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The NanoVNA Vector Network Analyzer: This New Open-Source Electronic Test and Measurement Device Will Change Both Remote and In-Person Educational Delivery of Circuits, Electronics, Radio Frequency and Communication Laboratory Course Delivery

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Abstract:

Vector Network Analyzers (VNA) are a foundational electronic test and measurement tool for measuring impedance in networks versus frequency, gain and reflection versus frequency, and time domain impulse/step response of systems. Many universities have VNAs in their research laboratories. Few universities offer undergraduate courses that expose all students to VNA technology primarily due to the cost of the instrumentation which can run from $5k for a 1 GHz model and $250k+ for a millimeter-wave model. In the last two years, an open source nanoVNA was developed and introduced to the market with a $50 price for a 1.5 GHz VNA and $150 for a 3 GHz VNA. This breakthrough in cost/performance now allows all universities to use VNAs in their laboratories. Each student can have access to their own VNA laboratory experiment set since the cost is now similar to a textbook. Low-cost nanoVNAs enable student ownership in their home laboratories for remote delivery of radio frequency and microwave laboratory sessions.

This paper will compare and contrast the features and specifications of a full-feature VNA versus the low- cost nanoVNA by direct measurement comparison on the same devices under test. It will also demonstrate example laboratory experiments that were performed in in-person laboratories and in remote delivery laboratories. Finally, a summary of faculty and student feedback using the nano-VNA for radio frequency, microwave and communication system laboratories is given.

Introduction:

Eddy555[1] developed an open-source hardware and software platform in 2016 for low cost Vector Network Analyzers (VNA) labeled the nanoVNA[1]. The nanoVNA units have been brought to the commercial market at a price point ($35-$150) and performance point (10 kHz to 1.5 GHz coverage) combination that is very attractive. VNAs ownership is now viable for students, faculty, universities, and anyone interested in electronics design work. The VNA is an essential design tool for engineers to measure impedance, reflection coefficient and transmission coefficient of an electronic network. The VNA can also function as a time domain reflectometer to measure impulse and step response for devices in both transmission and reflection.

In the past, it was uncommon for universities to offer universal access to Vector Network Analyzer measurement technology due to the high price of high-performance units from vendors. University VNAs were typically employed only in specialized research laboratories. The nanoVNA enables student ownership in their home laboratories. Education into the measurement of electronics at high frequencies can now be widely available. Universities can now offer the nanoVNA on the same bench as power supplies, function generators, digital multimeters and oscilloscopes that are typically found in general purpose Electronics Laboratory.

Figure 1 shows an example picture of the equipment that one receives when ordering a nanoVNA. There are many different vendors for nanoVNAs and this is a representative offering that the author group has worked with.

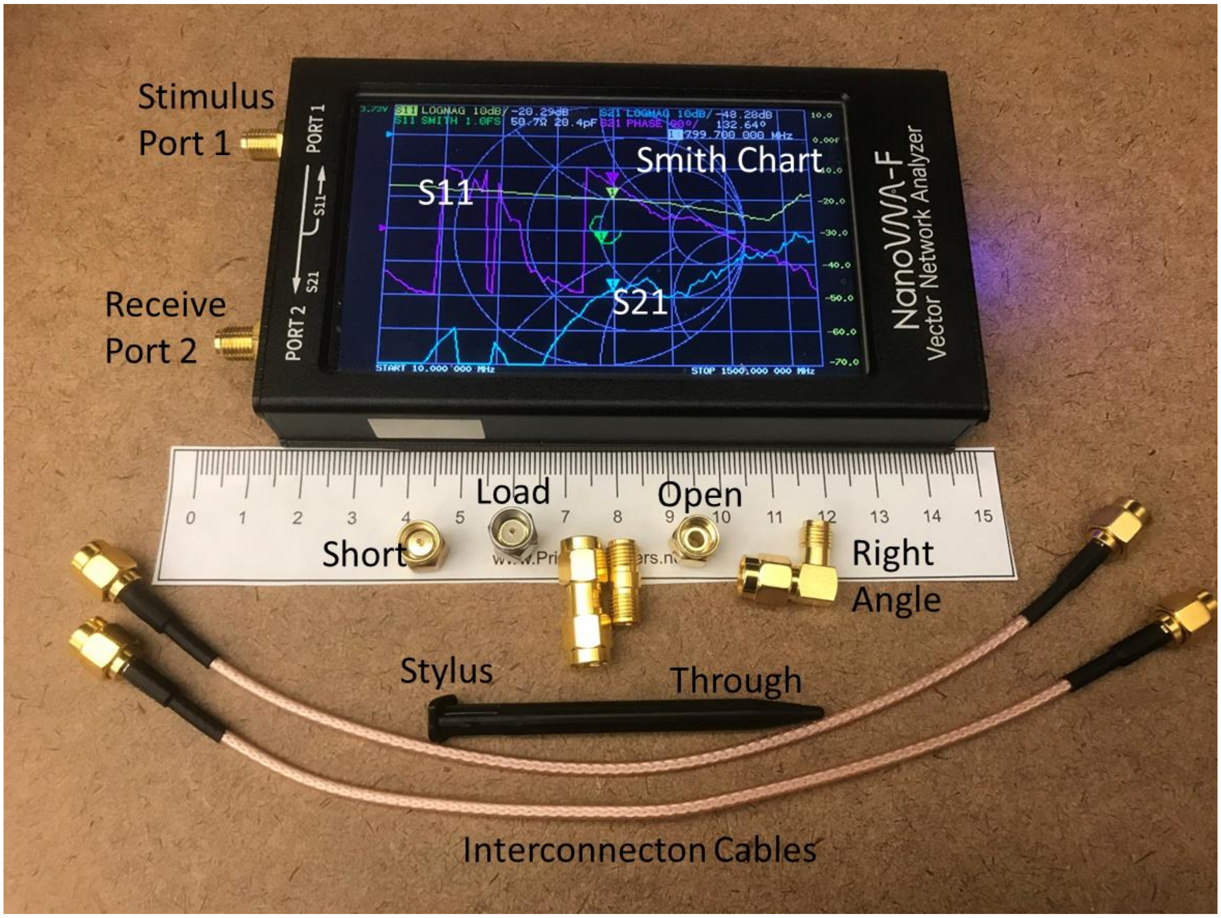


Figure 1: This is a picture of the typical items one receives in a nanoVNA kit. This particular unit was purchased for $100 from Amazon.

On the left-hand side of the nano-VNA are the two measurement ports with SMA connectors. Stimulus port 1 is used to provide a signal to the Device Under Test. Receive port 2 receives the response from the DUT. Before a measurement can be made, the VNA must be calibrated by connecting three impedance standards (Short, Open and Load) and one Transmission standard (Through Connection SMA). This nanoVNA covers the frequency range of 10 kHz to 1.5 GHz. The touch screen interface allows for user input with a convenient stylus pen. The touch screen output can simultaneously display the Scattering parameters S11 and S21 in many display formats including rectangular and the popular Smith Chart mode. An external computer can be used to control the nanoVNA via USB.

Figure 2 shows an example use case for a nano-VNA in a university or home laboratory.

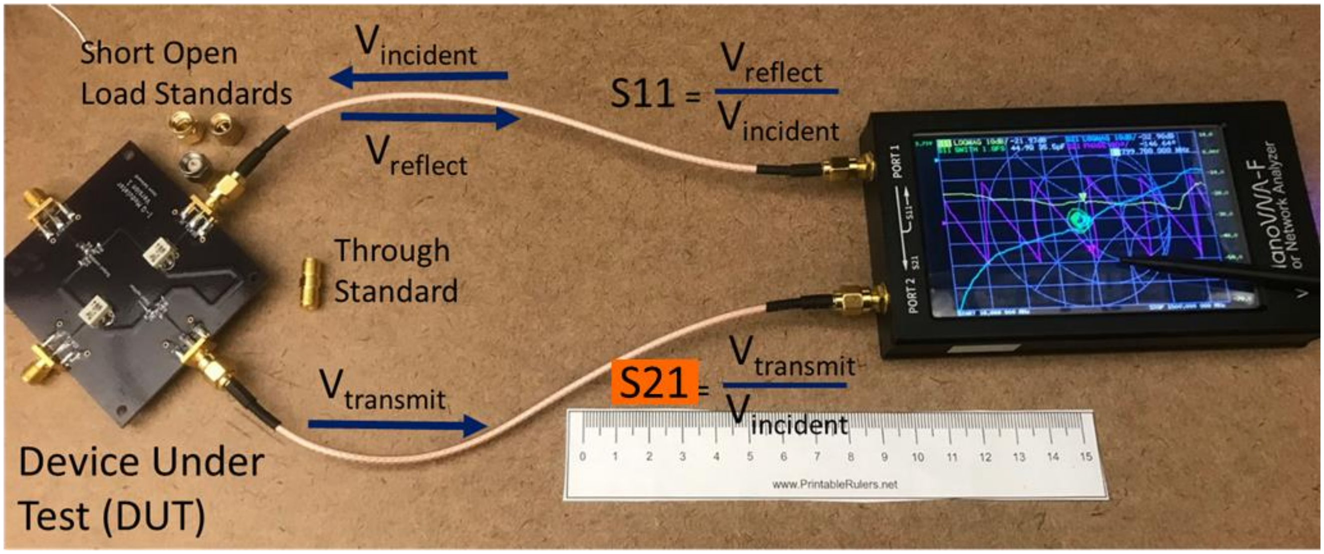


Figure 2: This figure shows how the VNA is connected to a Device Under Test (DUT) for an example measurement.

The nanoVNA provides a stimulus signal from port 1. The signal is transported with 50 ohm characteristic impedance coaxial cable to a device under test. The frequency range of the stimulus signal can be anywhere in the range from 10 kHz to 1500 MHz. In order to first use the nanoVNA in a calibrated manner, three impedance standards, (Short, Open and Load), must each be measured at the input connector of the DUT. This calibration steps help to correct for imperfections in the impedance of the source and imperfections in the port 1 resistive bridge directional detector. The reference through-loss standard also needs to be measured as part of the calibration process. At the Device Under Test (DUT), the Incident Voltage waveform, $V_{incident}$, encounters the input impedance of the DUT. If the impedance of the DUT matches the 50 ohm characteristic impedance of the coaxial cable, there is no reflection. If the impedance is other than 50 ohms a reflected signal, $V_{reflect}$, is sent back to port 1 of the nanoVNA. The nanoVNA has a directional detector behind port 1 that can independently measure the magnitude of the $V_{incident}$ and $V_{reflect}$ voltage. The ratio of the reflected and incident voltage is the Scattering Parameter matrix element S11. The DUT may allow some of the incident signal to pass through to its output as a function of stimulus frequency. The nanoVNA port 2 receives the $V_{transmit}$ signal entirely if port 2 is matched to 50 ohms. The nanoVNA measurement system can also operate indirectly in the time domain by mathematically taking the response of a series of harmonically related sinusoids and constructing the Fourier Series of a repetitive pulse stream. The step response or impulse response of the DUT can then be measured in both reflection and transmission.

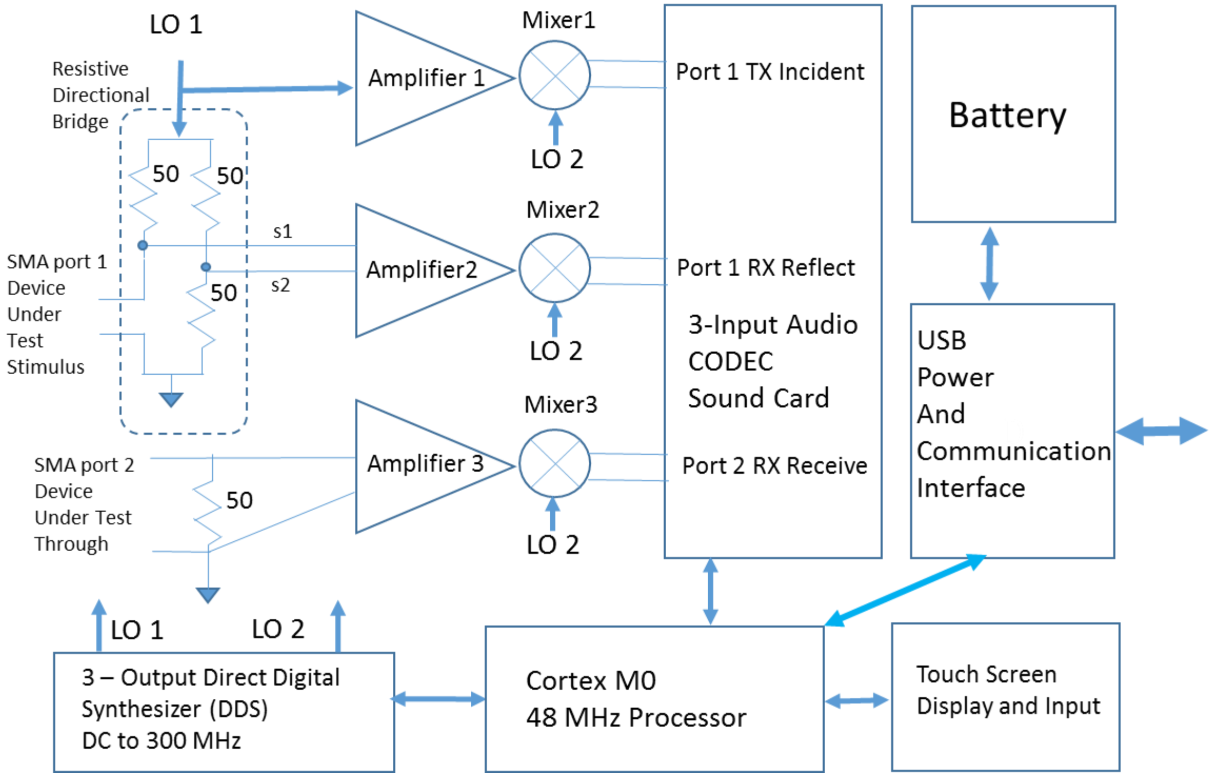


Figure 3; This figure illustrates the functional blocks that are found inside a typical nanoVNA.

Figure 3 shows an example block diagram of the open-source nanoVNA hardware architecture. At the lower left a DC to 300 MHz Direct Digital Synthesizer (DDS) puts out two different Local Oscillator (LO1 and LO2) signals that track each other with frequency offsets as the frequency is scanned from the start to stop frequency on the VNA. The output from the DDS is NOT sinusoidal and contains many harmonics in the DC to 300 MHz fundamental frequency range. The LO1 signal is applied to a device called a Resistive Directional Bridge. The directional bridge separates out incident and reflected signals to the Device Under test (DUT). The LO1 signal is sent out as a stimulus signal to SMA port 1 through the directional bridge and on to the Device Under Test (DUT). If the DUT is matched to 50 ohms, then the voltage at point s1 and s2 will be identical leading to no signal being applied to Amplifier 2 and Mixer 2. Amplifier 1 and Mixer 1 monitor the incident voltage to the device under test. The Scattering Parameter S11 can be obtained by ratioing the Mixer 2 level compared to the Mixer 1 level. Port 2 and the Amplifier 3/Mixer 3 pair monitor the signal that is transmitted through the Device Under test. Harmonics of the square wave coming from the DDS are used to find Scattering Parameters at frequencies above 300 MHz. The nanoVNA uses up to the 5th Harmonic of the DC to 300 MHz DDS signal in order to measure scattering parameters to 1500 MHz. The high frequencies at the inputs to Mixers 1 through Mixer 3 are down-converted in frequency to audio frequencies feeding into the Audio Codec (essentially comparable to the sound card in a Personal Computer). The Audio Codec provides the function of an audio sound card to measure the amplitude ratio and phase difference between each of three channels. The Cortex M0 processor takes care of all of the mathematics of channel signal processing, interfacing to the touch screen display and managing the power and communication tasks for the nanoVNA.

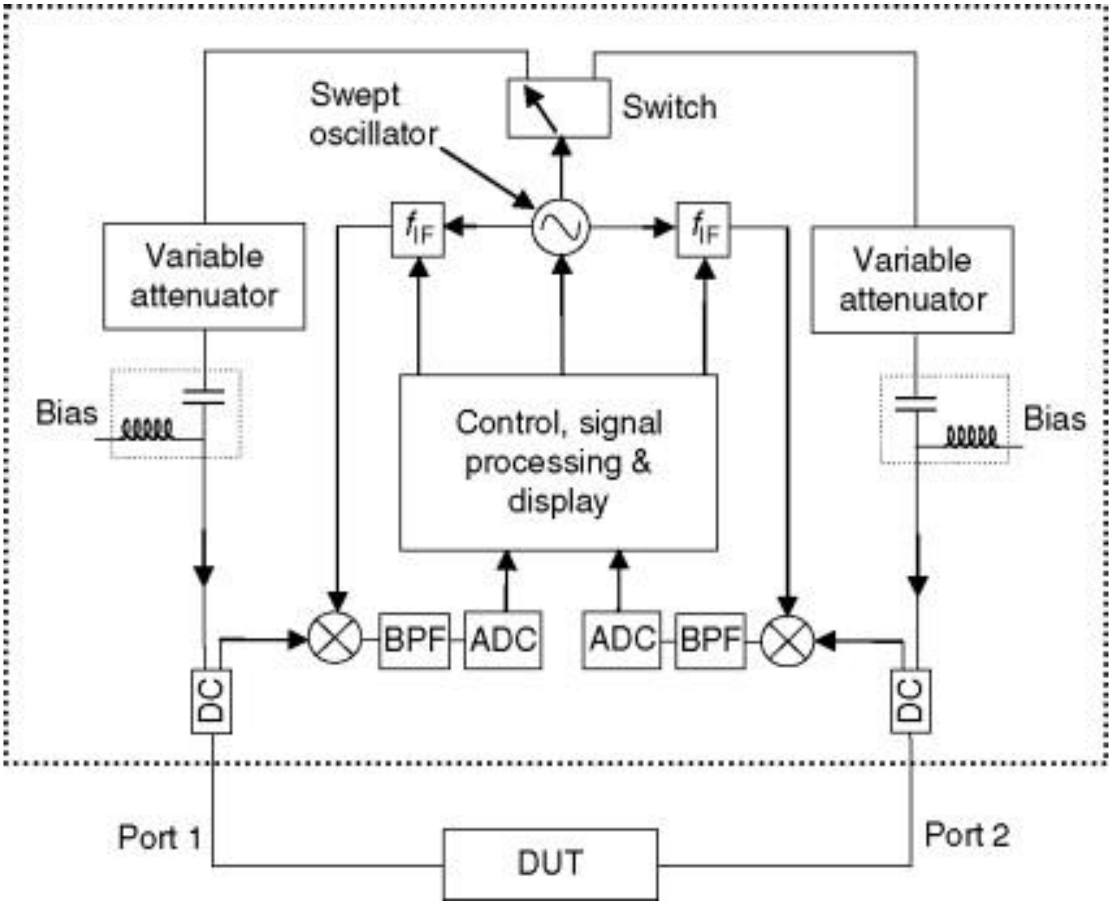


Figure 4; Example Block Diagram of a Full-Feature Vector Network Analyzer.

Figure 4 illustrates an example block diagram of a full-feature VNA to contrast against the nanoVNA approach. The full-feature VNA offers the ability to make a full set of S11, S21, S22 and S12 two-port scattering parameters with a single connection of the device under test due to a built-in transfer switch. The source for stimulating the device under test is always done at the fundamental frequency and not harmonics as is the case for nanoVNAs. At microwave frequencies, these tunable sources are very expensive compared to the Direct Digital Synthesizers used in the nano-VNA architecture. Each channel in the full-feature VNA has a variable attenuator to allow for measurement of high-gain amplifiers. Directional Detectors are found at both ports instead of the single port found in a nano-VNA. External Bias voltages and currents can be applied to the devices under test due to the use of Bias Tees. Components capable of working in the microwave and millimeter wave frequency bands are incorporated throughout the design. Nano-VNA components are mainly confined to the frequency bands below 2 GHz.

Table 1 provides a comparison summary of the feature set, architecture and performance capabilities of a nano-VNA versus a full-feature VNA. There are some basic differences between the nanoVNA offering and the architecture and performance found in more expensive full-feature VNAs.

Table 1: Example Comparison of a nanoVNA versus a full-feature VNA typically found in university laboratories.

Parameter	**nanoVNA**	**Full Feature VNA**	**Comments**
Frequency Range	10 kHz to 1500 MHz. Some of the newer nanoVNAs can now cover up to 3 GHz.	Upper frequency ranges into microwave and mm-wave bands.	Components for upper microwave and mm-wave bands are expensive
Dynamic Range	Only 30 dB of dynamic range at 1500 MHz 5th harmonic Band upper edge with 50 dB of dynamic range in the below 300 MHz band.	Excellent Dynamic Range over a wide bandwidth that can be greater than 100 dB	High frequency Local Oscillator components are very expensive
S – parameters coverage	S11 and S21 with no transfer switch.	S11, S21, S22, and S12 with built in transfer switch	Transfer Switch adds cost
Ability to measure high-gain amplifiers	Limited due to the lack of input power adjustment and lack of fundamental frequency excitation over the harmonic frequency coverage bands.	Fundamental Band excitation and input power adjustment are available for high-gain amplifier measurements.	NanoVNAs are best for low gain or passive devices.
Portability	Easy to transport, very light	The extra features add a lot of weight	Hard to beat the portability of the nano-VNA
Cost	$50 to $150 depending on model features	$5k to $100k+ depending on feature set	Each solution has its place in the world of VNA measurements
Robustness to Student Care	Still unproven, but if it does fail, one buys a new one.	Time tested. Need to be ESD aware. Expensive to fix.	Each solution has its place in the world of VNA measurements
Other Measurement add-ons available?	None	Non-linear analysis, Noise Analysis, Other upgrades, Bias Tees available to give DC bias to devices.	Unknown evolutionary path for future nano-VNA features

This paper has discussed a bit about the nanoVNA history, block diagram, functionality, and comparison to other solutions. The content will now focus on the use cases for utilizing nanoVNAs in the university environment both in the on-campus university laboratories and using them as a tool for remote education in the student's home laboratory. The authors spent time comparing laboratory exercises that utilize full-featured VNAs versus laboratory exercises that incorporate nanoVNAs. The investigation showed that nanoVNAs will be extremely useful in the educational environment, but they will not be a complete substitute for a full-feature VNA for most application where advanced research equipment in required. Several courses have now been taught utilizing the nano-VNA both for in-person and remotely-taught laboratory sections. The introduction to transmission line course uses VNAs as the primary measurement tool. This course has been taught both in on-campus and now remote learning environments due to the cost of the nano-VNA. A course on analog filters also uses the nano-VNA as the primary measurement tool for both in-person and remote usage. The university purchased an inventory of nano-VNA for remote learning. The University pays to mail the units to the student. The student pays to mail the units back to the university after the course finishes. For local students, pick-up and drop-off locations were established. Many of the students have chosen to purchase the nano-VNAs so that they can keep the capability in their home labs after the course ends. University clubs like the Amateur Radio group have found the units indispensable in their club project operations especially when building and maintaining their antenna systems. You-Tube videos were the primary source of education on how to use the nano-VNAs.

Example Measurements Comparing the nanoVNA to a Full-Feature VNA.

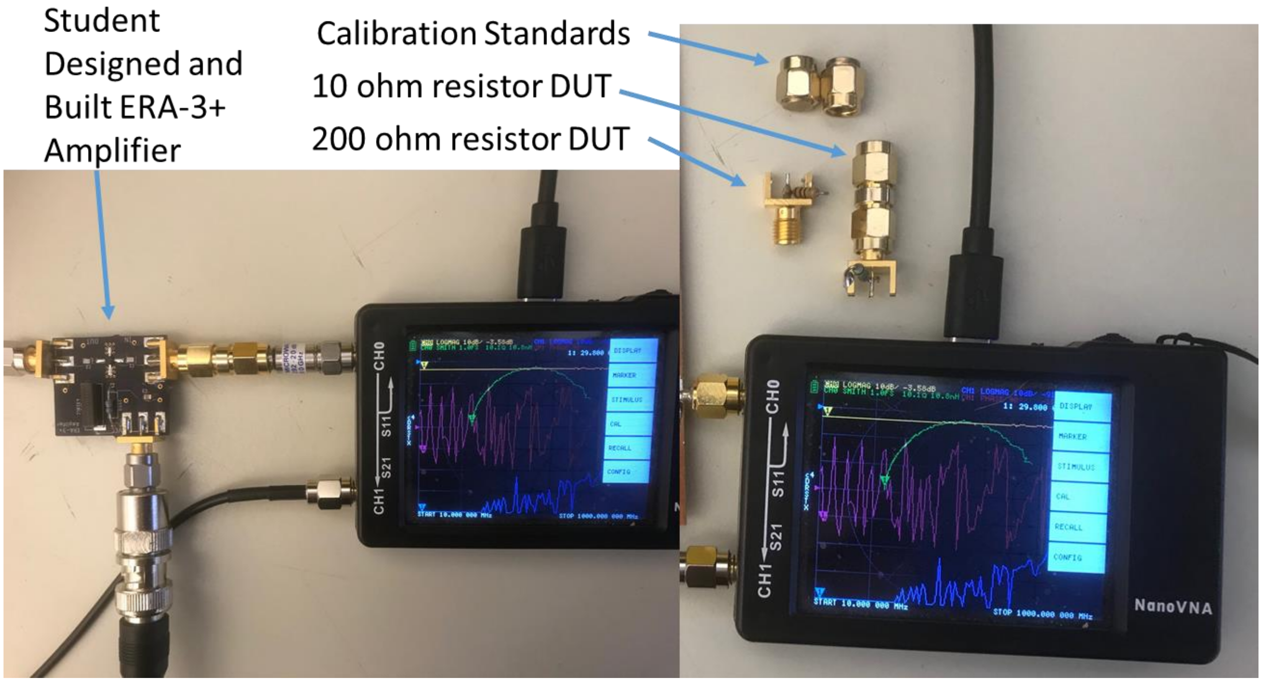


Figure 5: This figure shows two example measurements made with the nanoVNA. On the left is a student-built amplifier measurement. On the right is an electronic component measurement of a 10 ohm resistor and a 200 ohm resistor including their parasitic inductance.

A set of example student measurement activities were made for a comparison between a full-feature VNA and a nanoVNA. The frequency range of 10 MHz to 1 GHz was chosen. Figure 5 illustrates the devices that were used. On the left is student designed broad-band amplifier using the mini-circuits ERA-3+ chip. Note that a 20 dB attenuator is placed before the amplifier because the nanoVNA does not have a built-in attenuator compared to a full-feature VNA. On the right is a picture of two passive devices that were tested. A 10 ohm resistor and a 200 ohm resistor with a double male connector attached were used to compare passive component results. In order to make the measurement comparison between the full-feature VNA and the nanoVNA more uniform, the calibration kit for the nano-VNA was used in both cases. The calibration kit constants were also set to be equal between the two measurements. Figure 6 shows a comparison of the 10 ohm measurement device on the nanoVNA and a full-Feature VNA. Figure 7 shows a comparison of the 200 ohm measurement devices. Figure 8 shows a comparison of the ERA-3+ broadband amplifier.

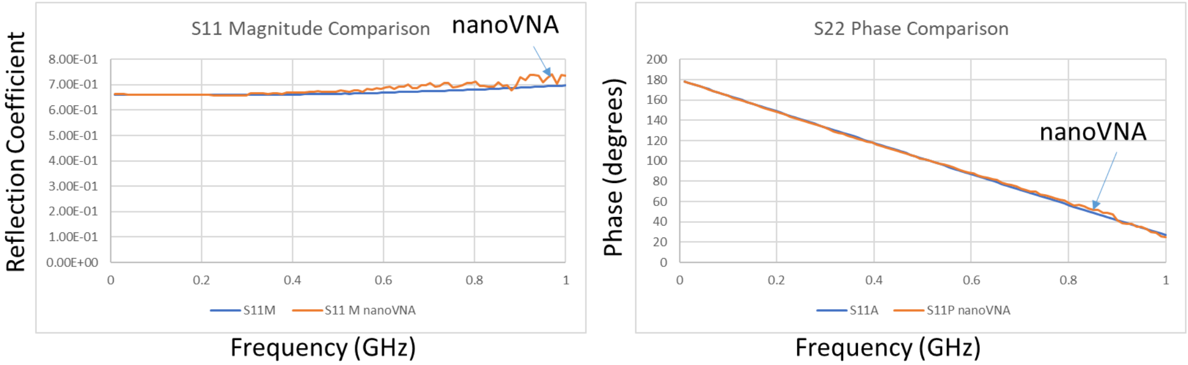


Figure 6. S11 measurement of a 0.25 Watt axial lead 200 ohm resistor with 2 cm double male SMA connector attached measurements. The nano-VNA measurement shows degraded measurement accuracy at the 1 GHz end of the range due to signal-to-noise limitations.

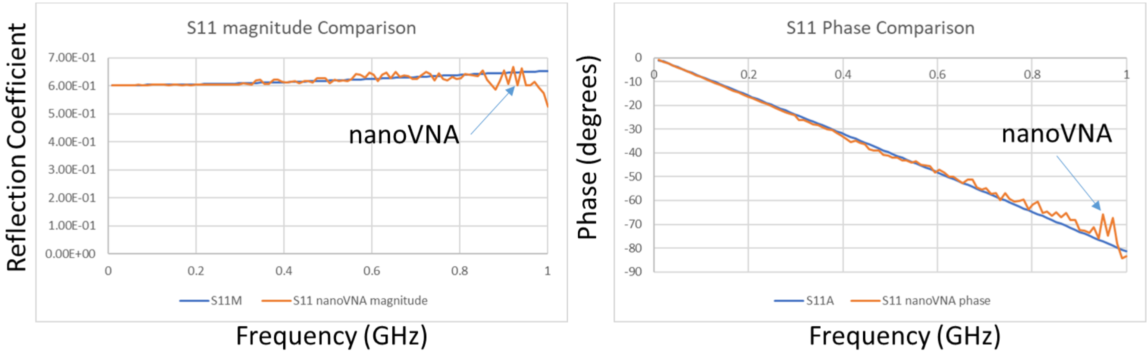


Figure 7. S11 measurement of a 0.25 Watt axial lead 10 ohm resistor with 2 cm double male SMA connector attached measurements. The nano-VNA measurement shows degraded measurement accuracy at the 1 GHz end of the range due to signal-to-noise limitations.

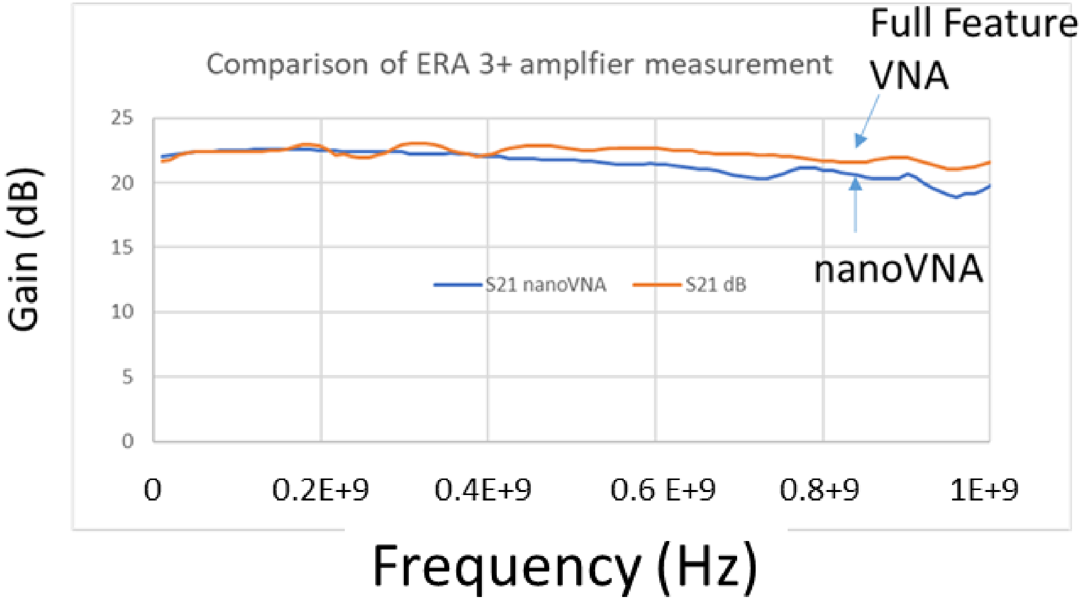


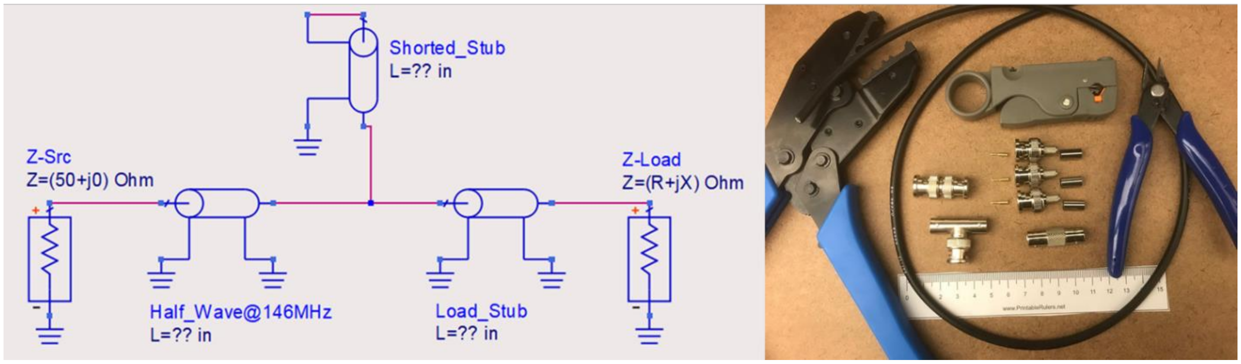
Figure 8. Student built ERA-3+ broadband amplifier. The nano-VNA needed an external 20 dB attenuator to make this measurement. The experimental apparatus for this measurement is shown in figure 5. The full-feature VNA used its own internal attenuator for the measurement.

Figures 6 and 7 show good agreement for passive device measurements. The figure 6 DUT is a 10 ohm axial lead resistor connected to an SMA connector. The figure 7 DUT is a 200 ohm resistor connected to an SMA connector. The impedance and reflection coefficient versus frequency clearly shows the affect of lead length and its associated inductance. The poorer signal-to-noise ratio found in the nano-VNA compared to the full-feature VNA causes the measurement to be noisy at the upper end of the frequency range near 1 GHz. The nano-VNA can make measurements up to 1.5 GHz but the specified S11 noise floor is only 30dB as shown in table 1.

Figure 8 shows an amplifier measurement comparison. The device under test is a mini-circuits ERA 3+ broadband amplifier chip that is incorporated into a student designed and constructed printed circuit board. In both the nanoVNA case and the full-feature VNA case, an input attenuator is needed to measure this high-gain broadband amplifier. The full-feature VNA has this attenuator built in. The nano-VNA needs an external attenuator to do the measurement. In figure 8, the agreement between the two systems is very close below 400 MHz. At higher 3rd and 5th harmonics of the nano-VNA fundamental frequency range of 10kHz to 300 MHz, there was increasing difference between the two measurements. These measurements illustrate that the nanoVNA can make a compelling set of measurements given its price-performance benchmark. The nanoVNA will not replace the full-feature VNA given its architectural limitations.

USE CASE Example: nanoVNAs in the University Lab environment.

NanoVNAs were used in a required electromagnetics and transmission line course for both in-person and remotely delivered sections. This in-person lab has six Full-feature VNA stations with 18 students in the lab. With the purchase of nanoVNAs, each student now has full access to their personal nanoVNA as well as shared access to the full-feature VNAs. Figure 9 illustrates an example experiment students perform with both their nanoVNAs and full-feature VNAs. The student is asked to design, test and measure an impedance matching circuit between an unknown load and a 50 ohm source. Students really enjoyed putting BNC connectors on RG-58 coax using the stripping and crimping tools. Students also must compensate for the length of the BNC adapters when simulating their solutions.


(a) Impedance matching network schematic

(b) Equipment used to assemble

Figure 9: (a) Students are given the assignment to match an unknown load (Z-load) to a 50 ohm load using 50 ohm impedance coaxial cable. Keysight ADS or similar CAD programs are used for this simulation. (b) Students fabricate the matching network elements using RG-58 coaxial cables and crimp-on connectors. Various adapters are then used to interconnect the entire matching network. Full feature VNA and nano-VNAs are then used to evaluate how well the matching network was designed and constructed.

The students learn how to calibrate VNAs using the Short-Open-Load-Through (SOLT) calibration software. Both the nano-VNA and the full Feature VNA are connected to a main computer through USB interfaces. Figure 10 shows an example interface for the NanoVNA illustrating Smith Chart views from each step of the calibration. Files are downloaded in standard S1P or S2P formats for plotting on the main computer.

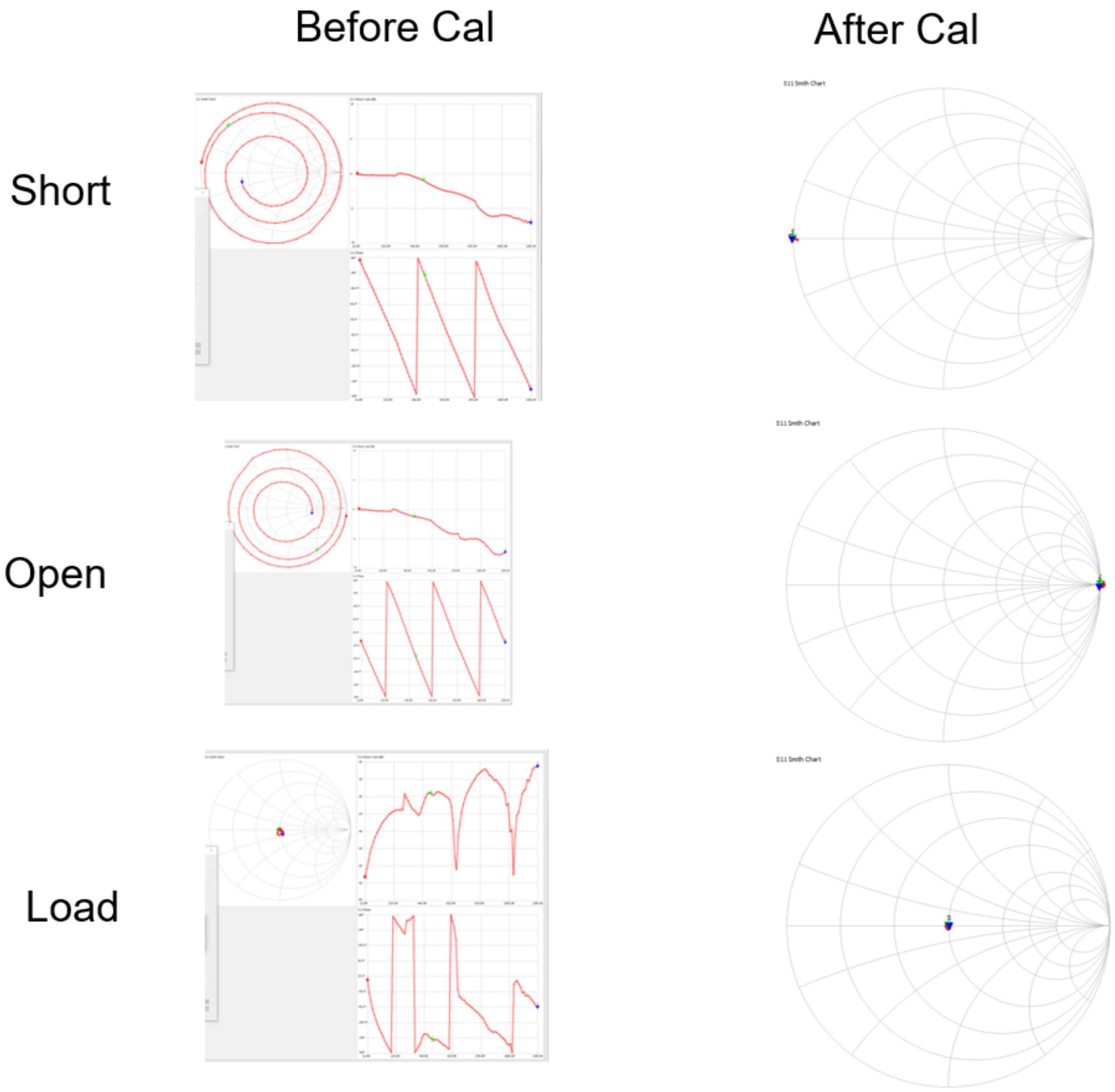


Figure 10: Nano-VNA computer interface view of the Short-Open-Load calibration steps students perform before the nano-VNA is fully calibrated. For the Short and Open component, the nano-VNA is given a standard for what constitutes 100% reflection and with 0 degrees and 180 degree phase on the reflection. The 50 ohm load illustrated to the vector network analyzer a case where no signal should be seen on reflection. Mathematical operations in the nano-VNA then compensate for internal imperfections inside the instrument.

The nano-VNAs are being used as the primary test and measurement tools for an analog filters class being offered in remote instruction mode in spring Quarter 2021. Students will purchase the nanoVNA and a create various electronic filters. Audio frequency filters, radio frequency filters and microwave filter prototypes will all be characterized using the nanoVNA at the students' home laboratories. As the university returns to a more in-person delivery modes, the nanoVNAs will continue to be a key electronic test and measurement tool for both our general purpose and specialized laboratories. This is made possible by the fact that a nanoVNA and a portable digital multimeter are now the same price.

Instructor Comments, Observations, and Student Feedback

Instructor feedback on the use of nanoVNAs in the curriculum was gathered from faculty technical area committee meetings. These technical area committee meeting deliberations began with instructor evaluation of nano-VNAs as each instructor received an evaluation unit. Committee members had decades of experience using the full-featured VNAs. The nano-VNA evaluation was initially greeted with skepticism given the low cost of the units. The technical area committees then authorized purchase of nano-VNAs and the modification of the curriculum to incorporate the units given positive feedback on performance. This same group gathered to evaluate how the units performed both for on-campus and remote learning sections of the electromagnetics lab and the analog filters lab. Student comments were provided by both written student evaluation comments and informal communication between the students and the lab instructors. Faculty and students have been using the nano-VNAs for two years since their introduction to the university setting.

- Whether using a full-feature VNA instrument or the nanoVNA, students are initially daunted at the prospect of using a VNA. Introductory narrative on theory of operation does much to relieve these feelings. However, working with a handheld instrument and the familiar PC environment was well received by students. The nano-VNA removed a certain amount of intimidation compared to using the very expensive full-feature VNA. Students were more willing to explore the nanoVNA directly and through the PC program since every student had one and there was no need to share between students. The nanoVNA user interface was less overwhelming in the number of options there are to choose from compared to the full-feature VNA.

- With each student using their own instrument, they could take their time with the procedure and not move on until they understood what they were doing. There was no pressure to move on and get things done by partners. In some cases, students would deviate from the procedure to pursue "what if" scenarios initiated by their natural curiosity.

- Students did appreciate having the opportunity to run the full-feature VNAs in addition to the nano-VNA units. Advanced RF and Microwave laboratories still need the full-feature VNA but the nano-VNA is a nice complement.

Summary:

The nanoVNA offers a step-change in the availability of vector network analyzers to every student. Gone are the days when VNAs only appear in university research labs. The $50-$150 price tag of these units means that they can be standard electronic test and measurement equipment in Electrical Engineering labs along side Digital Multimeters, Oscilloscopes, Function Generators and Power supplies. NanoVNAs also enable remote laboratories were students design electronic systems from 10 kHz to 1.5GHz. 3 GHz versions of the nanoVNA are also starting to appear on the market with fundamental frequency coverage over the entire range. These new nanoVNA variants show that the open-source community continues to advance this measurement capability at low cost. Measurements show that nanoVNAs can make high accuracy measurements within the limitations of the VNA architecture. Students find the units easy to use both in the university labs and at their home laboratories. Universities should consider adding nanoVNAs to their general-purpose laboratories, especially since the units can work over such a broad frequency range of 10kHz to 3GHz at the same price point as a portable digital multimeter. NanoVNAs should start showing up in university laboratories even in the second year of their curriculum as hands-on learning evolves.

Reference:

[1] Eddy555 is the anonymous inventor of the nanoVNA. The only reference on the inventor is found on the web site nanovna.com