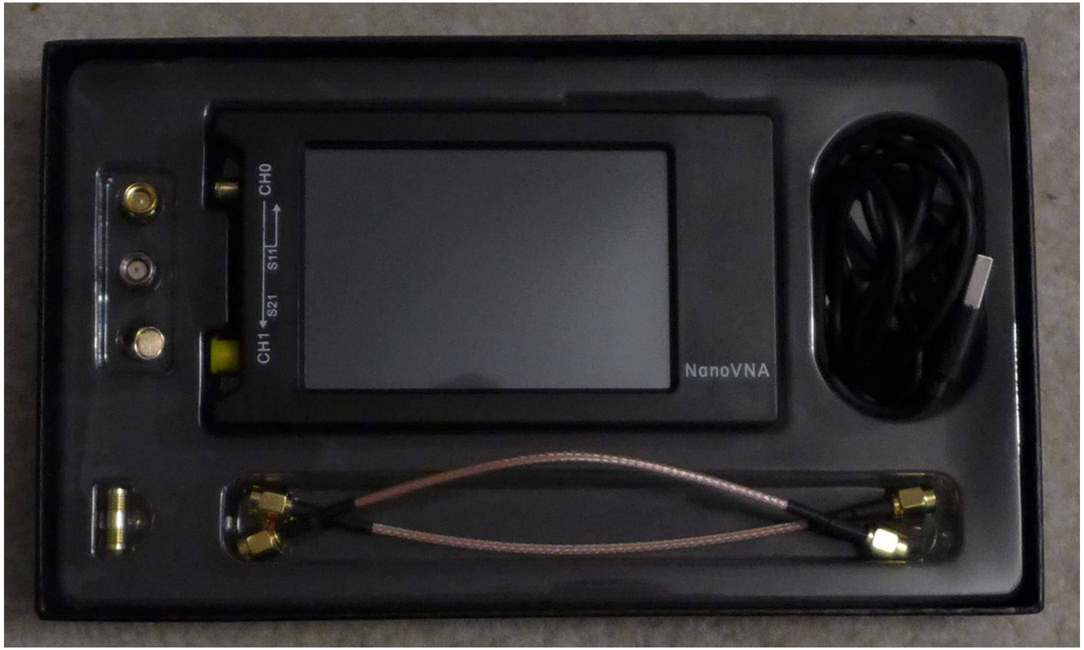
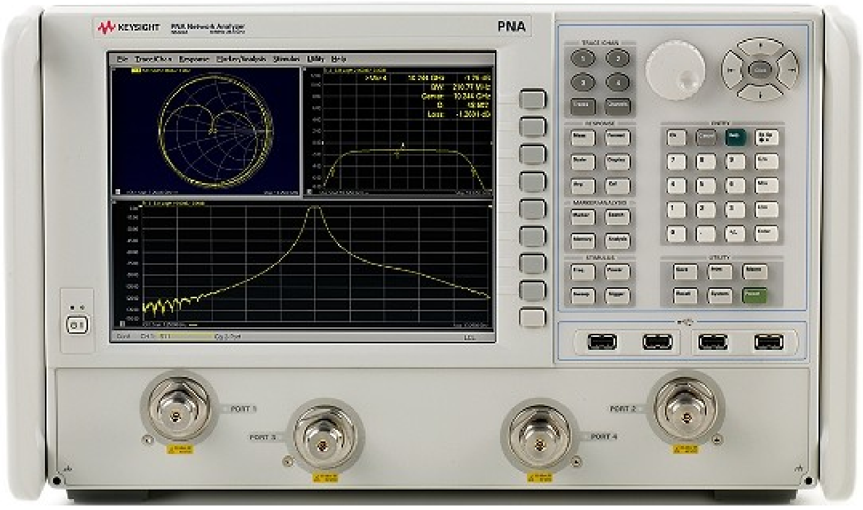
An introduction to the NanoVNA:
An amazing piece of kit for less than $100.



Presentation to Raleigh Amateur Radio Society by Daniel Marks KW4TI.
August 11, 2020

VNA: **V**ector **N**etwork **A**nalyzer

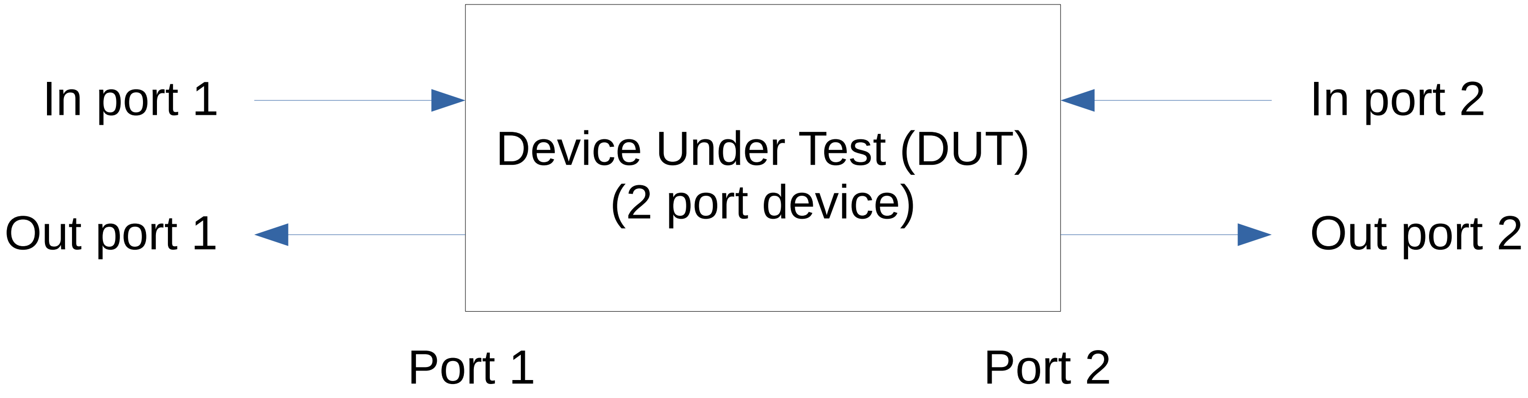
NanoVNA about $60 on
e-bay/Amazon/Aliexpress



Keysight N5222A, $150,000 to $200,000
(this does a lot more, however)

Having an affordable VNA is a **great boon** to amateurs! It puts great capability, much more than a simple antenna analyzer, in the hands of hams. It is like the “multimeter” of radio engineering.

What does a VNA do?



A VNA transmits an electromagnetic wave into a Device Under Test (DUT) and measures how much of that wave reflects from the device (reflection) and how much transmits through the device (transmission).

Some devices, like antennas, have only one port, and you only measure reflection. This is what antenna analyzers do: they are one port device testers.

What does a VNA do for an amateur radio enthusiast?

- Check if your antenna is accepting power (low SWR, low return loss) like an antenna analyzer. It does not know if your antenna is radiating efficiently (a dummy load accepts power but does not radiate efficiently).
- Find the lengths and discontinuities of cables.
- Measure the resistance and reactance of components from which, for example, inductance and capacitance can be calculated.
- Measure the transmission bandwidth of a filter as well as its reflection.
- Measure the self-resonance frequency of inductors and capacitors, for example, of traps on dipoles.
- Measure the choking impedance of a balun as a function of frequency.
- The permeability of ferrite toroids.
- Many other measurements...

But you have to know some of the theory and math to turn calculate these quantities from what the VNA tells you. If you want to learn more about radio engineering, a VNA is an ideal tool.

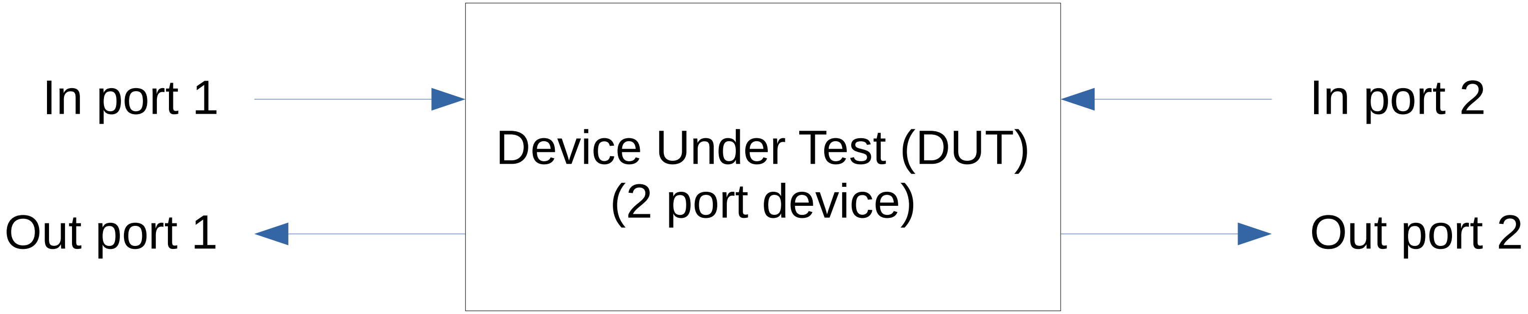
Conventions that hams use

Amateurs use conventions that are not used by professionals. Instead:

Ham convention	More modern convention
VSWR (Voltage Standing Wave Ratio): 1 (no reflection) to ∞ (complete reflection)	Return Loss: 0 dB for complete reflection, -∞ dB for no reflection
Power in watts (W), 1500 W is legal limit	dBm: 0 dBm is 1 mW, 10 dBm is 10 mW, 50 dBm is 100 W, 61.76 dBm is legal limit

A VNA measures S-parameters. What are they?

A S-parameter specifies the ratio of the electromagnetic wave exiting a port given that entering a port. For example:

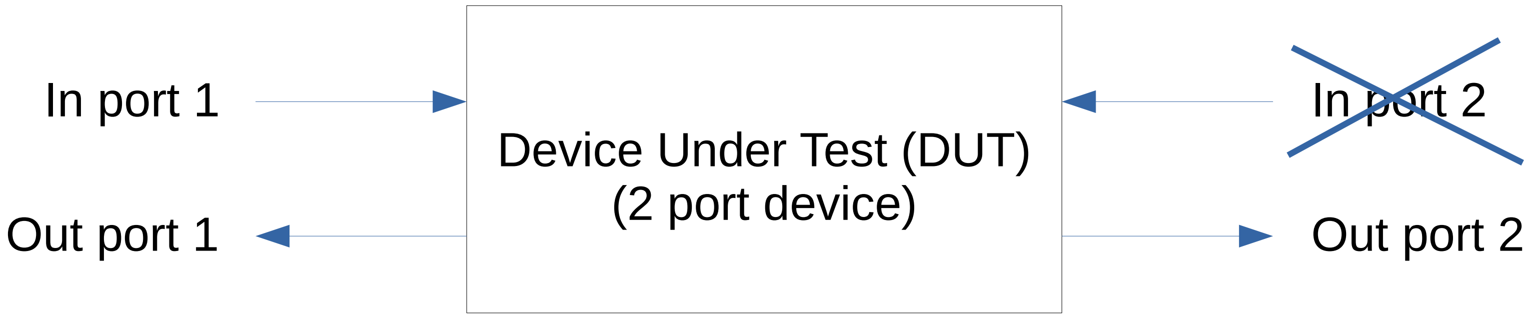


S11: ratio of wave exiting port 1 that is entering port 1.
S21: ratio of wave exiting port 2 that is entering port 1.
S12: ratio of wave exiting port 1 that is entering port 2.
S22: ratio of wave exiting port 2 that is entering port 2.

These are **complex numbers**, and so they have both an magnitude (dB) and a phase (degrees). For a passive device (like an antenna or a filter), the magnitude must be less than 1 (smaller than 0 dB), as the device can not amplify the signal.

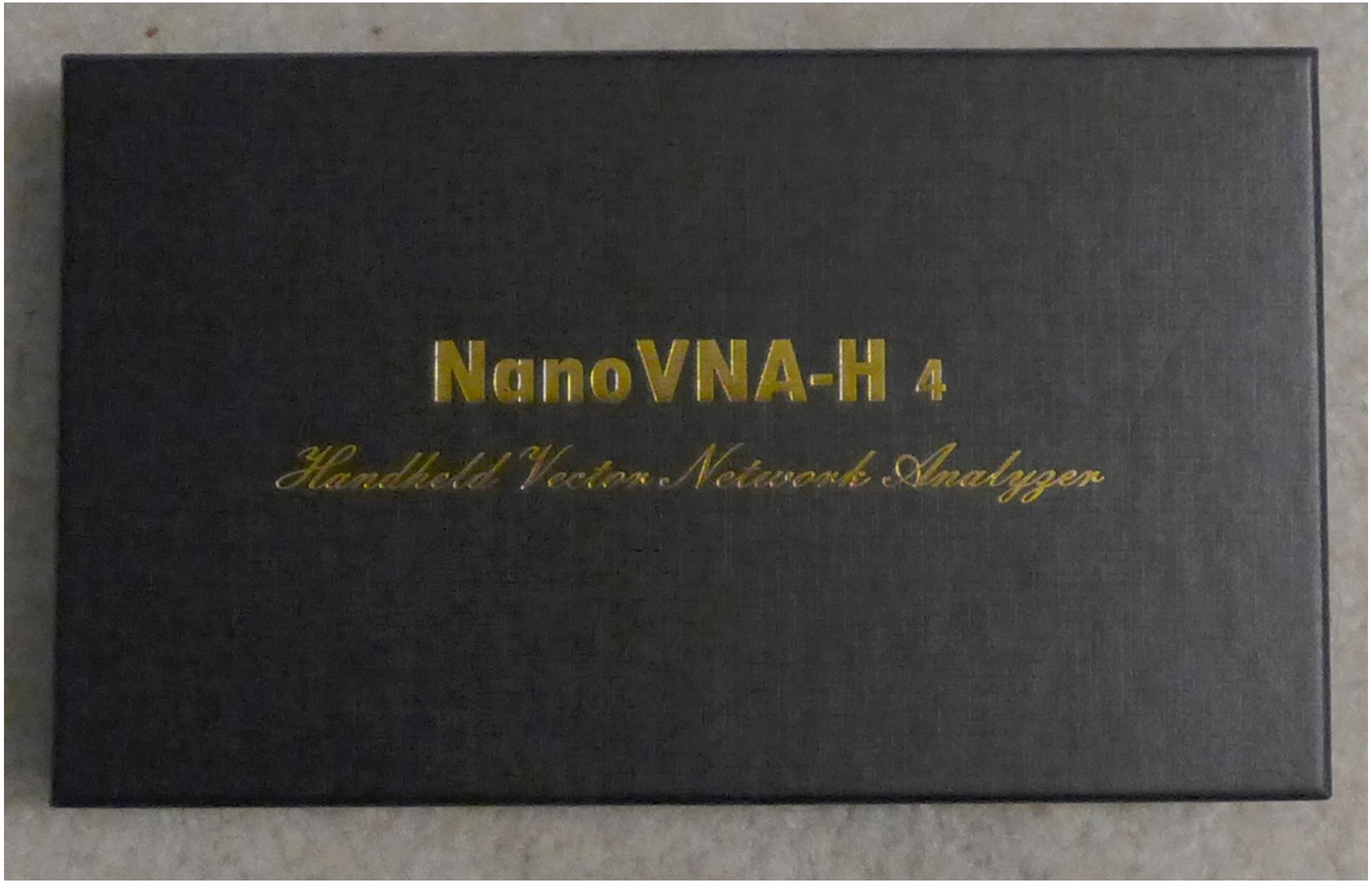
A limitation of the NanoVNA

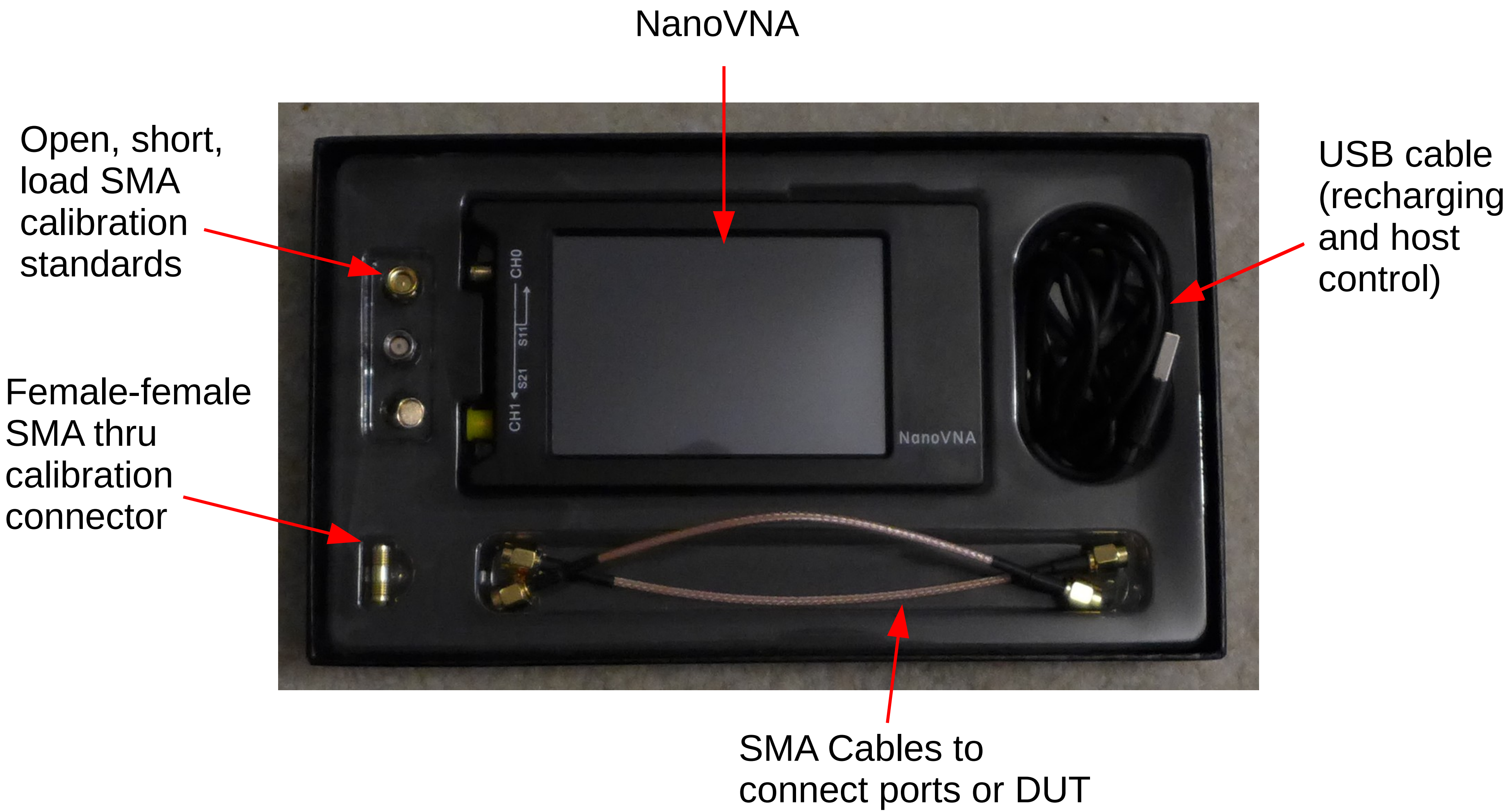
The NanoVNA can only transmit energy out of port 1, not port 2.



This means that it can measure only S11 and S21. If we want to measure S12 and S22, we need to swap the two connections of the DUT on the ports so that S12 becomes S21 and S22 becomes S11. A bit more trouble, but what do you want for $60?

Unboxing the NanoVNA



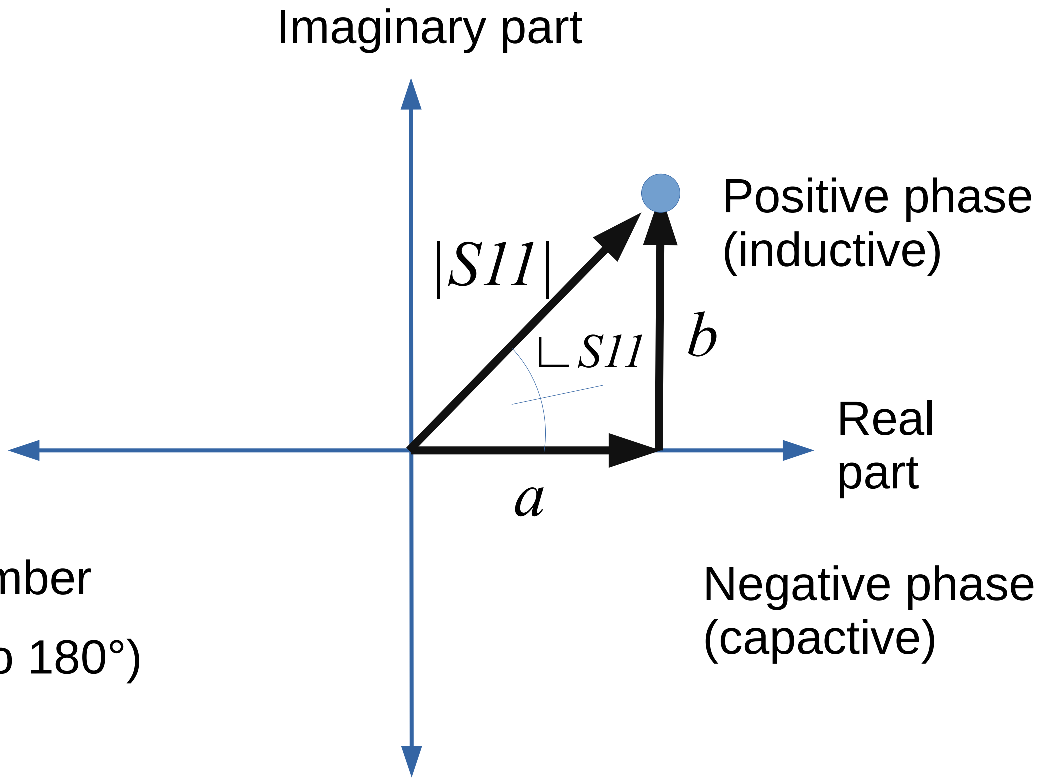

NanoVNA
Open, short, load SMA calibration standards
USB cable (recharging and host control)
Female-female SMA thru calibration connector
SMA Cables to connect ports or DUT
CH0
S11
S21
CH1
NanoVNA

Amplitude and phase of a complex number

A complex number is the sum of a real and imaginary part:

$$S11 = a + jb$$

A complex number can be represented by a point on a two dimensional graph:



$|S11|$ Magnitude of complex number

$\angle S11$ Phase of number (-180° to 180°)

For a negative phase, the current leads the voltage (capacitive).
For a positive phase, the current lags the voltage (inductive).

Amplitude to dB

Return Loss RL (dB) = $20\log_{10}|S11|$

$$SWR = \frac{1+|S11|}{1-|S11|}$$

Transmission G (dB) = $20\log_{10}|S21|$

$|S11|=1$ RL=0 dB SWR=∞
complete reflection

$|S11|=0.1$ RL=-20 dB SWR=1.22
reflection of 1% of the power.

$|S21|=1$ G=0 dB all power transmitted

$|S21|=0.1$ G=-20 dB only 1% of the power
transmitted

Reflection coefficient and impedance

If we know the reflection coefficient of a load, we can calculate its impedance.
We need to know the characteristic impedance Z0 of port, usually Z0=50 Ω.

$$Z = Z0\frac{1+S11}{1-S11}$$

This equation uses complex arithmetic!

Examples:

$S11=0$	$Z=50\ \Omega$
$S11=0.5$	$Z=150\ \Omega$
$S11=-0.5$	$Z=16.7\ \Omega$
$S11=0.3+j0.3$	$Z=70.7+j51.7\ \Omega$
$S11=-j1$	$Z=-j50\ \Omega$

Note: by convention, positive imaginary part $+j$ is inductive, and $-j$ is capacitive.

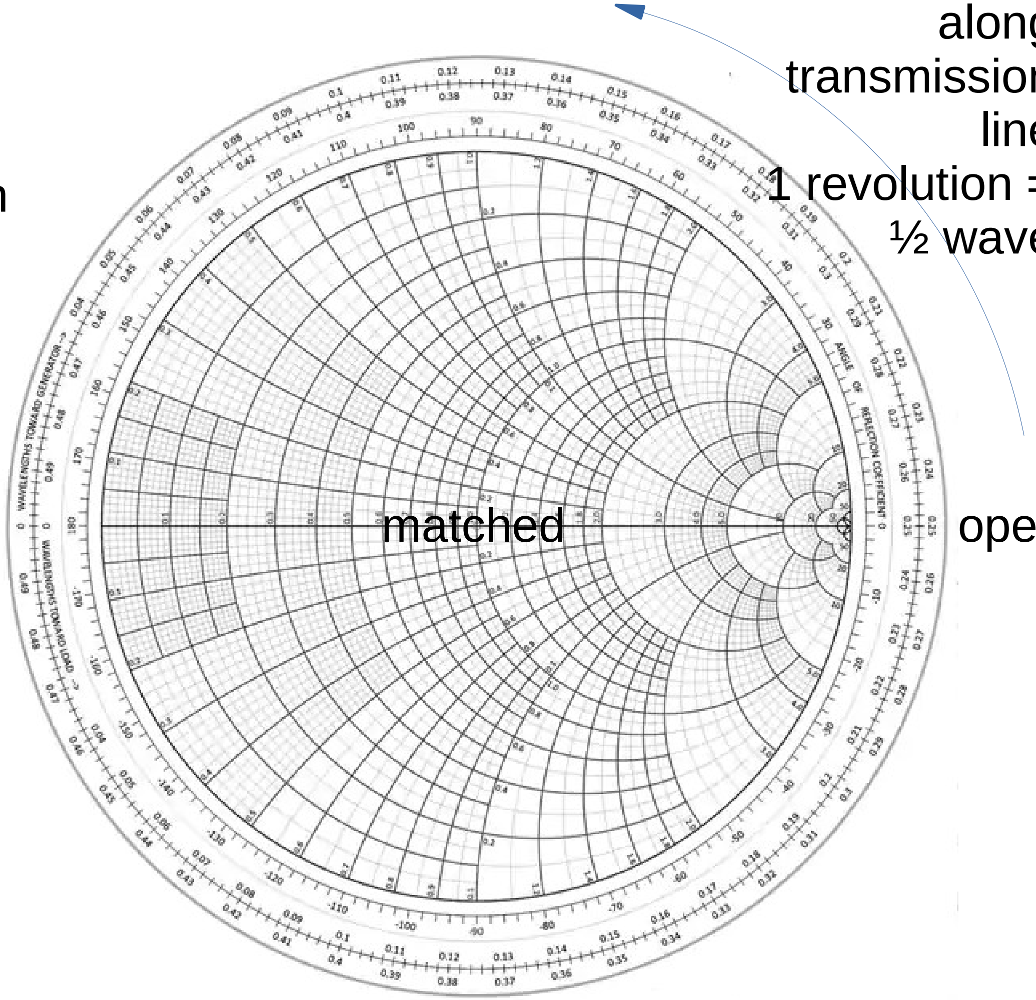
A reflection coefficient of $|S11|=1$ means than no power is lost. This corresponds to a lossless device such as a perfect inductor, capacitor, or a transmission line terminated in an open or short. The impedance of the device is purely imaginary.

Reflection coefficient and the Smith chart

The Smith chart is a nomogram which shows the relationship between reflection coefficient *S11* and impedance *Z* or the equation just shown:

$$Z = Z0\frac{1+S11}{1-S11}$$

How to use it is beyond the scope of this talk, but operations such as propagating on transmission lines, adding impedances or admittances, etc. can be performed graphically on this chart, and it is a helpful way to visualize these quantities. The NanoVNA can display Smith charts.



Calibration of your VNA

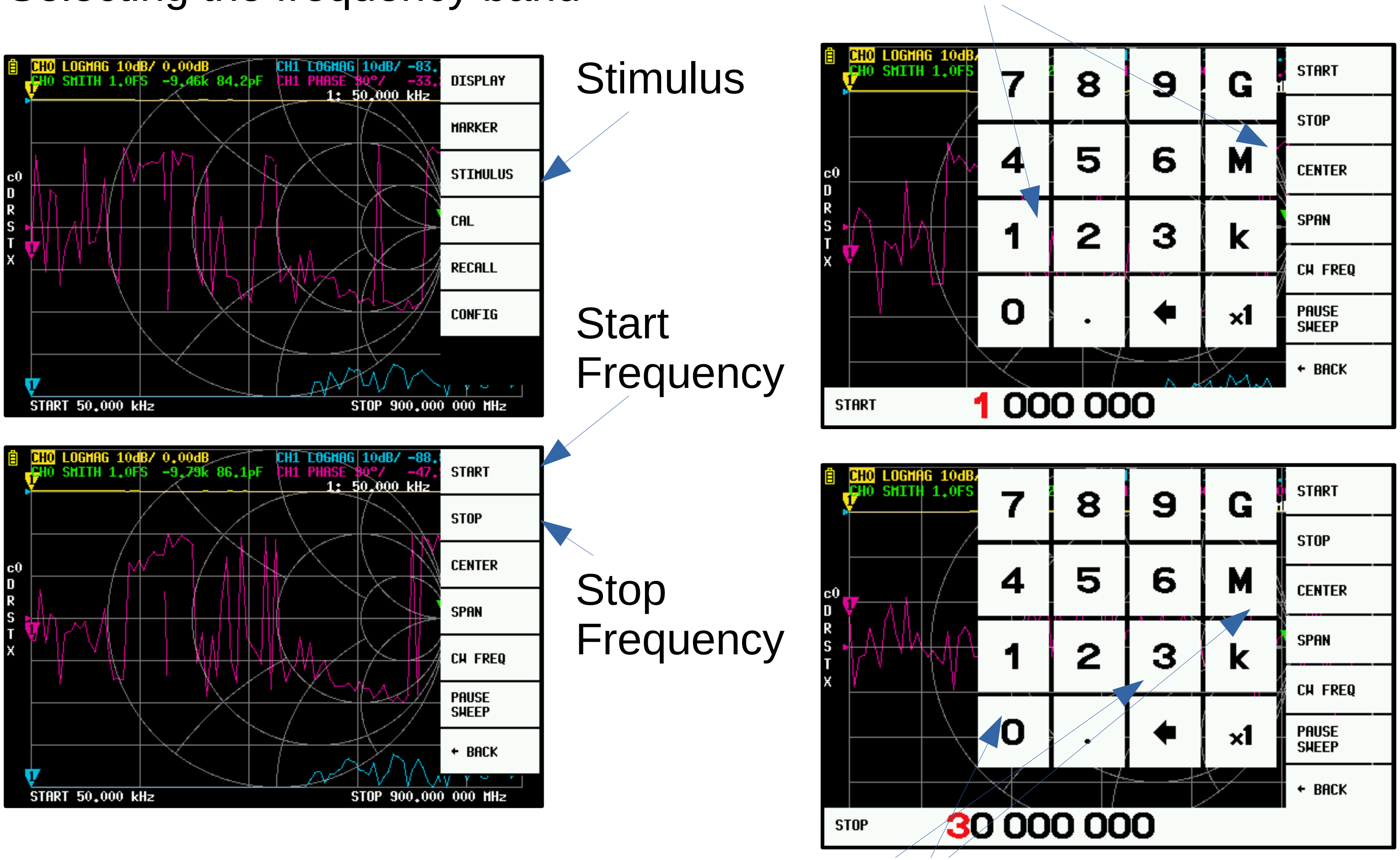
A VNA is a more precision instrument than an antenna analyzer. Because of this, it requires a calibration step to be used that a simple antenna analyzer does not.

The NanoVNA can store multiple calibration sets. A calibration set would be performed for a particular frequency range of interest, for example, an amateur radio band. You can recall the calibration set from the memory when you want to use your NanoVNA for that frequency range.

For best results, turn on the VNA, wait 10 to 20 minutes for its temperature to equilibrate, and then calibrate immediately in the frequency band to be tested before use. But if you just want a quick and dirty measurement, this is not required.

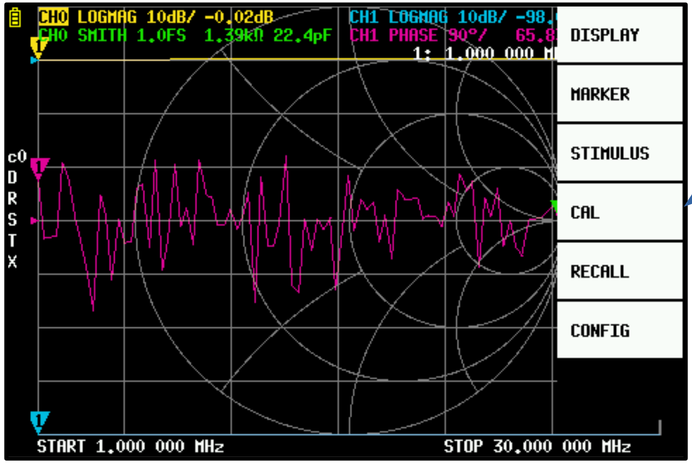
Selecting the frequency band

1M for 1 MHz start frequency



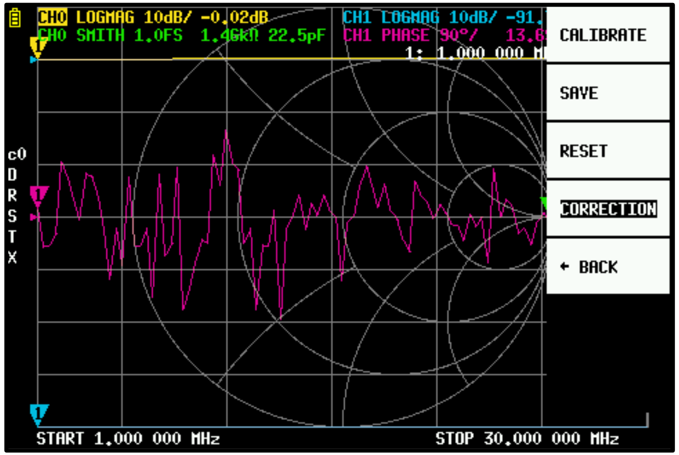
30M for 30 MHz stop frequency

Selecting the calibration mode

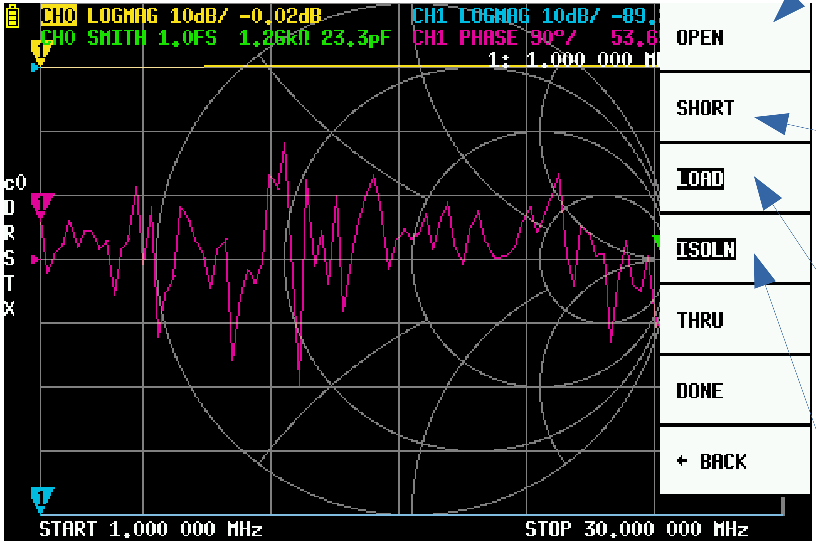


Calibration menu

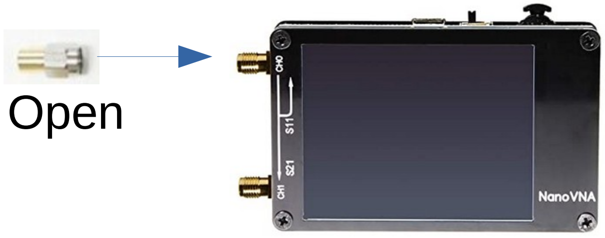
Calibrate option



Calibration steps for port 1

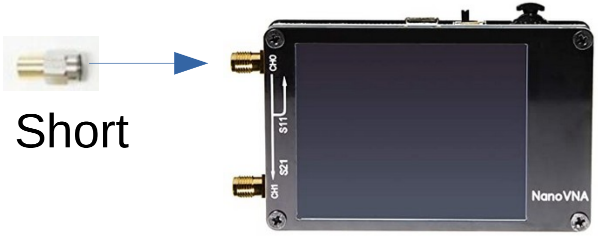


Open circuit: an open standard is connected to the transmit port 1.



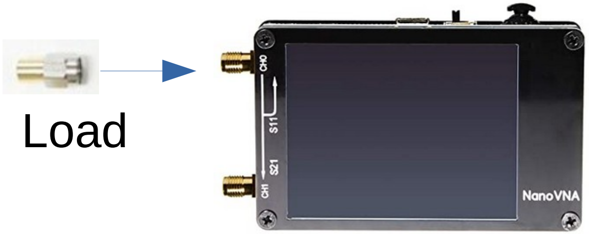
Open

Short circuit: an short standard is connected to the transmit port 1.



Short

Load: a 50 Ω load standard is connected to the transmit port 1.

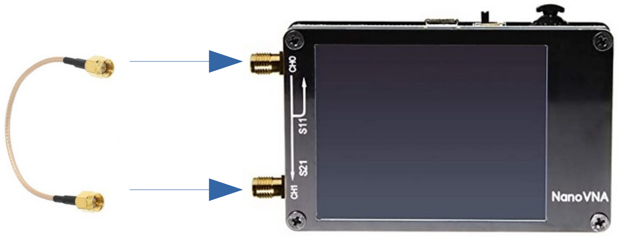


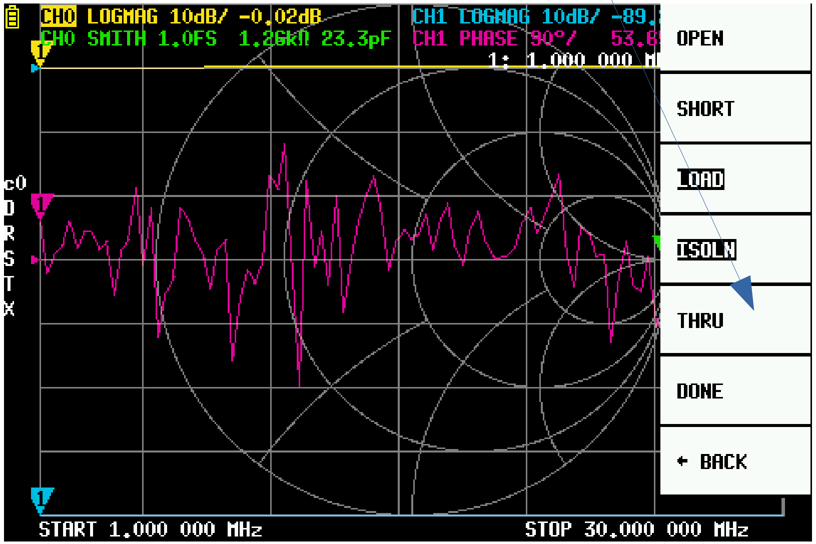
Load

Isolation: leave the 50 Ω load on port 1.

Calibration steps for port 2

Thru calibration: connect a coaxial cable between port 1 and 2.



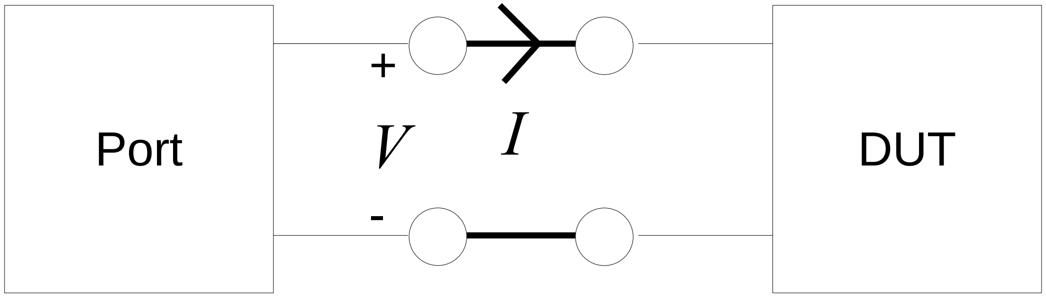


With a one-port calibration, you can take only reflection measurements.

With a two-port calibration, you can take reflection and transmission measurements, but there is the extra step.

The calibration "plane."

A calibration "plane" is the point in the circuit where the reflections and transmissions are measured to or from.   Each port has an electric current flowing out of it and a voltage across it:

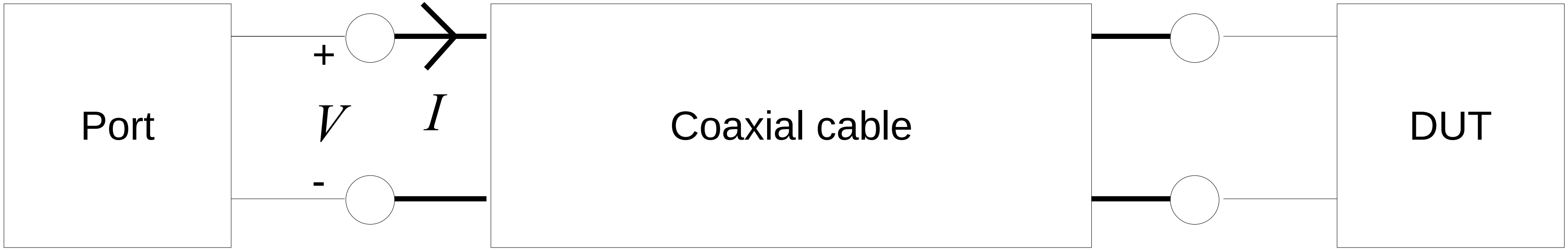


If the DUT is plugged into the port with a very short connection, the voltage across the DUT is the same as the port, and current flowing out of the port equals that flowing into the DUT.

The impedance of the DUT is then just the ratio between the voltage and current:

$$Z = \frac{V}{I}$$

The calibration "plane" continued



But what if the DUT is placed at the end of a coaxial cable? Because of standing waves on the cable, the impedance measured at the port is not the same as the DUT. We must account for the cable.

There are two ways to handle this:

1. Calibrate with the open, short, and load attached directly to the port and then mathematically compensate for the coaxial cable. This is less accurate.
2. Calibrate but attach the open, short, and load at the end of the coaxial cable where the DUT is. This is more accurate but more trouble. **This is moving the calibration plane to the end of the coaxial cable.**

Using a NanoVNA as an antenna analyzer

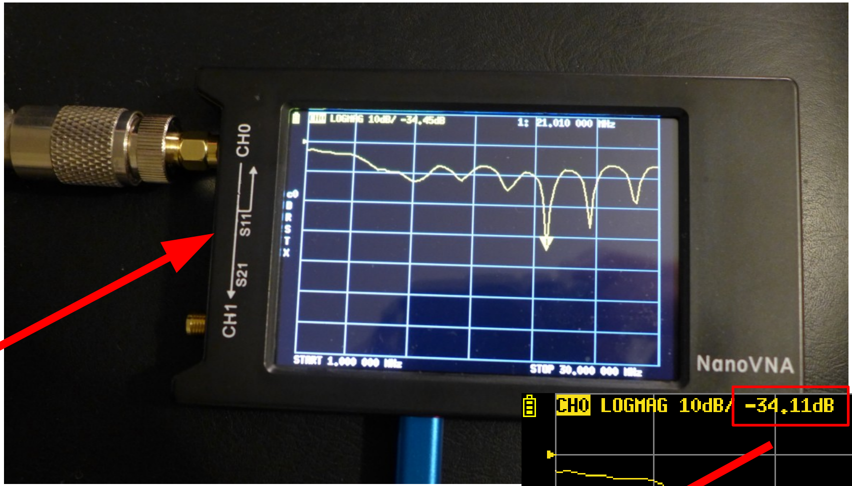
The NanoVNA can do a lot, but for the price can it do what an antenna analyzer does?

How to measure the reflection from your antenna:

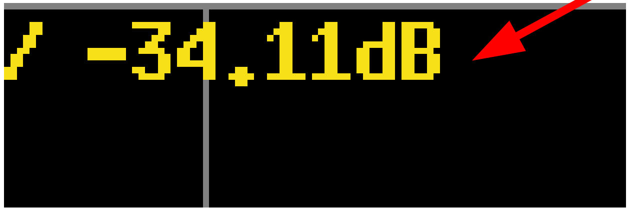
1. Calibrate the VNA in the frequency band of interest. If too large of a frequency band is used (the entire bandwidth from 50 kHz to 900 MHz for example), accuracy suffers for small frequency steps.
2. Connect port 1 to the antenna. This usually requires a SMA to BNC or SMA to UHF (PL-259) adapter.
3. Scan S11 in the frequency band of interest. This measures the **return loss** (RL) of the antenna. Typically both the magnitude (dB) and phase (degrees) are shown on the display.
4. The magnitude (dB) can be converted to VSWR using the formula mentioned earlier. With time, you probably will be able to read return loss directly.

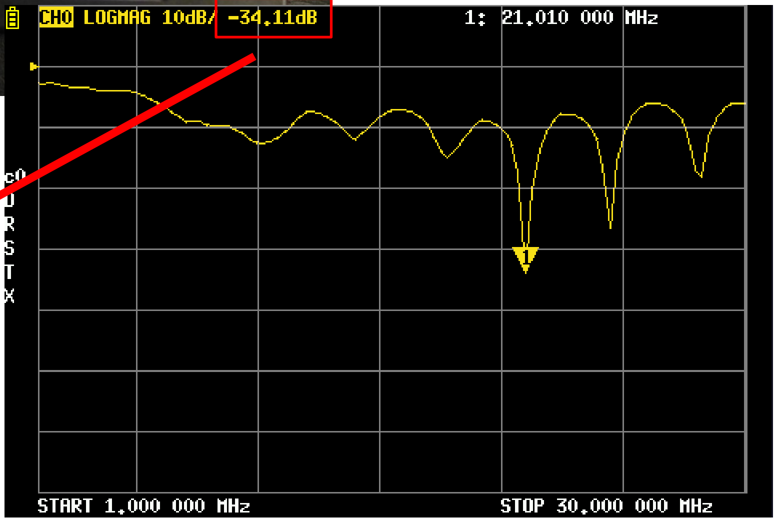
VSWR	RL (dB)
1.0	-∞
1.1	-26.4
1.2	-20.8
1.3	-17.7
1.5	-14.0
1.7	-11.7
2.0	-9.54
2.5	-7.36
3.0	-6.02
5.0	-3.52
10.0	-1.74
∞	0

Connect your antenna to port 1



SMA male to SO-239
(female UHF) connector





This is a very low reflection (less than
0.1% of the power!) at 21 MHz.

Using a NanoVNA to find the length of a coaxial cable:

Imagine we send a pulse down a coaxial cable:

Normally we would expect only to get a reflection from the end of the cable:

By measuring how long that takes, we can calculate the length of the cable:

$$\frac{\text{Total time there and back}}{2 \times \text{speed of wave in cable}} = \text{length of cable}$$

Time domain reflectometry (TDR)

TDR is sending a pulse down the cable and timing the echoes of the pulse that reflect back.

The NanoVNA can provide the same information a TDR does by scanning the frequency, measuring the reflection at each frequency, and then **calculating** what a TDR would show.

We can then look at the delay of a reflection, and knowing the velocity of the wave in the cable, calculate the length of the cable.

Cable velocity is given by "velocity factor" which is the fraction of the speed of light (3×10^8 m/s) the wave travels down the cable. Consult datasheet for more precise answer.

Cable type	Velocity Factor
Solid polyethylene RG-58U, RG-8U, RG-213U, RG-174	0.66
Foam-type RG-8U or RG-58U	0.78
PTFE RG-316U or RG-400U	0.69
LMR-400	0.85

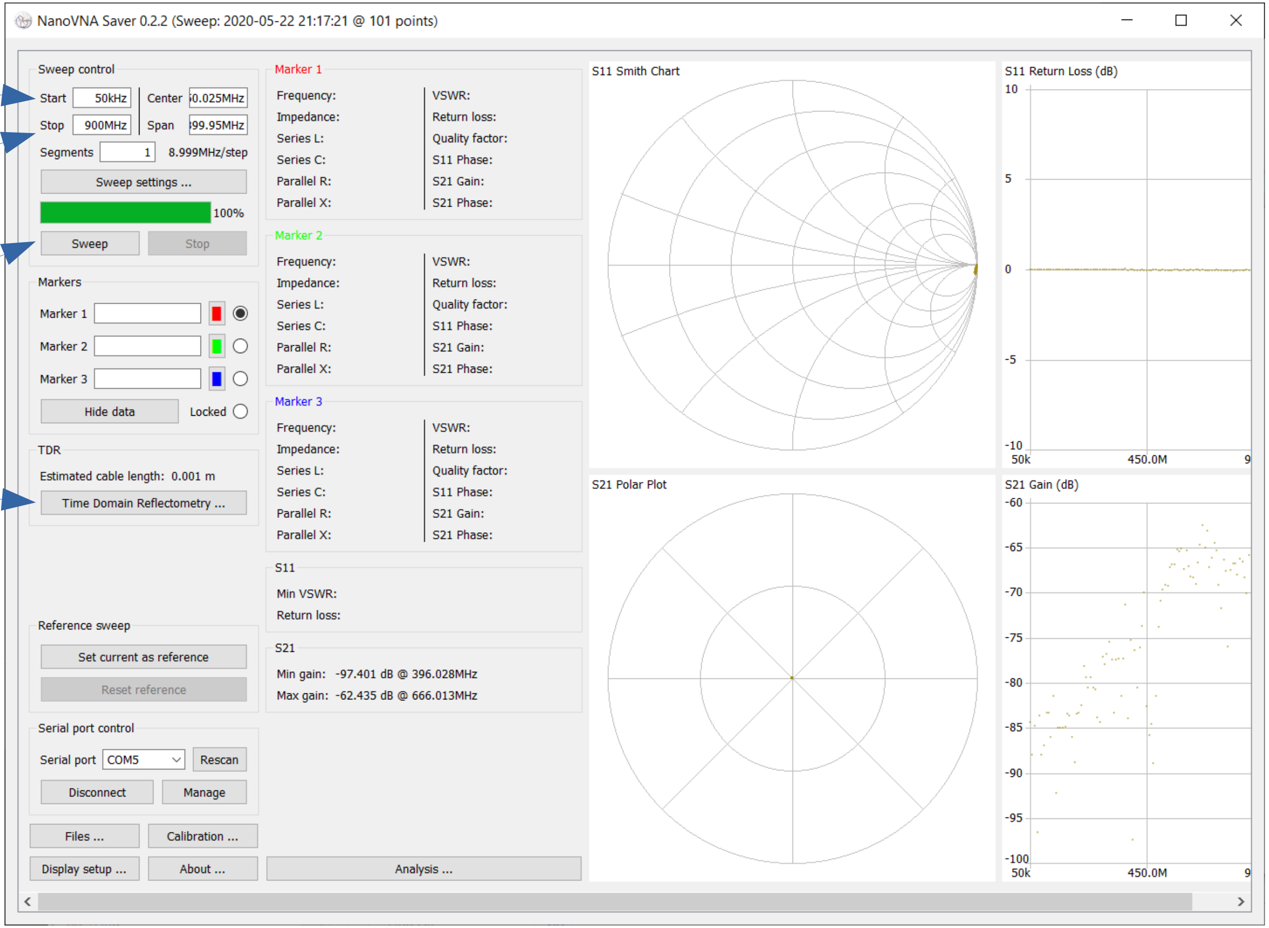
NanoVNA Saver: software on your PC to control and acquire data from the NanoVNA

Start Frequency

Stop Frequency

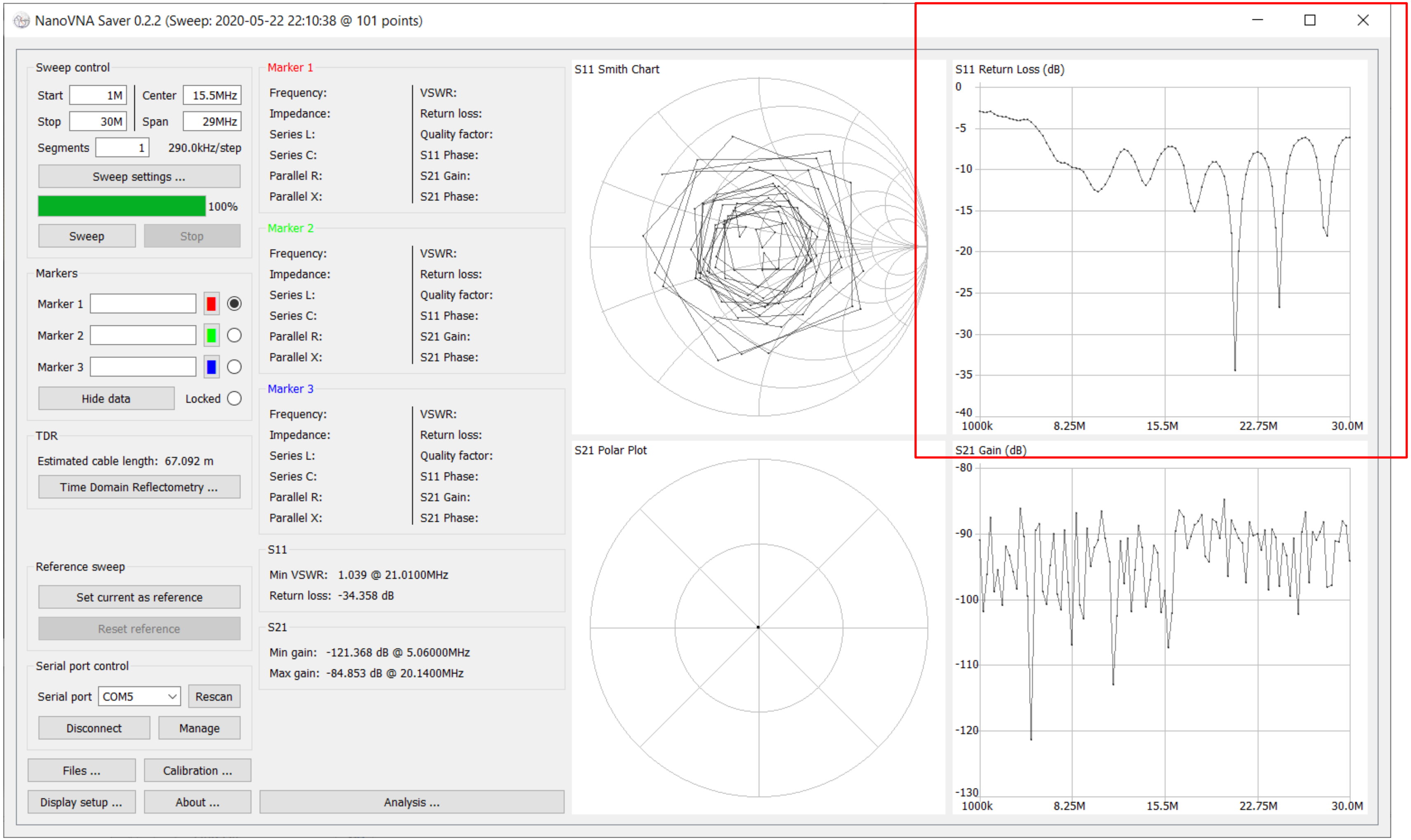
Initiate Sweep

Time Domain Reflectometry

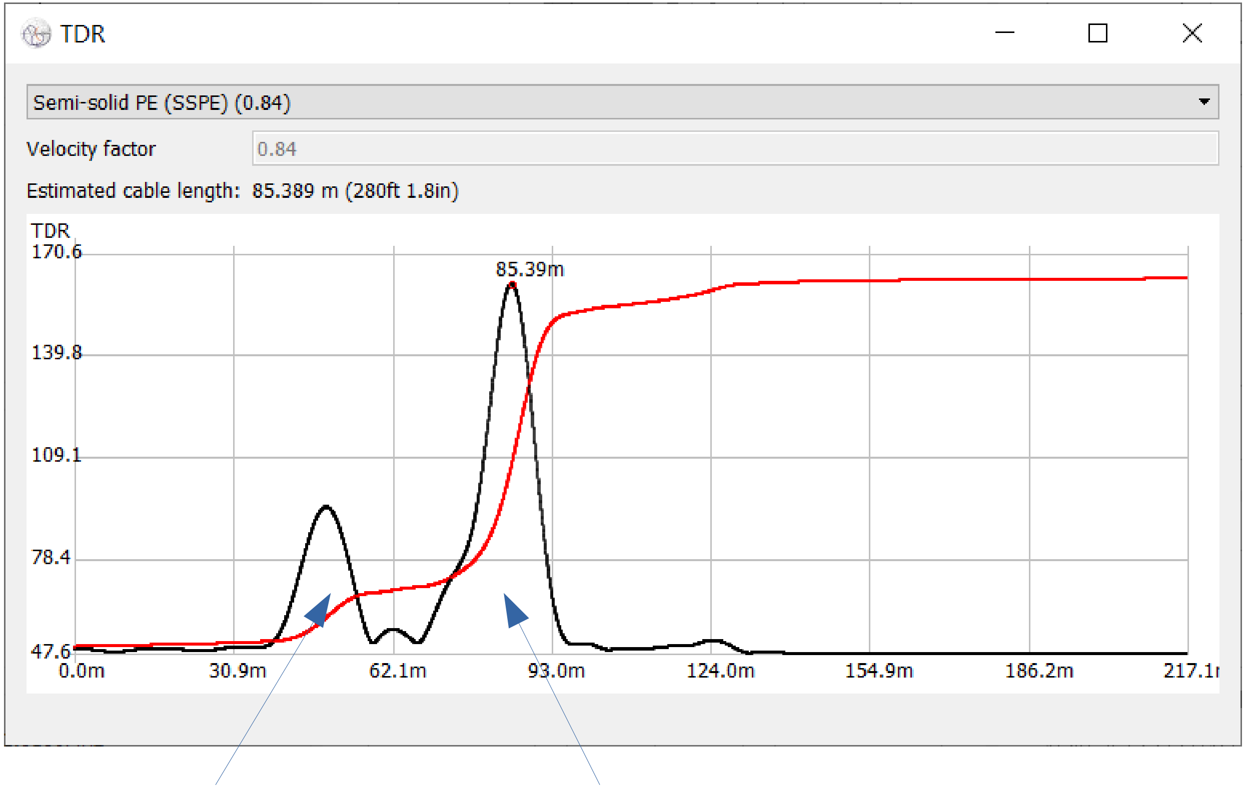


In general, you should calibrate using the NanoVNA internal calibration, but then you use NanoVNA saver to acquire your data.

Sweep of HF antenna: Long wire on 9:1 unun, approximately 160 feet of LMR400 cable



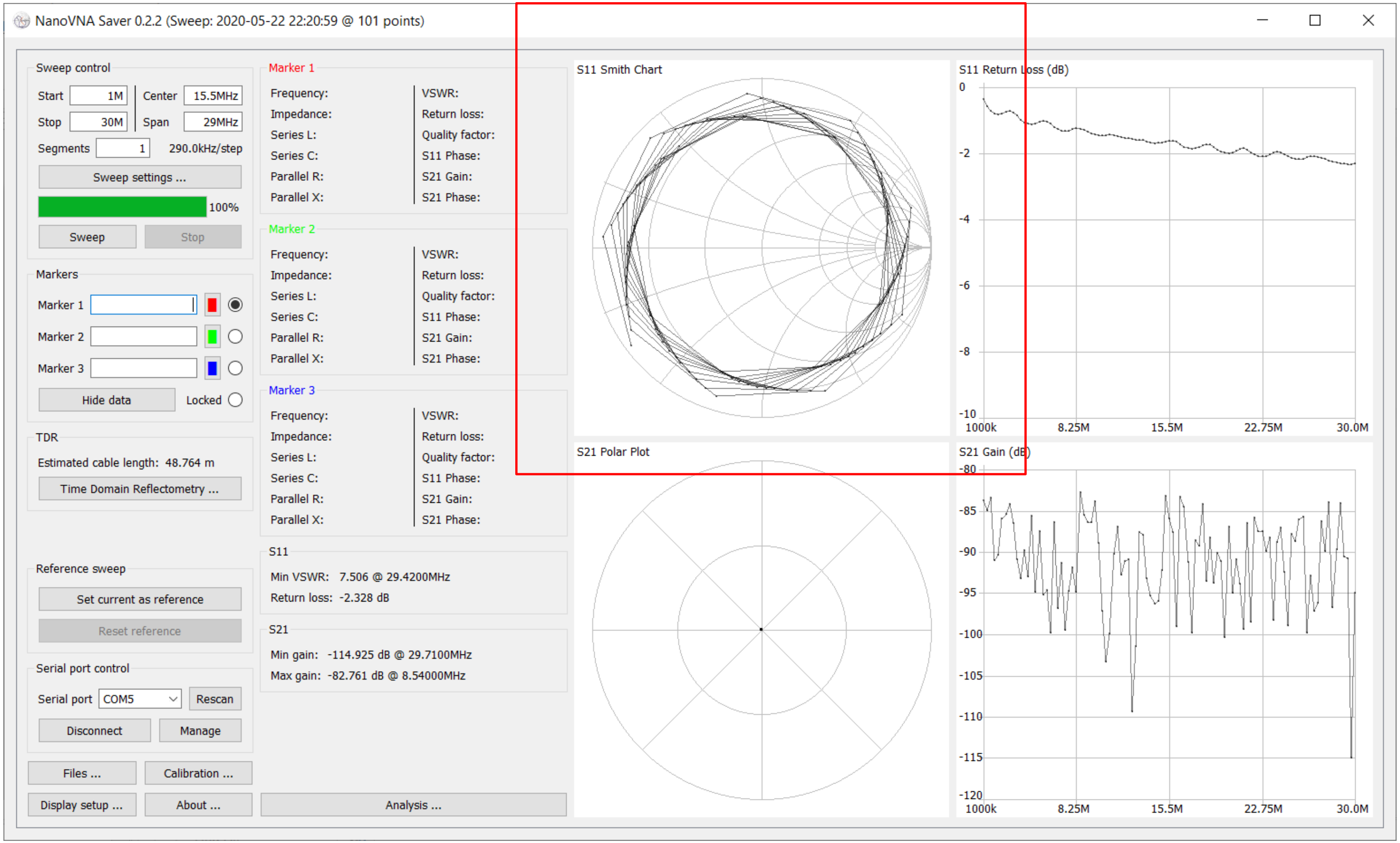
Time domain reflectometry of long wire antenna with 9:1 unun



Reflection
at 9:1 unun

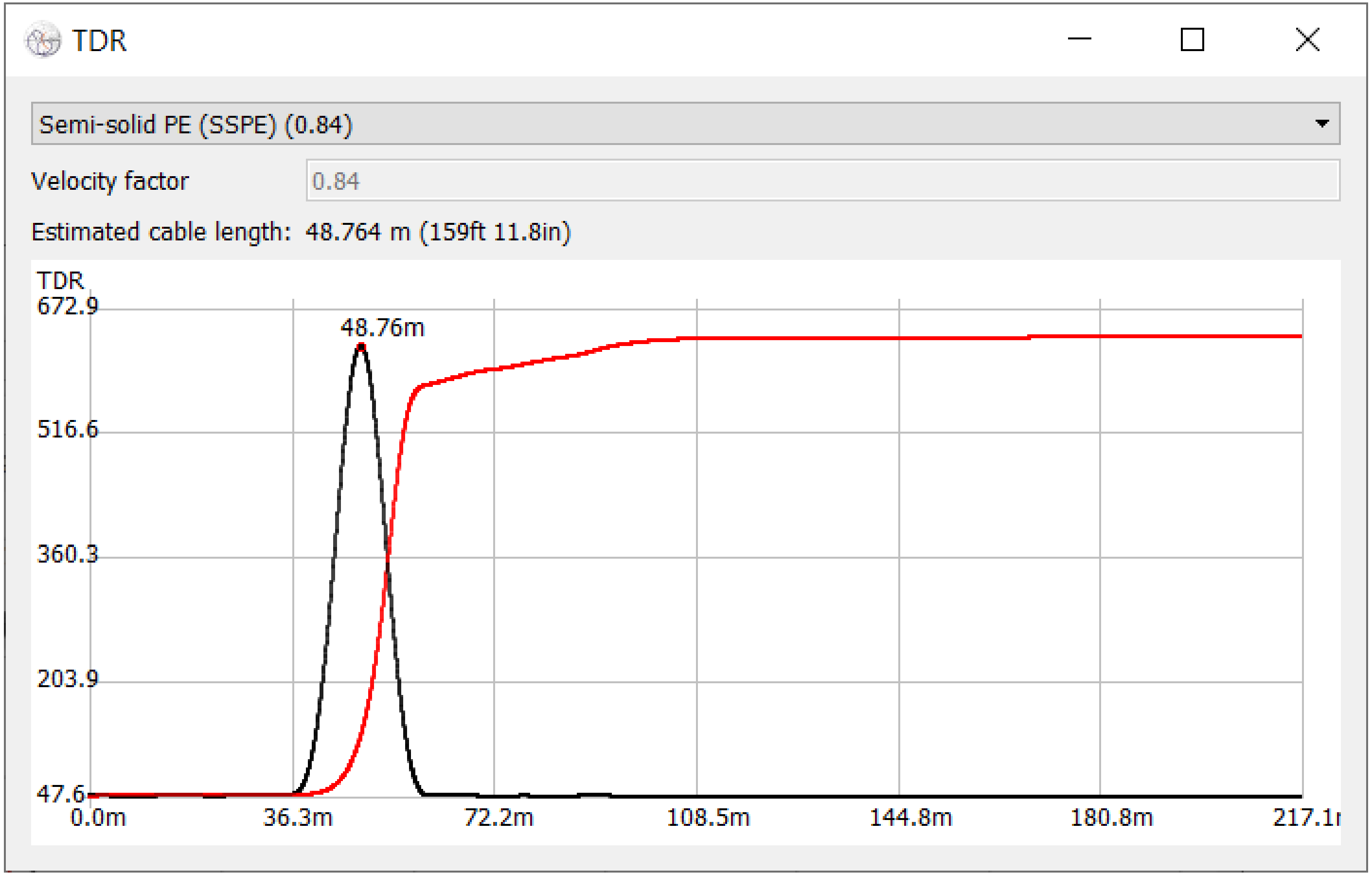
Reflection at end of long wire antenna
(approximately 40 m length)

Sweep of 160 feet of LMR400 cable with open end

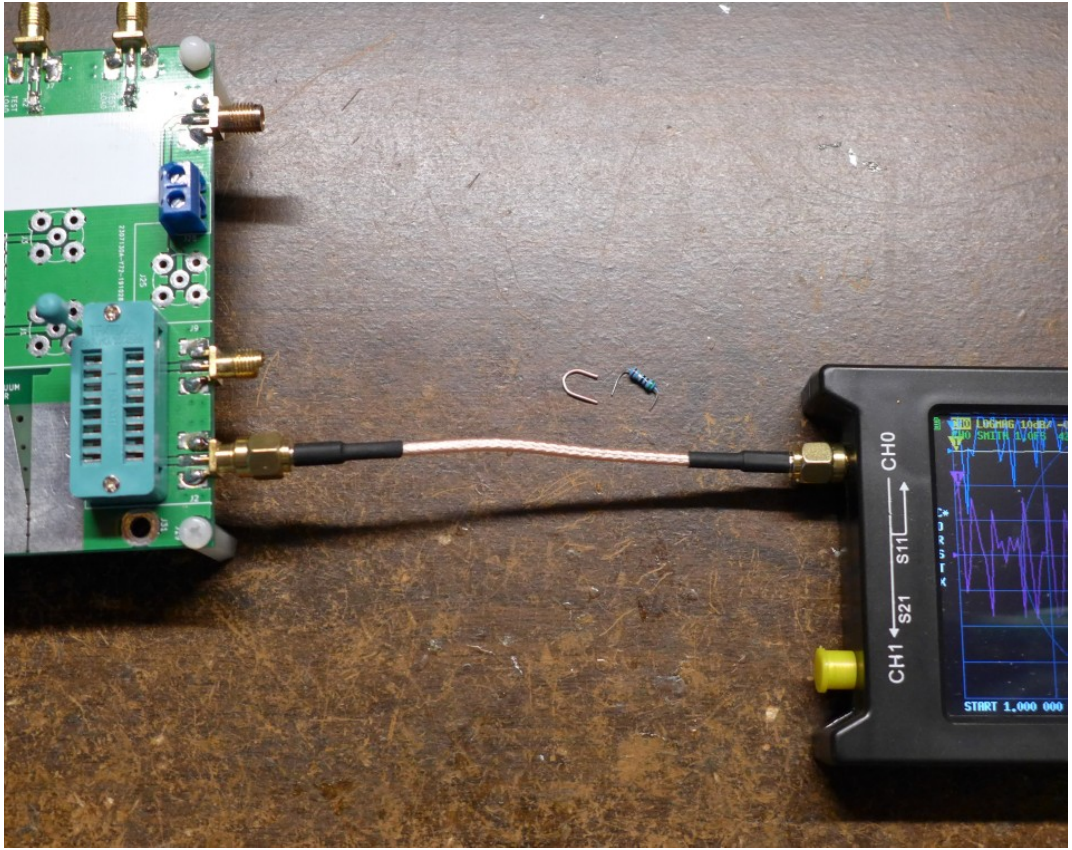


Inward spiral on Smith chart shows increased phase and attenuation with frequency

Time domain reflectometry of 160 feet of LMR400 cable with open end

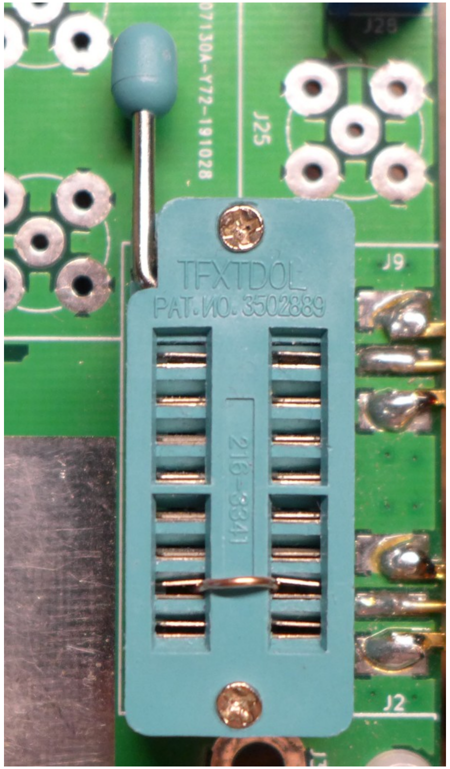


Using a ZIF socket fixture to measure components

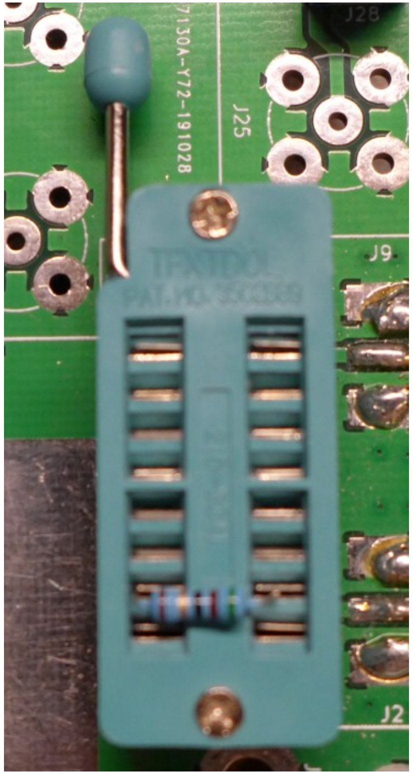


Calibration with the plane at the ZIF socket

Open: nothing in socket and lever up



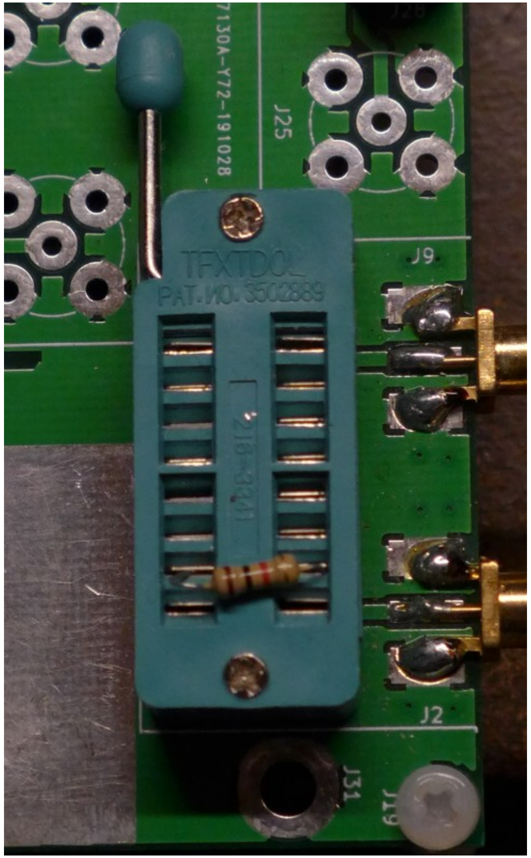
Short: copper wire between slots



Load: 51 Ω resistor between slots

Isoln: leave resistor in slot

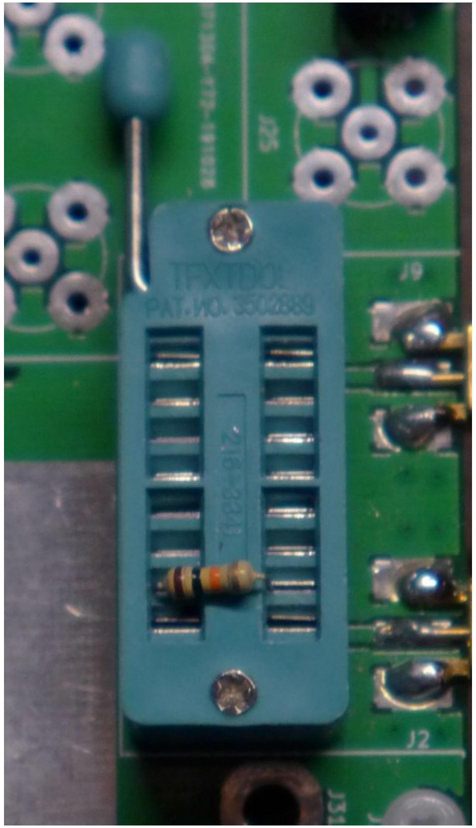
Thru: doesn’t matter, this is a one-port measurement just click it to get through it



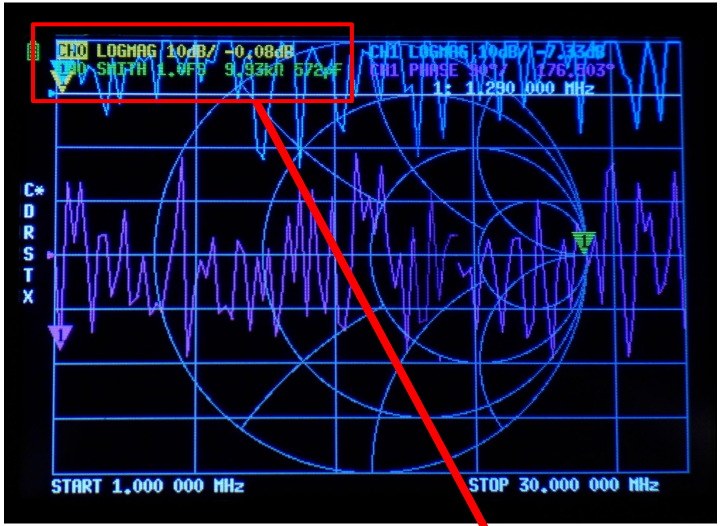
1000 Ω resistor

$$985\ \Omega \text{ resistor} \times \frac{51\ \Omega}{50\ \Omega} = 1005\ \Omega$$

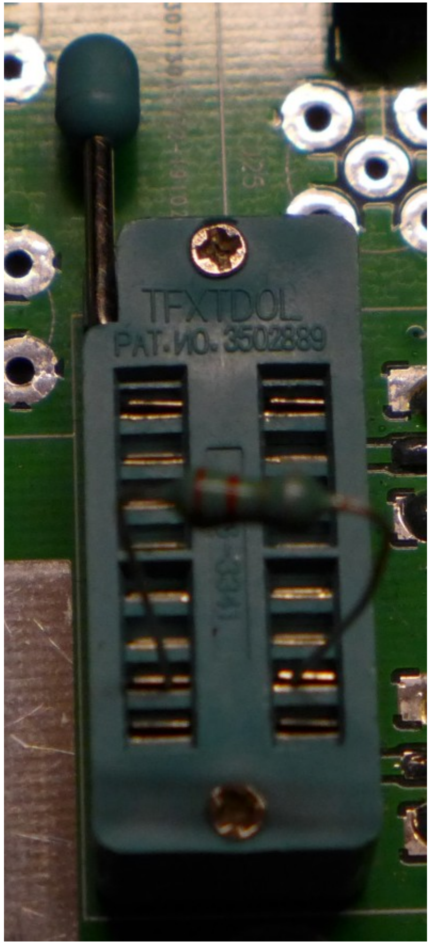
(within tolerance of 1% resistor value)



10k Ω resistor

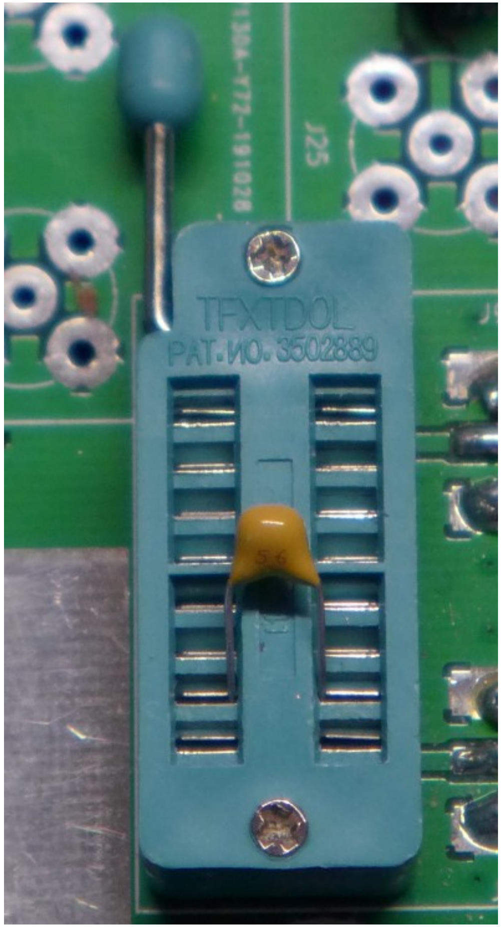


9.93 kΩ resistor $\times \dfrac{51\ \Omega}{50\ \Omega} = 10.1\ \text{k}\Omega$ (within tolerance of 1% resistor value) EXCELLENT

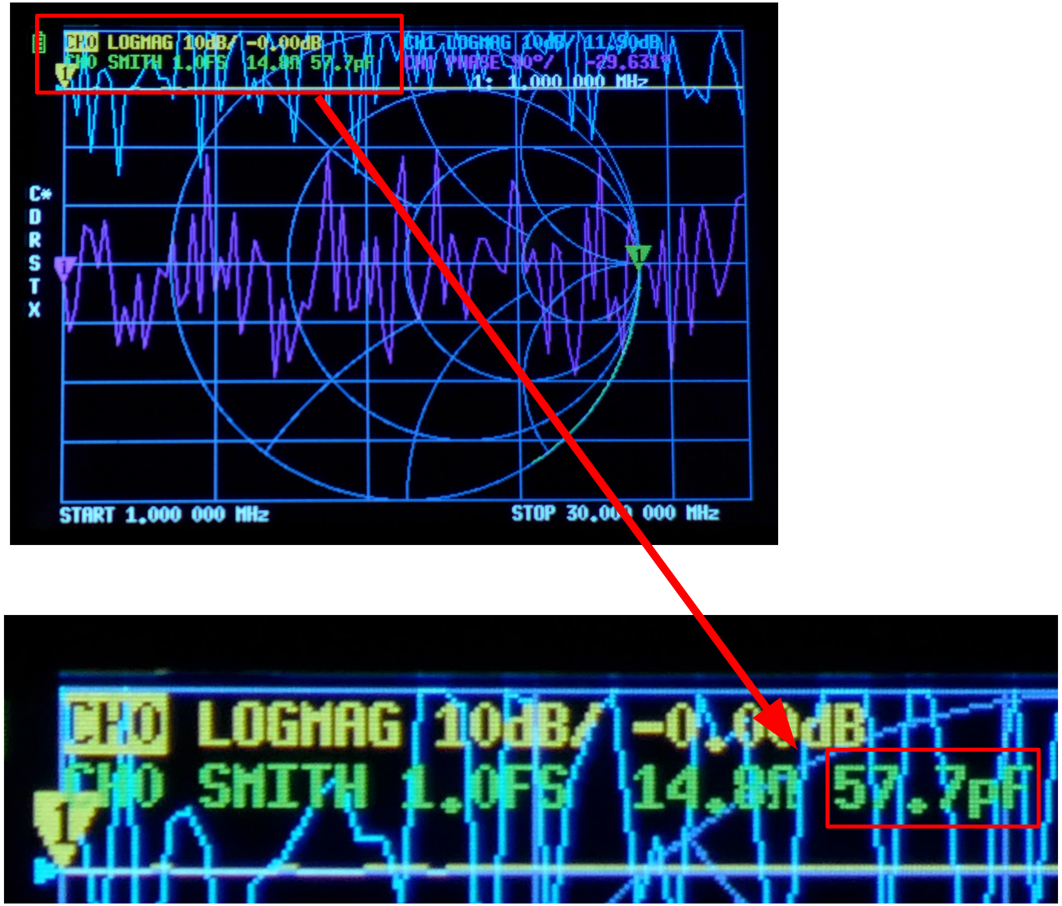


2.2 μH inductor

$$2.12\ \mu\text{H inductor} \times \frac{51\ \Omega}{50\ \Omega} = 2.16\ \mu\text{H}$$



56 pF capacitor



$$57.7\text{ pF capacitor} \times \frac{50\ \Omega}{51\ \Omega} = 56.6\text{ pF}$$

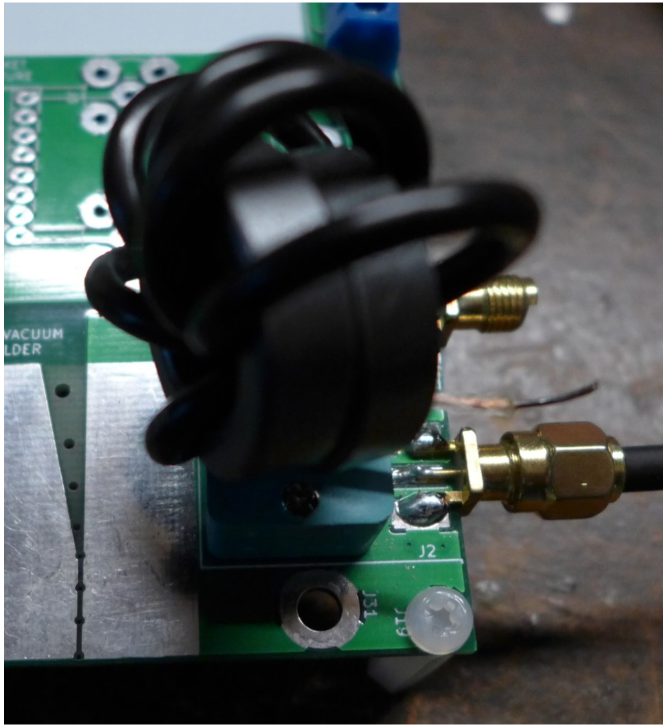
Measuring the impedance of your current balun

A properly built current balun should have an impedance far above 50 Ω at all frequencies of use.

A balun used with a tuner may need to be higher depending on antenna impedance at frequencies used.

Example balun: 6 turns of RG-174/U on two stacked FT82-43 cores.

Fixturing your balun



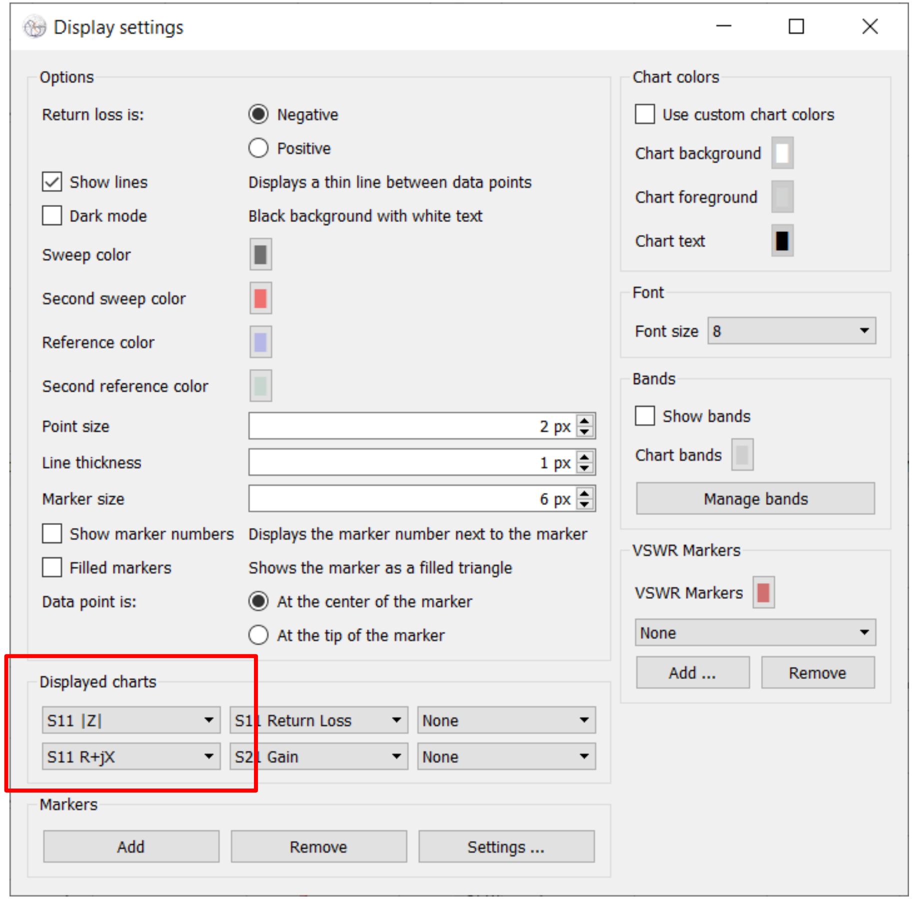
Balun in ZIF socket
fixture (not ideal).

The shield of the coax should be connected at both ends to the two terminals of the port to measure the impedance.

Using NanoVNA-saver to measure impedance

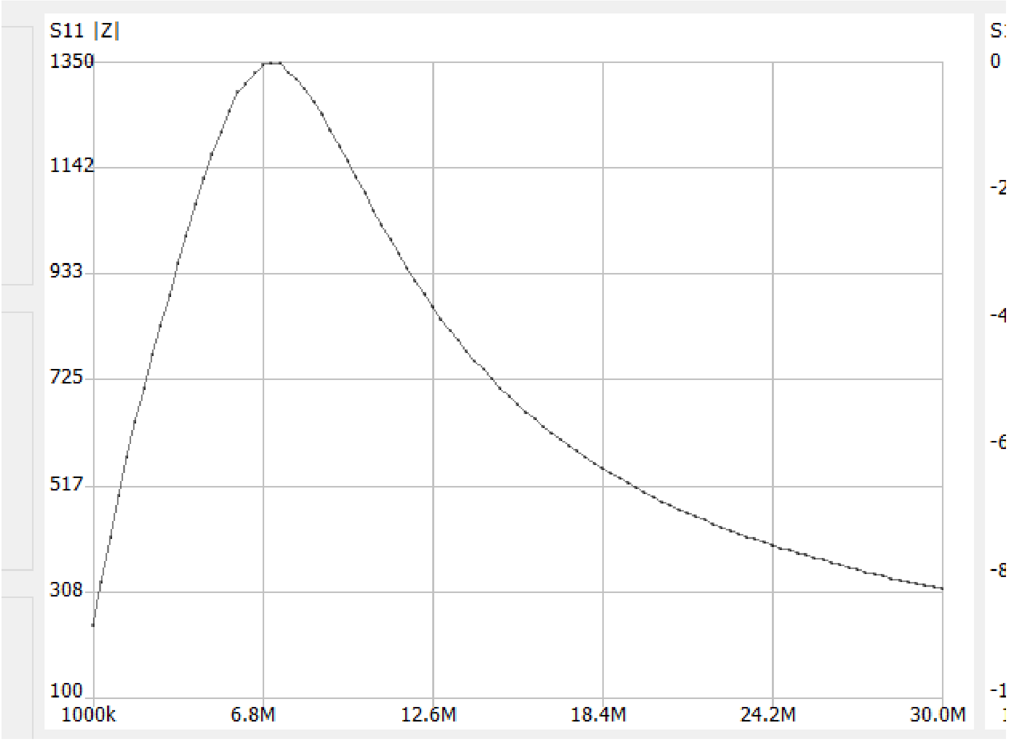
Under “Display setup...”

Select S11 |Z|
and S11 R+jX



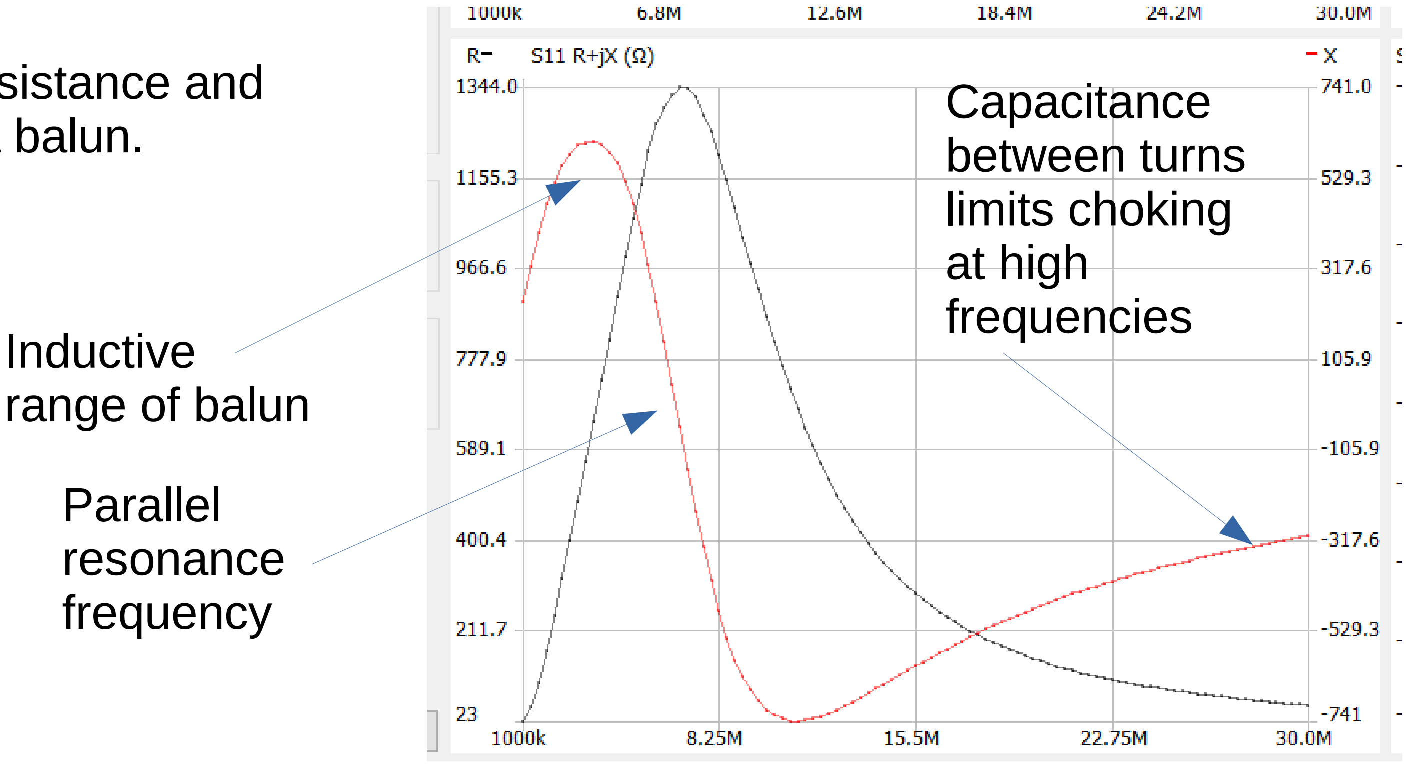
Using NanoVNA saver to measure impedance

This balun has a lot of stray capacitance. Not the best balun, but a quick example. Ideally 1000 ohms or more at all frequencies of use is better.



Balun impedance magnitude

Interpreting resistance and reactance of a balun.



Balun reactance (red), resistance (black)

In summary...

- The NanoVNA allows measurements of antenna reflections, component values, balun impedance, and lots of other useful quantities for ham radio.
- The NanoVNA does two port measurements such as of filters. Didn't have time to get to that in this talk.
- It is amazingly inexpensive for its capabilities.
- VNAs are powerful and great learning tools.
- If you master a VNA, you will understand a lot about amateur radio.

Also, see the VNA I designed based on the EU1KY antenna analyzer...

`http://www.github.com/profdc9/VNA`

Arduino-based, intended to be a kit and reproducible by individual hams.

The ZIF-socket fixture PCB is in the project as well.

Thanks for your attention! Any questions?