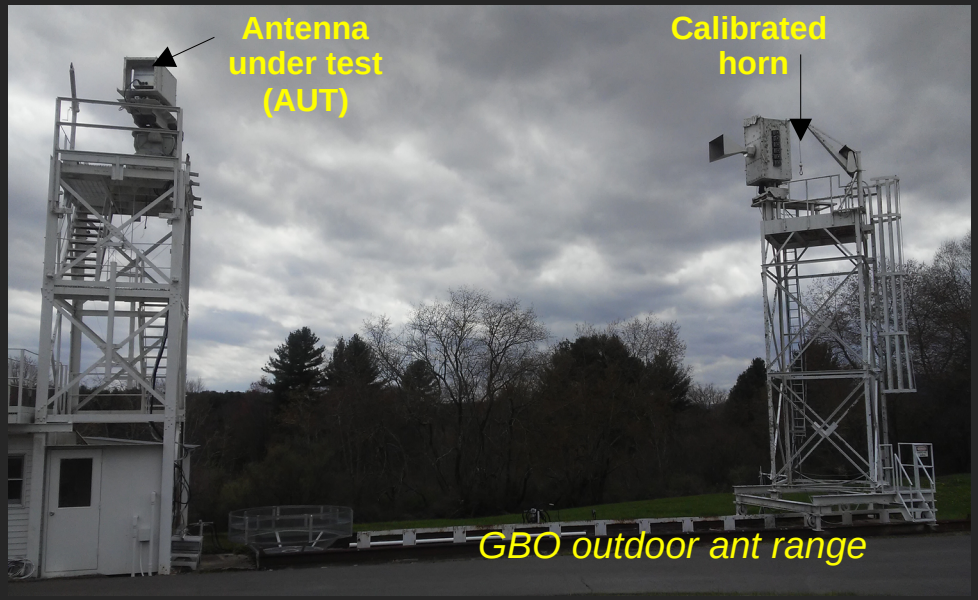
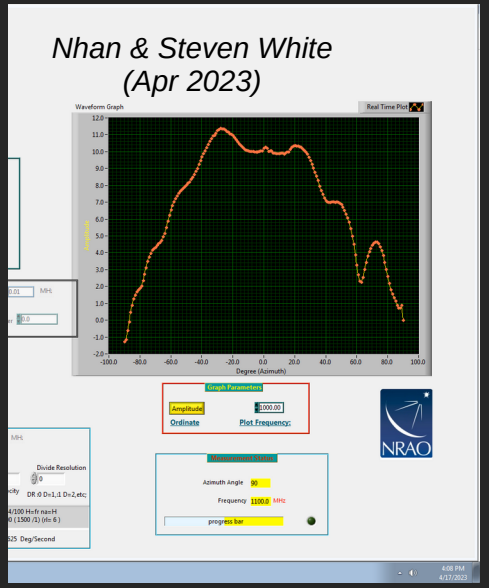
Antenna Range

Conventional Antenna Beam Measurement: Antenna Range



Rotate AUT to receive reference antenna transmission signal





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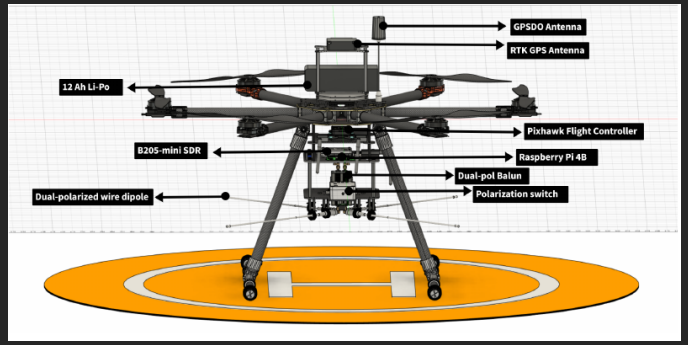
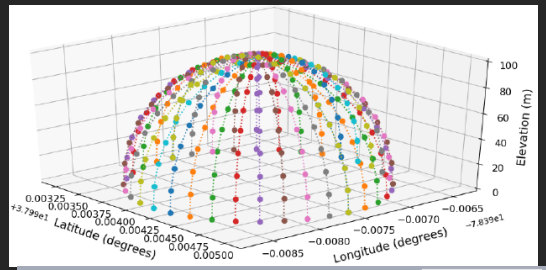
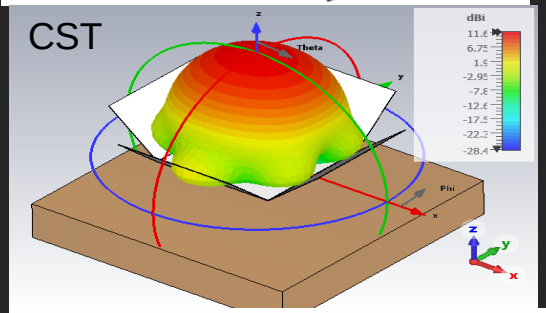
Drone SDR

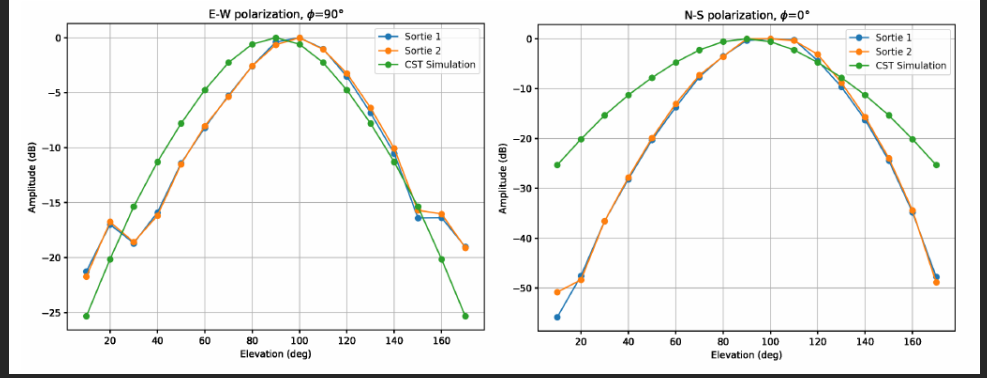
PRIAM (Precision Radio Instrument for Antenna Measurement)
Drone-based Beam Measurement System

Krishna Makhija (UVA/ECE) & Richard Bradley (NRAO/CDL)









PhD Thesis:
https://doi.org/10.18130/m9x2-da20

https://krishnamakhija.gitbook.io/priam
Demo video

Self-learning Resources

- EMViso Youtube Channel
  - Transmission Line Theory
- Antenna Theory Basics webbook
- What’s Vector Network Analyzer?