

Building Version 2 of an S-Parameter Test Set for the VNWA-3E

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1. Introduction

In the fall of 2013 I wrote about a shop-built S-Parameter Test Set for the VNWA-3E vector network analyzer [{ReeveSPTS}](#). The test set (hereafter called version 1 or V1) enables automatic bi-directional S-parameter measurements and eliminates the inconvenience of swapping the input and output cables when making measurements on a 2-port device such as a filter or amplifier. The V1 test set performed very well but I decided to make a version that is electronically simpler and mechanically more convenient to use. The resulting version 2 test set is described in this paper (figure 1).



Figure 1 ~ Upper: Front view of S-Parameter Test Set V2 is rigidly mounted on the top of the VNWA-3E. The RF connections between the two units are through commercial coaxial cables with right-angle SMA connectors. Lower: Rear view. The test set is powered by an external 28 Vdc power supply, and the VNWA-3E is USB powered. A control cable connects the VNWA-3E to the test set. The red cap on the VNWA-3E protects the unused external synchronization input. Images © 2016 W. Reeve.

2. Circuit Description

The block diagram is identical for both V1 and V2 test sets (figure 2). 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. In V1, the relay interface controls an intermediate 28 Vdc relay. This 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 redesigned the relay interface in V2 to eliminate the intermediate relay and to use a minimum number of parts. Both versions use the same software setup 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 (see Appendix for VNWA-3E software settings).

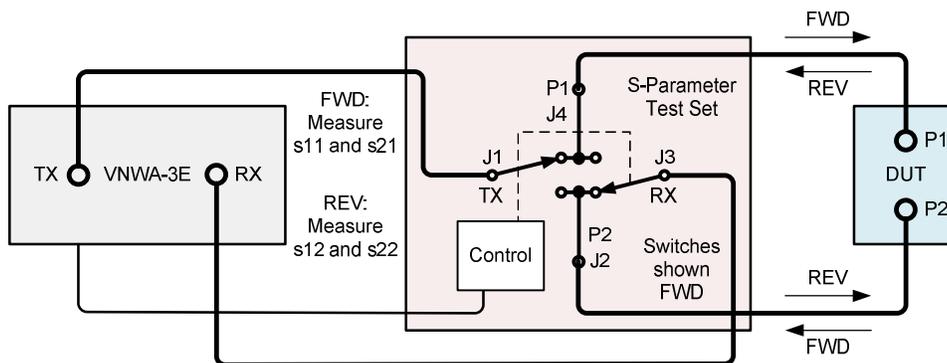


Figure 2 ~ System block diagram showing the S-Parameter Test Set in the middle. Key: P1 = Port 1, P2 = Port 2, TX = Transmit, RX = Receive, DUT = Device Under Test, FWD = Forward, REV = Reverse. Image © 2013 W. Reeve.

The V1 test set uses a Darlington transistor to control the intermediate relay. One disadvantage of the V1 design is that the VNWA-3E control interface could be exposed to 28 Vdc if the control transistor fails. To prevent such an over-voltage, I placed a 5.1 V zener diode across the relay interface input (refer to {ReeveSPTS} for a complete circuit description of V1). In the V2 test set I use an opto-isolator and MOSFET power switching transistor to control the coaxial transfer switch, thus eliminating the intermediate relay and possible over-voltage problem (figure 3). The resulting V2 test set is simpler, requiring only four components to control the transfer switch – a tiny opto-isolator integrated circuit, power MOSFET, a current limiting resistor and a bias resistor.

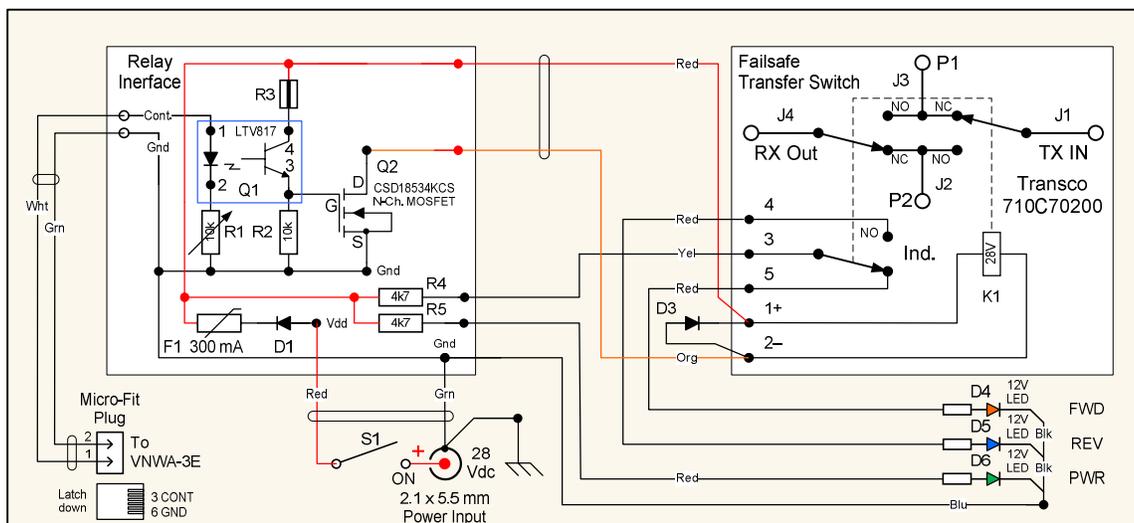


Figure 3 ~ S-Parameter Test Set V2 schematic. The relay interface is built on a small prototype printed circuit board. Image © 2016 W. Reeve

For the control input I chose the LTV-817 series opto-isolator because it can provide current transfer ratios up to 600% (that is, current gain up to 6X). However, the datasheet shows a 50% minimum CTR so I used that as an initial design value. The opto-isolator isolates the VNWA-3E control port from the 28 V power supply but they do share a common ground. About one-half of the control input voltage is dropped across the opto-isolator input LED. I used a series resistor to limit the control port drive current to < 0.3 mA at 3.3 V. I started with a 10k ohm current limiting resistor on the input. The input current is effectively transferred to the photo-transistor in the device output circuit; however, with the 10k ohm resistor on the input, there was not enough output current to bias the MOSFET into conduction when I reduced the control input voltage to 2.5 V (I used this lower voltage as a worst-case). Reducing the resistance to 6k ohms provided reliable switching, so I used a 10 kohm trimpot initially set to 6k ohm.



The CSD18534KCS power MOSFET current rating (73 A) is grossly over-sized for this application but it only cost a little more than 1 USD. I found by measurement that with a control input voltage of 3.2 V and input current of 0.3 mA, the opto-isolator provides an output current of 0.41 mA into the 10k ohm gate bias resistor, or 133% current transfer ratio. This biases the MOSFET gate at 4.1 V, causing it to switch on with about 0.8 mV drop from drain to source, equivalent to an on-resistance of 8 milliohms. The bias voltage and on-resistance are very close to the typical datasheet values for this MOSFET.



The transfer switch is the fail-safe type (same type but different model than V1). This means that when power is removed from the switch, it releases to its normally closed position if it is not already there. I chose the fail-safe type because the transfer switch always is in a known position (released) with no power applied to test set. Conversely, a latching switch remains in its last position when power is removed.



The switch I used has position indicating contacts, and I wired them to LED indicators through a common 4.7k ohm current limiting resistor chosen for 5 mA current with a 28 Vdc operating voltage. I determined the resistor value experimentally because the prewired LEDs I have in stock already include voltage dropping resistors for nominal 12 V operations.

In addition to the operating mode the important attributes of the transfer switch are frequency range, operating voltage, port-port insertion loss and port-port isolation. The VNWA-3E nominal frequency range is 100 kHz to 1.3 GHz, but it can be configured for frequencies below and above. To accommodate this range with some margin, the transfer switch should have a frequency range of at least dc to 2 GHz.

The most common transfer switch voltage is 28 Vdc, and that is the voltage required by the switch in the V2 test set. However, other voltages are available and could be adapted without much trouble. The Transco switch in V2 draws slightly more than 100 mA when activated. To reduce inductive kickback from the switch coil, I installed a diode directly across the coil terminals rather than put the diode on the relay interface board.

High 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 transmit and receive ports. In practical systems, there is some crosstalk coupling between transmit and receive ports due to leakage. The Transco

transfer switch datasheet shows minimum 80 dB isolation from dc to 1 GHz and 60 dB from 1 to 4 GHz. Measurements discussed later verify these specifications to 1.3 GHz.

Power is applied to the test set through a coaxial dc power jack, SPST toggle switch, polarity guard diode and a 300 mA, 60 V PTC resettable fuse. Power On is indicated by a prewired 12 V LED with a 4.7k ohm external voltage dropping resistor. The power indicating LED could be eliminated because one or the other transfer switch position indicating LEDs always is on when power is applied.

3. Component Selection and Construction

The bill of material (BOM, table 1) lists all parts used in V2 of the S-Parameter Test Set. The most critical component is the coaxial transfer switch, which should be of the highest possible quality. Used high quality switches are available from online auctions and used microwave equipment sellers for around 25 USD and up. Although a Transco p/n 710C70200 transfer switch is shown in the BOM, a Teledyne p/n CS37S1C and undoubtedly others also will fit the enclosure shown in the BOM (the critical dimensions are height and depth). The remaining parts cost around 25 USD and the six interconnection cables cost about 85 USD (the V1 test set uses only two interconnection cables).

Table 1 ~ Bill of Material for V2 S-Parameter Test Set (items marked "Generic" are not critical)

Item	Qty	P/N	Manufacturer	Description
1	1	710C70200	Transco (Dow-Key)	Coaxial transfer switch, fail-safe, 28 Vdc (see text)
2	1	B3-080-SI	Box Enclosures	Enclosure, extruded aluminum, silver anodized, 104 x 44 x 80 mm
3	1	MF-R030	Bourns	PTC resettable fuse, 300 mA hold current, 60 V
4	1	Generic	Generic	2.1 x 5.5 mm coaxial dc power jack
5	1	Generic	Generic	Toggle switch, SPST, sub-miniature
6	1	CSD18534KCS	Texas Instruments	Power MOSFET, N-channel, 60 V
9	1	LTV-817	Lite-On	Opto-isolator integrated circuit, $\geq 50\%$ CTR
10	1	1N5819	Generic	Diode, Schottky, 1 A, 40 V
11	1	1N4002	Generic	Diode, 1A, 100 V
12	1	Generic	Generic	LED, green, prewired (see text) 12 V, 3 mm, power indicator
13	1	Generic	Generic	LED, amber, prewired 12 V, 3 mm, forward indicator
14	1	Generic	Generic	LED, blue, prewired 12 V, 3 mm, reverse indicator
15	1	43640-0200	Molex	Plug, panel mount, 2-position Mini-Fit
16	1	43645-0200	Molex	Jack, cable housing, 2-position Mini-Fit
17	1	43031-0007	Molex	Male terminal contact, 20-24 AWG (for Mini-Fit plug)
18	1	43030-0010	Molex	Female terminal contact, 26-30 AWG (for Mini-Fit housing)
19	1	5-555042-3	AMP (TEC)	Modular plug, 6-position, 6-contact
20	1	Generic	Generic	Resistor, 10k ohm, 5%, 1/4 W
21	1	3296W-103	Bourns	Trimpot, 10k ohm, 1/2 W (preset to 6k ohm)
22	3	Generic	Generic	Resistor, 4k7 ohm, 5%, 1/2 W
23	2	Generic	Generic	Prototype printed circuit board, cut to size as required
24	2	Generic	Generic	Standoff, male-female, M3 x 5 x 6 mm (PCB mounting)
25	2	Generic	Generic	Machine screw, pan head, M3 x 8 mm
26	2	Generic	Generic	Hex nut, 3 mm
27	4	Generic	Generic	Washer, internal star, 3 mm
28	1	7317	Keystone	Ground terminal lug, internal star, #4 stud
29	2	Generic	Generic	Machine screw, pan head, 4-40 x 0.375 in

30	4	Generic	Generic	Hex nut, 4-40
31	3	Generic	Generic	Washer, flat, #4
32	7	Generic	Generic	Washer, internal star, #4
33	2	Generic	Generic	Machine screw, pan head, 4-40 x 0.25 in
34	4	Generic	Generic	Machine screw, flat head, 4-40 x 0.375 in
35	1	Generic	Generic	Standoff, insulated, 4-40
36	36 in	WH24-0X	NTE	Stranded hookup wire, 24 AWG, 300 V, X = color
37	4.5 in	Generic	Generic	Modular cord, 4 or 6-conductor (see text)
38	2	141-3SM+	Mini-Circuits	Hand-Flex cable, SMA-M : SMA-M, 0.141 in dia., 3 in long
39	4	086-4SBSMR+	Mini-Circuits	Hand-Flex cable, SMA-FB : SMA-MRA, 0.086 in dia., 4 in long

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

The control cable requires a 6-position, 6-contact modular plug (usually called RJ11 or RJ12) of the type used on telephone cords; however, most telephone cords use only two or four conductors on positions 3 and 4 or 2, 3, 4, and 5. The VNWA-3E uses positions 3 (control) and 6 (ground). There are two alternatives: 1) Make your own cable using a modular plug, a 4- or 6-conductor telephone cord and associated crimping tool available at most hardware or electronics stores (be sure the plug has 6 contacts); or 2) Find a modular cord with a 6-conductor cable and cut it to length. If you make your own with a 4-conductor cable, it needs to be offset to one side of the plug so that the wires terminate on positions 3, 4, 5 and 6. The modular plug pinout is shown in the lower-left corner of the schematic. The cable is terminated at the test set end on the Mini-Fit cable housing jack.

I used a piece of 1 x 3 in prototype printed circuit board for the relay interface (figure 4) but it could be much smaller. The type of construction is not critical. Brass standoffs hold the PCB to a sidewall in the enclosure. The rear panel holds the On-Off toggle switch, coaxial dc power jack and control input plug. The front panel holds the RF connectors and LED indicators.

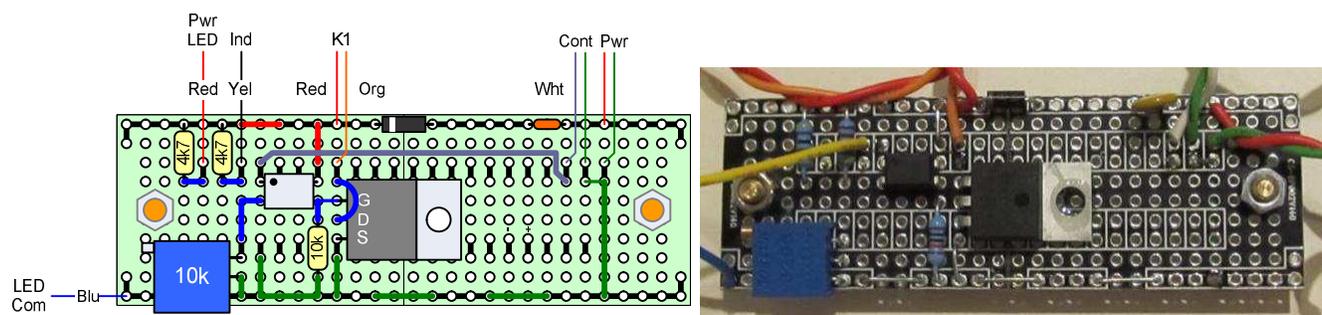


Figure 4 ~ Left: Scaled Visio drawing of the relay interface circuit board; dimensions are 1 x 3 inches. All components except the kickback diode across the transfer switch coil are mounted on the board. Right: Photo image of the finished board. The board was prewired with pigtailed and tested prior to mounting in the enclosure. Image © 2016 W. Reeve.

Since one of my goals was to physically match the S-Parameter Test Set to the VNWA-3E, I had to decide whether to build or buy an enclosure. I spent considerable time searching for a manufactured unit of the right dimensions and found one reasonably close so I decided to buy. The VNWA-3E dimensions are 104 x 50 x 68 mm not including connectors. The closest I could find is an extruded aluminum enclosure by a company

(appropriately) called Box Enclosures & Assembly Services with dimensions 109 x 45 x 81 mm, within 5mm in width and height but slightly deeper than the VNWA-3E. This enclosure is a tubular type and not split into two halves, making component installation somewhat tedious. The test set's coaxial transfer switch, relay interface and cables take up considerable space, but with a little layout planning I got everything to fit.

I laid out the panels in Microsoft Visio and printed the paper templates, which I taped to the blank panels for marking and then drilling (figure 5). The panel-mounted control plug is the only component with an odd shape. I drilled a series of 2.5 mm holes and then used jeweler's files for final shaping. I used a small amount of epoxy on the back of the front panel to hold the three LEDs in place. The self-adhesive labels on the enclosure are made with a labeling machine with black lettering on clear background (figure 6).

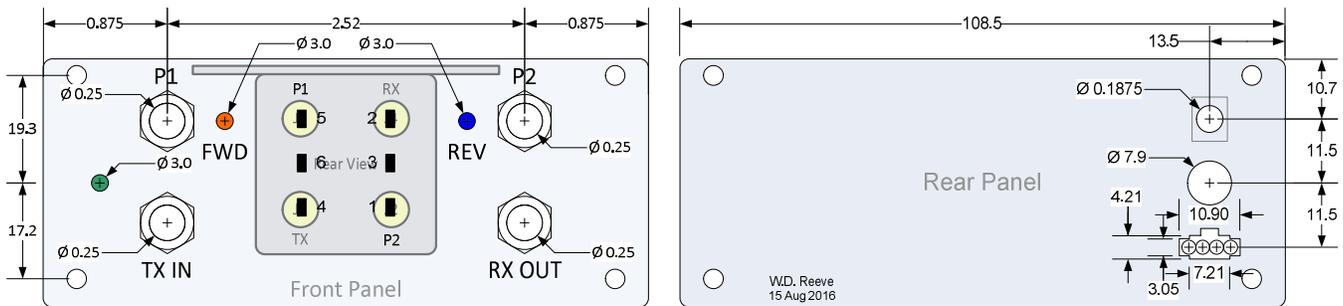


Figure 5 ~ Enclosure layout drawing shows the cutting and drilling dimensions. Dimensions in inches and millimeters accommodate datasheet values. The transfer switch mounting will depend on the actual switch used; in this case, I mounted the transfer switch on the enclosure ceiling so that its switch ports line up with the VNWA-3E ports. Image © 2016 W. Reeve.



Figure 6 ~ Front (left) and Rear (right) end panels. Labeling is with black on clear labels. What appear to be three empty holes in the front panel are the clear lenses of the power and transfer switch position indicating LEDs. In the right image, the control connector is between the power toggle switch (above) and dc power jack (below), but after cutting the holes I realized the dc power jack should have been placed between the switch and control connector to eliminate minor mechanical interference between the two cables. The Visio layout drawing in the previous figure is correct. Images © 2016 W. Reeve

I cut most holes with a pilot drill and enlarged as needed with another drill or step-drill. The LED holes need to be 3.0 mm diameter unless an LED holder is used. Two holes need to be cut in the upper clamshell cover of the VNWA-3E and matching holes need to be cut in the floor of the test set's tubular enclosure. To ensure alignment, I clamped the two parts together and cut with a tap drill. I then enlarged the holes in the VNWA-3E cover with a clearance drill and tapped the holes in the test set.

For internal coaxial connections I used Mini-Circuits 086-series *Hand-Flex* cables that have 0.086 in (2.2 mm) diameter and SMA connectors {MCL}. The connectors at the switch end are right-angle type. For external connections from the VNWA-3E to the test set I initially used the same series cables but later changed to the MCL 141-series *Hand-Flex* cables that have 0.141 in (3.6 mm) diameter. Both sizes use a solder-flooded braid, are relatively inexpensive and their electrical properties are very stable and well documented. Although Mini-Circuits will make cables having any length, I used their standard catalog cables: 4 in for the interior cables and 3 in for the exterior cables. The length tolerance of the *Hand-Flex* cables is 0.05 in (1.27 mm). A double-braid coaxial cable like RG-316/U could be substituted for the Mini-Circuits cables but considering the connector costs and tedium of SMA connector installations there may not be any worthwhile cost savings.

The transfer switch takes up the most space and the interior cables need to be routed around it and the relay interface board (figure 8). The power switch, power jack and control connector extend into the enclosure and need to be mounted to one side to avoid the interfering with the transfer switch and associated cables. Because of the enclosure's tubular construction, I had to install the parts in a specific, time-consuming order after cutting all the holes and test-fitting the individual parts. First, I installed the four cables on the transfer switch, torquing the connectors to 8 in-lb (90 N-cm) as recommended by Mini-Circuits. Next, I mounted the transfer switch inside the enclosure using flat head screws. I then mounted the pigtail-equipped relay interface board and wired it to the transfer switch and front panel. I also wired the front panel LEDs to the transfer switch and relay interface board. With the front panel wiring done, I installed the SMA bulkhead connectors on the panel and fasten the panel to the enclosure. Next, I prewired the rear panel and connected the pigtails from the relay interface to the rear panel. After fastening the rear panel to the enclosure and mounting the whole assembly to the top of the VNWA-3E, I installed the two interconnecting cables, torquing them to 8 in-lb (90 N-cm).

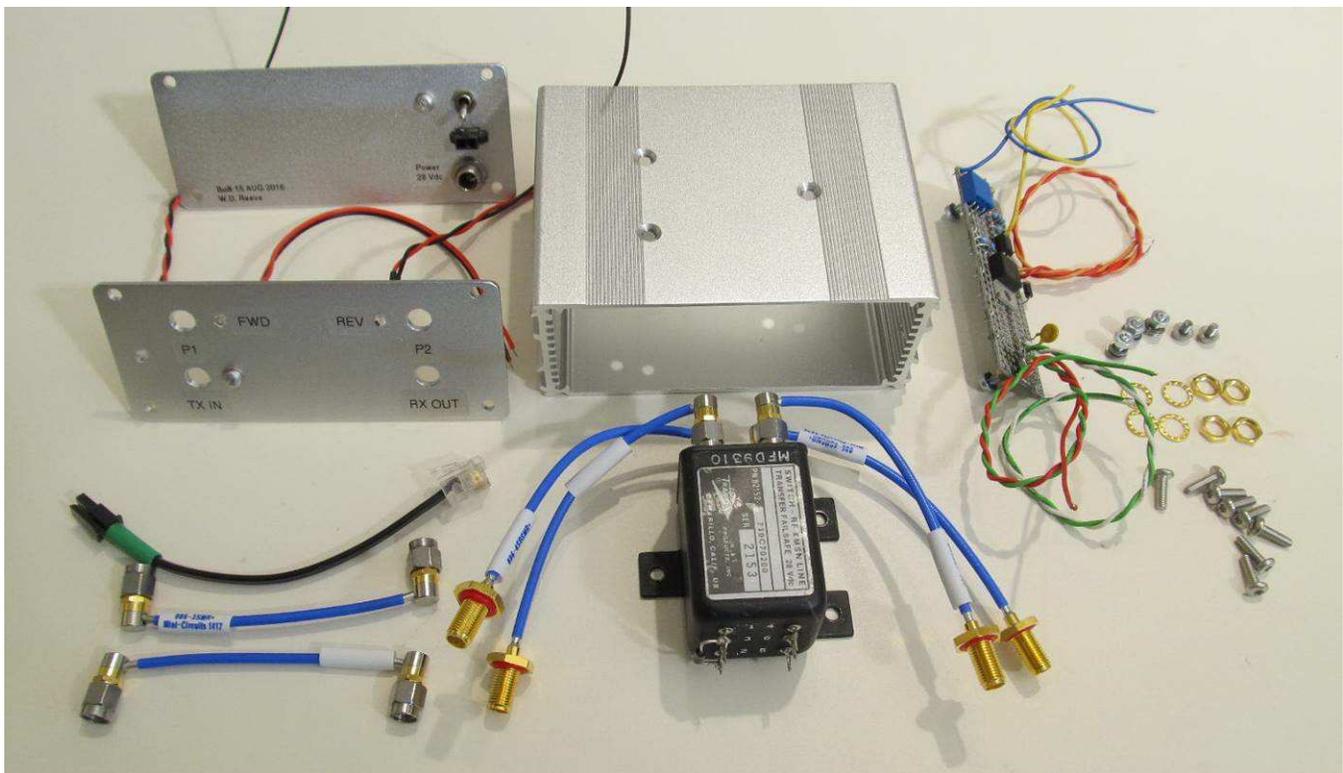


Figure 8 ~ All components and subassemblies predrilled and ready for installation. The front and rear panels (upper-left) and relay interface board (upper-right) have been prewired, and the internal coaxial cables have been pre-installed on the transfer switch (lower-middle). The two cables with blue sheath (lower-left) connect the S-Parameter Test Set to the VNWA-3E TX Out and RX In connectors. After this image was taken I replaced them with 0.141 in diameter cables. The black cable on the left is the control cable between the test set and VNWA-3E. Image © 2016 W. Reeve

4. Testing the Test Set

To verify that the S-Parameter Test Set and interconnection cables do not negatively affect device measurements I performed a series of tests as follows (these are the same tests used with V1):

- ⚙ Calibrate the VNWA-3E by itself and measure its port isolation, connect the test set, remeasure and compare
- ⚙ Calibrate the VNWA-3E by itself and perform a T-Check measurement, connect the test set, recalibrate the combination, remeasure and compare

The VNWA-3E was allowed to warm up for a couple hours before calibration and measurements, and calibrations were made with Rosenberger SMA-female calibration standards.

I found with the V1 measurements that isolation varies slightly with the way the VNA ports are terminated – open circuit, short circuit, 50 ohms or something else; also, the measurements varied slightly with each sweep (up to 5 dB) – showing that consistent measurements involving very low signal levels are very difficult to make. I decided to make all isolation measurements with both ports terminated in 50 ohms (figure 9).

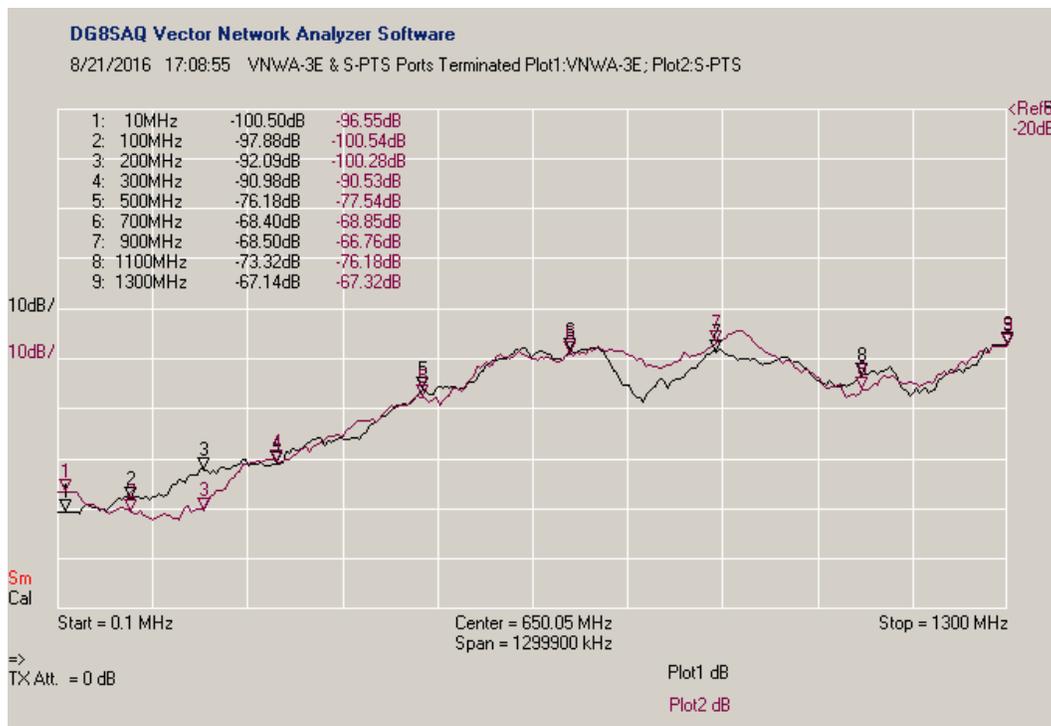


Figure 9 ~ Crosstalk coupling loss (isolation) was measured in the forward (S21) and reverse (S12) directions from 0.1 to 1300 MHz with 50 ohm terminations on both ports. Only the forward direction is shown here. Black trace: VNWA-3E by itself (transmit and receive ports terminated); Purple trace: Combination of S-Parameter Test Set and VNWA-3E (P1 and P2)

terminated). These results indicate only slight degradation at some frequencies and slight improvement at others; however, these differences could be due to measurement errors at extremely low signal levels. All measurements are in dB below the transmit power level. For example, a measurement of -80 dB indicates +80 dB isolation between the input and output ports. The plot reference is -20 dB at grid division 10 (top of plot) and the vertical scale is 10 dB/division. The markers indicate the coupling at selected frequencies.

As I mentioned in my V1 paper, the T-Check is a VNA accuracy test described by Rohde & Schwarz in [{T-Chk}](#). It is electrically and mechanically very simple, requiring only a coaxial T-junction and 50 ohm load at the branch (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 10) and a set of measurements taken.



Figure 10 ~ T-Check connections. A coaxial tee-junction (top-center of image at end of blue cables) with 50 ohm load on the branch is inserted between the two test set ports after calibration (calibration includes the two test cables). 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 the VNWA-3E). Image © 2016 W. Reeve

The 50 ohm external load on the T-Adapter 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

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

where S_{21}^* and S_{22}^* are complex conjugates. This formula is setup by the user in the VNWA-3E software as a text entry in a Custom Trace:

$$abs(s11*conj(s21)+s12*conj(s22))/(sqrt((1-abs(s11)^2-abs(s12)^2)*(1-abs(s21)^2-abs(s22)^2)))$$

For a perfect measurement the result is 100% (1.0, or no deviation) at each point. For practical measurements, there will be some deviation. Rohde & 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*)

The T-Check measurements of the VNWA-3E and V2 S-Parameter Test Set combination yielded good results with better than 96 to 101% (green) reading throughout the frequency range (figure 11).

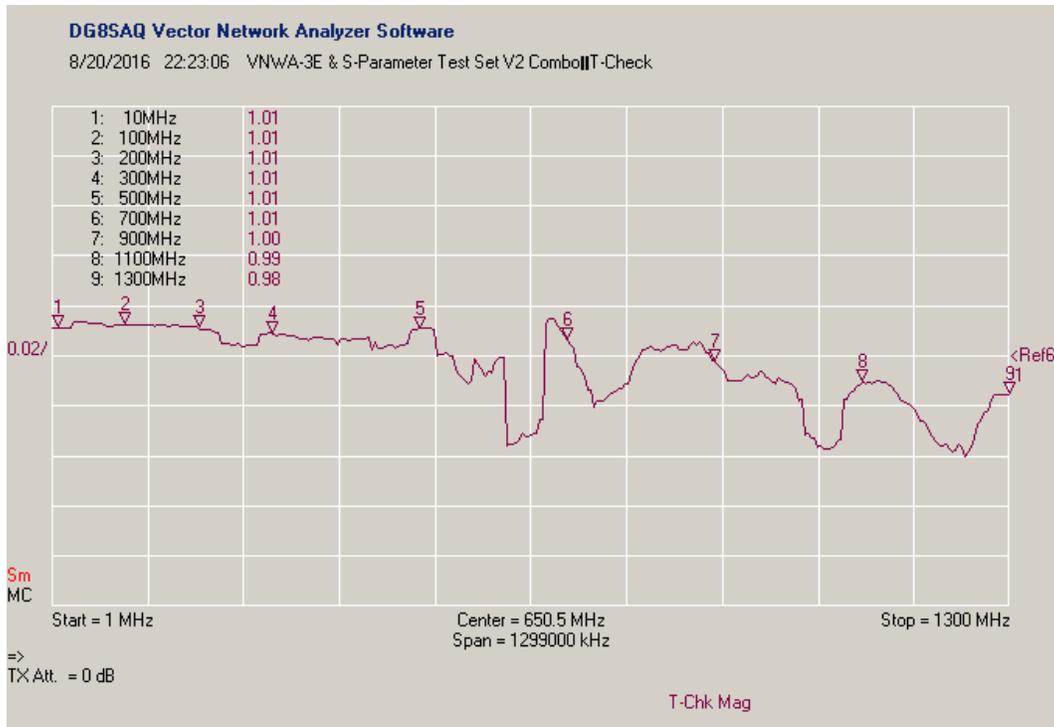


Figure 11 ~ T-Check results for the VNWA-3E and S-Parameter Test Set combination over a frequency range of 1 to 1300 MHz. The T-Check is setup as a Custom Trace labeled “T-Chk Mag”. The vertical scale is adjusted for a deviation of 2%/division with 100% on the 5th grid division. Ideally, the trace is a horizontal line at the 100% reference. The actual measured deviation from ideal is < 5% over the entire frequency range, which is considered a “Minor” deviation (see text).

I have made many comparative measurements and noticed no difference between the V1 and V2 test sets. A set of s-parameter measurements on a bandpass filter from 100 kHz to 100 MHz consistently showed < 0.05 dB difference. This is quite remarkable given that the uncertainty in the measurements probably exceeds 0.5 dB.

5. Conclusions

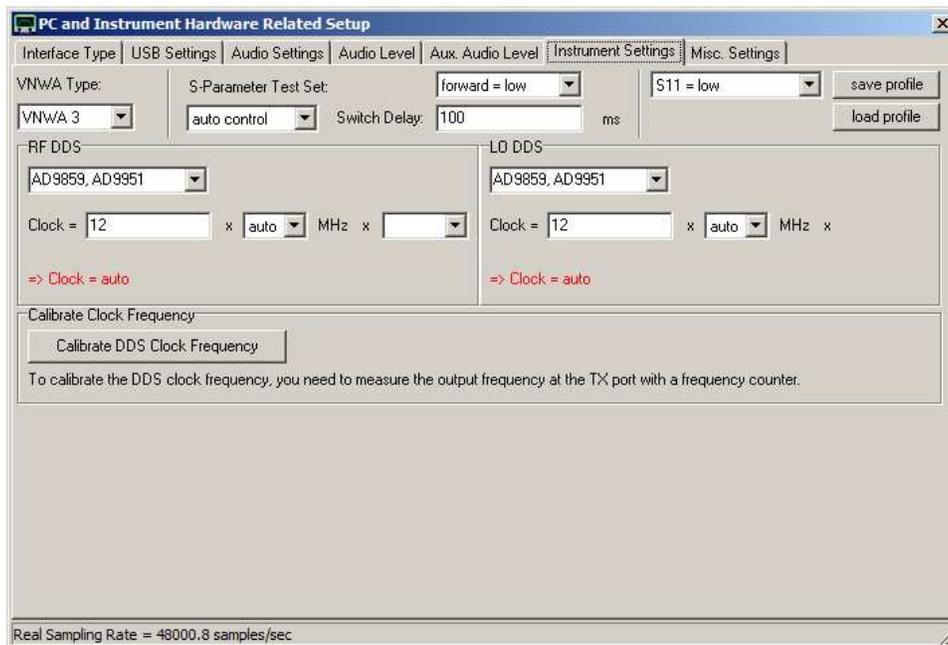
This article describes version 2 of an inexpensive and easily built S-Parameter Test Set for the VNWA-3E. Its performance is identical to version 1, but it is easier to store and can be moved without disturbing the interconnection cables. The cost of V2 is higher than V1 because V2 uses four additional high-quality coaxial cables.

6. References

- {MCL} http://www.minicircuits.com/products/test_flex.shtml
- {ReeveSPTS} Reeve, W., Building an S-Parameter Test Set for the VNWA-3E Vector Network Analyzer, 2013: http://www.reeve.com/Documents/Articles%20Papers/Reeve_S-ParamTestSet.pdf
- {T-Chk} T-Check Accuracy Test for Vector Network Analyzers Utilizing a Tee-junction, 1EZ43, Rohde & Schwarz, 1998:

Appendix

The screenshot below shows the VNWA-3E software settings appropriate for the S-Parameter Test Set (both V1 and V2). These are accessible from Options menu – Setup – Instrument Settings tab. The Switch Delay setting determines how long the software waits between completing the forward sweep and beginning the reverse sweep to provide time for the transfer switch to settle. Different setups can be saved in profiles if desired. The RF DDS and Calibrate Clock Frequency settings on this tab are unrelated to the S-Parameter Test Set.



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