ANTENNA & TRANSMISSION LINE BASICS

WØTLM TECH DAY – OCTOBER 29, 2022

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OUTLINE

- Electromagnetic Fields
  - How do radio signals propagate (move through space)?
  - Speed of propagation and wavelength
- Antennas
  - Antenna Gain
  - Impedance
  - Radiation efficiency
  - Polarization
  - Resonance
  - Directivity and radiation patterns
  - Near Field & Far Field

OUTLINE, CONT'D

- Transmission Lines
  - Feedline Basics
  - Velocity Factor
  - Feedline Impedance
  - Smith Charts
- SWR
- Impedance Matching
  - Antenna Tuner
  - Impedance Matching Examples
- BALUNs
- Questions

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ELECTROMAGNETIC FIELDS

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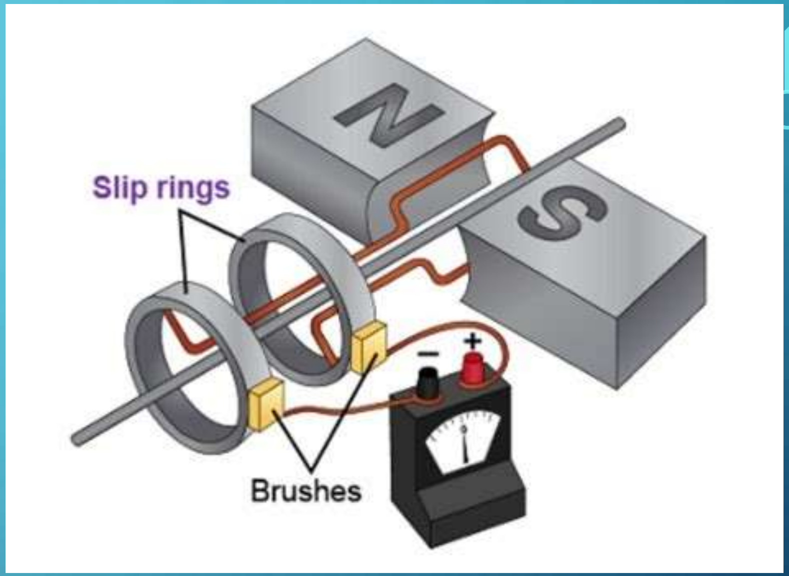
THE "MAGIC" OF RADIO WAVES

- Don't be intimidated by the next few slides. This will be a very brief discussion of the physics of radio waves (Electromagnetic (EM) Fields)
- There are two simple concepts you may remember from a high school science class
  - Moving a conductor through a magnetic field produces an electric field (voltage). This is how an electric generator or your car alternator works
  - Current in a wire creates a magnetic field. Think electromagnet
- These are the underlying principles in creating a radio (electromagnetic) wave



WHAT IS AN ELECTROMAGNETIC FIELD?

- It's a combination of an electric field (created by an electric charge (voltage)) and a magnetic field (created by electrons moving (current))
- Maxwell's equations form the foundation of classical electromagnetism, classical optics, and electric circuits providing a mathematical model for these technologies

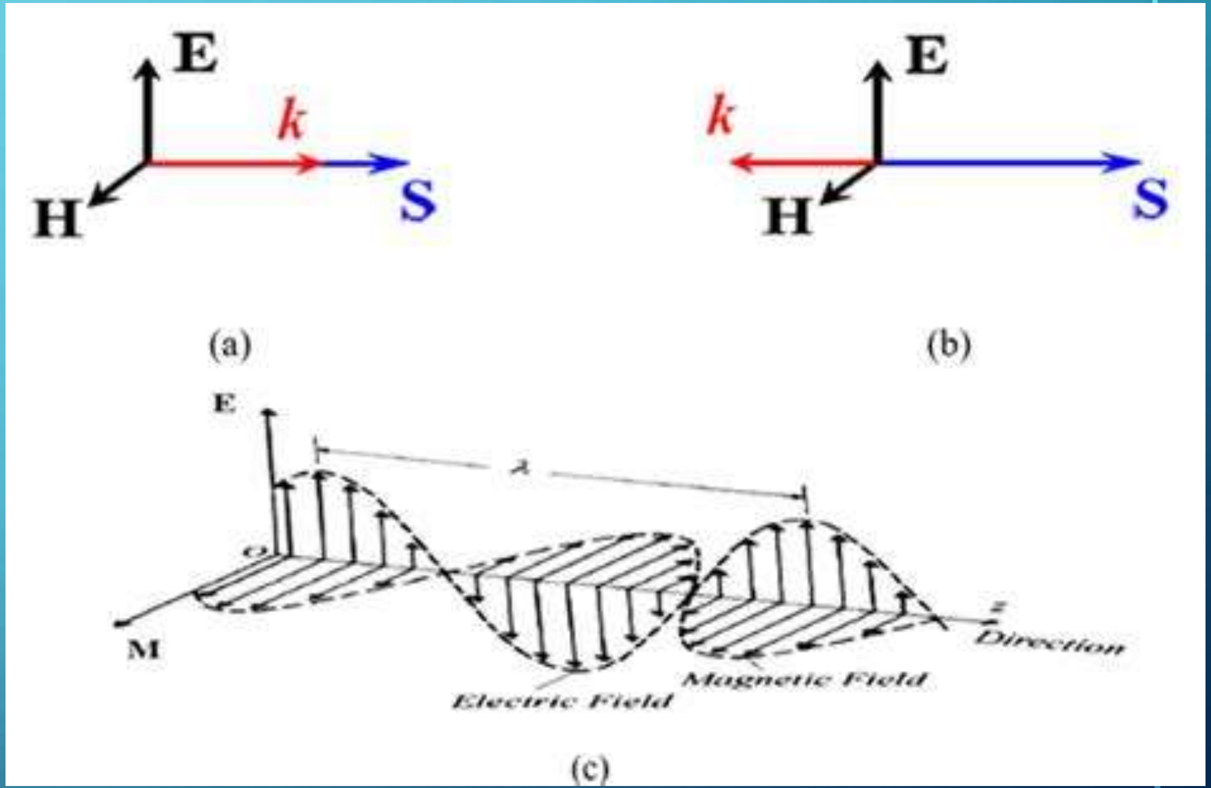
Maxwell's Equations

1.	$\nabla \cdot \mathbf{D} = \rho_V$	Gauss's Law
2.	$\nabla \cdot \mathbf{B} = 0$	Gauss's Magnetism Law
3.	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	Faraday's Law *(varying magnetic field creates an electric field)*
4.	$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$	Ampere's Law *(changing current creates a magnetic field)*

HOW DOES A SIGNAL PROPAGATE

$$\vec{E} \times \vec{H} = \vec{S}$$

- The cross product of the electric field vector (E) and the magnetic field vector (H) created by the voltage and current in the antenna results in the S (Poynting) vector. S represents the directional energy flux (the energy transfer per unit area per unit time) or power flow of an electromagnetic field
- Enough of the physics. On to practical things!



https://bigthink.com/starts-with-a-bang/secret-excellent-physicist/

WAVELENGTH

λ = C (Speed of Light in vacuum) / F (Frequency)

OR

λ = V (Wavespeed) / F (Frequency)

- λ (lambda) is the symbol for wavelength
- C = 299,792,458 meters/second (round to 3×10^8)
- Calculate wavelength of 14.275 MHz

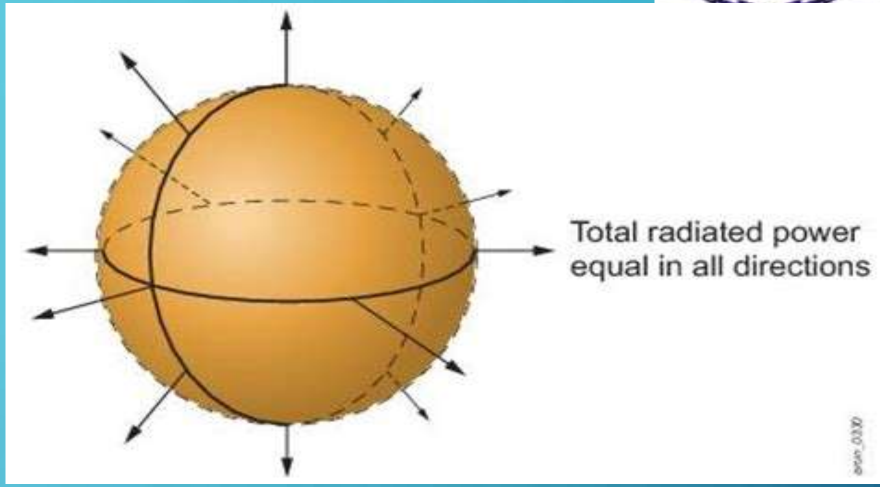
$$\lambda = 3 \times 10^8 / 1.4275 \times 10^7 = 21.01 \text{ meters (20M)}$$

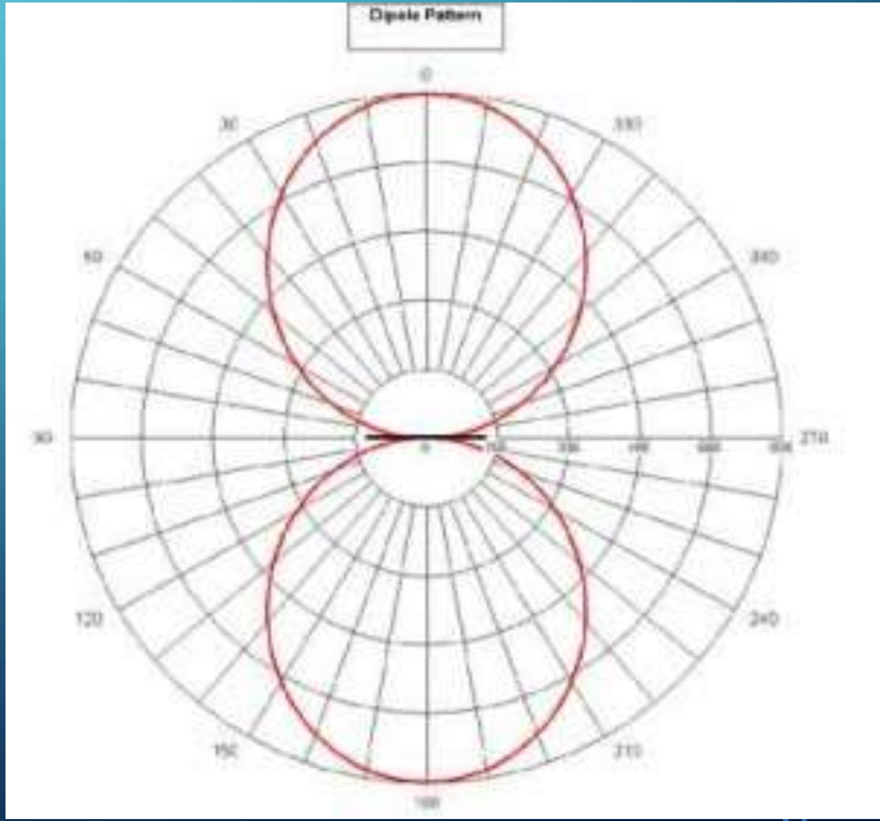
- We'll revisit this in transmission lines because the wavespeed in a coax cable is slower than the speed of light in a vacuum

ANTENNAS

ANTENNA GAIN

- Antenna gain is expressed in dBs compared to a reference antenna
  - The reference antenna is usually an isotropic antenna, a theoretical, omnidirectional antenna (Question E9A01 on Extra Class exam). Gain is expressed in dBi
  - The measured power density (watts/area) at any location the same distance from antenna would be identical
- Sometimes the reference antenna is an ideal dipole. Its gain is 2.15dBi (related to Extra Class exam questions E9A12)
  - In this case antenna gain is expressed as dBd





ANTENNA IMPEDANCE

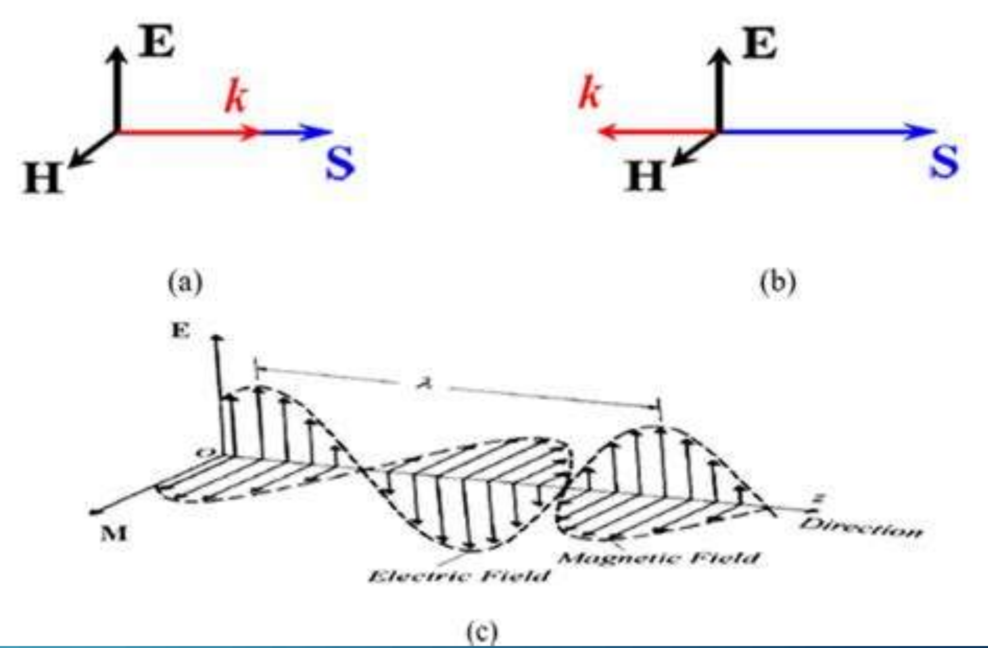
- There is a difference between Resistance and Impedance – both expressed in Ω (Ohms)
- $Z = R \pm JX$ (Resistance ± Reactance)
  - Consider $Z = 45 + J15$ (Rectangular Coordinates) (easier to use if adding vectors)
  - $\sqrt{Z} = \sqrt{(45^2 + 15^2)} = \sqrt{(2025 + 225)} = 47\ \Omega \angle 19^\circ$ (Polar Coordinates) (easier to use if multiplying vectors)
- Antenna impedance is comprised of two components
  - $R_{in} = R_R + R_L$ R_R = Radiation resistance R_L = Loss resistance (Ohmic)
  - Radiation resistance
    - Equal to the total Radiated power / I_{RMS}^2 (Average current at feedpoint of antenna) $R = P / I^2$
    - Is equal to the value of resistance that would dissipate the same amount of power as that radiated from antenna (Extra Class exam question E9A03)
  - Loss (Ohmic) resistance
    - Feedline Dielectric
    - Ground Loss
  - Short antennas have low radiation resistance resulting in low efficiency (Related to Extra Class exam question E9A04)

RADIATION EFFICIENCY

- Radiation efficiency of an antenna is a ratio of the power delivered to the antenna relative to the power radiated from the antenna (Extra Class exam question E9A09)
- Antenna losses are typically due to
  - Conduction losses due to conductivity of the metal that forms the antenna
  - Dielectric losses due to conductivity of a dielectric material near the antenna
  - Impedance mismatch losses (VSWR)
  - Low soil conductivity (hence need for radials) (Extra Class exam question E9A11)

POLARIZATION

- Remember our previous diagram
- Polarization is the pattern the E-field traces out while propagating
- A vertical antenna, as the name implies, is vertically polarized
- A dipole (horizontal to the ground) is horizontally polarized
- An antenna can be circular polarized
  - Eliminates the fading experienced when a satellite is tumbling
  - Arrange two Yagis perpendicular to each other with the driven elements at the same point on the boom fed 90 degrees out of phase. (Extra Class exam question E9D02)



ANTENNA RESONANCE

- An antenna (or any complex circuit) is resonant when the imaginary (reactive) component of the impedance is zero

$$Z = R \pm jX \quad \text{where } X=0$$

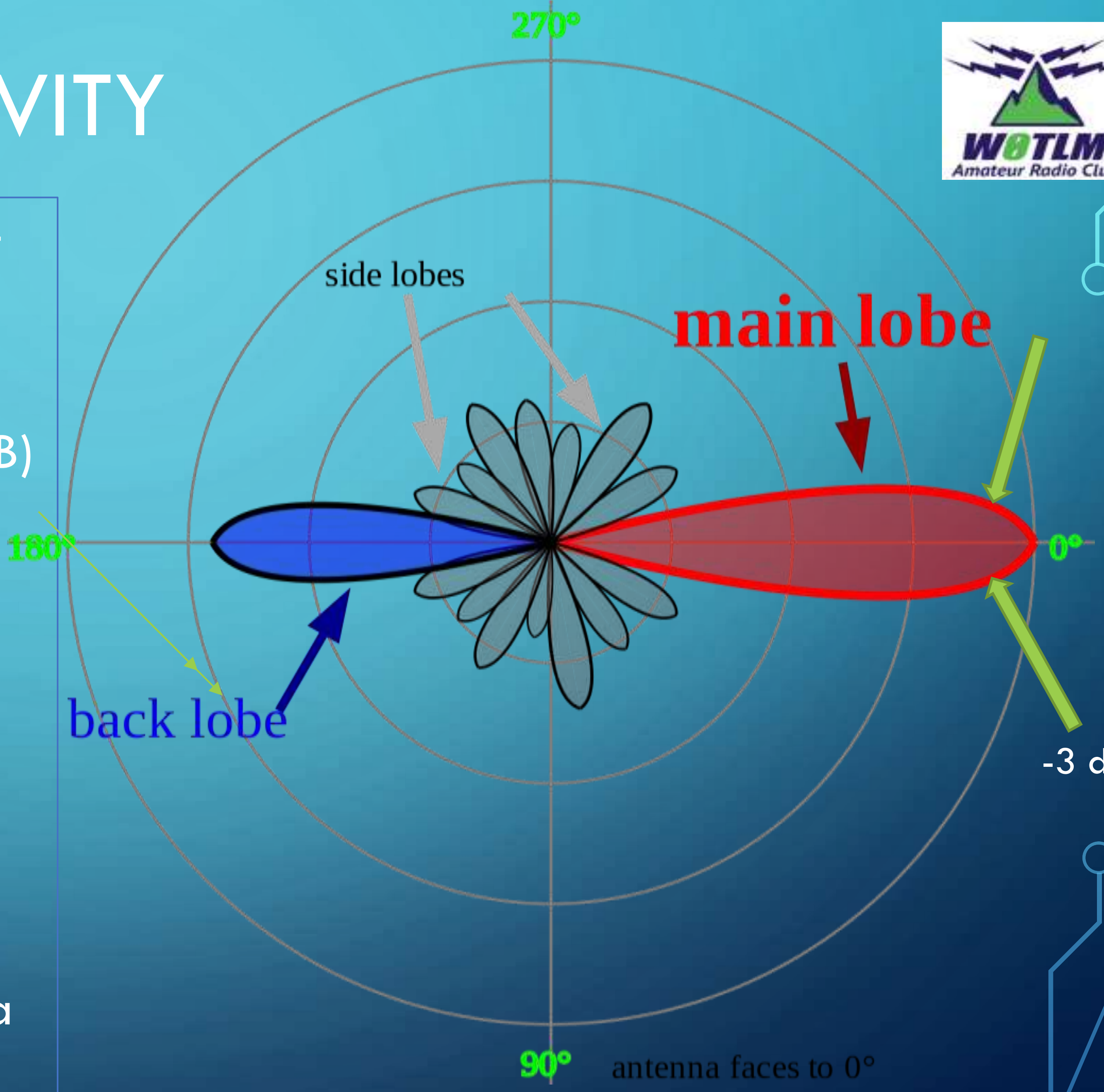
- Question: Does an antenna need to be resonant to radiate?

NO!

- A resonant antenna does not necessarily have a low SWR
- It is more important to match impedances
  - Transmitters may reduce power or be damaged by high SWR
  - More on this later

ANTENNA DIRECTIVITY

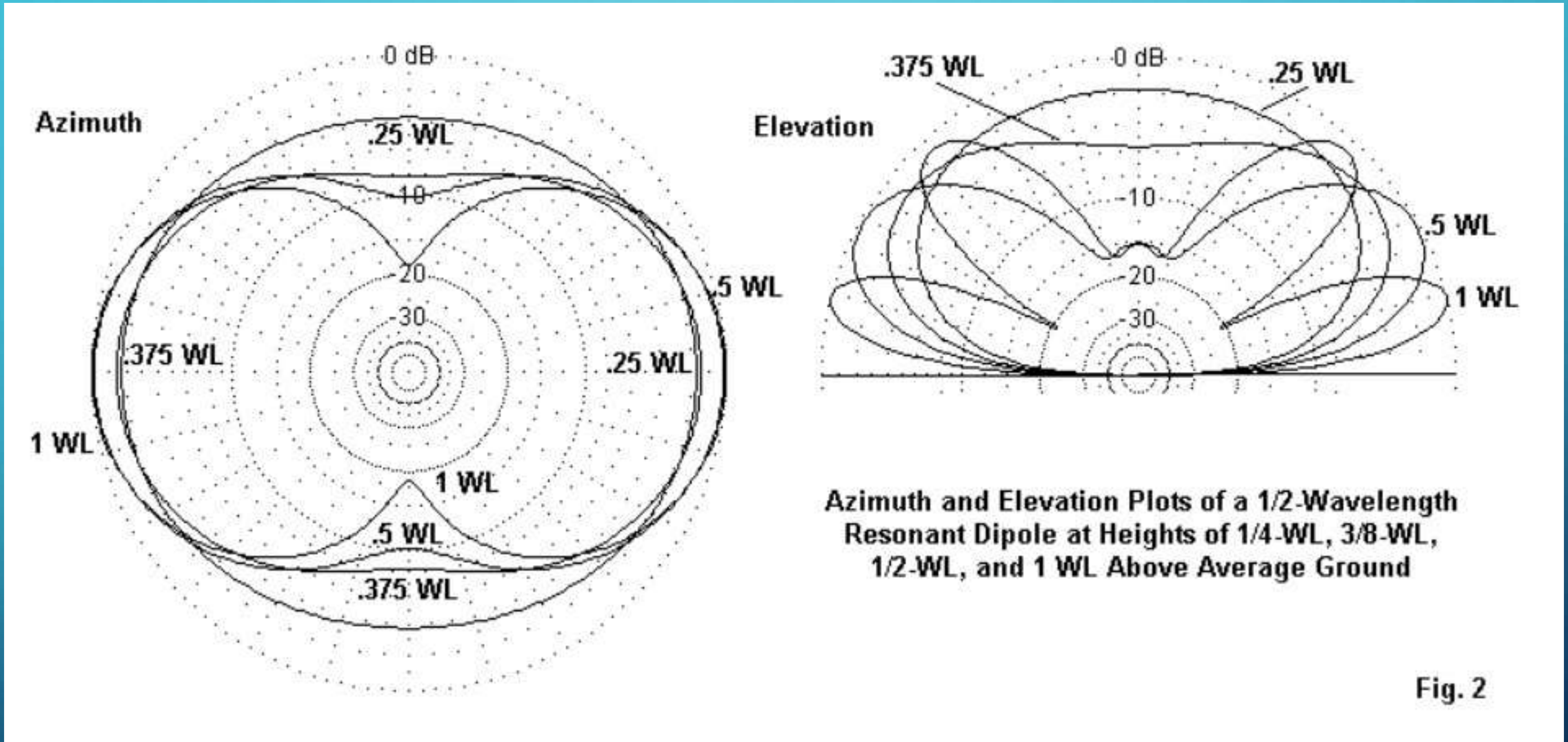
- **Front-to-Back ratio** equals amount of power in desired direction divided by power directed in opposite direction (expressed in dB)
- **Front-to-Side ratio** equals amount of power in desired direction divided by power off side lobe
- **Beam width** is defined as the number of degrees between –3dB on the main lobe
- Questions E9B01 – E9B03 on Extra Class exam



EFFECTIVE RADIATED POWER (ERP)

- ERP is the actual power radiated from the antenna taking into account all gains and losses in the system
  - ERP = Transmitter Output Power – Feedline and Matching system loss + Antenna gain
  - Question E9A13 in Extra Class exam

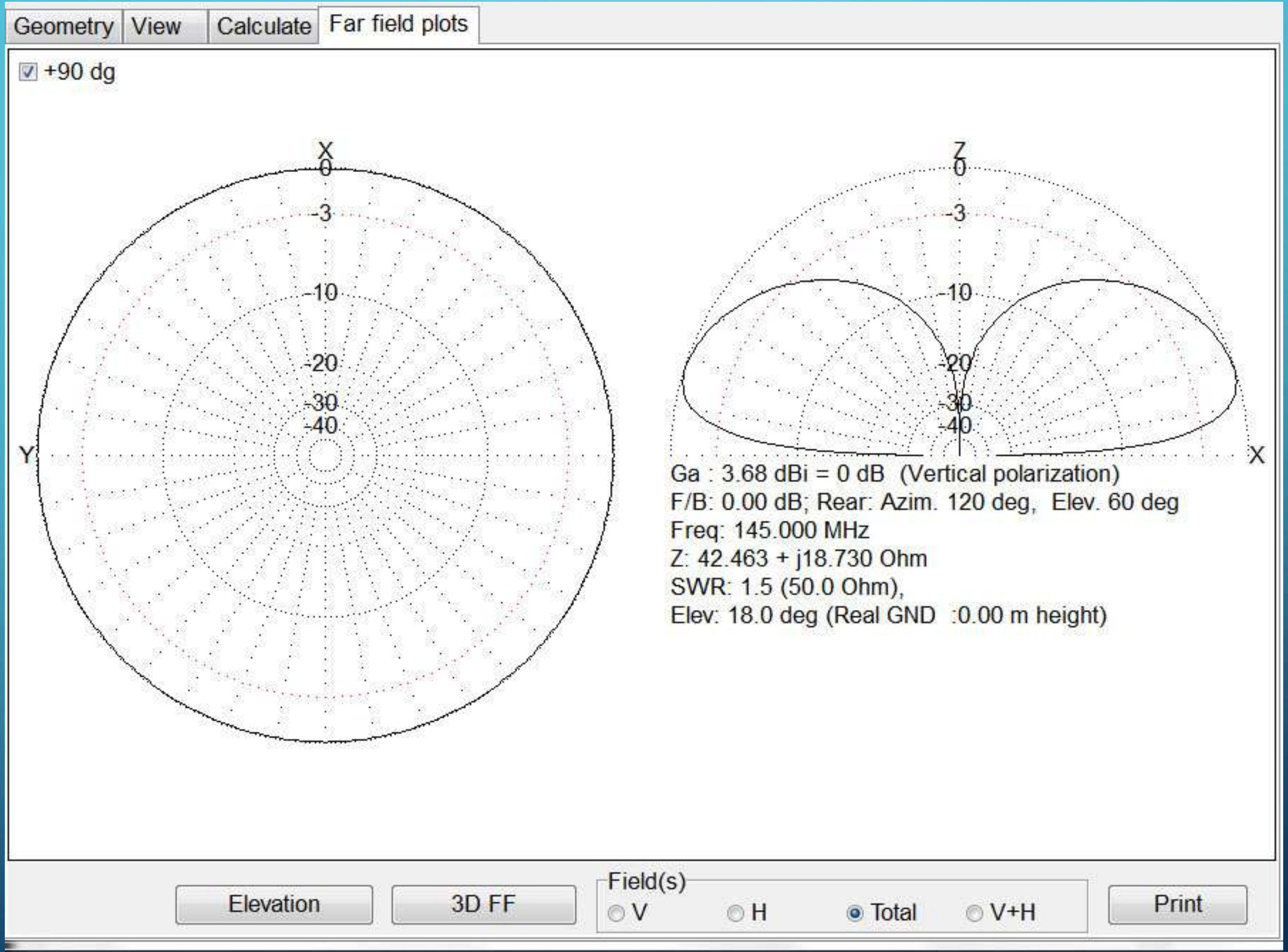
DIPOLE RADIATION PATTERN



https://www.zl2al.com/1636/hf-multiband-antennas/

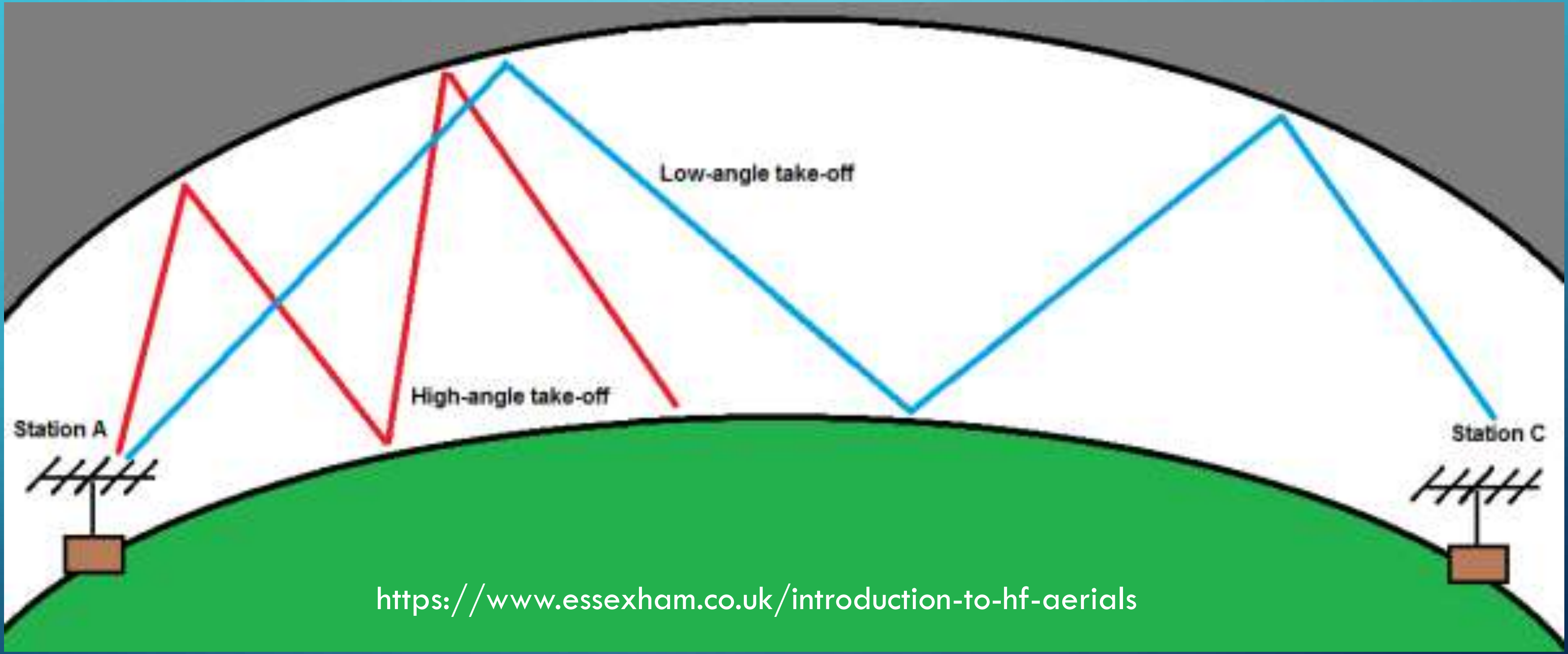
- Questions E9B05 – 06 on Extra Class exam

¼ WAVE VERTICAL GROUND PLANE RADIATION PATTERN



https://www.engineeringradio.us/blog/2015/07/the-emergency-fm-replacement-antenna/

TAKEOFF ANGLE IMPACT



- Ground mounted vertical antennas typically have a lower takeoff angle than a horizontal antenna
- Height above ground affects takeoff angle of horizontally polarized antennas

NEAR FIELD & FAR FIELD

- Far field is the region in which the field acts as "normal" electromagnetic radiation. The azimuth and elevation radiation patterns apply. (Extra Class exam question E9B08)
- Near field refers to regions near the antenna where the propagation of electromagnetic waves is interfered with.
- Radiated power intensity is subject to an inverse-square law. Doubling the distance results in a ¼ power decrease. This applies to antenna safety covered later today.

TRANSMISSION (FEED) LINES

WE'RE GOING TO USE TRANSMISSION LINE AND FEEDLINE INTERCHANGEABLY

FEEDLINE BASICS

- The feedline (or transmission line) is the RF power conduit from radio to antenna
- No feedlines are perfect. It will have losses (rated in DB/length)
- A feedline has a characteristic impedance (measured in ohms)
- Electromagnetic waves traveling on transmission lines such travel more slowly than they do in free space. The ratio of this speed to the speed of light is known as velocity factor

Coaxial Cable – RG-8X

Ladder Line (aka Twin Lead

Coaxial Cable – Hardline

VELOCITY FACTOR

- Calculate length of ¼ λ RG8U foam coax cable at 14.275 MHz
  - Velocity factor (VF) of RG8U foam = .78
  - Velocity factor of RG213U poly = .66
  - **1/4λ = 3 x 10^8 /4 x 1.4275 x 10^7 = 5.3 meters (20M) in free space**
  - 1/4λ (in coax) = ¼λ (free space) x VF = 5.3m x .78 = 4.1m
- This becomes important if phasing antennas or using lengths of coax for tuning (impedance matching)

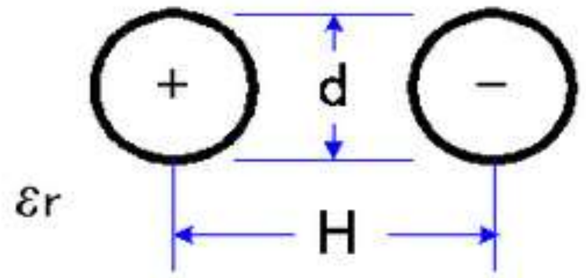
FEEDLINE IMPEDANCE CHARACTERISTICS

- First – Characteristic Impedance
  - Common Coax – 50 Ω (RG-58, RG-8, RG-213) or 75 Ω (RG-6 (Cable TV coax)
  - Ladder Line – 300 Ω or 450 Ω
  - Build your own ladder line?

2. Balanced two-wire line

Parameters:

εr		
H		**mm**
d		**mm**



$$Z_0 = \frac{120}{\sqrt{\varepsilon_r}} \ln\left(\frac{2H}{d}\right)$$

Calculation Results:

Z0		**ohms**

εr (Air) ~ 1
Relative Permittivity

[1] K. Chang, "Handbook of Microwave and Optical Components", Vol 1,John Wiley & Sons, New York, p. 8, 1989.

MORE FEEDLINE CHARACTERISTICS

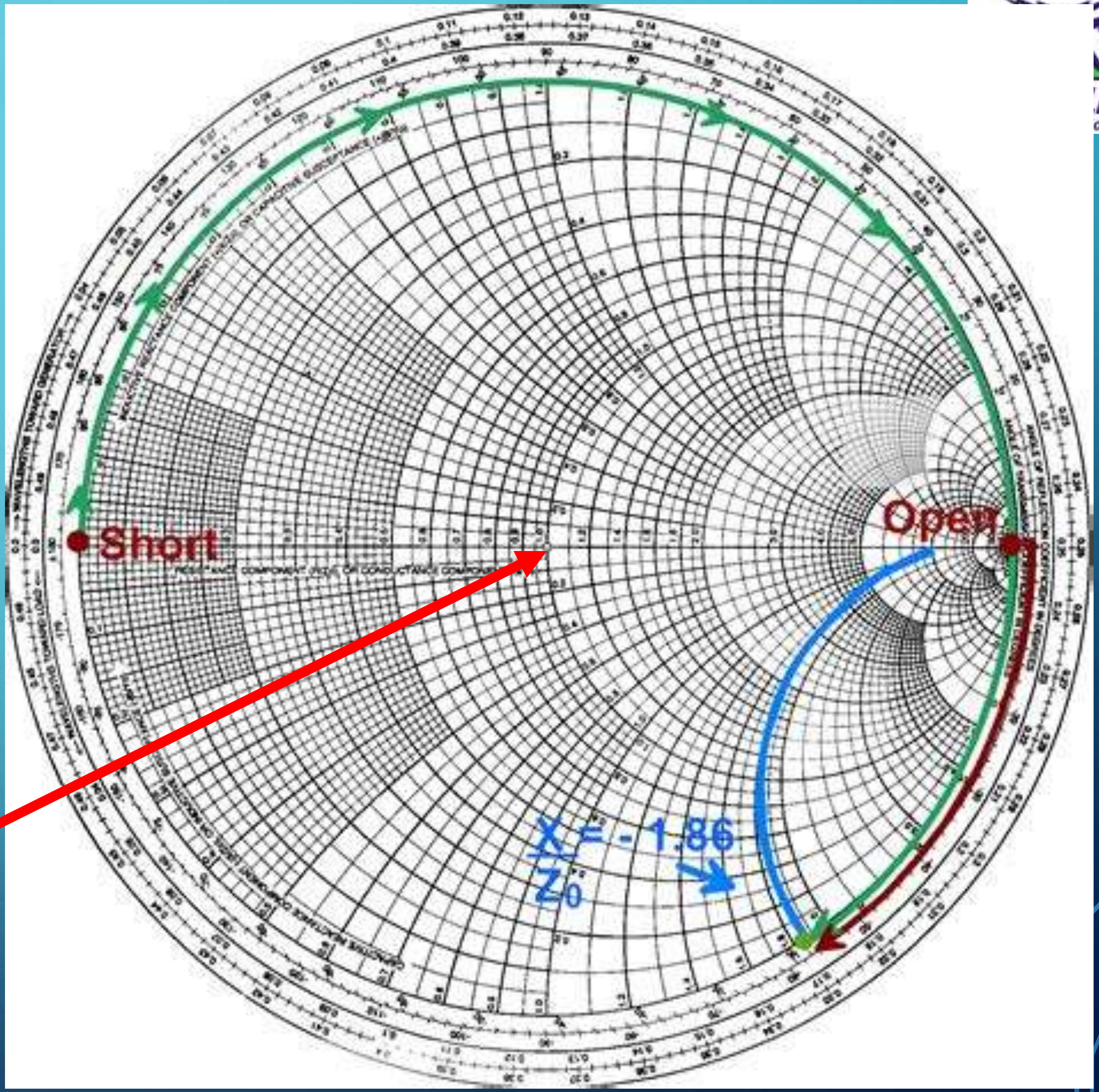
- Here's where it gets a little weird!
- Unless your antenna impedance is perfectly resistive (R + j0 Ω) and matches antenna impedance the impedance seen by your transmitter depends on the length of the feedline
- Example:

What is the impedance of a length of coax ¼ λ long if the far end is open circuit?

SMITH CHARTS

- Answer: 0 Ω Now you may ask how could that be?
- The feedline is acting as a transformer (an impedance transformation) best illustrated on a Smith Chart
- Impedance repeats every half wavelength around the chart (halfway around the chart is ¼ λ)

50 Ω pt (normalized to 1)
Note that if load is 50 Ω and feedline is 50 Ω any length feedline remains at 50



STANDING WAVE RATIO

SWR - VSWR – ISWR

THEY'RE ALL THE SAME, JUST MEASURED DIFFERENTLY

SWR – WHAT IS IT?

- SWR is a measure of the impedance matching of loads to the characteristic impedance of a transmission line
- SWR is usually thought of in terms of the maximum and minimum AC voltages along the transmission line, hence Voltage SWR (VSWR). SWR meters typically measure forward and reflected voltage
- Γ (Gamma) is the reflection coefficient
- SWR = VSWR = ISWR
- There are maximums and minimums along the transmission line because an impedance mismatch causes reflections of the signal
- A high SWR means a greater impedance mismatch

$$\mathrm{SWR} = \frac{|V_{\max}|}{|V_{\min}|} = \frac{1+|\Gamma|}{1-|\Gamma|}$$

IMPLICATIONS OF HIGH SWR

- May not be what you think!
- All of the reflected power is eventually transmitted because it is re-reflected back from the transmitter (except for losses in the feedline)
- Signal loss in feedline is dependent on feedline attenuation. At HF this may be insignificant. At VHF and UHF it is more likely problematic
- 1 S-unit is a 6 dB voltage difference (equates to a 3 dB power difference).
- From the chart this results from a 5:1 SWR
  - But this is probably not a healthy situation for your transmitter or amplifier

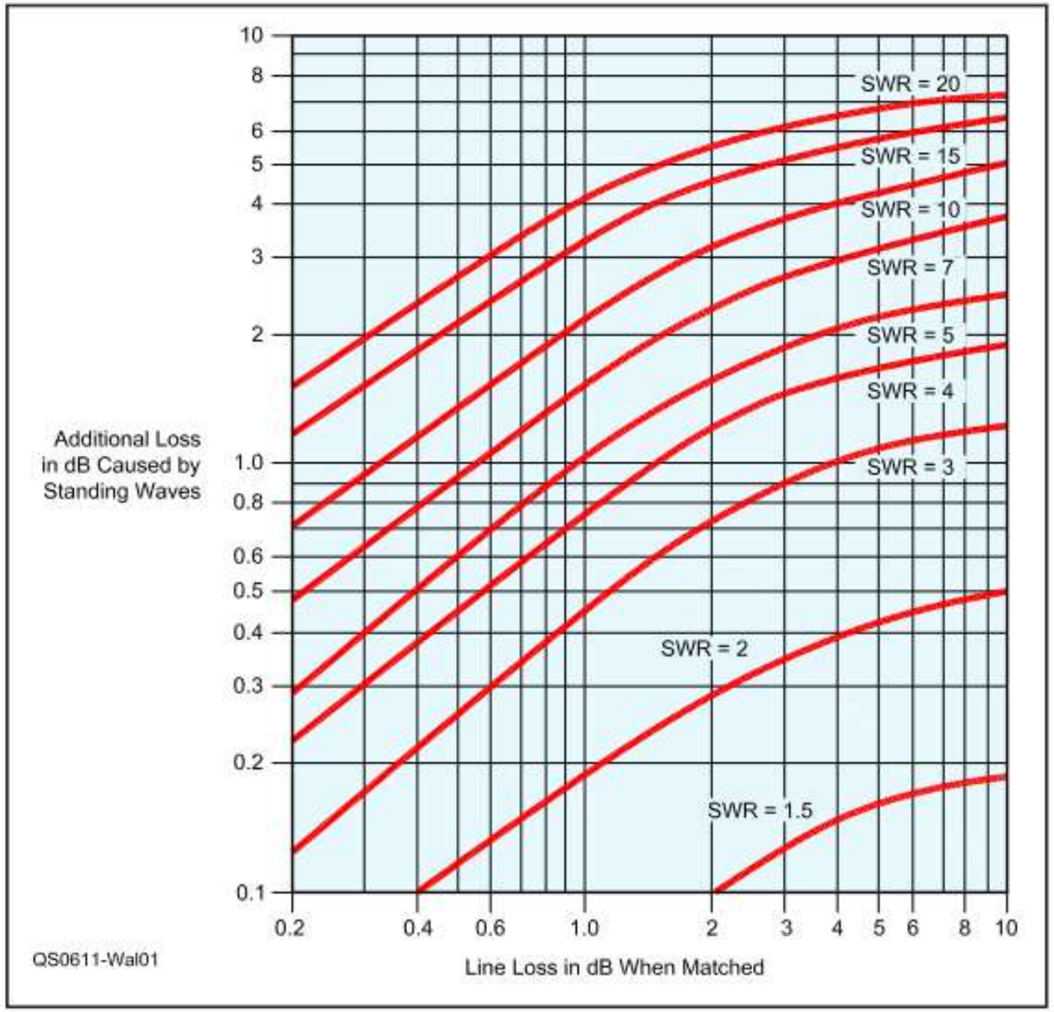
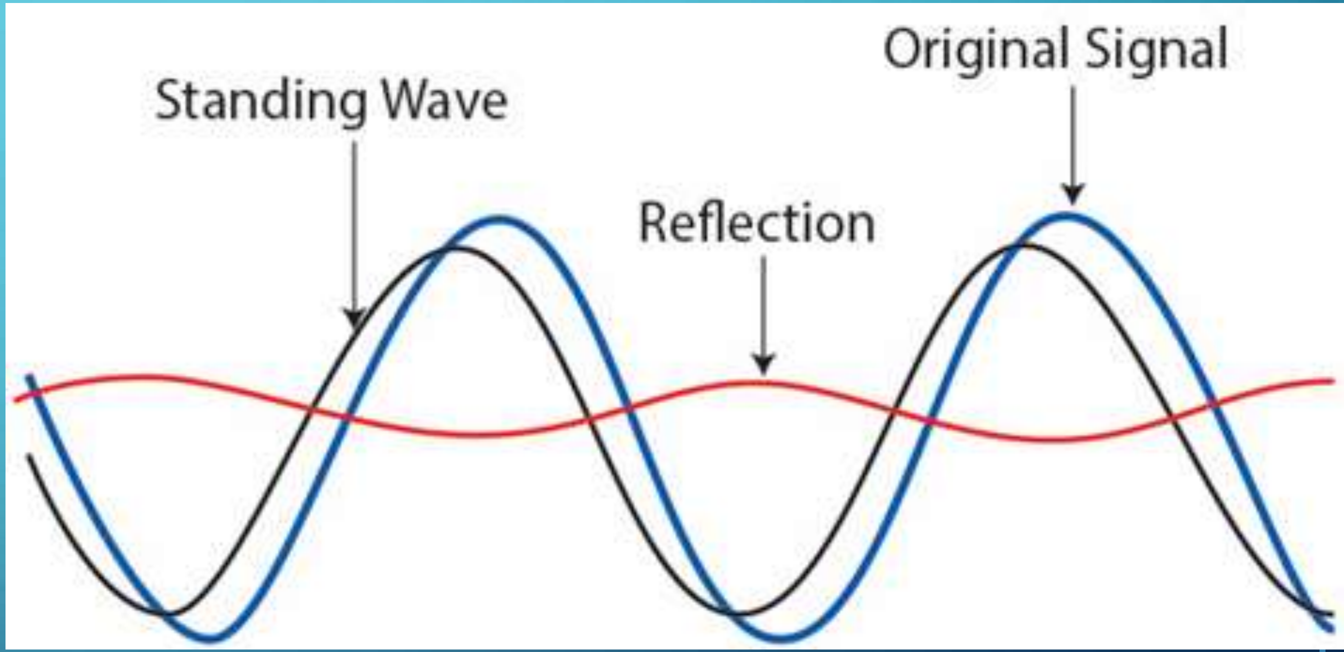


Figure 1 — A graph showing the additional loss in a transmission line due to SWR higher than 1:1.

From November 2006 QST © ARRL

VSWR ILLUSTRATION

- The reflection is out of phase with original signal because the load impedance is complex (has either inductive or capacitive element)

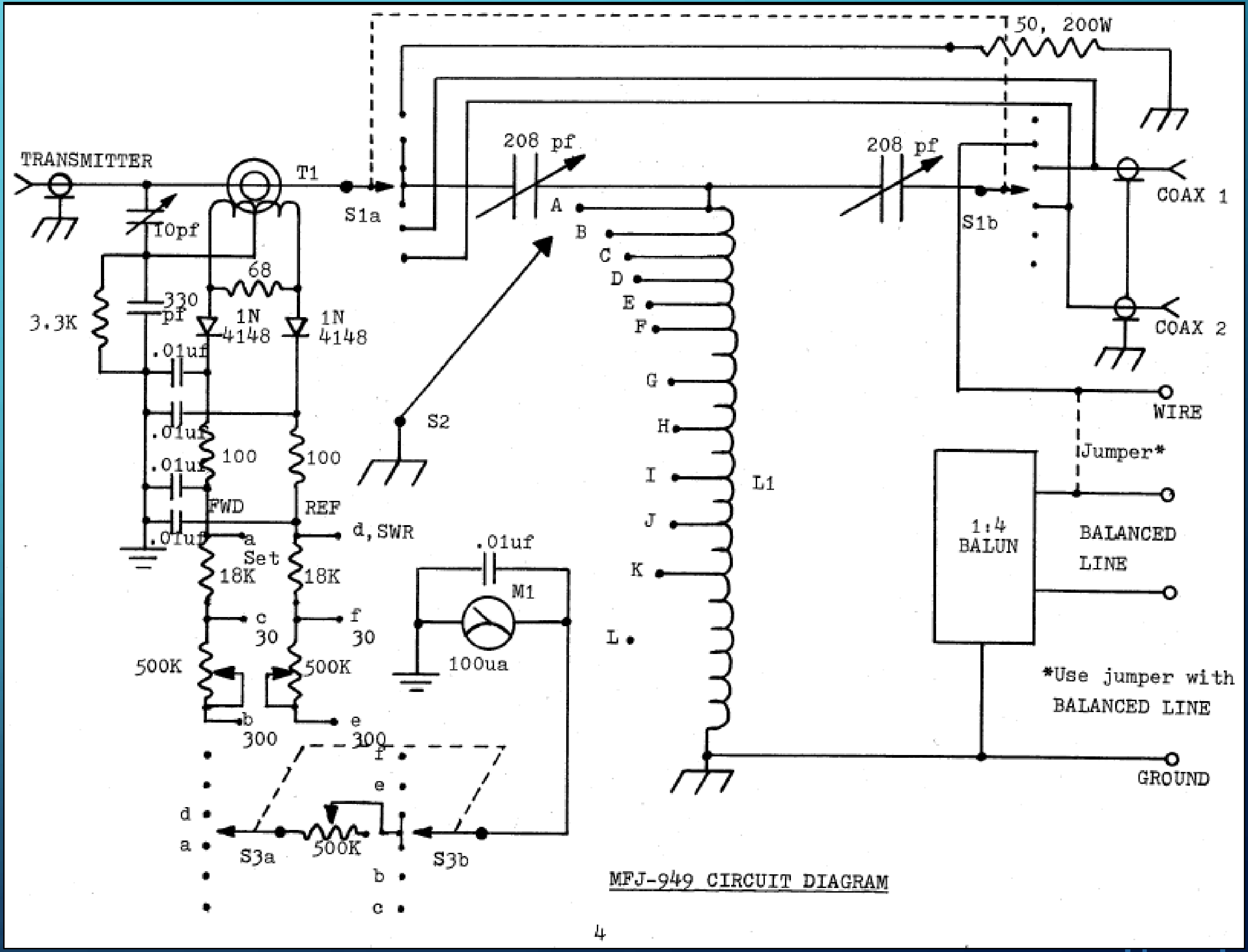


IMPEDANCE MATCHING

SMITH CHARTS, TUNERS, BALUNS, UNUNS

ANTENNA TUNERS (AKA TRANSMATCH)

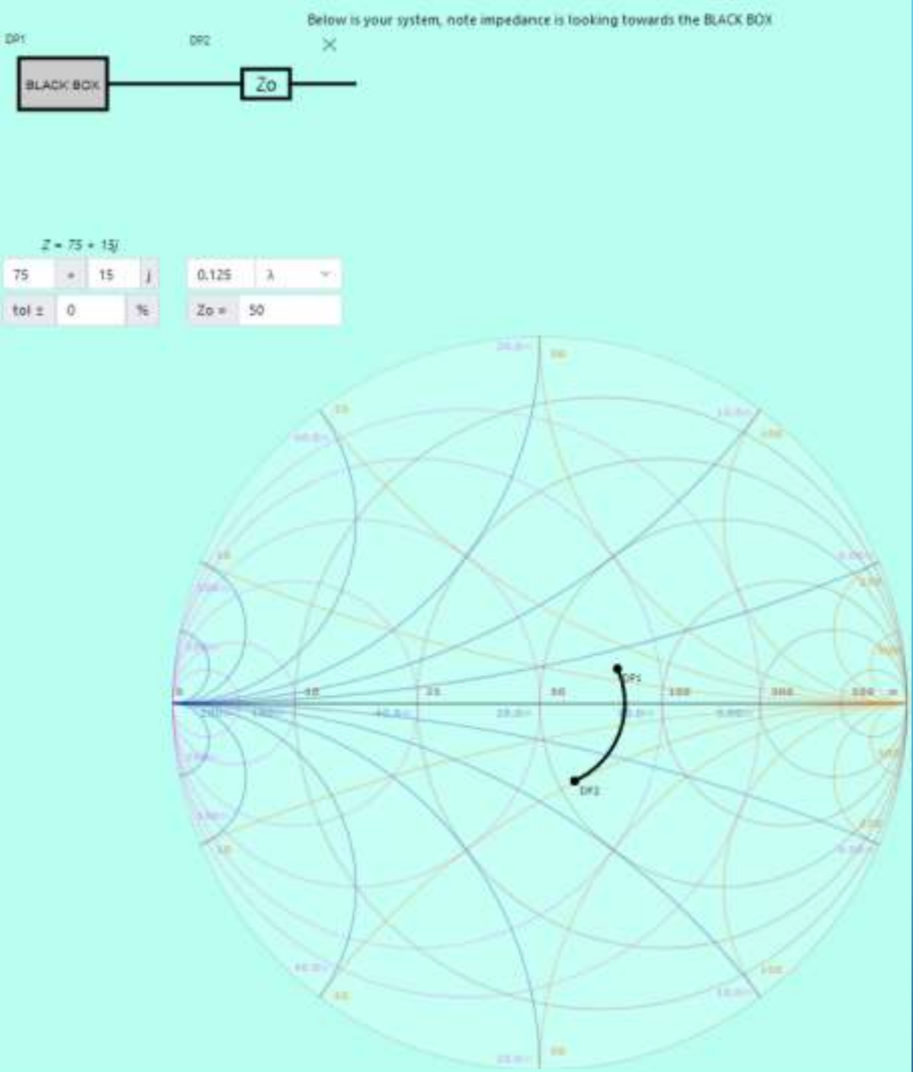
- The good news is that you don't need to do the math
- Switches, knobs, and dials can greatly simplify things



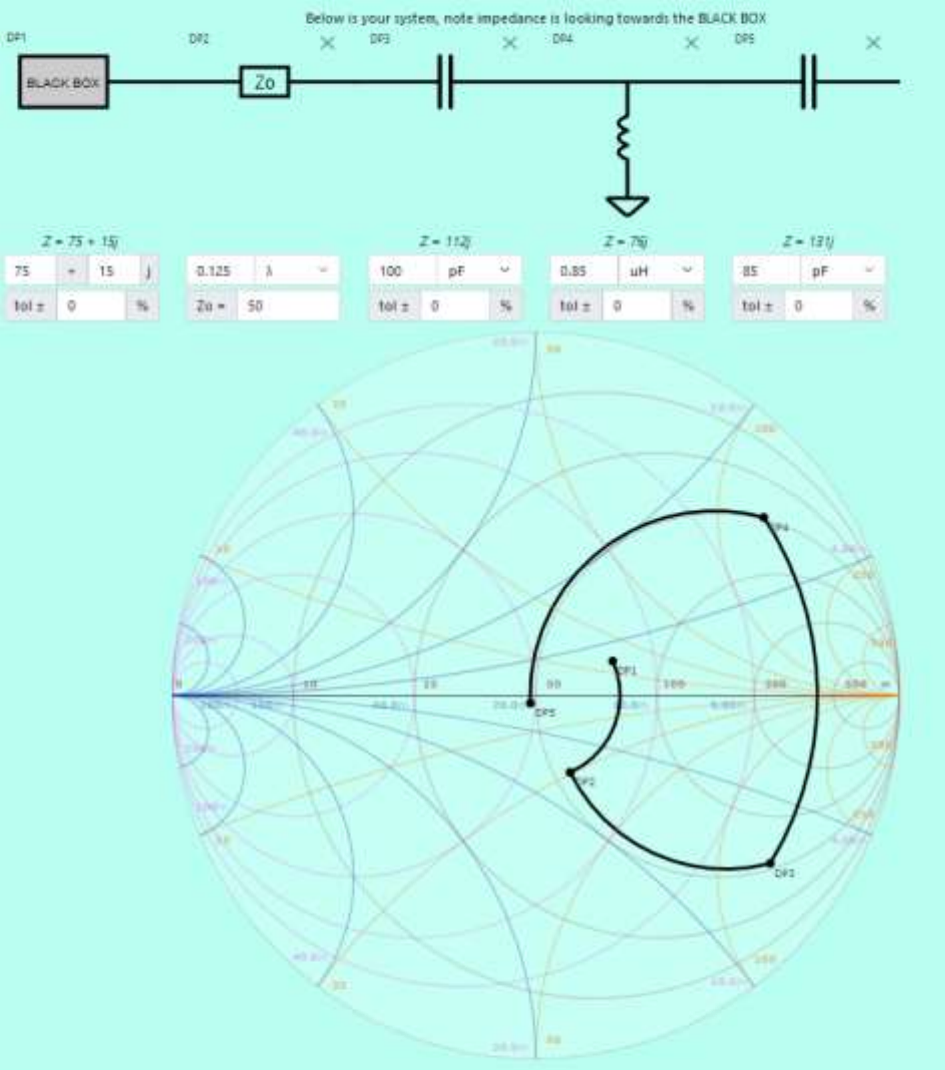
IMPEDANCE MATCHING – EXAMPLE

- $Z_T = 50\ \Omega$ (Transmission line characteristic impedance)
- $Z_L = 75 + j15\ \Omega$ (Antenna (Load) impedance)
- What load is presented to transmitter if feedline is 1/8 λ?
- And what is the VSWR?
- We'll be looking at what happens in an antenna tuner
- Source for Smith Chart: https://www.will-kelsey.com/smith_chart/
- Don't worry that you need to fully understand the Smith Chart but it is a great illustration of what is happening in your antenna and feedline system

DETERMINE LOAD SHOWN TO TRANSMITTER THEN TUNED

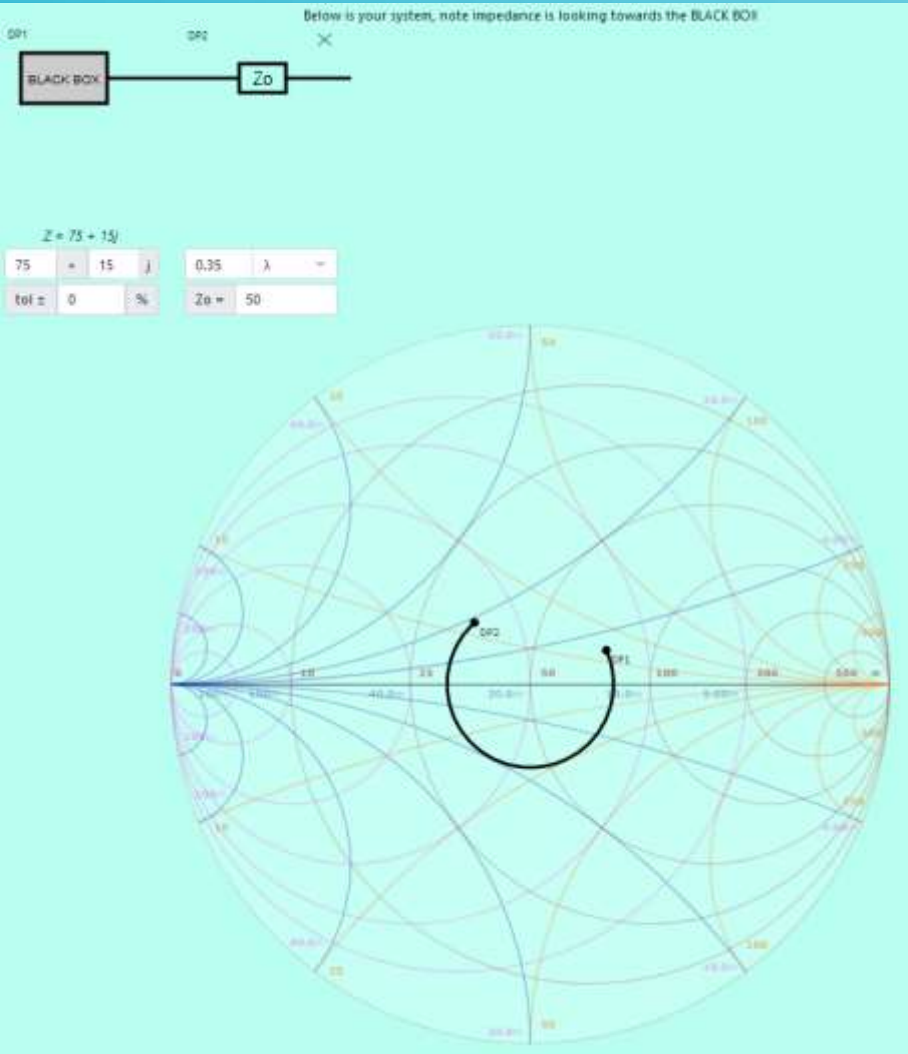


Impedance	54.7 - 24.5j
Reflection Coefficient	0.0946 - 0.211j
VSWR	1.60

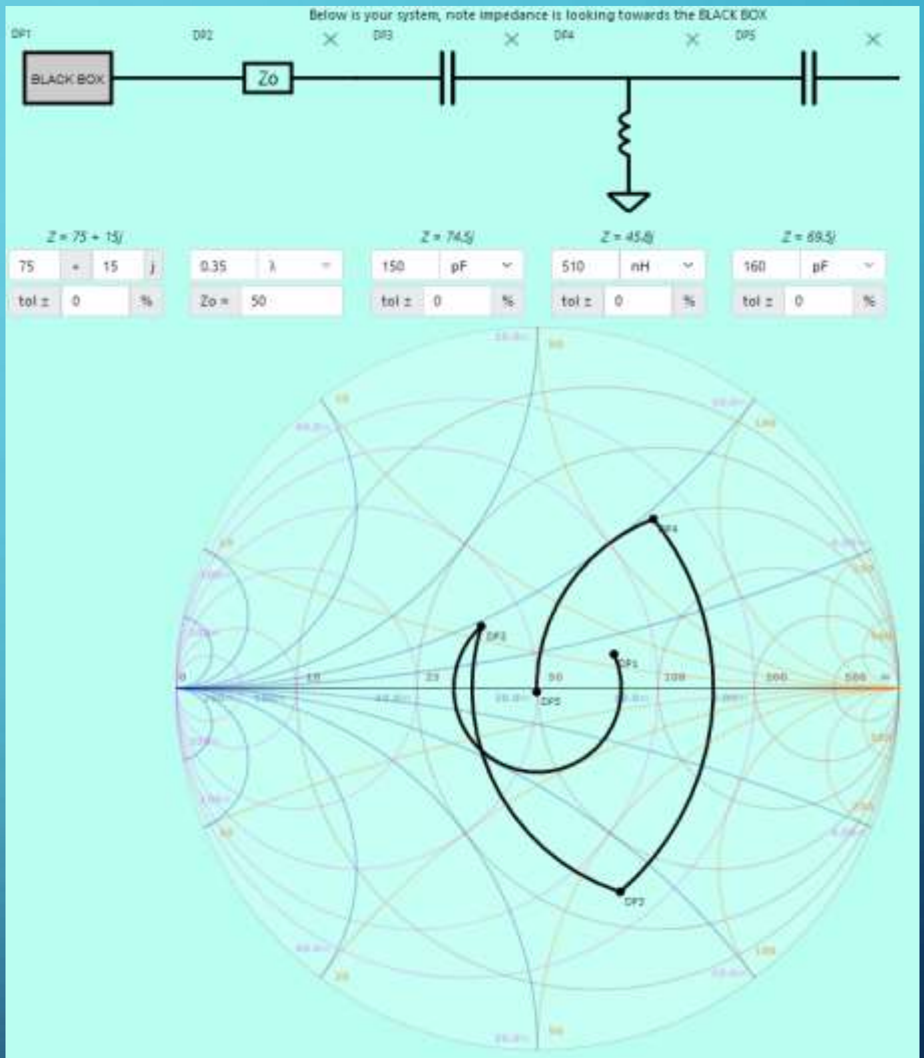


Impedance	48.5 - 2.04j
Reflection Coefficient	-0.0149 - 0.0210j
VSWR	1.05

CHANGE FEEDLINE LENGTH AND RETUNE

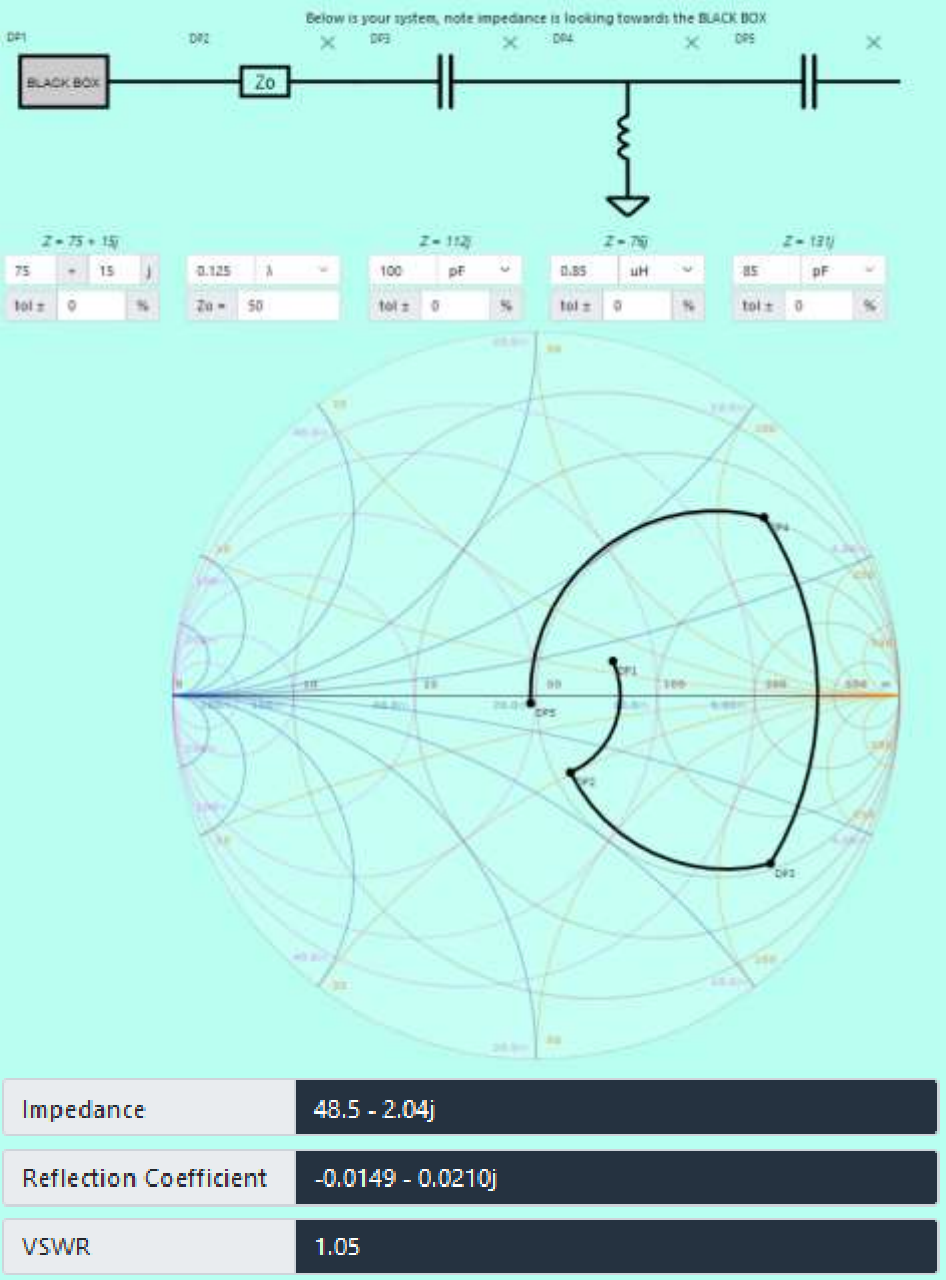


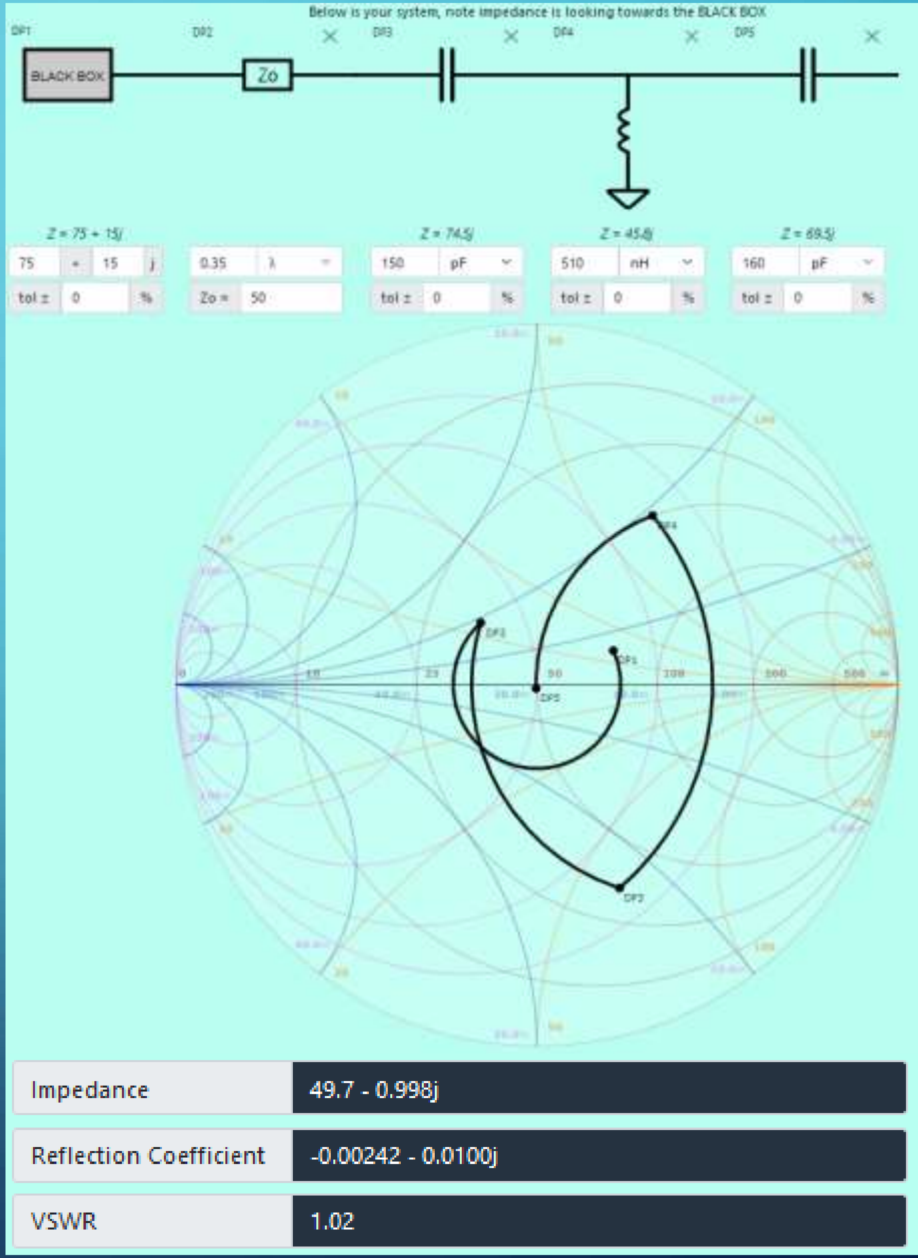
Impedance	34.7 + 12.6j
Reflection Coefficient	-0.155 + 0.172j
VSWR	1.60



Impedance	49.7 - 0.998j
Reflection Coefficient	-0.00242 - 0.0100j
VSWR	1.02

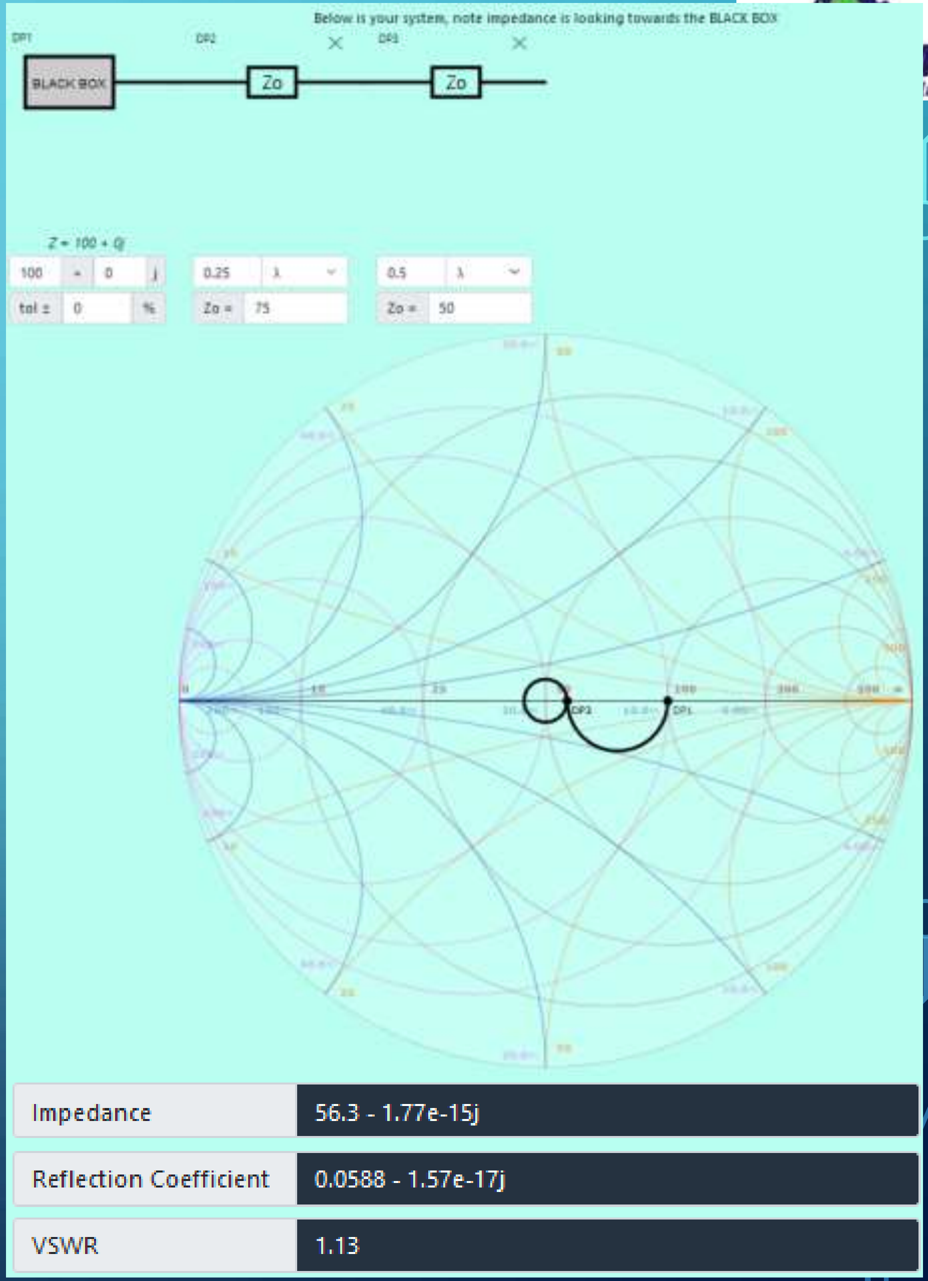
COMPARE TUNERS





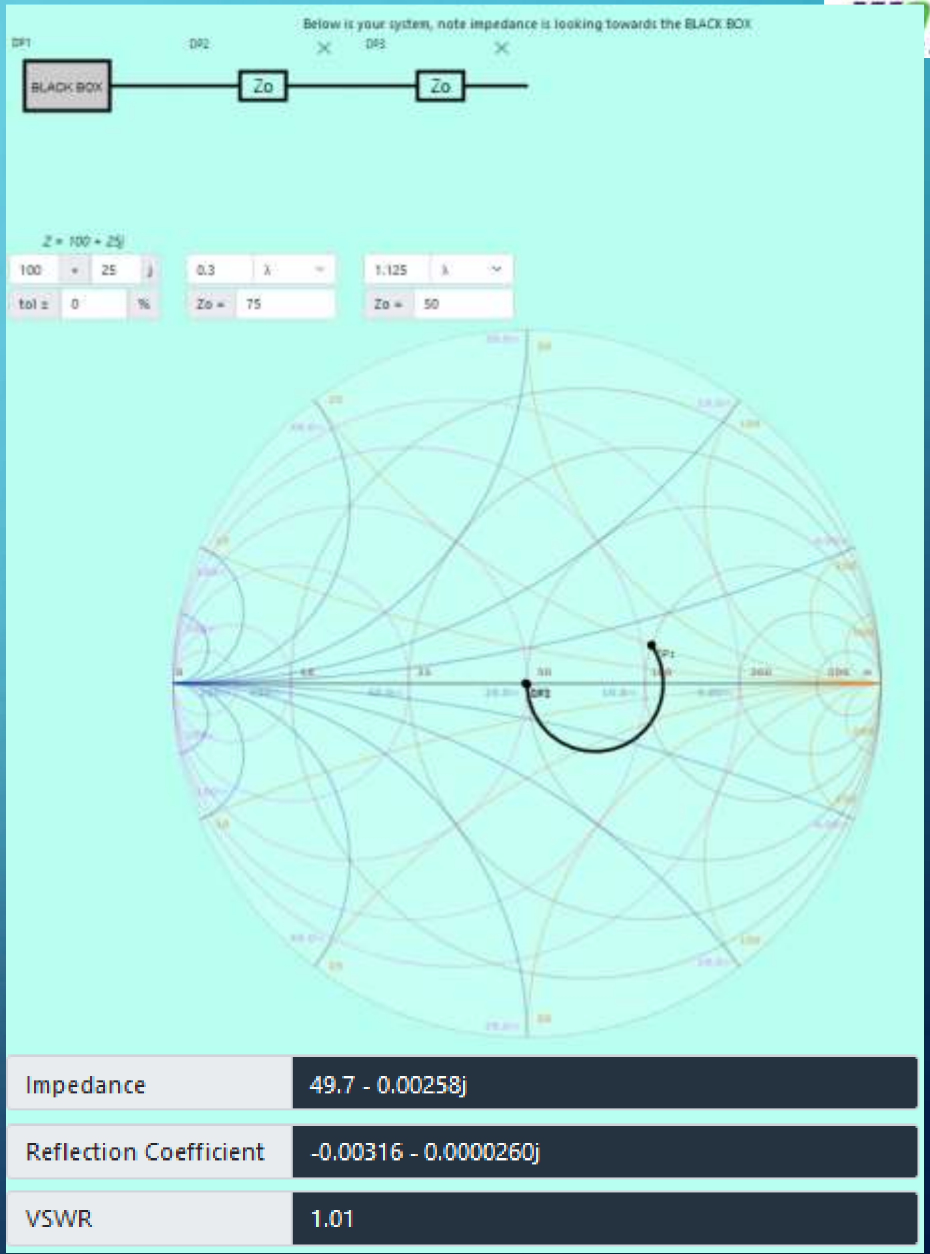
MATCHING USING TRANSMISSION LINE

- Question E9D06 on Extra Class exam asks “Which of these choices is an effective way to match an antenna with a 100-ohm feed point impedance to a 50-ohm coaxial cable feed line?”
  - Answer: Insert a ¼-wavelength piece of 75-ohm coacial cable transmission line in series between the antenna terminals and the 50-ohm feed cable



MATCHING USING TRANSMISSION LINE, CONT'D

- Can I still use a transmission line to match even if there is a reactive component at the antenna?
- Yes
- Don't feel like you have to remember these specific examples. The message is that there is often more than one way to accomplish this.

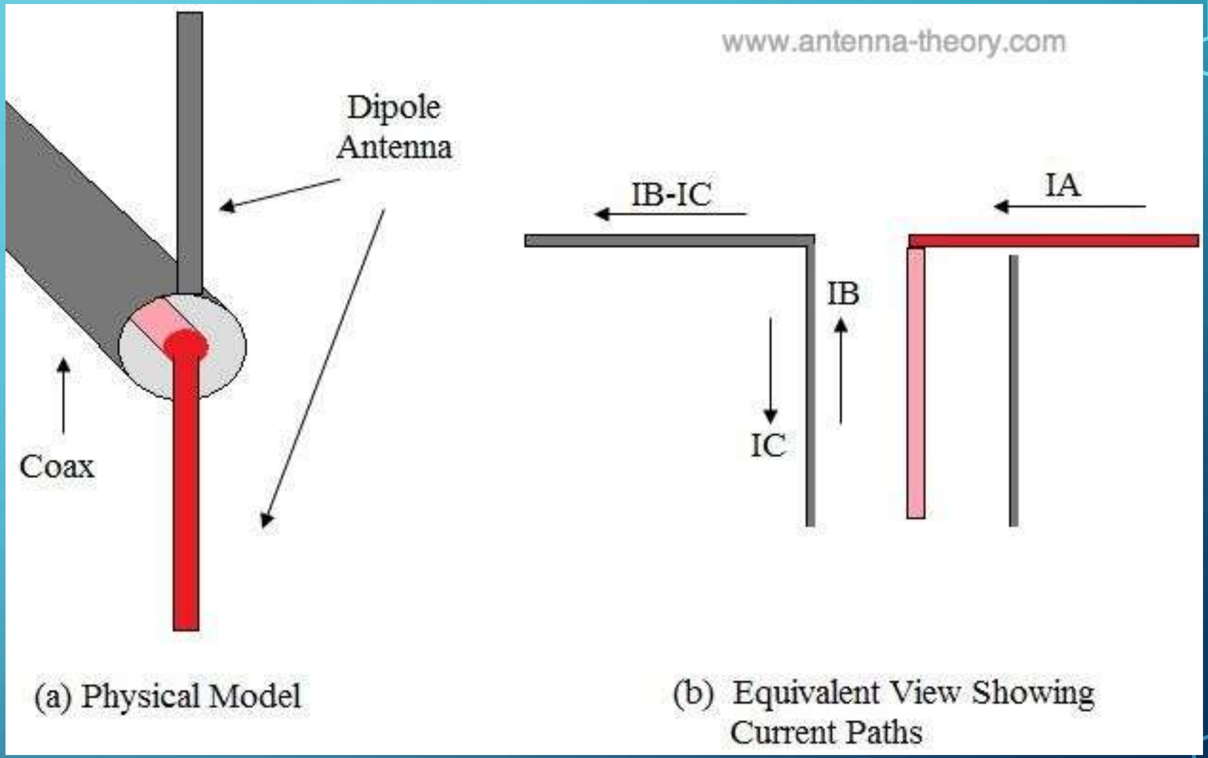


SWR MANIPULATION

- Question E9D06 on Extra Class exam asks "What happens to the SWR bandwidth when one or more loading coils are used to resonate an electrically short antenna?"
  - Remember that resonance means that the reactance element of the impedance is j0
  - But that occurs at only one frequency. Tuning the frequency away from that point changes the reactance
  - The result is that the SWR bandwidth is decreased. If you are using an antenna tuner this is why you have to retune if you make a significant change in frequency

LET'S TALK ABOUT BALUNS

- A BALUN is used to BALance UNbalanced systems
- It may or may not be a RF transformer
- Ideally, IC should be zero. If not, the radiation pattern is changed. This may or not be a bad thing. The antenna will still radiate.
- RF coming back down the feedline to the shack can be a problem. You sometimes here this called common mode current.



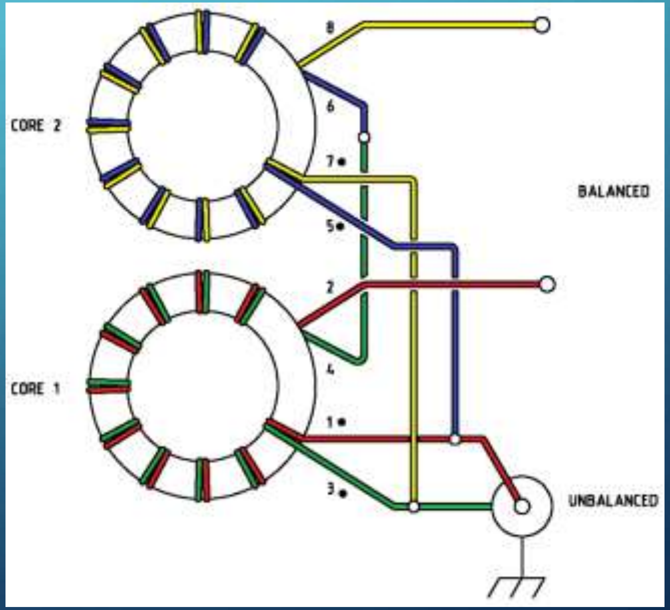
WHY WOULD I NEED AN UNUN?

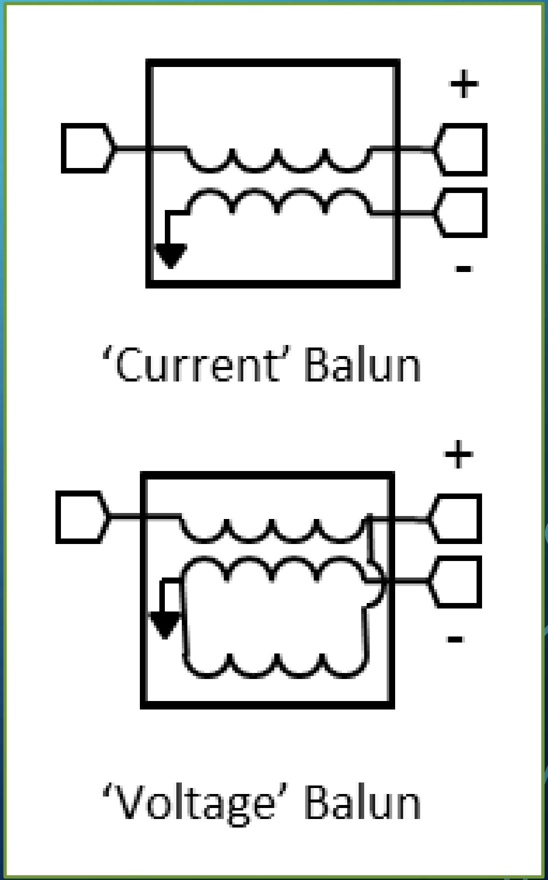
- UNbalanced UNbalanced
- End fed half wave and end fed non resonant antennas are unbalanced
- Antenna impedance of end fed antennas are much higher than center-fed dipoles
- The UNUN needs to be a transformer
  - 4:1 or 9:1 UNUNs are common
  - If it was 1:1 you wouldn't need the UNUN

https://www.wireantennas.co.uk/unun/-9-1-impedance-transformer-unun-

MORE ABOUT BALUNS

- For a ½ λ dipole, a 1:1 BALUN is typically used. Since we are trying to balance currents use a "Current BALUN", not a Voltage BALUN
- Non-resonant end fed antenna's impedance is typically 300 – 600 Ω
  - A 9:1 UNUN will simplify the impedance matching for the transmitter.
  - Transform 50 Ω to 450 Ω
- All BALUNS are not the same - DO YOUR HOMEWORK!!!
- There are lots of opinions out there





MORE ON COMMON MODE CURRENT

- Common mode current is a current flowing without equal, closely spaced return current.
- A common mode choke dissipates rf energy (common mode current) flowing on shield of transmission line.
- The ferrite toroid acts as an RF choke presenting a high impedance to the RF on the feedline
- The "Ugly BALUN" is an RF choke. It is not a BALUN. The feedline is still unbalanced.

Questions?