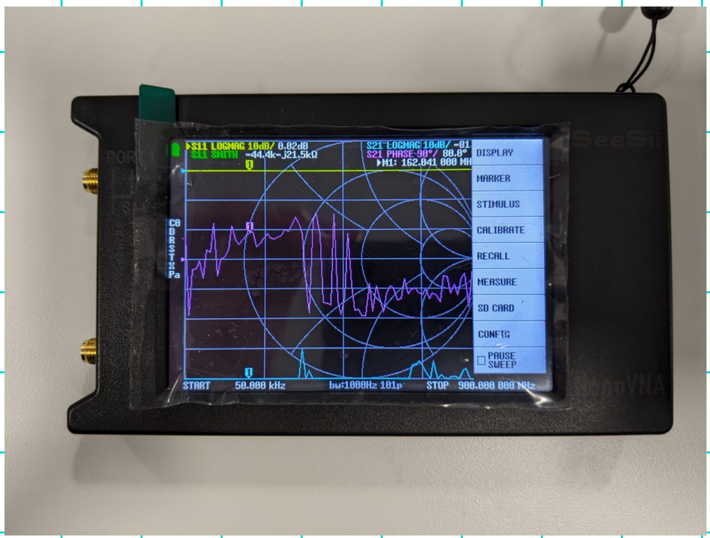
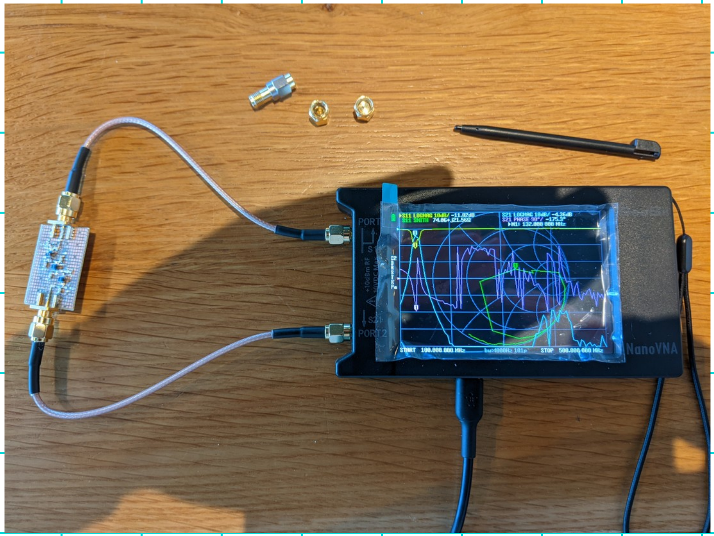
Southeast Michigan IEEE EMC Society Workshop: Hands-On With The NanoVNA





Outline

- Thank you to our event sponsors!
- Introduction (whoami)
- What is a VNA? How does it work? What can it measure?
- What are S (scattering) parameters?
- What is a NanoVNA? How does it perform measurements?
- NanoVNA User Interface
- Why do we need to calibrate a VNA?
- How do we calibrate the NanoVNA?
- Measurement Time: hands-on VNA measurements of various DUTs
- Questions (and maybe answers)?

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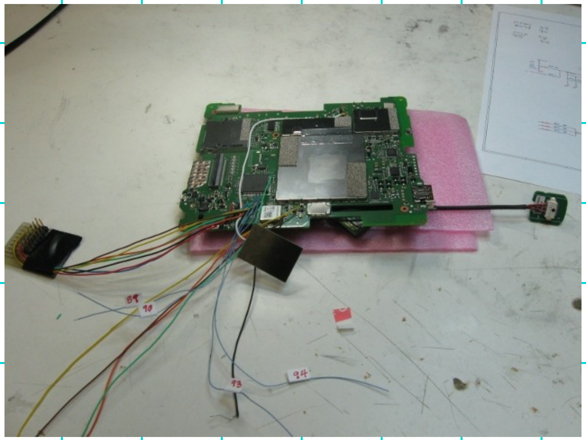
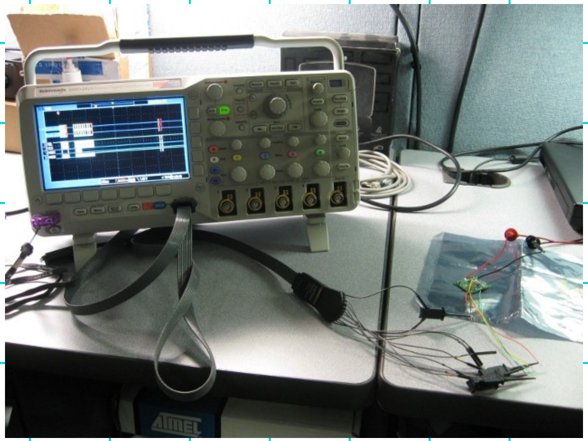
whoami

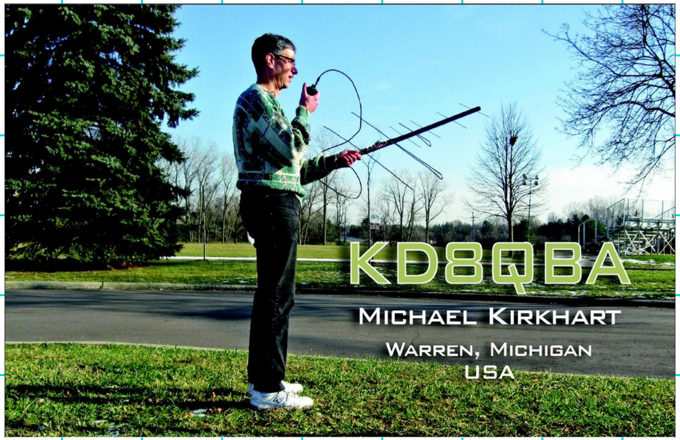
Electronics Engineer



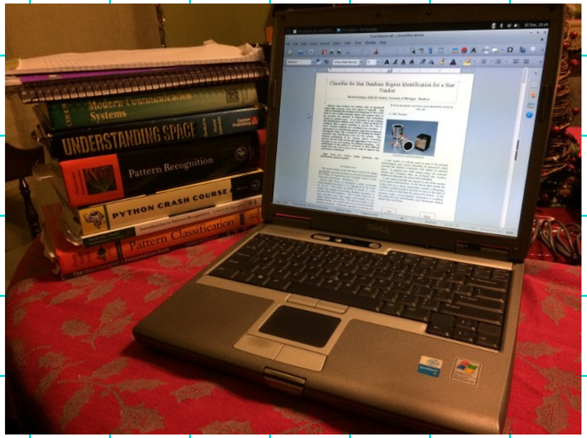
Hacker



Amateur Radio Operator



Lifelong Student

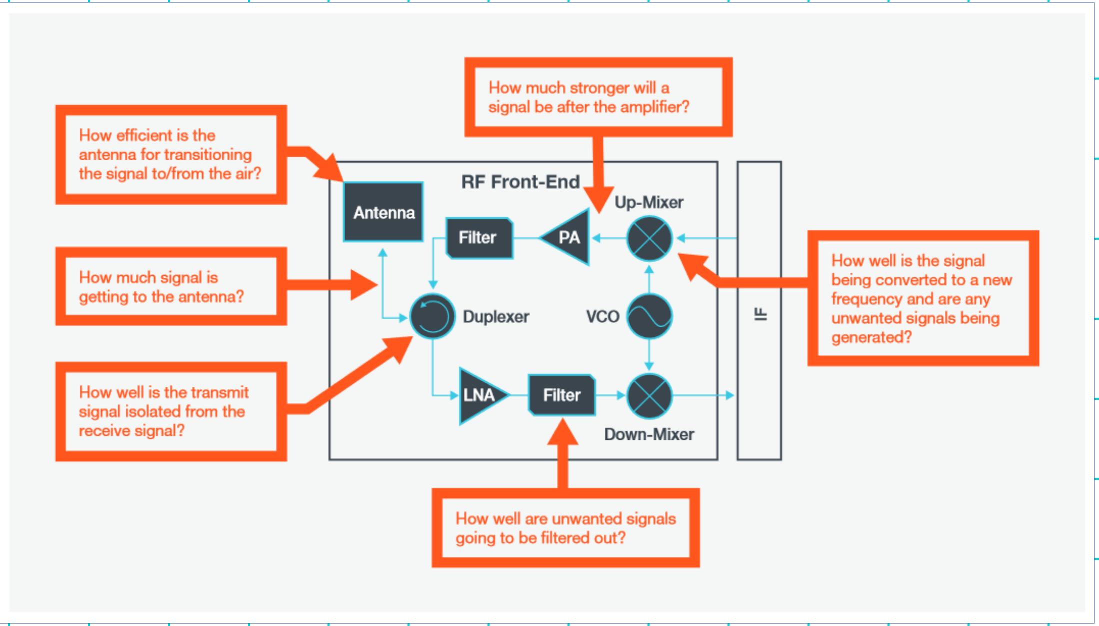


What is a VNA?

VNA = Vector Network Analyzer – "An instrument that measures the magnitude and phase of the reflection and transmission properties of the ports of a device versus frequency" (Alan Wolke)

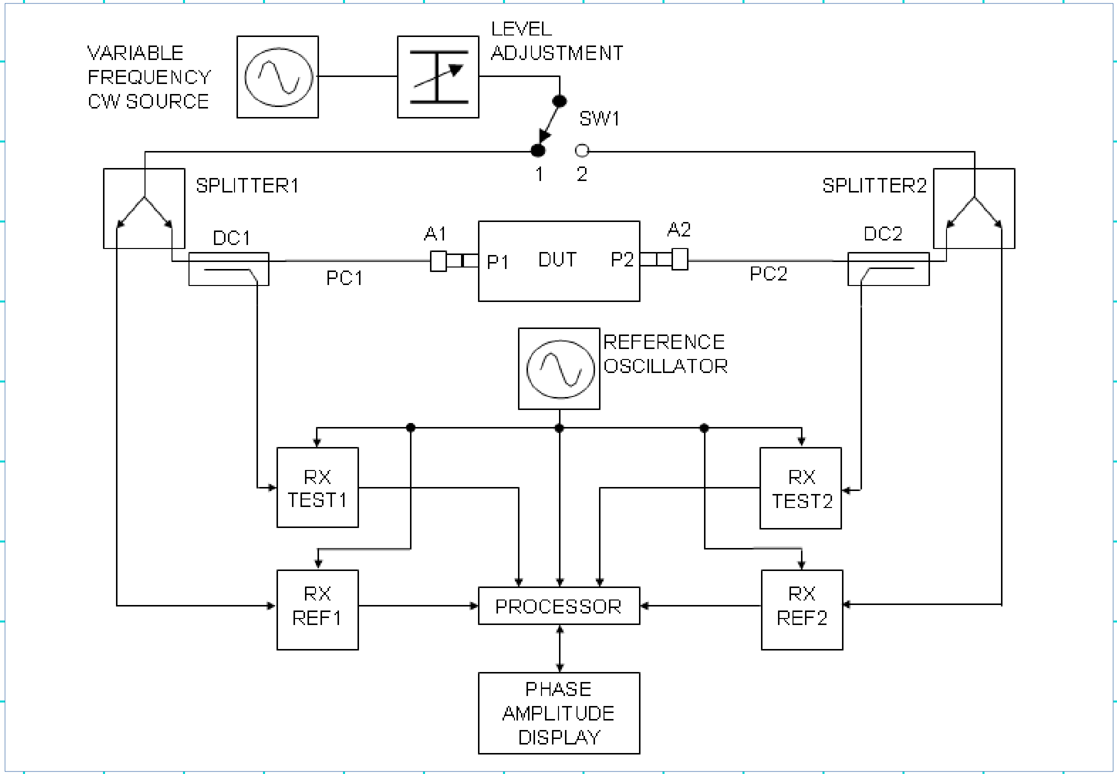
Typically used by RF engineers to characterize various components of an RF system

Here are a few of the potential questions about the performance of an RF system a VNA can be used to answer (from Tektronix "What is a Vector Network Analyzer and How Does it Work?")



How does a VNA work?

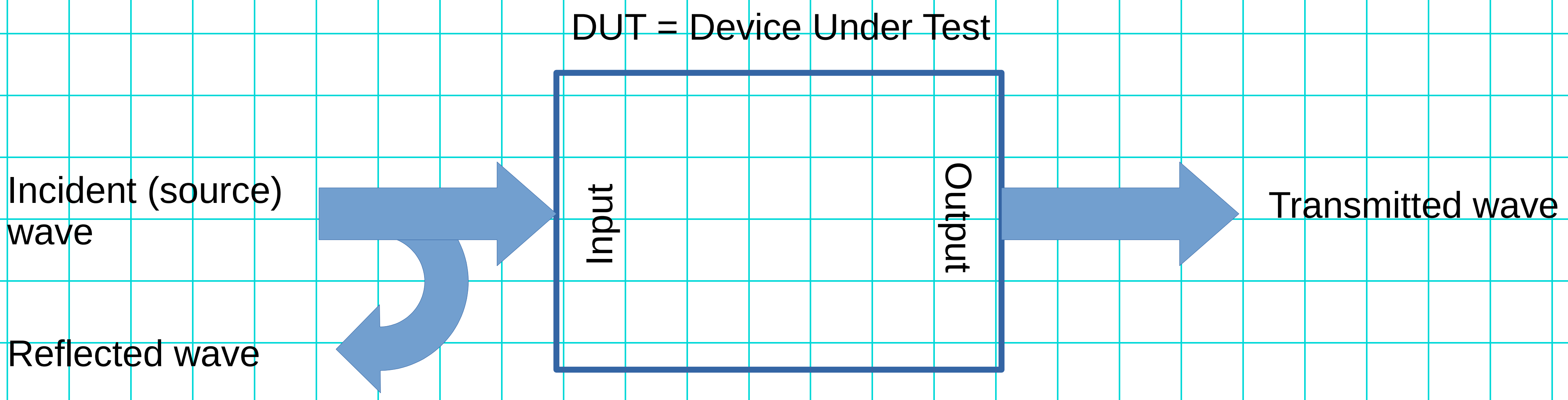
A VNA works by applying a known stimulus signal to one of its ports, and then measures the thru signal on the other ports along with any reflected signal on the stimulus port. This stimulus is swept in frequency, and the responses relative to the stimulus are displayed versus frequency.



What can a (2-port) VNA measure?

- Reflection Coefficient (S_{11})
  - Antenna feedpoint impedance
  - Voltage Standing Wave Ratio (VSWR)
  - Component impedance
- Transmission Coefficient (S_{21})
  - RF amplifier gain
  - Coaxial cable attenuation
  - Filter frequency response (bandwidth, insertion loss, phase delay, etc.)
- Output Reflection Coefficient (S_{22})
- Reverse Transmission Coefficient (S_{12})
- Coaxial cable length (via transform on S_{11})

What are S (scattering) parameters?



S_{xy} = response at port x resulting from stimulus on port y

$$S_{11} = \frac{\text{Reflected wave}}{\text{Incident wave}} \qquad S_{21} = \frac{\text{Transmitted wave}}{\text{Incident wave}}$$

Useful S11 related formulas

$$S_{11} = \Gamma_l = \frac{Z_l - Z_0}{Z_l + Z_0}$$

From definition of voltage reflection coefficient – Z_0 is the system impedance (usually 50 ohms)

$$S_{11}\,\text{logmag} = 20\log|\Gamma_l|$$

Voltage reflection coefficient log magnitude – 0 dB for full reflection, approaches infinity for zero reflection

$$RL = -20\log|\Gamma_l|$$

Return Loss – expresses how much incident voltage is absorbed by the load – in general, the higher, the better (negative version of logmag)

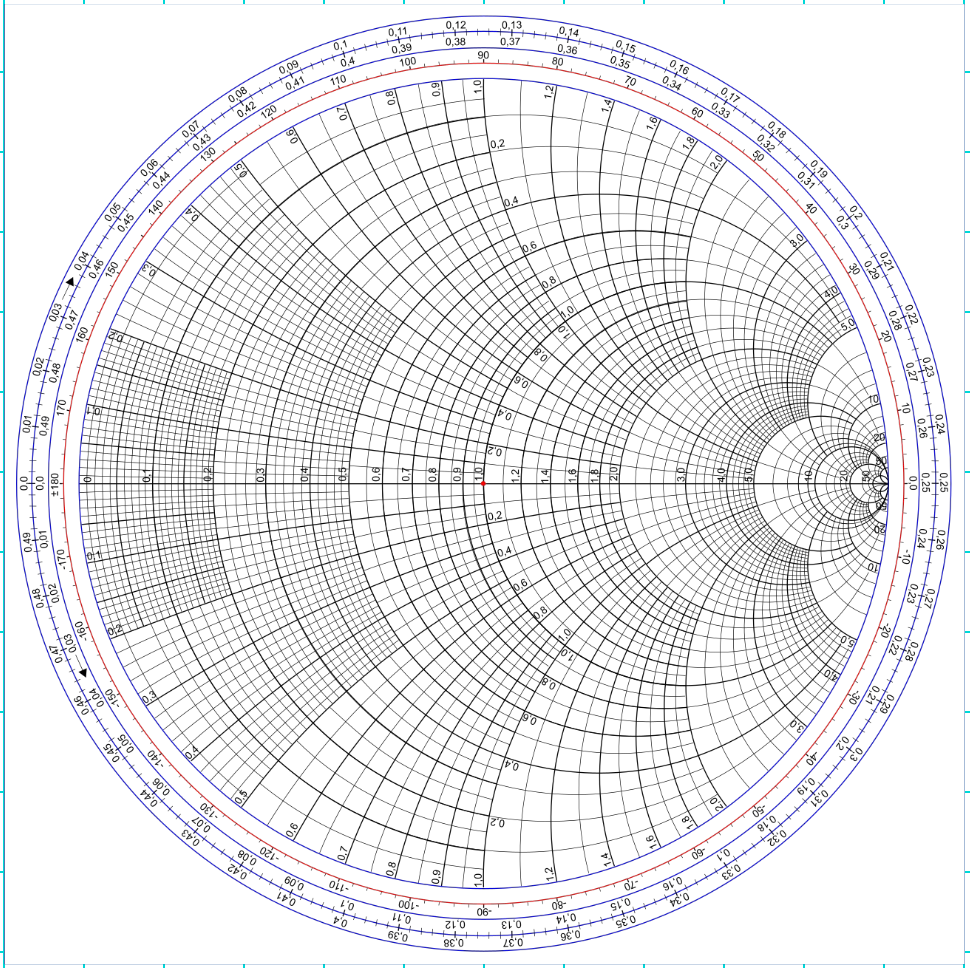
$$VSWR = \frac{E_{max}}{E_{min}} = \frac{1+|\Gamma_l|}{1-|\Gamma_l|}$$

Voltage Standing Wave Ratio – expresses the ratio between the maximum amplitude versus the minimum amplitude of any standing waves in the transmission line – will vary from 1:1 for a perfectly matched load, and approaches infinity for an open or shorted load

Useful S11 visualization: the Smith Chart

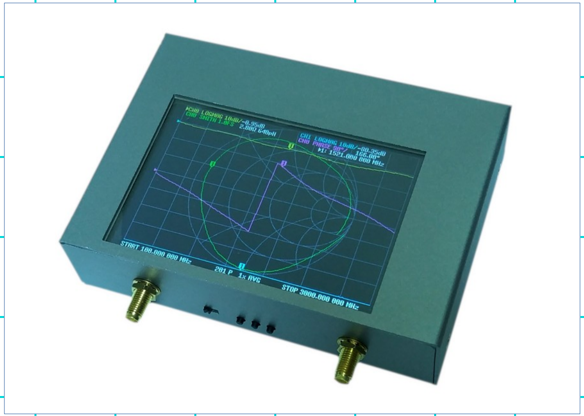
The Smith Chart is a graphical tool which maps the voltage reflection coefficient (a complex quantity) to a load impedance relative to the system impedance (again, usually 50 ohms). It was developed by Phillip H. Smith in 1939 as a way to graphically provide solutions to transmission line equations. While modern computers are able to perform these calculations easily, the Smith Chart is still used by RF engineers today to visually provide insights into the behavior of RF circuits (especially antenna engineers).

$$Z_l = \frac{Z_0 (1 + \Gamma_l)}{(1 - \Gamma_l)}$$

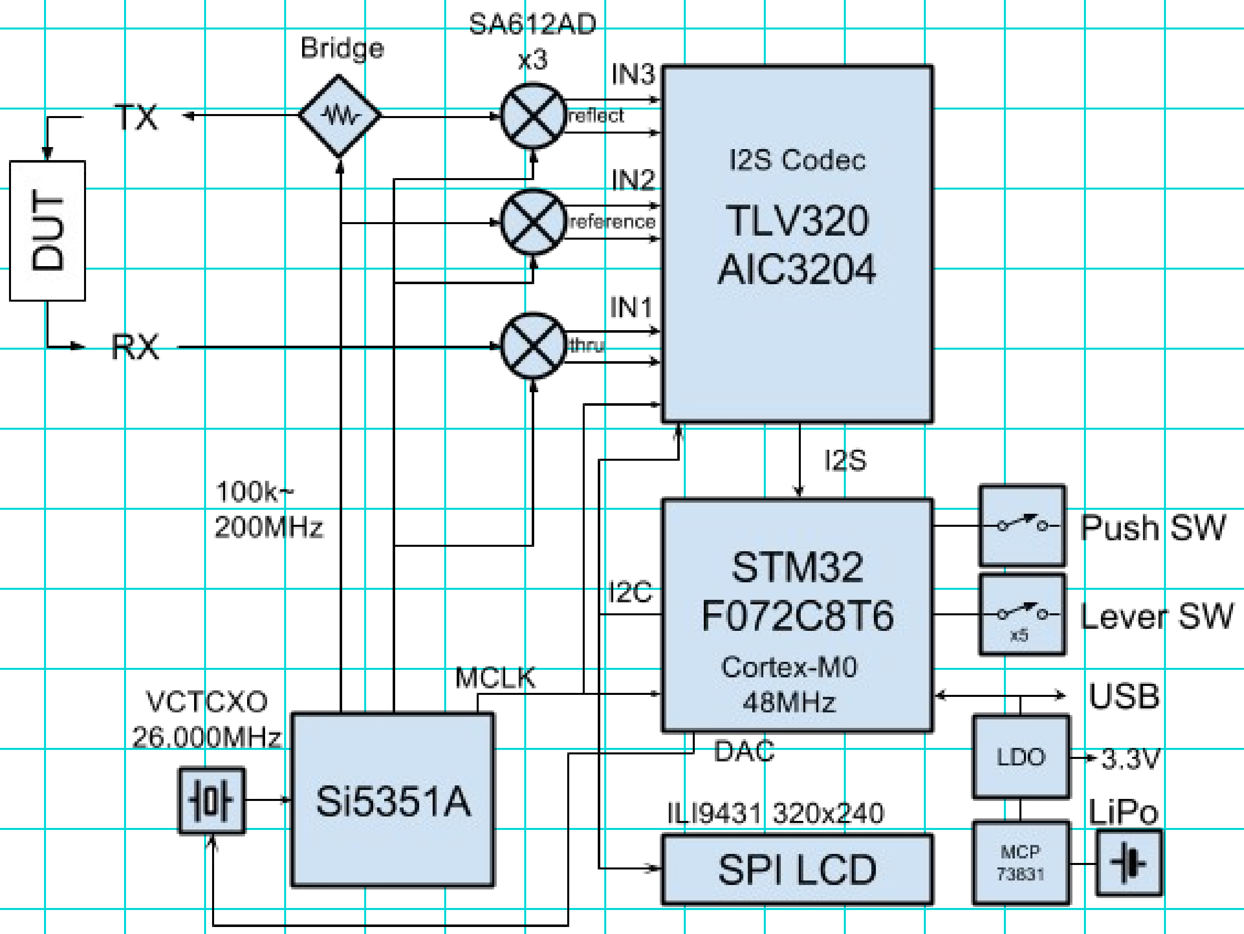


What is a NanoVNA?

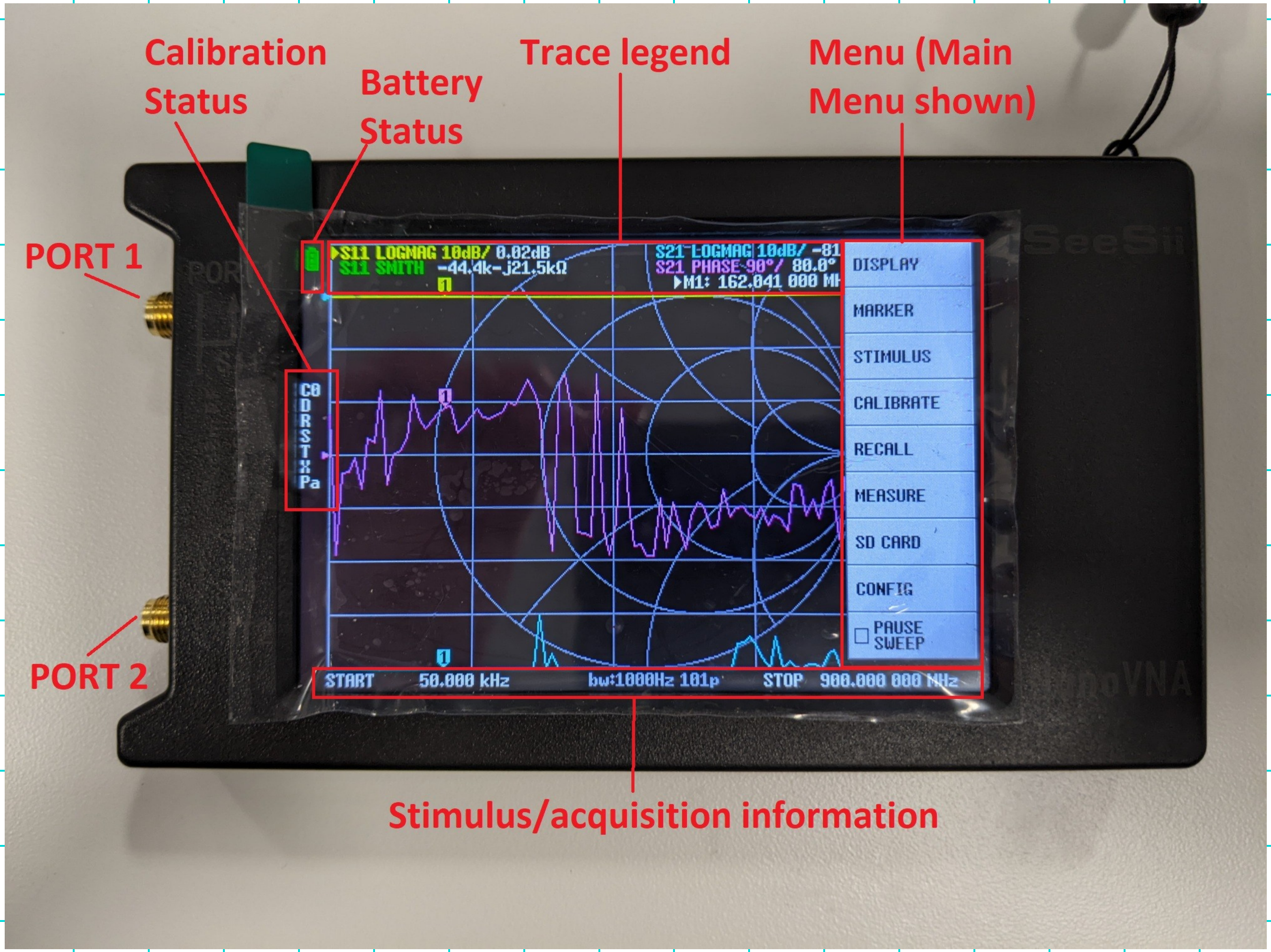
- Low cost (typically about $100), portable vector network analyzer
- Several versions exist from various vendors, with various frequency ranges, display sizes
- Typical frequency ranges:
  - 50 kHz – 900 MHz (original version)
  - 50 kHz – 1.5 GHz (H4 version)
  - 50 kHz – 3 GHz (V2 Plus 4 version)
- 2-port, 1-path measurement capability (S_{11}, S_{21})
- Includes low cost SOLT (Short, Open, Load, Thru) calibration kit
- Not nearly as capable as a professional grade VNA (for example, cannot perform full 2-port, 2-path measurements, cannot adjust stimulus power), but “good enough” for many basic measurements, and much, much lower in price



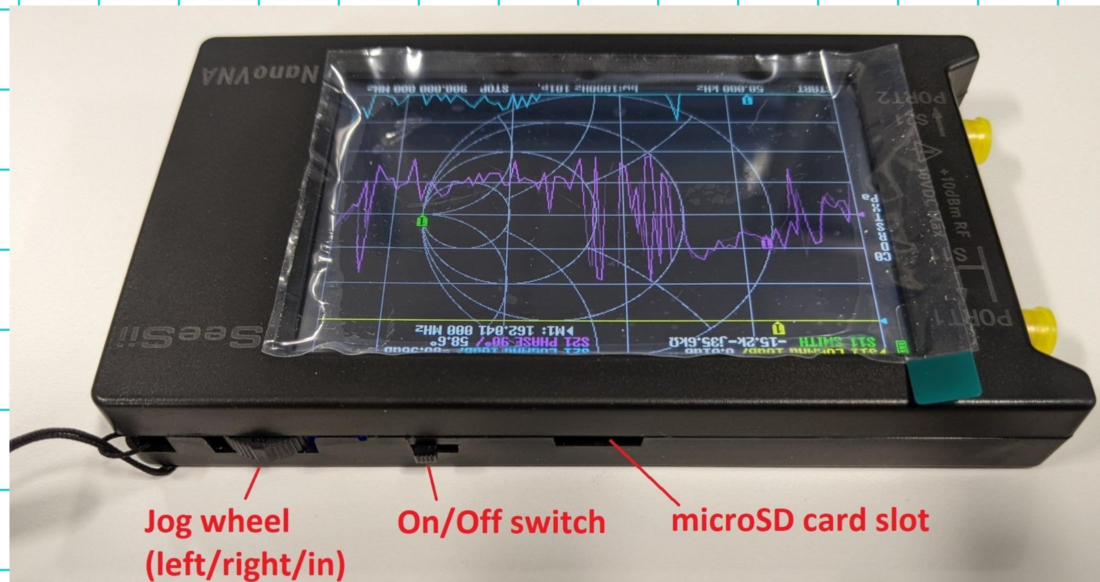
How does the NanoVNA perform measurements?

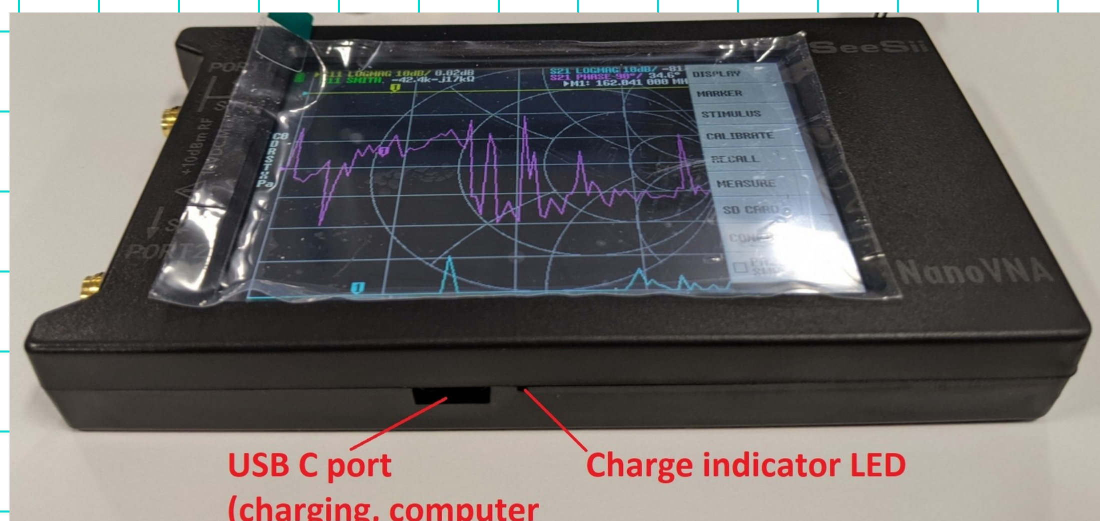


NanoVNA User Interface

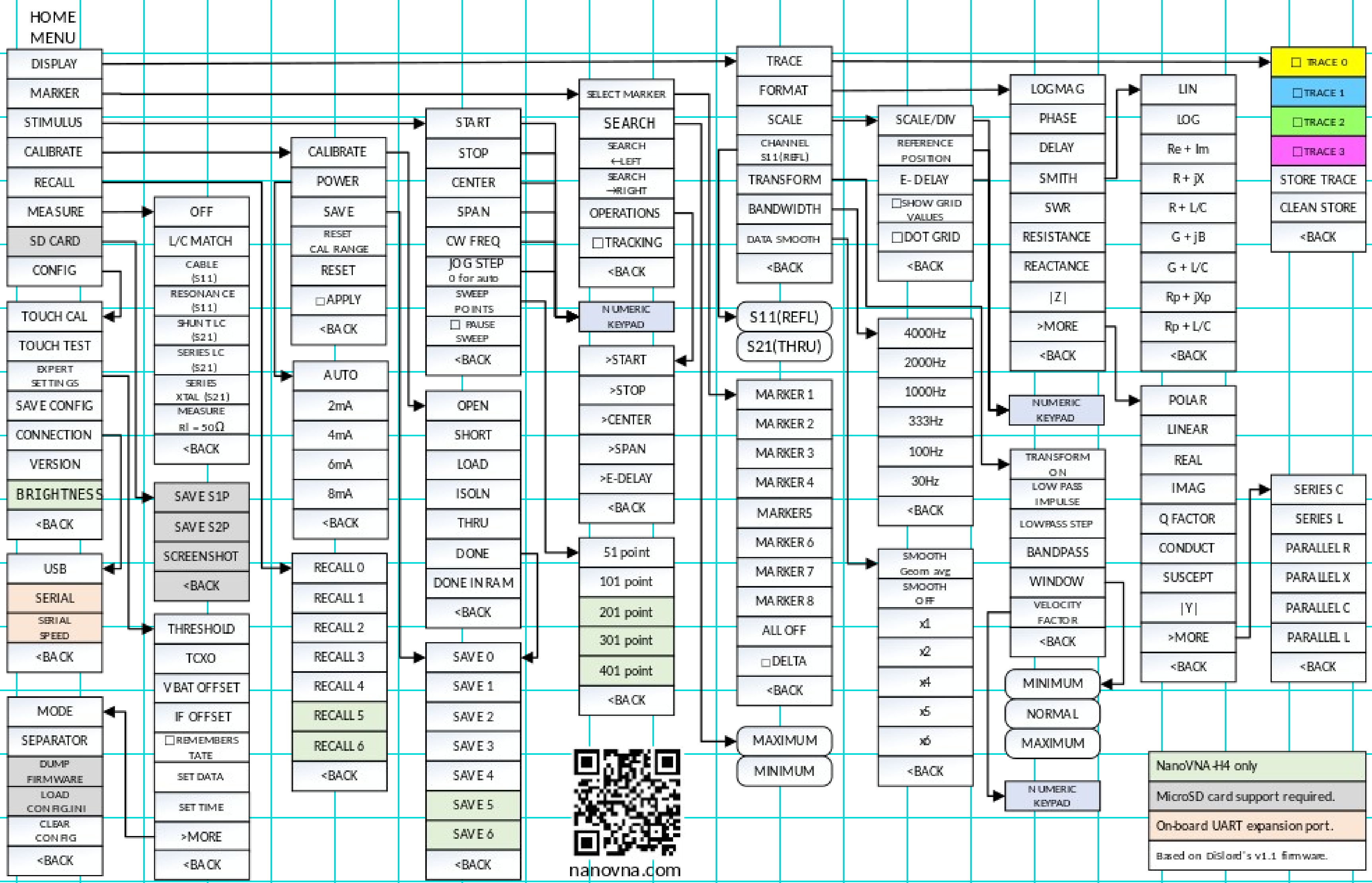


NanoVNA User Interface





NanoVNA Menu Structure



VNA Calibration

Why do we need to calibrate a VNA?

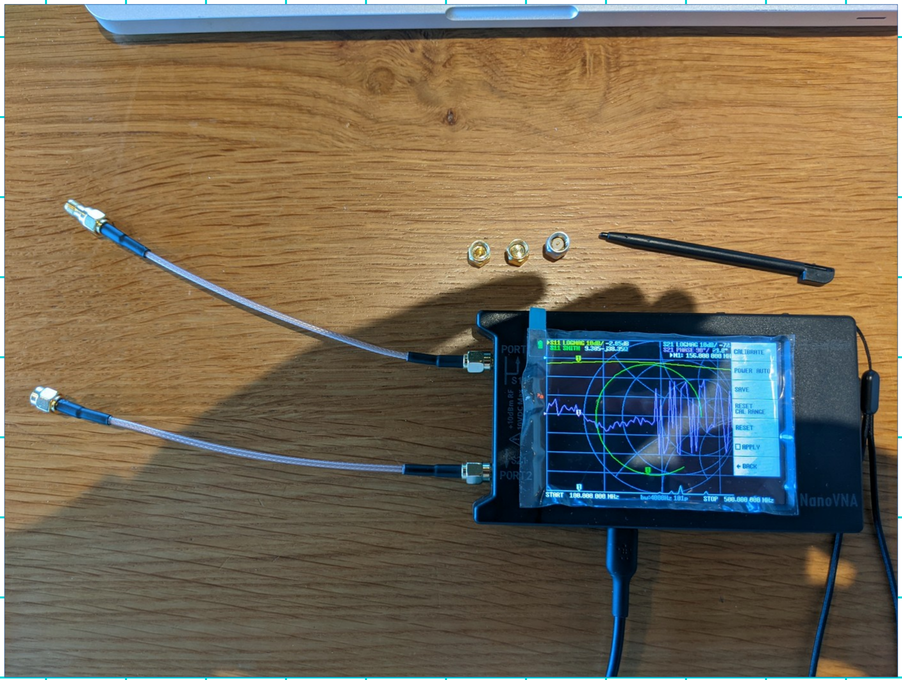
- Compensate for systematic errors
  - Imperfections in the port impedance matching
  - Imperfections in the directivity of the directional couplers/bridges used to measure reflected signals from the stimulus port
  - Imperfect isolation between the stimulus signal source and the receivers
  - Variations in the frequency response of the receivers
- Compensate for user measurement configuration
  - Cables/fixtures used to connect the VNA to the DUT attenuate signals, add phase delay
  - Desire is to have measurement planes at the terminals of the DUT

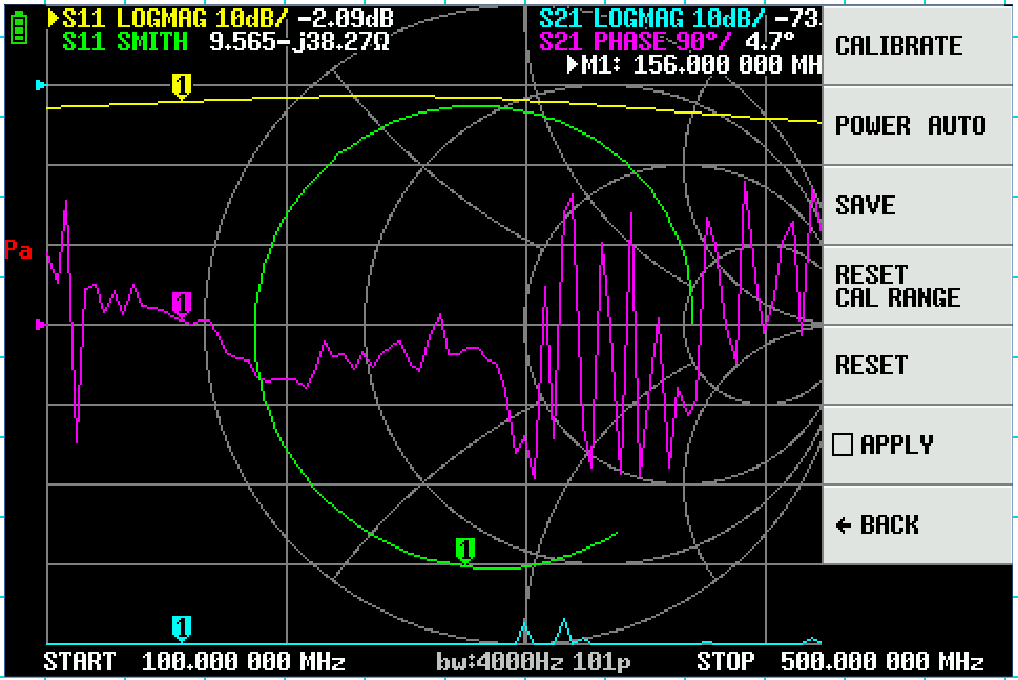
When do we need to calibrate a VNA?

- When changing the frequency range
- When changing the cabling/fixturing used to connect the VNA to the DUT
- When the operating environment of the VNA changes significantly (temperature, for example)

How do we calibrate the NanoVNA?

Calibration reset

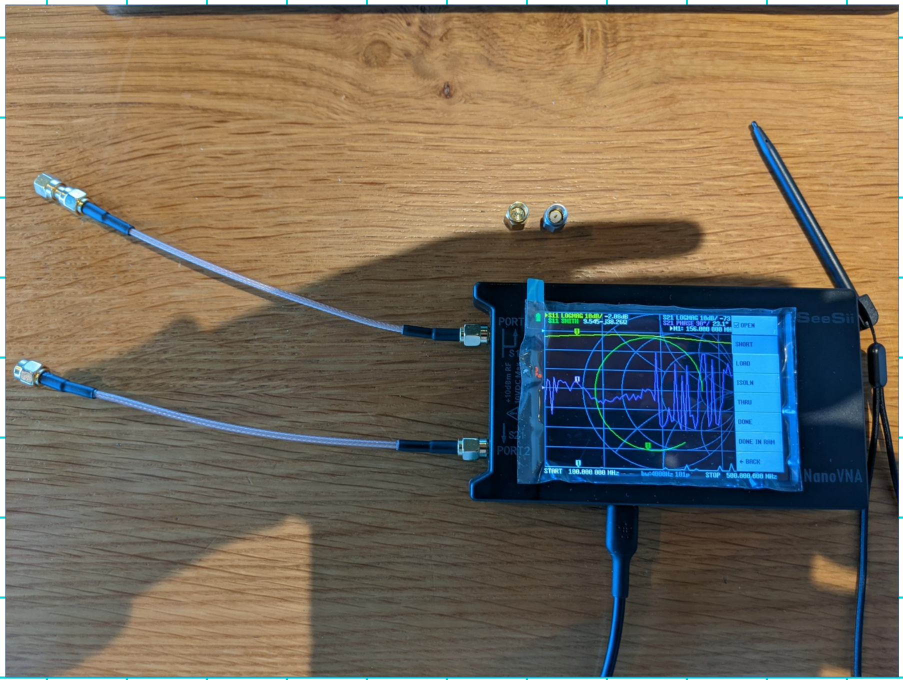


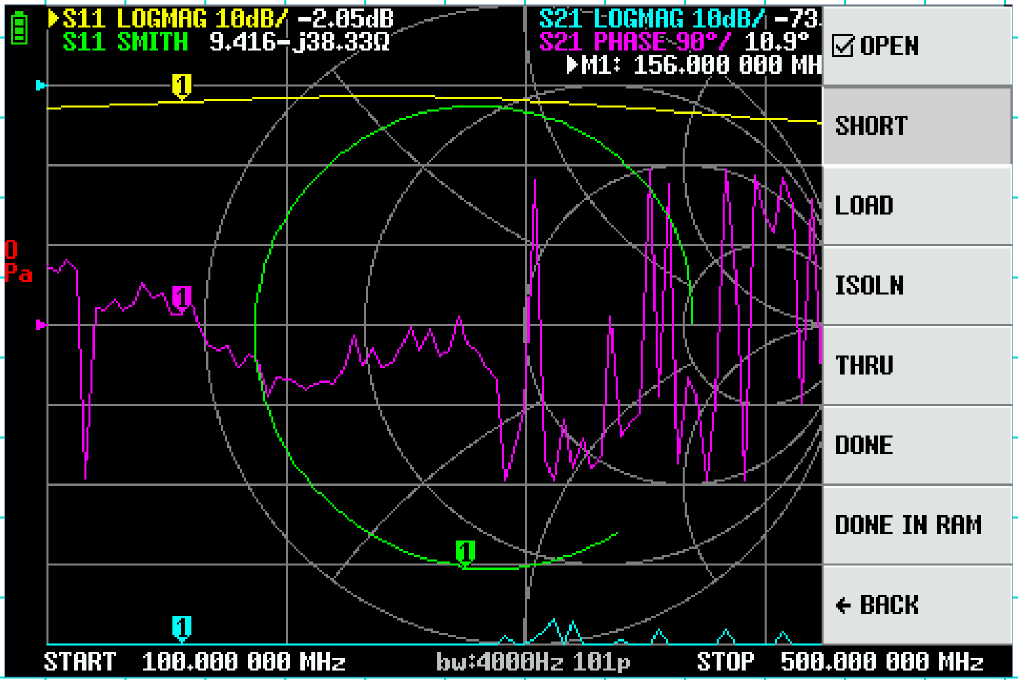


Reset the current calibration by going to the CALIBRATE menu, and then select RESET

How do we calibrate the NanoVNA?

Calibration open

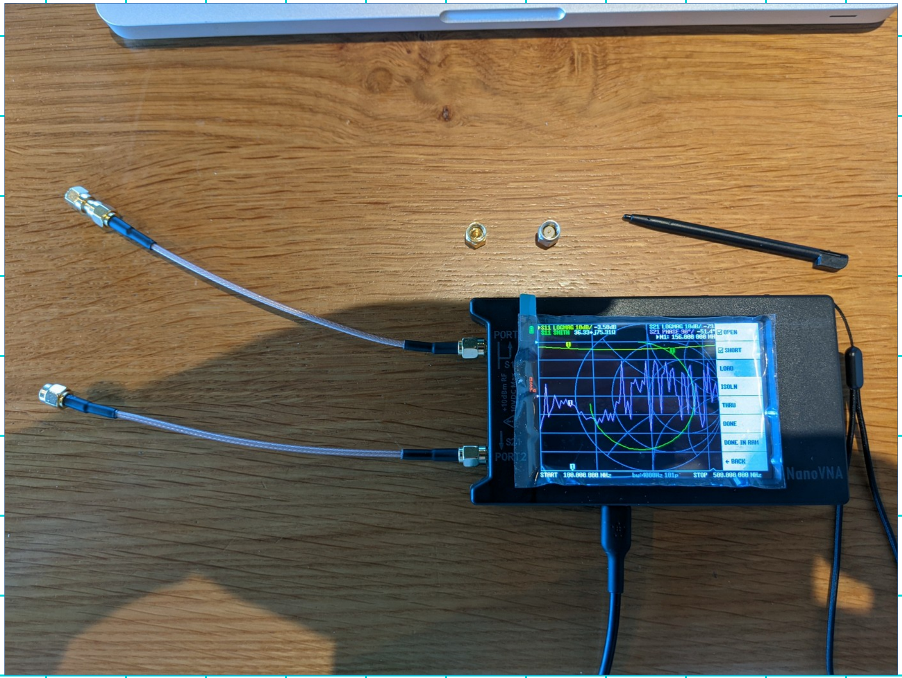


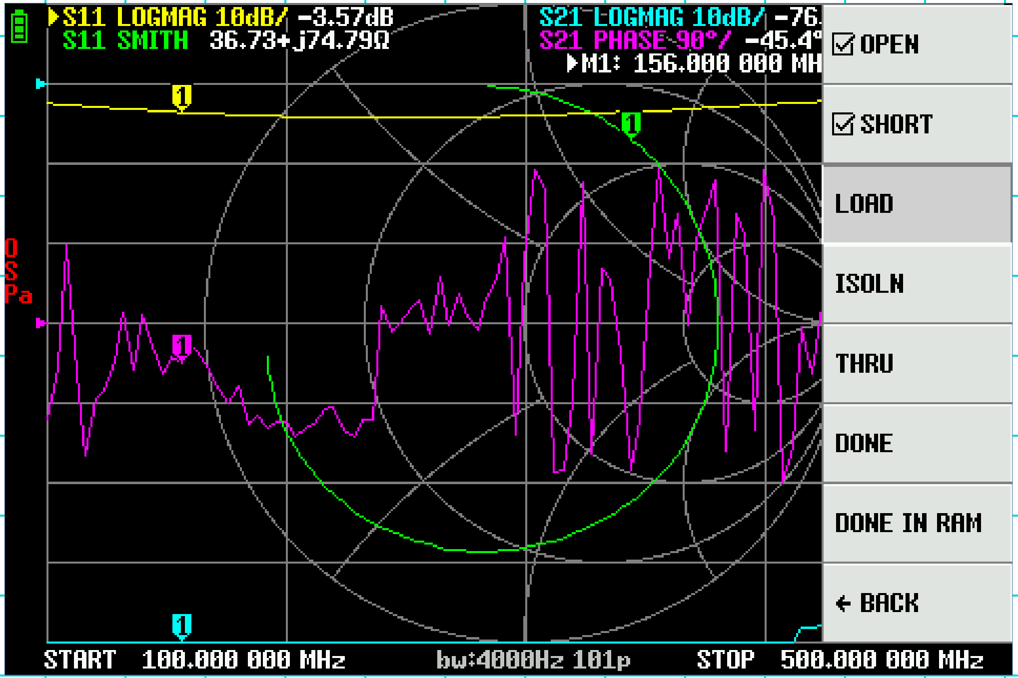


Now select the CALIBRATE menu, connect the open calibration standard to PORT 1, and select the OPEN button

How do we calibrate the NanoVNA?

Calibration short

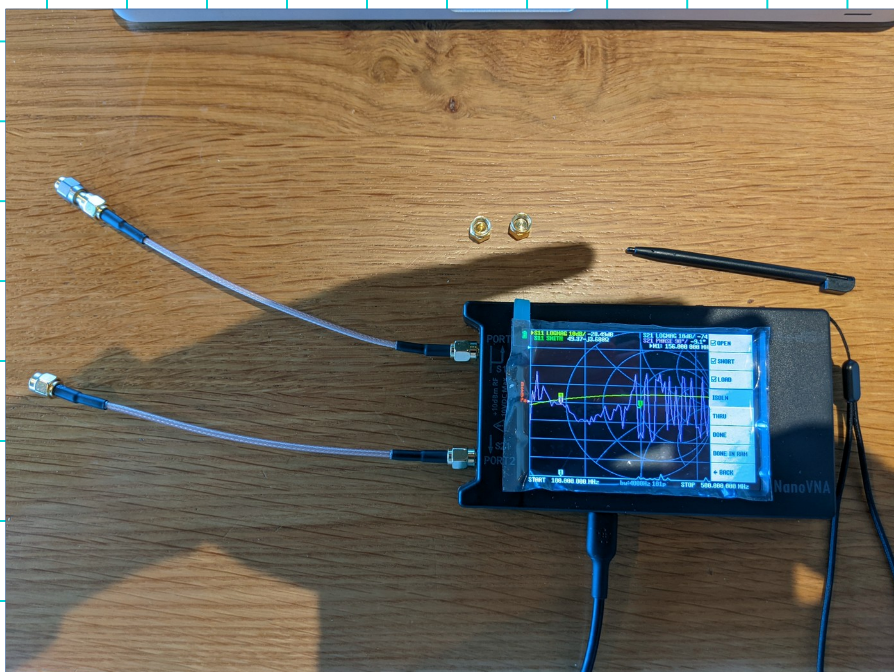


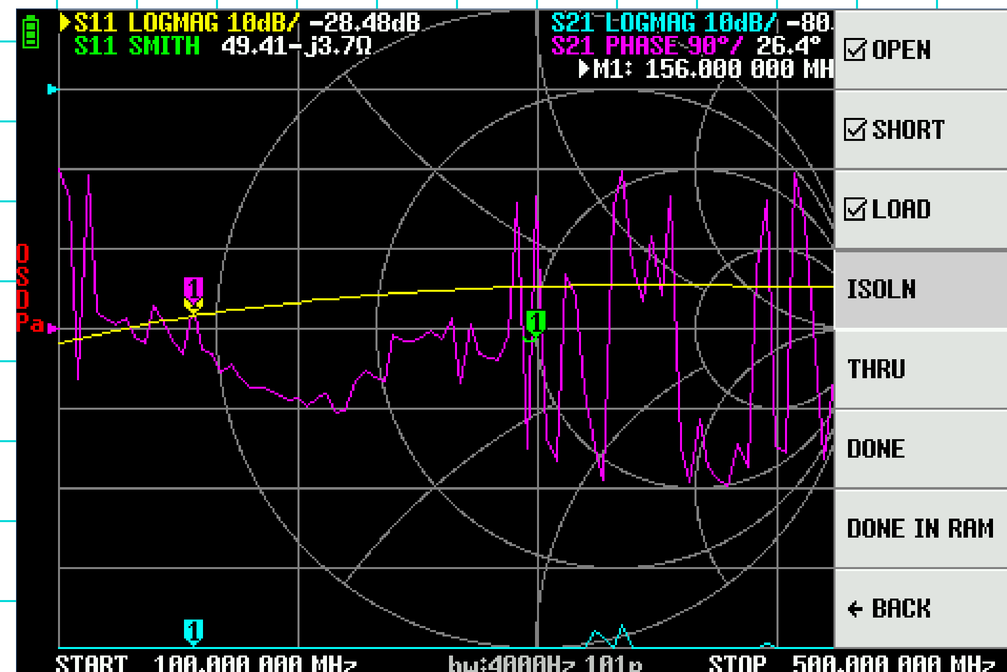


Remove the open calibration standard and connect the short calibration standard to PORT 1, and select the SHORT button

How do we calibrate the NanoVNA?

Calibration load

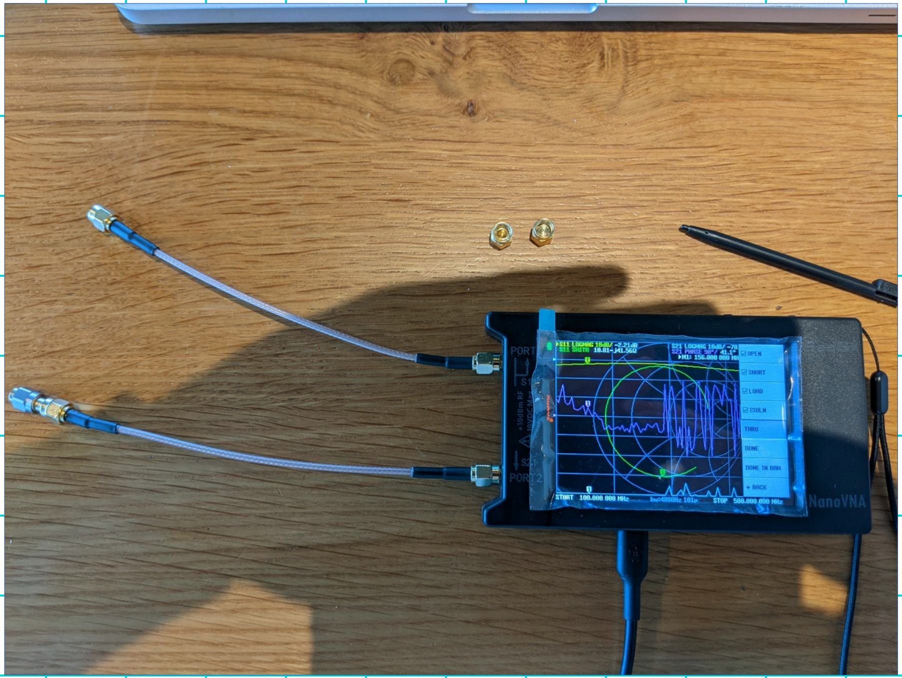


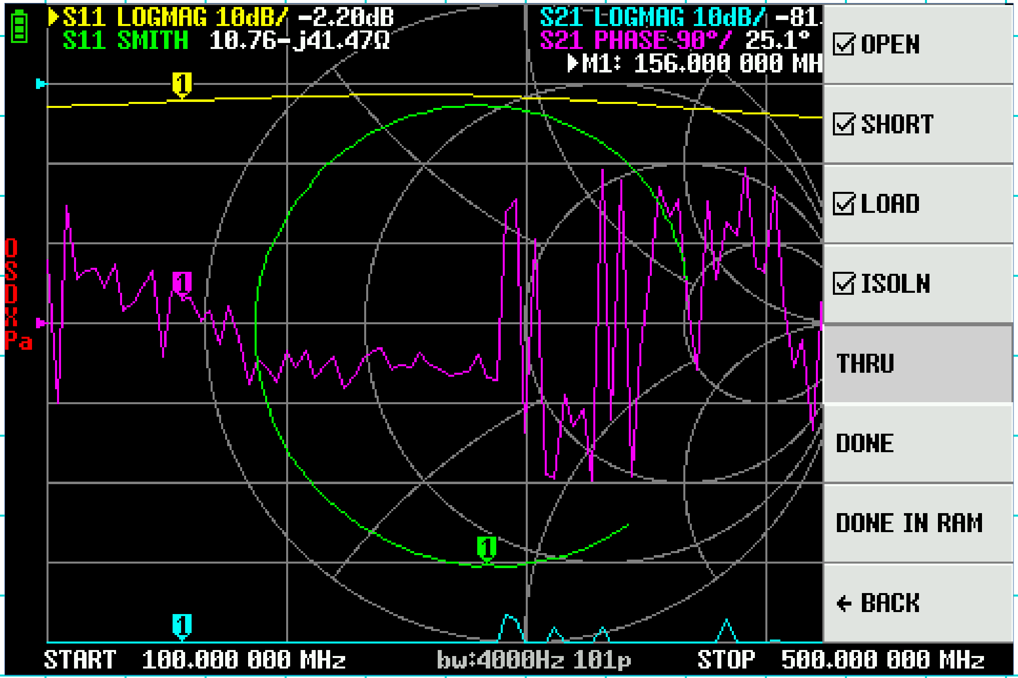


Remove the short calibration standard and connect the load calibration standard to PORT 1, and select the LOAD button

How do we calibrate the NanoVNA?

Calibration isolation

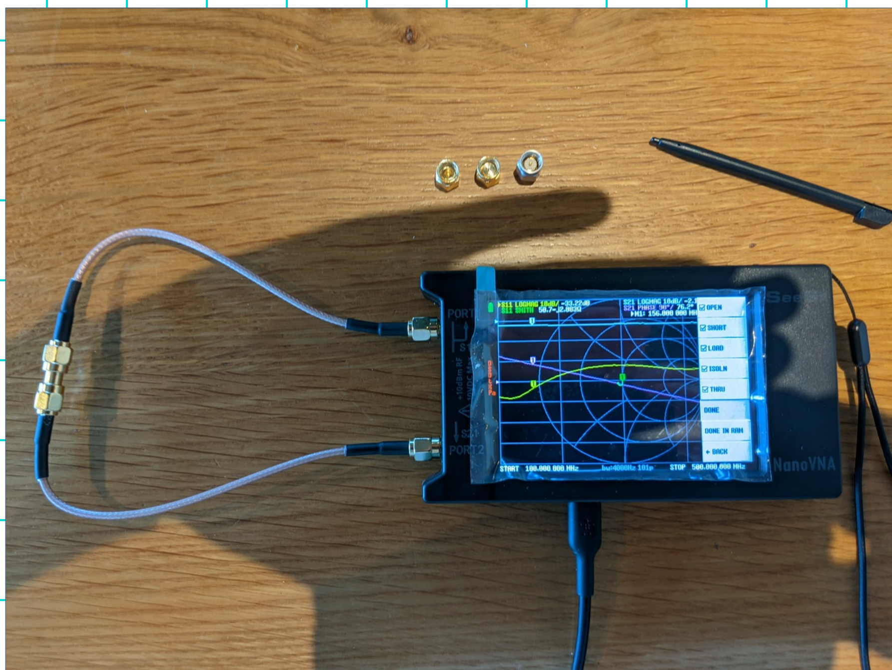


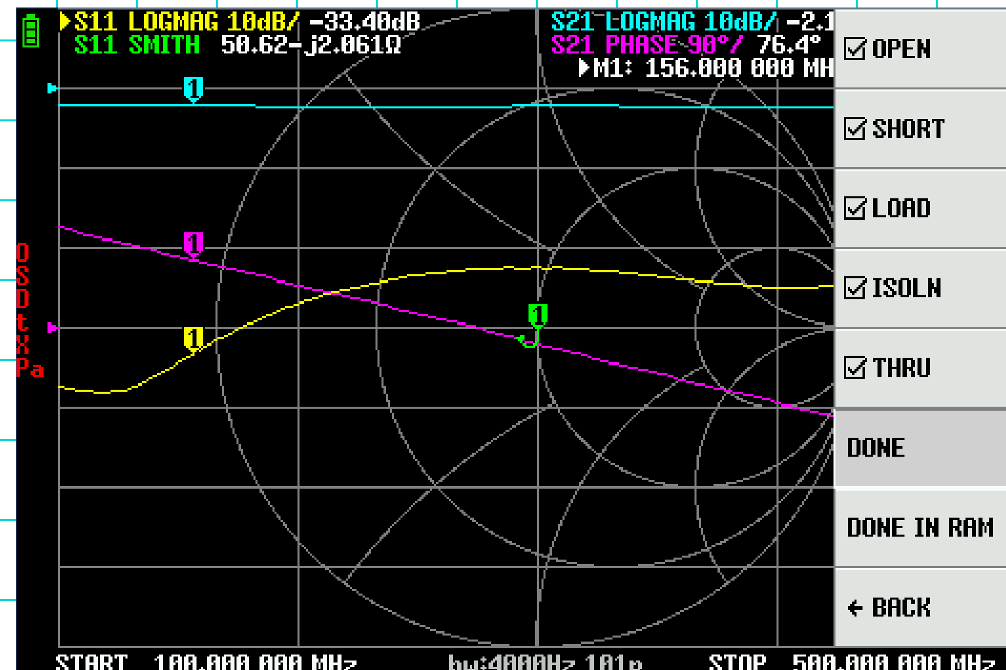


Remove the load calibration standard from PORT 1, connect it to PORT 2, and select the ISOLN button

How do we calibrate the NanoVNA?

Calibration thru

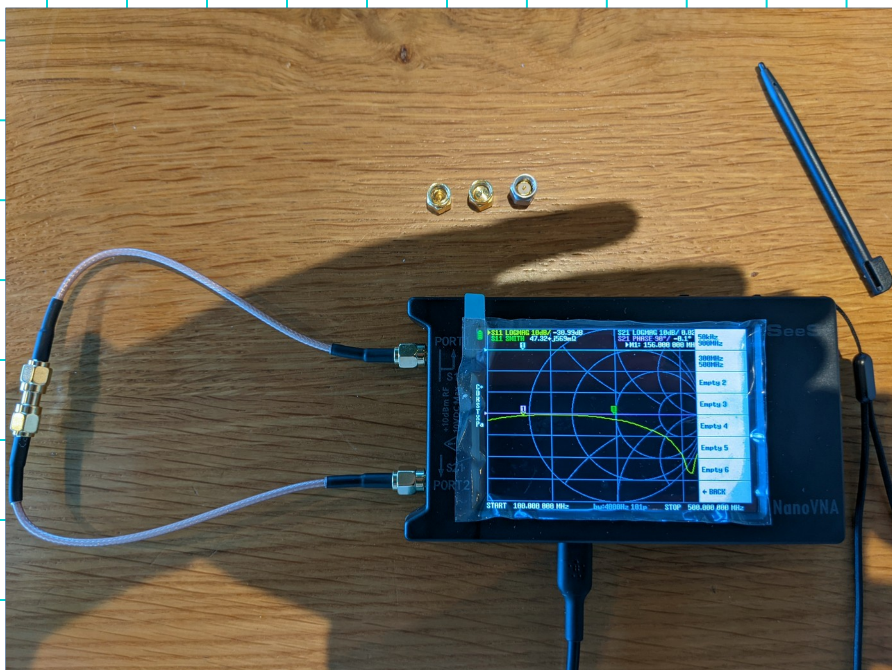


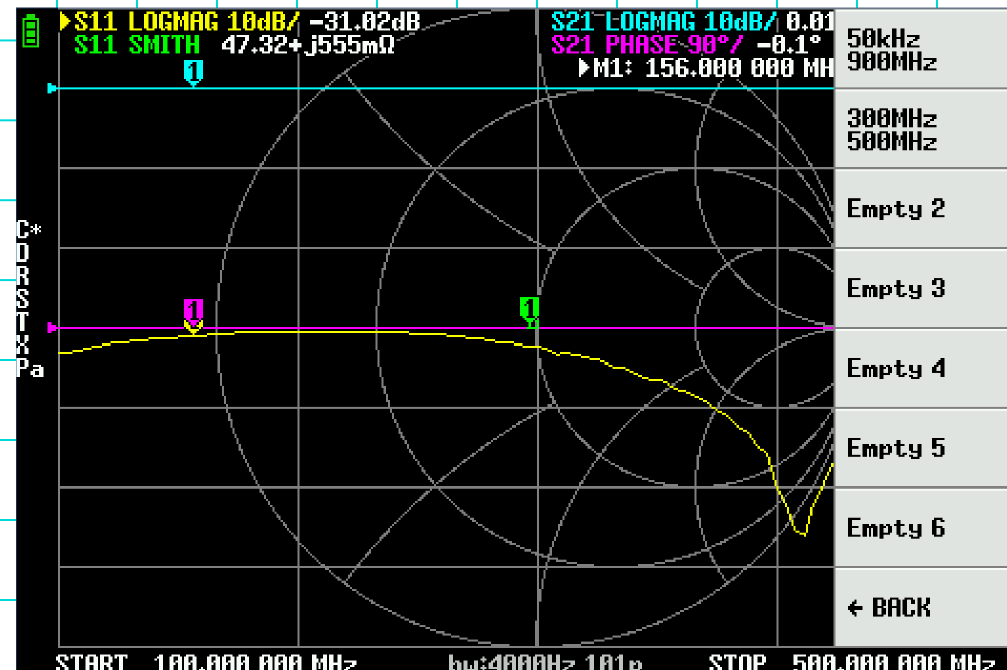


Remove the LOAD calibration standard from PORT 2, connect the thru calibration standard between PORT 1 and PORT 2, and select the THRU button

How do we calibrate the NanoVNA?

Calibration done

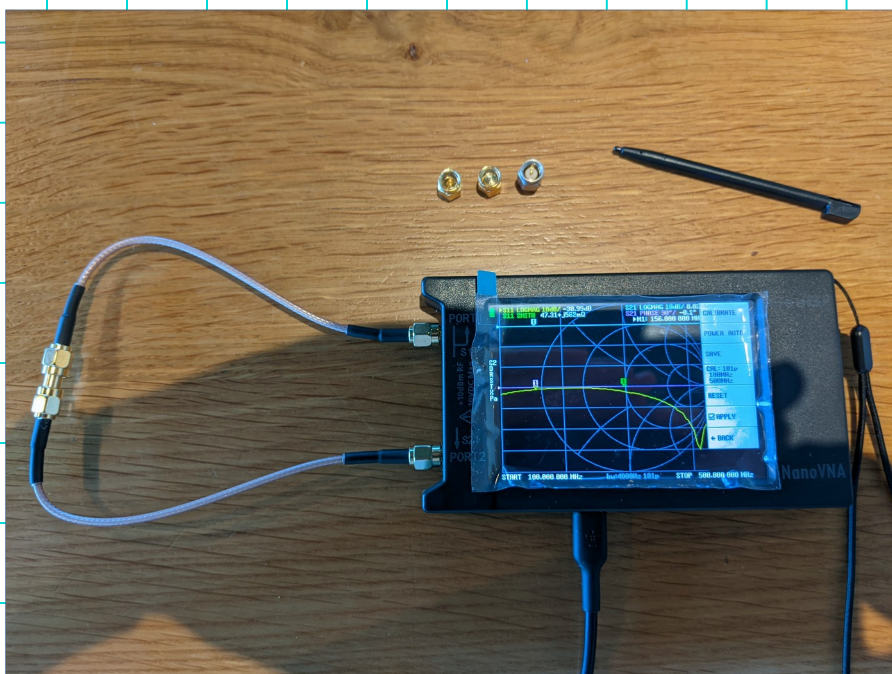


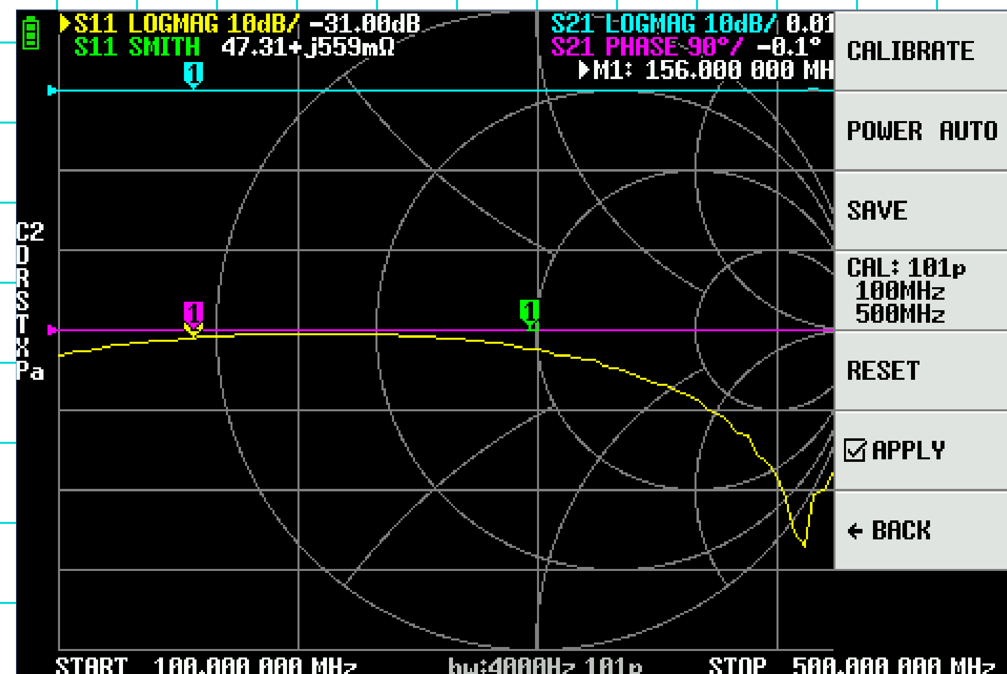


Select the DONE button, which will bring you to the saved calibration menu. Select one of the save slots to store the calibration.

How do we calibrate the NanoVNA?

Calibration saved

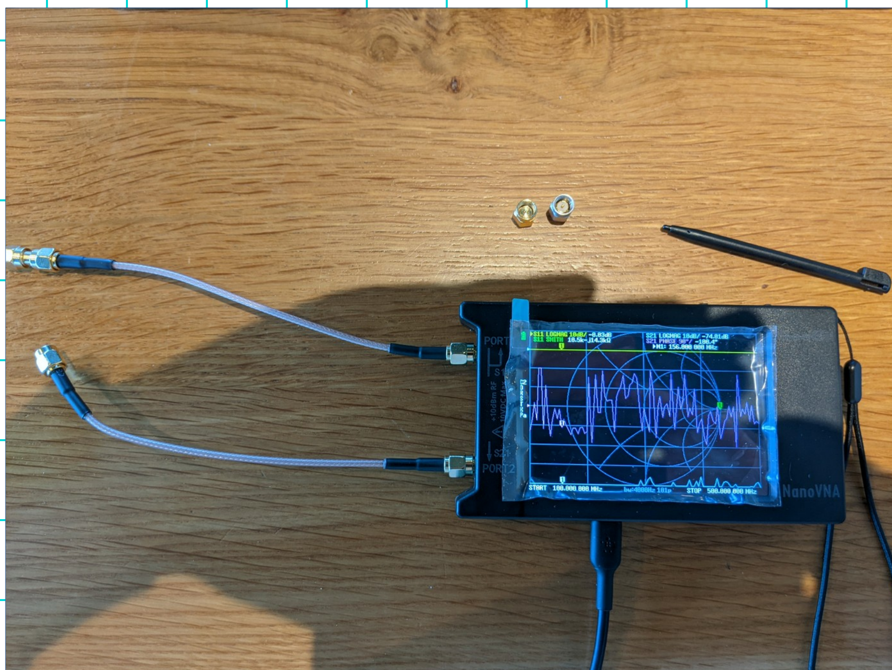


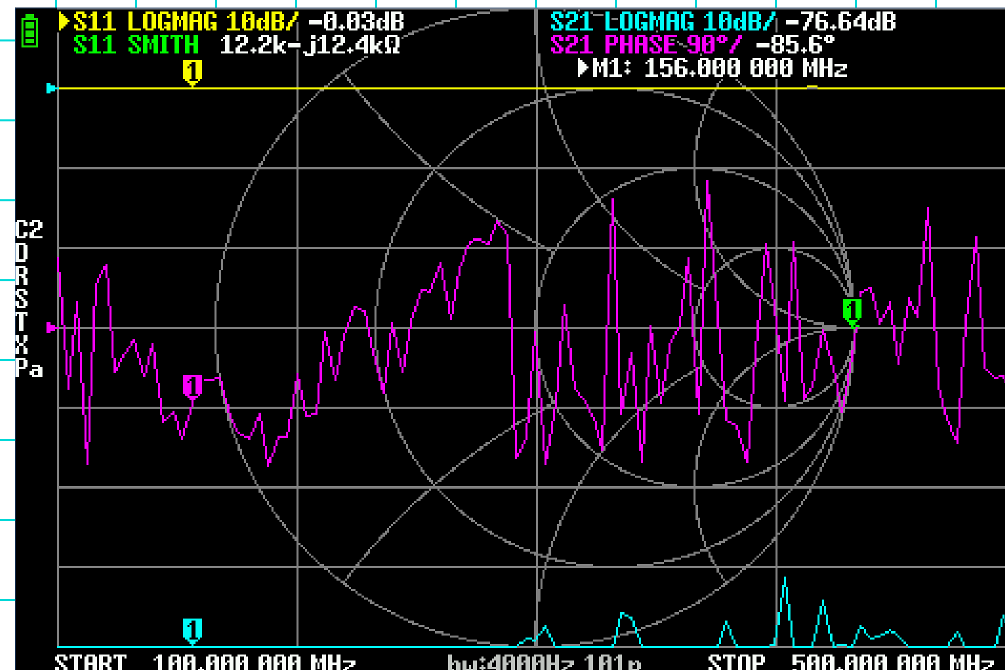


Calibration is now complete!

How do we verify the calibration?

Calibration verification - open

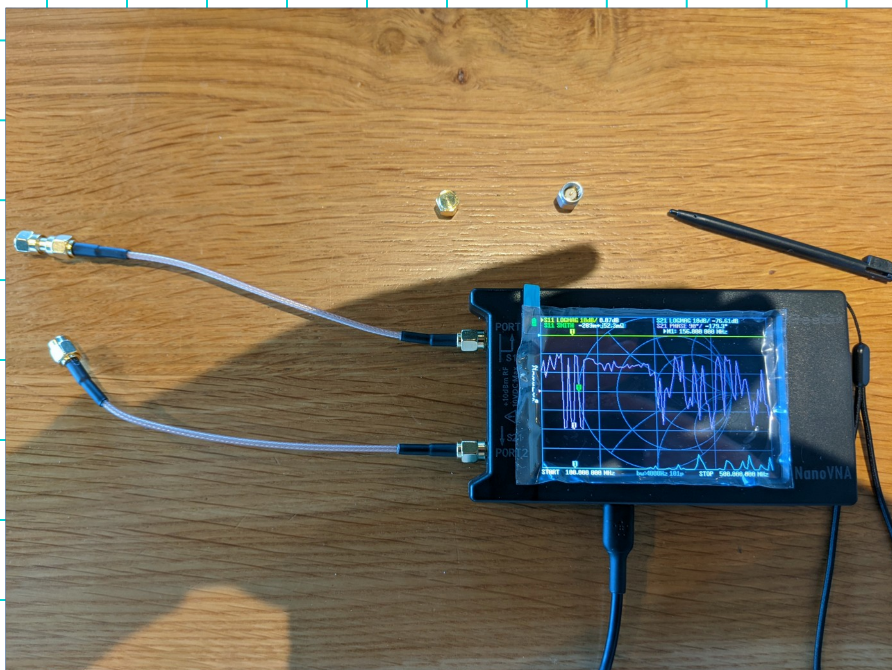


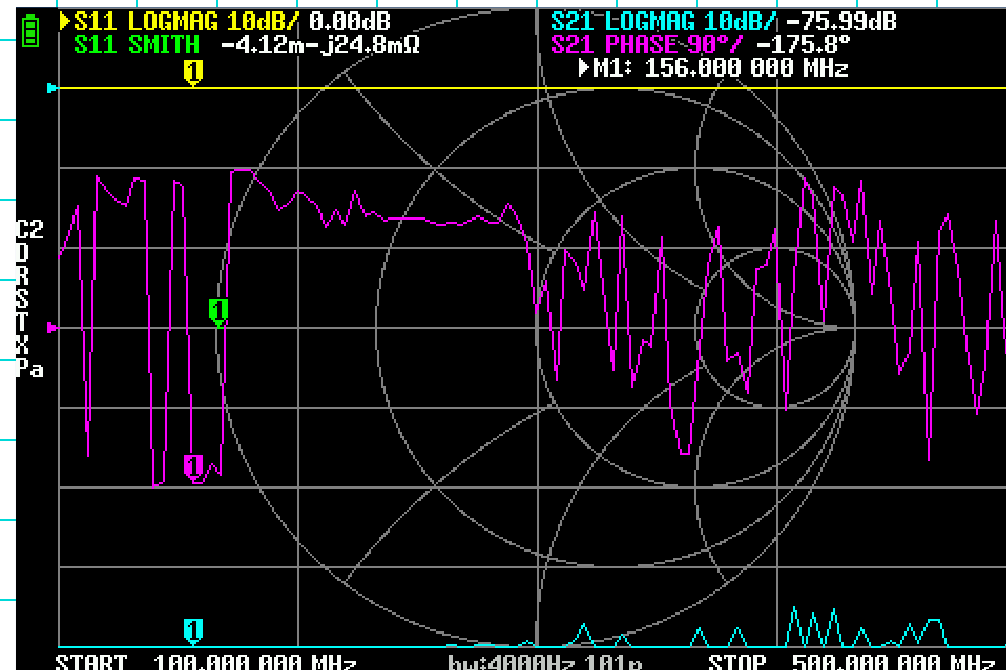


Note with the open calibration standard connected to PORT 1, the S11 SMITH trace (green) is all the way to the right (infinite impedance, or zero admittance)

How do we verify the calibration?

Calibration verification - short

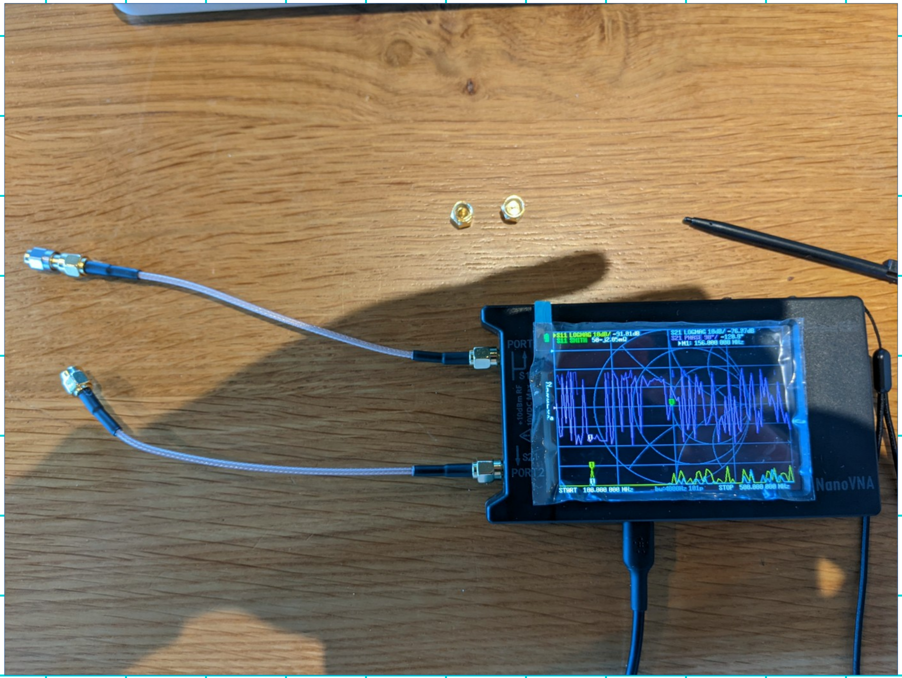


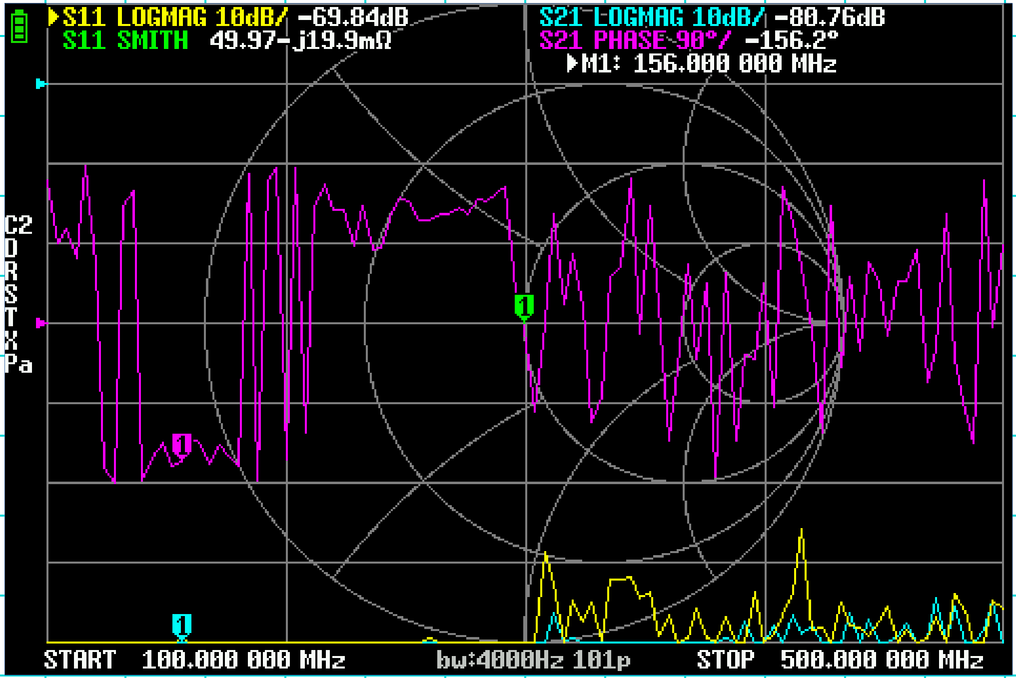


Note with the short calibration standard connected to PORT 1, the S11 SMITH trace (green) is all the way to the left (zero impedance, or infinite admittance)

How do we verify the calibration?

Calibration verification - load

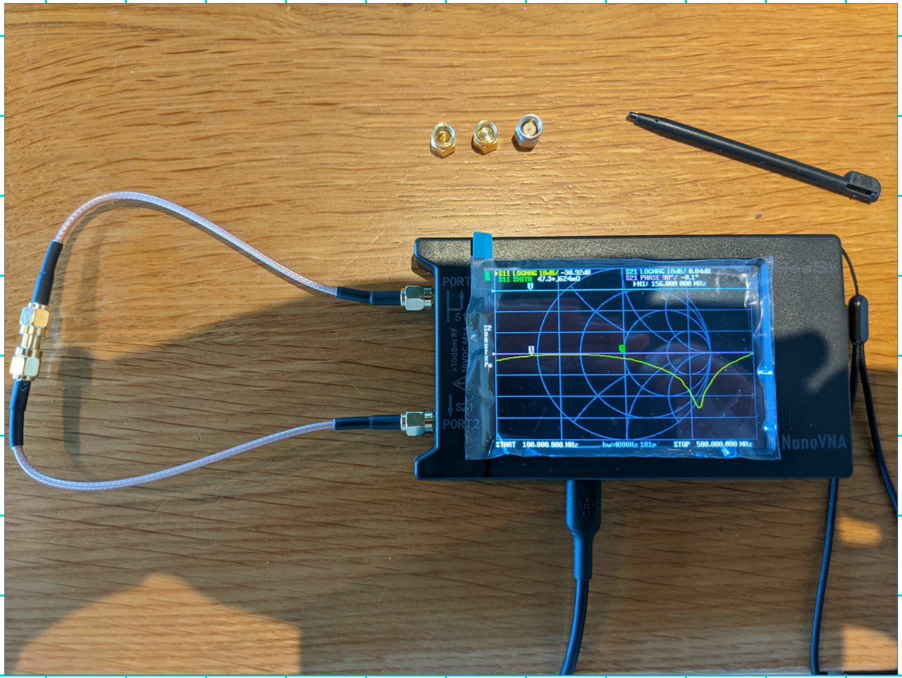


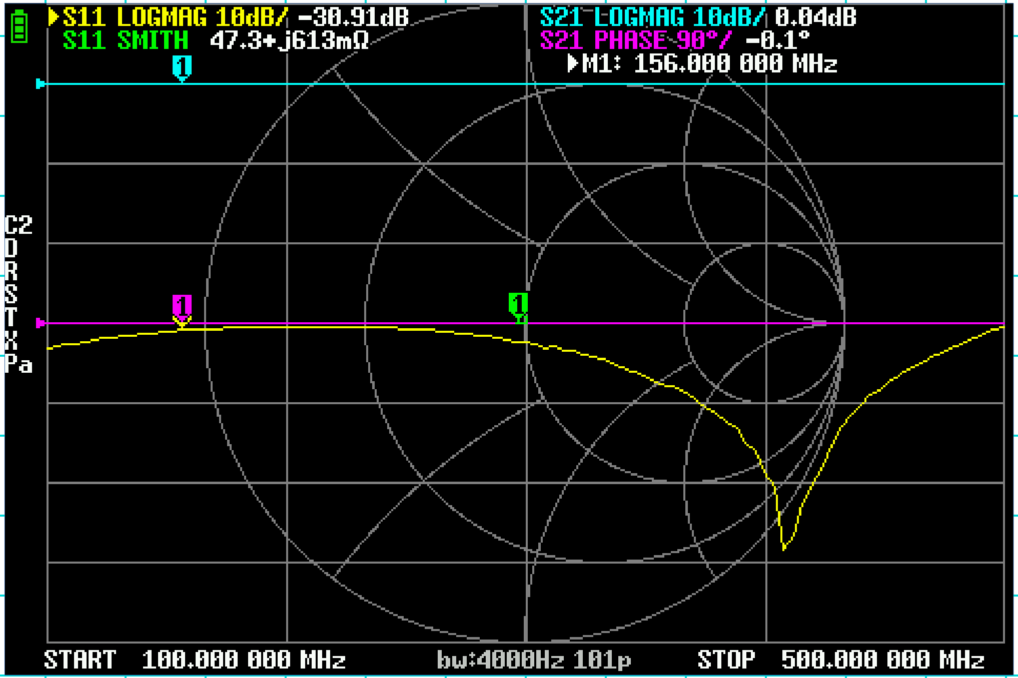


Note with the load calibration standard connected to PORT 1, the S11 SMITH trace (green) is right in the center of the chart (50 ohm resistance)

How do we verify the calibration?

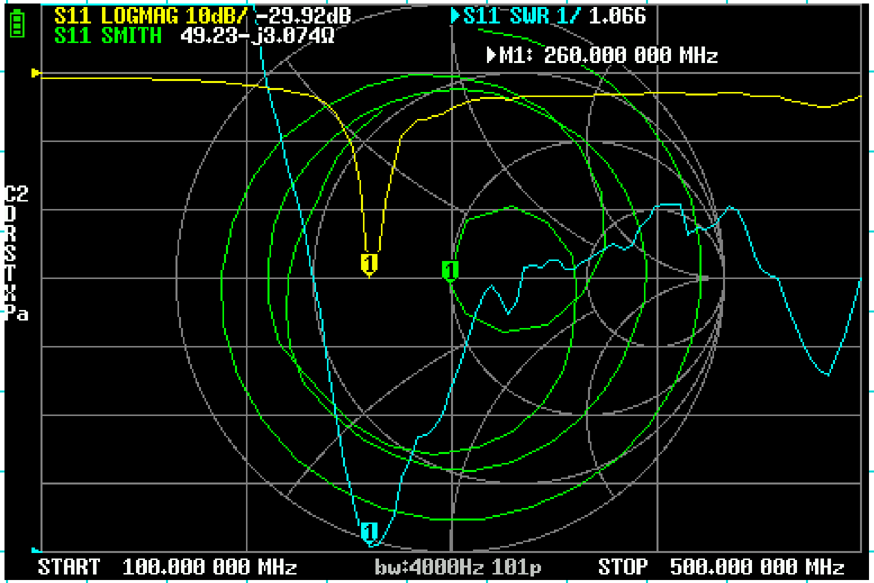
Calibration verification - thru





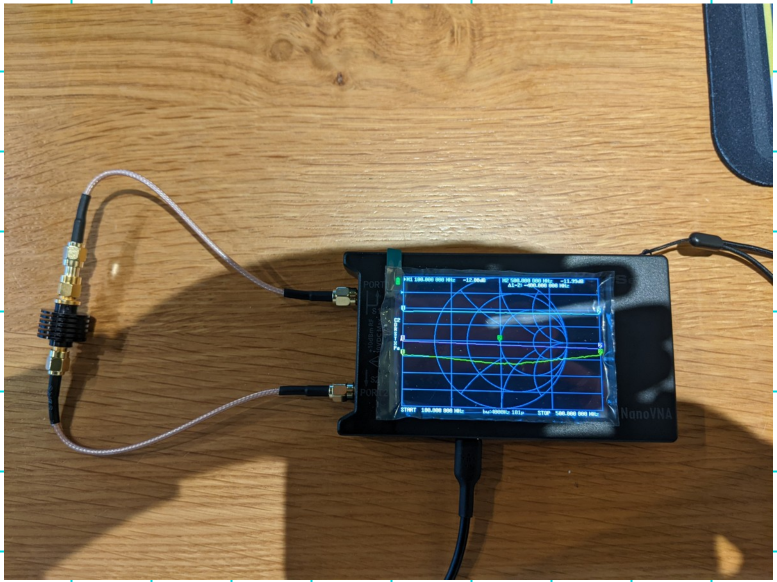
Note with the thru calibration standard connected between PORT 1 and PORT 2, the S21 LOGMAG trace (cyan) is at 0 dB, and the S21 PHASE trace (magenta) is at (or near) 0.0 degrees

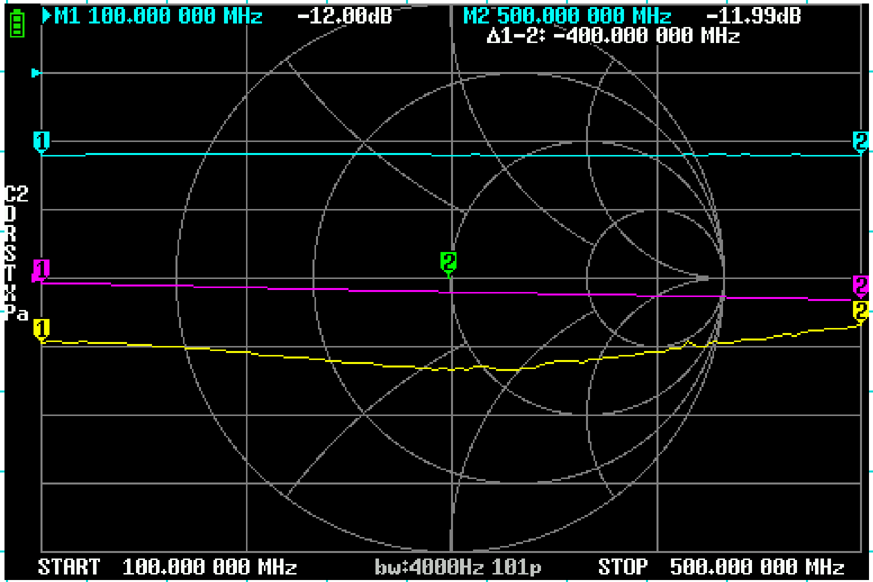
Measurement Time: Antenna feedpoint impedance



1. Set frequency sweep for start = 100 MHz, stop = 500 MHz
2. Perform calibration (either full OSLIT, or PORT 1 OSL)
3. Set trace 1 for S11 LOGMAG, trace 2 for S11 VSWR, trace 3 for S11 SMITH, and trace 4 OFF
4. Connect antenna feedline to PORT 1
5. Turn on MARKER 1, and move it to a minimum value on the S11 LOGMAG trace.

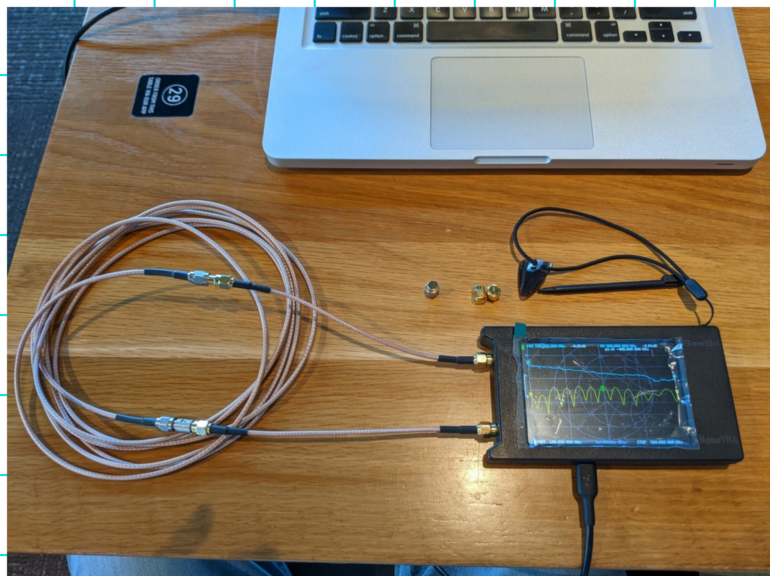
Measurement Time: In-line attenuator loss

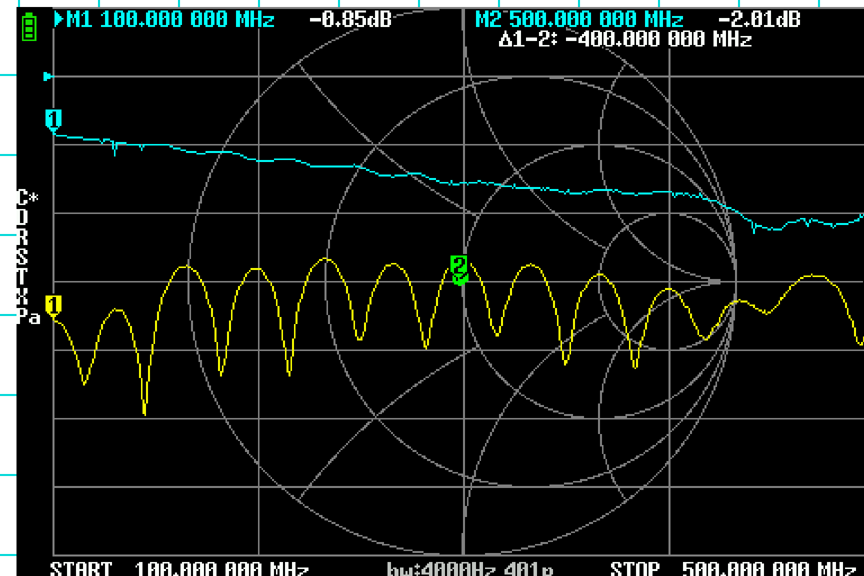




1. Set frequency sweep for start = 100 MHz, stop = 500 MHz
2. Perform calibration (full OSLIT)
3. Set trace 1 for S11 LOGMAG, trace 2 for S21 LOGMAG, trace 3 for S11 SMITH, and trace 4 for S21 PHASE
4. Connect inline attenuator (in this case, a 12 dB attenuator) between PORT 1 and PORT 2
5. Note the S21 LOGMAG trace values across the frequency sweep. Does it match expectations?

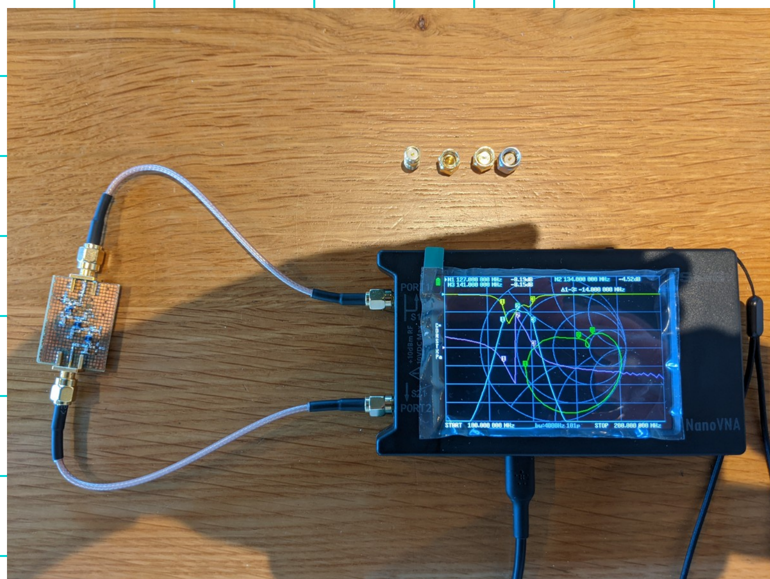
Measurement Time: Coaxial cable loss

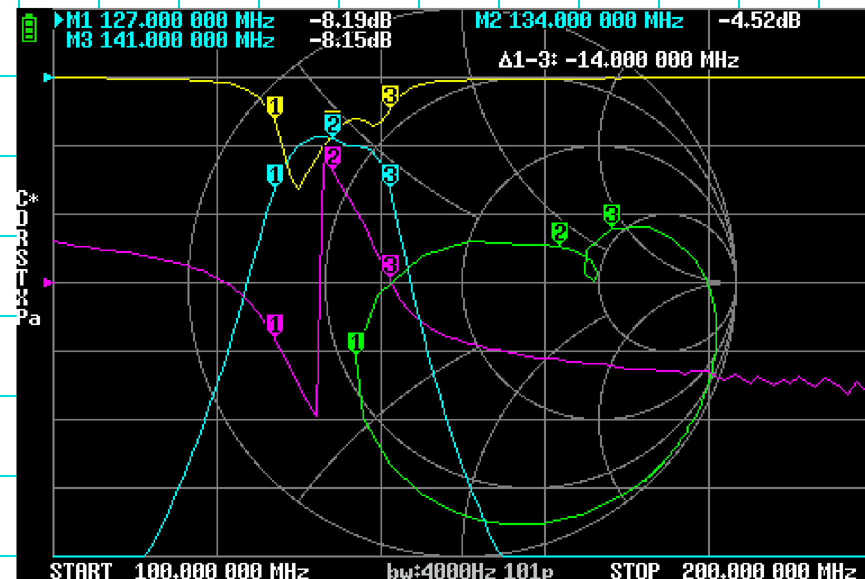




1. Set frequency sweep for start = 100 MHz, stop = 500 MHz
2. Perform calibration (full OSLIT)
3. Set trace 1 for S11 LOGMAG, trace 2 for S21 LOGMAG, trace 3 for S11 SMITH, and trace 4 for S21 PHASE
4. Connect 3 meter length of RG-316DS between PORT 1 and PORT 2
5. Put MARKER 1 at 100 MHz, and MARKER 2 at 500 MHz, and note the S21 LOGMAG values for each marker
6. If length is known, compare the measured loss vs. frequency to the coax data sheet. Does this loss match expectations?

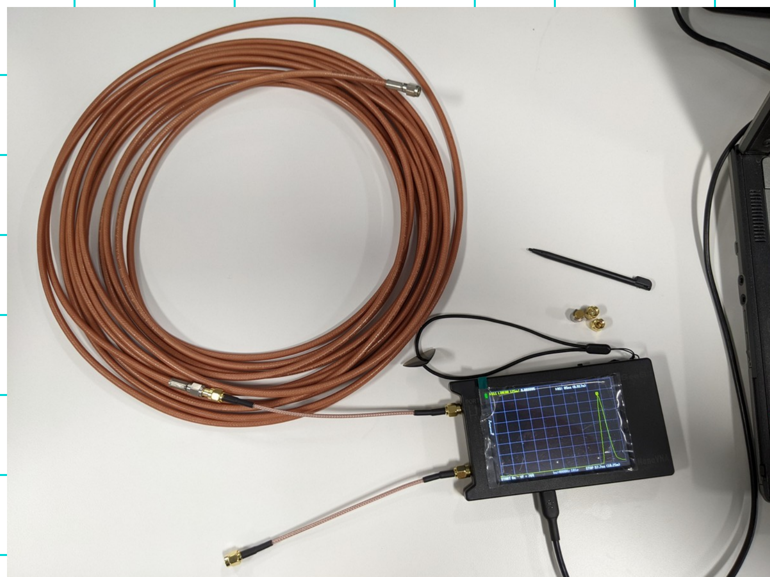
Measurement Time: Filter frequency response

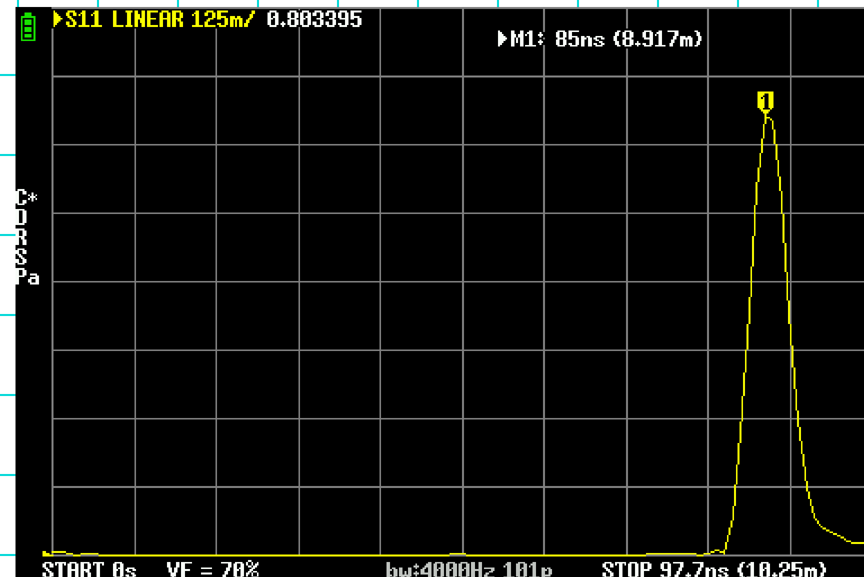




1. Set frequency sweep for start = 100 MHz, stop = 200 MHz
2. Perform calibration (full OSLIT)
3. Set trace 1 for S11 LOGMAG, trace 2 for S21 LOGMAG, trace 3 for S11 SMITH, and trace 4 for S21 PHASE
4. Connect “2 meter” bandpass filter between PORT 1 and PORT 2
5. Set MARKER 2 at the maximum S21 LOGMAG value, set MARKER 1 at the lower -3 dB point, and set MARKER 3 at the upper -3 dB point.
6. This filter was supposed to have a passband between 144 and 148 MHz and less than 1 dB insertion loss in the middle of the passband. Did it achieve these goals?

Measurement Time: Coaxial cable length

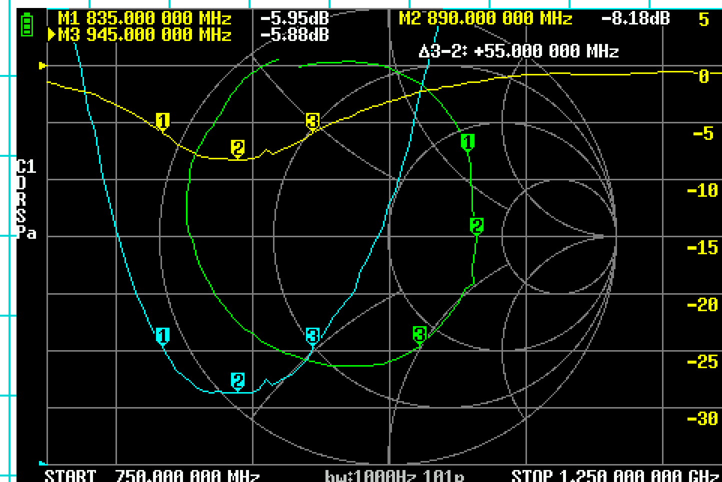




1. Set frequency sweep for start = 50 kHz, stop = 200 MHz
2. Perform calibration (either full OSLIT, or PORT 1 OSL)
3. Set trace 1 for S11 LINEAR, and all other traces OFF
4. From the DISPLAY-TRACE-TRANSFORM menu, select LOW PASS IMPULSE, and turn the TRANSFORM ON
5. From the DISPLAY-TRACE-TRANSFORM menu, select the VELOCITY FACTOR button, and enter 70(%).
6. Connect one end of the cable (RG-142 cable shown) to PORT 1
7. Turn on MARKER 1, move the marker to the peak of the trace. The length corresponding to the peak will be shown.

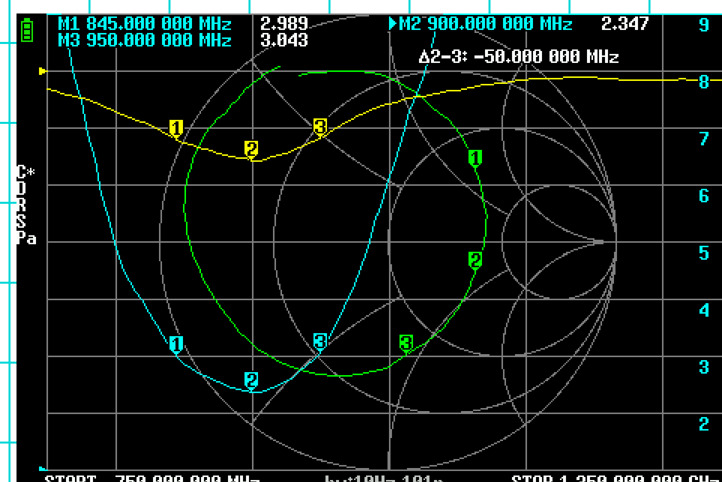
Questions (and maybe answers)?

Question: How to show grid scaling?



To show scale values for grid based displays, do the following:

From the main menu, go to the DISPLAY-SCALE menu, and select the SHOW GRID VALUES checkbox



The End

References (Slide 1)

- Tektronix. “What is a Vector Network Analyzer and How Does it Work?”. https://www.tek.com/en/documents/primer/what-vector-network-analyzer-and-how-does-it-work
- Angove, Chris. “The basic architecture of a two-port vector network analyser“. https://upload.wikimedia.org/wikipedia/commons/3/3b/Vna3.png
- The Smith Chart. https://www.antenna-theory.com/tutorial/smith/chart.php
- Smith, Phillip H. “Transmission Line Calculator”. Electronics, January 1939, pp 29-31.
- NanoVNA | Very tiny handheld Vector Network Analyzer. https://nanovna.com/
- “NanoVNA Block Diagram.” https://github.com/ttrftech/NanoVNA/blob/master/doc/nanovna-blockdiagram.png
- Satoh, Hiroh. NanoVNA User Guide (translated from Japanese to English). https://www.qsl.net/g0ftd/other/nano-vna-original/docs/NanoVNA%20User%20Guide-English-reformat-Oct-2-19.pdf
- Anritsu. “Understanding VNA Calibration”. http://anlage.umd.edu/Anritsu_understanding-vna-calibration.pdf
- GitHub – NanoVNASaver/nanovnasaver: A tool for reading, displaying and saving data from the NanoVNA. https://github.com/NanoVNA-Saver/nanovna-saver

References (Slide 2)

- Wolke, Alan (W2AEW). #312: Back to Basics: What is a VNA / Vector Network Analyzer. https://www.youtube.com/watch?v=Sb3q8f0NBZ
- Wolke, Alan (W2AEW). #313: Why a VNA needs to be calibrated | how to calibrate a nanoVNA. https://www.youtube.com/watch?v=x-tbvAbh9jk
- Wolke, Alan (W2AEW). #314: How to use the NanoVNA to sweep / measure an antenna system's SWR and optimize its tuning. https://www.youtube.com/watch?v=xa6dqx9udcg
- Wolke, Alan (W2AEW). #315: How to use the NanoVNA to measure a low-pass filter. https://www.youtube.com/watch?v=xa6dqx9udcg
- Wolke, Alan (W2AEW). #316: Use NanoVNA to measure coax length - BONUS Transmission Lines and Smith Charts, SWR and more. https://www.youtube.com/watch?v=9thbTC8-JtA
- Wolke, Alan (W2AEW). #329: Presentation recording: Intro to the VNA and NanoVNA for BayCon 2021. https://www.youtube.com/watch?v=o1eLK4EMpEQ

Additional Resources (Slide 1)

- nanovna-users@groups.io. https://groups.io/g/nanovna-users
- nanovna-saver PC software (multi-platform). https://github.com/NanoVNA-Saver/nanovna-saver
- NanoVNA-App PC software (Windows). https://github.com/owenduffy/NanoVNA-App
- NanoVNA-MATLAB: MATLAB scripts for NanoVNA vector network analyzer. Connect, save S2P file and display Logmag, Smith chart and TDR step response (not sure if they work with GNU octave). https://github.com/qrp73/NanoVNA-MATLAB
- tinyPFA (Phase Frequency Analyzer – uses NanoVNA-H4 hardware with custom firmware to measure the frequency and phase difference between signals applied to each of the ports). https://www.tinydevices.org/wiki/pmwiki.php?n=TinyPFA.Homepage

Additional Resources (Slide 2)

- Wolke, Alan (W2AEW). YouTube – W2AEW (lots of awesome electronics, RF, test and measurement tutorials). https://www.youtube.com/w2aew
- Wolke, Alan (W2AEW). #319: Measuring Crystals with NanoVNA and other tools. https://www.youtube.com/watch?v=G9zZRNzhsEE