Building an S-Parameter Test Set for the VNWA-3E

Whitham D. Reeve, Anchorage, Alaska USA (© 2013 W. Reeve)

1. Introduction

The vector network analyzer (VNA) is a high step up from the relatively simple antenna analyzers often used by amateur radio astronomers. Compared to antenna analyzers, VNAs have much more measurement capability and better accuracy and cover a wider range of frequencies. VNAs can be used to measure the electrical characteristics of devices such as filters, amplifiers, passive and active components, cables, and antennas. However, until a few years ago, the high costs of commercial VNAs put them out of reach of most individuals.

The DG8SAQ VNWA-3E used in this article (figure 1) along with its accompanying software (figure 2) is a semi-professional 2-port vector network analyzer that costs about US$700 (less expensive and less capable versions are available from the manufacturer: http://www.sdr-kits.net/). The VNWA-3E software has provisions for bidirectional measurements, but the hardware transmission ports are unidirectional. This means a 2-port device being tested (for example, an amplifier) must be connected one way for forward measurements and then manually reconnected for reverse measurements (figure 3). The inconvenience of manually reconnecting for the second set of measurements can be eliminated by adding an s-parameter test set under control of the analyzer's software. This article describes my implementation of such a test set at a cost of around US$140 (figure 4).

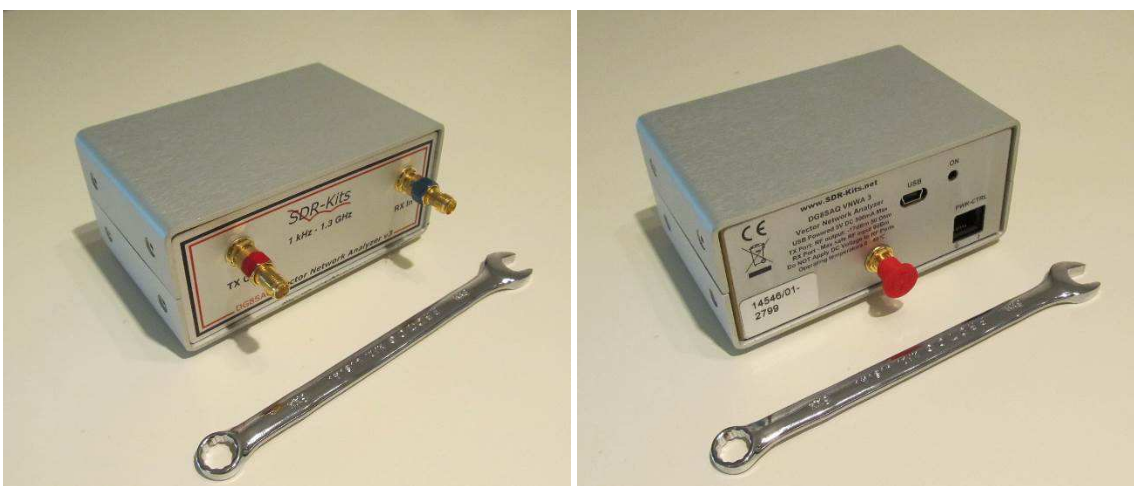


Figure 1 ~ VNWA-3E hardware front (left) and rear view next to an 8 mm wrench. The front shows the transmit and receive ports. The rear view shows the USB control/power port near the top-right. The S-Parameter Test Set control port is lower-right, and a red plastic cap protects the external reference oscillator port. The enclosure dimensions including connectors are 104 mm wide x 50 mm high x 85 mm deep (4.1 in x 2 in x 3.3 in).

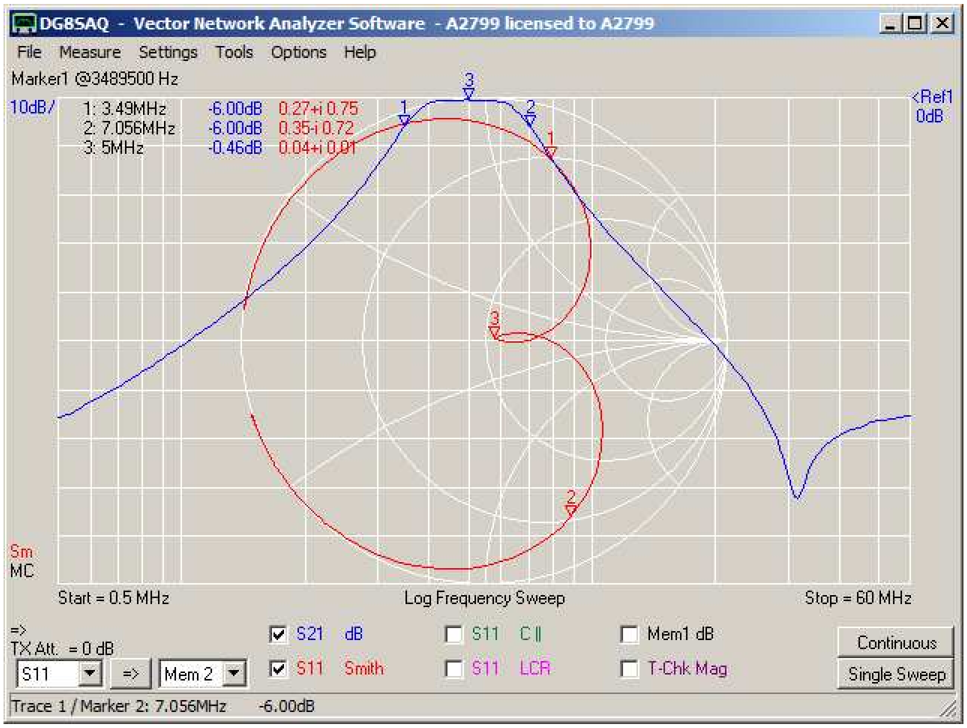


Figure 2 ~ VNWA-3E software screenshot is representative of a 2-port measurement. It shows the response of a simple Butterworth pi-filter from 0.5 to 60 MHz with markers at the center and –6 dB frequencies. The blue trace shows the filter response (s21) and the red trace shows the input impedance on a Smith Chart overlay. The markers, traces and vertical scales are user defined. The Smith Chart scale overlay may be turned on or off.

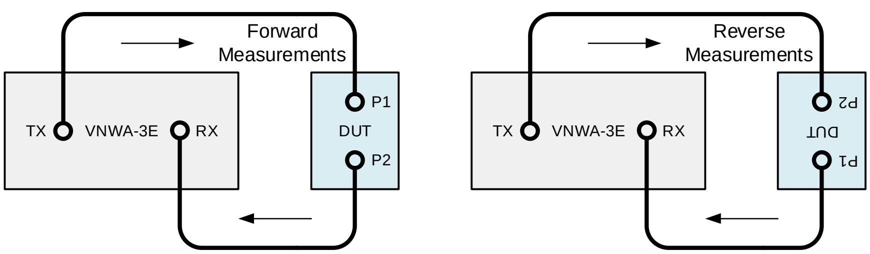


Figure 3 ~ Block diagram of manual VNA forward (left) and reverse (right) connections

Figure 4 ~ S-Parameter Test Set described in this article. Cost of all parts except coaxial cables was around US$100. Cables cost about US$40. The test set dimensions are 102 mm wide x 50 mm high x 102 mm deep (4 in x 4 in x 2 in). The black cable on the right is the control cable that connects the test set to the VNWA-3E control port. The two blue coaxial cables connected to the transfer switch in the middle-front of the test set connect to the transmit and receive ports of the VNWA-3E. The two loose blue cables on the left are used to connect the test set to the device under test.

2. VNA Measurements

When connected to a 2-port device for reflection measurements, the VNA compares its incident signal to the signal reflected from the device's input or output port (figure 5). For transmission measurements through a device, the VNWA-3E compares the incident signal with the signal coming out of the opposite port. Many unidirectional devices, like amplifiers, actually have leakage paths in the reverse direction and it is necessary to test them both ways. Typical results from bidirectional measurements are

- Reflection coefficients (s11, s22) – forward and reverse path reflection
- Transmission coefficients (s21, s12) – forward and reverse path transmission (isolation)
- Return loss (dB)
- Insertion gain or loss (dB)
- Complex impedance (R + jX ohms) , including magnitude (|Z|)
- Voltage standing wave ratio, VSWR

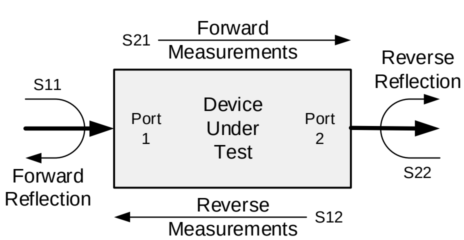


Figure 5 ~ Block diagram showing incident, reflection, transmission directions.

The scattering parameters (s-parameters s11, s12, s21, and s22) mentioned above are based on ratios that define a device's input and output relationships. S-parameters are most often used in radio frequency design and testing because they are easier to measure and use than other types of network analysis parameters. Most RF circuits will not operate properly unless their inputs and outputs are properly terminated, so s-parameter measurements use matched loads for terminations rather than short or open circuits as with other parameters. For a more complete discussion of s-parameters, see [HP] and for discussion of vector network analyzers, see [Agilent] and [Anritsu]. For an original description of the mathematical basis for s-parameters, see [RadLab8].

Vector network analyzers are best known for measuring s-parameters; however, the VNWA-3E has considerably more capabilities and can be used as a

- Spectrum analyzer
- Signal generator with CW, AM and FM modulation
- LCR (inductance, capacitance, resistance) meter at user defined measurement frequency
- Highly accurate frequency meter with µHz resolution
- Antenna radiation pattern measurements

The VNWA-3E has no front panel controls and for operation requires a personal computer (PC) running the supplied software. The software commands the hardware to produce digitized electrical measurements and then uses the data to calculate and display the user-specified parameters. The software is quite flexible, allowing a wide range of measurements and display customization. An advanced software feature allows storage of the entire instrument state – calibration data, trace settings, configurations and so on – so everything may be easily recalled later.

An important procedure in the use of a VNA is proper calibration, which usually is performed prior to each set of measurements. The most common type of calibration uses Short, Open, Fixed-termination (Load) and Thru circuits, denoted SOLT. These are precision components placed, in turn, on the VNA ports during calibration and then set aside. The calibration data is stored in a file, and the calibration components are not used during the measurements of a device.

Calibration kits with the SOLT components for professional VNAs cost from US$5000 to $35000 dollars depending on the connector type, frequency range and options. Suitable calibration kits (figure 5) for the VNWA-3E are much less expensive, costing about US$25 to $125. The VNWA-3E manufacturer sells a kit at the low end of the price range. A kit at the high end of that price range, model NA-EC1, is available from Heuermann HF-Technik in Germany: http://www.hhft.de/index.php?page=vna&subpage=network_analysis_p2b. Of course, users could put together their own calibration kit from individual components, but it is necessary to know detailed and accurate dimensional information about them (making a calibration kit is an interesting project by itself).

Figure 5 ~ Calibration kit used with the VNWA-3E, consisting of Short, Open, Load and Thru components that use SMA connectors. The Open and Thru are the same barrel connector shown upper-left. The slightly different reference plane locations of the Open and Short affect the calibration so a phase delay is manually entered into the software configuration to compensate. The Short and Load components are mechanically similar and have been color-coded for easy identification (red for the short and blue for the load). A coaxial tee-junction connector – used for the T-Check accuracy test described later – is shown lower-left.

For ordinary lab measurements, I prepare calibration files for different frequency ranges and instrument setups. Depending on the setup I may renew the calibrations before each set of measurements. When used to make bidirectional measurements on a 2-port device, the calibration process requires ten separate steps, five in the forward direction (FWD) and five in reverse (REV):

- Short, FWD and REV
- Open, FWD and REV
- Load, FWD and REV
- Thru, FWD and REV
- Thru Match, FWD and REV

Note: The calibration calculations made by the VNWA-3E software also include crosstalk coupling between the transmit and receive ports, so there actually are a total of 12 parameters; however, the VNWA-3E user normally allows the software to use assumed crosstalk values rather than measured values.

3. S-Parameter Test Set Circuit Description

The simplicity of the S-Parameter Test Set is indicated by its block diagram (figure 7). The major components are a coaxial transfer switch and a relay interface. The relay interface uses the 0 and 3.3 V logic output from the control port of the VNWA-3E to operate a 28 Vdc relay. The relay, in turn, operates the transfer switch, which configures port 1 and port 2 of the device under test (DUT) for forward and reverse measurements. I setup the VNWA-3E software for active high operation; that is, 0 V (logic low) releases the transfer switch for forward measurements and 3.3 V (logic high) operates the transfer switch for reverse measurements.

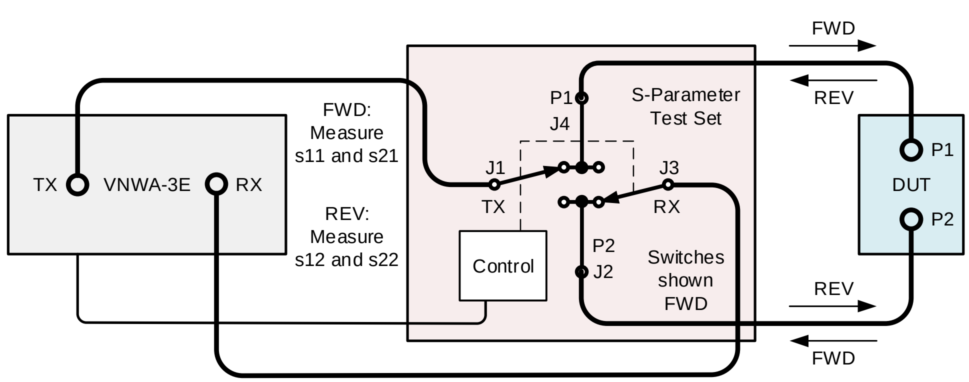


Figure 7 ~ S-Parameter Test Set block diagram (middle) including its connections to the VNWA-3E (left) and device under test. Key: P1 = Port 1, P2 = Port 2, TX = Transmit, RX = Receive, DUT = Device Under Test, FWD = Forward, REV = Reverse.

The schematic shows more detail (figure 8). The 5.1 V zener diode D1 across the relay interface input prevents over-voltage on the VNWA-3E control output if the relay control transistor Q1 fails with a collector-to-base short circuit. To reduce inductive kickback damage to the control transistor, an ordinary power diode D2 is reverse-connected across the relay coil. Resistor R1 limits the input current and R2 prevents false operation due to leakage current across the base-emitter junction of the NPN Darlington transistor.

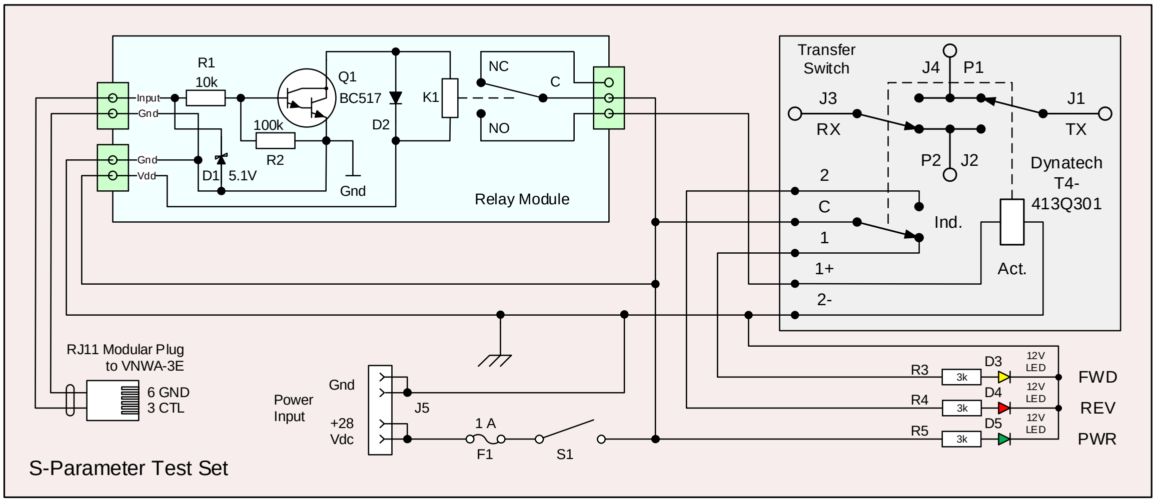


Figure 8 ~ S-Parameter Test Set schematic

At first it may seem the 28 V control relay K1 is redundant. However, the BC517 transistor used in my circuit has maximum collector current of 500 mA and the transfer switch TS1 operating current is about 300 mA. I felt there would be too little margin, so I used a relay K1 on the interface module to isolate the transfer switch operating current from the control transistor. K1 requires only 15 mA operating current.

The transfer switch is the fail-safe type. This means that when power is removed from the switch, it releases to its normally closed position if it is not already there. The switch has position indicating contacts, and I wired them to light emitting diodes (LED) D3 and D4 through current limiting/voltage dropping resistors R3 and R4. The 3k ohm resistors shown in the schematic are used with prewired LEDs that already have voltage dropping resistors for nominal 12 V operation. The additional 3k ohms provides 7 mA LED current with 28 V input (determined through testing). Power is applied to the circuits through power jack J5, SPST switch S1 and 1 A fuse F1 and is indicated by another 12 V LED D5 with 3k ohm voltage dropping resistor R5. The power indicating LED could be eliminated because one of the position indicating LEDs always is on when power is applied. For power input I used the Anderson PowerPole connectors. Builders can easily substitute another type of connector, such as a 2.1 x 5.5 mm coaxial dc power jack or a DIN connector.

4. Construction

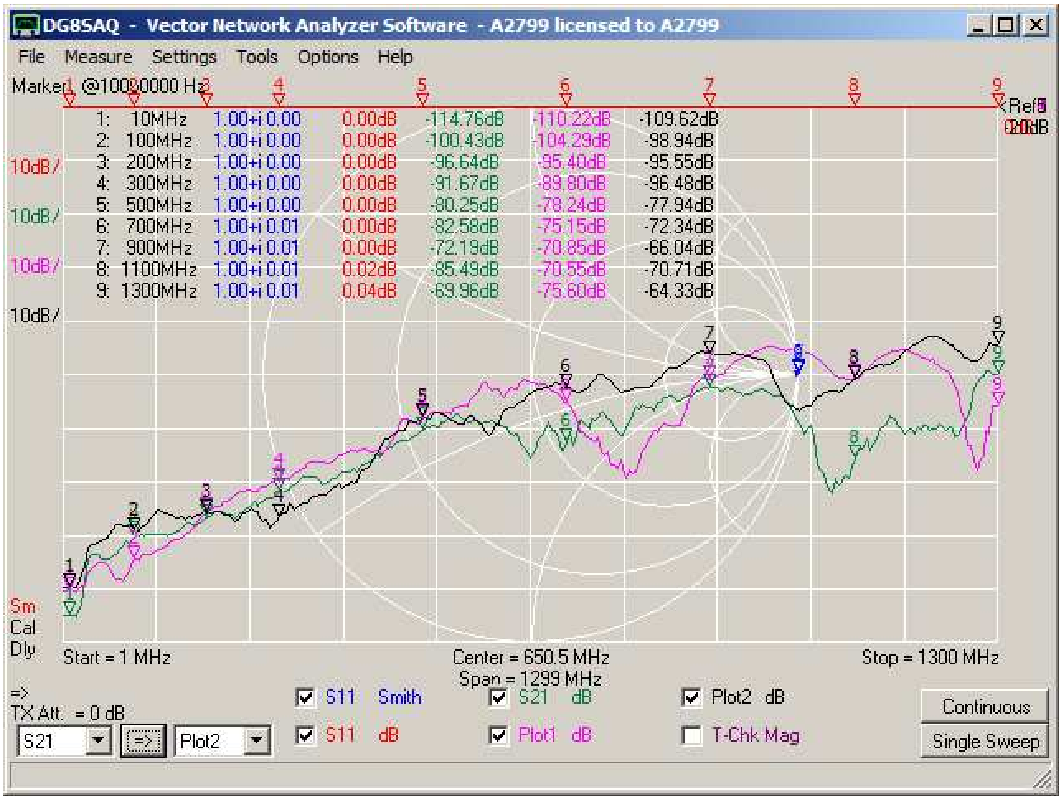
The bill of material (BOM, table 1) lists all parts used in my version of the S-Parameter Test Set. The most critical component is the coaxial transfer switch, and it should be of the highest possible quality. Used high quality switches are available from online auctions and used microwave equipment sellers at a cost of around US$50 and up. Two types of switches are available – fail-safe and latching. I chose the fail-safe type because the transfer switch always is in a known position (released) with no power applied to test set. A latching switch remains in its last position when power is removed from the actuating coil. Only minor circuit changes are needed when the relay interface described here is used with the latching type.

In addition to the operating mode (fail-safe or latching) the important attributes of the transfer switch are frequency range, operating voltage and port isolation. The VNWA-3E frequency range is 100 kHz to 1.3 GHz, but it can be configured for frequencies below 100 kHz. To accommodate this range with some margin, the transfer switch should have a frequency range of at least dc to 2 GHz. Most switches I am familiar with operate at 28 Vdc, and that is the voltage I used. Other voltages are available and could be adapted to this test set without much trouble.

Table 1 ~ Bill of Material for S-Parameter Test Set (items marked "Generic" are not critical)

Item	Qty	P/N	Mfr or Vendor	Description
1	1	T4-413Q301	Dynatech	Coaxial transfer switch, fail-safe, 28 Vdc (see text)
2	1	SRD-S-124D	Sanyou	Relay, 24 Vdc, Form C
3	1	AU-1083	Bud Industries	Enclosure (utility cabinet), aluminum, 4 x 4 x 2 in
4	1	TE-5-1	Littelfuse	Miniature fuse, 1 A, 250 V
5	1	HS4	Anderson	PowerPole, dual set, chassis mount
6	1	BC517	Generic	Darlington transistor
9	1	1N5338	Generic	Zener diode, 5.1 V, 5 W (substitute 1/2 W)
10	1	1N4002	Generic	Diode, 1 A, 100 V (substitute higher voltage)
11	1	Generic	Generic	LED, green, prewired 12 V, 3 mm (see text)
12	1	Generic	Generic	LED, amber, prewired 12 V, 3 mm
13	1	Generic	Generic	LED, red, prewired 12 V, 3 mm
14	1	SML-190-GTP	VCC	LED mount and lens, green, 3 mm (see text)
15	1	SML-190-ATP	VCC	LED mount and lens, amber, 3 mm
16	1	SML-190-RTP	VCC	LED mount and lens, red, 3 mm
17	1	Generic	Generic	10k ohm, 5%, 1/4 W resistor
18	1	Generic	Generic	100k ohm, 5%, 1/4 resistor
19	3	Generic	Generic	3k ohm, 5%, 1/2 W resistor
20	2	Generic	Generic	Prototype printed circuit board, cut to size as required
21	6	Generic	Generic	Standoff, male-female, 6 x 6 mm, 3 mm thread (PCB mounting)
22	6	Generic	Generic	Machine screw, 3 x 3 mm
23	6	Generic	Generic	Hex nut, 3 mm
24	12	Generic	Generic	Lock washer, split, 3 mm
25	2	Generic	Generic	Machine screw, 4-40 x 0.188 in (change as needed for transfer switch mounting)
26	2	Generic	Generic	Lock washer, split, #4
27	1	Generic	Generic	Ground lug, internal star, #6
28	1	Generic	Generic	Machine screw, 6-32 x 3/8 in
29	1	Generic	Generic	Hex nut, 6-32
30	30 cm	Generic	Generic	Stranded hookup wire, 24 AWG, 300 V
31	30 cm	Generic	Generic	Stranded hookup wire, 22 AWG, 300 V
32	2	141-3SM+	Mini-Circuits	*Hand-Flex* interconnection cable, SMA-M:SMA-M, 0.141 in dia., 3 in long
33	2	141-6SMRSM+	Mini-Circuits	*Hand-Flex* interconnection cable, SMA-RA-M:SMA-M, 0.141 in dia., 6 in long

Transfer switch port isolation is important because it reduces interaction between the VNWA-3E transmit and receive ports during calibration and measurements. Isolation is the ratio of the transmitted power to received power, measured in dB, with no direct connection between the transmit and receive ports. There will be some crosstalk coupling between the transmit and receive ports due to leakage. My measurements of the VNWA-3E show the amount of coupling depends on the way the receive port is terminated – open circuit, short circuit, 50 ohms or something else. Measured isolation exceeds 100 dB below approximately 100 MHz (most likely limited by the VNWA-3E noise floor), falling to around 70 dB at 900 MHz and continuing to drop to about 65 dB above 900 MHz. These measurements may be compared to measurements of the combination VNWA-3E and the S-Parameter Test Set (figure 9).



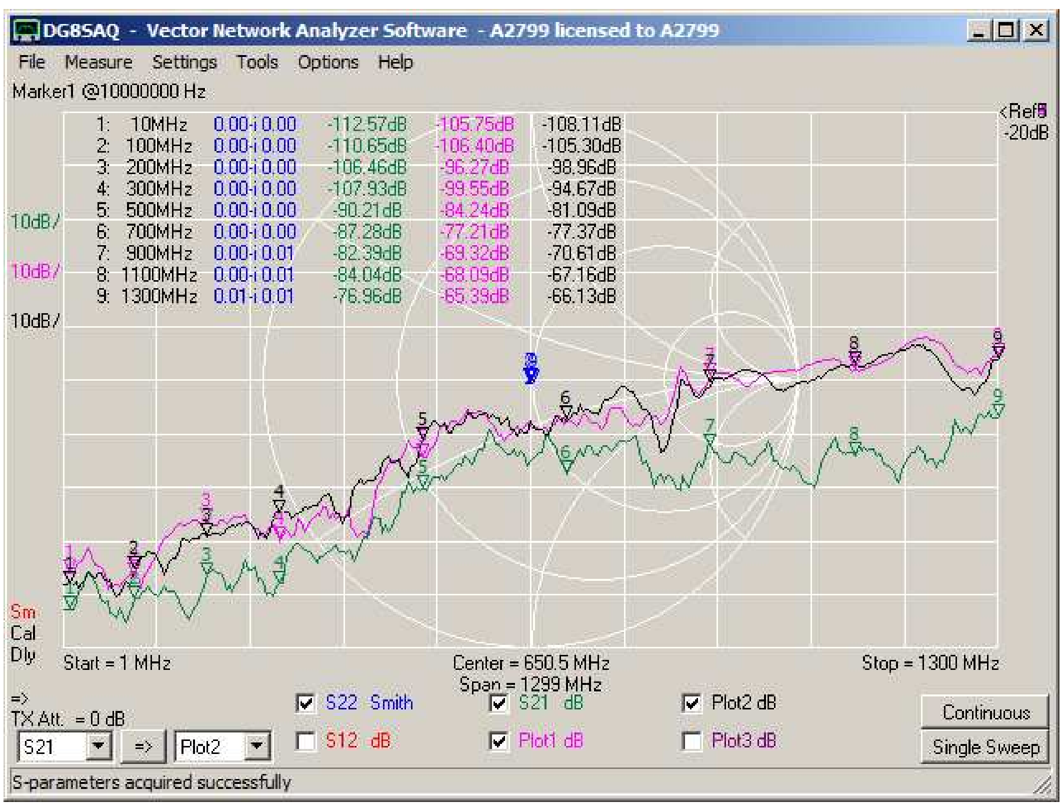


Figure 9 ~ Crosstalk coupling loss measurements of the VNWA-3E by itself (upper) and combination VNWA-3E and S-Parameter Test Set (lower). Measurements are from 1 to 1300 MHz. For the VNWA-3E measurements, the short cable used for the Thru calibration was left connected to the receive port and terminated with Open (violet trace), Short (black trace) and 50 ohm (green trace) terminations. Crosstalk was measured with Open (violet trace), Short (black trace) and 50 ohm (green trace) terminations on both test set ports (P1 and P2). The lower plot shows only the forward direction; measurements of the reverse direction were similar. All measurements are in dB below the transmit power level. For example, a measurement of –80 dB indicates +80 dB isolation between the ports. The plot reference was set to –20 dB at division 10 (top of plots) and the vertical scale was set to 10 dB/division. The markers indicate the coupling at selected frequencies. A comparison of the combination plot to the VNWA-3E by itself shows that the transfer switch has improved the overall isolation under many conditions and, more importantly, has not significantly degraded it.

Ideally, the transfer switch isolation exceeds the VNWA-3E's inherent isolation by at least 10 dB. This requirement is quite demanding and is not available with many transfer switches. The datasheets for the Dyntaech transfer switch listed in the BOM as well as Teledyne Microwave, Transco Dow-Key and Narda switches in my stock all show 80 dB isolation from dc to 3 GHz. The isolation indicated on datasheets is the worst case. It is tempting to assume the isolation is better at, say, lower frequencies. It well may be, but there is no basis for this assumption without measurements.

It is for the reasons discussed above that I recommend builders do not buy a used transfer switch unless a datasheet for the specific model being considered can be obtained beforehand. This may require considerable online search because many auction sellers do not know what they are selling. Comparative measurements should be made to confirm proper operation and isolation. As an aside, it is possible to achieve much more than 100 dB switch isolation by using four single-pole, double-throw (SPDT) coaxial relays and carefully made interconnections. However, this arrangement requires considerable mechanical redesign and some electrical redesign of the test set described here.

The BOM shows metric and non-metric hardware and fasteners because I used what I had on-hand or needed for compatibility with other parts. Builders should use their own resources and modify the BOM accordingly. Control and power wiring is point-to-point and not critical. I used 24 AWG stranded wire for all wiring except the power input, which is 22 AWG, and the prewired LEDs, which have 26 AWG leads.

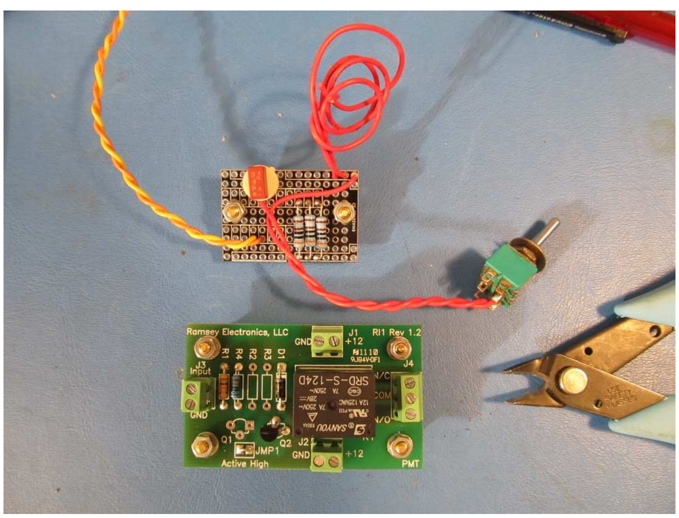


Figure 10 ~ PCBs for the wire junctions, fuse and resistors (top) and relay interface. The upper PCB was prewired before installation. The relay interface PCB was taken from a Ramsey Electronics kit (http://www.ramseyelectronics.com/) but populated with components specifically for the S-Parameter Test Set.

I used a small piece of prototype printed circuit board for power and ground junctions and to hold the 3k LED resistors and fuse, and I installed the relay interface components on a Ramsey RI1 relay interface PCB because I had one on-hand (figure 10). All components could be installed on one piece of prototype PCB rather than two separate PCBs as in my test set. The chassis-mount power jack in my test set has two sets of connectors. I wired them in parallel so that one pair is used as power input and the other pair could be used to power an external 28 Vdc accessory such as a noise source or a device being tested.

Metal enclosures are mandatory for RF equipment and for this project I used a 4 x 4 x 2 in Bud Industries aluminum enclosure, which provided a perfect fit for all the pieces (figures 11 and 12). The PowerPole power jack requires a rectangular hole 1 x 1.25 in, which I cut with a 1 in square chassis punch and a nibbler. All other holes were cut with ordinary drills or a step-drill. The enclosure was painted with self-etching primer and satin sage spray paint after preparation (washing off cutting oil with lacquer thinner, roughing the surface with wet-dry sandpaper, cleaning again with lacquer thinner and final scrubbing in hot water with liquid soap). After the paint had cured for 48 hours, I installed the LED lens mounts and LEDs with a dab of 5-minute epoxy to keep the LEDs from coming loose from the mounts during installation of the other parts. The self-adhesive labels on the enclosure are made with a labeling machine with black lettering on clear background.

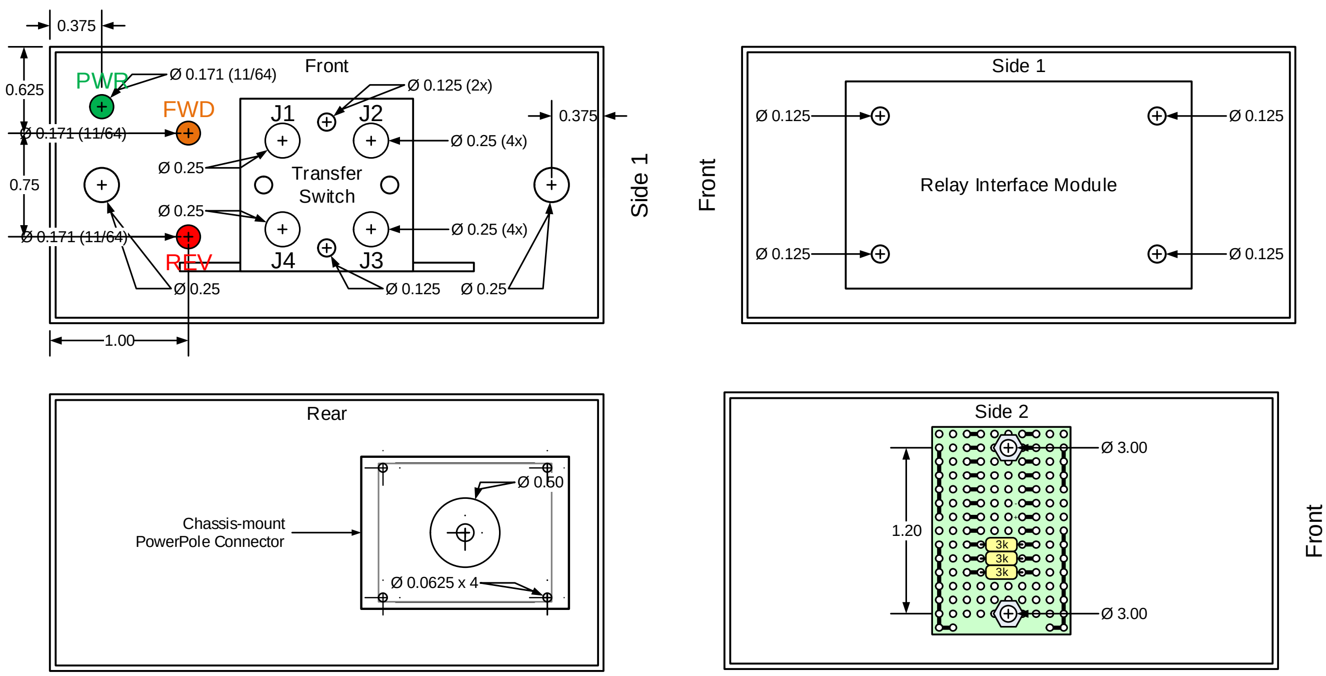


Figure 11 ~ Enclosure layout drawing shows the cutting and drilling dimensions. All dimensions are in inches unless noted otherwise. The transfer switch mounting dimensions will depend on the actual switched used. As mentioned in the text, the PWR LED may be eliminated.

For coaxial cable interconnections I use Mini-Circuits 141 series *Hand-Flex* cables with 0.141 in (3.6 mm) diameter and SMA connectors (http://www.minicircuits.com/products/test_flex.shtml); these are relatively inexpensive and their electrical parameters are very stable and well documented (figure 13). The length tolerance of this line of cables is 0.05 in (1.27 mm). Some builders may try to save a few dollars by making their own cables but this can prove to be false economics unless done very carefully. To further ensure calibration and measurement consistency, I uniquely color coded the cables and always connect them to the same port on the VNWA-3E and S-Parameter Test Set. I also use color-coded SMA male-female adapters on the VNWA-3E port connectors to reduce wear and tear (the adapters can be easily replaced whereas the port connectors cannot).

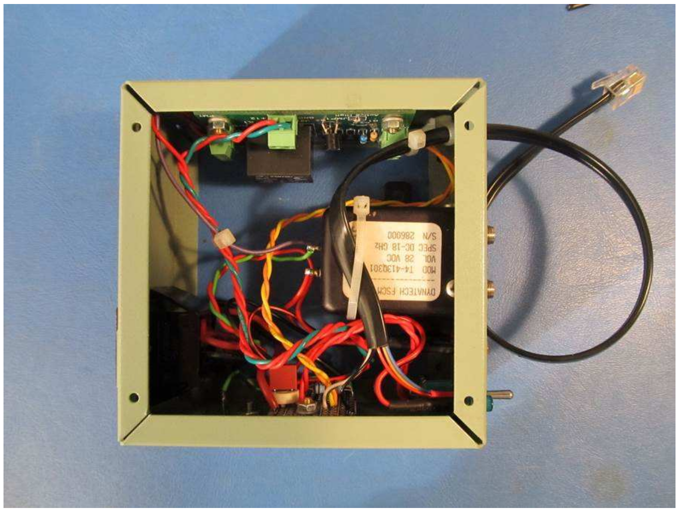


Figure 12 ~ Interior view of the test set shows that it is compact but not crowded. The transfer switch is on the right and relay interface at the top. The black cable with modular plug connects to the VNWA-3E control port.

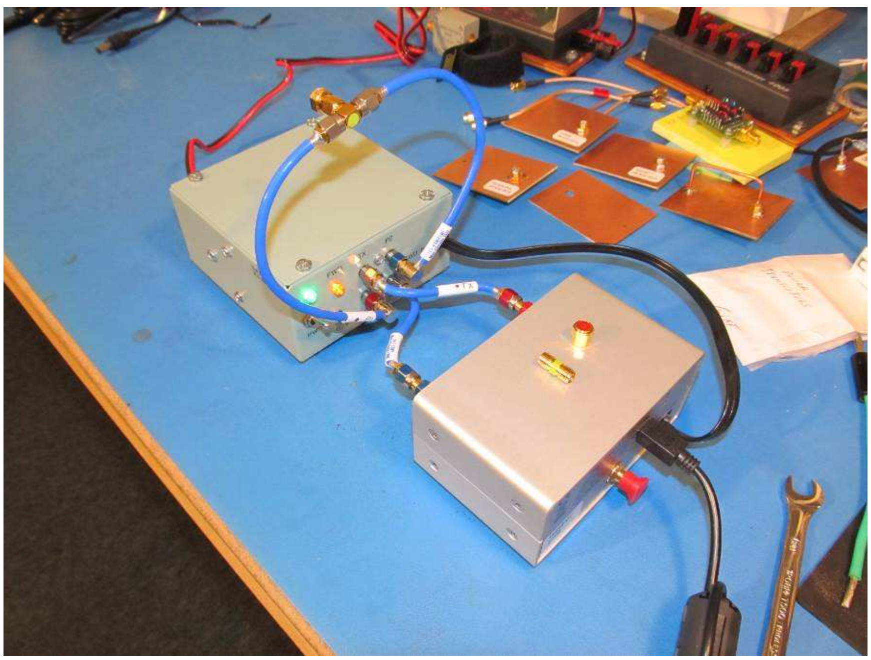


Figure 13 ~ S-Parameter Test Set and VNWA-3E interconnection cables are corrugated shield, semi-rigid Mini-Circuits *Hand-Flex* cables and have a blue jacket.

5. Setting Up and Testing the Test Set

Perhaps the most important aspect of VNA measurements is the calibration that is done before actual measurements are taken. For consistency, it is necessary that calibration be performed with the test set connected as it would be for later measurements. Any imperfections introduced by the test set and interconnection cables are cancelled out during the calibration process and thus become part of the calibration file used in later measurements. The VNWA-3E is allowed to warm up for at least 30 minutes before calibration and measurements.

To verify that the S-Parameter Test Set and added interconnection cables do not negatively affect device measurements I performed a series of tests as follows

- Calibrate the VNWA-3E by itself and measure some devices and components, connect the test set, recalibrate, remeasure and compare
- Calibrate the VNWA-3E by itself and perform a T-Check measurement, connect the test set, recalibrate, remeasure and compare

The utility of the comparative measurements in the first point above should be obvious. However, the T-Check requires additional explanation because it is a little known method. The T-Check is a VNA accuracy test described by Rhode & Schwarz in [R&S]. It is electrically and mechanically very simple requiring only a coaxial T-junction and 50 ohm load at the junction (the assembly is called a T-Adapter). After normal calibration, the T-Adapter is inserted between the two test ports of the VNA or test set (figure 14) and a set of measurements taken.

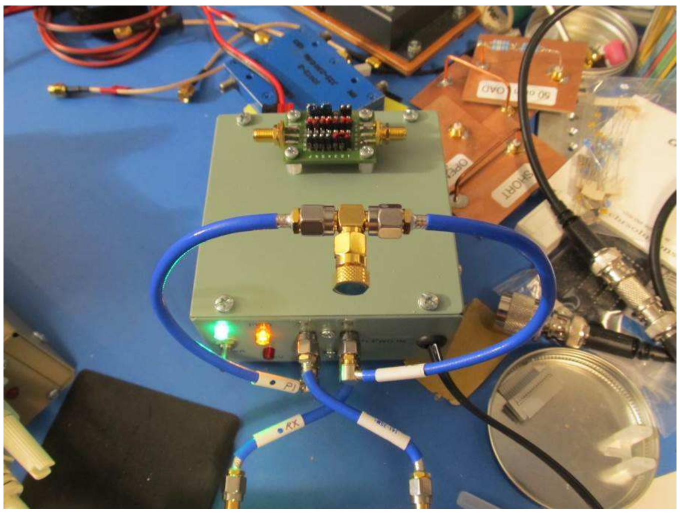


Figure 14 ~ T-Check connections. A coaxial tee-junction (center of image) with 50 ohm load on the branch is inserted between the two test set ports after calibration. The resulting s-parameter measurements are then used in the T-Check formula to calculate deviation from the ideal parallel 25 ohm impedance (50 ohm load in parallel with 50 ohm receive port on VNWA-3E).

The 50 ohm external load is in parallel with the 50 ohm internal impedance of the VNA receive port giving a combined impedance of 25 ohms. The VNA measures a full set of forward and reverse s-parameters and the software applies them to the following T-Check formula at each measurement point

$$\frac{\left|S_{11}S_{21}^{*}+S_{12}S_{22}^{*}\right|}{\sqrt{(1-\left|S_{11}\right|^{2}-\left|S_{12}\right|^{2})(1-\left|S_{21}\right|^{2}-\left|S_{22}\right|^{2})}}$$

where S_{21}^{*} and S_{22}^{*} are complex conjugates. This formula is setup by the user in the VNWA-3E software. For a perfect measurement the result is 100% (1.0, or no deviation) at each point. For practical measurements, there will be some deviation. Rhode & Schwarz uses a simple deviation grading system as follows:

- Green: 100 ± 10% (“Minor”)
- Yellow: 100 ± 10 to 15% (“Acceptable”)
- Red: 100 ± 15% and higher (“Unacceptable” or “Red alert”)

All the above comparative measurements showed very close correlation. In particular, the two T-Check measurements are very close (figure 15). After the validation tests are successfully completed, the S-Parameter

Test Set is proven to be transparent and ready to use with confidence. I normally leave it connected to the VNWA-3E even for 1-port measurements.

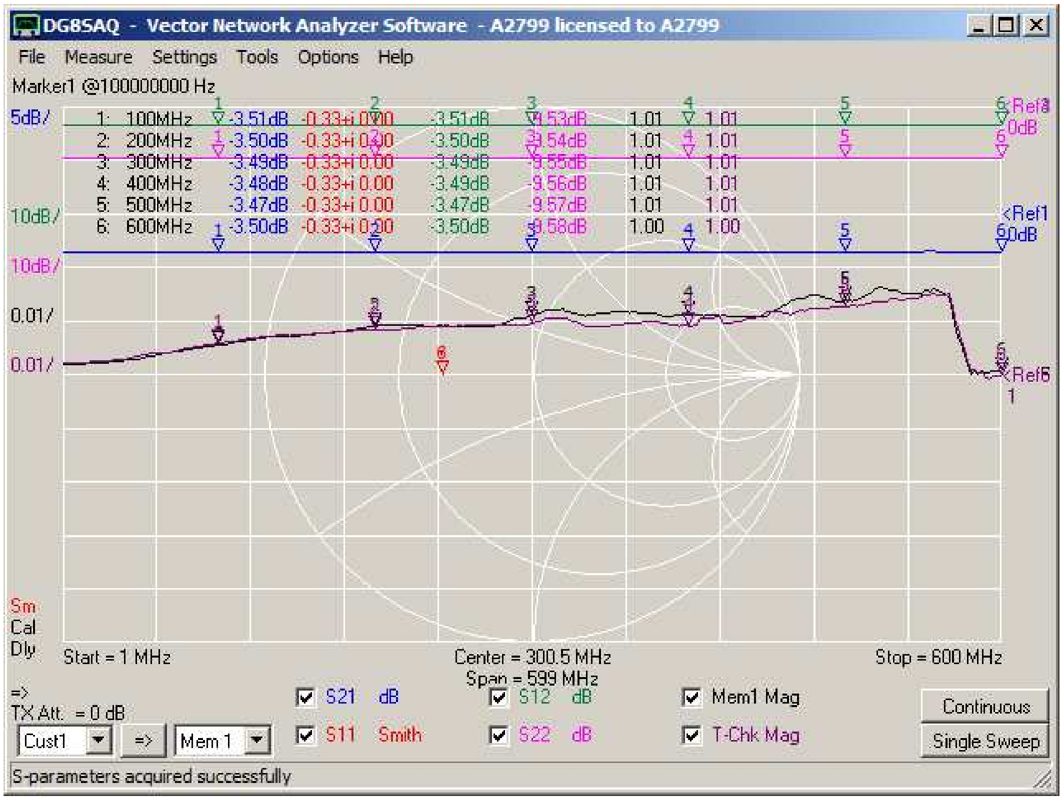


Figure 15 ~ Comparison of T-Check results for the VNWA-3E with and without the S-Parameter Test Set over a frequency range of 1 to 600 MHz (magenta and black traces, respectively, near the middle of the plot). The vertical scale for the two traces of interest is setup to indicate deviation of 1%/division. Ideally, the traces are horizontal lines at the 100% reference (5th grid division for this plot). The two traces are nearly identical and measured deviation from ideal is < 1.5% for both sets of measurements. The red triangle near the middle actually is six overlapping marker positions at 25 ohms on the Smith Chart overlay.

6. Conclusions

This article describes an inexpensive and easily built S-Parameter Test Set that turns the VNWA-3E into an automatic, bidirectional vector network analyzer, adding convenience and enhancing its usefulness. Measurements indicate that the test set is for all practical purposes transparent, a key requirement for accurate measurements.

7. Acknowledgements

I am grateful to Kurt Poulsen for his assistance setting up the T-Check measurements and for his technical review and comments on this article. Additional detailed information on using the VNWA-3E may be found on his website: http://www.hamcom.dk/VNWA-E.html.

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Author: Whitham D. Reeve
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Revisions: 0.0 (Draft started 5 Aug 2013)
0.1 (Revisions, 20 Aug 2013)
0.2 (Added images and edited text, 25 Aug 2013)
0.3 (Minor edits, 27 Aug 2013)
0.4 (Add'l edits, K. Poulsen comments, 30 Aug 2013)
0.5 (Switch isolation and VNWA-3E applications, K. Poulsen comments, 3 Sep 2013)
1.0 (Final edits for distribution, 22 Sep 2013)