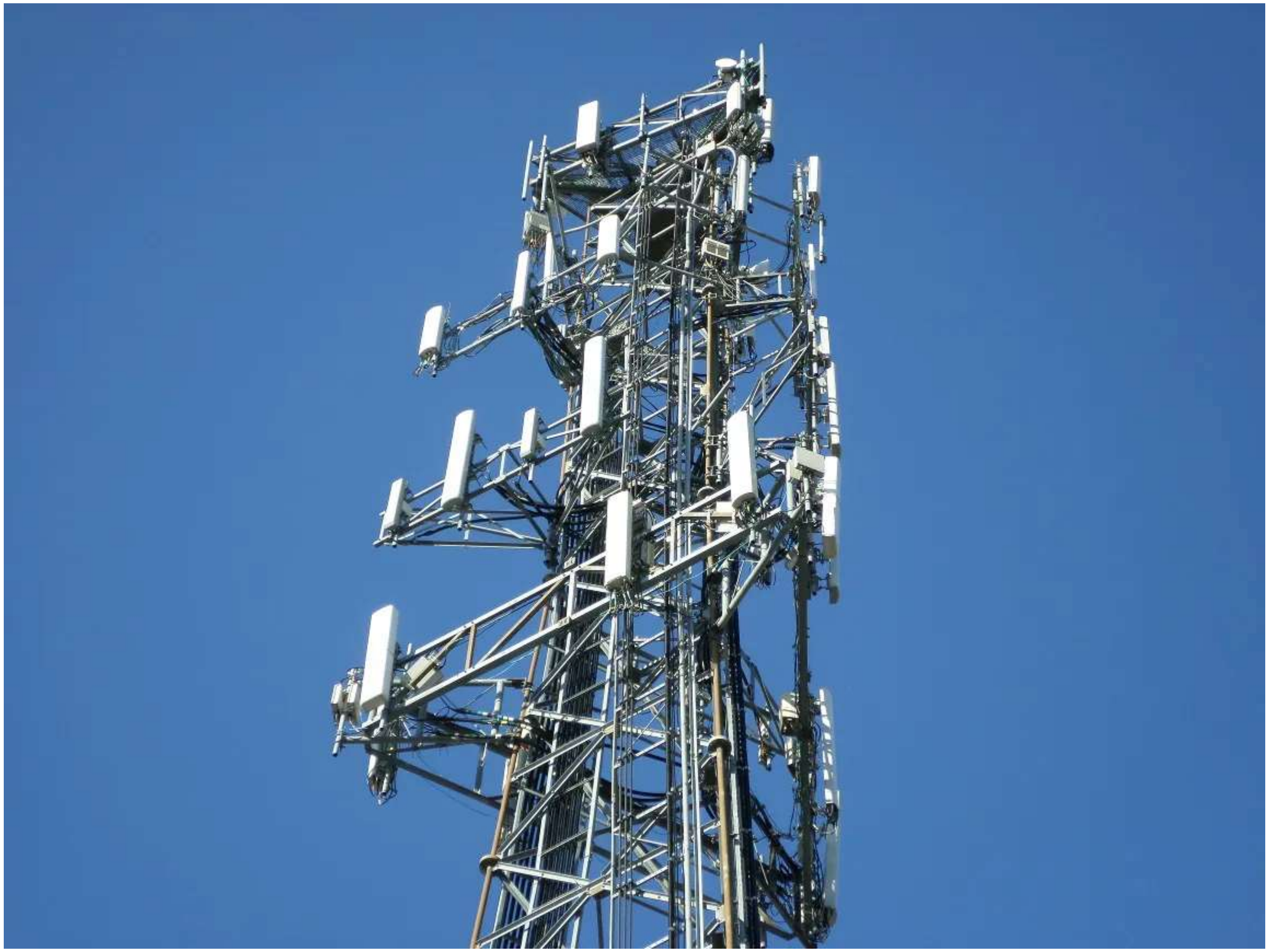
S-Parameters & Smith Charts



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Preamble

“If you can't explain it simply, you don't understand it well enough.”

Albert Einstein

Introduction

- Circuit Analysis
- Problems with Circuit Analysis
- Solutions for High Frequency Complex Systems
- S-Parameters
- How to Measure
- VNA Results Displays
- VNA Examples
- Summary
- Questions?

Circuit Analysis

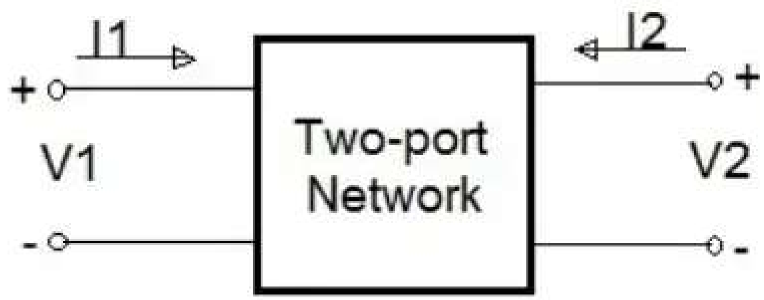
- Need to model analogue circuits before building them
- Ability to modify elements quickly and easily
- Estimate performance over a range of conditions
- Substitute components for zero cost
- SPICE is a commonly used free software
- Has undergone continuous development since 1972
- Commercial versions are available

Problems with Circuit Analysis

- Models get quite large for complex circuits
- Modeling real-world components at higher frequencies difficult if not impossible
- Difficult to model PCBs at high frequencies
- Too much detail when interest is only in inputs/outputs
- Need to simplify analysis to what is needed

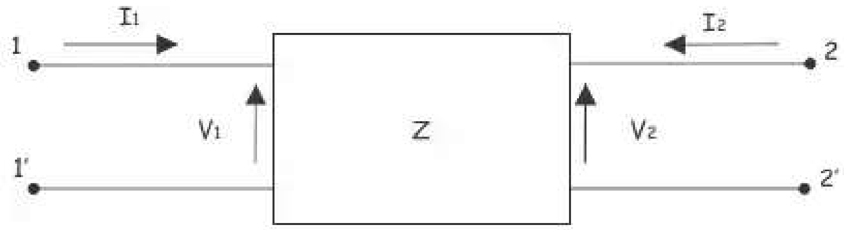
Solutions for Complex Systems

- Need to treat linear circuits as a black box
- 2-port analysis became an alternative to detailed component modeling



- Multiple representations based on type of analysis
  - Z parameters Impedance
  - Y parameters Admittance
  - H parameters Hybrid
- However there are still problems with high frequency analysis

Example Z Parameters



The Z Parameters are:

Z_{11} = Input impedance keeping output open = V_1/I_1 I_2=0

Z_{22} = Output impedance keeping input open = V_2/I_2 I_1=0

Z_{12} = Reverse transfer impedance keeping input open = V_1/I_2 I_1=0

Z_{21} = Forward transfer impedance keeping output open = V_2/I_1 I_2=0

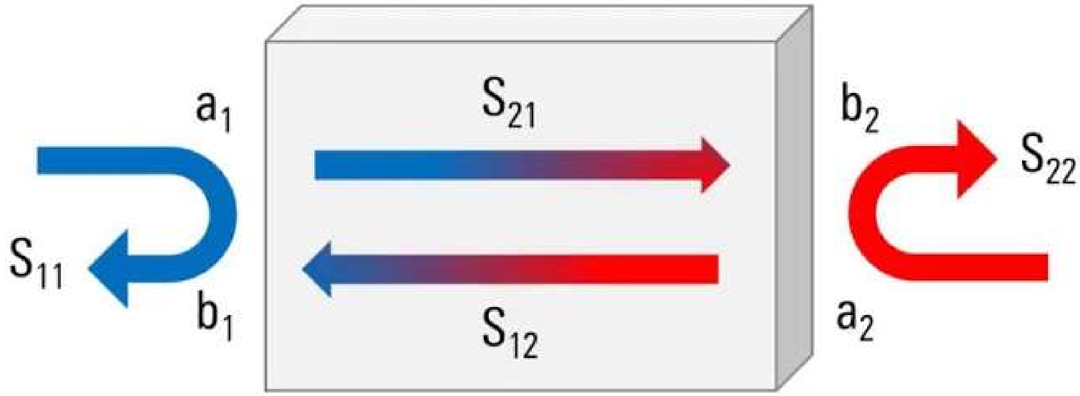
Do we have a headache yet?
This is why the EE degree is a 4 year University course!

S Parameters

- At higher frequencies voltages and currents become far more difficult to relate to the performance of our black box
- ‘Scattering Parameters’ were developed to overcome these difficulties
- First mention of them occurred in 1920 so they are not new
- Became popularised in the 1960s due to HP test equipment and a Bell Labs researcher who published a book
- From the Wikipedia entry on Scattering Parameters:

> They differ from traditional 2 port parameters (Z,Y,H), in the sense that S-parameters do not use open or short circuit conditions to characterize a linear electrical network; instead, matched loads are used. These terminations are much easier to use at high signal frequencies than open-circuit and short-circuit terminations.

S Parameters

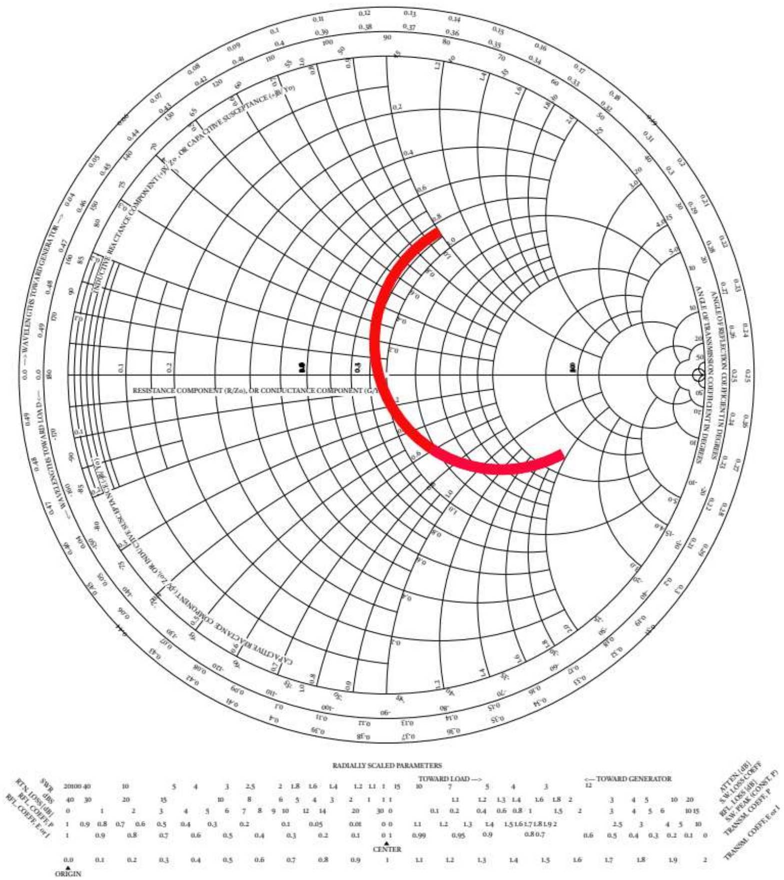


- The scattering parameters are named using ‘S’ and a pair of subscripts (S_{xy})
  - The first subscript is the port from which energy exits
  - The second subscript is the port at which energy enters
- The 2 port scattering parameters are S_{11}, S_{21}, S_{12} and S_{22}

S Parameters

- S parameters are complex values with both Magnitude and Phase
- S parameters can be cascaded to predict overall response of a linear system
- The reflection coefficients S_{11} can be plotted on a Smith Chart

The Smith Chart was developed by Philip Smith and Mizuhashi Tosaku independently in the late 1930s. It was designed as a graphical calculator for simplifying the rather tedious computations before there were PCs and programs involving complex impedances in transmission lines, antennas and other high frequency components.



S Parameters

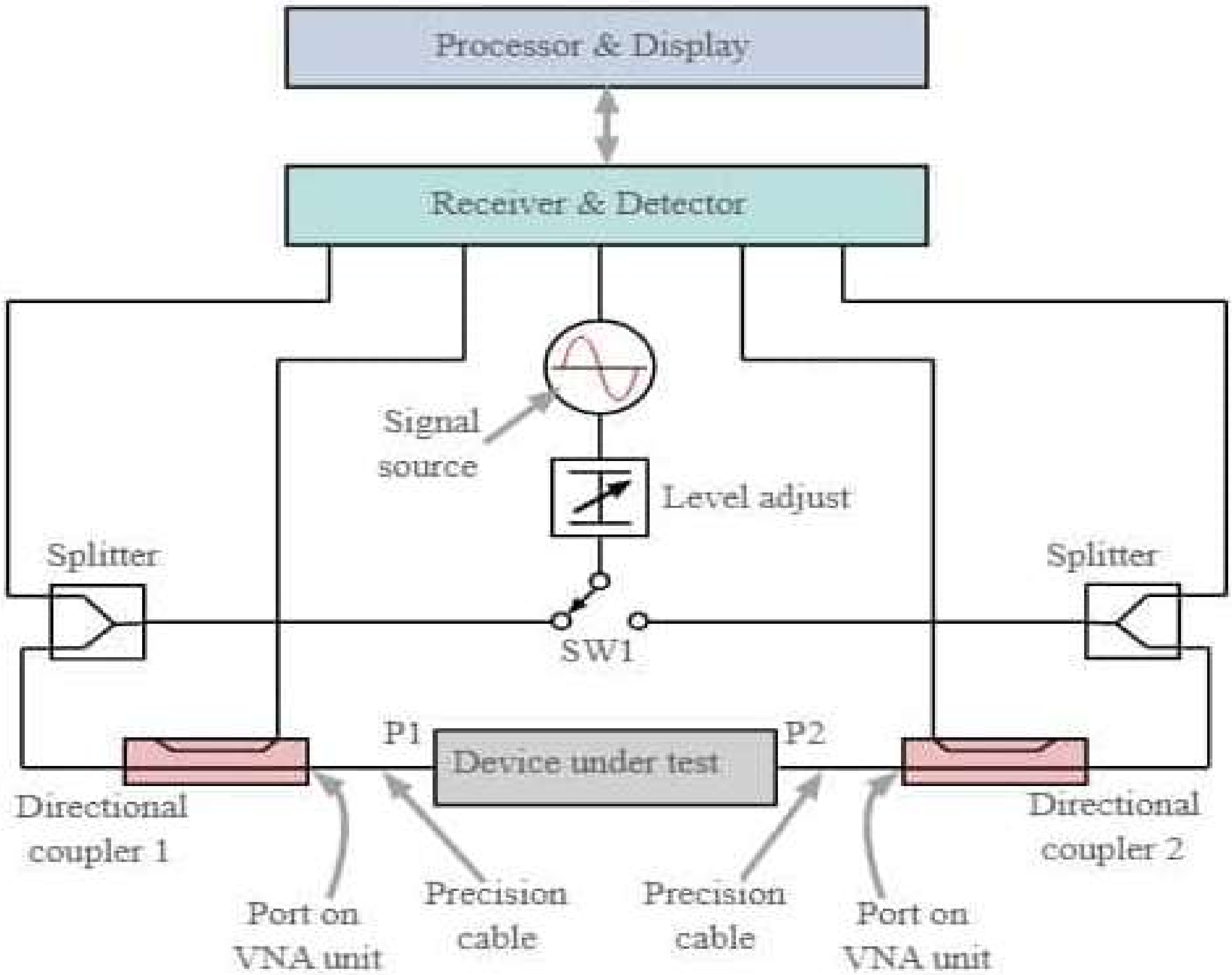
- Mapping S parameters to common names:
  - Reflection Coefficients
    - S_{11} input match, return loss, VSWR
    - S_{22} output match, return loss, VSWR
  - Transmission Coefficients
    - S_{21} gain or loss
    - S_{12} reverse isolation/attenuation

How to Measure

- S parameters are measured with a Network Analyser
- They come in 2 ‘flavours’
  - Scalar which only measures magnitude
  - Vector which measures magnitude and phase
- Scalar network analysers have been popular due to their lower cost and availability as an example the Spectrum Analyser with Tracking generator is a scalar network analyser
- Vector network analysers have substantially replaced scalar analysers due to better overall capabilities and improved cost

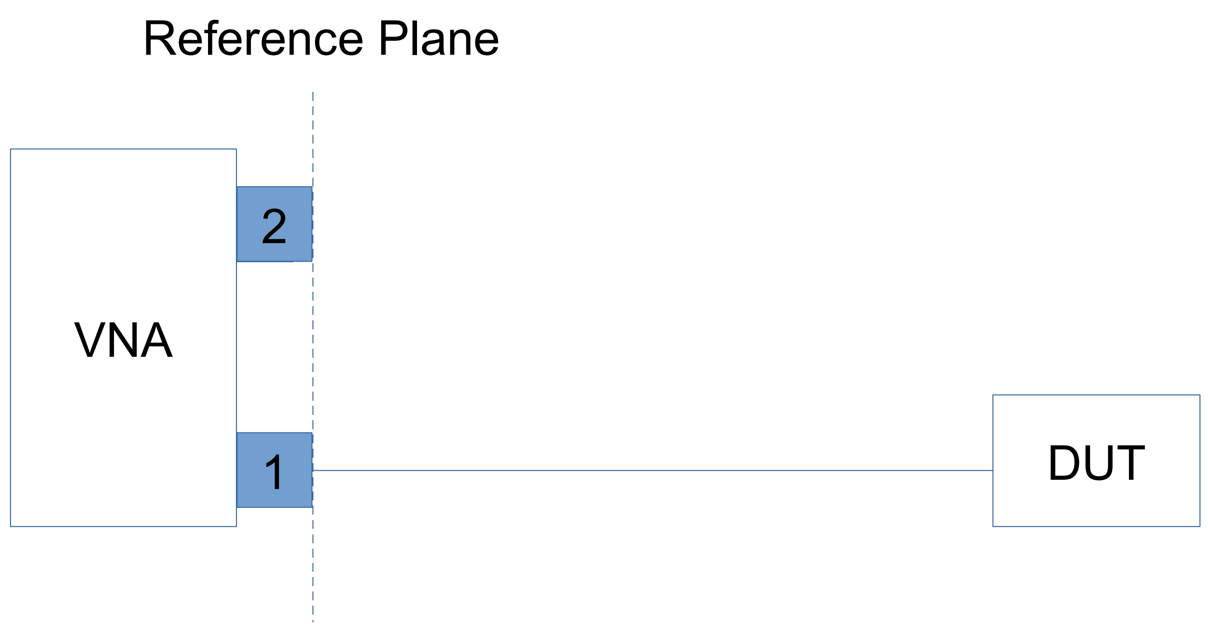
How to Measure

A 2-Port Vector Network Analyser



How to Measure

- User calibration is required to establish what known impedances look like to the analyser
- Short, Open, Load and Through (SOLT) components are used to calibrate the VNA prior to use
- The reference plane must be established before calibration is carried out



How to Measure

- The reference plane allows a shift of where the measurements are made some distance from the VNA
- Example: how to measure the feed point impedance of an antenna but not the feed line

- The losses in connections to the device under test must be considered as the VNA has limited output power and detector sensitivity (Dynamic Range)

VNA Results Displays

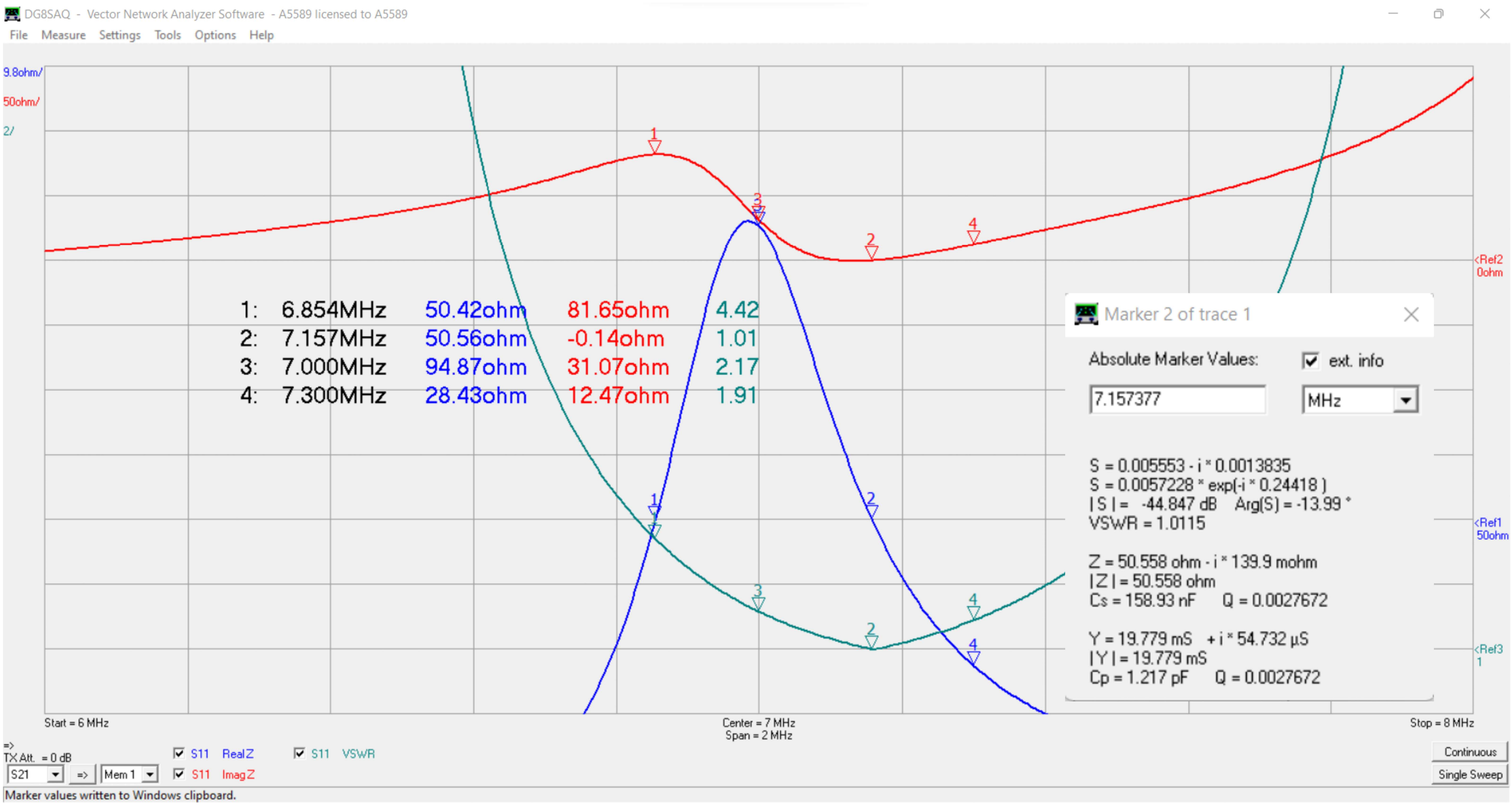
- Most results are displayed as graphical data
- Linear-Logarithmic X-Y charts where X is frequency and Y is the response generally in dBm
- Y can also be linear to display VSWR
- For reflection coefficient S_{11} can also be displayed on a Smith Chart
- Markers can be set to show detailed impedance/VSWR values at specific frequencies

VNA Results Displays

- Refresher dB, dBm, dBW
- Ratio of powers on a logarithmic scale unit is the bel (B)
- This is too big so we divide it by 10 and get the decibel (dB)
- $10Log_{10}$ (P_2/P_1) or $20Log_{10}$ (V_2/V_1)
- There are also absolute units where P_1 and/or V_1 are fixed at agreed reference values
- dBm referenced to 1 milliWatt and dBW referenced to 1 Watt
- 0 dBm = -30 dBW = 1 milliWatt
- 30 dBm = 0 dBW = 1 Watt
- 50 dBm = 20 dBW = 100 Watts
- 60 dBm = 30 dBW = 1000 Watts
- -120 dBm = -150 dBW = 1 x 10^{-15} Watts (typical Rx sensitivity)

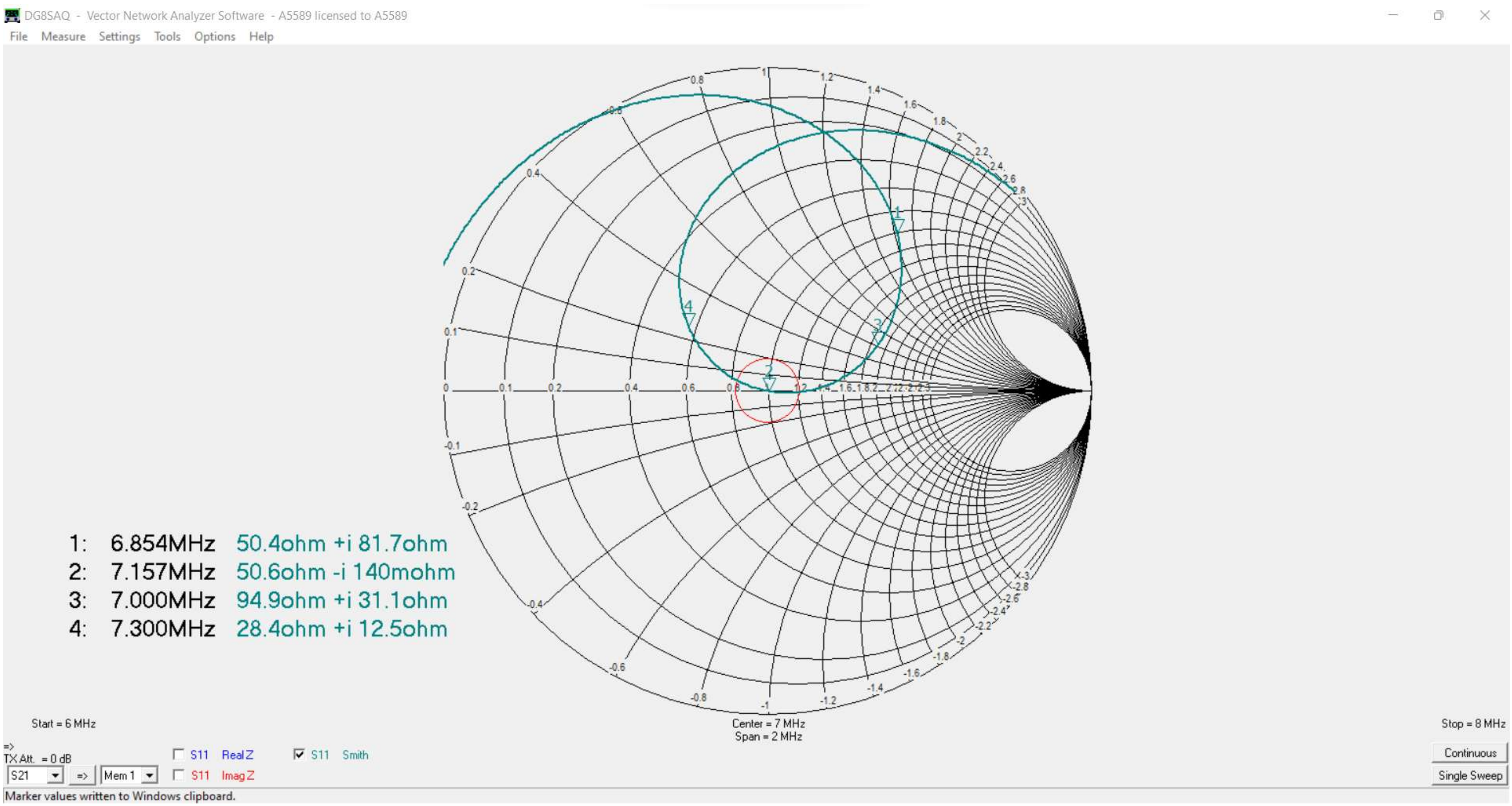
VNA Results Displays

Inverted V 40M   6 – 8 MHz
Real, Imaginary Impedance and VSWR S_{11}



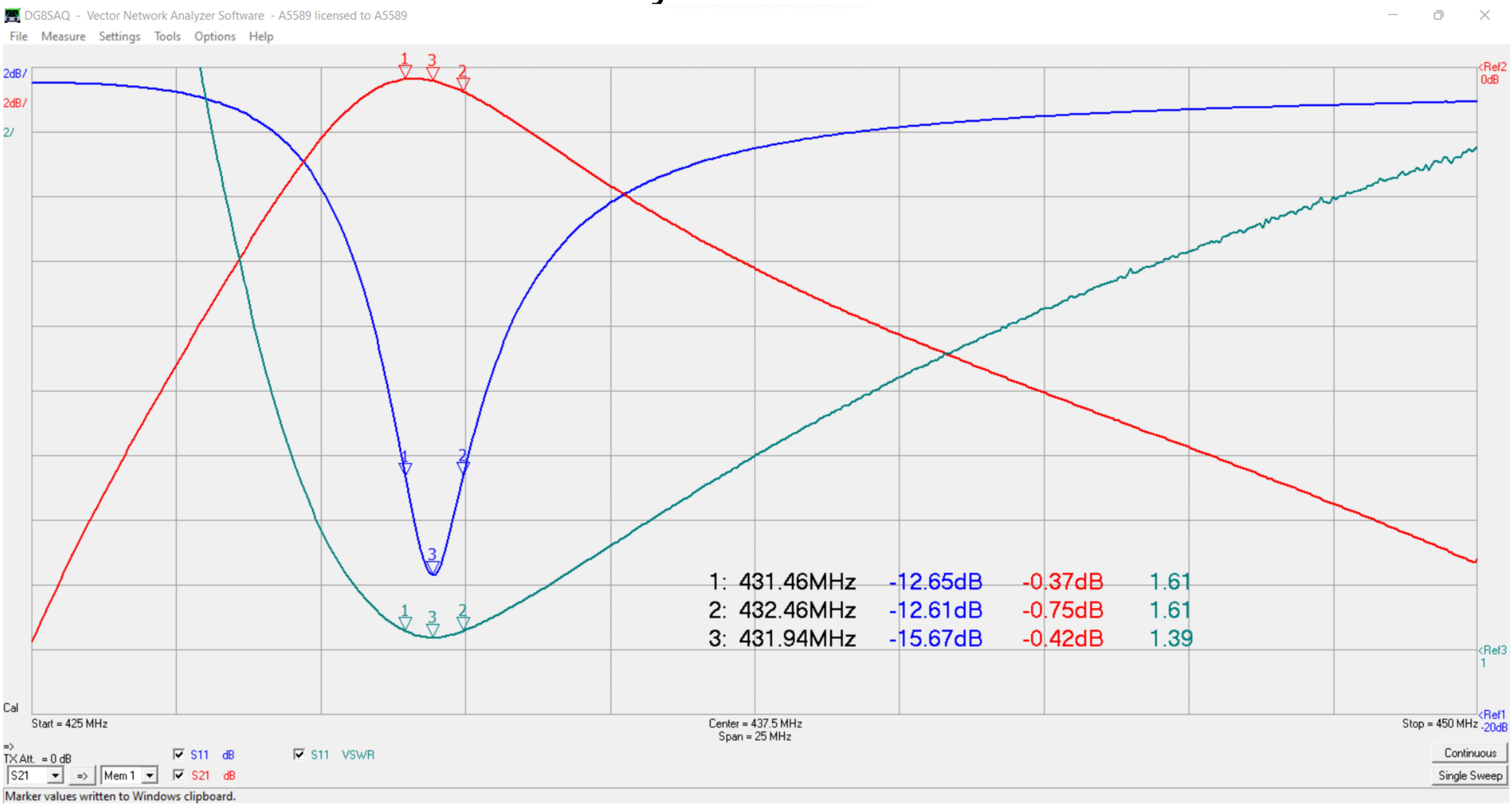
VNA Results Displays

Smith Chart Inverted V 40M 6 – 8 MHz VSWR S_{11}



VNA Results Displays

UHF Cavity Filter 425-450 MHz



Example of 4 GHz NanaoVNA

- NanoVNA V2 Plus4 $299.00 USD
- https://nanorfe.com/nanovna-v2.html
- https://www.tindie.com/products/hcxqsgroup/nanovna-v2-plus4/
- Screen Size 4 inches
- Frequency Range 50 kHz – 4.4 GHz
- Dynamic Range 90 dB
- Maximum Points 1024
- Sweep Speed 0.25 sec

Example of 6 GHz NanaoVNA

- NanoRFE VNA6000A $818, VNA6000B $1,528 USD
- https://nanorfe.com/vna6000.html
- https://www.tindie.com/products/hcxqsgroup/nanorfe-vna6000/
- Display Size 4 inches
- Frequency Range 50 kHz – 6 GHz
- Dynamic Range A-95 dB B-110 dB
- Maximum Points 1024
- Sweep Time 0.2 sec

Example of a Professional VNA

Keysight NA5205A PNA-X 4 Port, 50 GHz Network Analyser

Example of a Professional VNA

- Frequency Range 10 MHz to 50 GHz
- Dynamic Range 129 dB
- Output Power +13 dBm
- Built in ports 2 or 4
- Technical specifications runs to 124 pages
- Used price for 2 port >$300,000 USD
- Used price for 4 port >$500,000 USD
- New price P.O.A.

Example of a Professional VNA

Example of a Professional VNA

- Keysight FieldFox Microwave and RF Analysers
- Specification sheet is 73 pages long
- Can be used in 50 as well as 75 ohm systems
- Models 4/6.5/9/14/18/26.5/32/44/50 GHz
- Screen Size 6.5 inches
- Options TDR, Vector Voltmeter, Spectrum Analyser, GPS, I/Q Analyser, Noise Figure, OTA LTE FDD/TDD, Power Meter and many more
- Prices from $10,236.00 (4 GHz) to $55,936.00 (50 GHz) USD
- PC Software for analysis and reports
- Swiss Army Knife of RF Analysers

Summary

- S parameters are used to quantify RF device performance
- The Vector Network Analyser will provide those S parameters
- The VNA can do so much more (VSWR, polar plots etc.)
- Semi-professional performance analysis of antennas, filters and amplifiers is now available to amateur radio operators at reasonable cost <$400
- Questions?