VSWR and VNAs

What VSWR is and why you should care

Antenna Analysis using a Vector Network Analyzer

Smith Charts

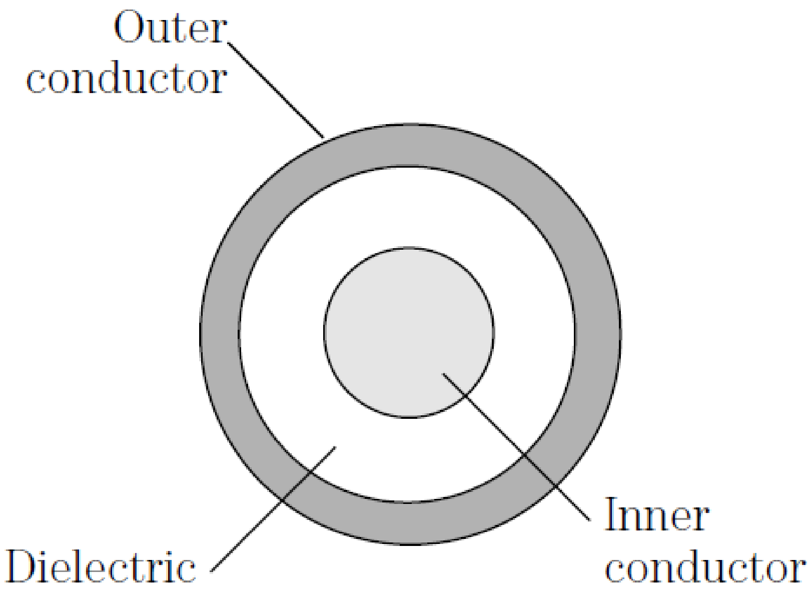
Other stuff

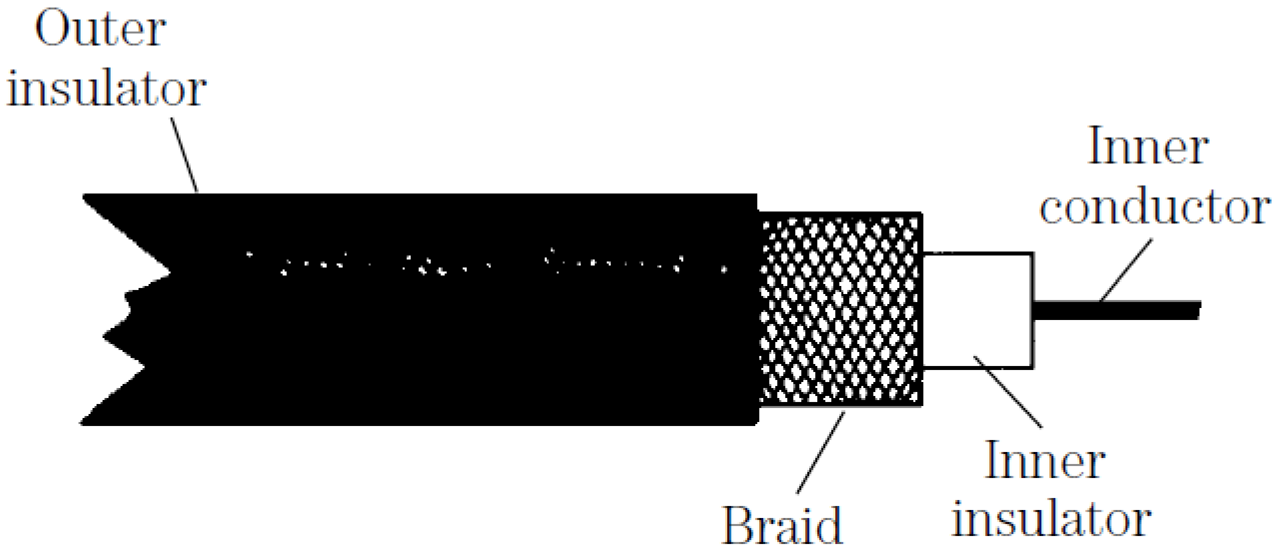
Presented by Carl Foster KB7AZ for RST, OVARC, CRC, and AOCC

What is VSWR

- VSWR is an acronym for Voltage Standing Wave Ratio
- It is a measurement of the standing waves on a transmission line that are due to a partial or full reflection of a signal at the load end
- To understand its meaning, we must first understand RF transmission lines
- This presentation is limited to coaxial cables, but is applicable to ladder lines and waveguides

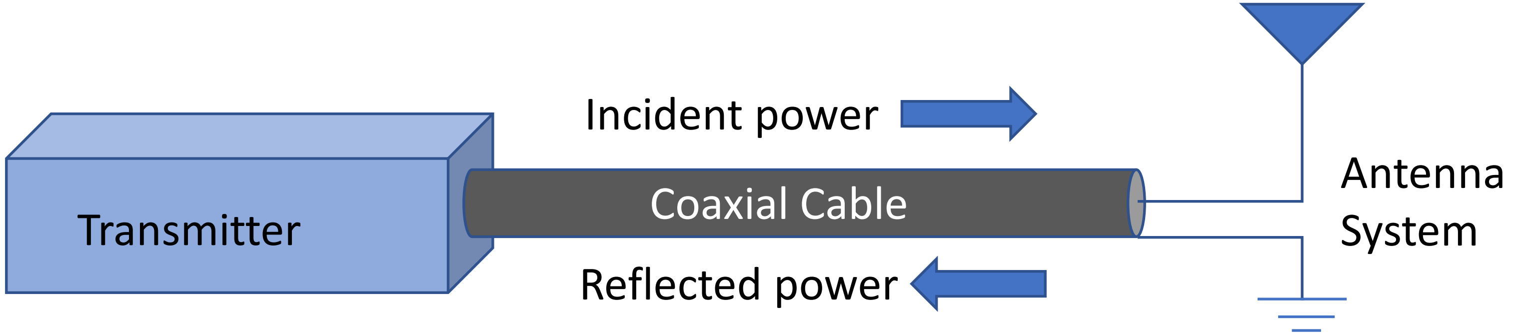
Coaxial Cable Review





Transmitter-to-antenna Connection

Typical RF transmitter connection using coaxial cable



- Ideally, all of the transmitter power is delivered to the antenna system
- In reality, some of the incident power at the antenna system is reflected back toward the transmitter
- The combination of the forward signal and the reflected signal travelling in the opposite direction causes a standing wave in the coaxial cable

Characteristic Impedance

$$Z_o = \sqrt{\frac{R + j\,\omega\,L}{G + j\,\omega\,C}}$$

where

Z_o is the characteristic impedance, in ohms
R is the resistance per unit length, in ohms
G is the conductance per unit length, in mhos
L is the inductance per unit length, in henrys
C is the capacitance per unit length, in farads
ω is the angular frequency in radians per second ($2\pi F$)

Practical Cable Impedance

- In practice, coaxial cable impedance can be calculated using the simplified expression
  - L = inductance per unit length
  - C = capacitance per unit length

$$Z_0 = \sqrt{\frac{L}{C}}$$

- Another calculation is $Z_o = \frac{138}{\sqrt{\varepsilon}} \log\left(\frac{D}{d}\right)$ where
  - D = The diameter of the outer conductor
  - d = The diameter of the inner conductor
  - ε = The dielectric constant

Impedance vs. Resistance

- Impedance is a complex value that is a combination of resistance and reactance
- Resistance is the real portion of impedance
  - Resistance can absorb and dissipate energy
- Reactance is termed the imaginary part of impedance
  - Reactance cannot absorb or dissipate energy
- The general form of impedance is $R + jX$ where
  - $R = \text{Resistance}$
  - $X = \text{Reactance}$

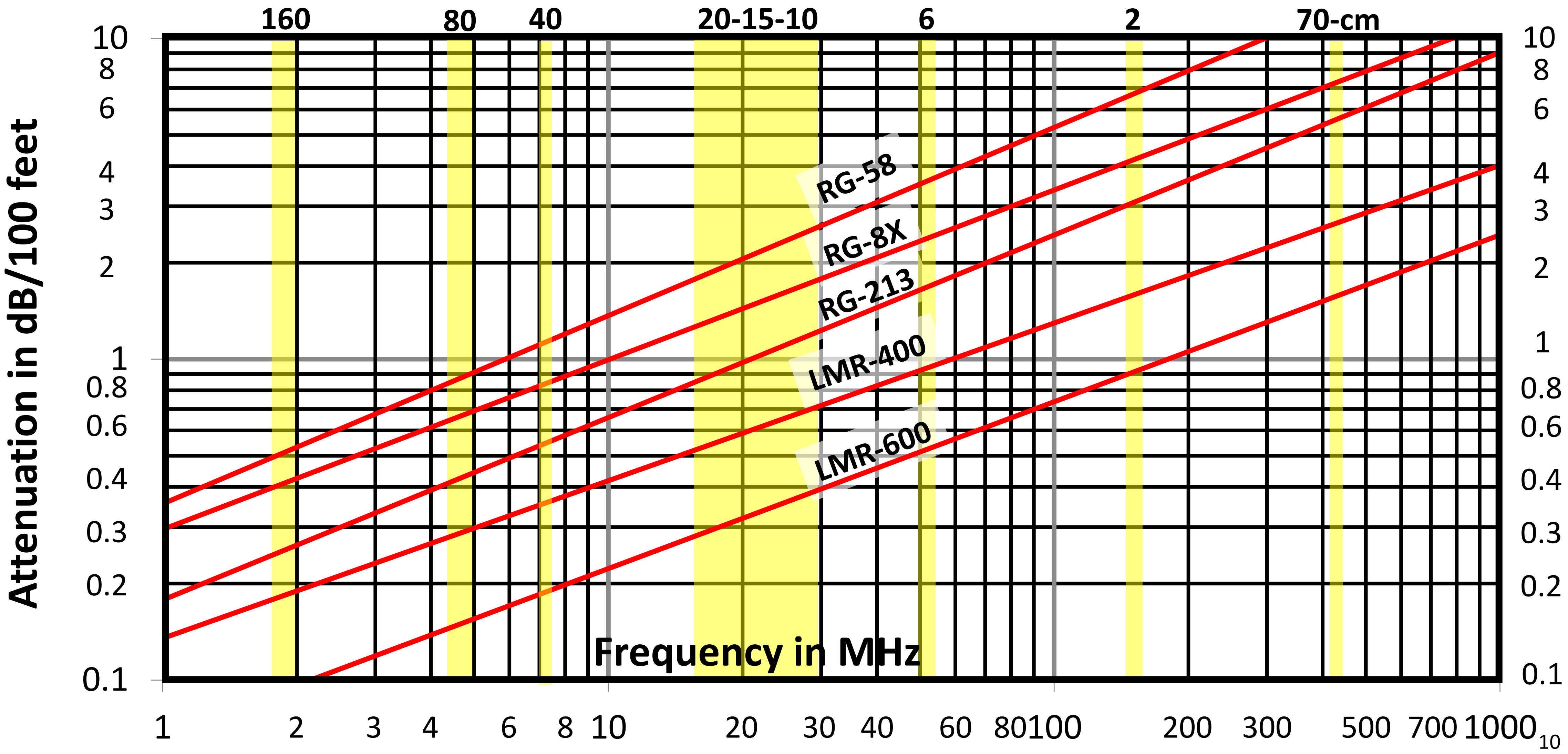
Velocity Factor

- The velocity of the wave (or signal) in the transmission line is less than the free-space velocity (i.e., less than the speed of light).
- The velocity is related to the dielectric constant of the insulating material that separates the conductors.
- Velocity factor Vp is usually specified as a decimal fraction of c, the speed of light (3×10^8 m/s).
  - For example, if the velocity factor of a transmission line is rated at "0.66," then the velocity of the wave is 0.66c, or (0.66) (3 × 108 m/s) = 1.98×10^8 m/s.
- Velocity Factor $Vp = \frac{100}{\sqrt{\varepsilon}}$ where ε is the dielectric constant

Practical Applications

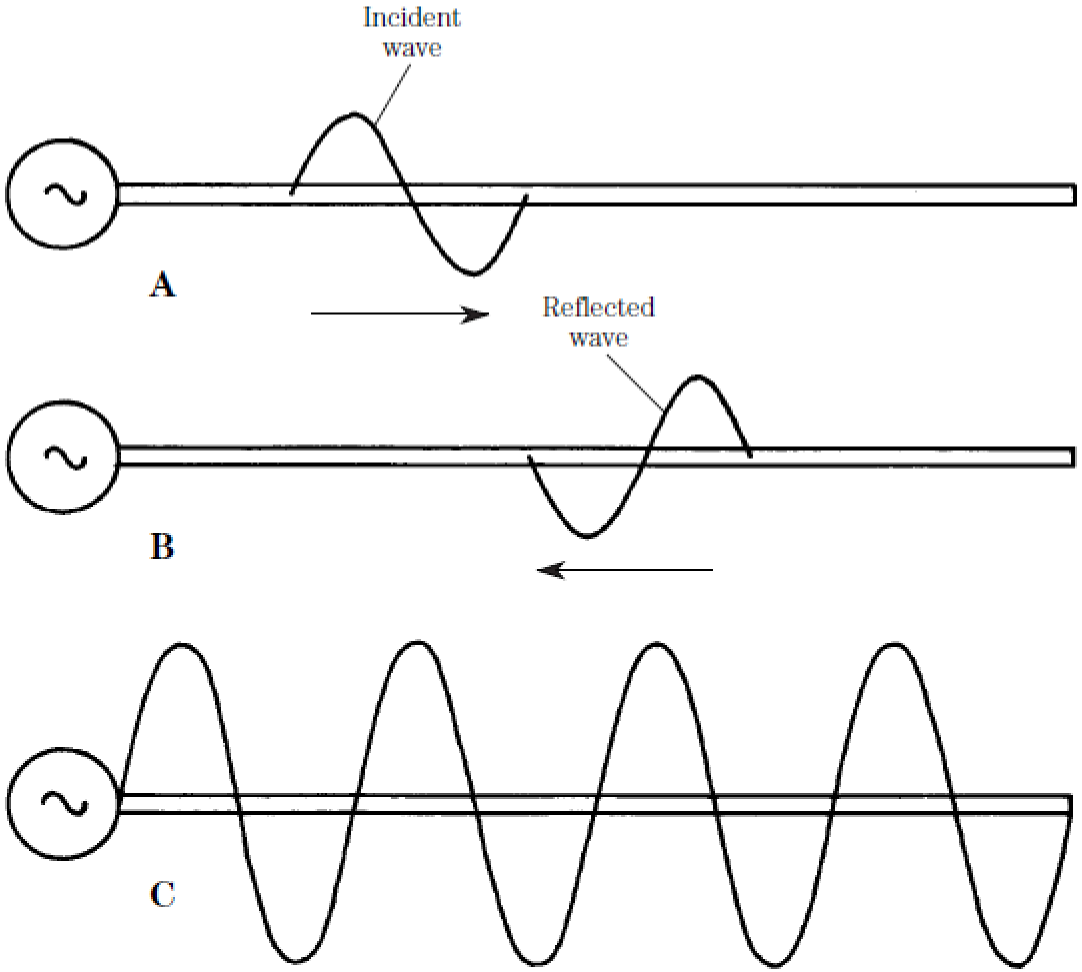
- The most common coaxial cable impedance is 50 Ω
- Common types are RG-58, RG-8X, RG-213, LMR400, LMR600
- Larger diameter cables have lower loss and higher power handling capability
- Each cable has a different loss characteristic at different frequencies.
- Cable loss us usually expressed as dB per 100 feet

Coaxial Cable Loss Characteristics

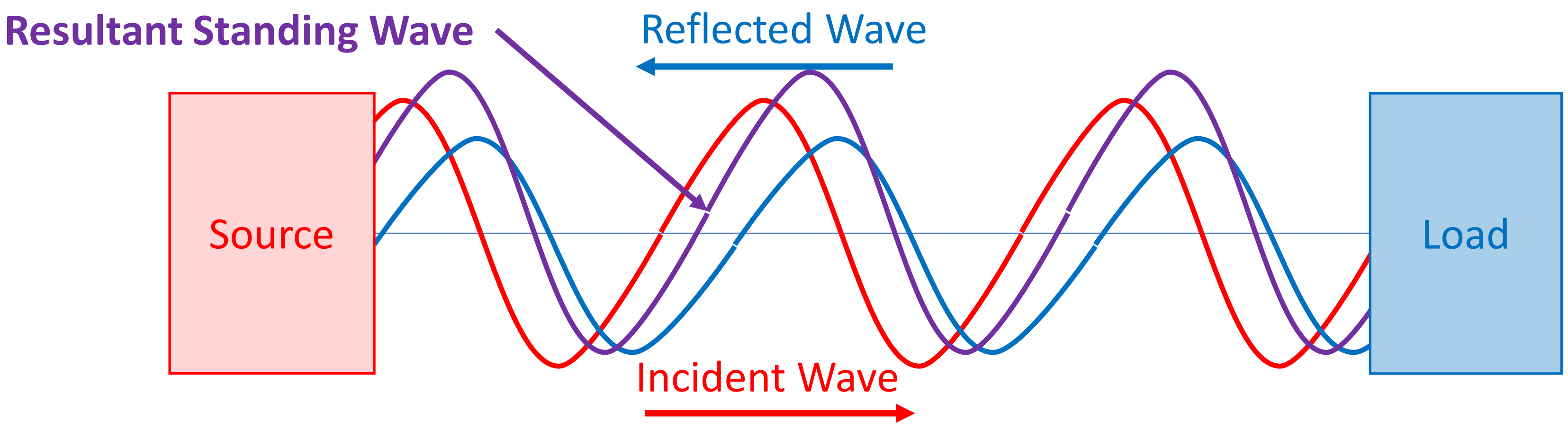


Generating Standing Waves

- In an actual situation, most of the incident power is absorbed by the antenna.
- The power that is not absorbed is reflected power.
- The two waves add in phase and subtract when out of phase, which results in voltage peaks and current peaks in the cable.
- The peaks and valleys are in steady positions on the cable.



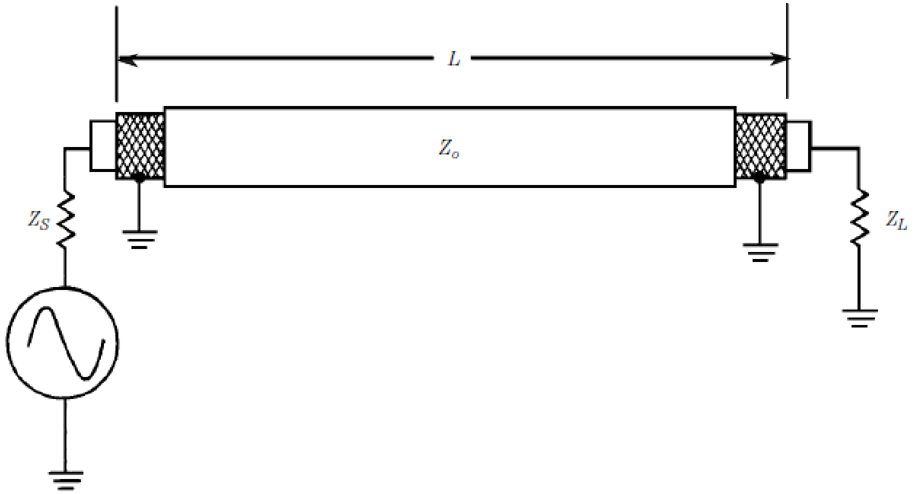
Standing Wave Illustration



- The reflected wave combines with the incident wave to form a standing wave.
- The voltage peaks are called loops.
- The voltage minima (current peaks) are called nodes.
- The loops and nodes repeat every half wavelength.

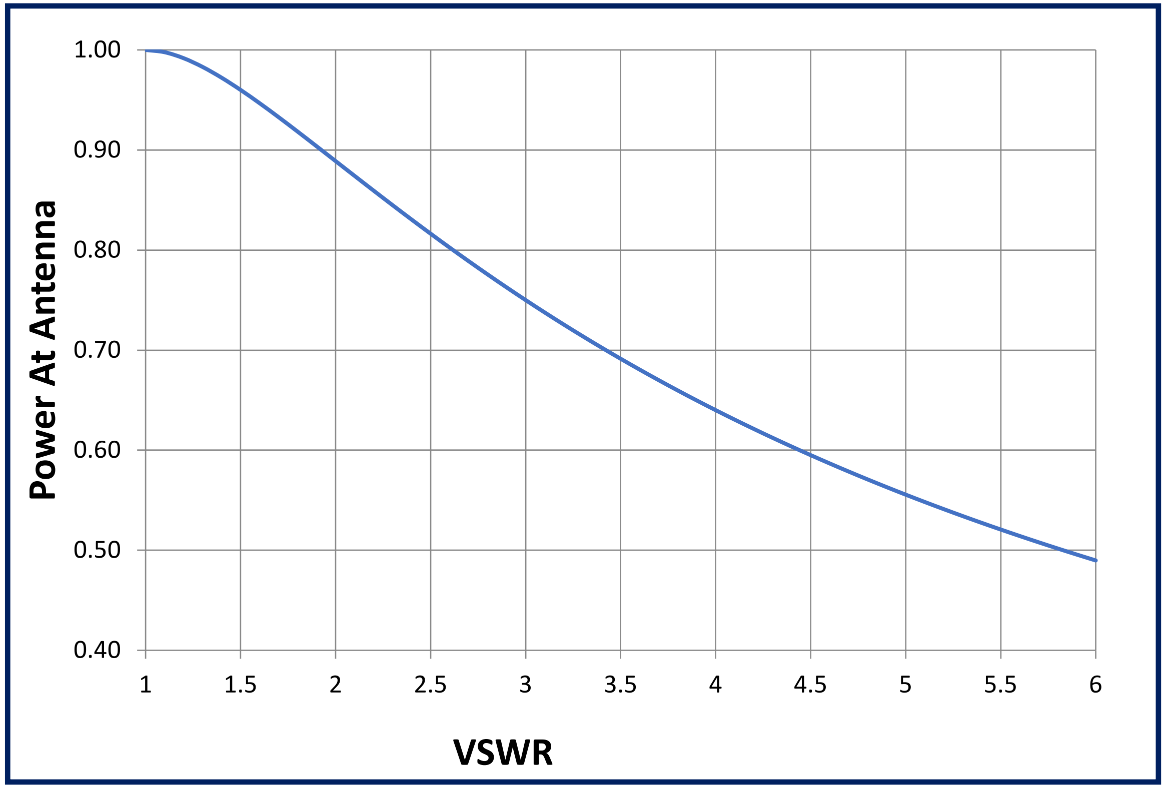
Calculating VSWR

- To avoid a lot of equations and for practical amateur radio purposes, the VSWR is the ratio of the coaxial cable characteristic impedance and the load impedance.
- VSWR is always expresses as a number greater than zero.
- Example:
  - The coaxial cable impedance Z_0 is 50 Ω
  - Load impedance = 25 Ω
    - The resultant VSWR will be 2:1
  - Load impedance = 100 Ω
    - The resultant VSWR will be 2:1
  - Load impedance = 12.5 Ω
    - The resultant VSWR will be 4:1

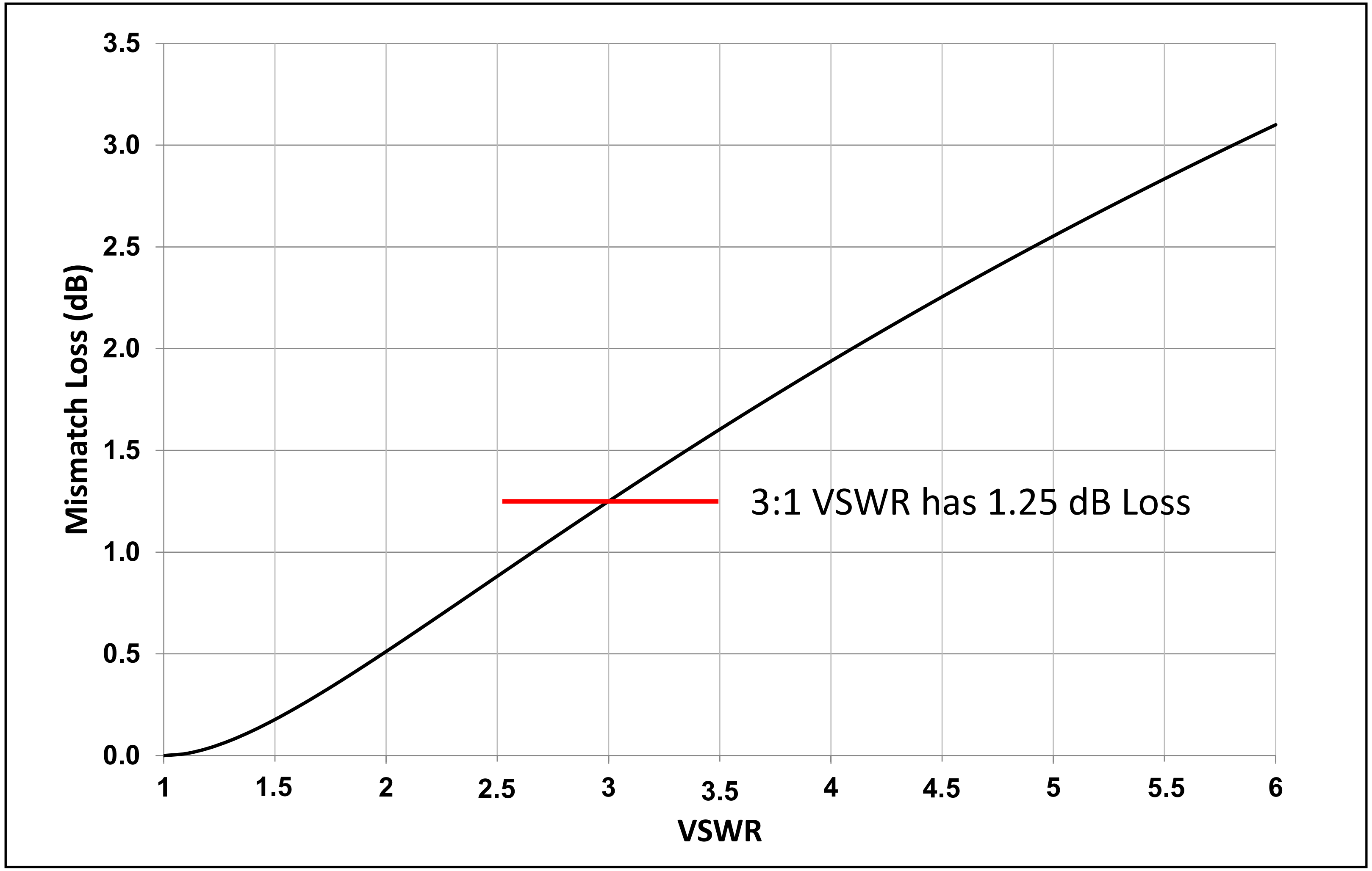


Mismatch Loss

- The power loss due to a cable-to-antenna mismatch is not a great as many people make it out to be.
- Here is a chart showing the power loss vs. VSWR at the antenna end of the cable.
- A 2:1 VSWR results in a power loss of 11%, or 0.51 dB.
- For reference, one S-unit is 6 dB.

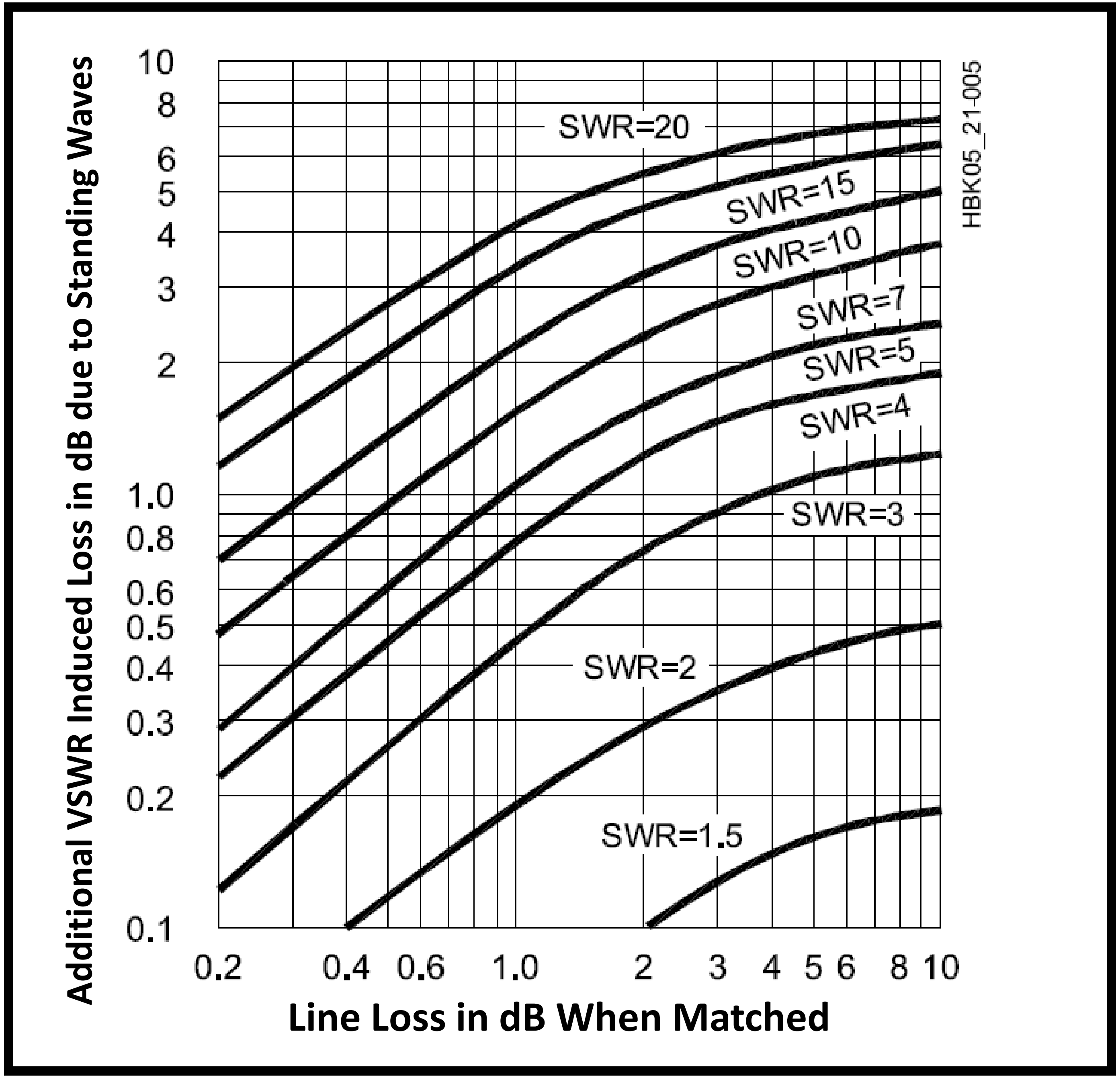


Mismatch Loss (dB)



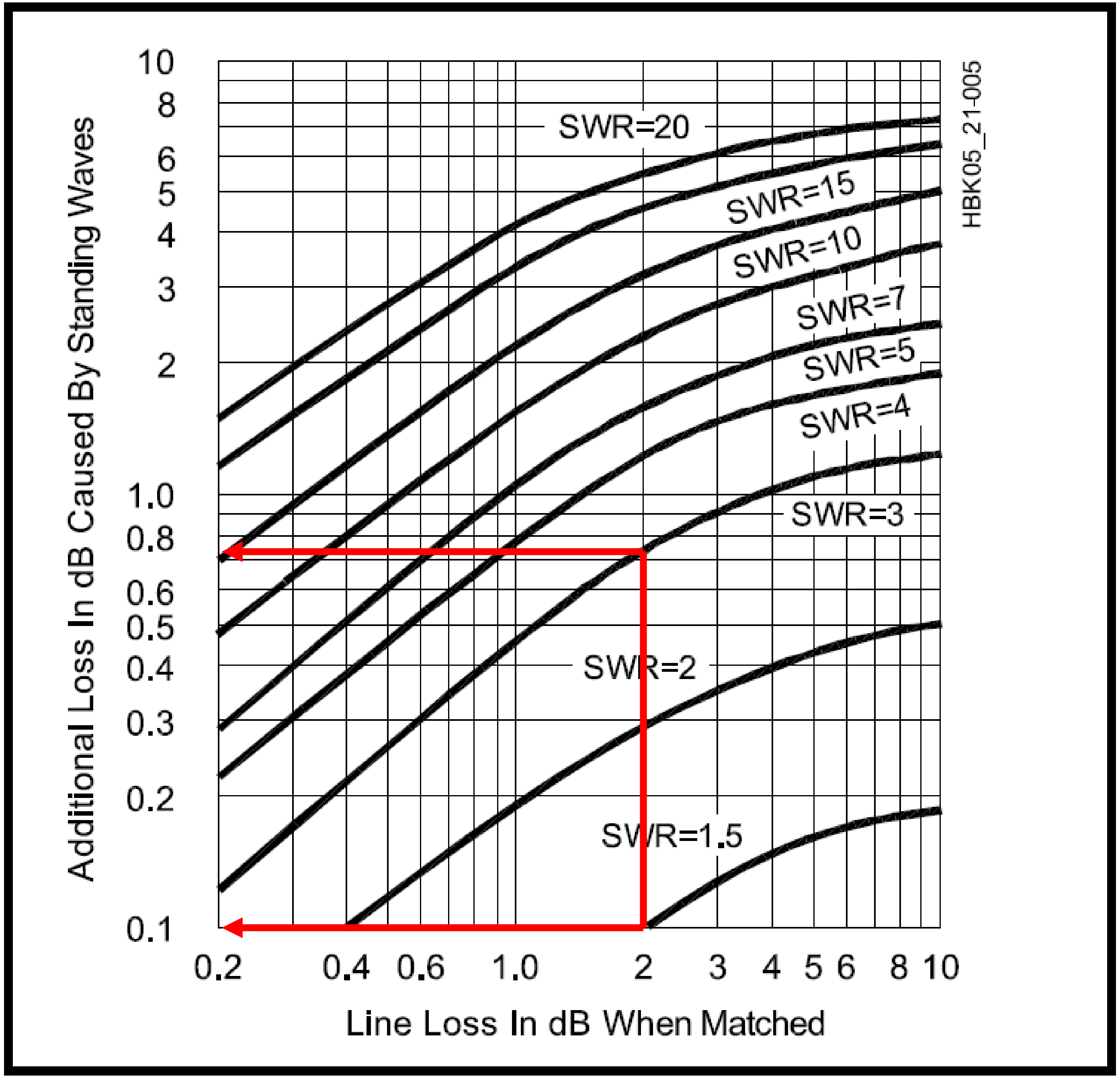
VSWR Loss

- The loops and nodes increase the attenuation of the coaxial cable.
  - The nodes increase the resistive (i^2R) losses
  - The loops increase the dielectric (V^2/R_D) losses.
- The baseline line loss is the loss per unit length times the length
- The total loss is basic loss plus VSWR-induced loss



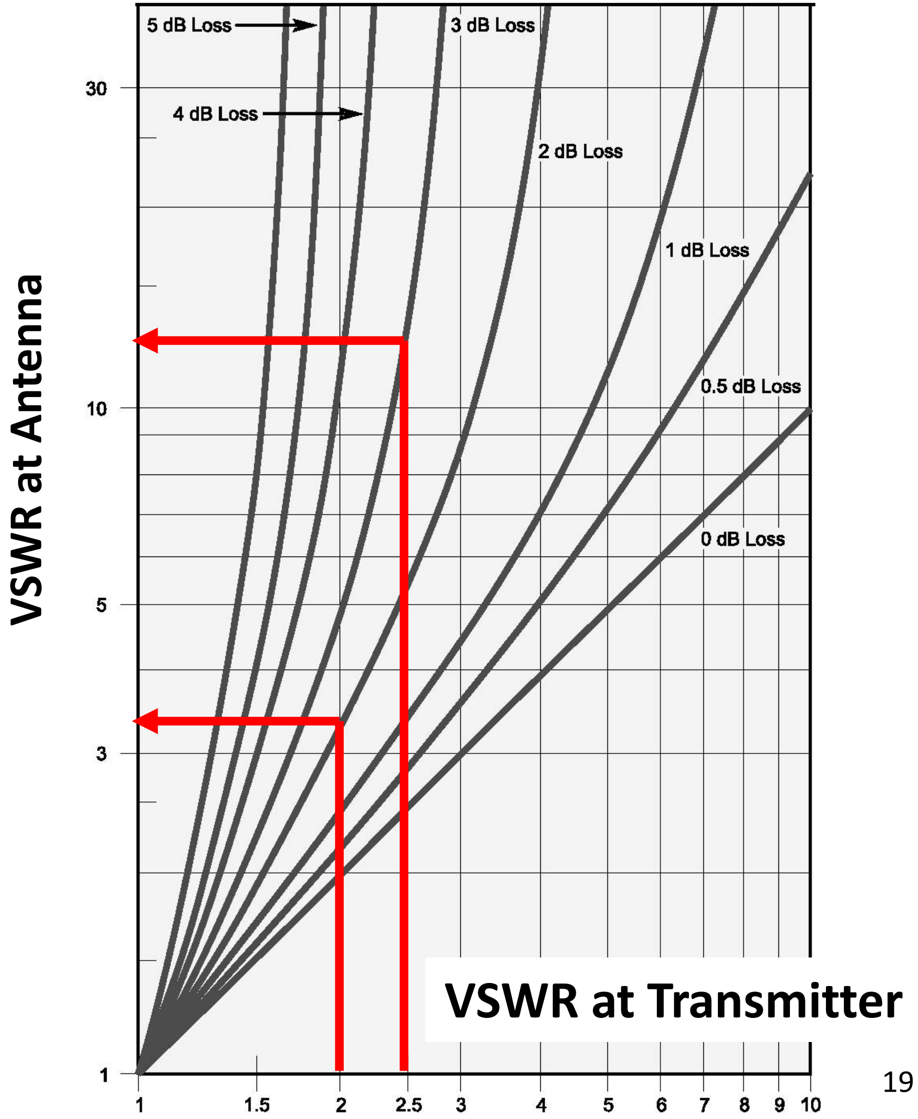
VSWR Loss Examples

- Cable matched loss is 2 dB
- Load VSWR = 1.5:1
  - VSWR loss = 0.1 dB
  - Total loss = 1.6 dB
  - Mismatch loss adds 0.2 dB
  - With mismatch = 1.8dB
- Load VSWR = 3:1
  - VSWR loss is 0.7 dB
  - Total loss = 2.7 dB
  - Mismatch loss adds 1.3 dB
  - With mismatch = 4.0 dB



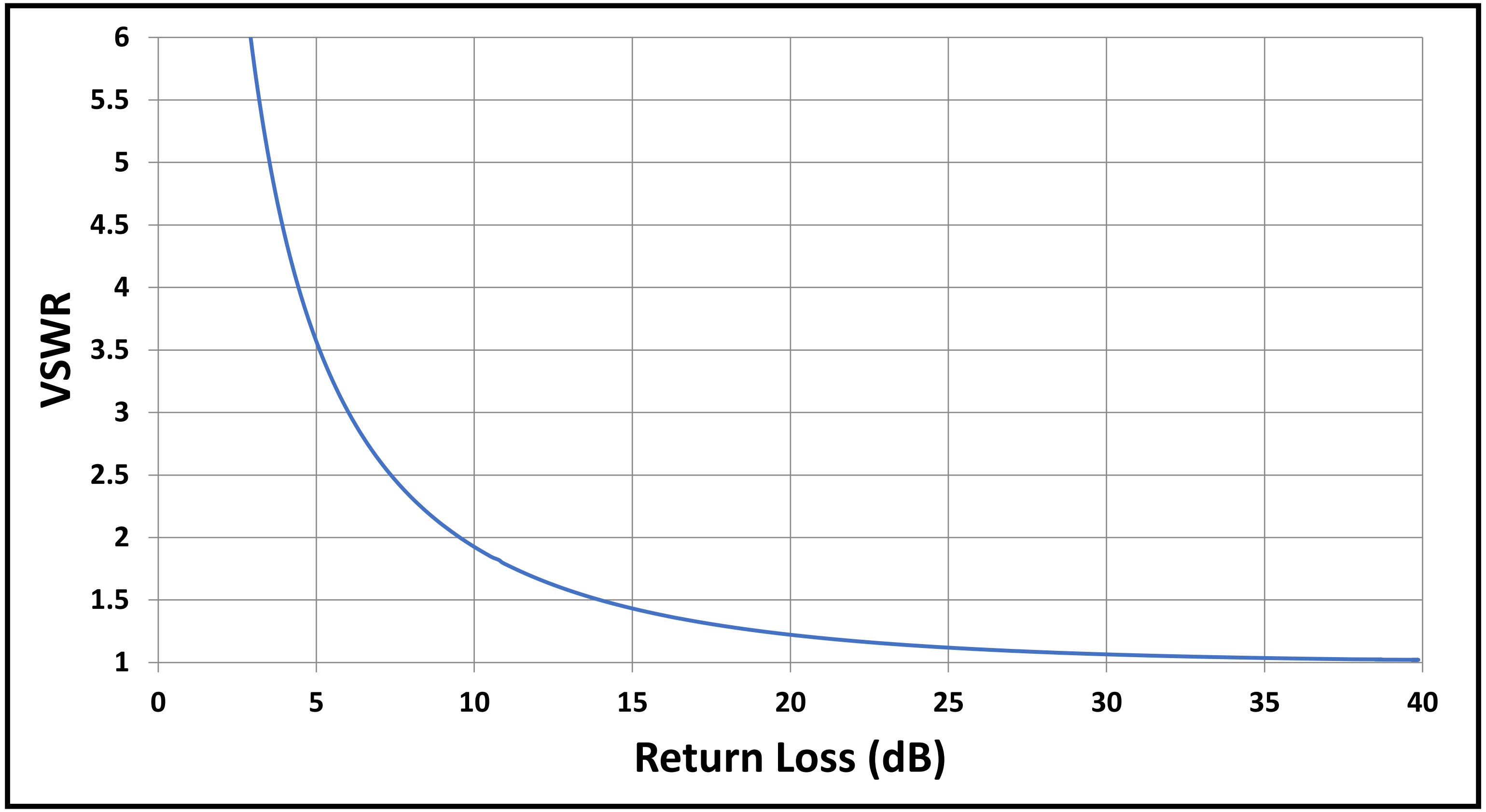
Apparent VSWR

- Coaxial cable loss improves the apparent antenna VSWR seen by the transmitter
- Example 1
  - Cable loss = 2 dB
  - VSWR at transmitter = 2:1
  - Antenna VSWR is 3.2:1
- Example 2
  - Cable loss = 3 dB
  - VSWR at transmitter = 2.5:1
  - Antenna VSWR is 13:1



Return Loss

- VSWR is a linear function.
- Return Loss is a log (dB) function.
- For small values of VSWR, the return loss is more illustrative.



How Important is VSWR?

- The answer depends on the situation
- Using short cables on 160 meters: Not very important
- Using longer cables on 10 meters: Starting to have an effect
- Using cheap cable on 2 meters: Important
- Using any cables on 70 cm (430 MHz): Very Important

Various Scenarios

- The following charts show the effects of high VSWR on different frequencies and cable lengths
- The first calculation is the basic cable loss at 1:1 VSWR
- The second calculation includes VSWR loss and mismatch loss, as appropriate

160 Meters with LMR 400

- Cable: LMR-400
- Length: 100 feet
- Antenna VSWR: 1:1
  - Basic loss = 0.2 dB
  - Measured VSWR: 1:1
- Antenna VSWR: 5:1
  - Loss = 0.2 dB + 0.21 dB VSWR loss = 0.41 dB
  - Measured VSWR: 4.2:1
  - Using an antenna tuner so the mismatch loss is low
- VSWR difference is 0.21 dB, or 4.7%

160 meters with RG-8X

- Cable: RG-8X
- Length: 100 feet
- Antenna VSWR: 1:1
  - Basic loss = 0.4 dB
  - Measured VSWR: 1:1
- Antenna VSWR: 5:1
  - Loss = 0.4 dB + 0.38 dB VSWR loss = 0.78 dB
  - Measured VSWR: 3.4:1
  - Using an antenna tuner so the mismatch loss is low
- VSWR difference is 0.38 dB, or 8.4%

10 Meters with LMR 400

- Cable: LMR-400
- Length: 100 feet
- Antenna VSWR: 1:1
  - Basic loss = 0.7 dB
  - Measured VSWR: 1:1
- Antenna VSWR: 5:1
  - Loss = 0.7 dB + 0.6 dB VSWR loss = 1.3 dB
  - Measured VSWR: 2.6:1 so probably use an antenna tuner
  - Using an antenna tuner so the mismatch loss is low
- VSWR difference is 0.6 dB, or 13%

10 Meters with RG-8X

- Cable: RG-8X
- Length: 100 feet
- Antenna VSWR: 1:1
  - Basic loss = 1.8 dB
  - Measured VSWR: 1:1
- Antenna VSWR: 5:1
  - Loss = 1.8 dB + 1.1 dB VSWR loss = 2.9 dB
  - Measured VSWR: 2.1:1
  - Using an antenna tuner so the mismatch loss is low
- VSWR difference is 1.1 dB, or 22%

2 Meters with LMR 400

- Cable: LMR-400
- Length: 100 feet
- Antenna VSWR: 1:1
  - Basic loss = 1.6 dB
  - Measured VSWR: 1:1
- Antenna VSWR: 5:1
  - Loss = 1.6 dB + 1.1 dB VSWR loss + 2.6 dB mismatch loss = 5.3 dB
  - Measured VSWR: 2.2:1
- VSWR difference is 3.7 dB, or 57%

2 Meters with RG-8X

- Cable: RG-8X
- Length: 100 feet
- Antenna VSWR: 1:1
  - Basic loss = 4.1 dB
  - Measured VSWR: 1:1
- Antenna VSWR: 5:1
  - Loss = 4.1 dB + 1.6 dB VSWR loss + 2.6 dB mismatch loss = 8.3 dB
  - Measured VSWR: 1.5:1
- VSWR difference is 4.2 dB, or 62%

70 cm with LMR 400

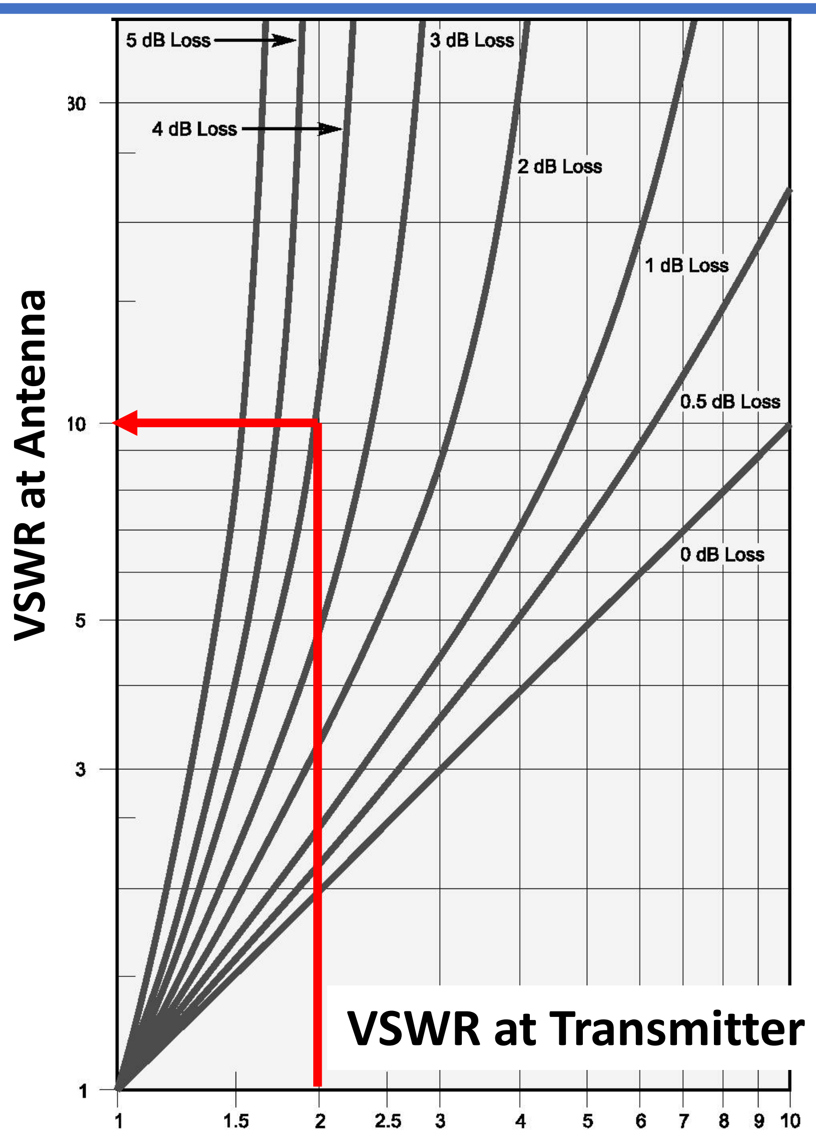
- Cable: LMR-400
- Length: 100 feet
- Antenna VSWR: 1:1
  - Basic loss = 2.6 dB
  - Measured VSWR: 1:1
- Antenna VSWR: 5:1
  - Loss = 2.6 dB + 1.7 dB VSWR loss + 2.6 dB mismatch loss = 6.9 dB
  - Measured VSWR: 1.7:1
- VSWR difference is 4.3 dB, or 63%

Homebrew 2-meter Antenna Example

- K7XYZ uses 100 feet of RG-8X to connect his brand new 50-watt 2-meter transceiver to a homebrew stealth antenna.
- He used Belden 9258 instead of a Chinese knock-off.
- He fires it up and measures 2:1 VSWR at the transmitter.
- He thinks “Not great, but good enough.”
- He invites his Elmer over to admire his work.
- Let’s see what his Elmer finds.

Homebrew Antenna Analysis

- 100 feet of RG-8X has a loss of 4 dB at 146 MHz
- A 2:1 VSWR at the transmitter shows an actual antenna VSWR of 10:1
- This adds another 3dB of VSWR loss
- The mismatch loss adds another 5 dB
- The grand total loss is then 12 dB
- His 50-watt transmitter is only delivering about 3 watts to the antenna
- The other 47 watts is keeping his coaxial cable warm



Change to LMR-400

- Basic loss is only 1.5 dB at 146 MHz
- A 10:1 antenna VSWR would read 4:1 at the transmitter
- This would indicate that the antenna matching needs to be addressed to reduce mismatch losses on both ends

Antenna Tuner Effect

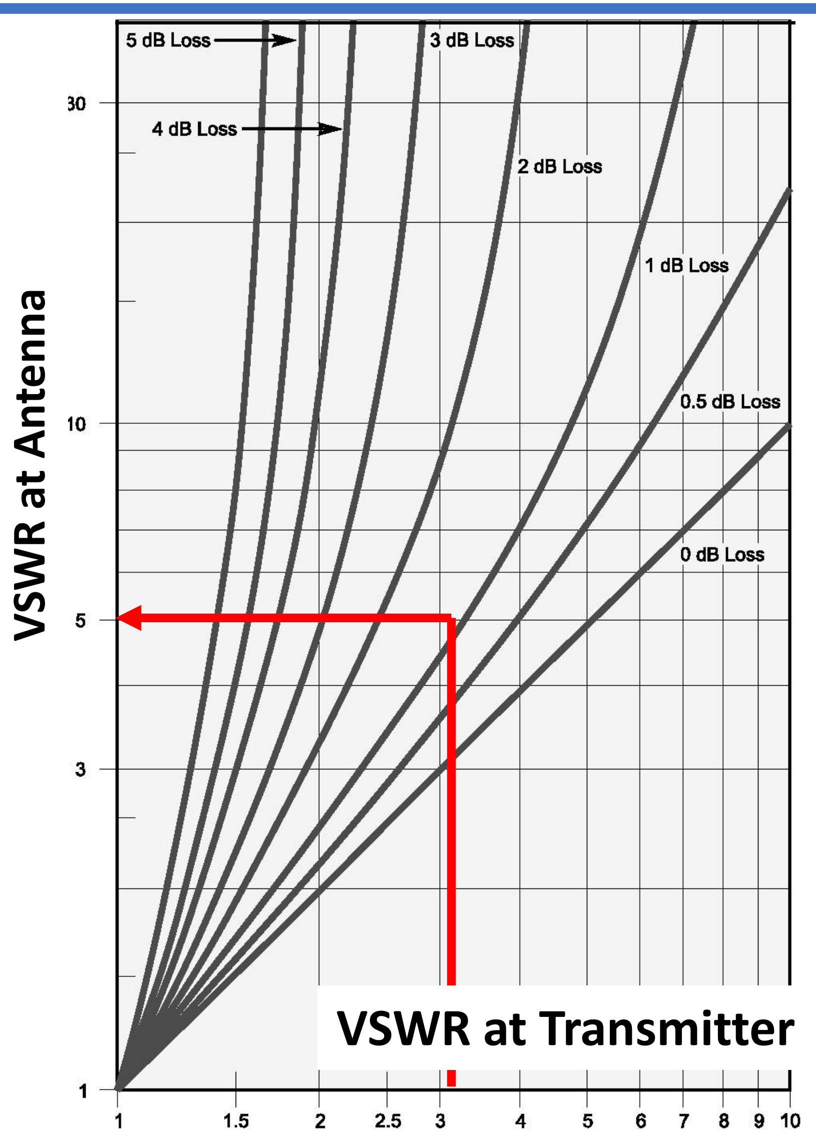
- An antenna tuner will match the transmitter output to the apparent impedance of the driven end of the coaxial cable.
- The antenna tuner forms a resonant circuit and re-directs the reflected power back to the load.
- An antenna tuner negates most of the mismatch loss.
- Antenna tuners are most useful at HF frequencies

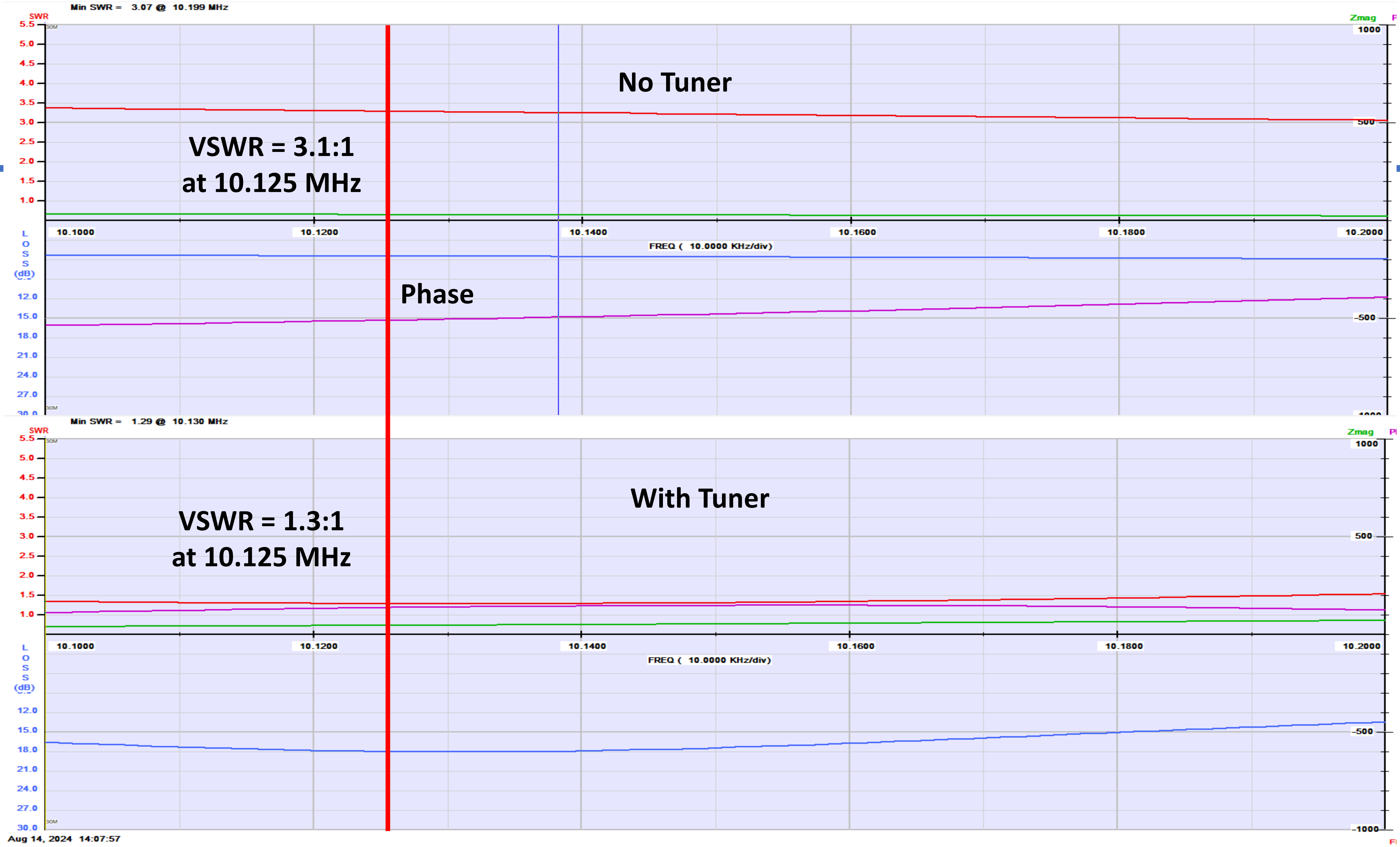
Antenna Tuner Effect

- Antenna is 80-meter Off Center Fed (OCF) dipole
- Frequency = 10.125 MHz (center of the band)
  - Impedance at the transmitter end = 21.05 – j23.55
  - Cable VSWR = 3:1
  - Reflected power = 24.9%
- With antenna tuner
  - Impedance at transmitter end = 39.44 + j4.22
  - Cable VSWR = 1.3:1
  - Reflected power (to the transmitter) = 1.6%
  - The VSWR on the cable is still 3:1, but the power delivered to the antenna system is a lot higher because the transmitter can drive the power into the cable.

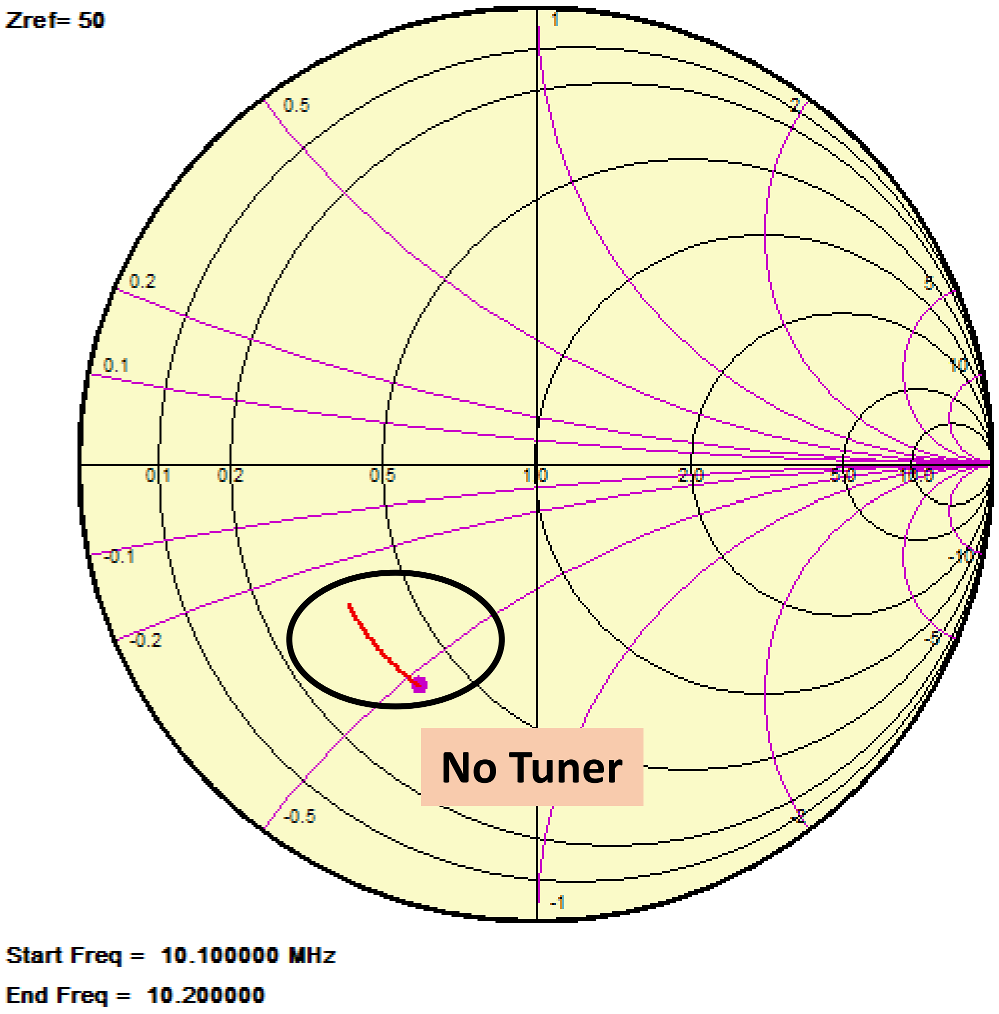
Antenna Tuner Effects

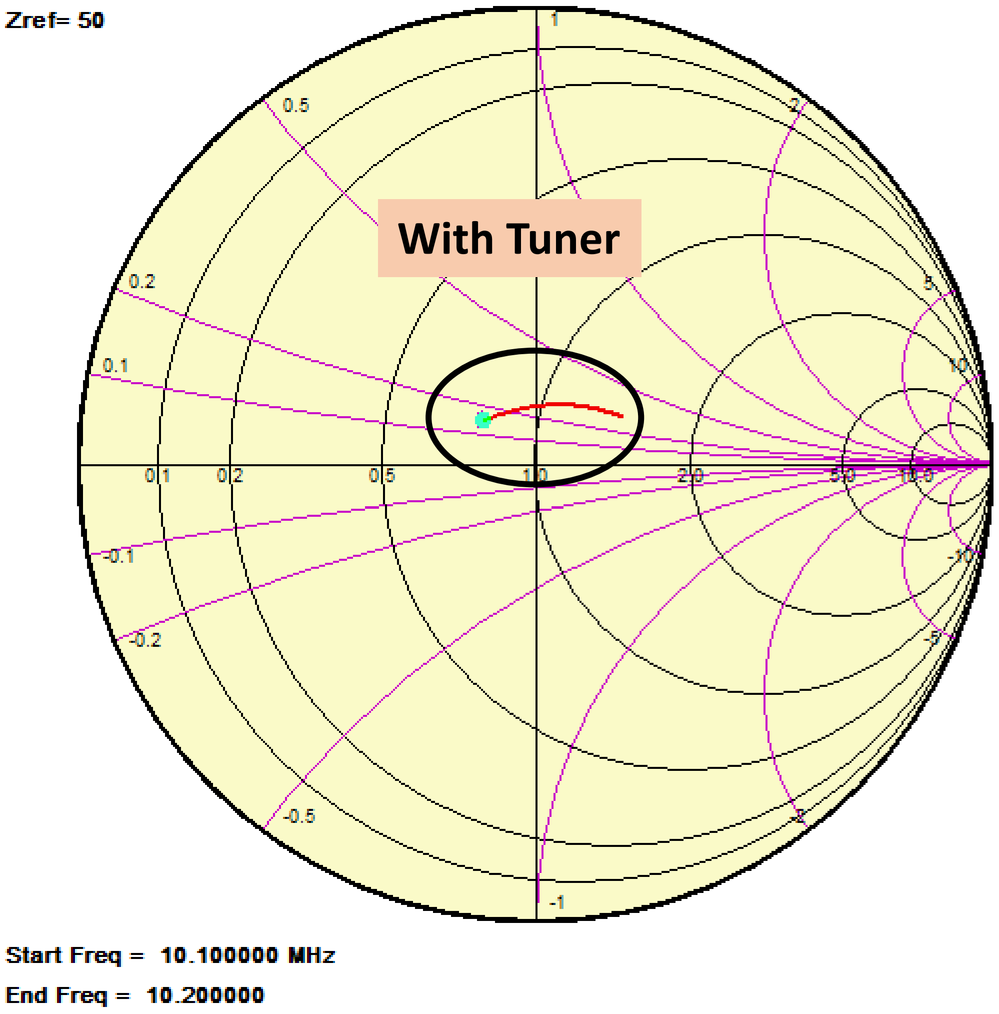
- Antenna is an 80-meter OCF dipole
- Not particularly effective on 30 meters (10 MHz)
- The next slide shows the VSWR trace without the antenna tuner on the top and with the antenna tuner on the bottom
- The cable is approximately 220 feet of RG-213/U
  - Attenuation is 1.2 dB per the Belden 8267 data sheet (0.55 x 2.2)
- At 10.125 MHz the VSWR is 3.1:1
- The VSWR at the antenna is 5:1




Min SWR = 3.07 @ 10.199 MHz
SWR
Zmag
No Tuner
VSWR = 3.1:1
at 10.125 MHz
10.1000
10.1200
10.1400
10.1600
10.1800
10.2000
FREQ (10.0000 KHz/div)
LOSS (dB)
Phase
Min SWR = 1.29 @ 10.130 MHz
With Tuner
VSWR = 1.3:1
at 10.125 MHz
Aug 14, 2024 14:07:57

Smith Chart of the Same Sweeps

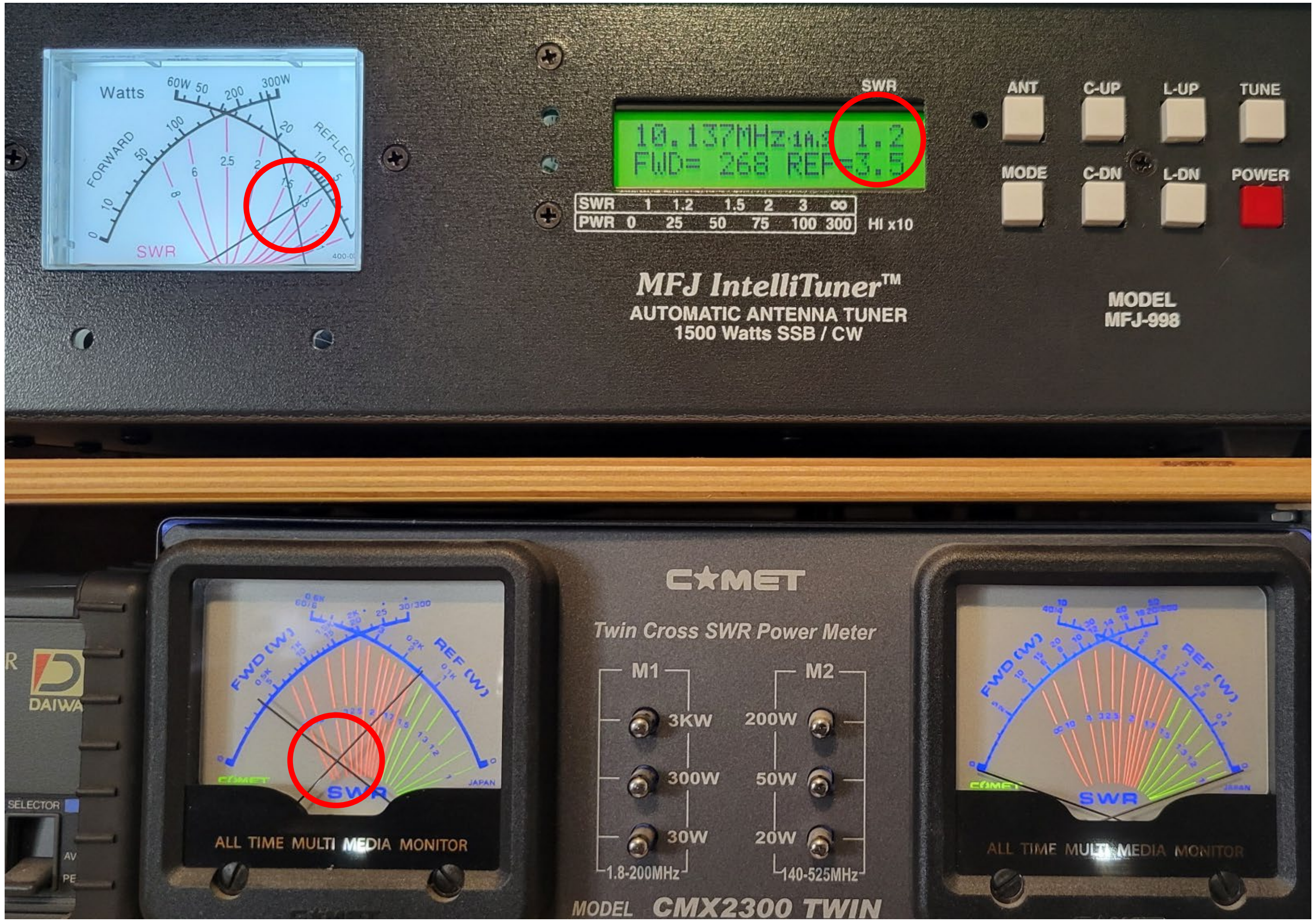




VSWR Measurements

VSWR seen by the transmitter = 1.2:1

VSWR on the coaxial cable = 4:1

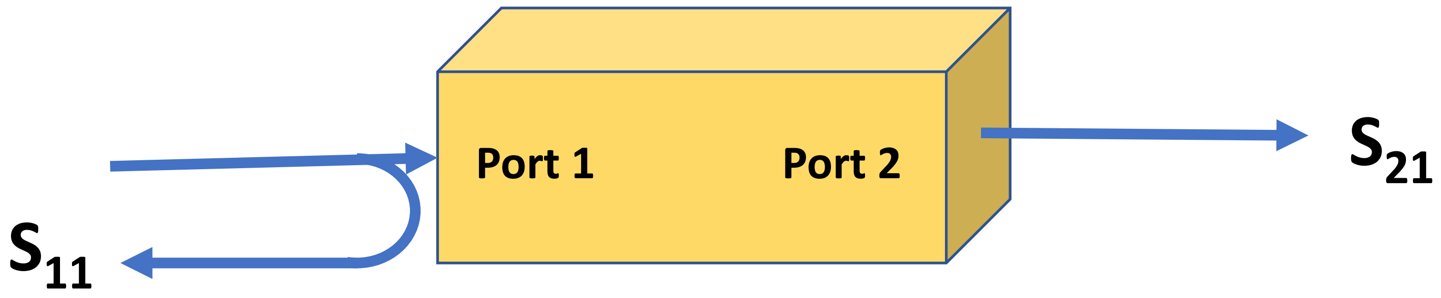


S-parameters

- S-parameters, or scattering parameters, describe how RF energy moves through multi-port networks, highlighting the linear properties of electronic components.
- S-parameters are frequency-dependent, requiring frequency information and characteristic impedance for accurate measurements, essential for high-frequency applications.
- S-parameters include reflection coefficients (S_{11}, S_{22}) and transmission coefficients (S_{12}, S_{21}), which help understand signal behavior in networks.

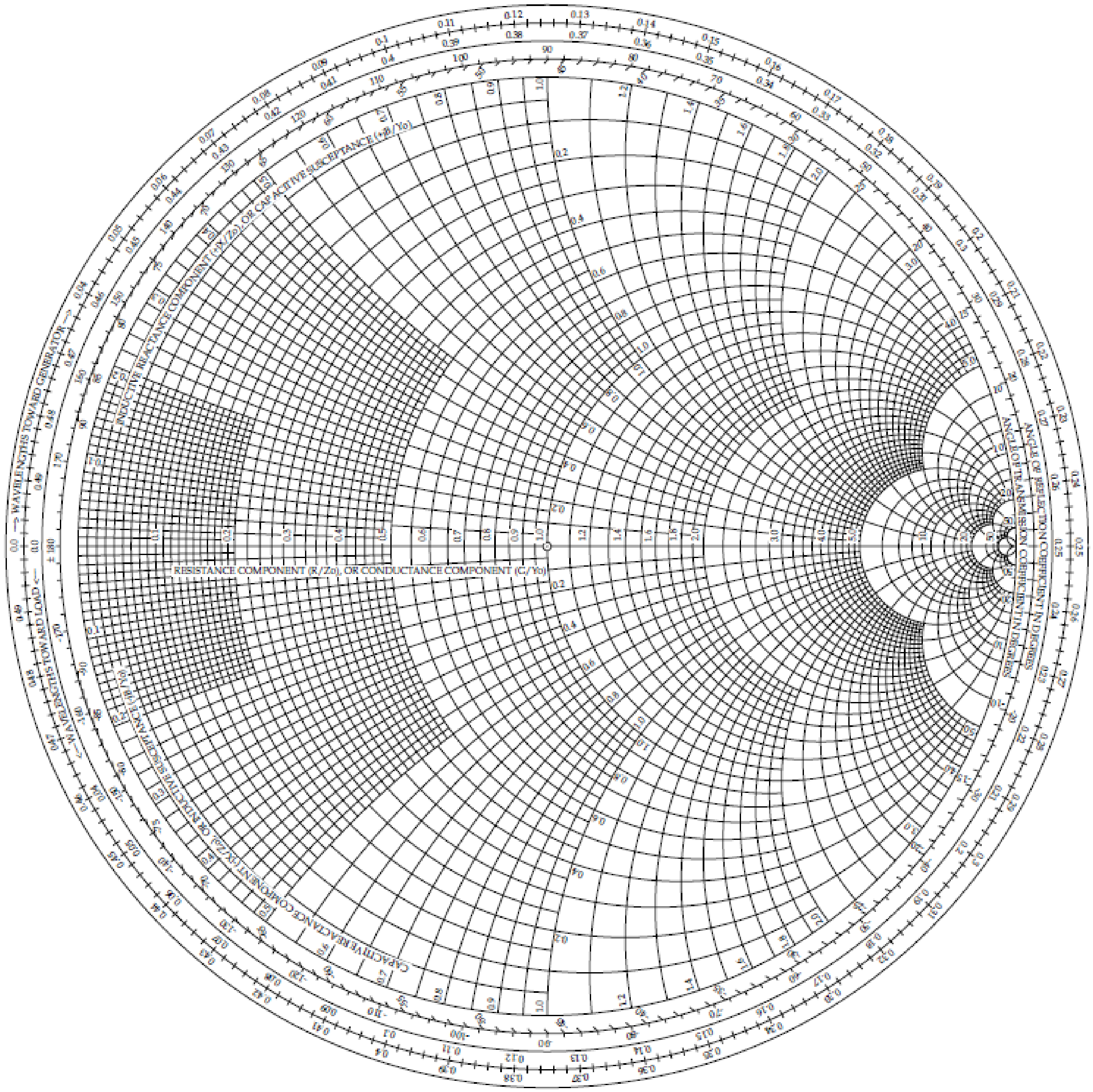
S-parameter Notation

- Notation is the letter "S" with two subscripts
  - First subscript is where the RF power emerges (output port)
  - Second subscript is where the RF power enters (input port)
- S_{11} is the reflected RF power out of the input port
- S_{21} is the through power of a two-port object, such as a filter



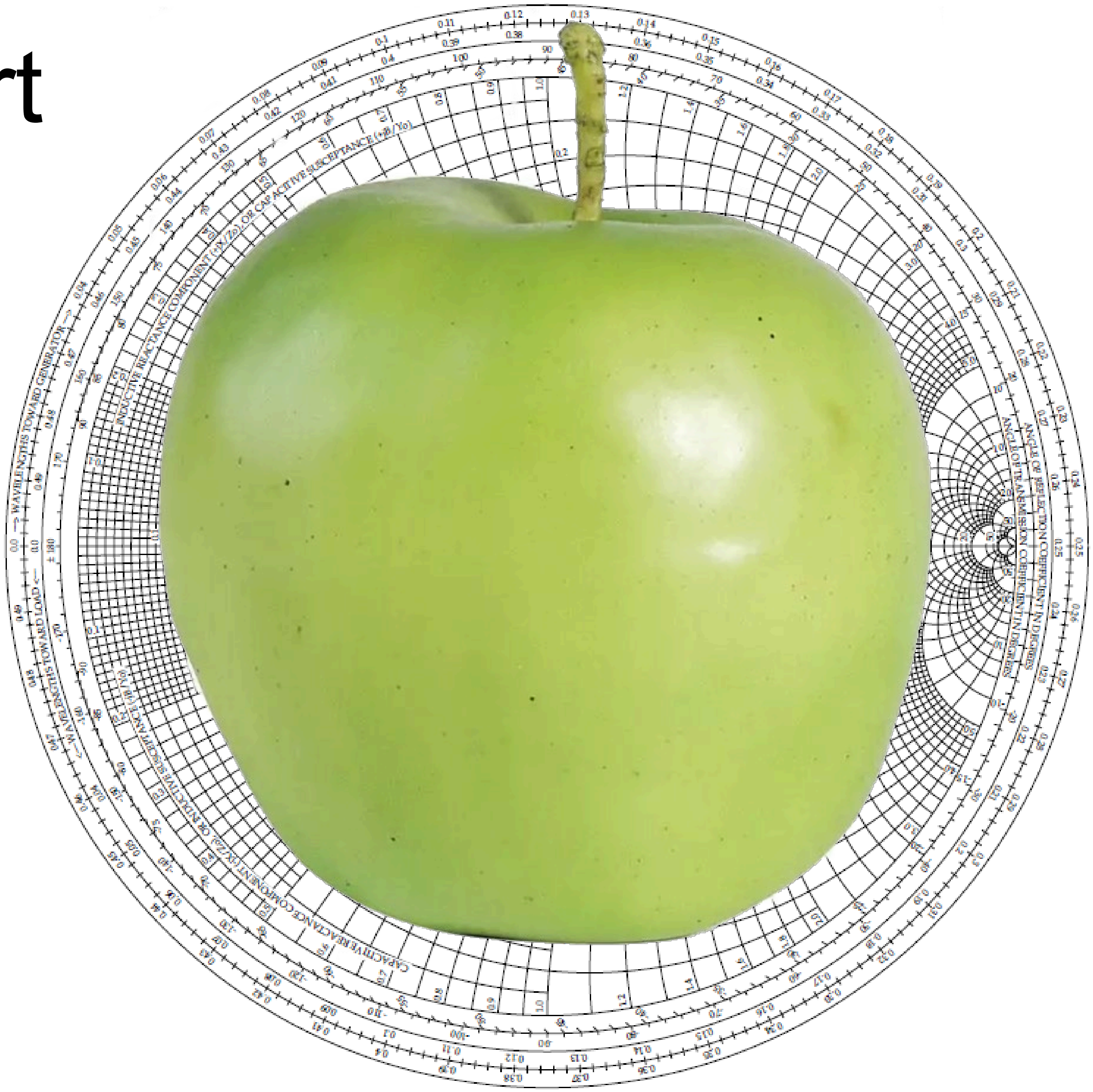
Smith Chart

- Easily visualize complex impedances
- Provides graphical depiction of impedance vector
- A 1:1 VSWR is in the center of the chart
- This chart is normalized so that a perfect non-reactive impedance is at the center (1 +j0)
- Can be used for impedance matching



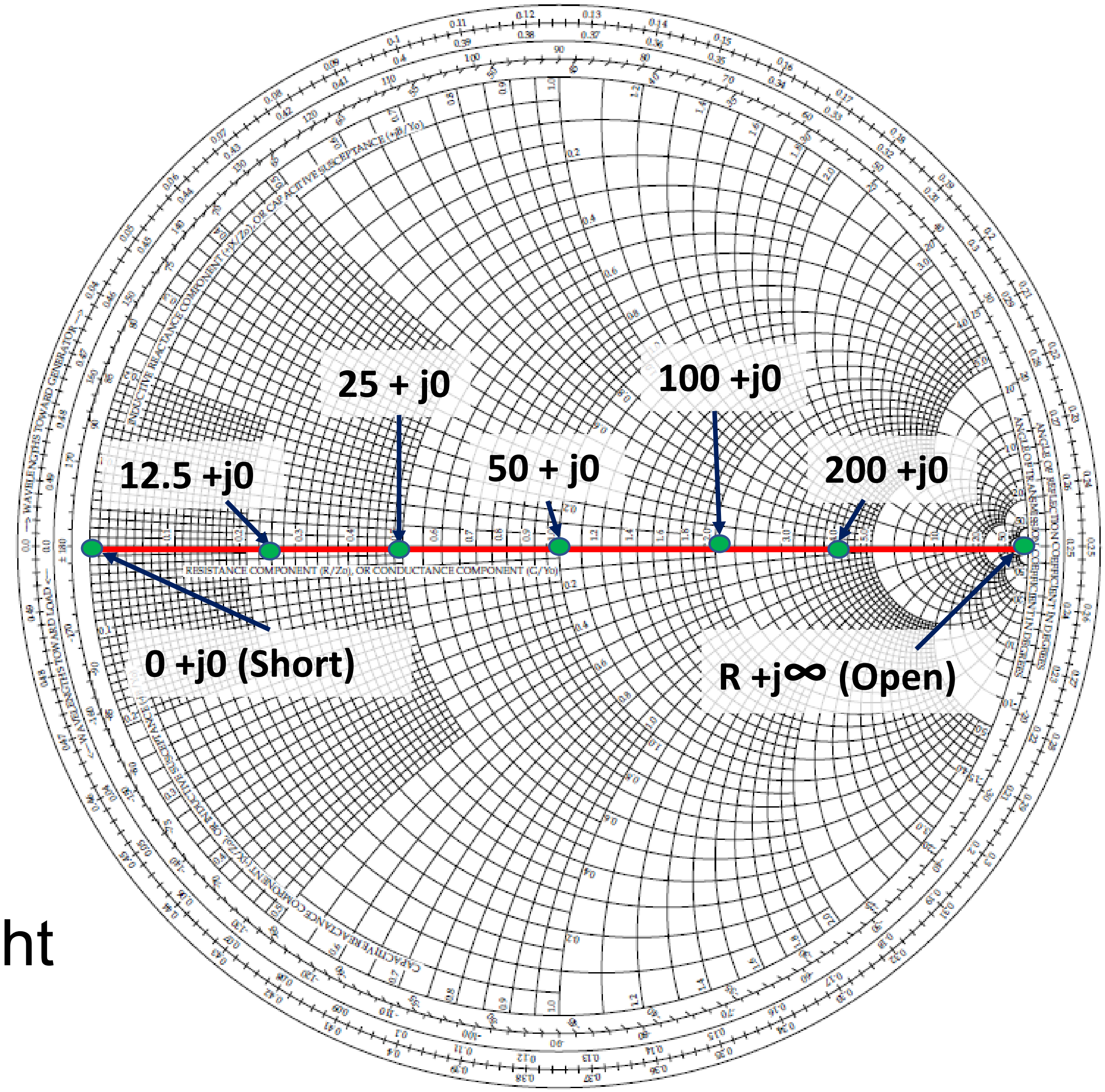
Granny Smith Chart

- Please get a copy of the PDF that was sent with the meeting invitation or handed out.
- The chart notations are too small to show up on a presentation.



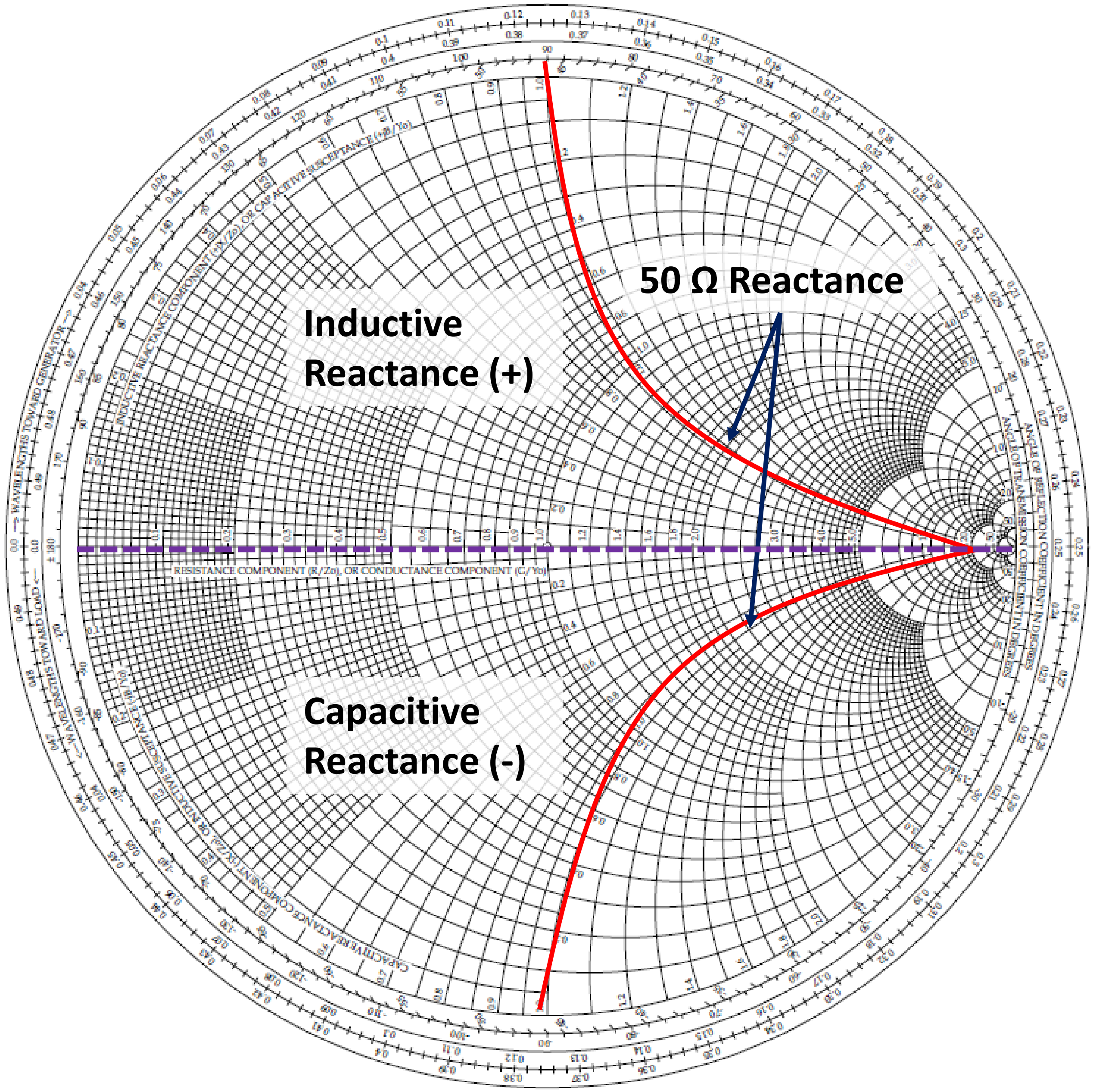
Resistance Axis

- The chart is normalized to 1 Ω
- Line of zero reactance
- Z_0 is in the center (1 + j0)
- In this case 50 Ω
- A 50 Ω non-reactive load is in the center of the chart
- A short is on the left
- An open (infinite reactance and/or resistance) is on the right



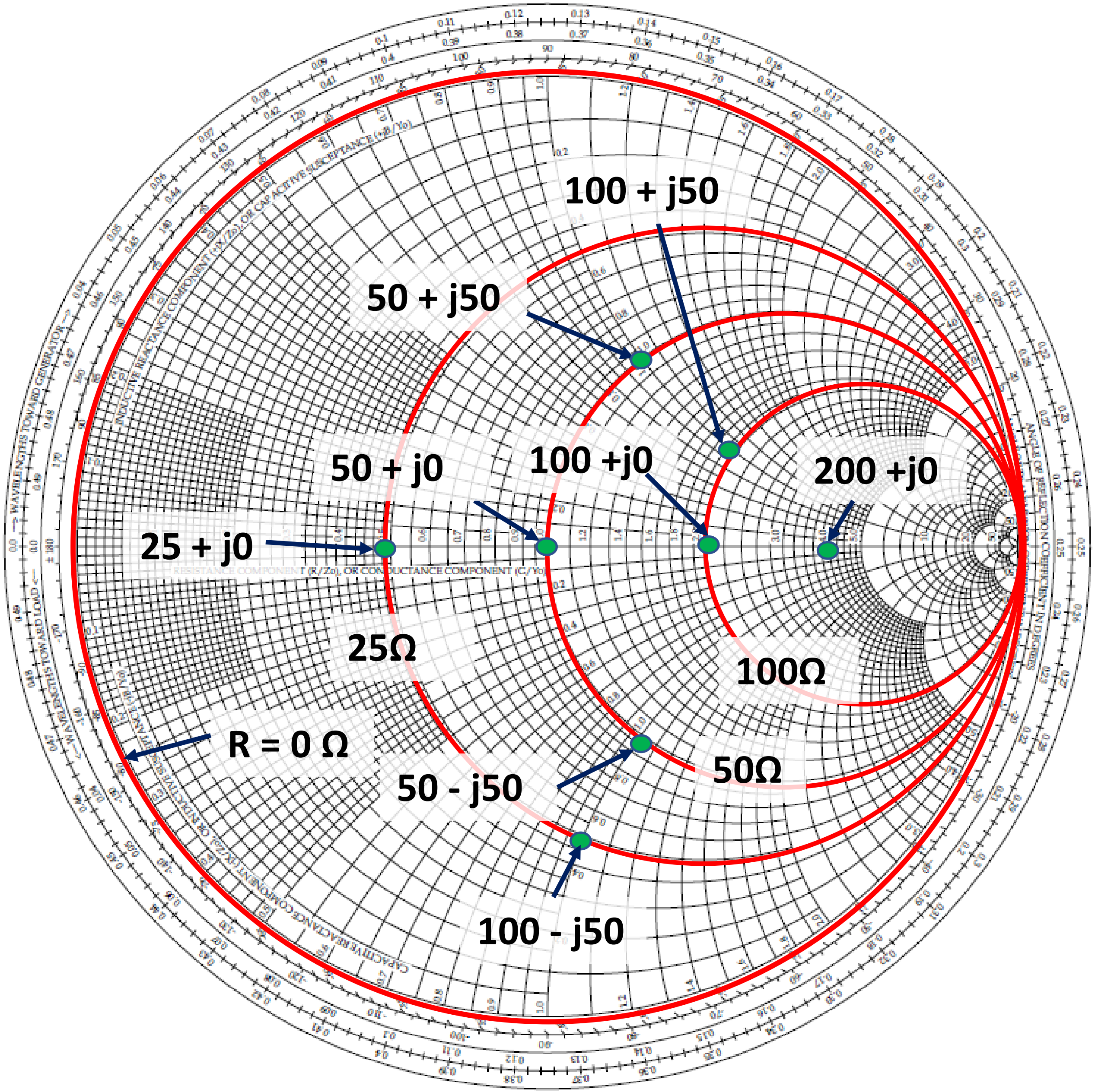
Reactance Lines

- Reactive components of impedance are above and below the pure resistance line.



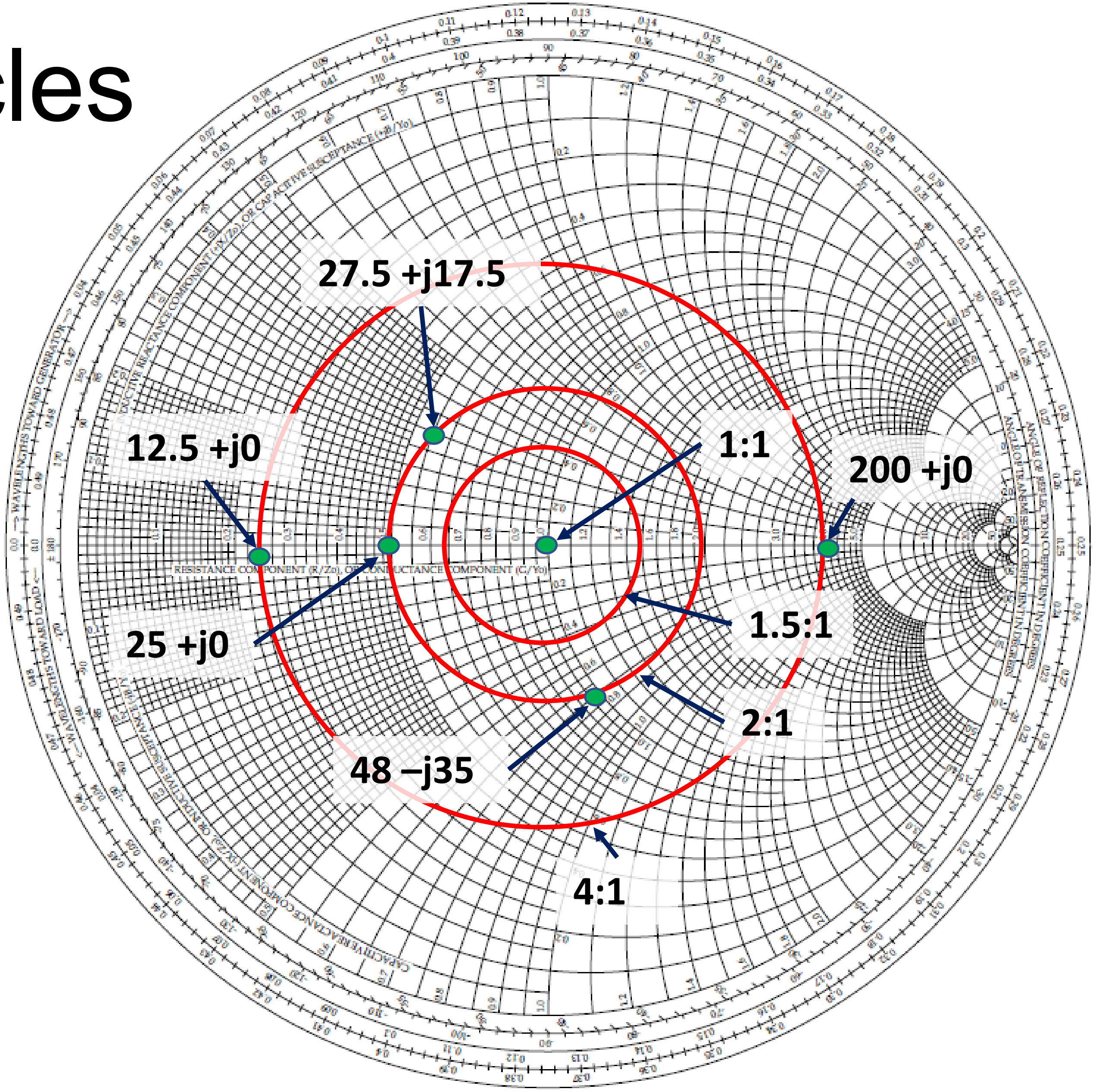
Resistance Circles

- The red circles show constant resistance.
- Inductive reactance (+) is above the line
- Capacitive reactance (-) is below the line
- An open circuit is on the right end of the resistance axis at R + j∞
- A pure reactance is on the R=0 outer circle 0 + jx



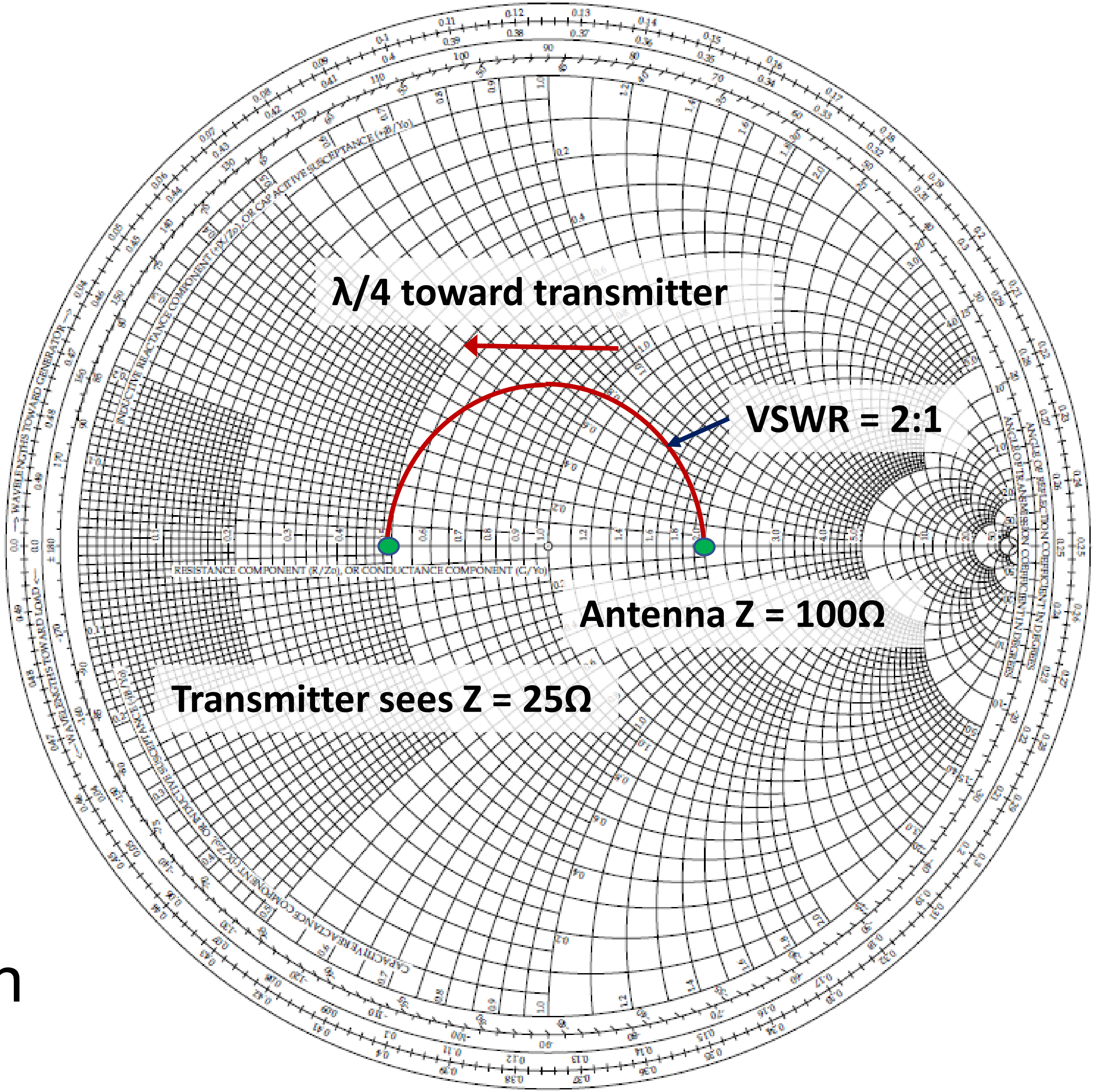
Constant VSWR Circles

- The center is a 1:1 VSWR
- Each circle is a constant VSWR
- A 2:1 VSWR can be anywhere on the 2:1 circle
- (27.5+j17.5), (25+j0), and (48-j35) all are 2:1 VSWR



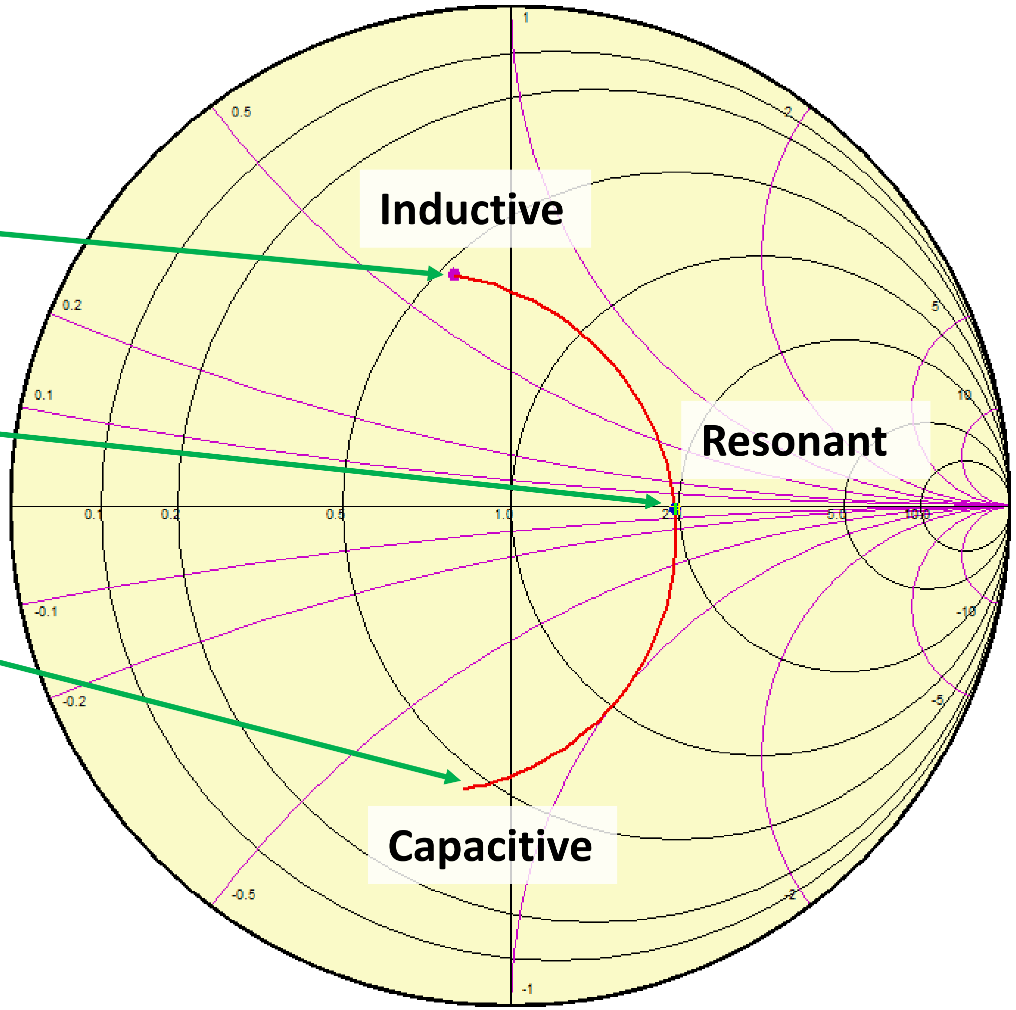
Moving Around

- The red circle shows exactly one-half electrical wavelength of cable length.
- Clockwise is toward the transmitter.
- Counter-clockwise is toward the antenna.
- A quarter wavelength is diametrically opposite.
- A quarter wave cable is shown



160-meter Antenna Example

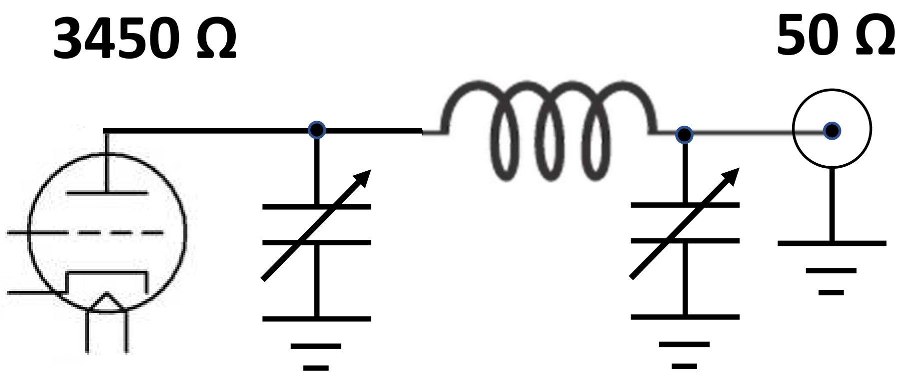
- **2.0 MHz: Z = 22.2 –J37.2, VSWR = 3.67:1**
- **1.9 MHz: Z = 98.6 +j0, VSWR = 1.97:1**
- **1.8 MHz: Z = 26.8 +j31.0, VSWR = 2.8:1**

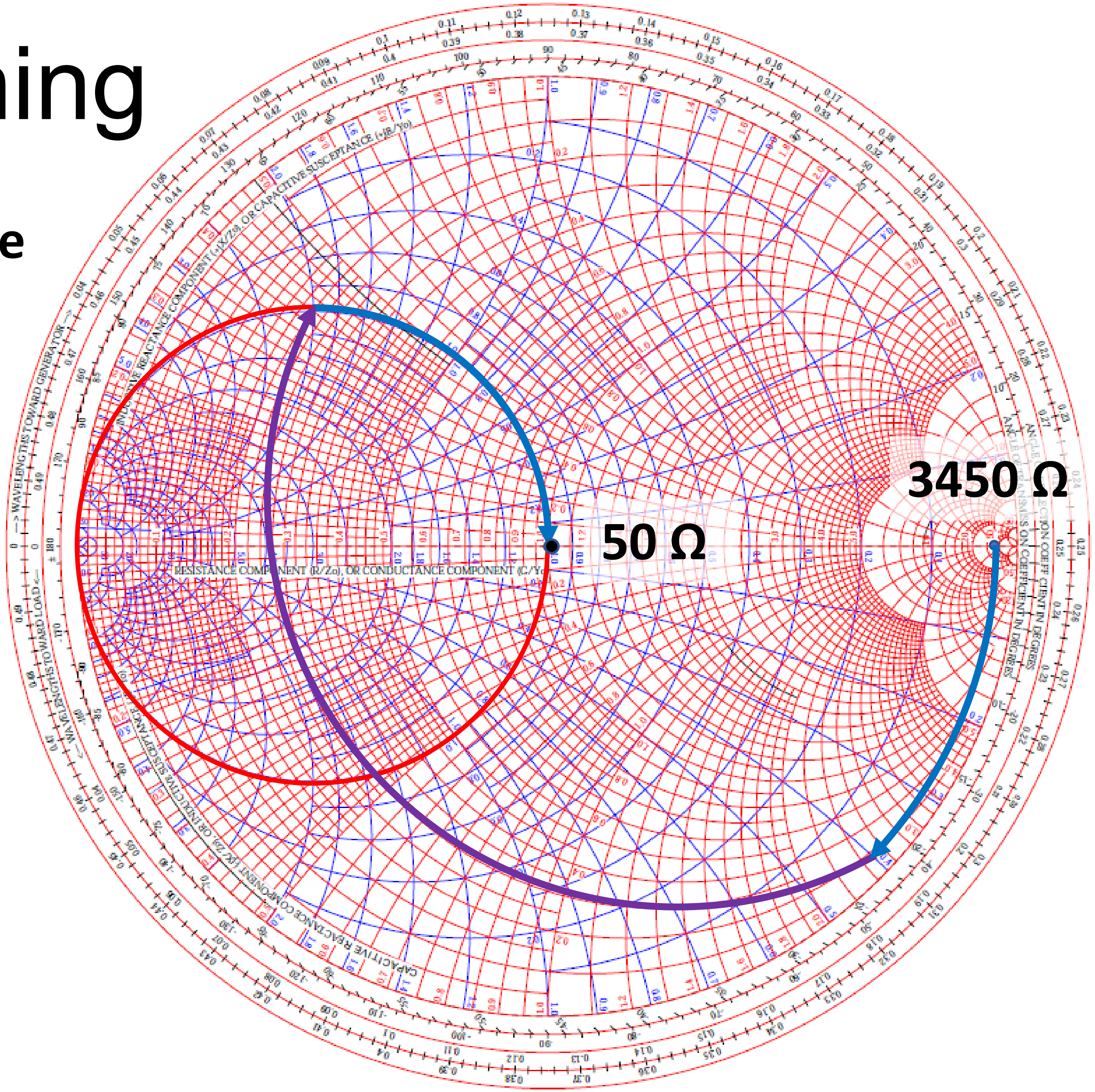


Tube Output Matching

Note: Using a Smith chart for impedance matching is a separate subject and is shown here to illustrate a point.

A typical π network will easily tune over a 3:1 VSWR range



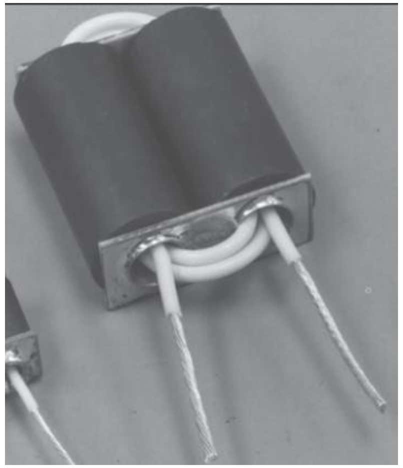


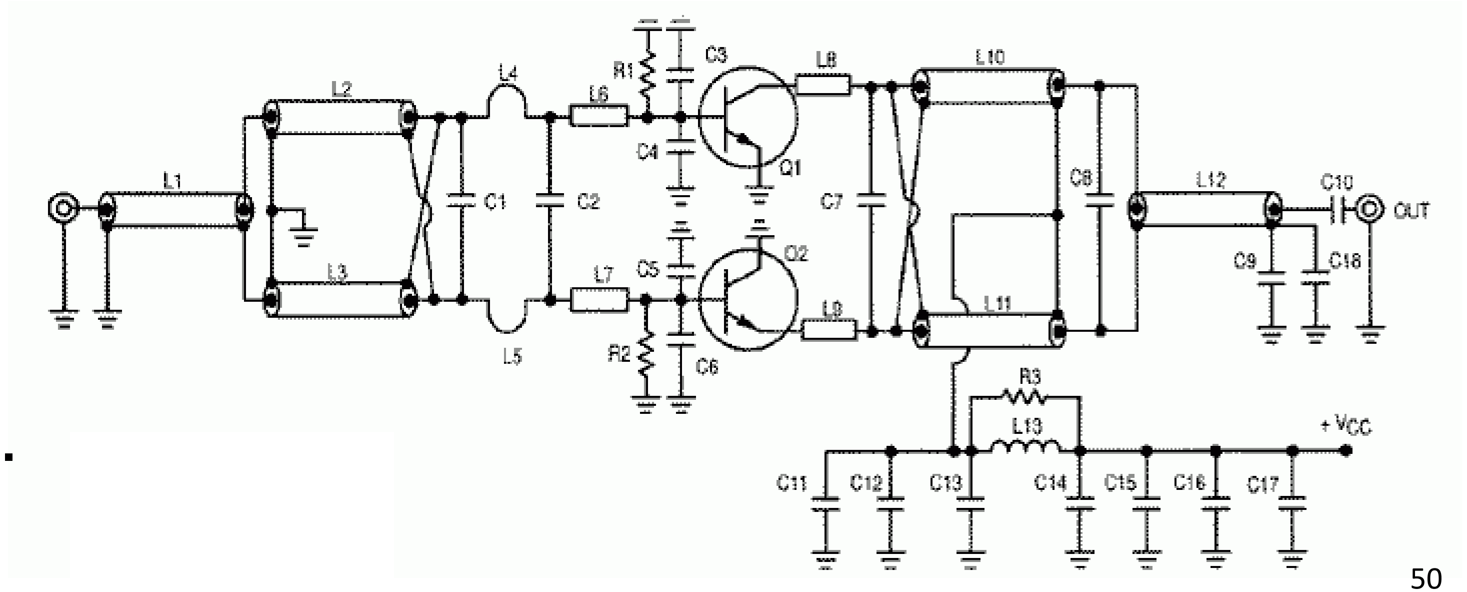
Transistor (or FET) RF Amplifier

- Most amateur radio transceivers and solid state amplifiers have built-in antenna tuners.
- Solid state RF power amplifiers are matched to 50 Ω using a transformer.
- The transformer impedance ratio is fixed.
- Reflected power is dissipated in the transistors.

$$Z_0 = \frac{(VCC - VCESAT)^2}{2\ Po}$$

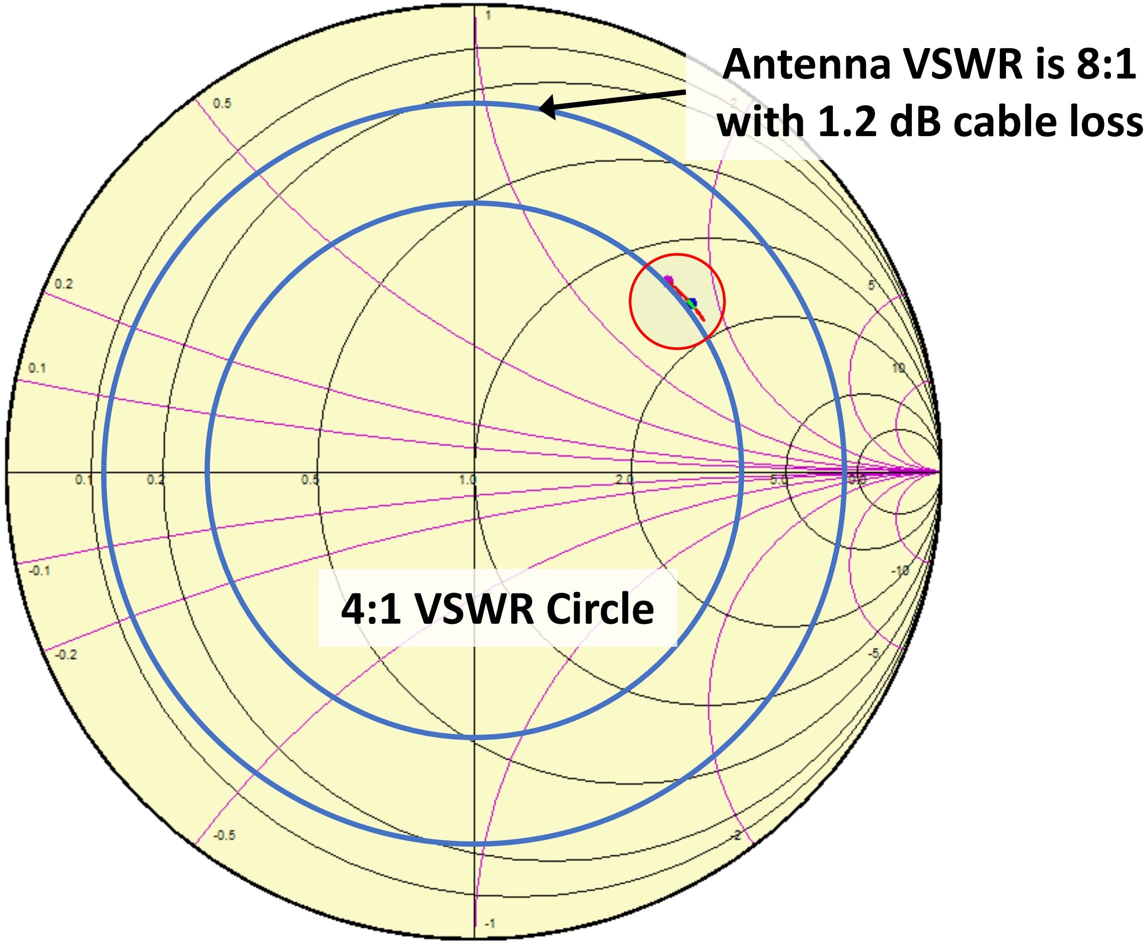
- **For 100 watts out, each transistor is putting out 50 watts and they are in series.**
- **Each has an output impedance of 1.44 Ω**
- **2.88 Ω to a 16:1 transformer is 46 Ω**



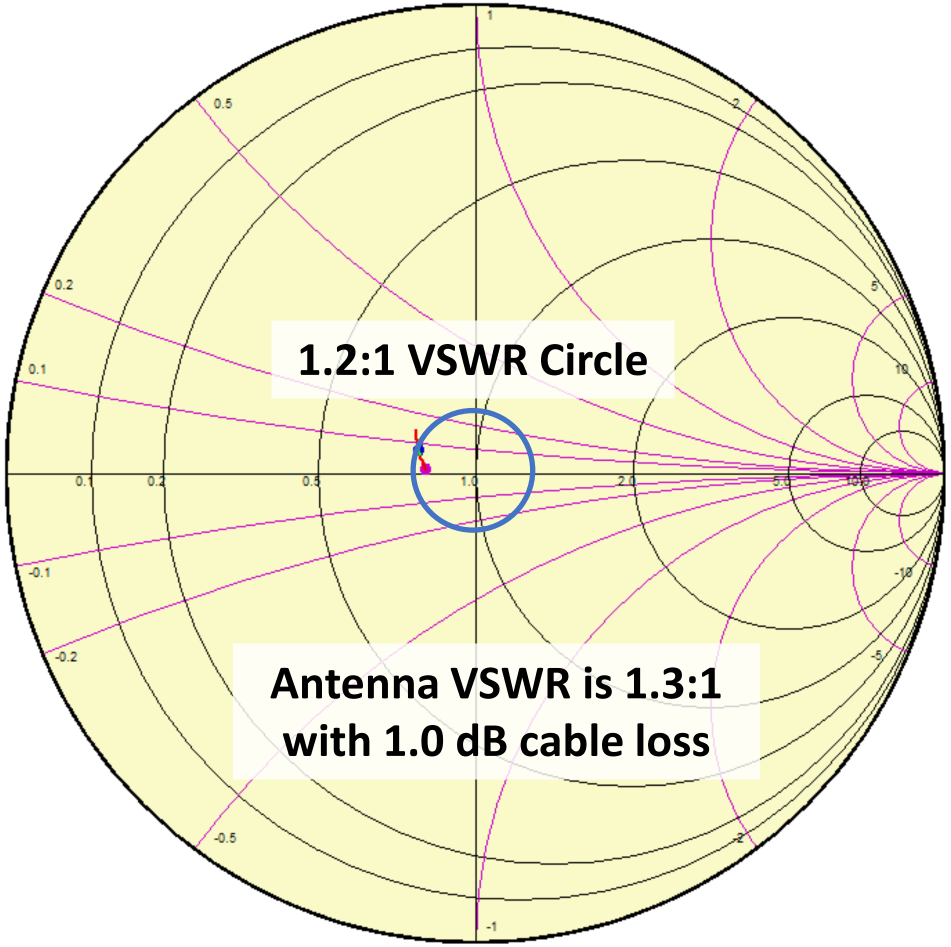


Impedance Matched Antennas are Best

OCF Dipole VSWR = 4:1 at transmitter

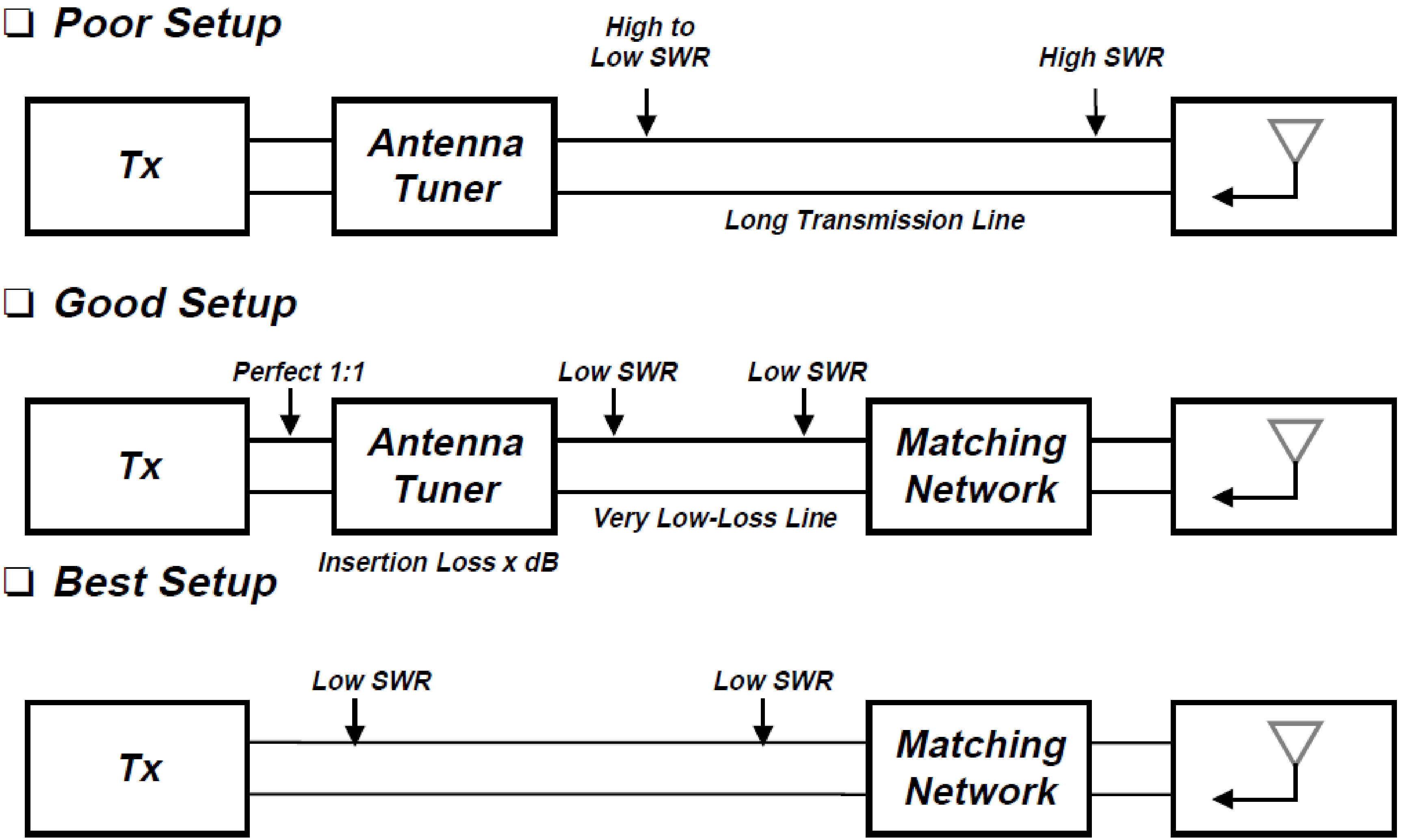


30-meter Dipole VSWR = 1.2:1 at transmitter



Antenna Tuner Placement

- The "Poor Setup" is what most stations use, and works well at lower frequencies.
- At VHF and up, it is best to match the antenna impedance to the coaxial cable impedance.



Using VNAs to analyze Antennas

- The advantage that a VNA has over VSWR measurements is that the VNA provides phase information.
- The Smith Chart provides a better graphic representation of the antenna parameters than a VSWR-only sweep.
- The VSWR sweep and Smith chart information are used for tuning antennas.

Using the Nano VNA

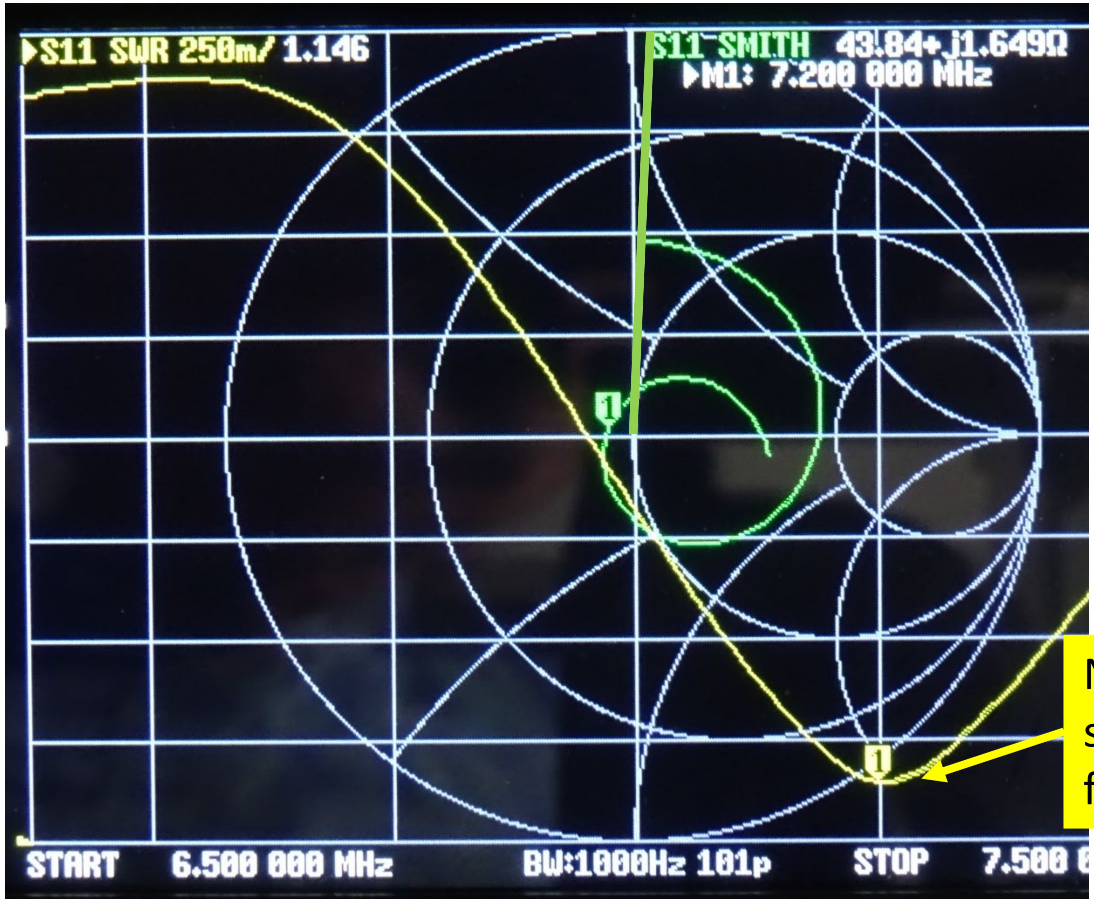
- Charge its internal battery
- Select the measurement frequency range
- Calibrate over the selected frequency range
    - Open
    - Short
    - Load (50Ω)
    - Isolation (if testing a filter)
    - Through (if testing a filter)
- Demo video follows

Using VNA Data

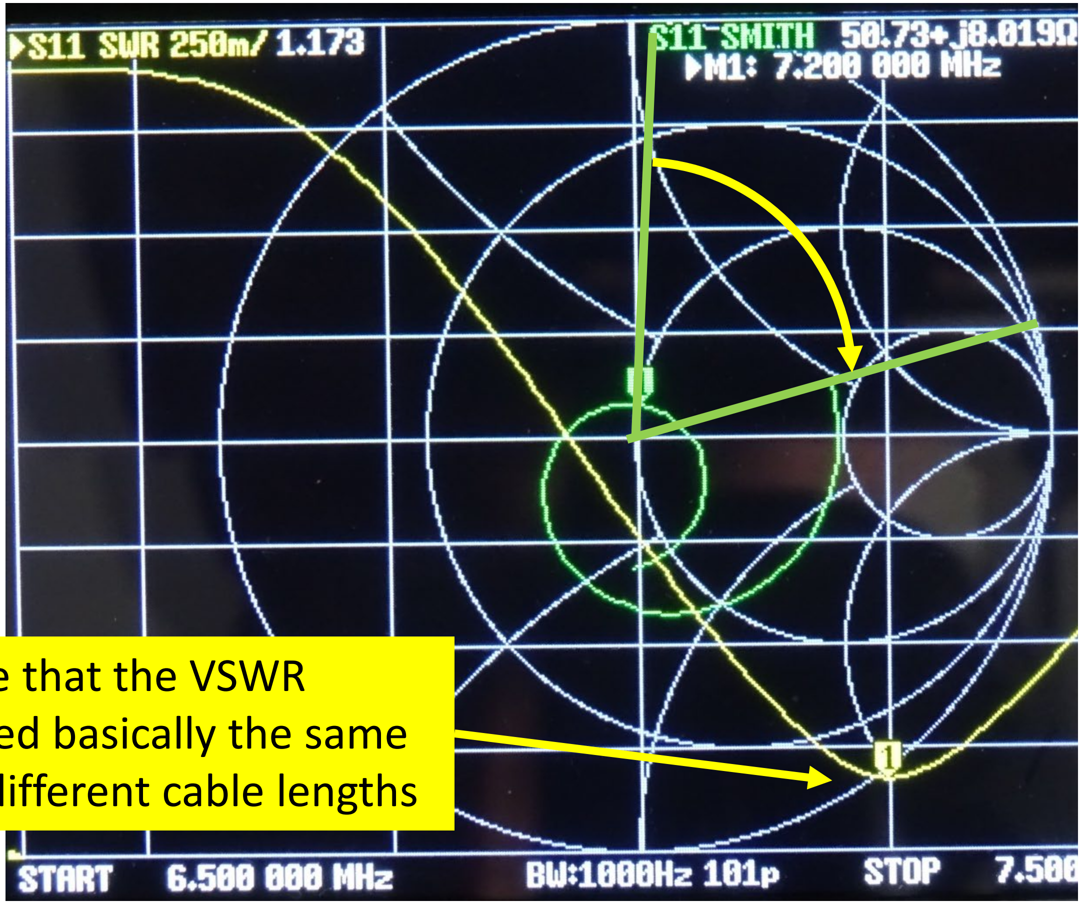
- A popular use of a VNA is to tune an antenna
- Build the antenna with elements longer that calculated
- Run VSWR and Smith chart plots
- Decide how much to trim the antenna
- Make an adjustment and run another plot
- Bear in mind that the resonant frequency of an antenna is not necessarily the frequency with the lowest VSWR
  - For example, a horizontal dipole has an impedance of about 73Ω at resonance (1.46:1 VSWR)

Cable Length Effect

Shorter Cable 43.84 + j1.65



Longer Cable 50.73 + j8.02



Note that the VSWR stayed basically the same for different cable lengths

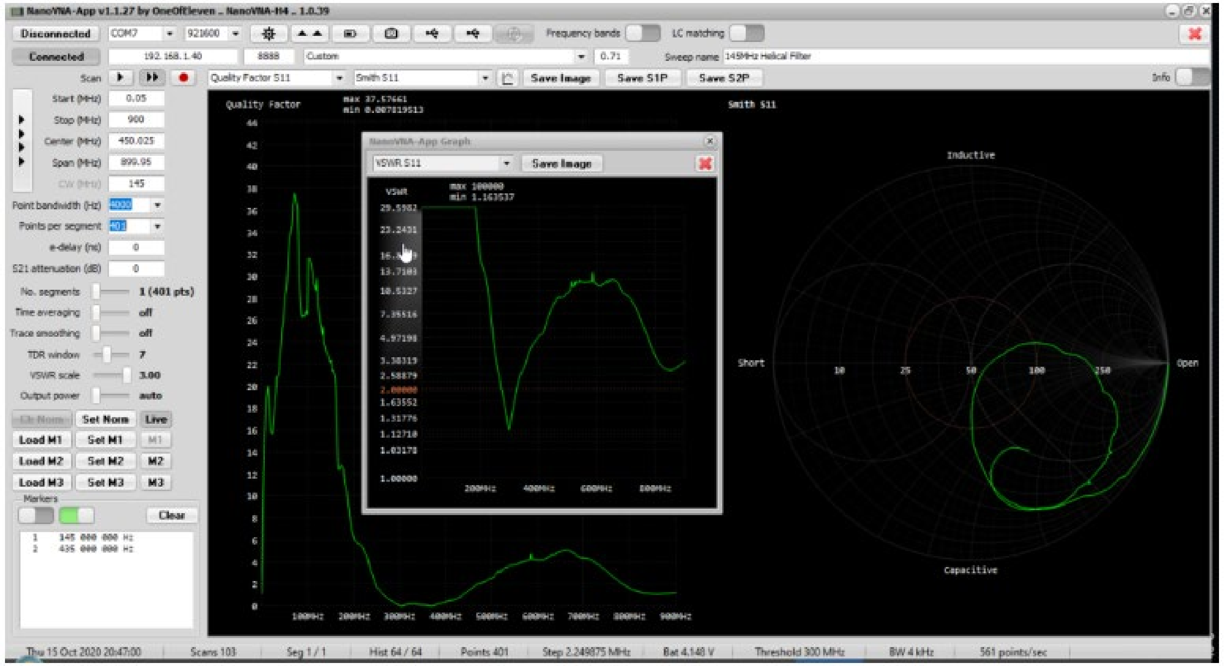
Software

- **There are several versions of software for the Nano VNA**
- **This one is: https://nanovna.com/?page_id=141**
- **Load the software**
- **Find the COM port**
- **Connect**
- **Note that the software view is not the same as what is on the Nano VNA screen**
- **The software will allow up to 401 measurements, while the unit only has 101**

NanoVNA-App

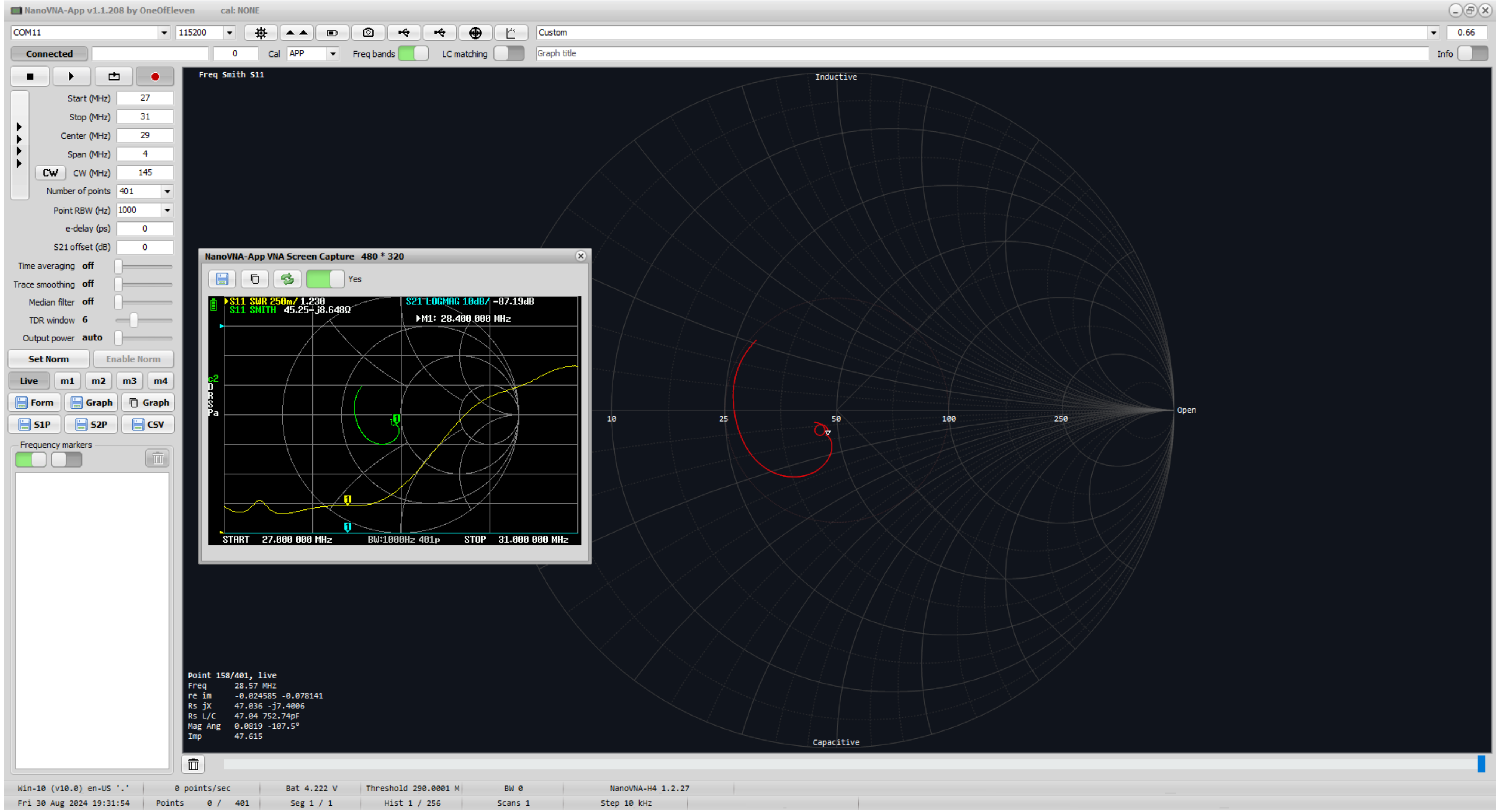
NanoVNA-App is the very powerful windows software developed by OneOfEleven for NanoVNA and LibreVNA.

You can download the pre-compiled software here.



If you wish to participate in the development, you can access the source code here.

10-meter Ground Plane Using Software



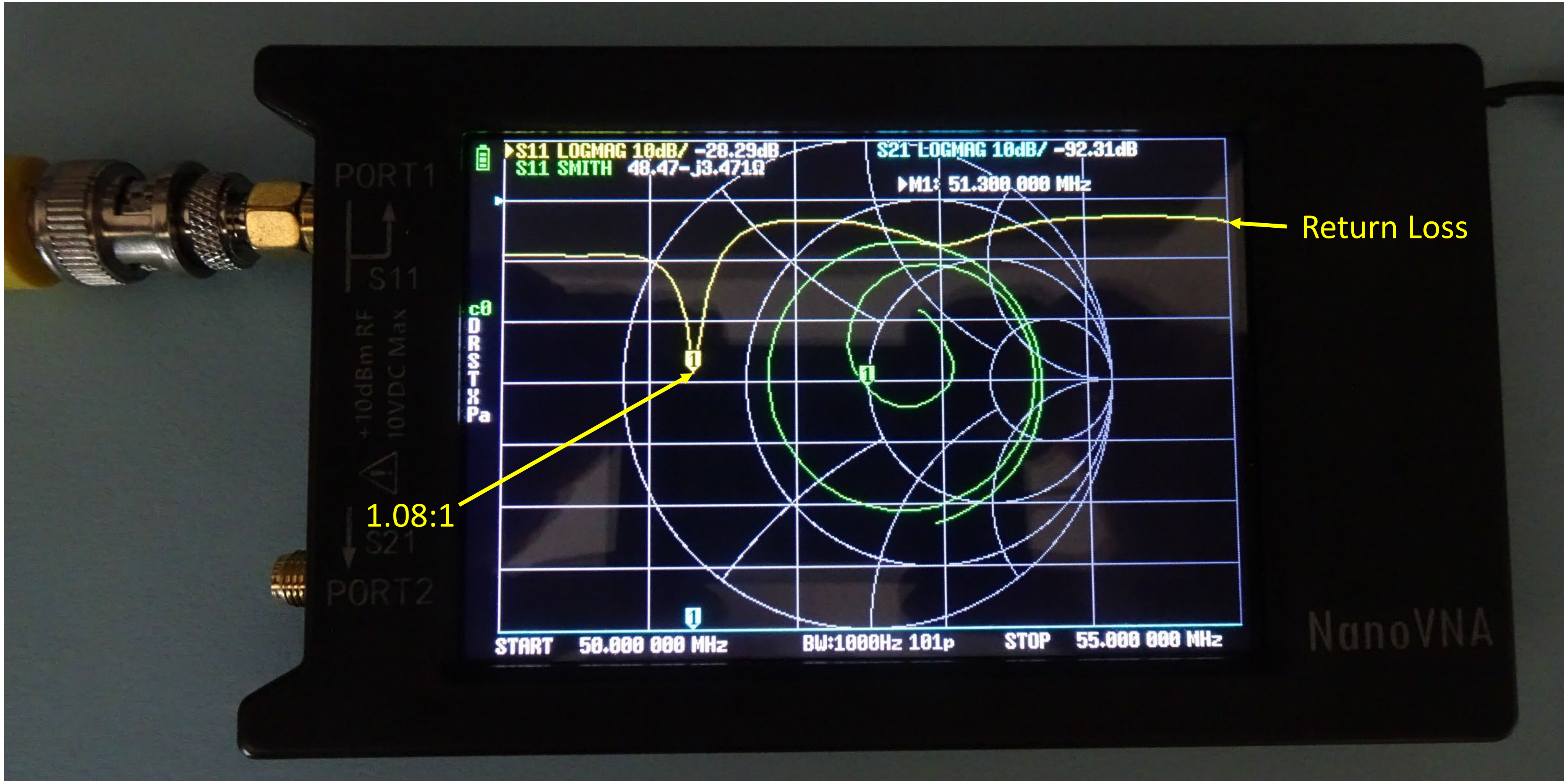
Calibration Using Software

- Similar to the stand-alone procedure
- Software can use 401 calibration and display points instead of the 101 point limit on the Nano VNA itself
- Calibration data is stored on the computer, not the Nano VNA
- Live demo follows (if time permits)

Not covered in this presentation

- Time-domain reflectometer
  - For finding faults in installed antenna systems
- Tuning repeater diplexers
- Filter testing (low-pass, high-pass, bandpass)
- Pre-tuning an antenna tuner on SOTA and POTA activations
  - Does not use battery power for tuning
- Cable impedance testing
  - Personally, I don’t use unknown cables

The End


S11 LOGMAG 10dB/ -28.29dB
S11 SMITH 48.47-j3.471Ω
S21 LOGMAG 10dB/ -92.31dB
M1: 51.300 000 MHz
Return Loss
1.08:1
PORT1
S11
S21
PORT2
START 50.000 000 MHz
BW:1000Hz 101p
STOP 55.000 000 MHz
NanoVNA