Microwave Update 2024

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Vector Network Analysis

Measurements for Amateur Radio Communications

Don Westacott VE6HQ
October 2024

I would like to thank Microwave Update conference organization for the opportunity to discuss with you the topic of **Vector Network Analysis**.

I am Don Westacott, VE6HQ. I have rejoined the amateur radio community after a nearly half century absence.
Its is truly great to be back.

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We should not be intimidated by the technical title a I would suggest we all have some type of RF network analysis technology in our amateur radio equipment inventory.

Certainly, for myself when I entered the amateur radio hobby in the 1960's, a RF network analyzer was one of the first measurement devices that I purchased. However, to be clear back in those times it was called an SWR bridge / meter.

As we all recognize, a lot of technology change has occurred in the last 50 years and I appreciate the opportunity to discuss moving from scalar to vector RF measurement technology.

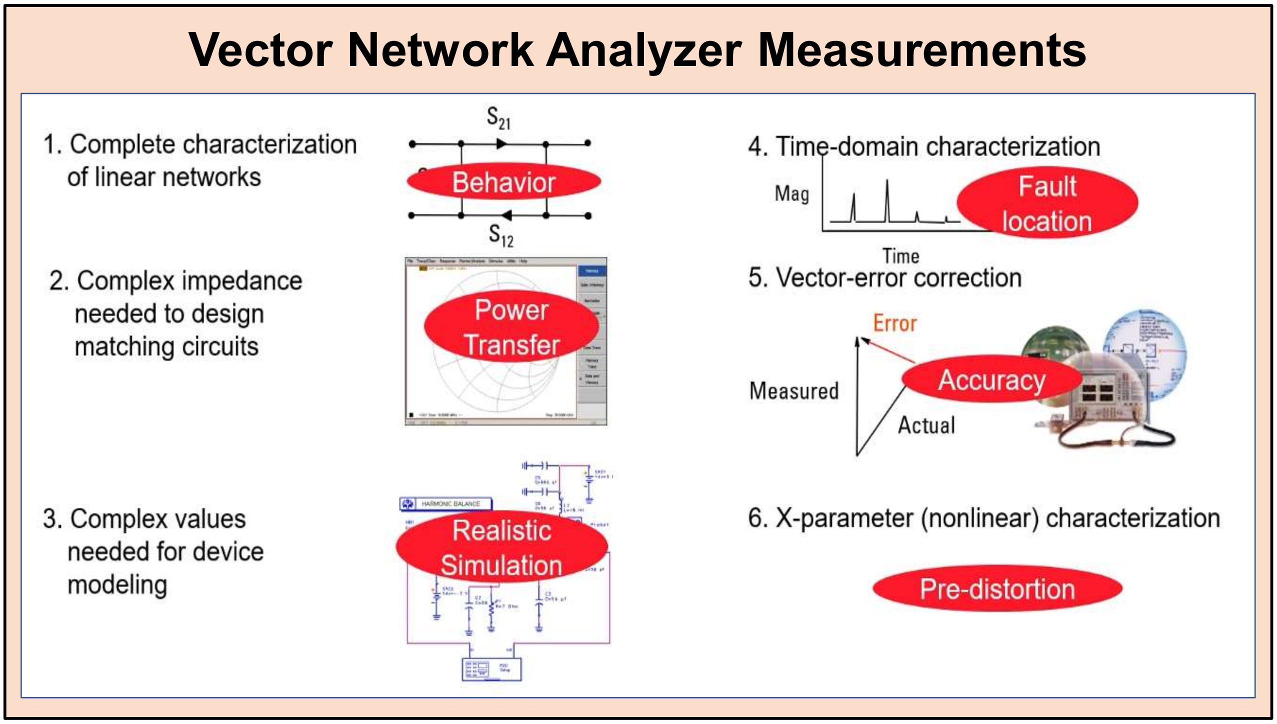
Vector Network Analyzer

A vector network analyzer (**VNA**) is a device used to measure the electrical properties of RF and microwave devices and networks. It does this by sending a signal down a transmission line and measuring the reflected and transmitted signals. The VNA then uses these measurements to calculate the S-parameters of the device or network.

The first VNA was invented around 1950 and was defined as an instrument that measures the network parameters of electrical networks.

The first network analyzer capable of swept amplitude and phase measurements was the Hewlett-Packard 8407 RF network analyzer, which was based on the HP 8405 vector voltmeter. The 8407 allowed comparison of the amplitude and phase of two waveforms up to 110 MHz.

In 1967, HP introduced the 8410 network analyzer, which extended swept capability to 12 GHz. This was a benchtop system based on multiple boxes that were integrated to perform the network analysis function



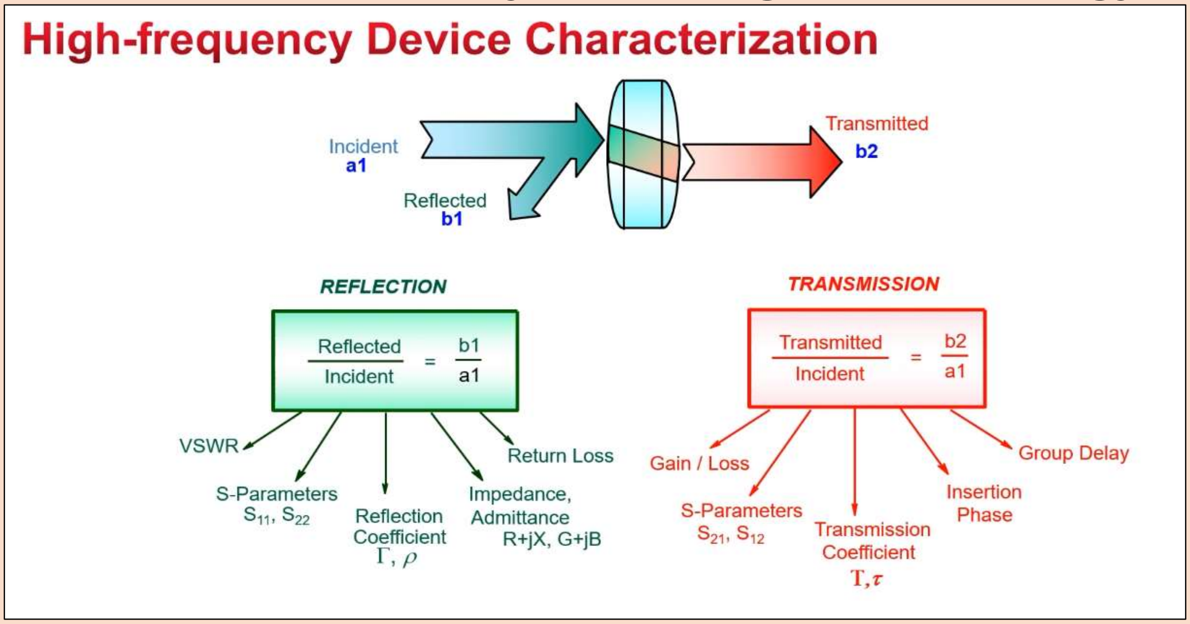
Occasionally a vector network analyzer is described as an antenna analyzer.

While it is correct that a VNA can perform critical measurements on an RF antenna systems,

it is also important to recognize that this technology maybe applied to a broad range of RF measurements including

RF filters, transmission lines, amplifiers, duplexers, couplers , mixers and much more.

Vector Network Analyzer Lightwave Analogy

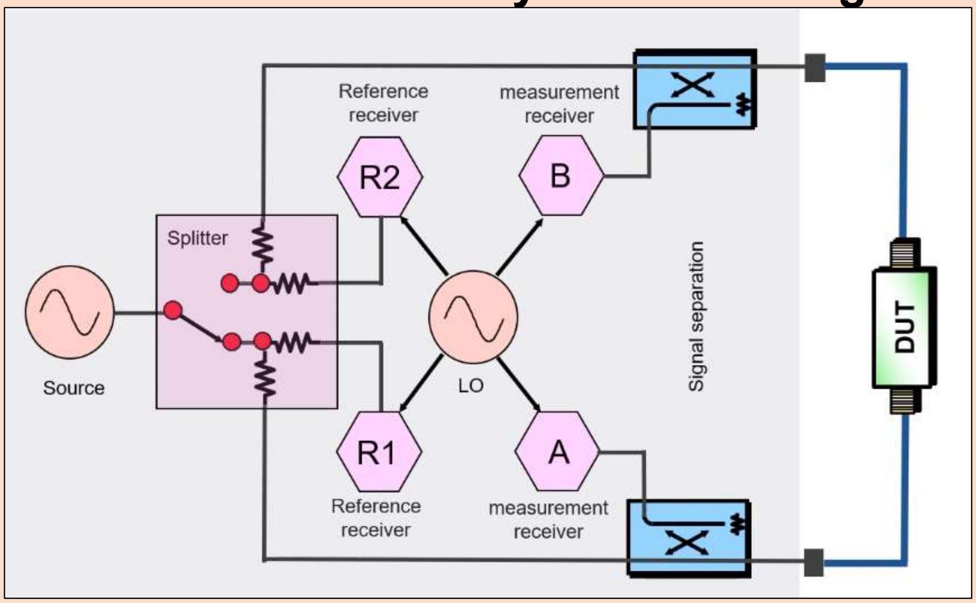


Fundamental principles of a VNA may be explained by using the analogy of a light wave incident upon a lens (the device under test).

Through measurements we gain knowledge of incident, reflected and transmitted energy.

This energy transfer is commonly characterized by the use of complex scattering values known as S parameters.

Vector Network Analyzer Block Diagram



This illustration depicts a generalized block diagram of a vector network analyzer.

A radio frequency source is directed to the device under test (DUT) using a directional bridge coupler such both incident and reflected wave properties may be measured. A switchable signal splitter is used to route the rf signal source alternatively between input and output ports of the device under test.

Historically this VNA technology was both complex and expensive and thus not available to the vast majority of amateur radio operators.

NanoVNA H

0.5 MHz - 1.5 GHz

2.8" TOUCHSCREEN

NanoVNA H4

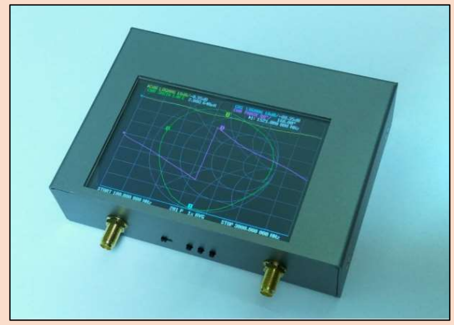
0.5 MHz - 1.5 GHz

4" TOUCHSCREEN

NanoVNA SAA2N

0.5 KHz - 3.0 GHz

4" TOUCHSCREEN



NanoVNA V2 Plus4

0.5 KHz - 4.0 GHz

4" TOUCHSCREEN

NanoVNA F V2

50 kHz – 3 GHz

4" TOUCHSCREEN

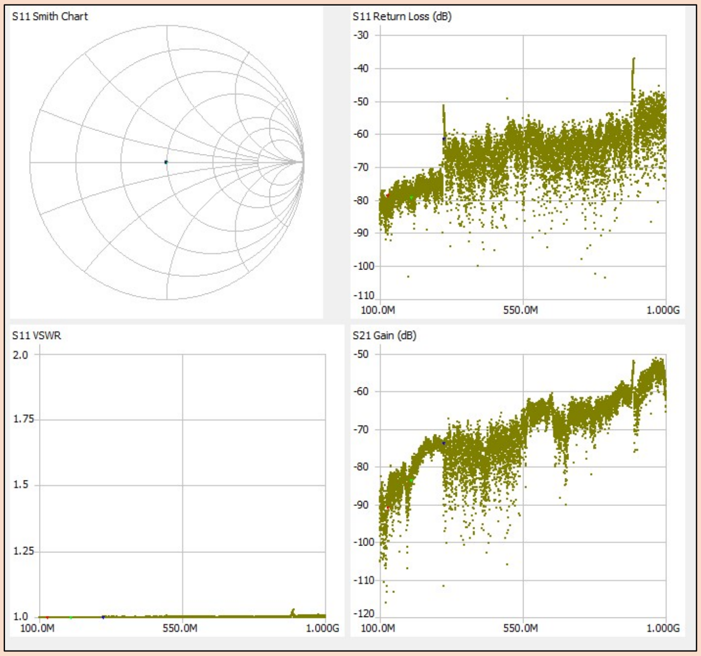
A step change when the NanoVNA was introduced in 2019 and has gained a wide acceptance in the amateur radio community.

I acknowledge that a wealth of information and technical publications currently exist for tis device further supporting the utility of this instrument within our community.

I purchased the NanoVNA model H, a very early model, when I reentered amateur radio in late 2020.

I was a bit skeptical that this $ 50 dollar device would be of any real value.

Let me present some information that I have learned about this technology and its applications.



Accuracy

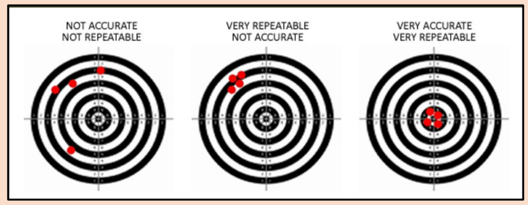
designates how close a measured value is to the **true quantity** of what is being measured.

Resolution

is the **smallest increment** the system can display or measure.

Repeatability

describes how well a system or device can **reproduce an outcome.**



Example NanoVNA H 50 ohm load

When conducting any scientific experiment or making technical measurements the terms Accuracy, Resolution and Repeatability are important factors to consider.

Also we must consider additional factors including:

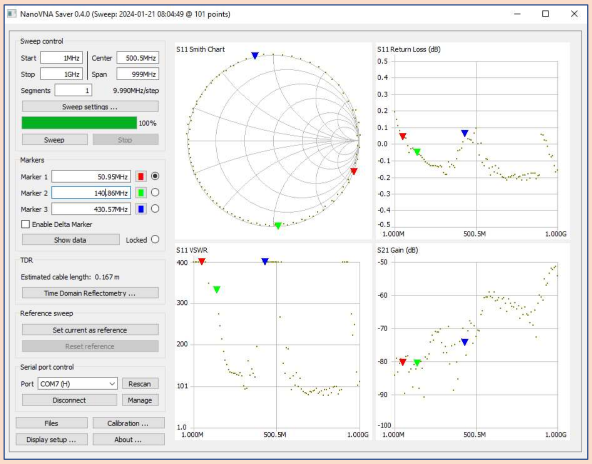
economic costs

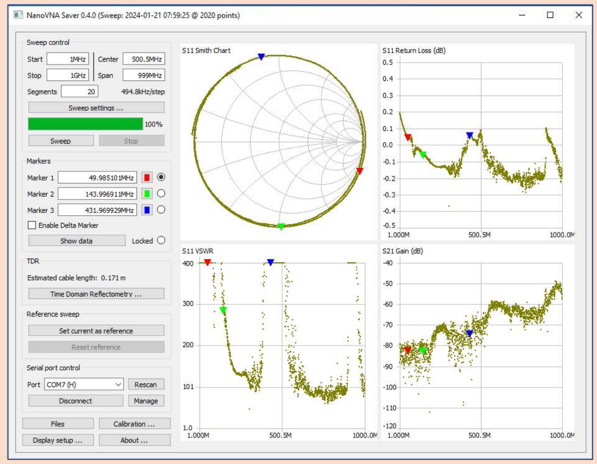
test measurement equipment utilization

and obsolescence.

In short, I was faced with the challenge of making effective test measurements while limiting investment in a large range of expensive test equipment.

NanoVNA Saver Software



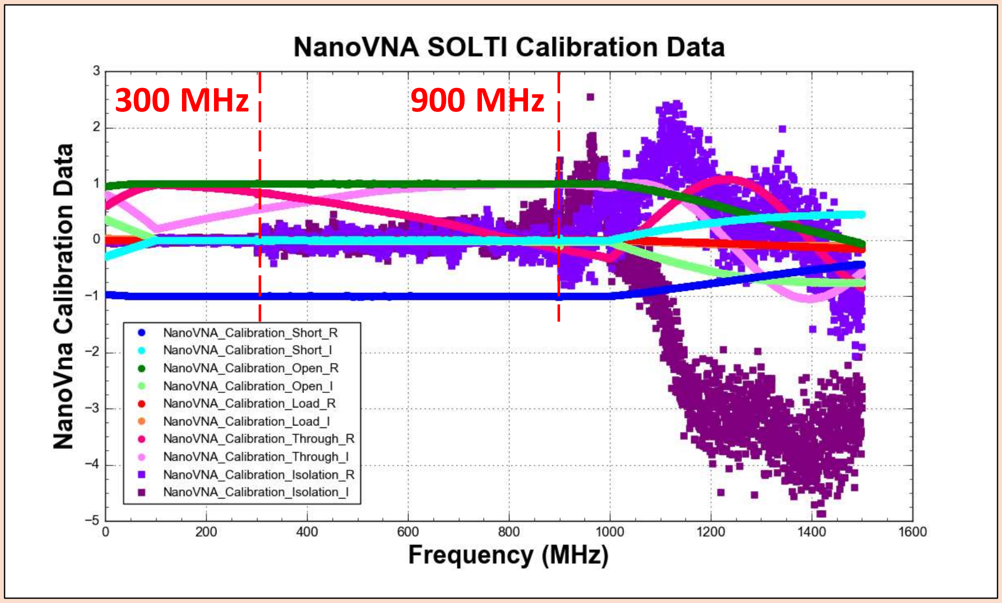


1 MHz – 1000 MHz, 1 Segment **1 MHz – 1000 MHz, 20 Segments**

It is important to recognize that the NanoVNA model H is limited to 101 discrete frequency values within the principle sweep frequency segment. This applies to both calibration and measurement functions.

Software may be applied to enhance frequency resolution by segmenting the entire sweep frequency range into multiple segments and thus significantly improving frequency and calibration resolution.

NanoVNA Calibration Data SOLTI

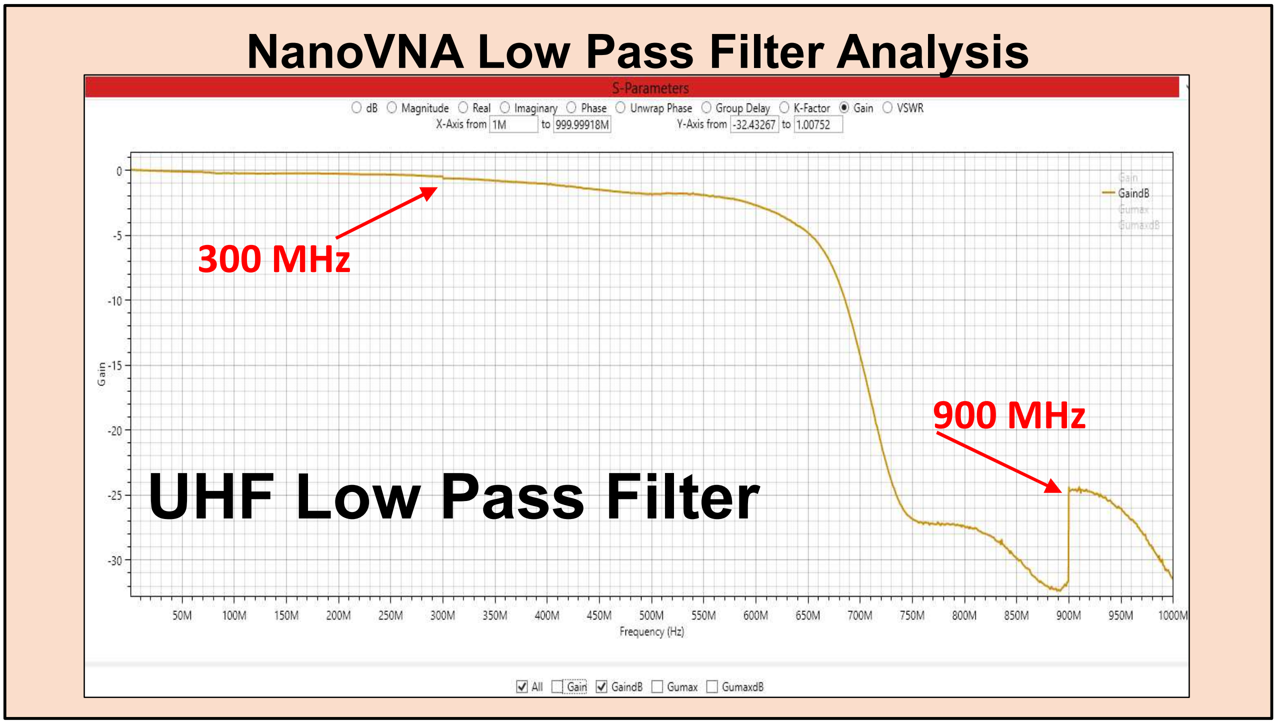


Short, Open, Load, Through, Isolation, R and I Data

Calibration of the VNA is accomplished using short, open, load, through and isolation measurements.

This calibration data example shows calibration values obtained through this procedure.

You may notice change of characteristic values at 300 Mhz and increased data value variation at 900 MHz and beyond.



A UHF low pass filter was tested using the 2 port setup for the NanoVNA.

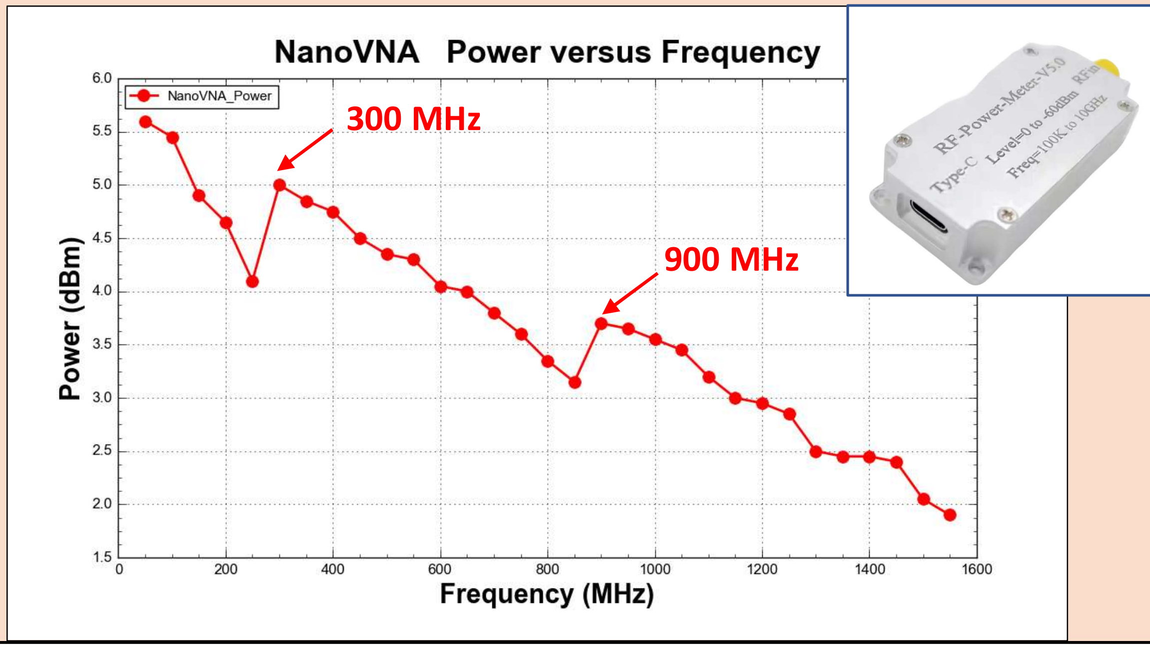
Attenuation versus frequency data is shown.

You may observe a small discontinuity at 300 MHz and a much larger discontinuity at 900 MHz.

It is important to acknowledge the NanoVNA signal source has a maximum fundamental frequency of 300 MHz

and utilizes odd order harmonics of the square wave signal for these higher frequency measurements.

NanoVNA RF Power Measurement



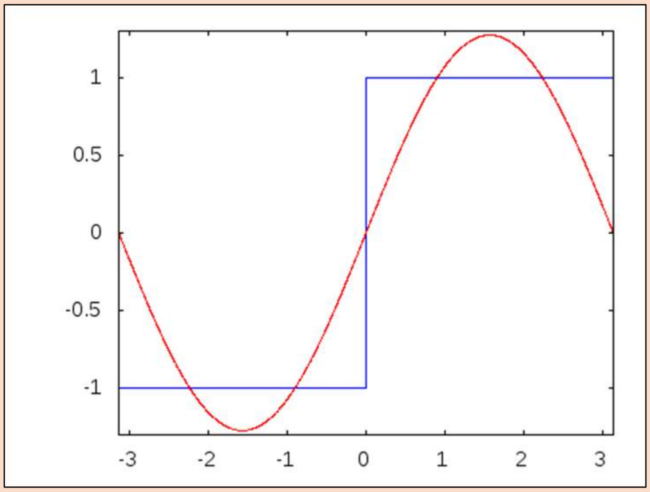
A calibrated digital power meter was used to measure the NanoVNA power level at discrete frequency from 50 MHz to 1500 MHZ. The NanoVNA was place in CW mode to conduct these measurements.

It was observed that a decrease of RF power of approximately 4 dB was observed over this frequency range.

In addition RF power events were observed at 300 MHz at 900 MHz corresponding to the 3rd and 5th order harmonic points of the 300 MHz fundamental signal.

While reviewing this data I came to the conclusion this information was misleading and not correct.

Square Wave Time and Frequency Analysis



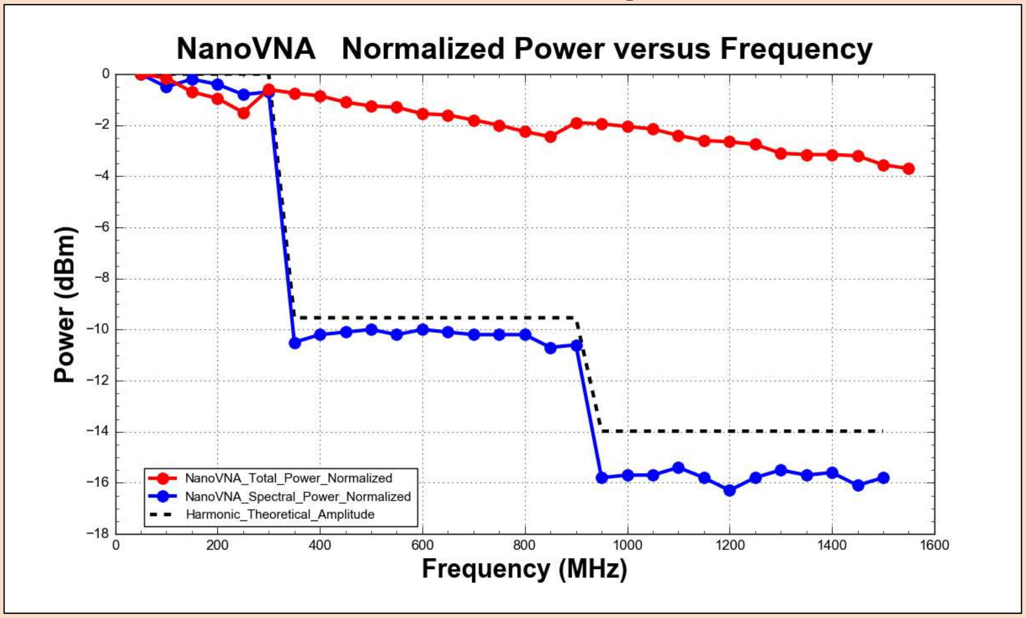
$$
\begin{aligned}
b_k &= 2\int_0^1 f(x)\sin 2\pi kx\,dx \\
&= 2\int_0^{1/2} \sin 2\pi kx\,dx - 2\int_{1/2}^{1} \sin 2\pi kx\,dx \\
&= 2\left[-\frac{\cos 2\pi kx}{2\pi k}\Bigg|_{x=0}^{x=\frac{1}{2}} + \frac{\cos 2\pi kx}{2\pi k}\Bigg|_{x=\frac{1}{2}}^{x=1}\right] \\
&= 2\left[-\frac{\cos \pi k}{2\pi k} + \frac{1}{2\pi k} + \frac{\cos 2\pi k}{2\pi k} - \frac{\cos \pi k}{2\pi k}\right] \\
&= \frac{2}{\pi k}\left(\sin^2\frac{\pi k}{2} - \frac{1}{2}\cos \pi k + \frac{1}{2}\cos 2\pi k\right) \\
&= \begin{cases} \frac{4}{\pi k} & \text{if } k \text{ is odd} \\ 0 & \text{if } k \text{ is even,} \end{cases}
\end{aligned}
$$

Square Wave is composed of a series sinusoid's of **odd ordered harmonics**, (1, 3, 5, 7,…….)

I recognized that the NanoVNA produced a square wave signal and utilizes odd order harmonics to acquire measurements beyond the principle or fundamental frequency range of zero to 300 MHz of the instrument.

Fourier, through his famous transforms, has taught us the expected amplitudes of these harmonic signals, thus let's reexamine the RF power measurement.

NanoVNA Total and Spectral Power

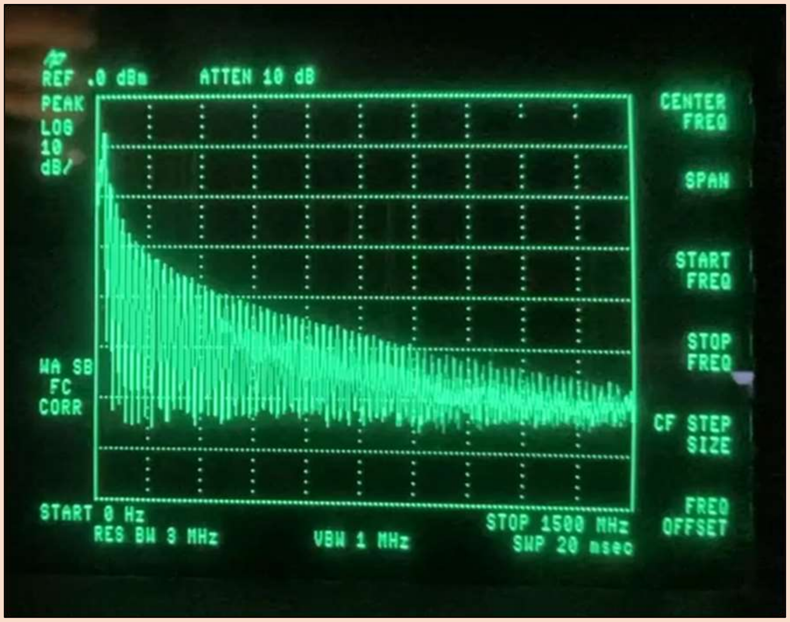


I again conducted the RF power measurements, however spectral analysis methods where applied to measure RF power levels at specific frequency values as shown by the blue coded data values.

This data shows some 16 decibel reduction of power for frequencies greater than 900 MHz compared to the sub 300 MHz values.

This reduction in signal level at elevated frequencies places some limitations on measurement accuracy principally due to reduction of signal to noise values.

NanoVNA Frequency Sweep 1 MHz – 1500 MHz



Note

frequency repetition

when

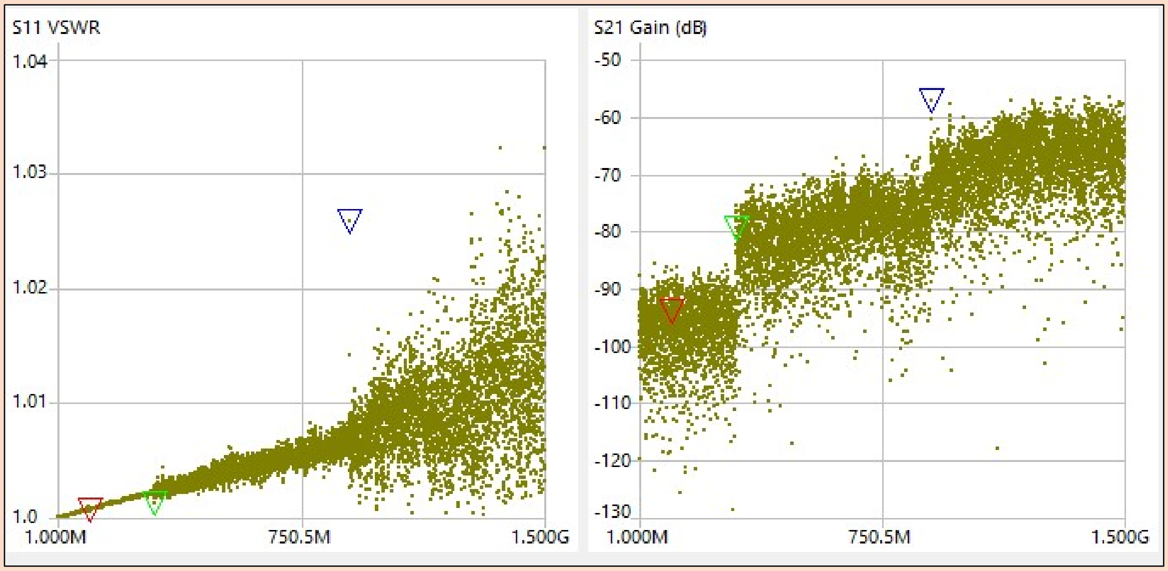
Frequency = 300 MHz.

To illustrate the sweep frequency and square wave harmonic data of NanoVNA a video recording of RF spectral data using an HP spectrum analyzer was conducted.

The frequency transition from 300 MHZ from fundamental to odd order harmonics maybe observed.

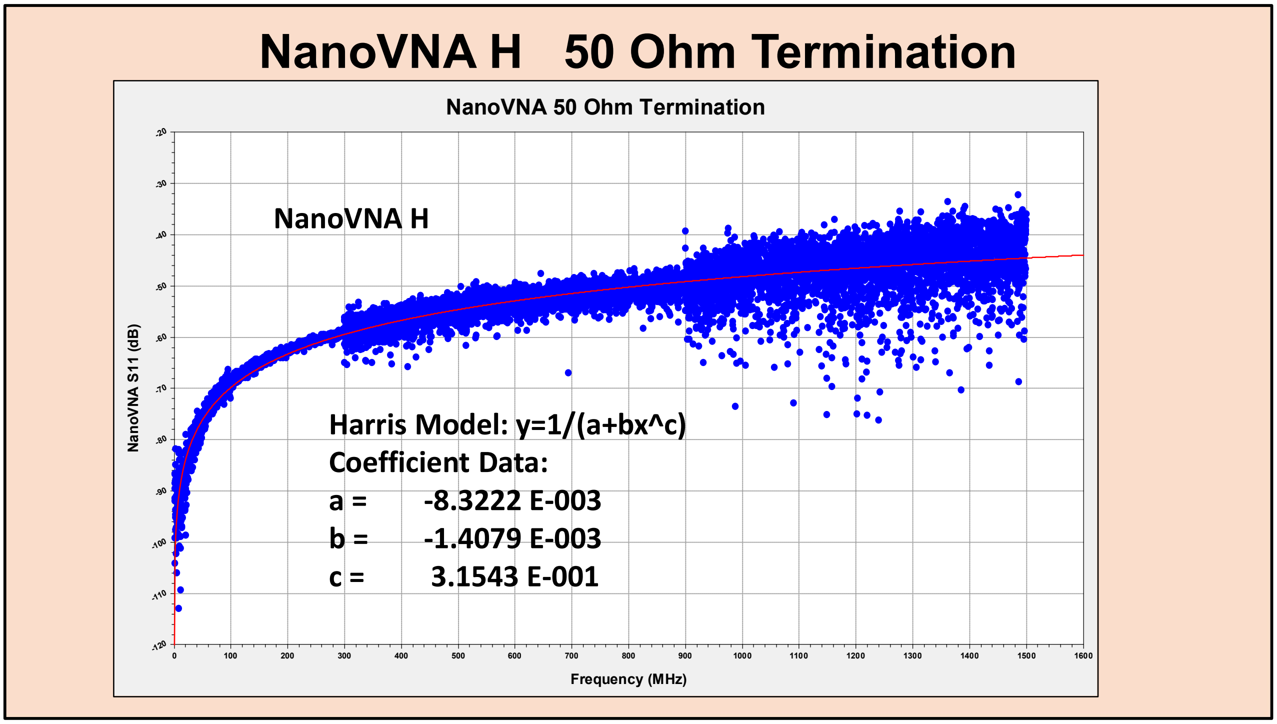
It is important to recognize that additional RF components are present beyond simply fundamental and odd order harmonics. Without going into specific details, we will call simply call these unwanted signals Noise.

NanoVNA H   50 Ohm Termination



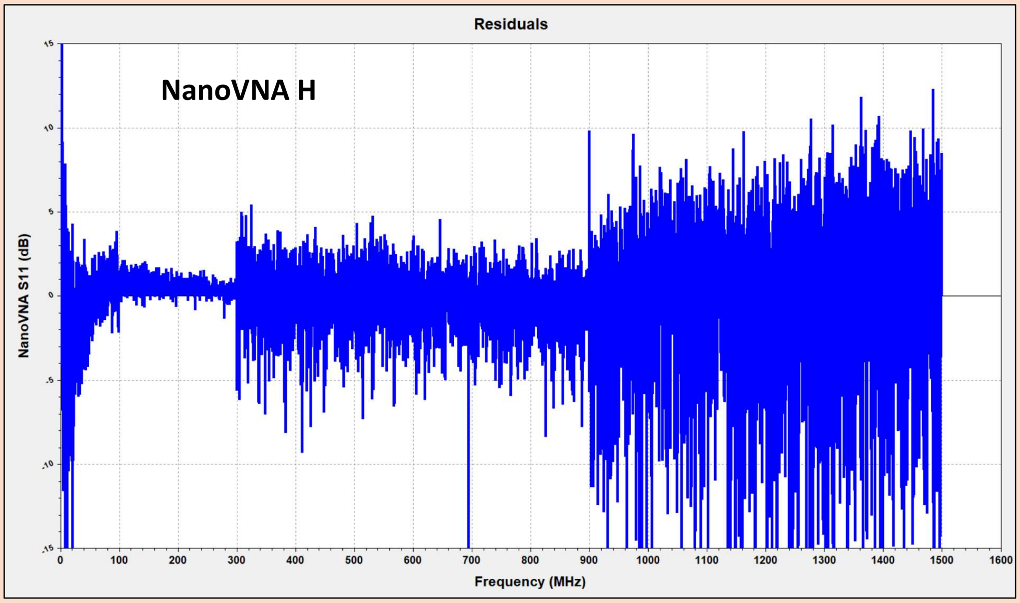
Indication of this instrument signal and noise data may be examined using a 50 ohm termination over the sweep frequency range 1 to 1500 MHz.

Once again the 300 and 900 MHz harmonic points are clearly evident.



I began a mathematical and somewhat statistical analysis of this data.

NanoVNA H   50 Ohm Termination



However after a short period of time decided an alternate approach was required to determine accuracy, repeatability and resolution values for the NanoVNA instrumentation.

Benchmark Comparison

Anristu SiteMaster S331L

2 MHz – 4 GHz

$ 8500 introduced 2012

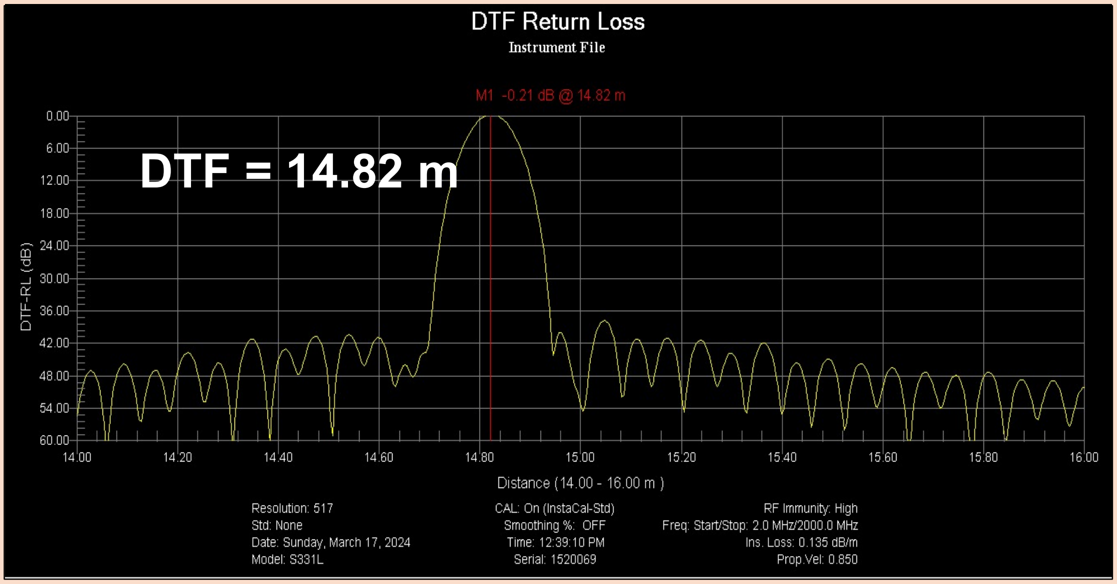
NanoVNA H

50 KHz - 1.5 GHz

$ 75 introduced 2019

A Sitemaster S331L VNA was available and used to conduct benchmark comparison tests with the NanoVNA model H.

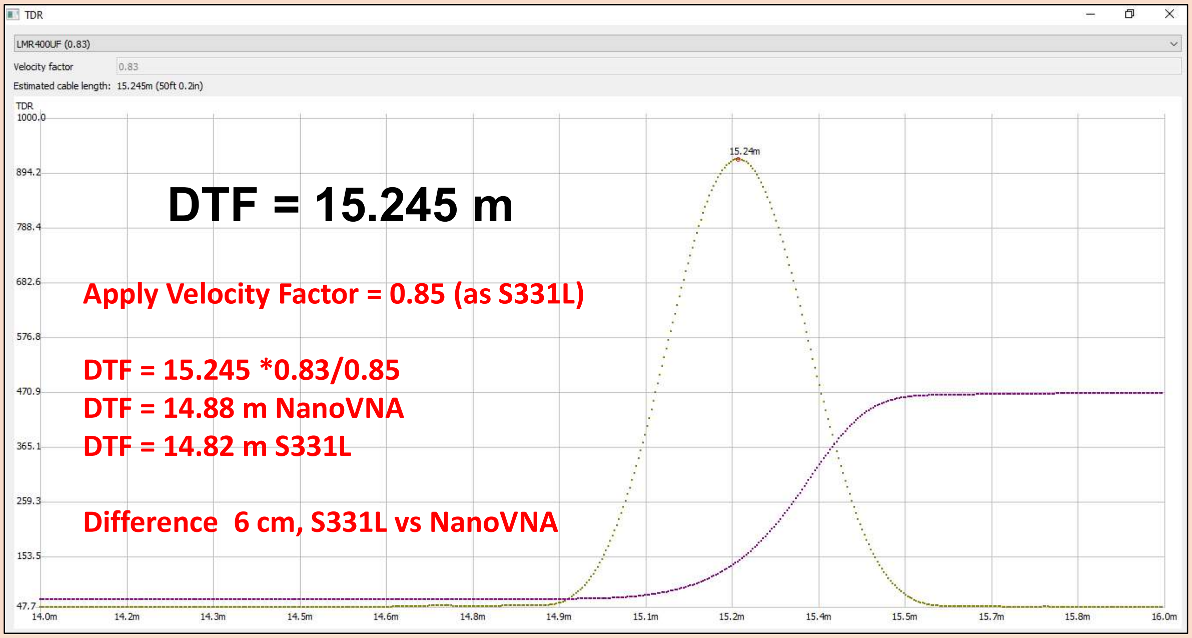
It was noted that the ***"As New"*** purchase price difference is a factor of 100 between these instruments.



SiteMaster S331L LMR 400 15 m (50 ft) Shorted

A distance to fault test was conducted using 15 meters of LMR-400 coaxial cable terminated in a short zero impedance

The S331L returned a distance value of 14.82 m.



NanoVNA_H LMR 400 15 m (50 ft) Shorted

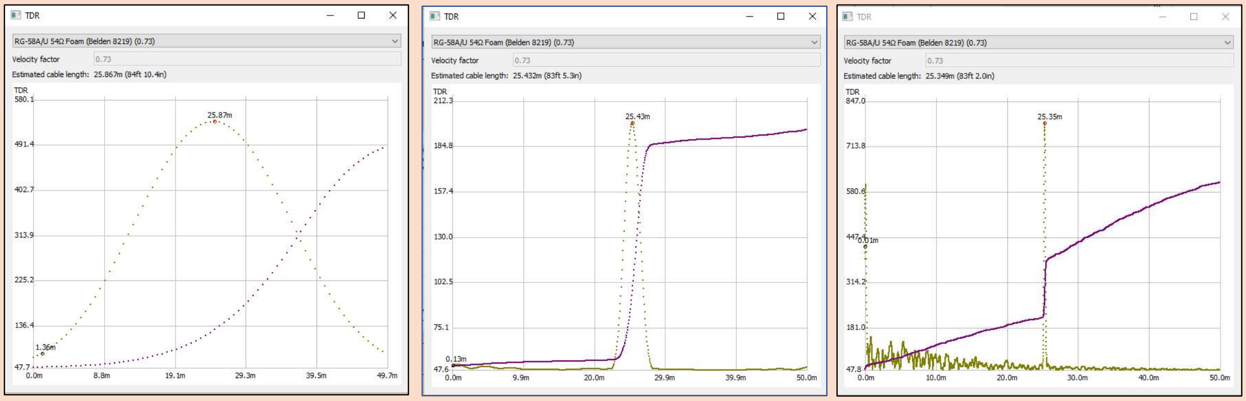
The same LMR400 shorted cable test was conducted on the NanoVNA.

After correction of incorrect cable velocity entered during this second test (operator error) a difference of 6 cm was noted.

The LMR400 was connected directly to the S331L N connector However the NanoVNA utilized a 2.5 inch SMA to N jumper cable for mechanical reasons.

Thus results are essentially identical and also illustrate the importance to understand reference plain calibration of VNA instrumentation.

Fourier Transform and Spatial Resolution



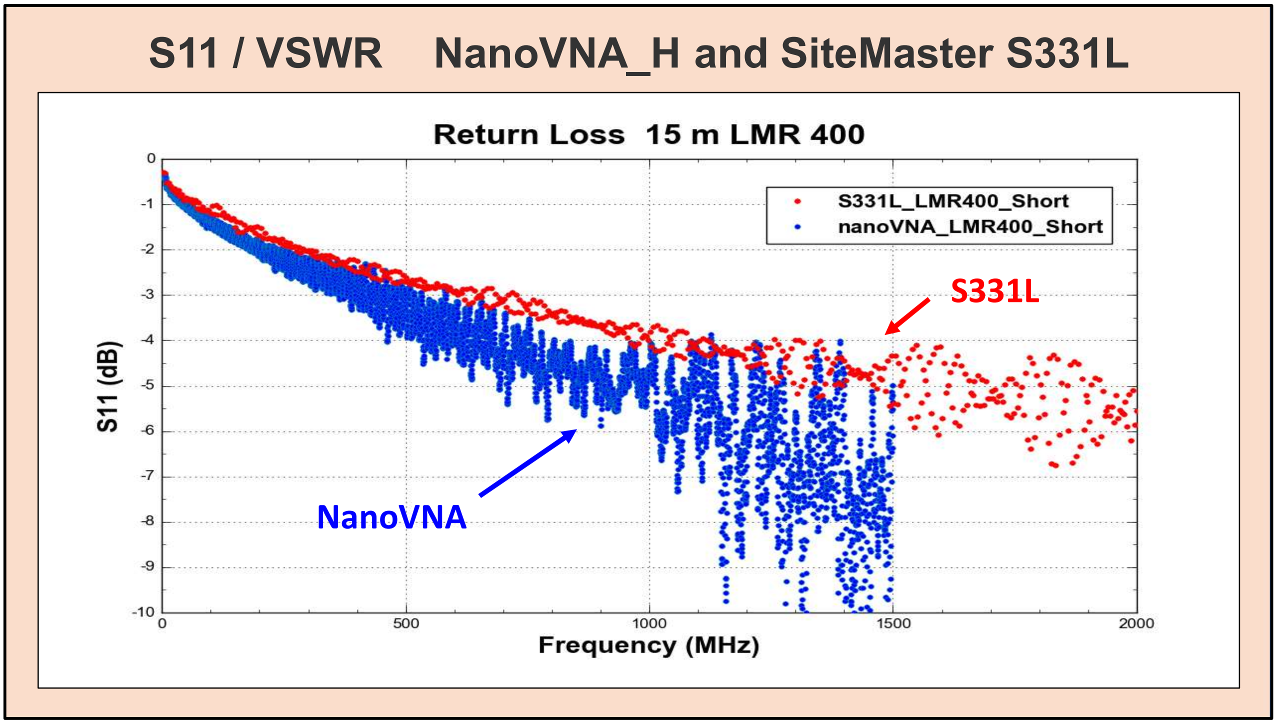
0.1 – 10 MHz **0.1 – 100 MHz** **0.1 – 1000 MHz**

NanoVNA data

Most VNA technology utilizes frequency domain reflectometry and frequency inversion using the inverse discrete fast Fourier transform to yield time and ultimately distance data.

Fourier methods are of particular interest to me and yield great insight to frequency and time spatial resolution interdependencies.

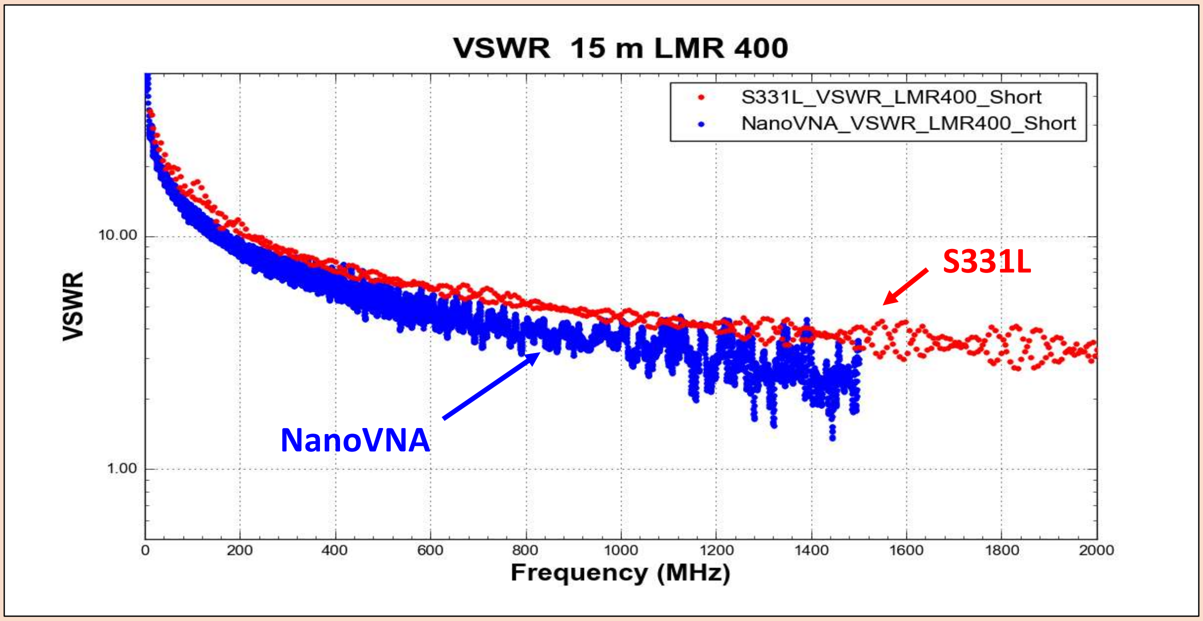
This single slide may invoke an extensive discussion of Fourier methods and signal processing and thus for the sake of time and brevity I will simply move ahead.



We may examine the S11 return loss that was measured for both instruments.

Large difference was noted particularly above 1 GHz should be noted.

S11 / VSWR   NanoVNA_H and SiteMaster S331L



We may convert the S11 reflection data to possibly a more common reference that being VSWR.

I would caution any perception that the variation between instrumentation has apparently decreased,

But rather suggest that the use of a semi log presentation of the data somewhat smooths the response to visual observation.

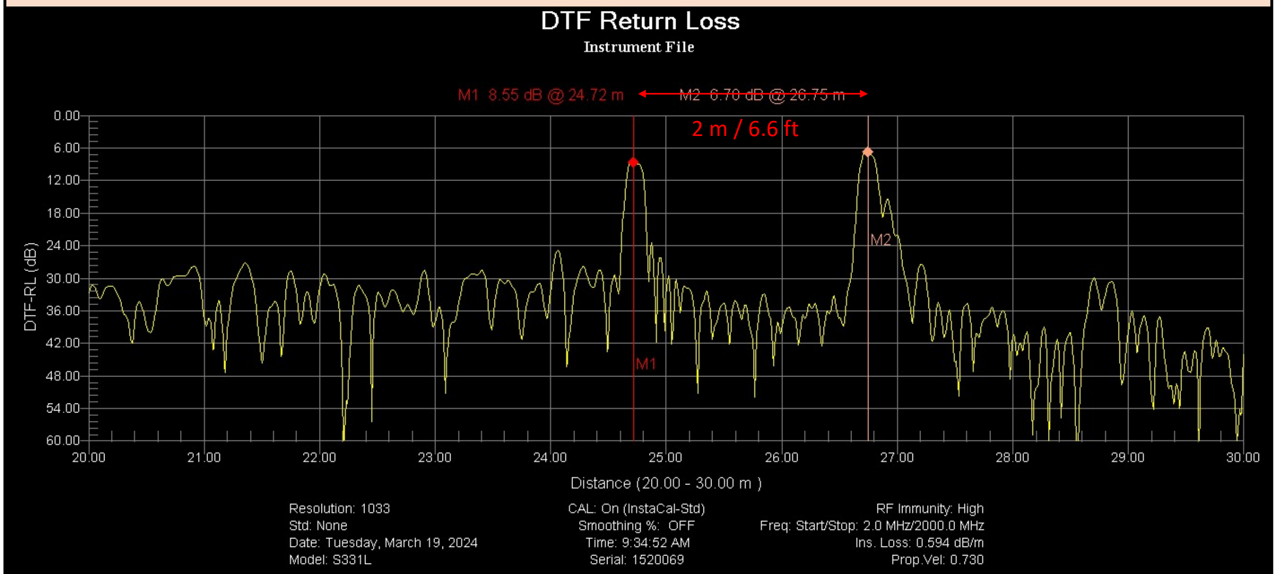
Benchmark Tests

Transmission Line Network

- **RG 58a/u Z= 50 ohm 75 feet**
- **RG 59u Z = 75 ohm 6 1/2 feet**
- **Load Z = 50 ohm**

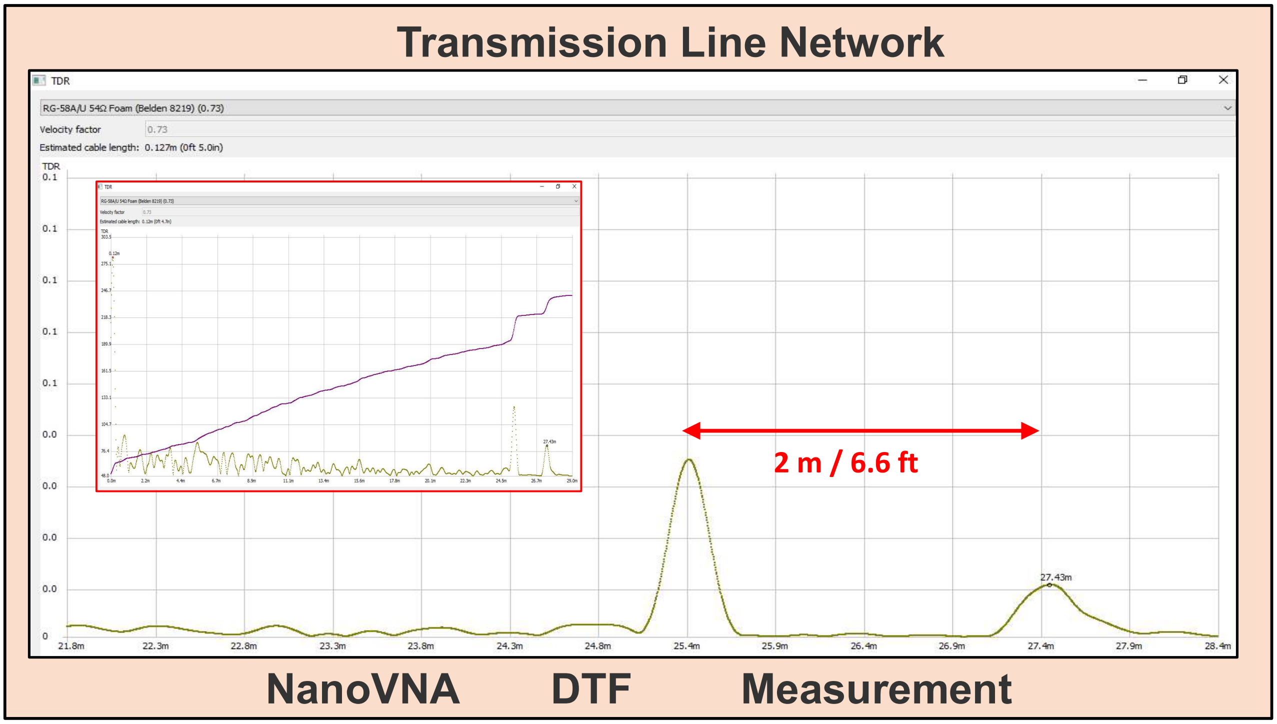
I constructed a slightly more complex RF network using 50 ohm and 75 ohm coaxial transmissions lines plus a 50 ohm load used for termination.

Transmission Line Network



SiteMaster S331L DTF Transmission Line Network

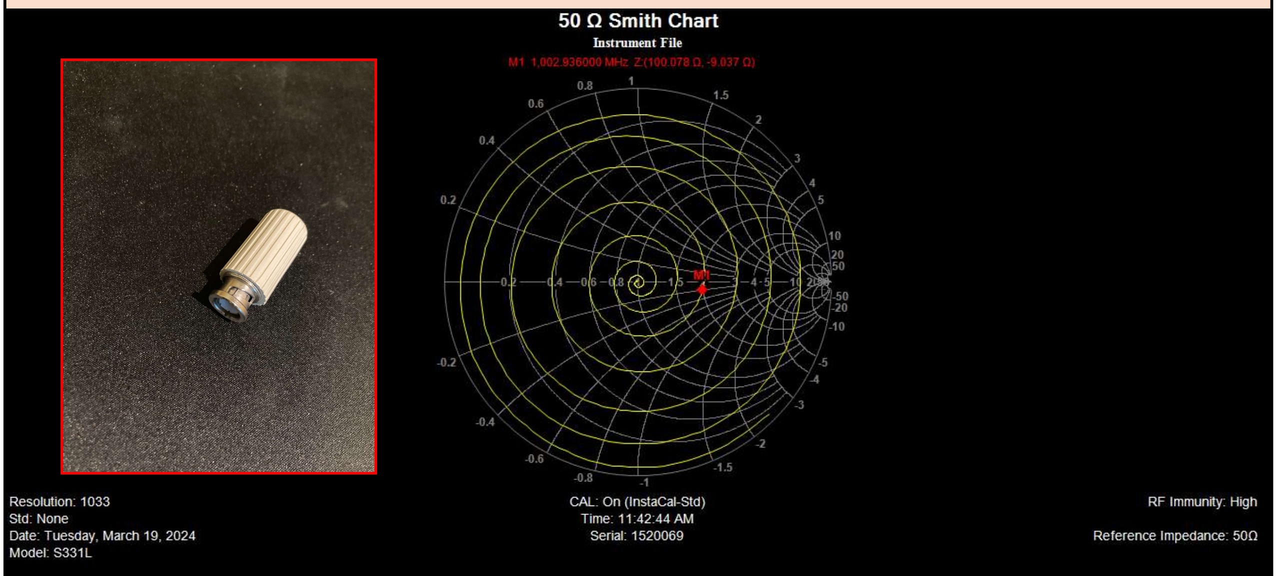
Once again the S331L was used to determine distance to fault through previously discussed frequency sweep and inversion technique.



The test was repeated using the NanoVNA and results show the same 6.6 feet between impedance discontinuities within the transmission line network.

However the spatial resolution is observed to be somewhat smoothed compared to the S331L data set.

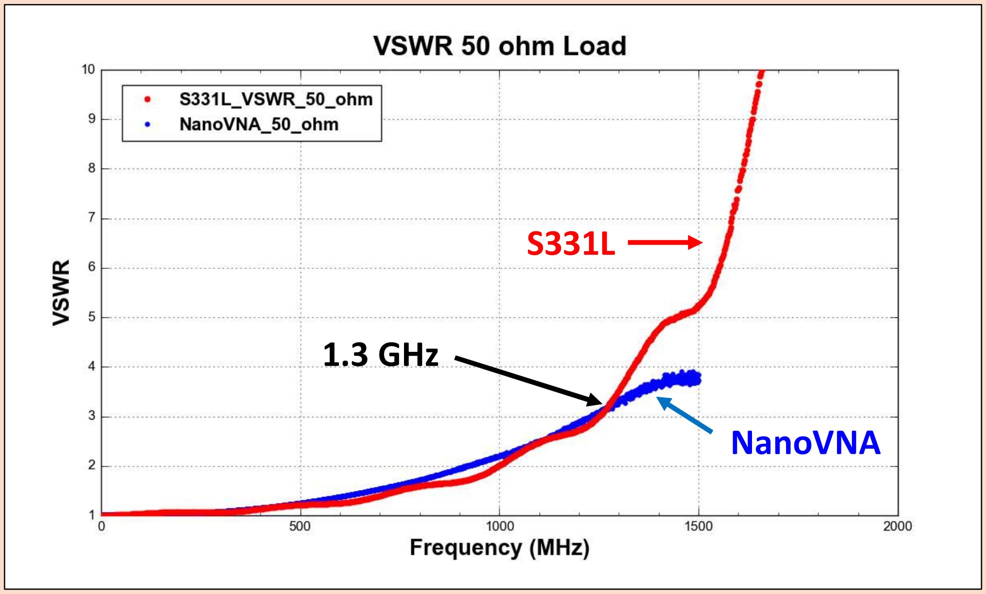
Differences in data processing techniques, number of data samples and sweep frequency range would largely account for differences in these results.



SiteMaster S331L Smith Chart **50 ohm Load**

A somewhat dated RF 50 ohm termination that was used on 10base2 networks was discovered in a storage bin.

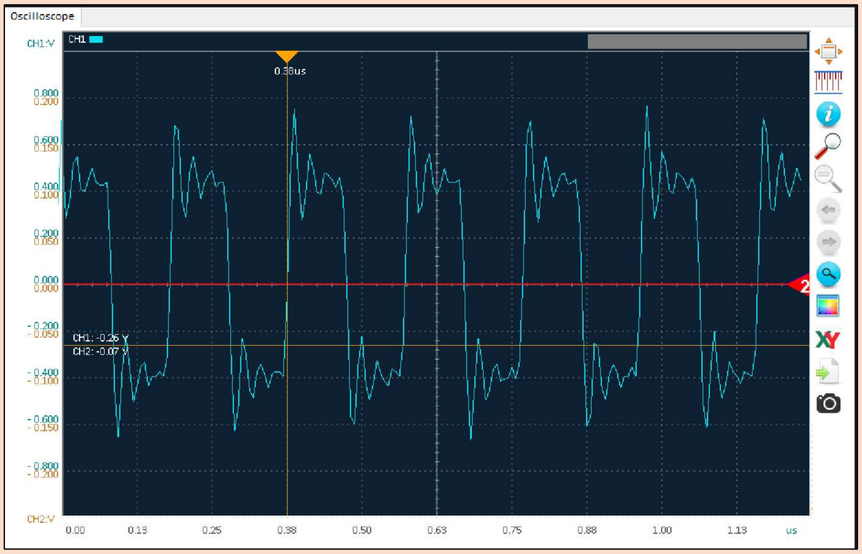
SiteMaster S331L and NanoVNA VSWR 50 ohm Load



Comparison of VSWR derived from S11 data shows reasonable agreement of the NanoVNA versus the S331L dataset.

Divergence of data occurs at approximately 1.3 GHz .

NanoVNA Frequency Analysis



NanoVNA 2 MHz Signal

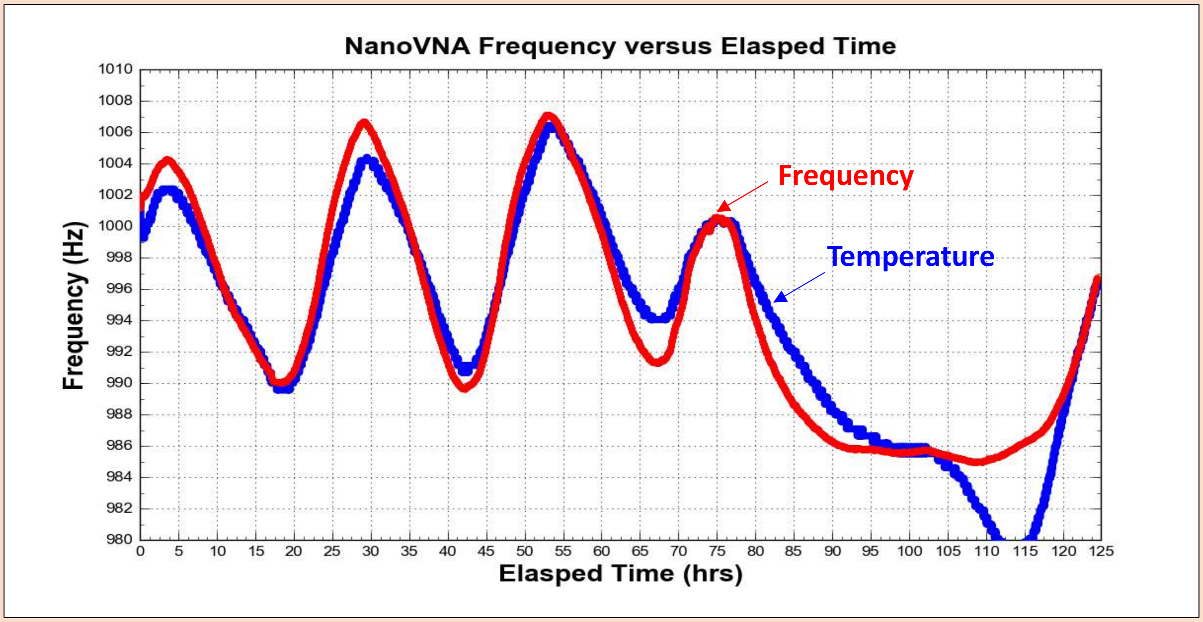
Frequency

Accuracy

Stability

I wanted to understand additional information regarding the NanoVNA Rf frequency source with respect to frequency accuracy and stability. This was motivated with the concept to use the device both as a VNA and also as a computer controlled RF signal generator.

NanoVNA Frequency Stability



The NanoVNA was placed in CW mode with a frequency of 432.2 MHz. Frequency data was obtained using the heterodyne technique and a GPSDO controlled SDR receiver.

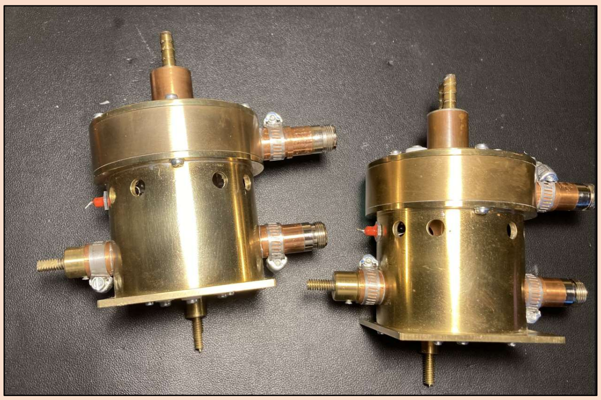
Data obtained over a 5 day interval shows frequency variation of approximately 20 Hz, or 0.05 ppm.

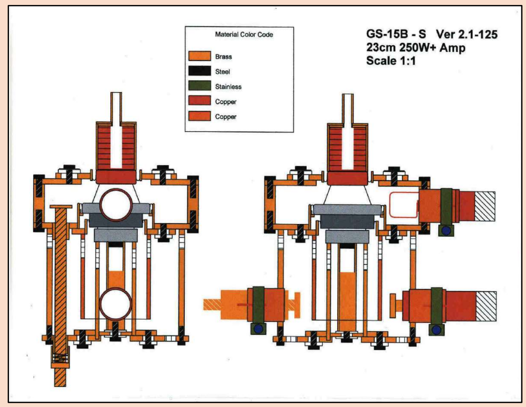
NanoVNA absolute accuracy Frequency error averaged 50 Hz (0.1 PPM).

Surprisingly I carried out this frequency experiment in a non-temperature controlled environment my workshop RF laboratory. Recorded temperature versus time data clearly indicates that improved frequency stability would be expected in a controlled setting.

23 cm Resonant Cavity Amplifier

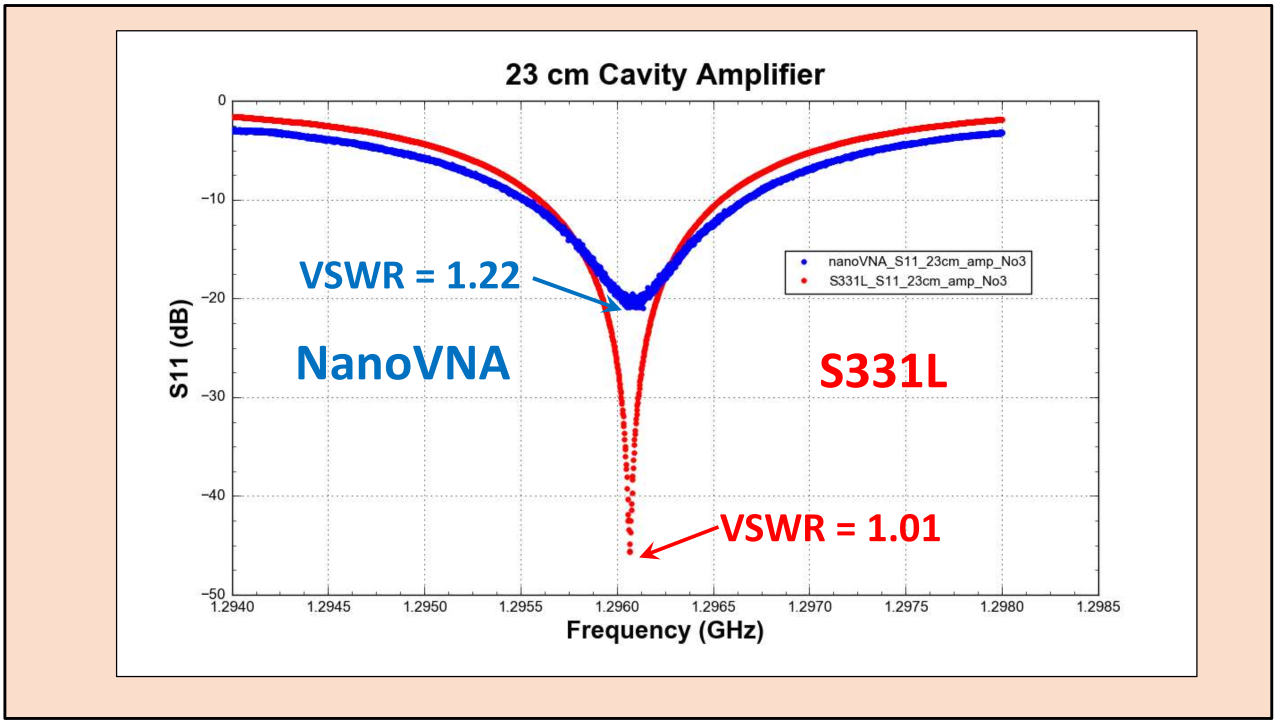
GS15B Grounded Screen 250W PA for 1296 MHz





A VNA may provide significant information for initial testing of RF amplifier input and output matching networks.

A fellow ham gifted these rather unique resonant cavity vacuum tube amplifiers.

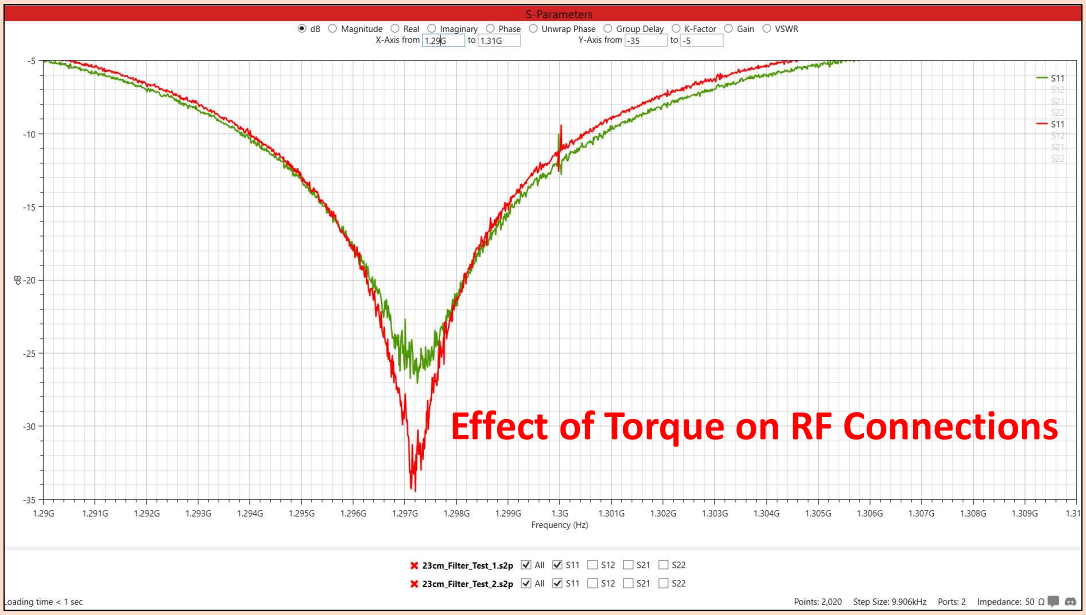


S11 data was obtained using the S331L and NanoVNA instrumentation.

Differences of results were noted, however it important to realize exact comparisons are difficult at elevated RF frequencies since additional and different connectors and cable lengths are required to attach each instrument to this resonant cavity amplifier.

For critical measurements calibration at a suitable and appropriate reference plane should be considered.

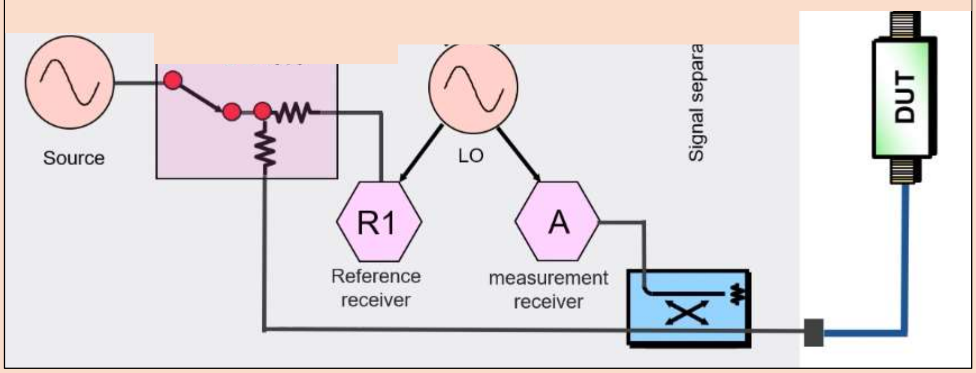
NanoVNA Mechanical / Electrical Effects



Mechanical & electrical effects are also important. This example shows changes in S11 data values between a “hand attached” and correctly torque wrench tightened SMA connection.

Vector Network Analyzer Block Diagram

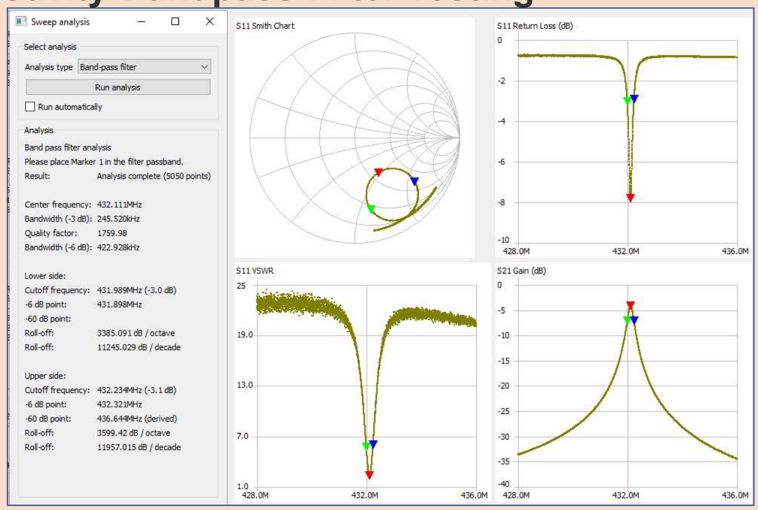
S331L Single Port VNA



I should not be overlooked that full functionality comparison between the S331L and NanoVNA is technically not possible.

Despite the significant increase in cost, the S331L is a single port VNA that limits it functionality to conduct DUT 2 port testing (i.e. DUT Gain / Attenuation measurements).

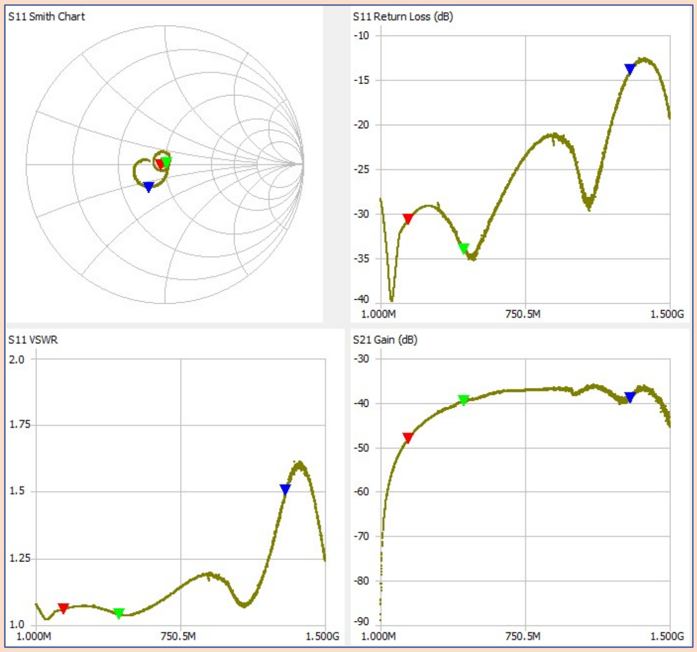
UHF Resonant Cavity Bandpass Filter Testing



Center Frequency	**421.111 MHz**
Bandwidth	**245.520 KHz**

In contrast the NanoVNA provides a second active port and as such the critical S21 gain data for more comprehensive 2 port network measurements.

An example shown here is the NanoVNA used to characterize a UHF resonant cavity filter device.



RF Coaxial Directional Coupler
400 - 470MHz
40dB 500 Watt

In addition, 2 port NanoVNA measurements may provide knowledge of directional coupler characteristics.

In this case, the 70cm rated directional coupler shows very reasonable characteristics within the 23cm amateur radio band.

Vector Network Analyzer

Recommendations and Conclusions

• **Facts**	Understand the application and limitations of technology.
• **Charge the Device**	Ensure your analyzer is fully charged for uninterrupted use.
• **Calibration**	Follow the manual for calibration.
• **Firmware Update**	Check for the latest firmware to improve functionality.
• **Interface Familiarity**	Get comfortable with the menu and functions.
• **Test Port Connection**	Securely connect the test cable to avoid errors.
• **Sample Testing**	Perform a test run with a known load to ensure it's working.
• **Environment Prep**	Set up in a space with minimal RF interference.
• **Reference Plane**	Understand the effects of cables and connectors to the DUT

Don has pursued a lifelong interest in science and engineering beginning as a youth in western Canada. He received his first amateur radio license at the age of 15 while attending high school in Edmonton, Alberta, Canada.

Don continued this interest and graduated from the University of Alberta receiving a Bachelor Science in Electrical Engineering. During the last 41 years he has worked in energy industry in Canada, the United States, Europe, South America, the Middle East and the Far East.

His technical area of interest lead to publications of nuclear magnetic resonance applied to reservoir characterization. He was granted numerous US patents for developments of pressure core technology. Don was honored to be the Distinguish Speaker at the Harvard University Energy Conference. During 2020, Don received the prestigious Hart Energy Innovators Award.

I obtained an amateur radio license in 1967 as VE6ANW, a year later achieved the advanced certification as VE6RI. I initially pursued 20-meter DX working. Soon after, I became interested in weak signal UHF propagation. After more than 50 years have passed, I have rejoined the amateur radio ranks and currently active on 20 meters and VHF / UHF bands.

About the Presenter