

Vector Network Analyzer

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1. Abstract

Using the wrong antenna or improper filter will ruin the performance of a project. Inappropriate antenna match may even kills a radio emitter.

The **Vector Network Analyzer (VNA)** is one of the most important tools when dealing with antennas and analog filters.

The VNA provides the required helps to:

- doublecheck existing antenna/filter (sureness is essential with radio waves).
- tune an antenna under construction.

In the past the VNA were reserved to professional because their very expensive price (> 10.000 Eur).



Fig 1: Rohde & Schwarz ZNLE6 vector analyzer 1Mhz to 6 GHz

Luckily, NanoVNA devices are now available for a fraction of the price (<250 EUR).



Fig 2: NanoVNA

NanoVNA offers restricted frequency range usage and requires frequent calibration to get reliable result from it.

2. What is a VNA?

It will be appropriate to review the behaviour of more common measurement devices before entering the Vector Network Array capabilities.

2.1. Where does it come from?

Let's start with the basics measurement done within a VNA: the voltage. Then step up from a very basic measurement device up to the the VNA to understand what's make that VNA device so unique.

2.1.1. The voltmeter

The voltmeter (or multimeter set on "Volts") is made to measure voltage. It can do the measurement on a DC Voltage and also on a AC (alternative) voltage.

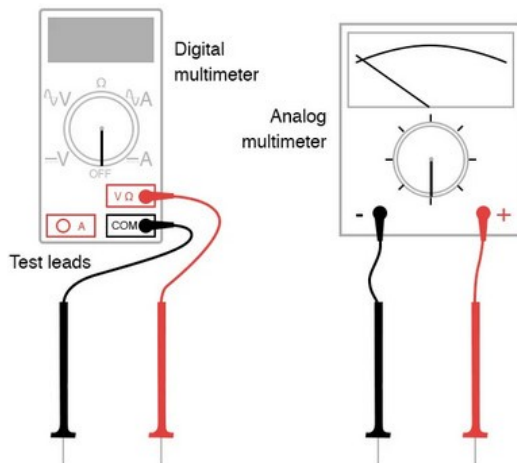


Fig 3: voltage

Need to measure a current? No problem, insert a small resistor (0,010 Ohms) inside the circuit then we measure the voltage across the resistor. Thanks to the Ohms law, we can calculate the current flowing through the resistor from the voltage drop.

Unfortunately, this device shows an instant value, **no chart with historical values**. Moreover the display show a average value.

2.1.2. The oscilloscope

Need the see the voltage/current curves in time span to make proper calculation and estimate? Let's take the oscilloscope, a Swiss knife for electronic bench.

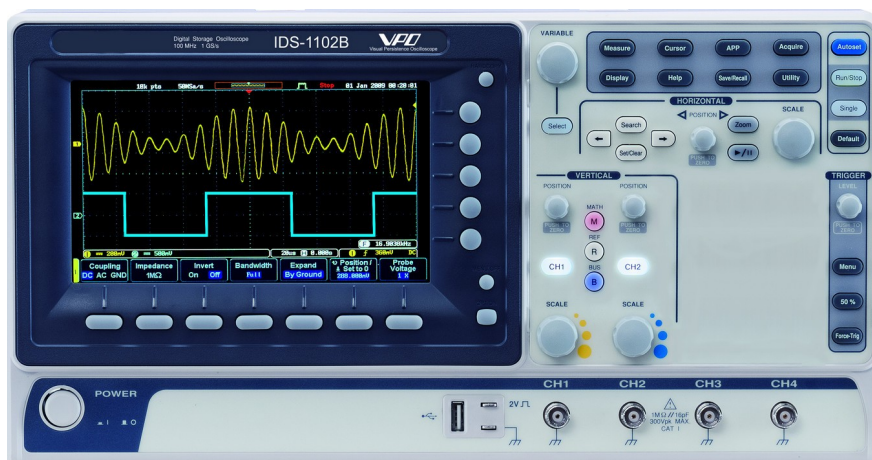


Fig 4: oscilloscope

The oscilloscope allows to see the signal getting impacted by a modification on the circuit (turning the potentiometer, the variable capacitor, etc).

This time the signal is visible and the real value can be measured (y axis) over different time location (x axis) of the curve.

Oscilloscope make measurements over a time period. The Y axis show the amplitude of signal and the X axis shows the time.

Unfortunately, working with **antenna and filter requires to study the signal amplitude relative to the frequency** instead of time!

In Radio Frequency world, the signal amplitude (its strength) may quickly attenuates in a ratio of 10, 100, 1000, 10000 or even more.

For this reason, the reading device must: (1) be very sensitive, (2) **output the values in dB** (decibels) which is a logarithmic scale and (3) use frequencies on the Y axis (instead of time).

2.1.3.The spectrum analyzer

This time we have a device that show amplitude in decibels (dB) on Y axis while X axis are frequencies. The spectrum analyser scan frequencies and shows the level of signal measured for each of the frequency shows in the X axis.

This represents hundreds measurements in the frequency range. Spectrum Analyzer requires lot of precessing power to perform their job.

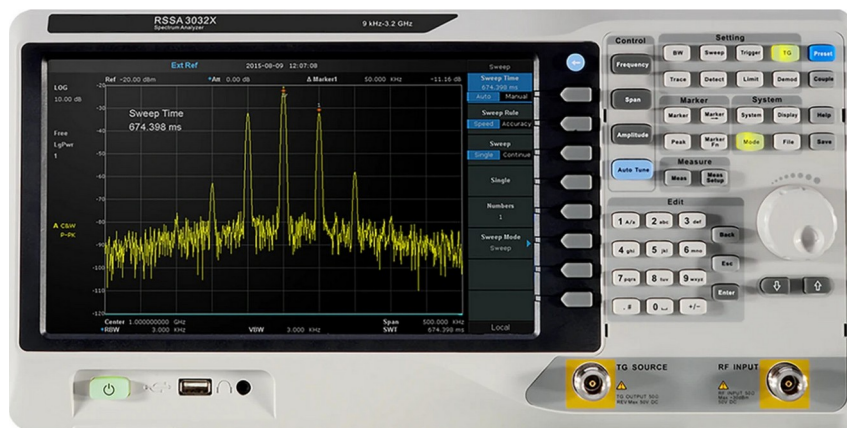


Fig 5: spectrum analyzer at work

Spectrum Analyzer are good to detect peak of power emitted and the sub-frequencies ranges where it occurs. Thanks to the decibels Y axis, the signal power can be evaluated at the peaks.

The decibels are a logarithmic based calculated values (roughly says that the dB value is proportional to the number of zeros appearing the real value). As Radio Frequency world the amplitude can quickly attenuates in a ratio of 10,100,1000,10000 or more, using decibels do shows the measurements with some linearity characteristics (more comfortable to view and evaluates).

The figure 6 tries to represent the Spectrum Analyzer result without using the decibel scale (aka: without logarithmic representation). Most of the reals values are so low compared to the peak that all the measurements are squeezed down to the bottom of chart making them almost usefulness.

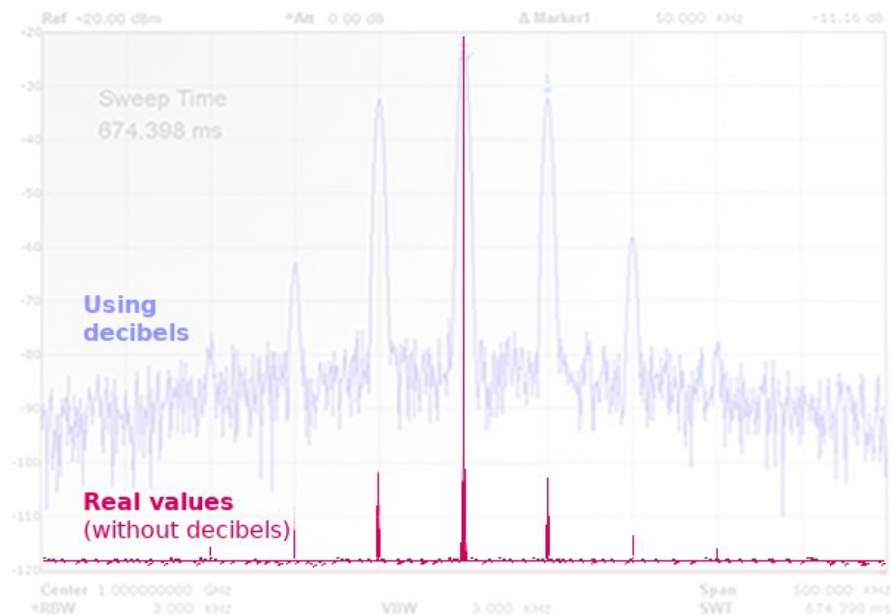


Fig 6: A spectrum graphics without using decibels scale

However, the spectrum analyzer only performs passive measurement... meaning that it measure something that is already running like the radio module + antenna.

We do **need a device** that performs the **measurement like the Spectrum Analyzer** and that is also capable to **provides the excitement signal** to the Device Under Test (DUT, out antenna).

The device doing that job is named a Vector Network Array analyzer (a VNA for short).

2.2.The Vector Network Analyzer

The **VNA provides excitement to the DUT (Device Under Test) and measure (1) the power passing the DUT and (2) the power reflected by the DUT.**

VNA excitement covers a range of frequencies and measurement are done over the same range. Measurement are "similar" to the Spectrum Analyzer process and are used to display meaningful charts.

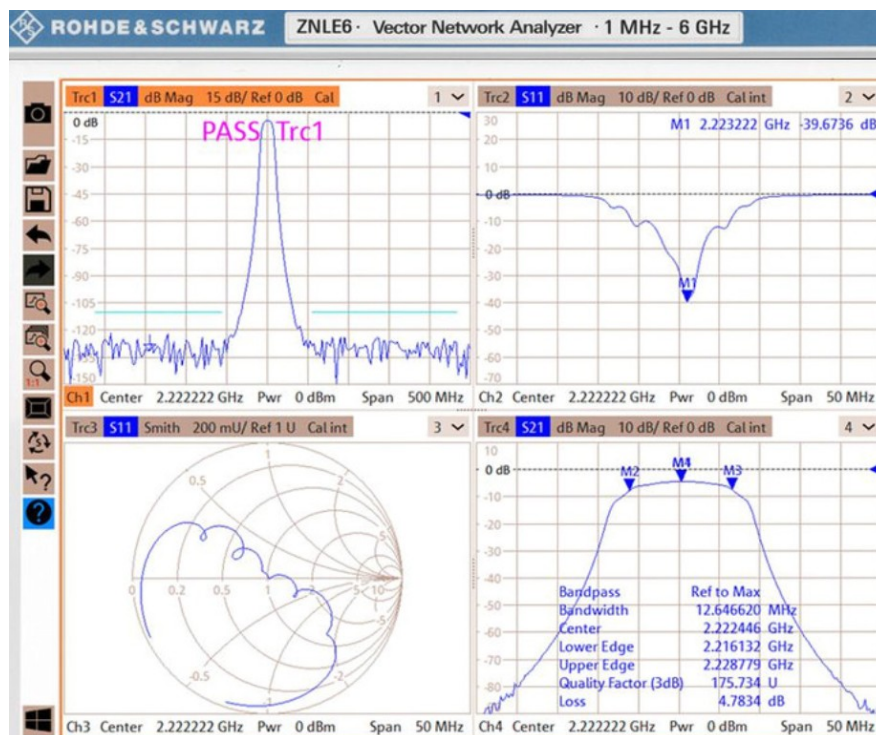


Fig 07: Charts produced by a VNA

With the VNA, it is possible to obtain the frequency characteristic of a Device Under Test (DUT) like an antenna or a RF Filter.

Note: RF filter are electrical network mainly composed of resistor, inductance and capacitor.

3. NanoVNA

The NanoVNA is Vector Network Analyzer with limited features. As any VNA, it measures the frequency characteristics of reflected power and passing power of a high frequency network (RF Network) also named DUT (Device Under Test).

In this document, the VNA is the tool used to find the correct match between the emitter and the antenna (or tune the antenna for it to match the emitter).

3.1. General usage

The nanoVNA is fitted with two RF connectors:

- **Port 1:** generates the signals over a range of frequencies injected to into the DUT (device under test). The default frequency range starts at 10 KHz up to 3 GHz (default). Port 1 also measure the signal reflected to the emitter (amplitude & phase).
- **Port 2:** does measure the remaining signal behind the DUT (amplitude & phase).

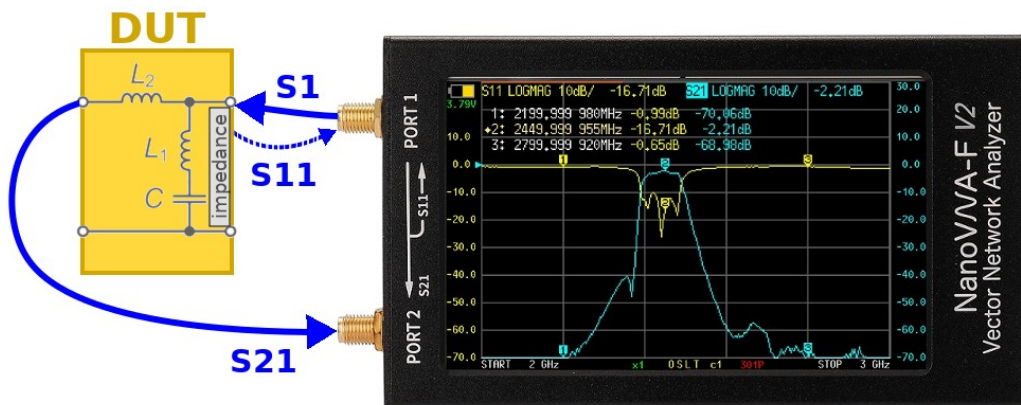


Fig 8: Common usage for NanoVNA

The signals are generated by the NanoVNA is labelled S1.

The reflected signal on the DUT is visible on the curves labelled S11.

The input impedance can also be displayed into a Smith chart. Remind that input impedance may vary depending on the components presents in the DUT.

The DUT output curve is labelled S21 (Signal on Port 2 coming from Port 1). The RF Network in the DUT will alter the input signal in many way (amplitude & phase), S21 is there to measure the changes in the signal and to display as a curve.

3.2. Antenna usage

An antenna is a particular DUT without output since all the power is supposed to be send into the air. There is no measurement for S21.

On antenna we do expect a given impedance (usually 50 or 75 Ohms) and a minimal power reflection (S11).

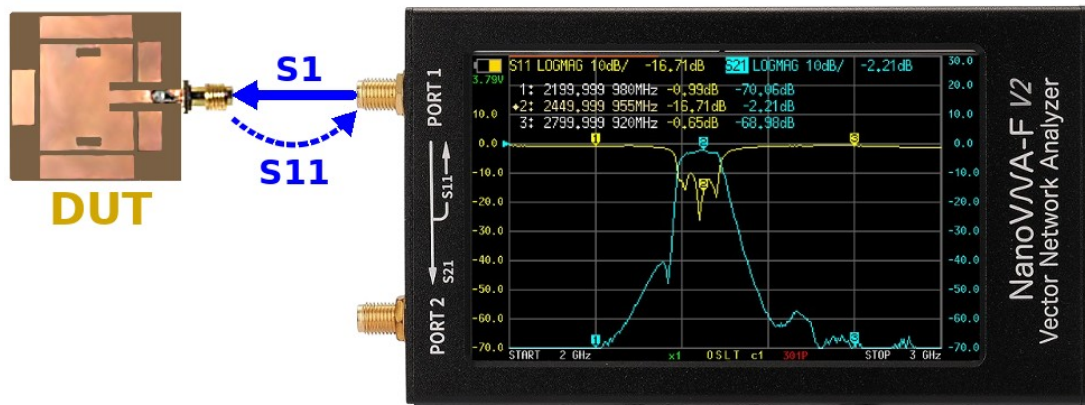


Fig 9: Usage of VNA with antenna

4. NanoVNA limitation and consequence

Professional VNA are fully calibrated and calibration data are stored within the device. This also explain the high price of such device.

Such professional VNA can also performs thousands of measurement to display charts where as NanoVNA is usually limited to one hundred of point due to power calculation limitation. So NanoVNA offers best precision on shorter range of frequencies.

The NanoVNA is a cheap device that can provide reliable result when it is properly calibrated. NanoVNA device doesn't contains calibration data. As a consequence, **user must proceed manual calibration** on the target frequency range before doing any measurement.

Calibration is proceed by measuring well known value then calculates corrective information from it. Using 3 comparison points/value are enough to get a good correction on the measurement.

Thankfully, the NanoVNA do have a simplified calibration procedure that will calculate corrective data to apply on the coming measurements.

Before jumping into the calibration procedure it is important to understand two concepts:

- Impedance
- Smith diagram

5. Resistance and impedance

The resistance R is quite easy to understand. When inserted into an electrical circuit, the current flowing through it create a voltage drop across the resistor. The resistor creates a power lost which is dissipated as heat.

The resistance R usually refer to the DC world where it is commonly used. The **impedance Z** is a term used when working in the AC (alternative current). For sure it also exists resistors for alternative current that mostly produce heat when powered in AC (EG: heating element). For sure, a resistor is also coil of wire si it will also have some inductance ($\mathcal{L}$).

As rule of thumb, the impedance Z can be seen as composed of:

1. pure resistance R +
2. inductance $\mathcal{L}$ (a coil) +
3. capacitance $\mathcal{C}$ (a capacitor).

$Z = R + \mathcal{L} + \mathcal{C}$ which result into a Complex number with the real part for the resistance part and imaginary part for the $\mathcal{L} + \mathcal{C}$ parts. This document will not focus on complex number calculation, however having read and imaginary part in a complex number will allow to draw them into a chart. Just remember it when this document will introduce the Smith Chart (as well as the phase shift describes below).

The capacitance $\mathcal{C}$ as the inductance $\mathcal{L}$ are sensitive to frequency, this means that their respective behaviour will change with the frequency of the signal.

So the impedance Z will have changing behaviour depending of the frequency of the signal going through it.

5.1. The pure resistor

Except voltage drop and limiting the current, the resistor R does not have major impact in a circuit.

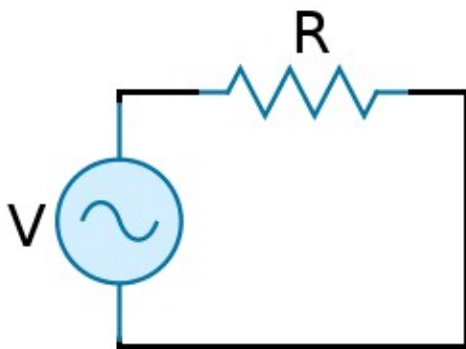


Fig 28a: Resistive circuit

Also, the Voltage and Current stays in phase (say “aligned together”).

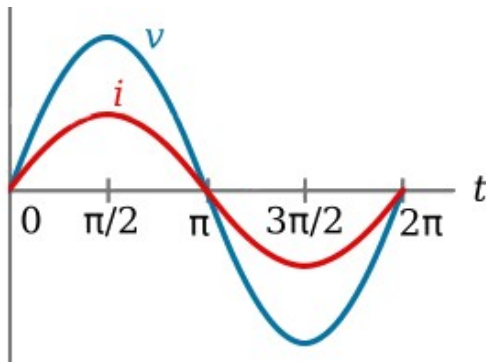


Fig 28b: Resistor Voltage (v) and Current (i)

5.2.The inductance

The inductance $\mathcal{L}$ is made of a winding made of a piece of isolated wire. Inductor may be simple winding or winding around a core.

In DC current, the inductor act as a simple wire but is act as a bottleneck stopping/slowing the current on high frequency.

Notes: long trace on a PCB may act as inductance face to high frequency signals.

When the coil is opposing to the current, it store energy as an electromagnetic field that can be released in no time creating RL voltage spikes. This is why they are used to build DC/DC voltage converter.

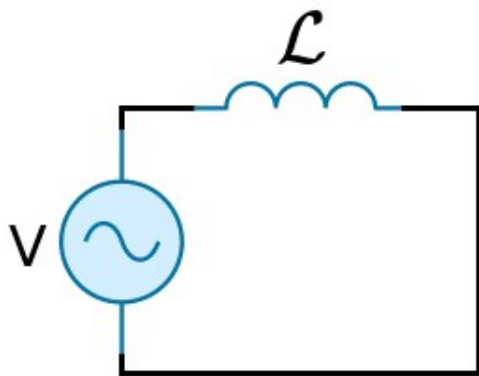


Fig 29a: Inductor circuit

The inductance creates a phase shift between the voltage and current (they are not aligned anymore).

The maximum voltage is ahead on the maximum current (the current goes to its maximum after the the voltage maximum). The voltage is leading the current. The phase shift is maximum 90° ($\pi/2$).

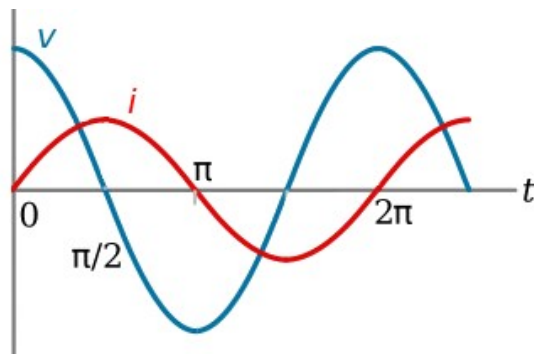


Fig 29b: voltage is ahead on the current

5.3.The capacitance

The capacitance $\mathcal{C}$ is made of an insulating materiel placed between two electrodes. Inductor may be simple winding or winding around a core.

In DC current, a capacitance store electrical charge that can -later- be released in the circuit. That act like energy reservoir. High frequency signals pass through capacitance (more or less efficiency).

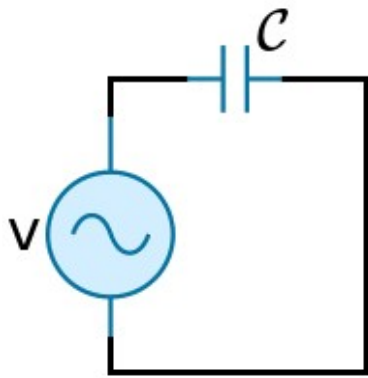


Fig 30a: Capacitance circuit

Notes:

- Traces on the top and bottom of a PCB are placed between insulation material. This is exactly the definition of a capacitor. This will store a bit of electrical charge at lower frequency and may disturb signals.
- It is common to place 0,1 μ F capacitor near the supply pins of logic component. Such capacitor will become conductive for high frequency noise to conduct them to the ground. A great way to avoids malfunctioning because of noise on the power line.

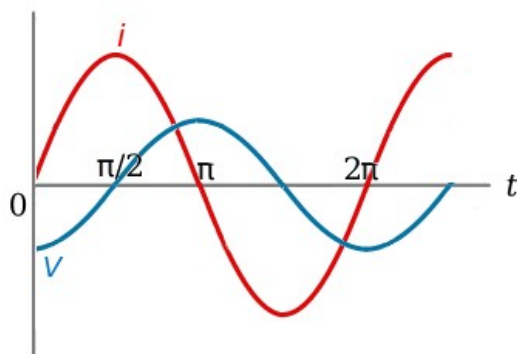


Fig 30b: voltage is behind the current

The capacitance also creates a phase shift between the voltage and current (in the opposite direction than inductance).

In opposite of inductance phase shift, this time, the max voltage occurs after (later) the max voltage on the current. The current is leading the voltage and this opposite phase shift can reach 90° ($\pi/2$) for purely capacitive circuit.

5.4.Phase shift consequences

The phase shift angle is usually identified with φ (phi grec letter) from -90° to 90° .

Regarding the power circuit, a **phase shifting will mainly cause power lost** (usually converted into heat). Phase Shift may also be the cause for signal degradation.

A good practice with power circuit is to avoids or reduce the phase shift ($\varphi = 0^\circ$) to get as close as possible of a resistive circuit.

Adding capacitance to an inductive circuit can fix the phase shift φ (and vice-versa).

Radio emitter are power circuit connected to an antenna.
 So the phase shift matter and should close of $\varphi = 0^\circ$. Except other rule, the antenna impedance Z should be 50 Ohms (resistive)

5.5.Summary

- 1.Resistive material is not sensitive to frequency. **Great!**
- 2.Inductive material will creates phase shift. Inductance is sensitive to frequency.
- 3.Capacitive material will creates phase shift (in the opposite direction). Capacitance is sensitive to frequency
- 4.Phase shift can be fixed by adding inductance or capacitance as appropriate.
- 5.Antenna circuit should have 50 Ohms impedance (no phase shift).

6.Smith Diagram

The Smith Diagram is used to show the reflected power ratio of the DUT relative to the DUT input impedance. This graph is made of multiple points, each point calculated for a given frequency in the frequency range.

As consequence, the graphic shown on the Smith diagram is representative of the kind of impedance (resistive, capacitance, inductance).

Additional information about [Smith Diagram on Wikipedia](#).

6.1.Resistive path

The figure 10 shows the path followed on the chart for pure resistive charge with three remarkable SWR points (those are very important).

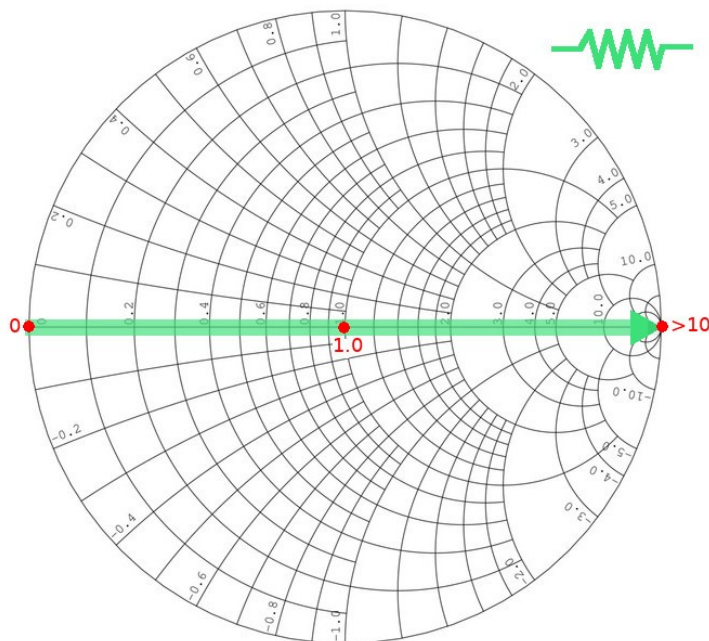


Fig 10: Path of pure resistive chart on Smith Diagram

- **SWR = 0**: meaning that no power of the emitter goes into the circuit. This is only possible with a resistor so small that it transform all the power into heat as soon as it reach the DUT. So this point correspond to a **0 Ohms resistor (short circuit)**.
- **SWR = 1**: meaning that no power is reflected to the emitter. All the power entering the DUT goes to the DUT output (nothing reflected to the emitter). It is a perfect **50 Ohms load**.
- **SWR > 10**: meaning that all power is reflected back to the emitter. This is point correspond to an **infinite resistance (open loop)**

6.2.Capacitance path

The figure 11 shows the path followed on the chart for a pure capacitive charge.

This figure indicates how the measurement travels along the chart when capacitive charge is involved.

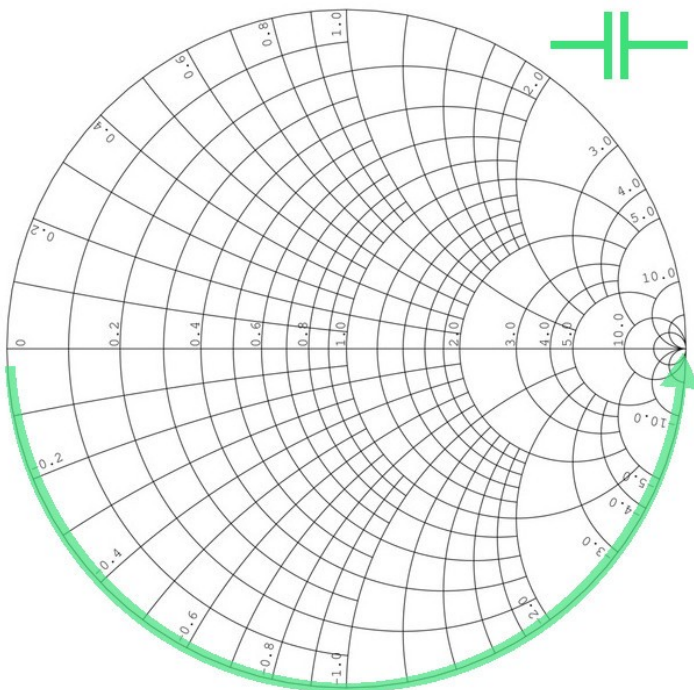


Fig 11: path of pure capacitive charge

6.3.Inductance path

The figure 12 shows the path followed on the chart for a pure inductive charge.

The figure indicates how the measurement travels along the chart when inductive charge is involved.

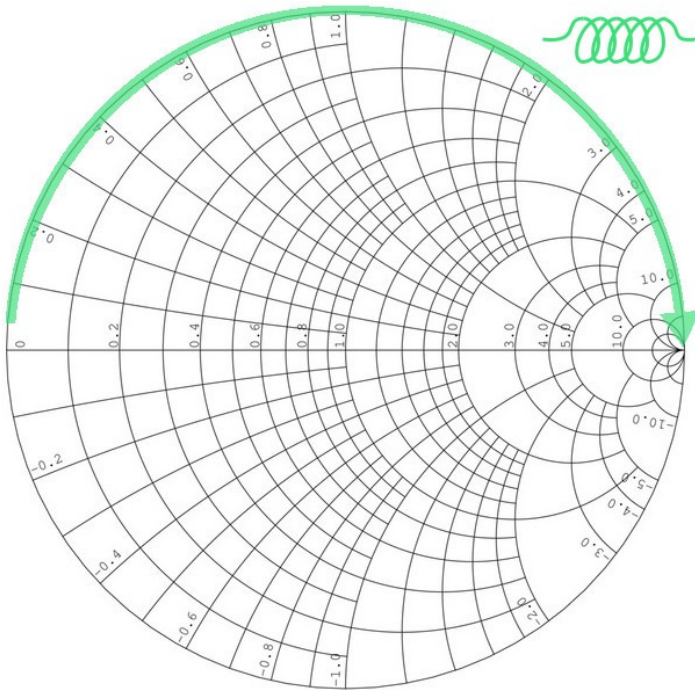


Fig 12: path of pure inductance charge

6.4.Real World Exercise

The figure 13 shows a 10 KOhms potentiometer (resistive component) wired to a coax connector. This setup can be used to test the Smith Diagram. It will also demonstrate how small changes in a component may affect the results.

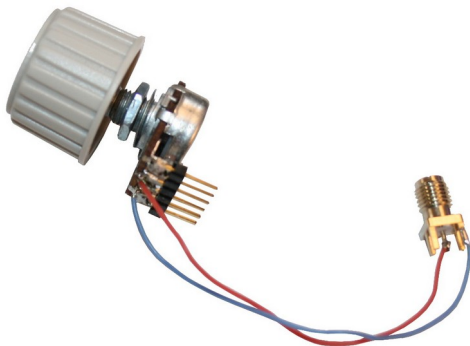


Fig 13: potentiometer wired to RF connector

As you can see, the component is wired with flying wires so we can expect some inductances because of the wires themselves. Due to its constitution, the potentiometer is a cursor moving onto a resistive wire (so inductance behavior again).

Two wires with insulation between them (air also being an insulator) act like a capacitor. The header on the potentiometer also captures the air (an insulation) between two conductors (mounted in parallel with the resistor).

So, depending on the frequency range and the position of the potentiometer, the impedance may also show some inductance / capacitance behavior.

Following pictures are taken in the **frequency range of 1 MHz to 5 MHz**.

The figures 14 here below show an ideal potentiometer position! From 1 to 5 MHz, the impedance is almost 50 Ohms mainly resistive (great!). The drawing is almost

positioned on $SWR = 1$, the ideal point with 42,3 Ohms resistance + 55,2 nH inductance).

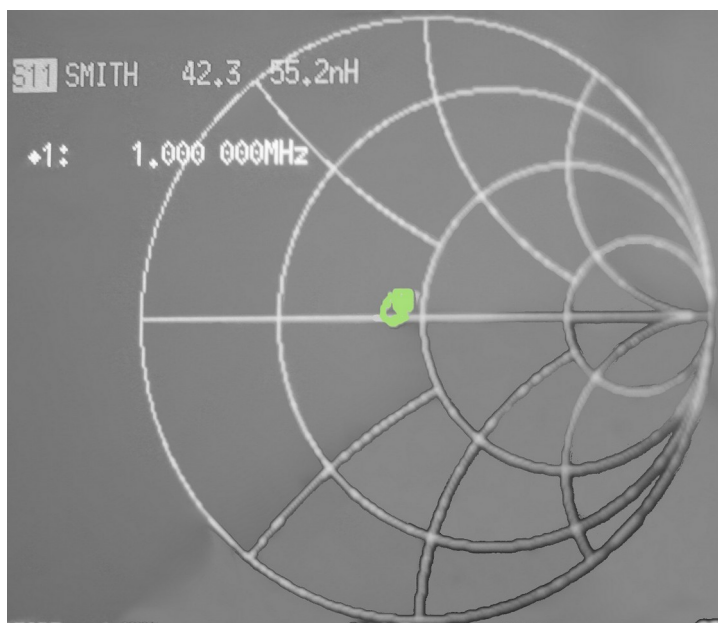


Fig 14: almost ideal position.

Moving a bit the potentiometer (figure 15) do moves the impedance in the inductive area with 60 Ohms resistance + 4,5 μ H impedance. With just a small variation of the resistance, the circuit inductance takes over the the capacitance.

By increasing the position of the potentiometer, we add more wiring in the resistor by moving the potentiometer cursor.

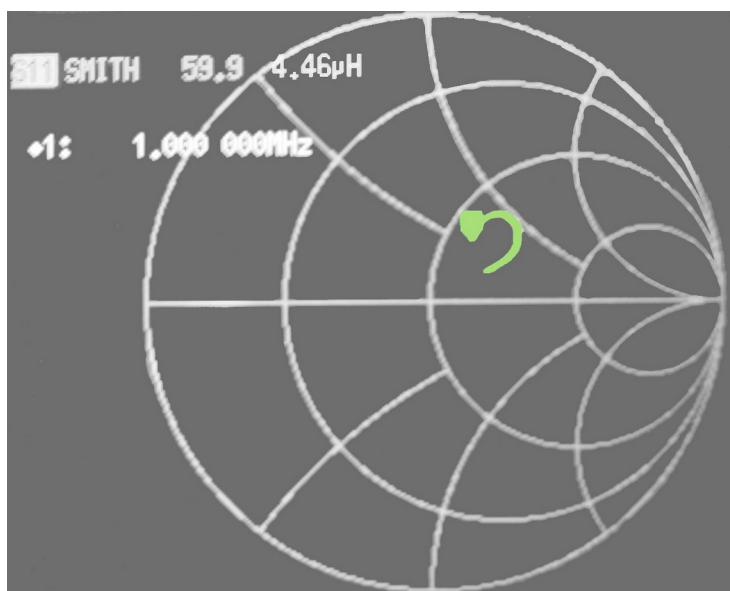


Fig 15: Inductive impedance

Moving again the potentiometer (figure 16) do jump into the capacitance area with 14 Ohms resistance + 11 nF capacitance. This time, the capacitance effect takes over the inductance one.

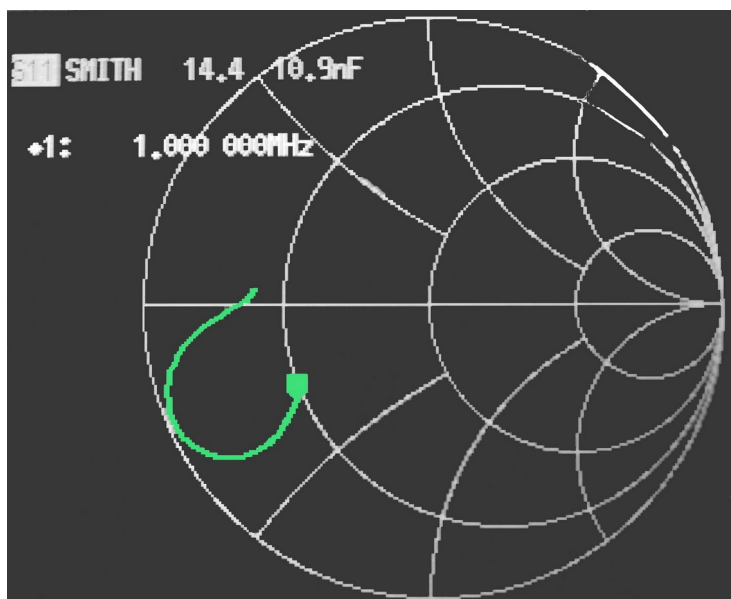


Fig 16: capacitive impedance

This time, the potentiometer cursor is moved to lower the resistance. This shortens the length of wire meaning that the air gap between the wire is now prevalent (the air between two conductors acts as a capacitor).

This example shows how much an RF Network or antenna is sensitive to the change of its value. It also demonstrates that wiring conditions may have a deep impact on RF Network/Antenna characteristics.

Antenna build must be done with great care and attention to details.

6.5. Corrective action

Smith diagrams could also be used to take corrective action on an existing setup.

Let's say we have an antenna setup for 433-434 MHz not good enough (SWR is too big). The Smith diagram will show a trace away from the ideal spot (the center where SWR=1).

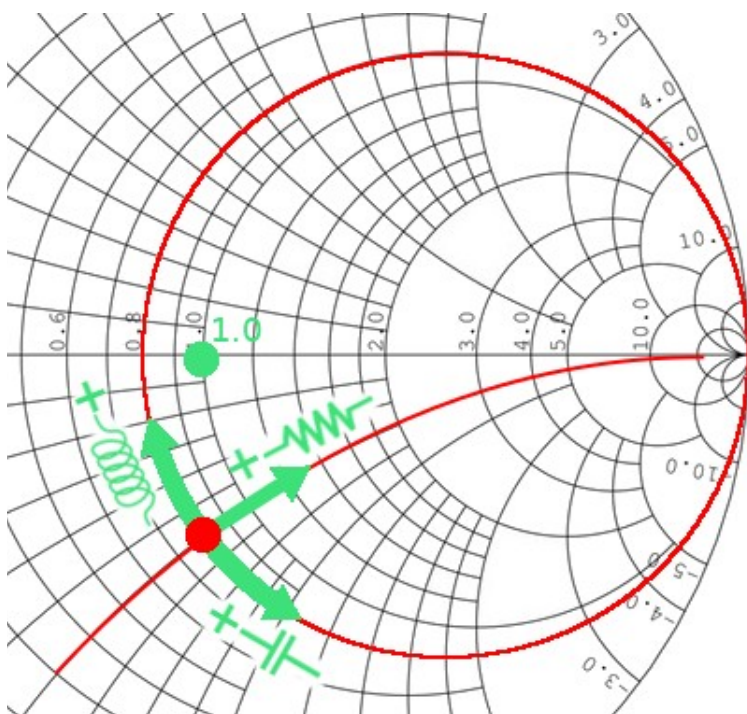


Fig 17: taking corrective action with Smith Diagram

As shown on the figure 17, adding some resistance and inductance will move the measurement point closer of the center.

7.Calibration

As seen earlier, the resistive path in the Smith diagram spots 3 remarkable points:

- SWR=0 where the resistance is 0 Ohms (short-circuit)
- SWR=1 where the resistance is 50 Ohms
- SWR>10 where the resistance is infinite (open-loop)

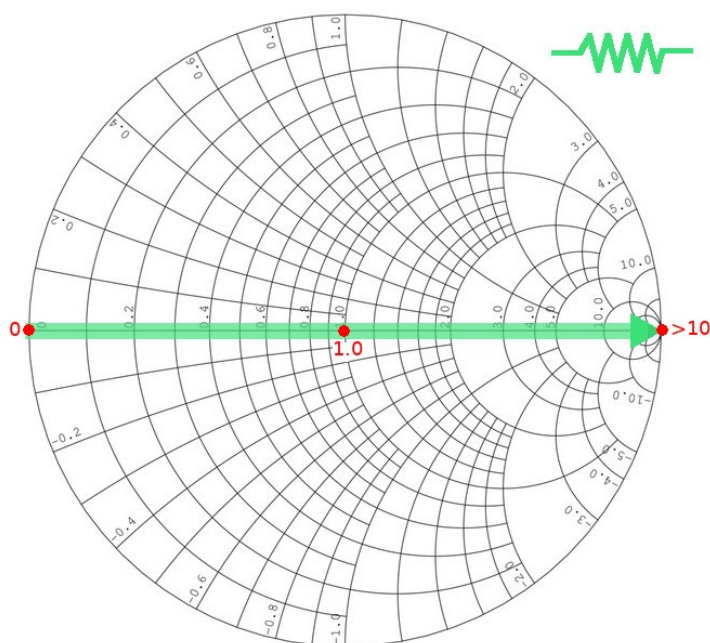


Fig 10: Path of pure resistive chart on Smith Diagram

So we have 3 well-know points for the calibration process. Those 3 points are enough to calculate reliable correction for all the measurements done in the frequency range.

NanoVNA should be provided with a calibration set made of 3 RF connectors.



Fig 18: Calibration set

The **load** is usually easy to identify as have a central pin with dielectric and larger cap on the back. This node is 50 Ohms but it exists other load values.

The **short** connects the central pin to the surrounding ground. The pictures shows the connecting part at the base of pin (whereas the load do have the dielectric).

The **open-loop** don't have central pin but an empty chamber.

7.1. Select frequency range

Lets calibrate the NanoVNA for a frequency range of 420 MHz to 440 MHz.

Start you nanoVNA then click the menu button (or touch the screen center).

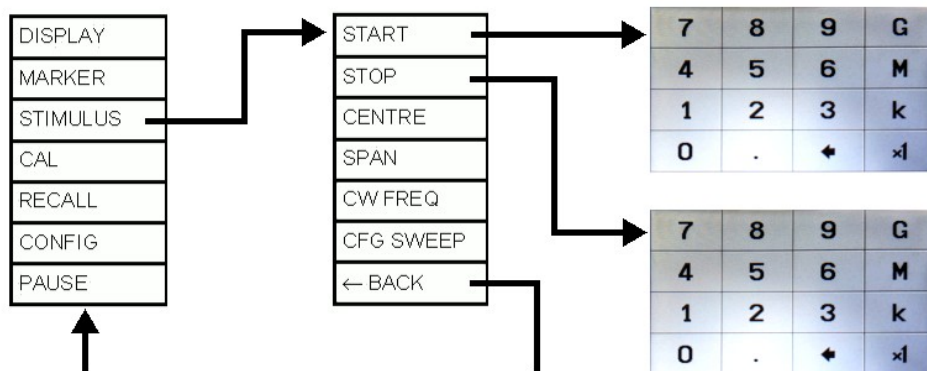


Fig 19: Setting the frequency range

The frequency range is set via the main menu **STIMULUS**. In the sub-menu, set the **START** and **STOP** frequencies. When the keypad is prompted, respectively enter **420M** and **440M** (the M stand for Mega-Hertz).

When finished, you may need to select “Back” to return to the main menu.

7.2. Calibrate frequency range

Once the frequency range is define, you can proceed the calibration process.

Click the menu button (or touch the screen center) to access the main menu.

Select the **CAL** entry for calibration, this shows the calibration sub-menu.

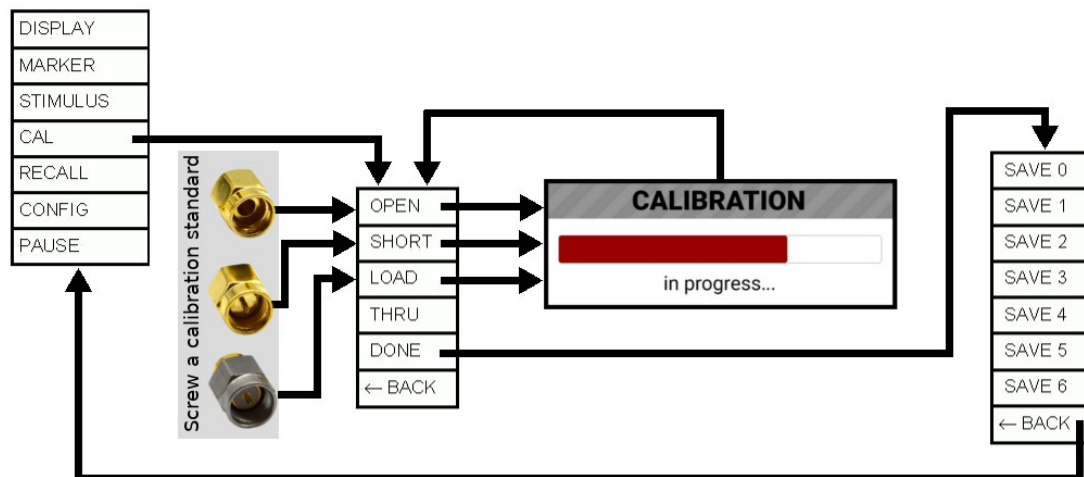


Fig 20: Calibration process

Screw a calibration standard on the nanoVNA (EG: open-loop calibration) then **select the corresponding menu entry** (EG: OPEN). A calibration message will appears will proceeding measurements over the current frequency range.

Execute the steps for the three calibration standard (Open-loop, short and load). Once finished, press the **DONE**. This shows the six save slot (that can be recall when appropriate).

Press “Back” to return to the menu without permanent backup of the calibration data (calibration data is lost when the NanoVNA is turn off).

Remark: slot 0 is usually reserved for full frequency range of the NanoVNA (50 KHz to 3 GHz). Slot 0 should already contains the full range calibration (initialised by the manufacturer).

7.3.Connector adapter

When using connector adapter to connect the DUT (or antenna) then calibration must be conduct with the adapter screwed on the NanoVNA!

As a consequence, a “Calibration Set” must also be available for the adapter to proceed the calibration.

In the figure 21, the SMA Male connector (NanoVNA) to N Male connector (Radio Antenna), implies that we must have a N Male Calibration set.



Fig 21: SMA to N connector

8.Measurements

This section focus all the information around the measurements for antenna.

8.1.Calibrated or not?

Never use a NanoVNA without calibration data!

Follows the steps describes at “7 Calibration” to calibrate the NanoVNA for the wanted frequency range.

It is quite easy to check if the current measurement is done with calibration correction. The bottom of screen shows various statuses. **A “C” is visible in the statuses when the calibration data are available.**



Fig 22: NanoVNA statuses

The label "C*" indicates a successful calibration (not stored in a slot).

The label "C6" indicates a reloaded/stored calibration (in slot 6).

8.2.Curve selection

NanoVNA shows lot of curves on the screen it is too much for getting a clear view.

Here how to select the curves to display/hide.

Click the menu button (or touch the screen center) to access the main menu.

Select the **DISPLAY** entry then TRACE for the sub-menu. This show the list of traces.

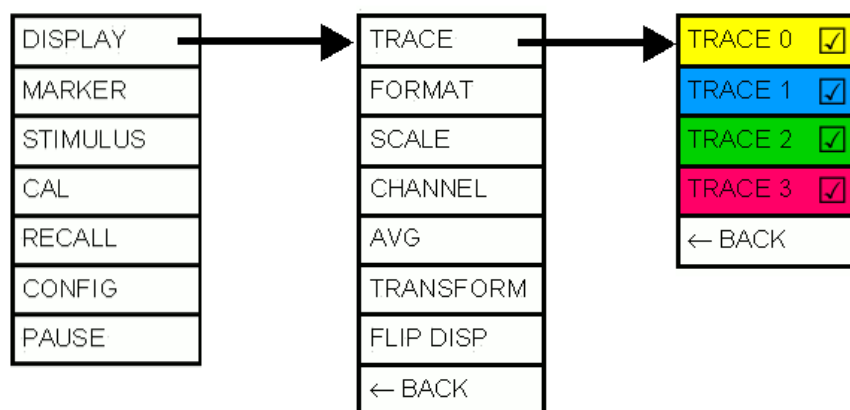


Fig 23: Trace selection

Click twice a trace to toggle checkbox. Only the selected traces are visible on the NanoVNA.

Click once a trace select it as the active trace (the letter A is displayed in the checkbox). Activate a trace is useful to modify its format, scale or to move cursor along the trace.

Traces are identified by color:

- Yellow:** S11 LOGMAG. Show the attenuation of the returned power to the emitter (port 1). The value is shown in dB.
- Green:** display the input impedance (port 1) on a Smith Diagram.

•**Blue:** S21 LOGMAG. Used with RF Network DUT. This show the power transmitted to the receiver (port 2).

•**Red:** S21 Phase. Used with RF Network DUT. Display the phase shift (in degrees) on the receiver (port 2)

With antenna design, the most useful trace is the **yellow** showing the **LOGMAG**. (attenuation of the power reflected to the emitter).

8.3.LOGMAG - Emit frequencies

When checking an unknown antenna, the S11 LOGMAX (yellow trace) over the full range frequency range will help in locating the ideal emit frequencies of the antenna.

Usually, an antenna can work for a fundamental frequency and its multiples resonating frequencies.

Ensure that the NanoVNA is calibrated for the whole frequency range!

Select the S11 trace (yellow trace) via the menu **Display** → **Trace** → **Trace 0** (yellow).

S11 should be displayed in LOGMAG format (check S11 title). The trace can be reconfigured via the menu **Display** → **Format** → **LOGMAG**. This displays the magnitude onto a logarithmic axis.

This trace measure the attenuation of the reflected signal in dB.

•**Lower is the trace** and higher is the attenuation (meaning that lower is the signal reflected back toward the emitter).

•**Higher is the trace** and lower is the attenuation (meaning that higher is the signal reflected back toward the emitter).

The figure 24 show a quarter-length antenna ($\lambda/4$) calculated for 433 MHz frequency.

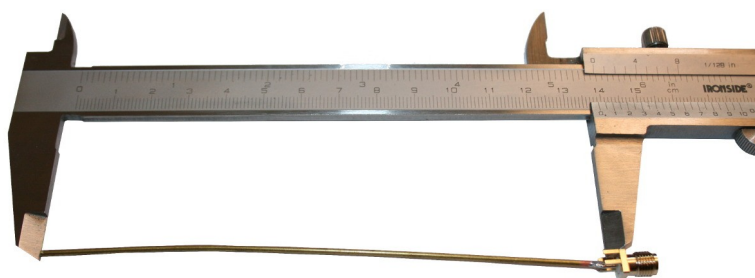


Fig 24: 433 MHz Quarter Length ($\lambda/4$) antenna

The S11 measurement shows the curve in the figure 25. It shows several falls in the curve. The first one is the most important below -20 dB.

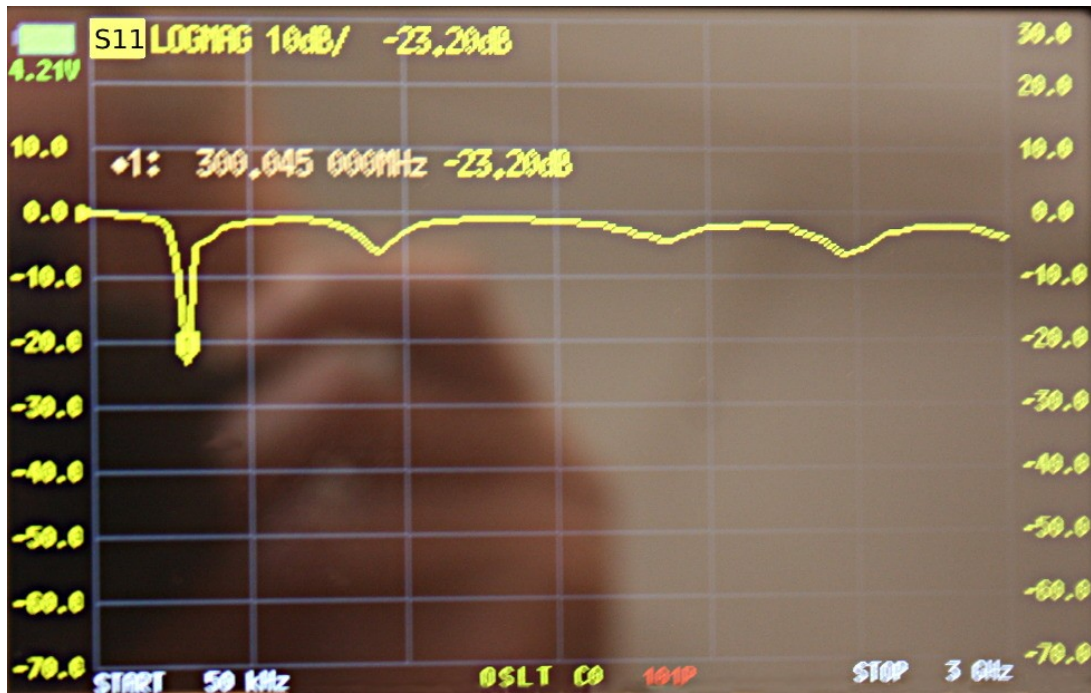


Fig 25: measurement of reflected signal

By using the cursor and moving it into the curve pit we can have an estimate of the emitting frequency. In this case, the frequency is **around** 300 MHz.

The word “around” is important in this case because the NanoVNA only makes 100 measurement over 3GHz. That means one measurement every 30 MHz (3000 MHz / 100).

To get a more precise measurement it will be necessary to reduce the frequency range around 300 MHz. Do not forget to calibrate the new frequency range!

Remark 1:

The calculation were made for a 433 MHz antenna but NanoVNA reveals a emitting frequency around 300 MHz. Previous chapters put into light some parameters that may influence antenna performance. The material and the element diameter are usually the main reasons for such difference between theoretical calculation and the practical reality.

Remark 2:

As the resonate frequency is at 300 Mhz this correspond to a longer antenna (theoretical calculation).

Say it another way: *“the antenna think it is longer”*.

So, the antenna can be shorten to raise its resonating frequency toward 433 MHz. Proceed a step by step shorten+measuring will allow to tune the antenna to the target frequency.

Remark 3:

Below -20 dB are great values meaning that most of the power is emitted to the air.

Remark 4:

LOGMAG chart is really great to identify resonant frequencies over a wide frequency range. Despite its advantage, it is better to switch to SWR chart on shorter frequency range.

8.4.SWR measurement

SWR (Standing Wave Ratio) were already presented in the chapter 2 with, as rule of thumb, a SWR below 1,5.

See chapter 2 for more details about SWR measurement.

Chapter 2: antenna parameters - Point 5: impedance matching - 5.2: Matching and SWR measurement.

The NanoVNA is able to transform the LOGMAX chart into SWR chart with some calculation.

Select the S11 LOGMAX curve (yellow) as active curve.

Then change the display **FORMAT** to **SWR**.

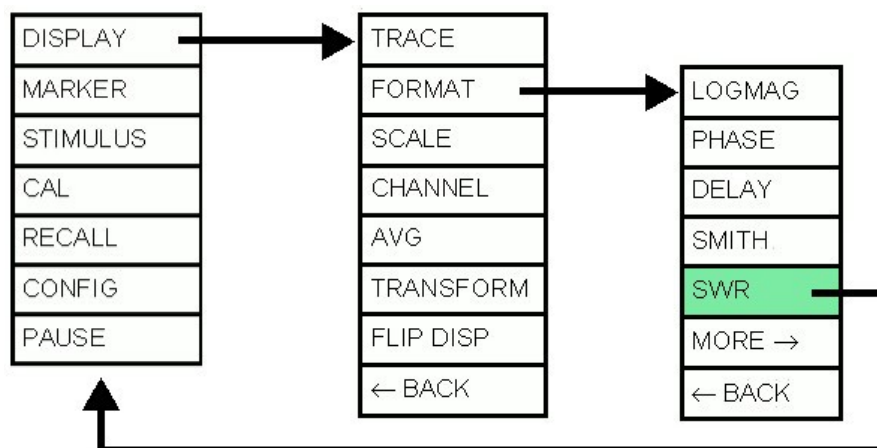


Fig 26: activate SWR format

The figure 27 show a SWR measurement from 380 MHz to 435 MHz.

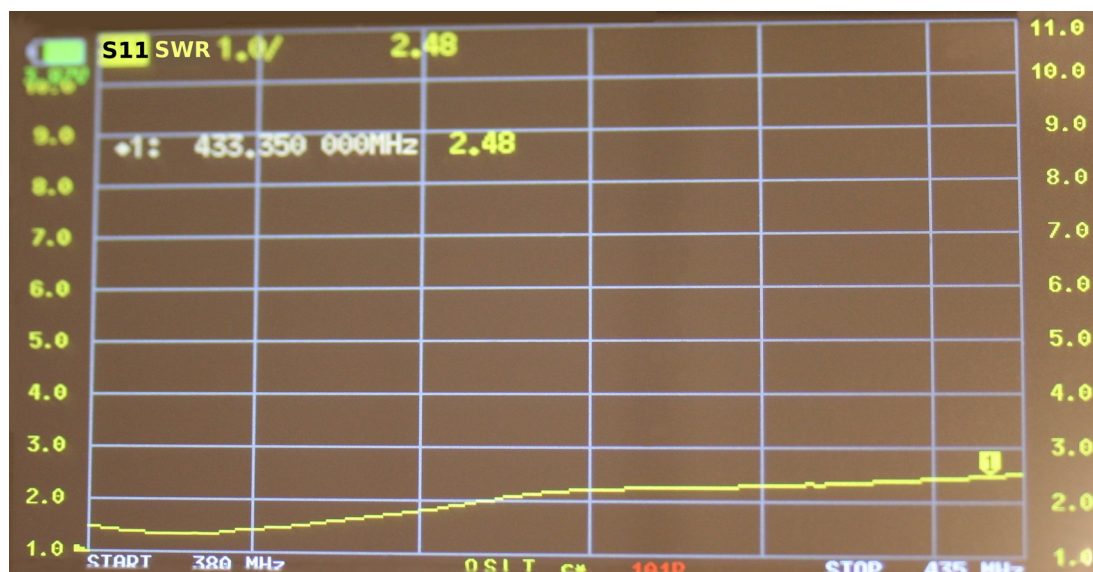


Fig 27: SWR measurement

The left side of the SWR falls under 1,5 on the left side of the curve (so around 380 MHz).

The cursor is visible on the right side of the curve. The cursor is positioned at the desired resonance frequency (433 MHz) where the measured SWR of 2,48 is really bad!

As with the LOGMAG curve, the antenna resonates at the lower frequency (currently 380 MHz) meaning that the antenna is acting like a longer one/

With other words, "the antenna thinks it is longer". So the antenna can be shortened to move the resonating frequency toward 433 MHz.