



# The NanoVNA and Some of Its Many Uses in the Ham Shack

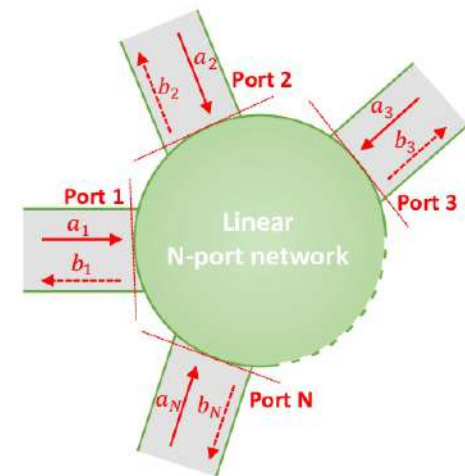
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ak3y@arri.net

# Outline of Talk

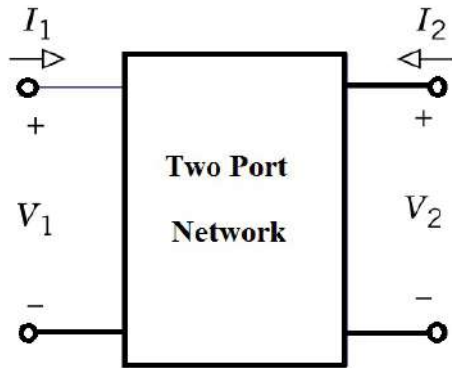
- N-Port Linear Networks
- Scattering Parameters
  - S-parameters and Return Loss, VSWR, Gain, Impedance
  - Antenna Analyzers vs. Vector Network Analyzers
- NanoVNA Hardware Architecture
- Smith Chart Basics
- Using the NanoVNA
  - Measuring Antennas
  - Measuring Passive Networks – Diplexers, Filters
  - Designing Crystal Ladder Filters
  - RF Amplifier Characterization (Gain & Impedance)
  - Coax Cable Measurements ( $Z_0$  and loss)
  - Grid Dip Oscillator
  - Time Domain Reflectometry (Fault detection)
  - Matching Networks
  - Antenna Gain and Radiation Pattern

# N-Port Linear Networks

- Examples of 1-Port Networks
  - All of the basic circuit elements – R, L, C, Voltage and Current sources
  - Complex impedances – e.g., LC tank circuits
  - Antennas
- Examples of 2-Port Networks
  - Filters
  - Matching networks
  - Transmission lines
  - Transformers
  - Small-signal models for transistors (e.g., hybrid- $\pi$  models), FETs
- Examples of N-Port Networks
  - Duplexers, diplexers
  - Directional couplers
  - Power dividers/combiners (hybrids)



# Two-Port Network Analysis



$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad \text{Matrix Representation}$$

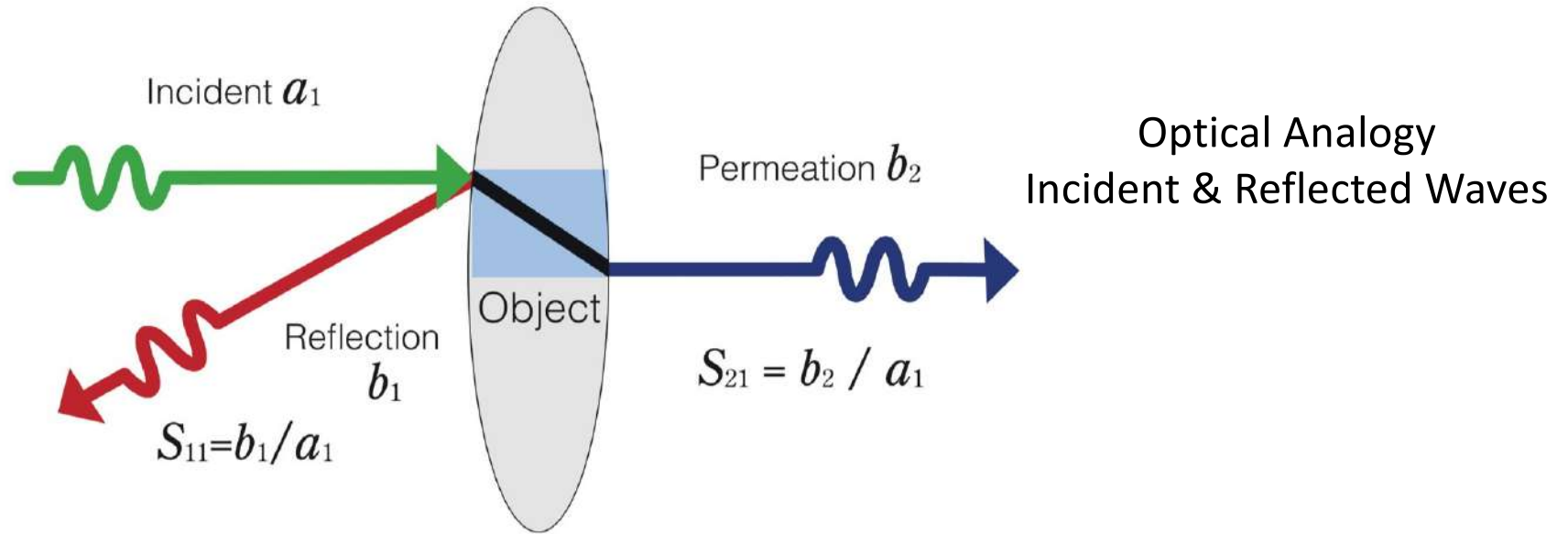
$$\begin{aligned} V_1 &= Z_{11}I_1 + Z_{12}I_2 \\ V_2 &= Z_{21}I_1 + Z_{22}I_2 \end{aligned}$$

- The 2-port network can be completely described by a set of 4 complex impedance parameters  $Z_{11}$ ,  $Z_{12}$ ,  $Z_{21}$  and  $Z_{22}$

$$Z_{11} = \left. \frac{V_1}{I_1} \right|_{(I_2 = 0)} \quad Z_{12} = \left. \frac{V_1}{I_2} \right|_{(I_1 = 0)} \quad \text{etc.}$$

- Very difficult to directly measure RF current or to implement an open circuit at very high frequencies (stray capacitance and inductance)

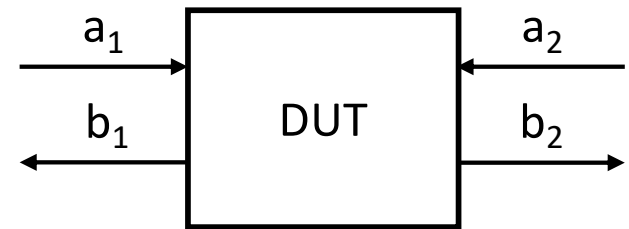
# Scattering or “S” Parameters



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad \text{Matrix Representation}$$

$$b_1 = S_{11}a_1 + S_{12}a_2$$

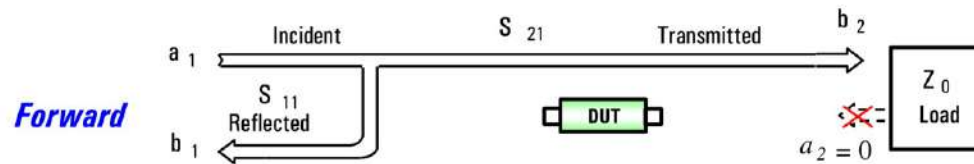
$$b_2 = S_{21}a_1 + S_{22}a_2$$



## Measuring S-Parameters

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

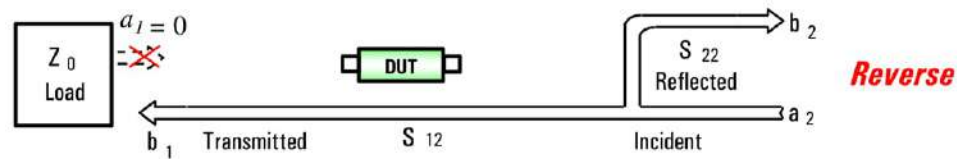


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1} \Big|_{a_2 = 0}$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1} \Big|_{a_2 = 0}$$

$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_2}{a_2} \Big|_{a_1 = 0}$$

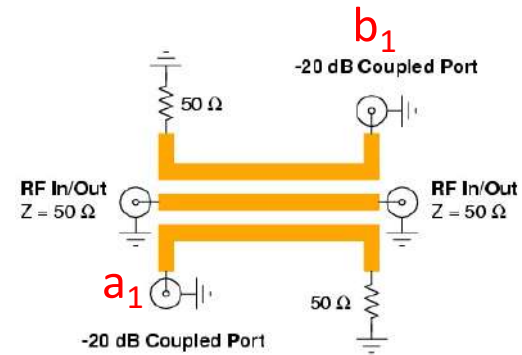
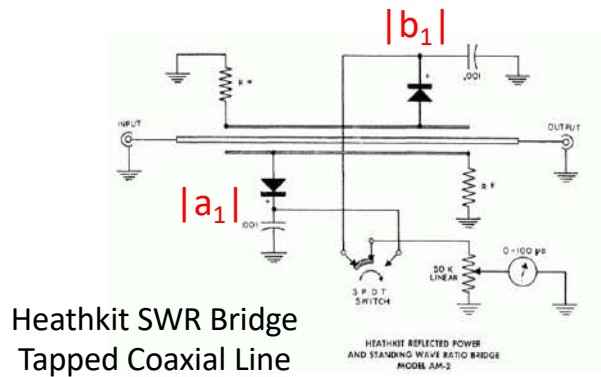
$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2} \Big|_{a_1 = 0}$$



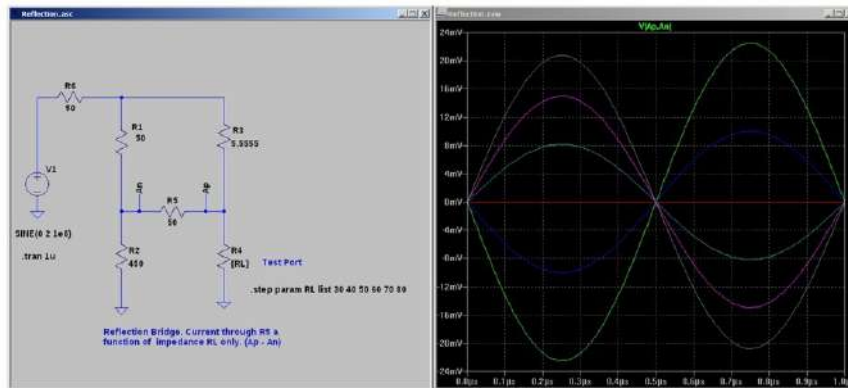
$a_2=0$  ( $a_1=0$ ) occurs when line is terminated with a load having characteristic impedance  $Z_0$

# How does one physically measure a scattering parameter?

- Directional Couplers (limited bandwidth)



- Wheatstone Bridges (wide bandwidth ~ multiple GHz)



## Basis of NanoVNA

“The Wheatstone Bridge: How Does It Impact VNA Measurements?” Brian Walker, *Microwaves & RF*, 25 July 2018

Current through bridge resistor R5 directly proportional to reflection coefficient at Test Port (R4)

# Common Quantities in Terms of S Parameters

- Return Loss (RL)

$$RL = 10 \log_{10} \frac{1}{|S_{11}|^2} = -20 \log_{10} |S_{11}| \quad \text{dB}$$

- Voltage Standing Wave Ratio (VSWR)

$$\text{VSWR} = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

- System Gain (G) or Loss

$$G = 10 \log_{10} |S_{21}|$$

- Impedance

$$Z = Z_0 \frac{1 + S_{11}}{1 - S_{11}}$$

$$\Gamma \equiv S_{11} = \frac{Z - Z_0}{Z + Z_0} \quad \text{“reflection coefficient”} \quad (0 < |\Gamma| < 1)$$

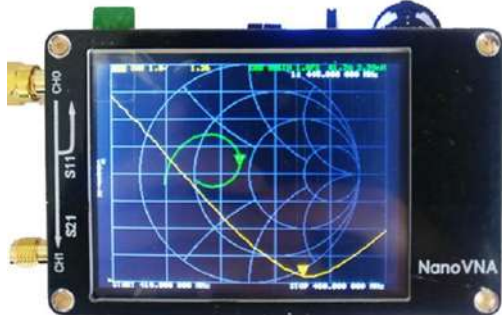


# Antenna Analyzers vs VNAs

- Antenna Analyzers

- Only measure one-port (two terminal) networks
  - Antenna VSWR and driving point impedance
  - Cannot remove effects of connecting cables, low-pass or high-pass filters, etc.

RigExpert AA-600  
0.1 - 600 MHz  
\$519.95



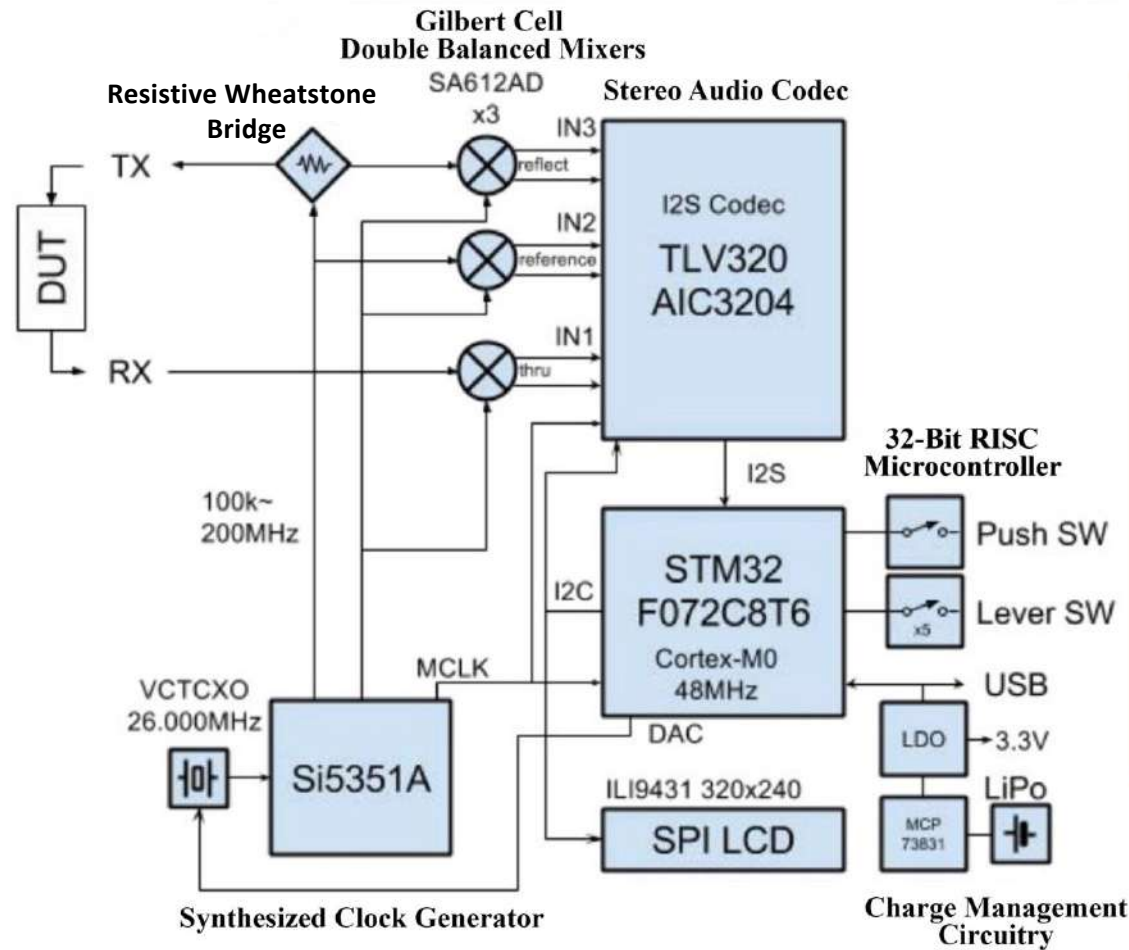
NanoVNA  
0.01 - 1500 MHz  
\$65.95

- Vector Network Analyzers

- Can measure two-port (four terminal) networks
  - Antenna VSWR and driving point impedance
  - Filter parameters, small-signal transistor parameters, multi-port networks (e.g., duplexers, diplexers, couplers), transmission lines, etc.
  - Can remove effects of connecting cables and other passive circuitry through calibration at measurement plane

See, for example, the article by Denis Nechitailov, UU9JDR  
<https://rigexpert.com/a-short-review-of-antenna-and-network-analyzers/>

# NanoVNA System Block Diagram



**Frequency Range: 10 kHz to 1500 MHz**

**RF Output: -13 dBm (-9 dBm max)**

**Dynamic Range:**

- 70 dB (10 kHz to 300 MHz)
- 60 dB (300 MHz to 600 MHz)
- 50 dB (600 MHz to 900 MHz)
- >30 dB (900 MHz to 1500 MHz)

**Power: External: USB 5V 120mA**  
**Internal: LiPo 400 mAH**

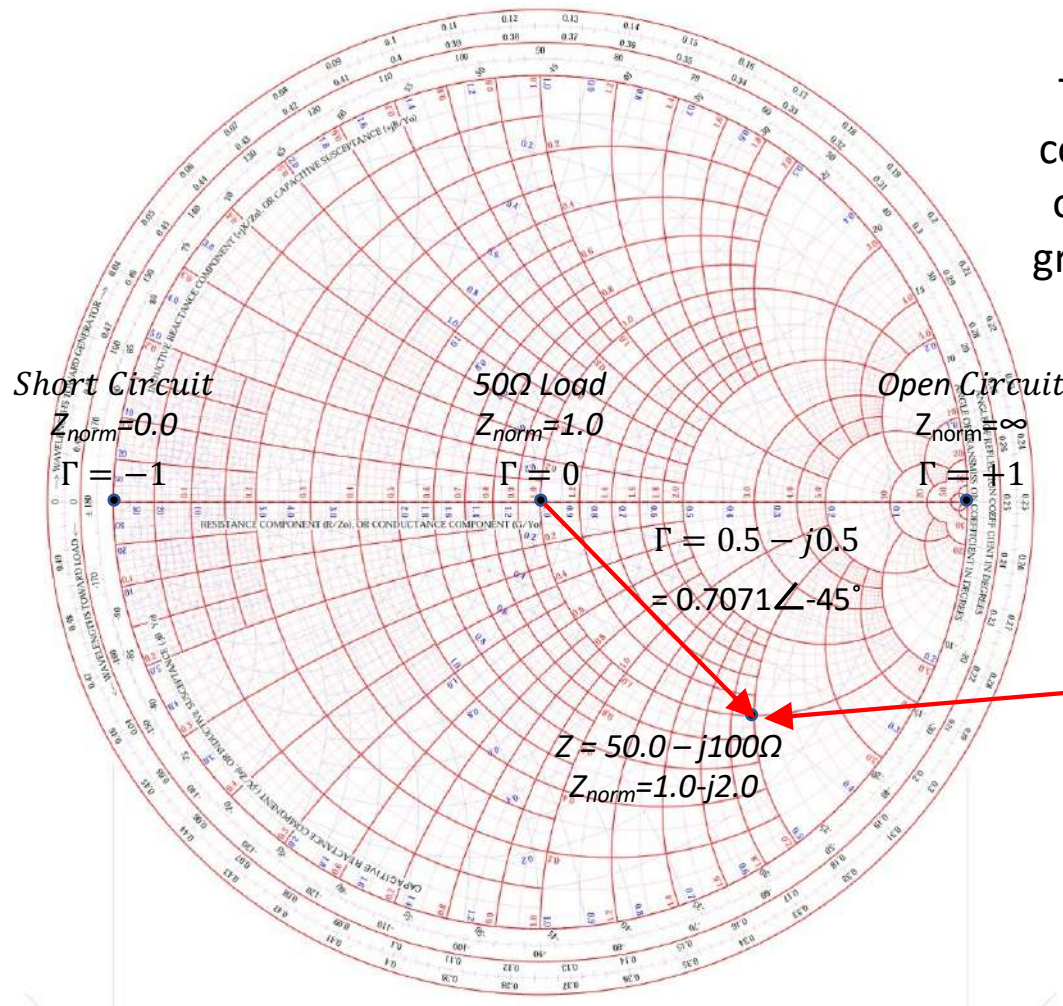
**USB Interface: Type C (power & data)**

**Display: 4 traces, 4 markers**  
**5 memories for calibration**

**Frequency Accuracy: < 0.5ppm**

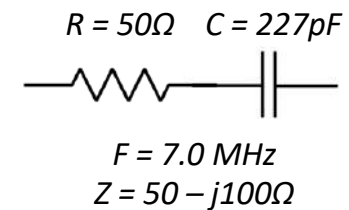
**Data: Internal 101 data points**  
**Use NanoVNA-Saver software for larger number of points**

# Smith Chart Basics

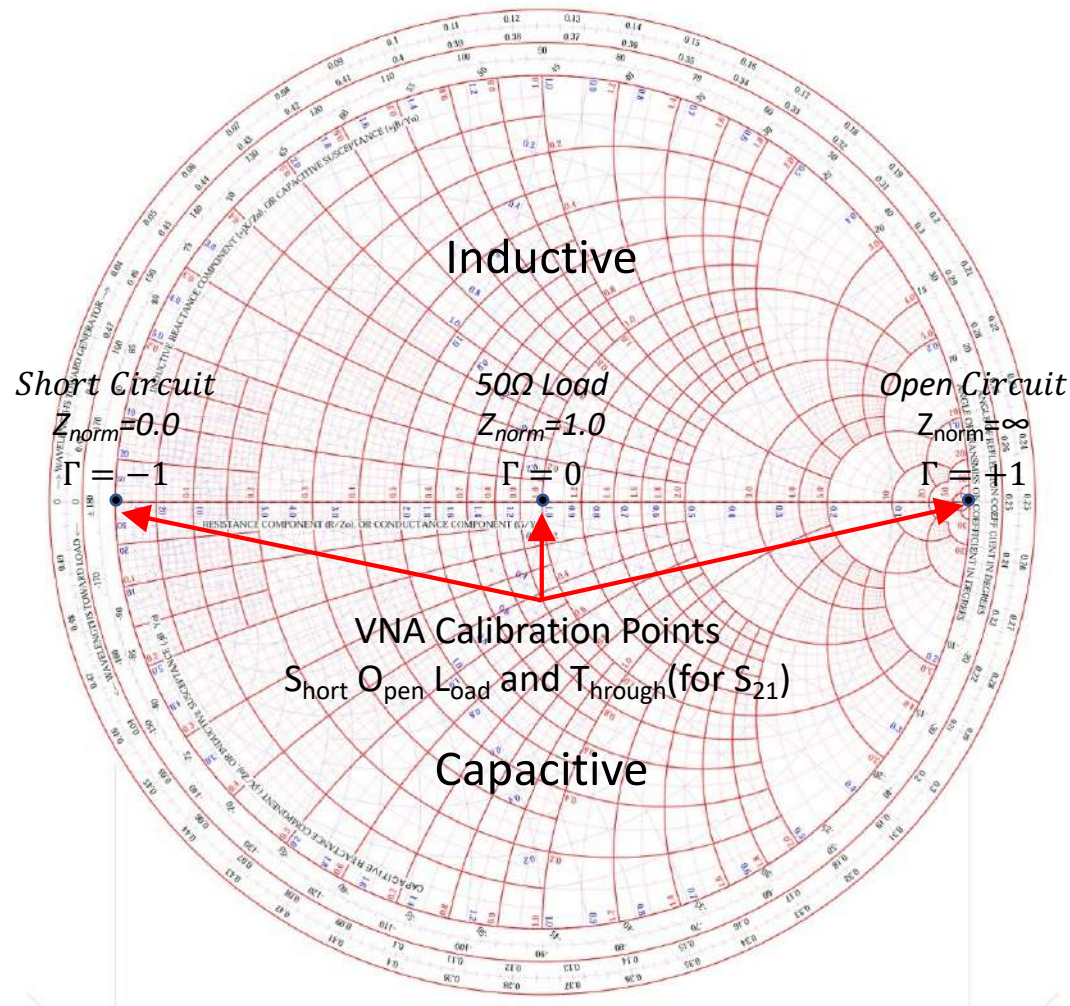


The Smith Chart is simply a plot of the complex reflection coefficient  $\Gamma$  overlaid onto an impedance and/or admittance grid referenced to a 1-ohm characteristic impedance

$$\Gamma \equiv S_{11} = \frac{Z - Z_0}{Z + Z_0}$$



# Smith Chart Basics



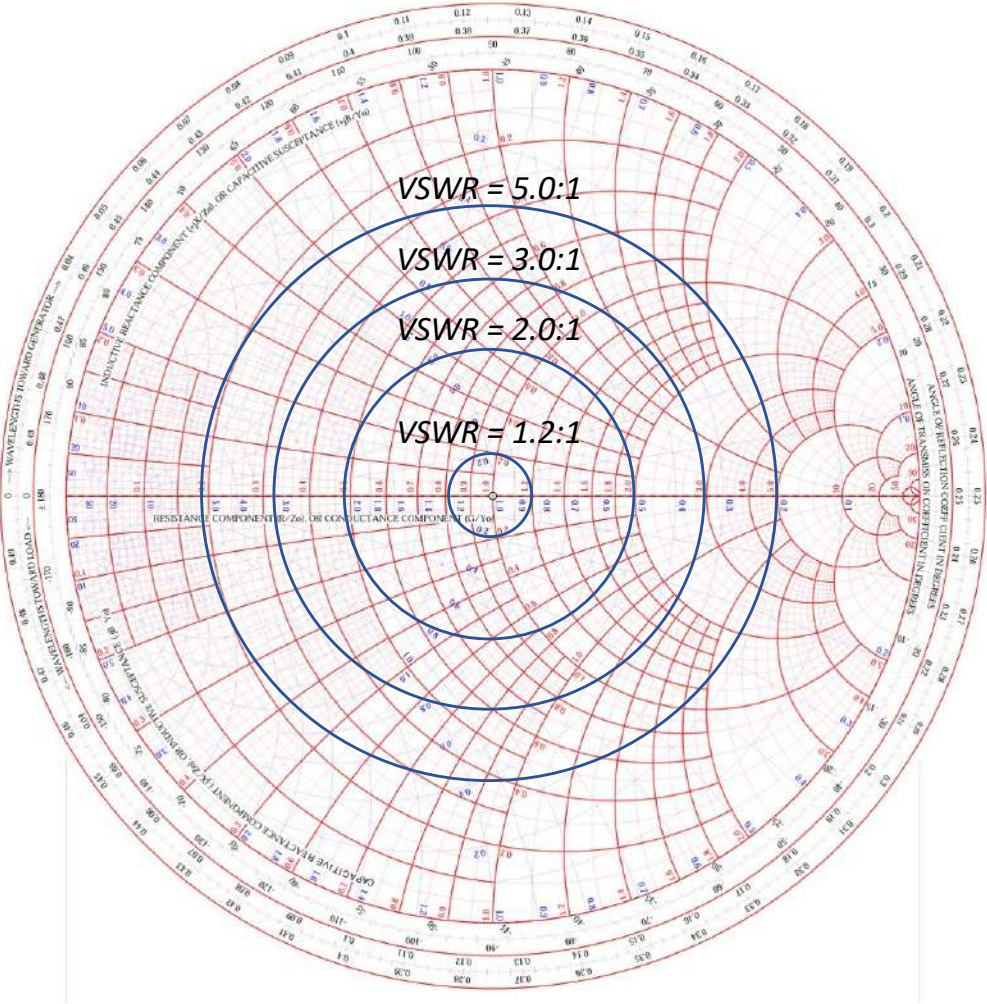
Two Extremes on the Real Axis of the Smith Chart Represent Short & Open Circuits

Center of Smith Chart Represents a Perfect Match ( $Z = Z_0$ )

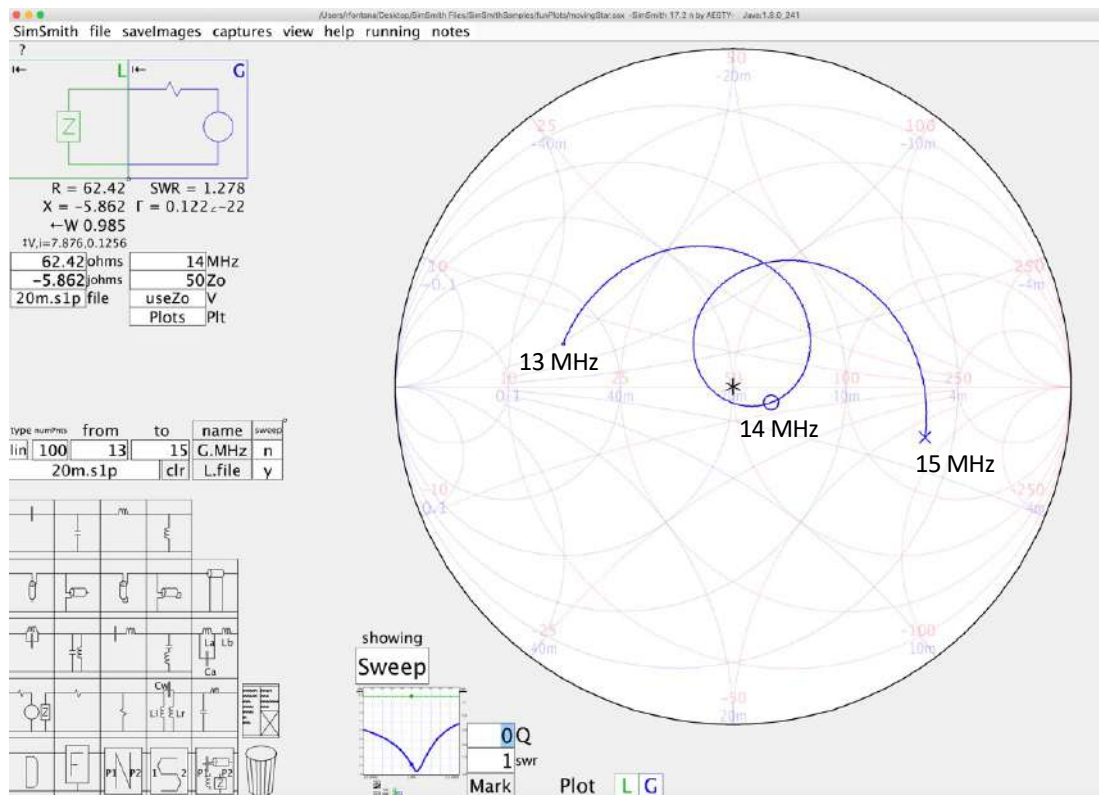
Calibration of a Vector Network Analyzer is Performed at these 3 points – Short, Open and Load (Additional “Through” CAL for  $S_{21}$ )

# Points with Constant VSWR Form Circle Around Center

The closer to the origin, the better the VSWR



# Why the Smith Chart?



Myantennas.com EFHW8010 at AK3Y  
20 meter band (span 13-15 MHz)

- Graphical method for visualizing complex impedance, reflection coefficient and VSWR as a function of frequency
- Extremely useful for designing impedance matching networks
  - Interactive Smith Chart programs are available, e.g. *SimSmith* by AE6TY
  - [http://www.ae6ty.com/Smith\\_Charts.html](http://www.ae6ty.com/Smith_Charts.html)
- NanoVNA data can be exported to programs like *SimSmith* using Touchstone file format

# Using the NanoVNA

## Calibration

- The purpose of calibration is to
  - (a) align  $S_{11}$  measurements with the purely real -1, 0 and +1 positions on the Smith Chart; and,
  - (b) properly normalize  $S_{21}$  “through” measurementsto account for cables, connectors or other devices which have been inserted between the DUT and the VNA
- Calibration kit consists of an SMA short, open,  $50\Omega$  load, (2) through coax sections and SMA “bullet” for through measurements
- Calibration should be done (redone) whenever the frequency range of interest changes, or changes have been made to the position of the “measurement plane” (i.e., location of device under test)
- When using NanoVNA-Saver software, calibration should be done within the software itself and *not* directly on the NanoVNA
  - Store all calibration data in either on-board memory locations or in files on your hard drive



Short Open Load Through

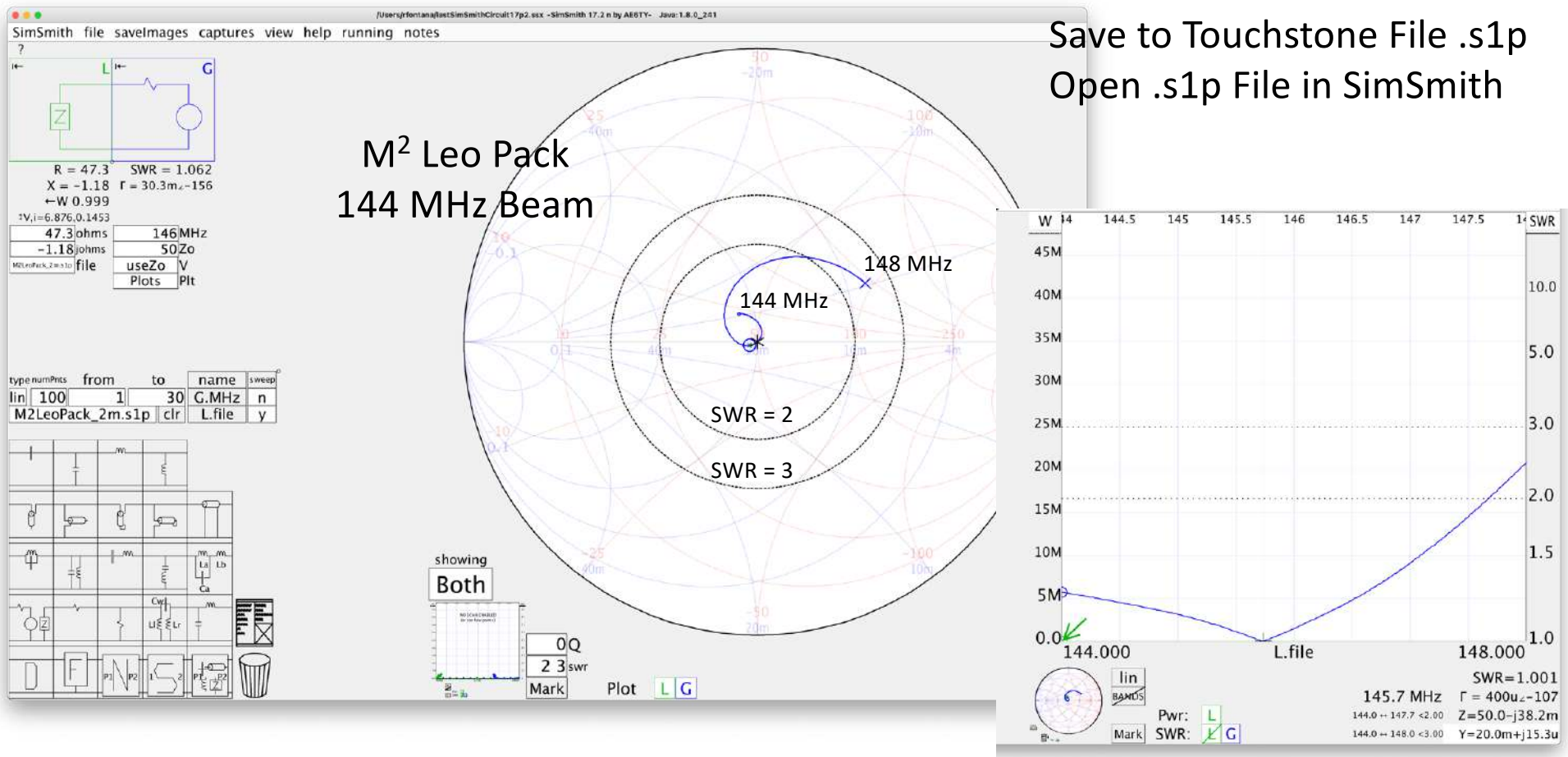
# Steps for Calibrating the NanoVNA

1. Determine the frequency range of interest – limit calibration to this range to provide better accuracy (101 data points on NanoVNA, unlimited in software)
2. Determine the measurement plane(s) – this is the point(s) at which the characteristics of the device under test (DUT) are to be measured
3. On the NanoVNA, perform a calibration RESET first (not needed when using NanoVNA-Saver or NanoVNA-qt software)
4. Perform an SOLT calibration process (Short, Open, Load and Through)  
On the NanoVNA, this is accomplished with the menu items  
In the NanoVNA-Saver software, use the *Calibration Assistant*
5. Save the calibration results!  
On the NanoVNA, use one of the nonvolatile memory locations  
With software, save calibration files to disk  
Calibrations will remain good if measurement configuration has not changed “appreciably”, i.e. less than  $0.1 \lambda$  changes



# Measuring Antennas

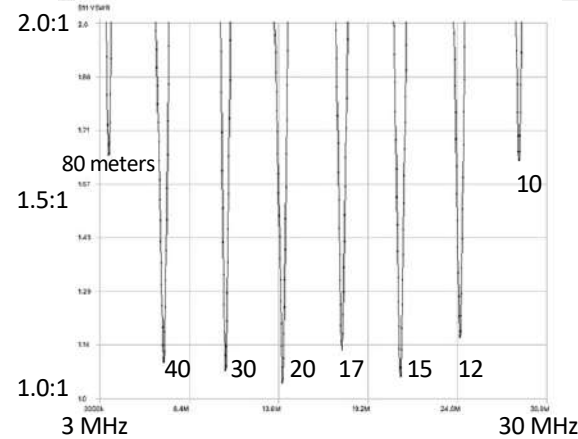
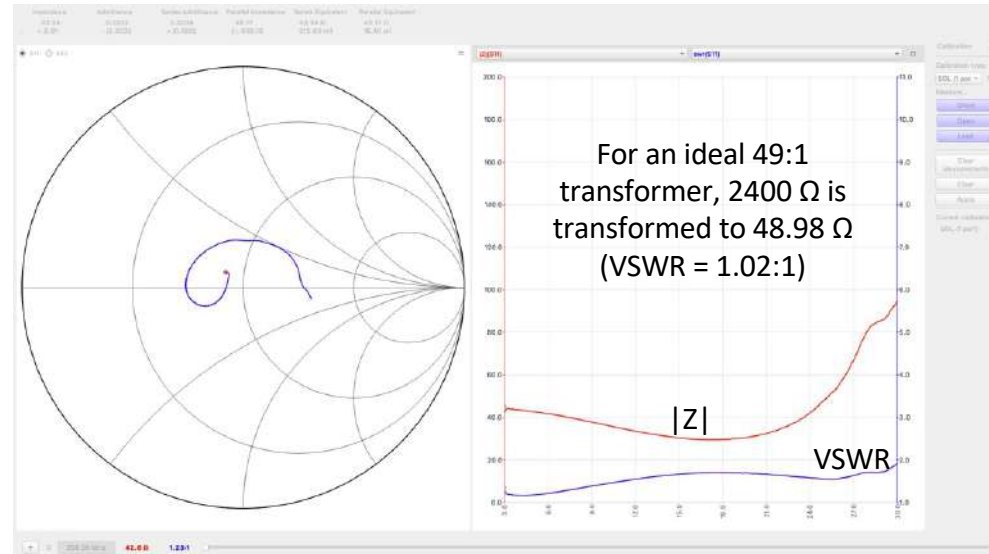
Measure S11 on NanoVNA  
 Save to Touchstone File .s1p  
 Open .s1p File in SimSmith



# Measuring Passive Networks



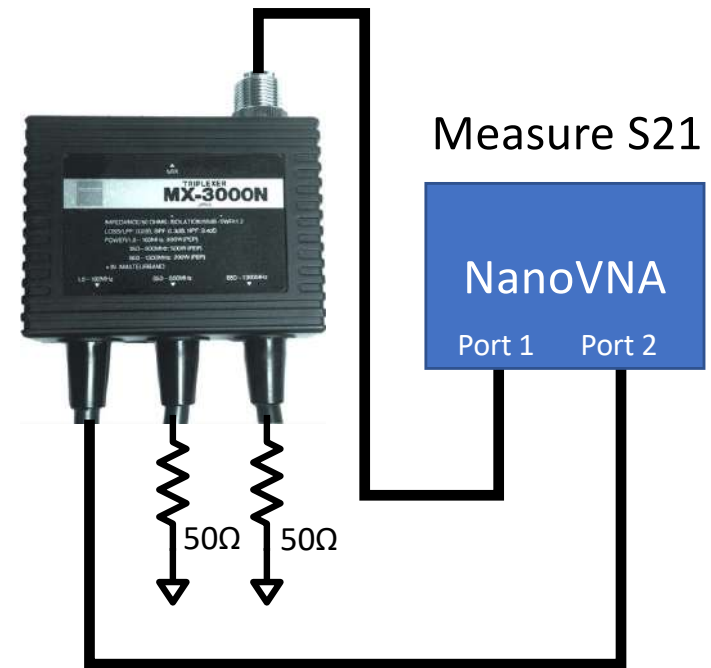
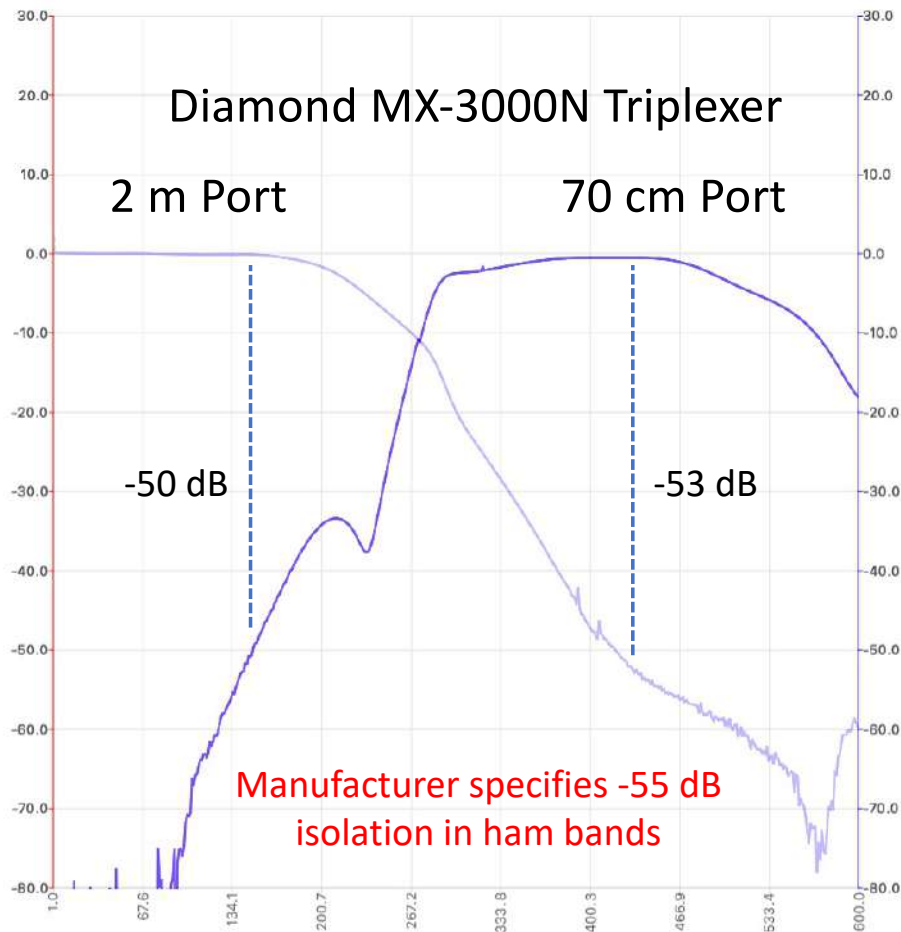
49:1 Endfed Transformer



Measured VSWR using 49:1 transformer with 132 Foot Wire

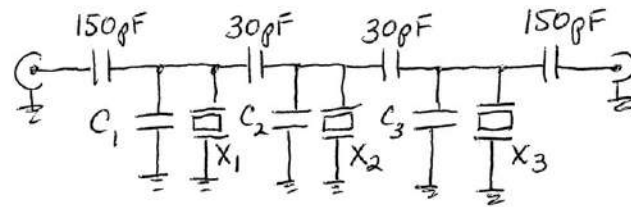
*MyAntennas* EFHW=8010  
80 meter  $\frac{1}{2} \lambda$

# Diplexer Performance

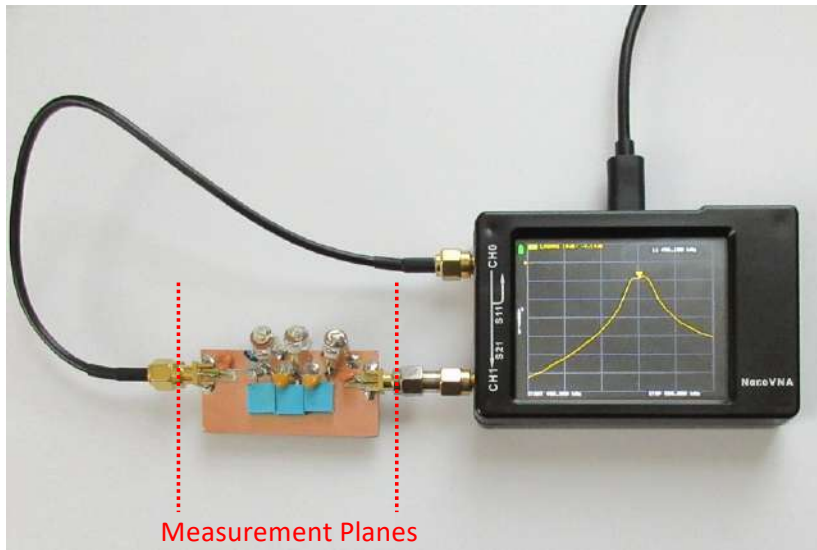


Measurement errors may be due to noise floor limitations of VNA (-50 dB below 1.5 GHz for SAA-2N)

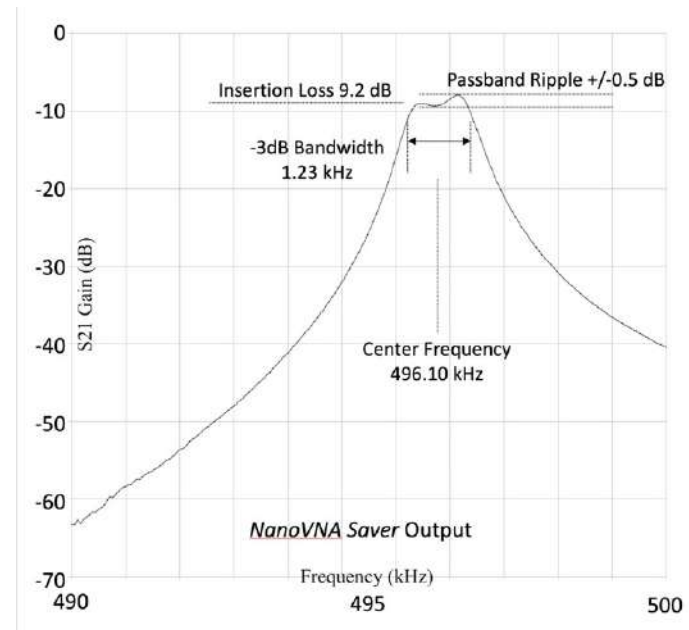
# Measuring Filter Responses



Ceramic Resonator  
SSB Filter\*

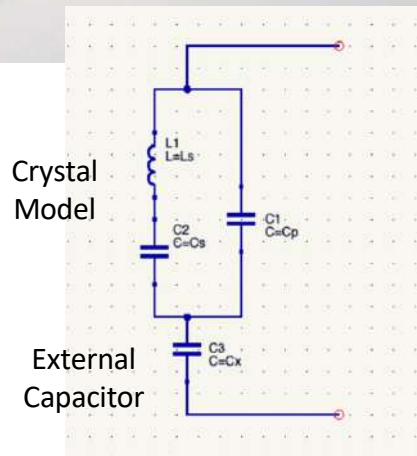
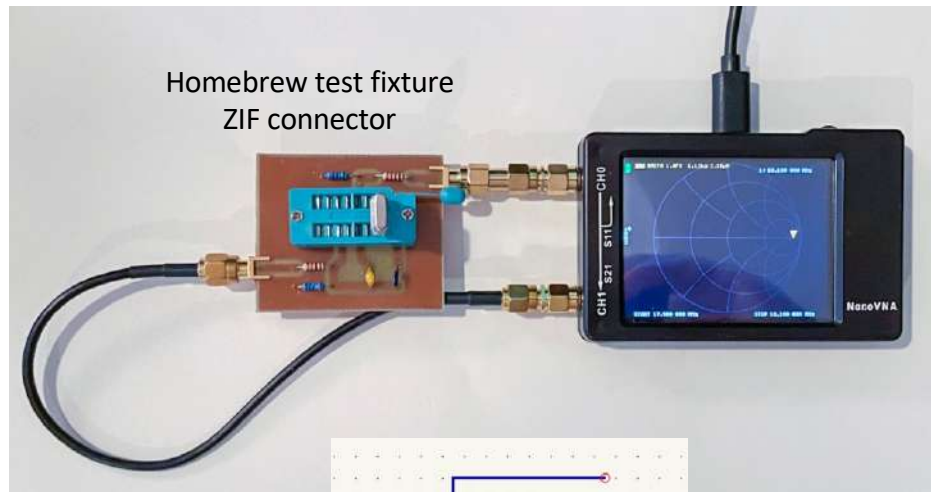


\*Using the NanoVNA to Design an SSB Ceramic Resonator Filter, Bob Fontana AK3Y, QEX Nov/Dec 2020, pp. 8-12

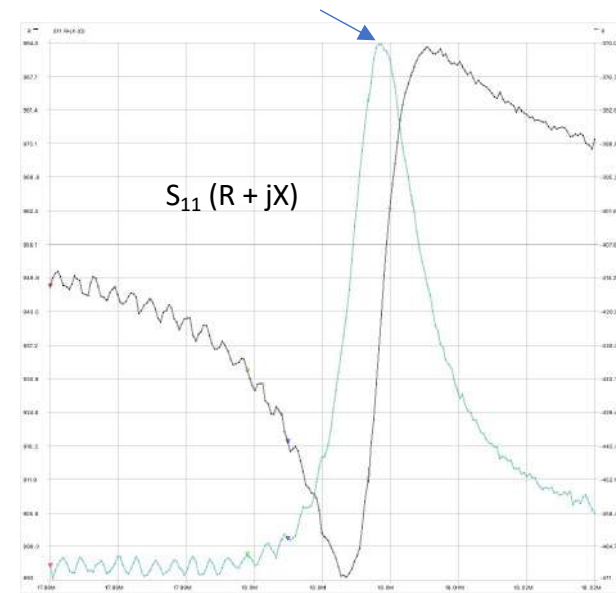


# Designing Crystal Filters

## Step 1: Determine Crystal Parameters



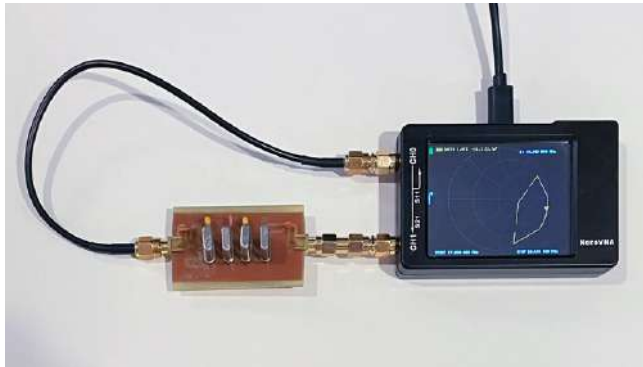
Resonance @ 18.003158 MHz  
with 10.3 pF loading



- Connect capacitors in series with crystal and measure resonances with NanoVNA (e.g., 0 pF, 10.3 pF and 30 pF)
- Determine  $L_s$ ,  $C_s$  and  $C_p$  (3 equations in 3 unknowns)
- Use crystal parameters to determine optimum filter design\*
- "Crystal Ladder Filters for All," DJ6EV and G3JHIR, *QEX* Nov./Dec. 2009, pp. 14-18
- "Modern Network Theory Design of Single-Sideband Crystal Ladder Filters," Milton Dishal, *Proceedings of the IEEE*, Sept. 1965
- Crystal Ladder Filter Design Software – [www.arrl.org/qexfiles](http://www.arrl.org/qexfiles) (look for 11x09\_Steder-Hardcastle.zip)
- "Crystal Motional Parameters: A Comparison of Measurement Approaches," J. Smith K8ZOA, [https://www.mikrocontroller.net/attachment/473317/Crystal\\_Motional\\_Parameters.pdf](https://www.mikrocontroller.net/attachment/473317/Crystal_Motional_Parameters.pdf)

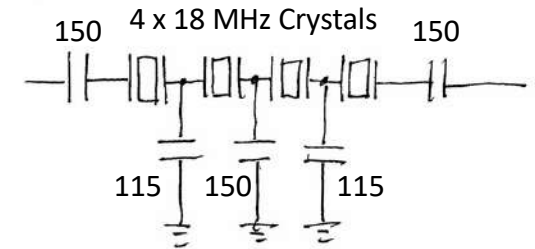
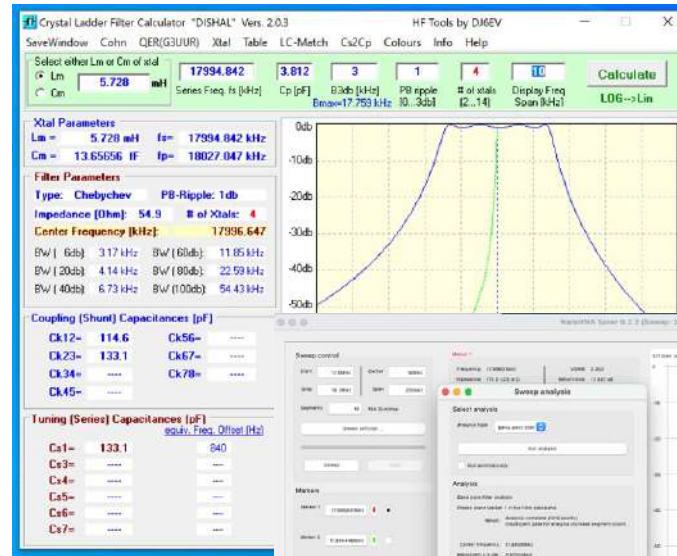
# Designing Crystal Filters (cont.)

## Step 2: Determine Ladder Filter Capacitors



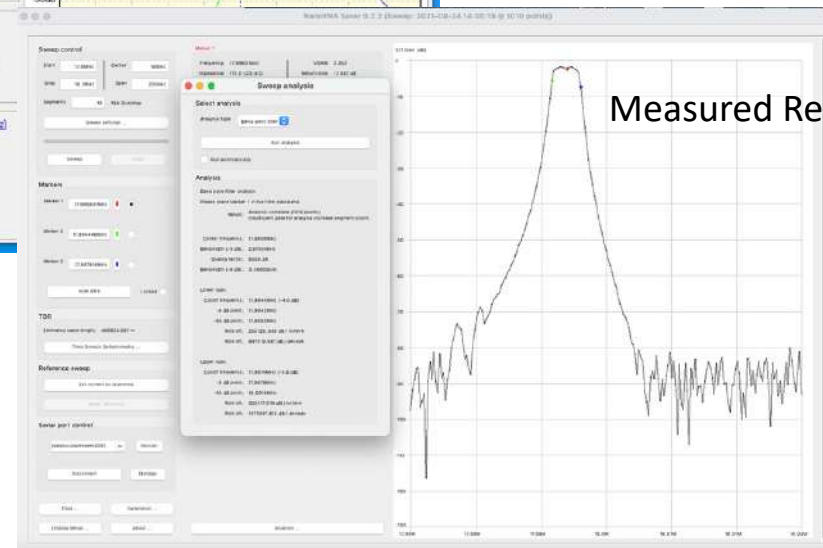
### Measured Crystal Parameters

$L_s$  (motional inductance) = 5.728 mH  
 $C_s$  (motional capacitance) = 13.656 fF  
 $C_p$  (parallel capacitance) = 3.812 pF

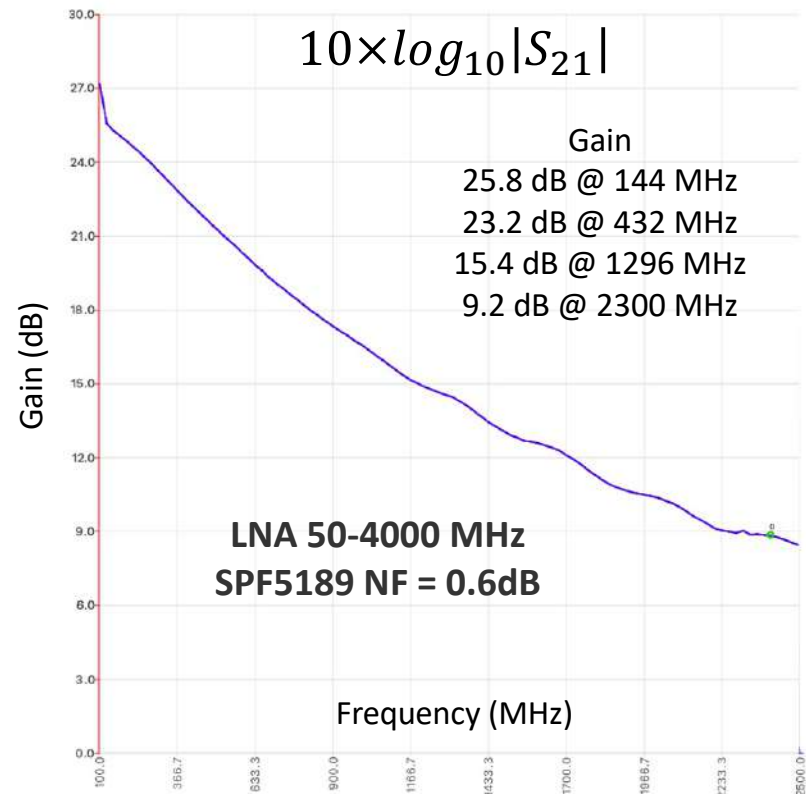
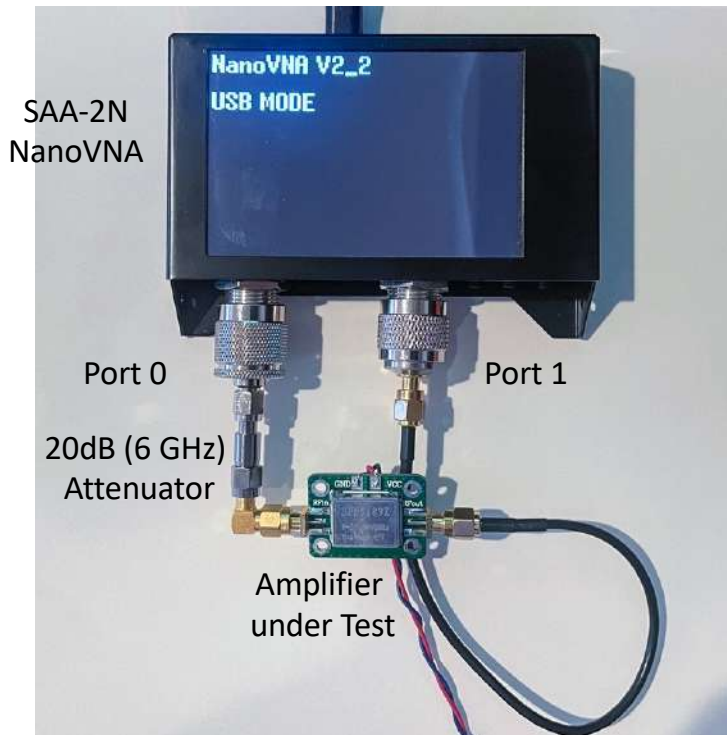


### Filter Parameters

	Design	Measured
-3dB BW	3.00 kHz	2.97 kHz
Center	17.9966 MHz	17.9959 MHz
-6dB BW	3.17 kHz	3.37 kHz
-60dB BW	11.85 kHz	11.70 kHz
PB Ripple	1 dB	1.1 dB

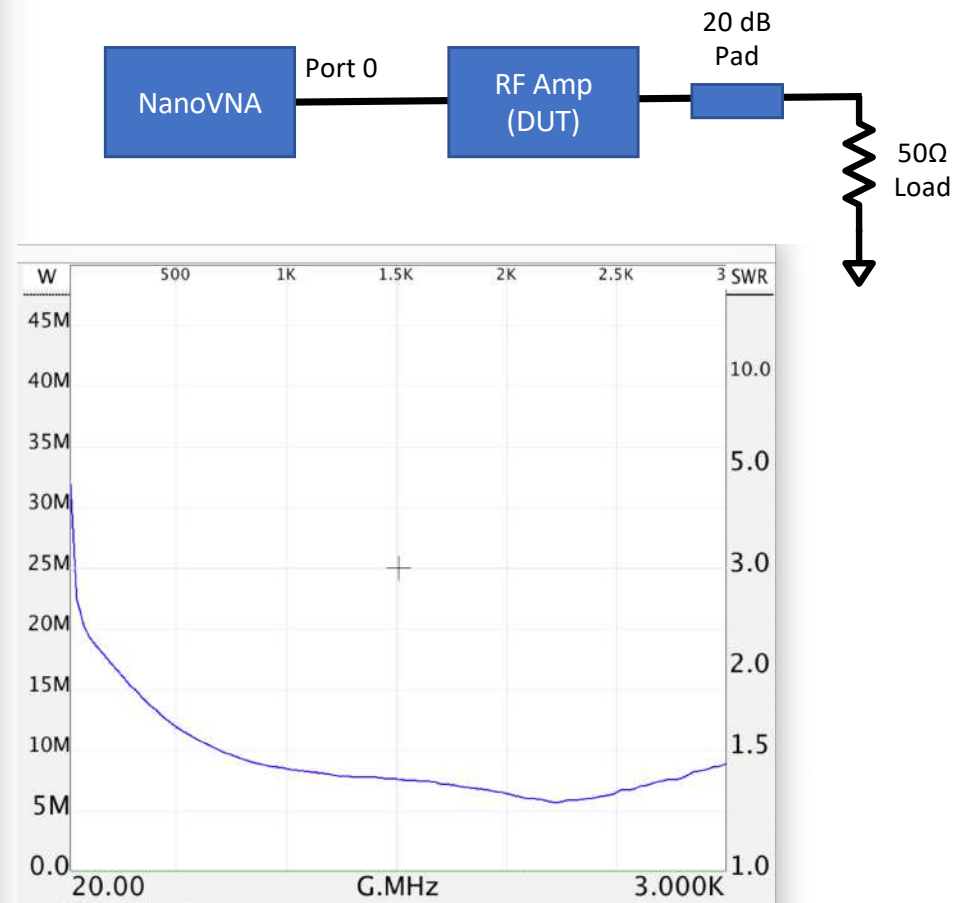
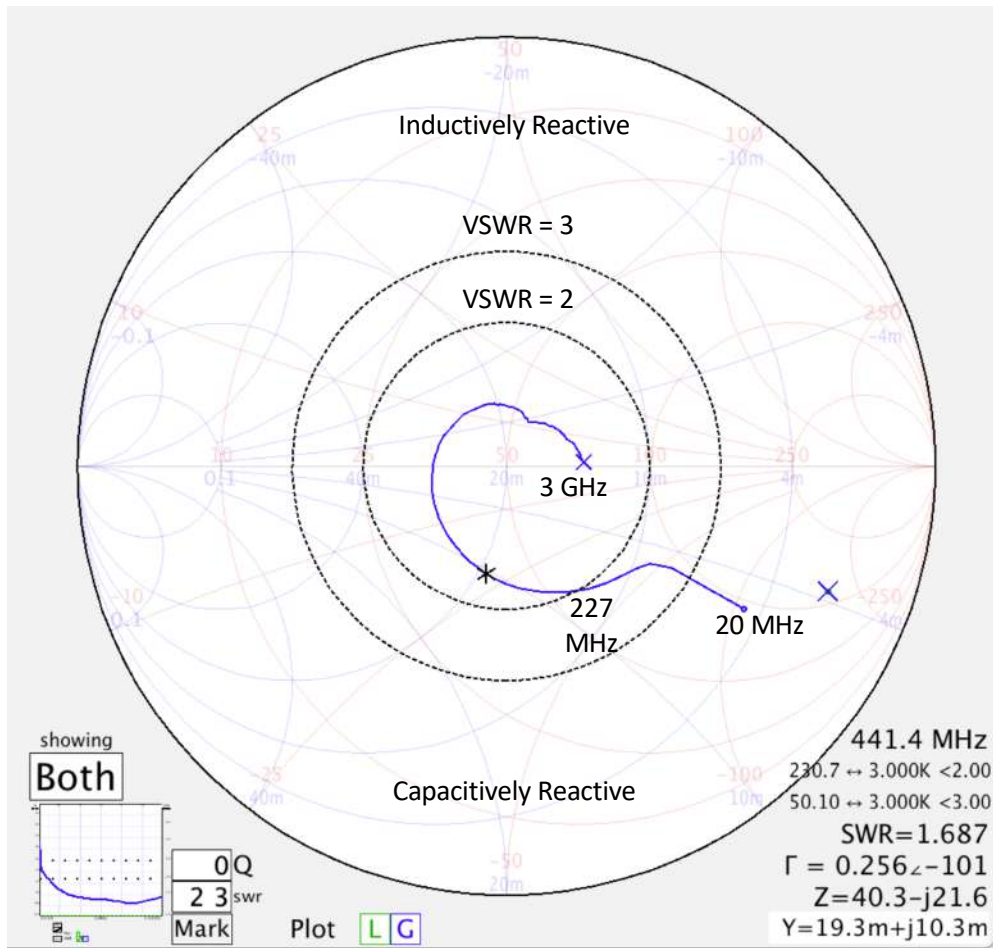


# Measuring RF Amplifier Gain



Signal output from Port 0 = +15 dBm  
Added 20dB pad to prevent amplifier from going into saturation or overloading VNA  
Attenuator and cabling "calibrated out" during SOLT calibration process

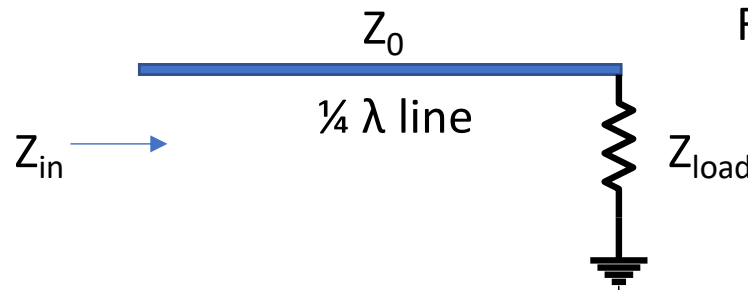
# Measuring RF Amplifier Input Impedance





# Measuring Coaxial Cable Characteristics

## Characteristic Impedance $Z_0$

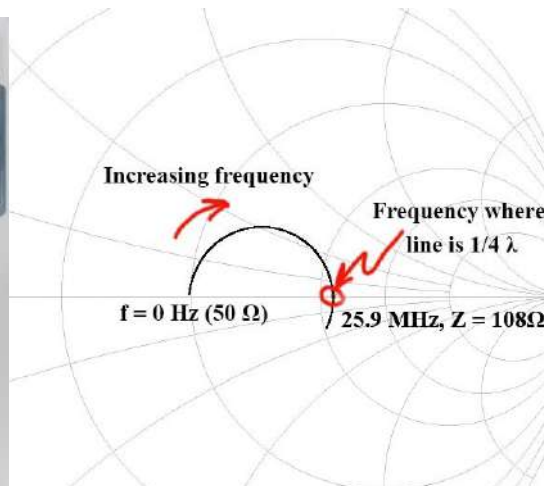


For a quarter-wave line

$$\frac{Z_{load}}{Z_0} = \frac{Z_0}{Z_{in}}$$

$$Z_0 = \sqrt{Z_{load} \times Z_{in}}$$

Set  $Z_{load} = 50\Omega$  and adjust frequency for an exact  $\frac{1}{4}$  wavelength  
 Measure  $Z_{in}$  and compute  $Z_0$



$Z_{in} = 108\Omega$  at 25.9 MHz

$Z_0 = \text{sqrt}(50 \times 108) = \mathbf{73.48\Omega}$

Length = 73.5 inches (1.867 meters) =  $\frac{1}{4} \lambda$

Freq (free space) = 40.17 MHz

Measured  $\frac{1}{4}\lambda$  frequency = 25.9 MHz

Velocity factor =  $25.9/40.17 = \mathbf{0.654}$

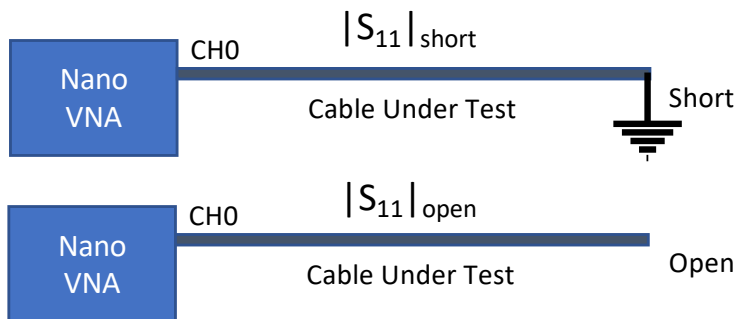
**RG59/U 73.5Ω, velocity factor = 0.66**

# Coaxial Cable Loss vs Frequency

S11 Measurement with  $Z_{load} = 0\Omega$  (short) or  $Z_{load} = \infty$  (open)

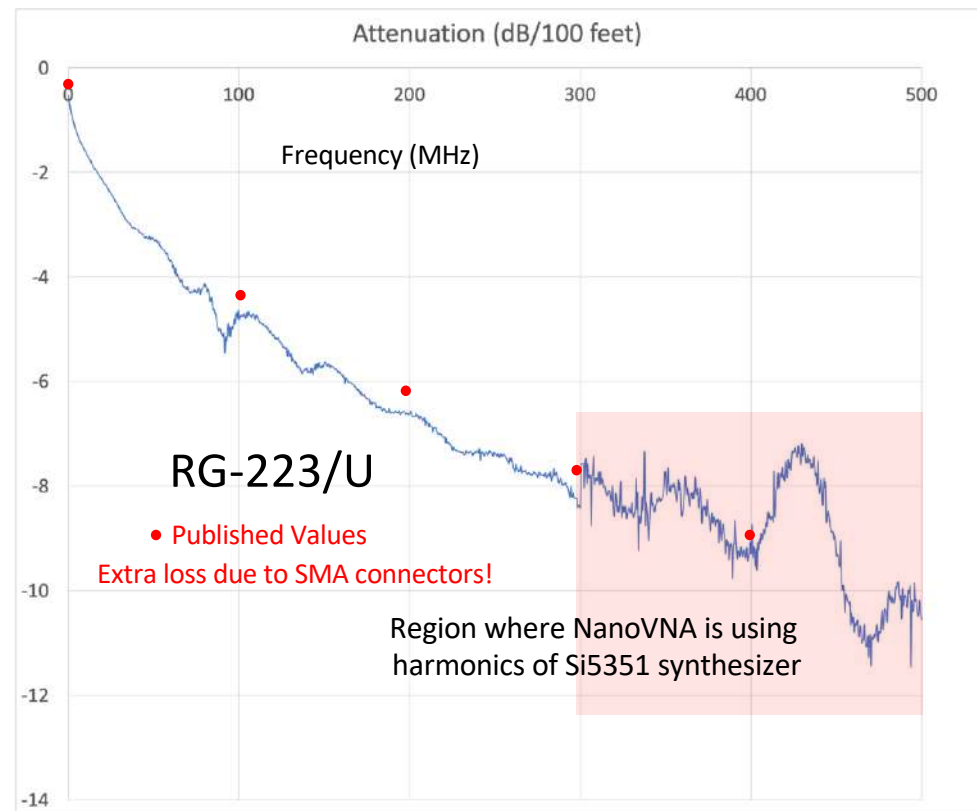
In both cases, all energy is reflected from the load back to the source

$|S_{11}|$  measures **two-way** path loss



$$Loss = \frac{1}{2} \left[ \frac{20 \times \log_{10} |S_{11}|_{short}^2}{2} + \frac{20 \times \log_{10} |S_{11}|_{open}^2}{2} \right]$$

- Resonances cancel yielding more accurate response
- Can be used when  $S_{21}$  measurements are impossible or difficult (e.g., buried cables, tower installations, etc.)

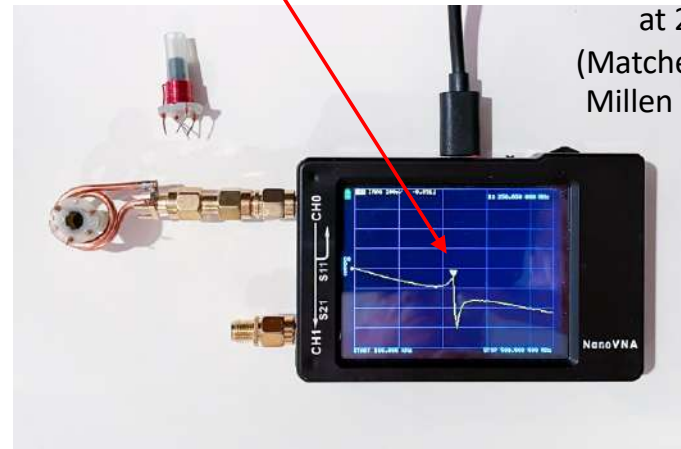


# NanoVNA as Grid/Gate Dip Oscillator



Construct small loop attached to SMA connector

Sharp transition occurs at circuit resonant frequency

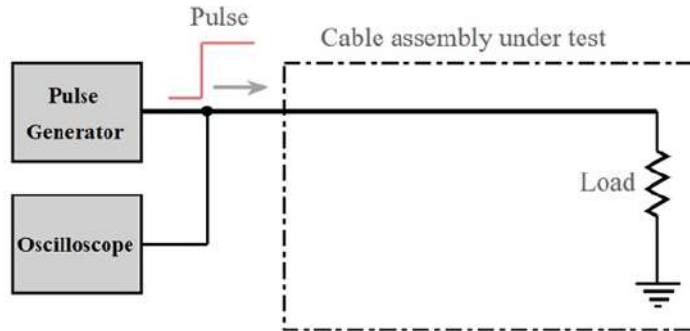


Coil is self-resonant at 250 MHz (Matches result with Millen 90661 GDO)

Display imaginary component of CH0 impedance

- Resonant circuit produces an abrupt impedance discontinuity at resonance
- No calibration required (need sufficient number of points for good resolution)
- Useful for determining self-resonance frequency of amplifier plate chokes, tuned circuit frequencies of receiver/transmitter stages, etc.

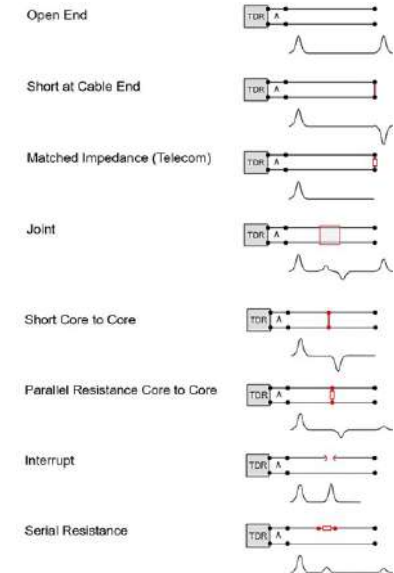
# Time Domain Reflectometry



Time Domain Approach

- Generate an impulse or fast rising pulse waveform
- Observe reflections vs time on oscilloscope
- Difficulties in generating and measuring these pulses

As the pulse travels down the coax, any change in characteristic impedance will result in a portion of the incident energy to be reflected back toward the source



Magnitude of reflection

$$\rho = \frac{Z_d - Z_0}{Z_d + Z_0}$$

# Frequency Domain Approach (VNA)

Fourier transform – expresses a signal in terms of its frequency content

$$F(f) = \int_{-\infty}^{+\infty} f(t)e^{-j2\pi ft}$$

and vice versa!

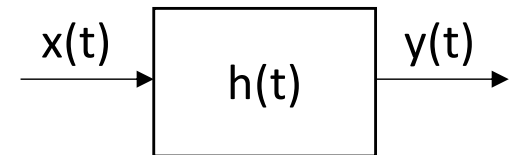
$$f(t) = \int_{-\infty}^{+\infty} F(f)e^{+j2\pi ft}$$

For a linear system  $h$ , the output  $y(t)$  is related to the input  $x(t)$  by the convolution integral

$$y(t) = \int_{-\infty}^{+\infty} x(u)h(t-u)du$$

In the frequency domain:

$$Y(f) = X(f)H(f).$$



If the excitation signal  $x$  is an impulse, then one can show that  $X(f) = 1$  for ALL frequencies, and

$$y(t) = h(t) \text{ and } Y(f) = H(f)$$

**S11 (reflection coefficient) is a function of the distance from the source or, alternatively, a function of time given the speed of propagation!**

# Time Domain Reflectometry with VNA

- Setup an excitation signal which covers a wide frequency range (near DC to a frequency  $f_{\max}$ , where  $1/f_{\max}$  is the desired time resolution)

The number of sampling points  $N$  multiplied by the time resolution  $1/f_{\max}$  is the maximum time over which a reflection can be observed (max coax length)

- Measure  $S_{11}(f)$ , and then convert to  $S_{11}(t)$  using the inverse Fourier Transform

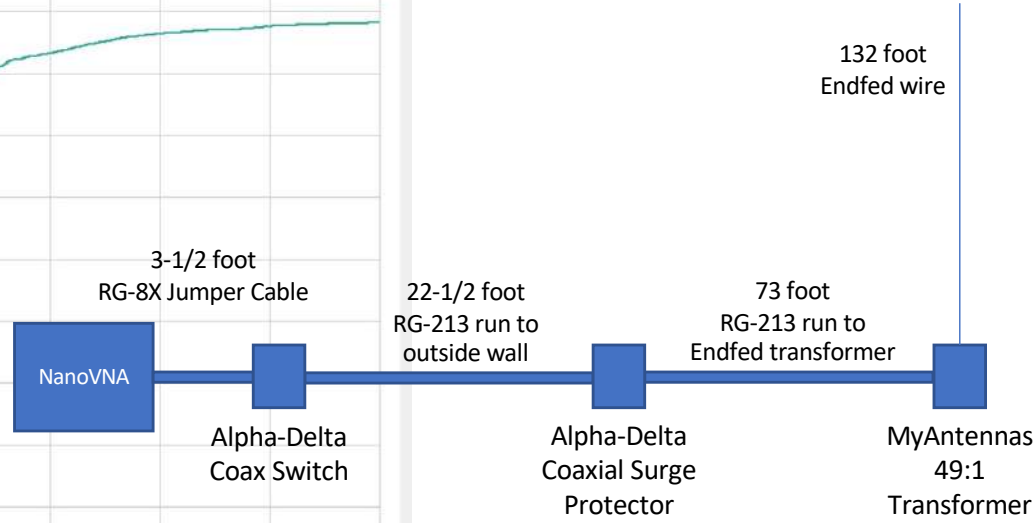
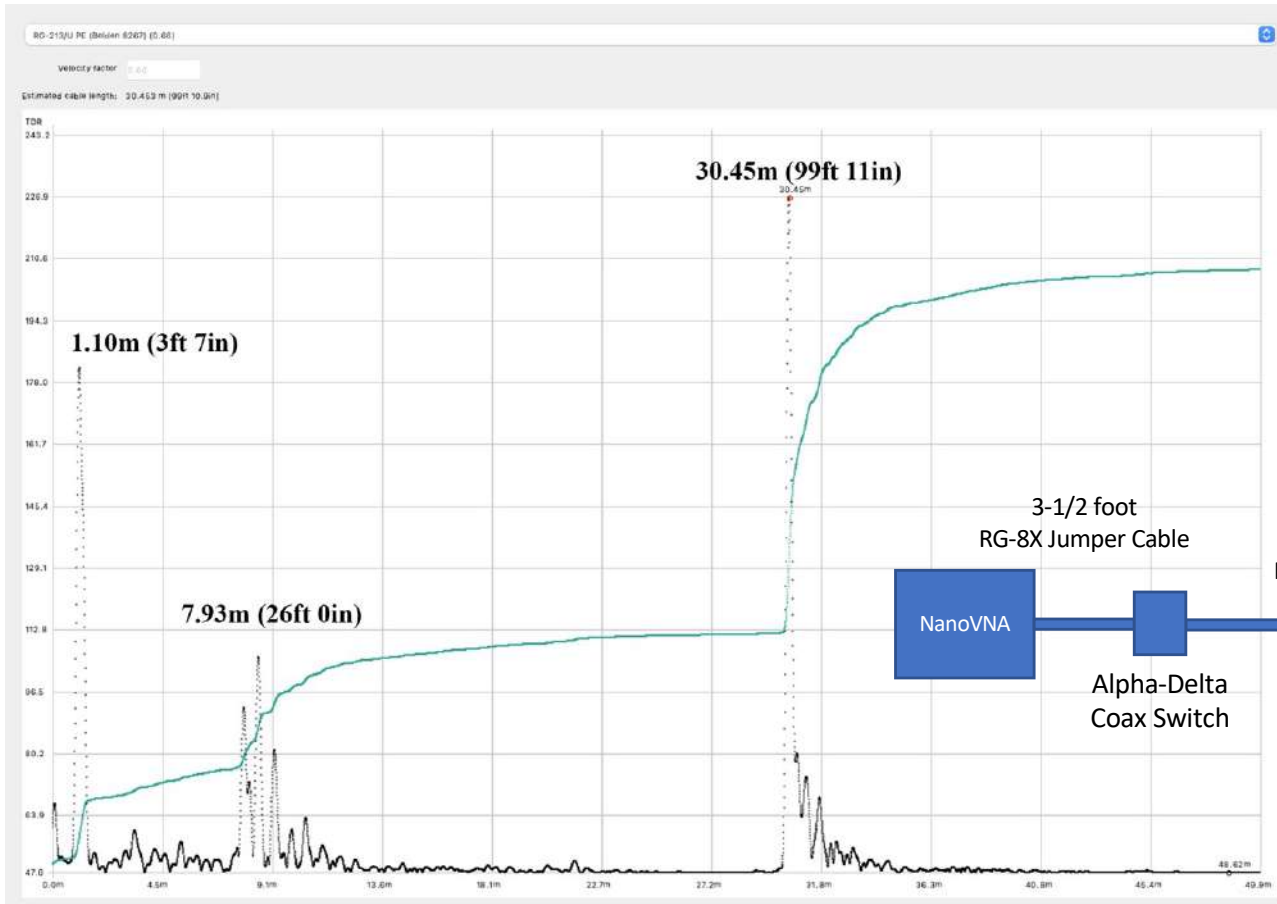
This is done automatically in the NanoVNA-Saver software

- $S_{11}(t)$  will now show the discontinuities in the reflection coefficient (impedance changes) as a function of time – system “impulse” response
- Convert time into distance from the source by taking into account the velocity of propagation (e.g., 0.84 for RG-8X, 0.66 for RG-213. etc.)

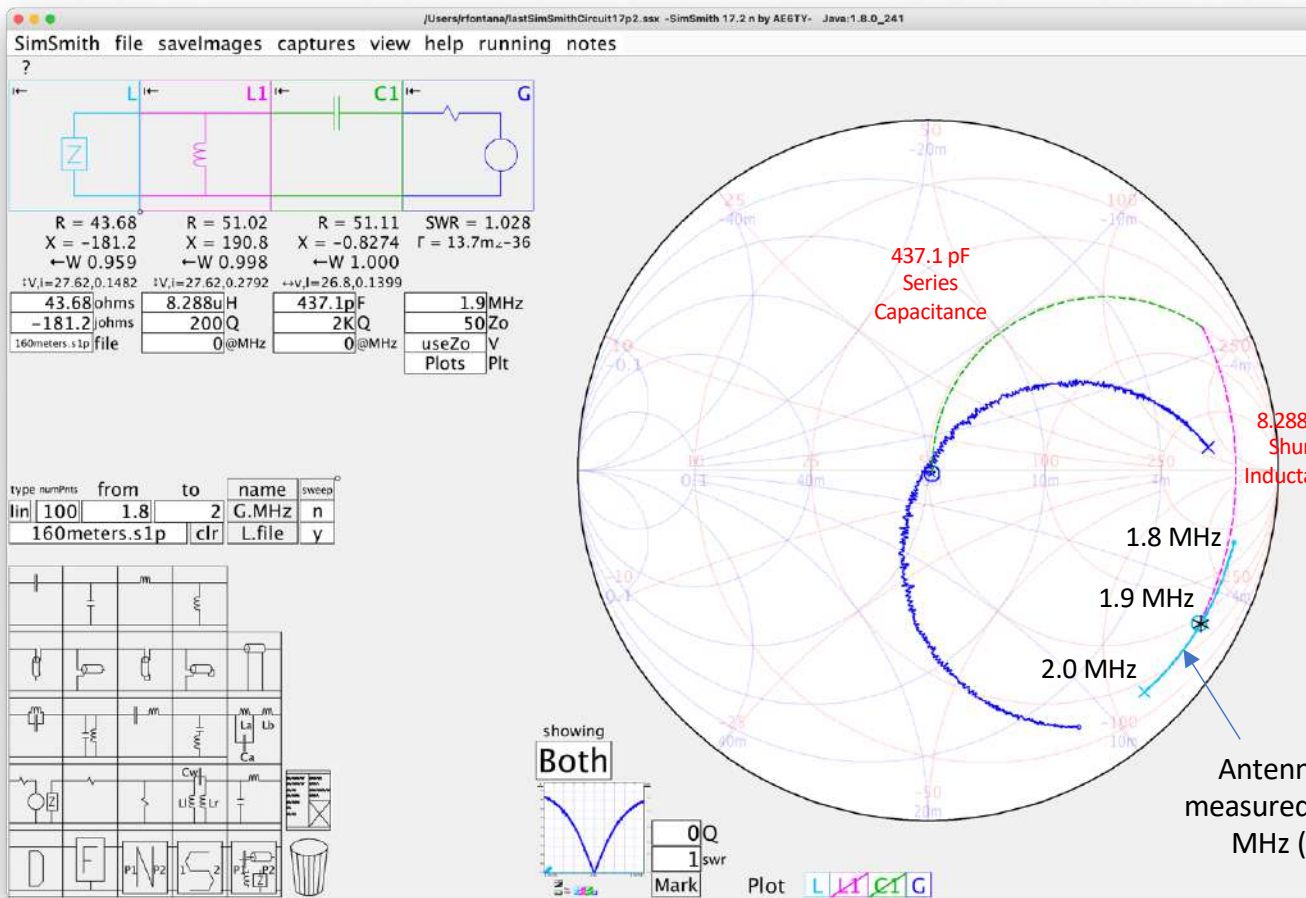
# Example TDR Response

NanoVNA calibrated from 0.1 to 1000 MHz

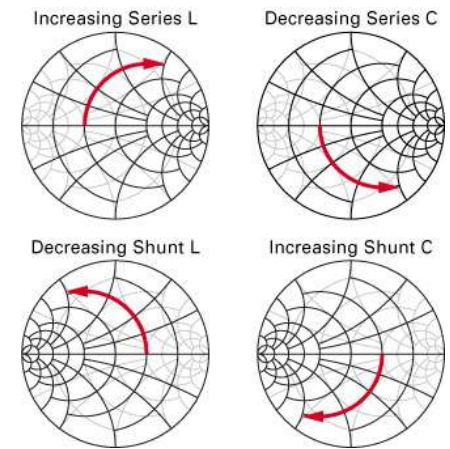
Calibrate from as low a frequency as possible to minimize sampling artifacts



# Matching Networks



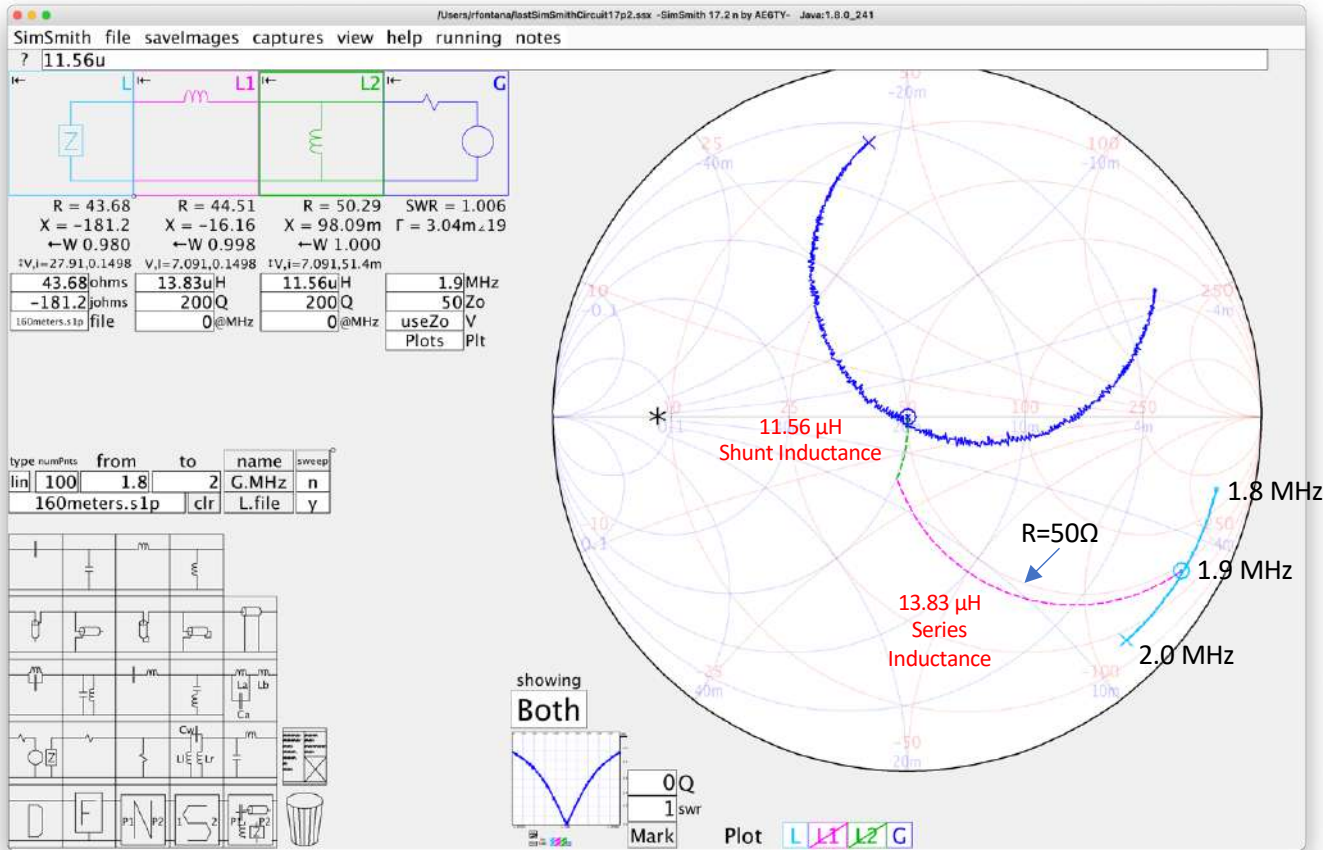
## Smith Chart Basics



- Use NanoVNA to measure S11
- Export S11 as .s1p Touchstone file
- Open .s1p file in SimSmith
- Apply transformations (drag and drop)



# Matching Networks (cont.)

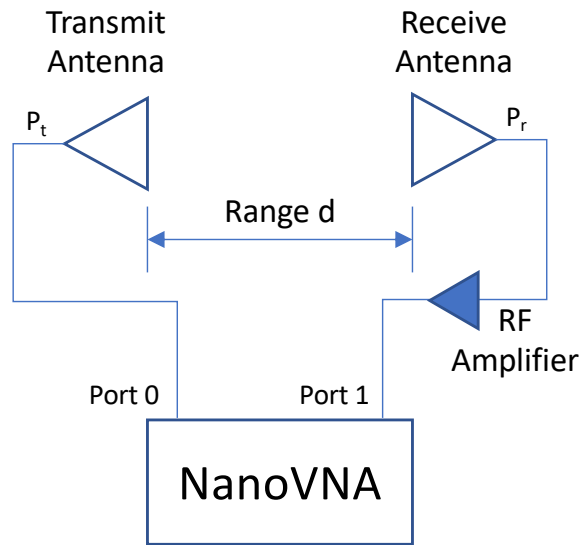


More than one way to construct a matching network!

Unfortunately, this matching network will not work below approximately 1.88 MHz – cannot reach  $R = 50\Omega$  curve!

Another reason why one matchbox may work, while another cannot find a solution!!

# Measuring Antenna Gain & Pattern



$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \quad \text{Friis Transmission Equation}$$

$$\frac{P_r}{P_t} = |S_{21}| = \frac{G_t G_r \lambda^2}{(4\pi d)^2}$$

Using identical antennas ( $G_t = G_r = G$ )

$$G = \frac{4\pi d}{\lambda} \sqrt{|S_{21}|} = G(f, \theta)$$

- Range  $d$  should be chosen to be in the far field of the antenna pattern; i.e.,  $d > 2D^2/\lambda$  where  $D$  is the largest (linear) dimension of the antenna (Fraunhofer distance)
- RF amplifier gain should be chosen to compensate for path loss between antennas (e.g., if  $d = 2\lambda$ , loss = 28 dB)
- VNA calibration should take out the effects of coaxial cables, connectors and RF amplifier gain
- Build antenna for higher frequency and scale!

# Summary

- In the past, vector network analyzers (VNA) were primarily used at VHF and higher frequencies where direct voltage and current measurements were difficult, if not impossible, to achieve accurately due to stray reactances. In addition, these VNAs usually cost in the 4-5 figures and higher, the price of a luxury automobile!
- The VNA measures incident and reflected waves, using directional couplers and I/Q signal processing to obtain the complex “scattering” or “S” parameters of a linear, two-port network. These parameters completely characterize a linear system and can be used to determine any one- or two-port parameters.
- With the advent of extremely low cost, microwave frequency synthesizers, wideband logarithmic detectors and high speed signal processors, the “nano” VNA concept has become a viable option for the average ham shack
- To fully understand how to make the best use of a VNA, a solid understanding of the Smith Chart is a great first step
- References
  - Rohde & Schwarz tutorials on S-params & Smith Chart
    - <https://www.youtube.com/watch?v=rUDMo7hwihs>
  - Smith Chart Basics by W2AEW
    - <https://www.youtube.com/watch?v=gw1TYWwfvGk>
  - NanoVNA-Saver software for PC, Mac, Linux
    - <https://github.com/NanoVNA-Saver/nanovna-saver/releases/tag/v0.3.9-pre>
  - *SimSmith* interactive Smith Chart software
    - <http://www.ae6ty.com>

# Thank you!

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A copy of the viewgraphs for this presentation  
can be found at  
[http://www.ak3y.com/NanoVNA\\_MARC.pdf](http://www.ak3y.com/NanoVNA_MARC.pdf)