Accurate Calibration of Vector Network Analyzer

When various models of test equipment are in use for a given product line, department or application, each with varying capability, it makes sense to use a procedure that can be used by both older and newer models to calibrate the test system. Due to technological advancements, the newer equipment will likely have better resolution, smaller error terms, improved repeatability and / or capabilities that allow the measurement error, dynamic range, etc. to be improved. The goal of this document is to present a procedure that can be used by all Agilent network analyzers currently in use throughout the company including, 8720,8722,8753,5070 and PNA series analyzers. The error term will be tied to the measurement error of the equipment being utilized, cleanliness of the standards and system components (connectors, cables, etc.) consistency of applied torque during the calibration process and the quality, and the repeatability of the contact / grounding upon insertion of the DUT into the test fixture. The contribution of most of these terms can be minimized by performing a careful, thorough calibration.

First and foremost a calibration will be limited by the worst component of the system. Included in this “system” are the VNA, cables, adapters, calibration standards test fixture and any thru line that represents fixture performance. The VNA should be calibrated by an authorized facility and the standards verified at least once (preferably twice) annually. Each connector interface should be clean and free of lint, dirt, debris etc. The calibration standards should be carefully cleaned as needed. Typically this is one or more times daily in a production environment. Lint free swabs are available for this purpose and are recommended as they will minimize the chance of damaging the pin and there are no fibers to get lodged in the inner contact or center conductor interface. These may be dampened with a small amount of Isopropyl Alcohol. Since typically the connectors mating the test cable to the VNA are rarely removed, once it is determined that these are clean and in good condition there is no need to remove them every time for cleaning. A nylon brush dipped in alcohol is adequate for cleaning the threads. Refer to Figure 1 below.

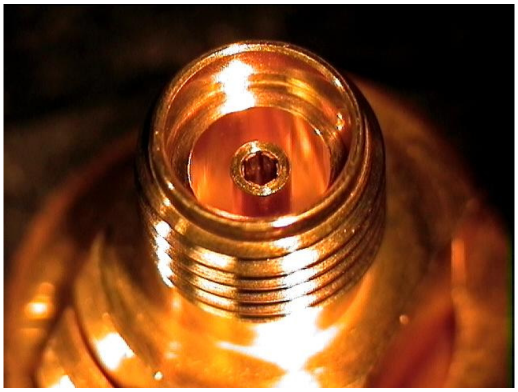

Figure 1 – a clean 3.5mm female adapter

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One key to making repeatable measurements is the use of a breaking style torque wrench set at 6-8 in/ lb for use during calibration (and test in the case of coaxial devices). Within Agilent there has long been discussion over which value is correct 6 or 8 in / lb but for the sake of consistency I recommend we use 8 in/ lb as the standard. This does not cause excessive wear on the adapters and allows for a solid connection and good contact at the reference plane. These should be calibrated at least once annually. Figure 2 shows a "break-away" style torque wrench commonly used for this application.

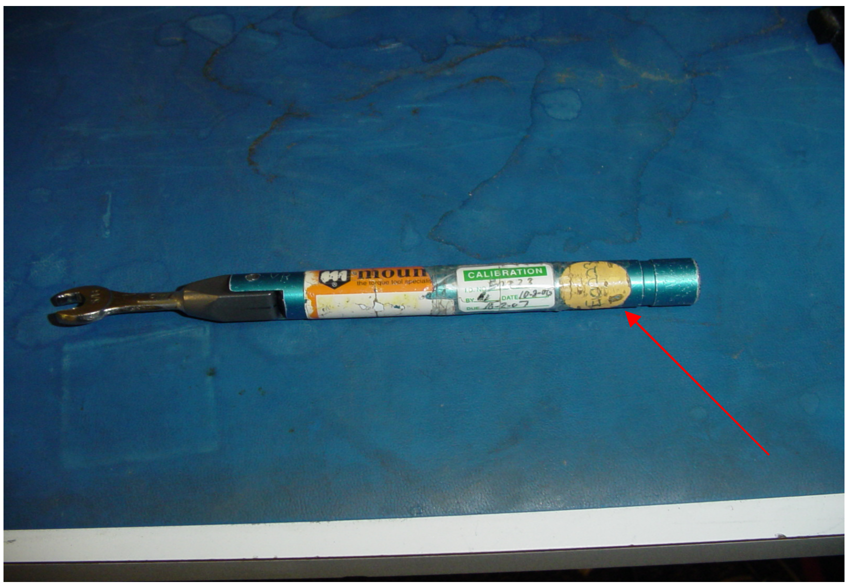

Figure 2 – "breaking" style torque wrench, note calibration sticker

To effectively correct for all reflections, insertion losses phase errors as well as to allow the same calibration to be performed on all equipment currently in use the 'substitution' method of calibration is recommended. This was the preferred calibration method for 'non-insertable" devices such as drop-in circulators per Agilent for many years prior to the advent of newer means such as E-Cal kits, smart cals, etc. To accomplish this, the use of phase matched adapters is required. The recommended adapters are Maury Microwave 8021, 3.5mm precision adapters. These are phase matched in series adapters and as such have the same electrical length regardless of gender. These are installed onto the end of the cables intended to be used for test and will mate to the test fixture once the calibration is complete (refer to Fig. 3 below). Typically the test cables terminate in an SMA male so a Maury 8021C2 (male to female) would be installed on the end of each cable prior to beginning the calibration procedure. A third adapter, a Maury 8021A2 (female to female) will be required during the calibration process.

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Prior to beginning the calibration the network analyzer should be configured as follows:

Frequency: Look up operating frequency in chart below and set VNA using the "Swept" frequency values.

	Operating Frequency Band **(MHz)**		Swept Frequency, Start **(MHz)**	Swept Frequency, Stop **(MHz)**	Swept Frequency, Center **(MHz)**	Span Frequency **(MHz)**	Marker 1 **(MHz)**	Marker 2 **(MHz)**	Marker 3 **(MHz)**
MODEL	**F1**	**F2**	**F_start**	**F_stop**	**Center**	**F_span**	**M1**	**M2**	**M3**
882	869	894	***782***	***982***	882	200	***869***	***882***	***894***
902	890	915	***802***	***1002***	902	200	***890***	***902***	***915***
940	920	960	***840***	***1040***	940	200	***920***	***940***	***960***
943	925	960	***843***	***1043***	943	200	***925***	***943***	***960***
1747	1710	1785	***1647***	***1847***	1747	200	***1710***	***1747***	***1785***
1843	1805	1880	***1743***	***1943***	1843	200	***1805***	***1843***	***1880***
1960	1930	1990	***1860***	***2060***	1960	200	***1930***	***1960***	***1990***
2018	2010	2025	***1918***	***2118***	2018	200	***2010***	***2018***	***2025***
2140	2090	2190	***2040***	***2240***	2140	200	***2090***	***2140***	***2190***

Table 1: Frequency and Marker Settings.

Span: For small percentage bandwidth designs (<10%) set to 200MHz.
IF Bandwidth: Set to 1kHz to allow reasonable sweep times but reduce noise.
Averaging: None (except during calibration if desired)
Smoothing: None
Scales / Reference: Log format reference should be set at position 7 (3 divisions from top); Polar: 200mU. See Chart below for additional details.

S-Parameter	**S11**	**S12**	**S21**	**S22**
Channel	1	3	2	4
Position on Split Displays	Upper Left	Lower Left	Upper Right	Lower Right
Scale/Div	5	5	0.2	5
Reference Position	3 divisions below top	3 divisions below top	3 divisions below top	3 divisions below top
Reference Value	-20 dB	-20 dB*	0 dB	-20 dB
Port Extensions	Polar Only - fixture dependant	-	-	Polar Only - fixture dependant

Table 2: VNA Display Formatting

Perform a full 2 port S-parameter calibration using the proper cal kit that has the correction factors stored in the network analyzer for the calibration kit being used, including the revision. Refer to the manufacturers' user manual for the calibration kit being used for additional detailed information regarding the calibration standards. The use of "averaging" during the calibration can improve the correlation and is

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recommended; this is especially helpful when lower quality test cables are being utilized and as test frequencies increase. It may be turned off after the calibration is completed, prior to saving the calibration. Another step that may be taken to minimize noise at a minimal impact to measurement speed and that is to reduce the IF bandwidth to 1kHz.

The manual standards for the "short", "open" and "broadband load" (SOLT) shall be used to perform the reflection part of the calibration at each port. Prior to their use their condition and cleanliness should be verified as outlined above. The standards should be installed by hand initially. This minimizes the chance of cross threading and subsequent damage. Under no circumstances should the connector, cable or calibration standard be rotated as this will cause excessive wear over time at the reference plane interface. The 8 in / lb torque wrench should be used to torque each connection during the calibration process.

For the transmission part of the measurement, remove one of the Maury 3.5mm 8021C2 (male to female) adapters and replace it with a Maury 8021A2 (female to female) adapter (refer to Fig. 4 below). We can now connect the cables together using the adapters (refer to Fig. 5). Since these adapters are phase matched and electrically identical, the insertion loss of the adapters and the cables will be removed once the calibration is complete. Torque each nut using the torque wrench. Measure all 4 S-parameters as you normally would during the "transmission" part of the measurement. Omit the isolation portion of the calibration as it is not needed. Finally, save the calibration, naming it if desired.

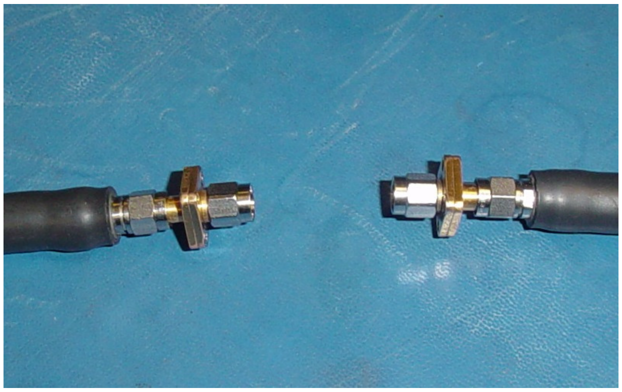

Figure 3: Maury 8021C2 adapters installed on test cables.

Lastly, the calibration should be verified. While the Maury 8021A2 (female to female) and the 8021C2 (male to female) are still connected verify the transmission portion of the calibration. Measure S11 and S22 and be sure they are < -50dB, S12 and S21 should appear linear and if a slope does exist it should be monotonic and measure <-0.02dB. If circulators will be tested, the 3rd port will need to be terminated with a high quality coaxial termination. Typically, the 3 ports of a circulator are symmetrical. The measured isolation is a function of the return loss of port 3 (S33), the launch and the quality of the

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50 ohm termination installed on the test fixture. To minimize the effects of the termination, it should measure < -40dB return loss across the operating frequency band if possible. This typically requires measuring several terminations until one is found that is of sufficient quality. A convenient time to verify this is while the Maury 8021A2 (female to female) is still connected to the cable. Disconnect the Maury 8021A2 (female to female) from the 8021C2 (male to female) and test several inexpensive male coaxial terminations until one that measures <-40dB is found (not calibration standards). Now, remove the Maury 8021A2 (female to female) adapter and replace it with the Maury 8021C2 (female to male) adapter. Torque the "broadband load" onto the adapter on port 1 and measure S11. Worst case return loss for S11 should measure <-50dB. Repeat for port 2 (S22). If the calibration does not meet these values it is recommended that the cables, standards and adapters be inspected using a 10x microscope for damage, debris and fibers that could be causing the degradation. Refer to Agilent document titled "Repair Manual 3.5mm and Type N slot-less contact". If a good calibration cannot be obtained inspect the calibration kit, cables, and adapters and be sure they are clean and in good condition. If a subsequent attempt fails to yield an acceptable calibration, change out one component of the test system at a time, starting with adapters and cables, then calibration kit and finally the VNA in an attempt to isolate the faulty component(s).

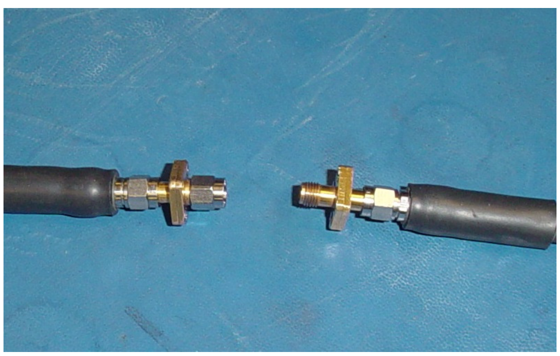

Figure 4: Maury 8021C2 (left) and Maury 8021A2 (right)

Figure 5: Maury 8021C21 and 8021A2 connected for "transmission" portion of calibration sequence.

For "non-insertable" devices such as drop-in circulators, a test fixture similar to the one shown below in Figure 6 is used.

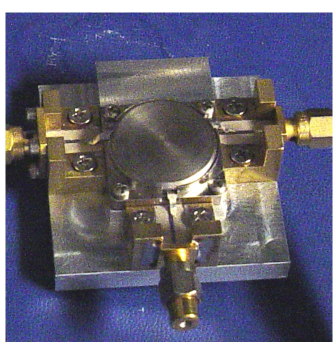

Figure 6
1" Circulator installed into test fixture.

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A "matching" thru-line which uses identical connectors and is the same electrical length as the test fixture should be used to mathematically correct for the added insertion loss of the fixture. See Figure 7 below. The return loss of all test fixture launches should be better than -35dB across the operating frequency band and S21 should be monotonic. Connect the fixture "thru-line" to the test cables and torque the connectors. Measure S21 and verify that the return loss is at least <-30dB. Save the S21 trace to memory and enable the math function "data / memory" so that the trace now falls on the reference line reading 0dB ±0.02dBm. This removes the insertion loss associated with our fixture from the S21 measurement.

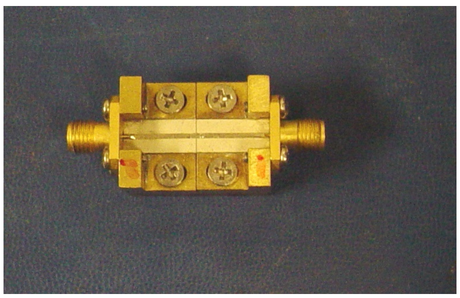

Figure 7
Test Fixture "thru-line"

After the calibration is complete and has been verified the port extensions should be set. This corrects the phase due to the added transmission line on port 1 and 2 of the test fixture by effectively moving the reference plane of our calibration from the connector interface at the end of the test cable to the edge of the microstrip trace on the test fixture where the DUT will make contact. Install the test fixture and view S11. Figure 8 below shows a typical response for an 840-1040MHz frequency range. Notice the phase for the "open" response of the fixture launch connected to port 1.

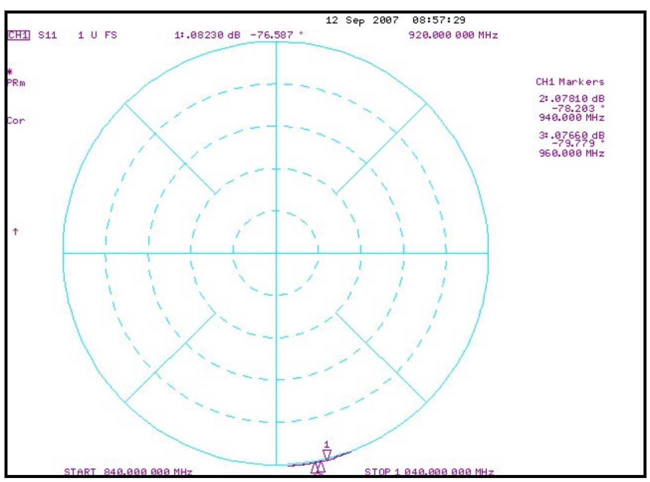

Figure 8 – Typical initial "open" response of fixture for 840 -1040MHz band.

Turn on "Port Extensions" typically located under the calibration menu and select "Port 1". Now slowly rotate the knob on the front of the VNA until the signal appears to be a

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tight ball shape at 0 degrees which corresponds to an “open” – the port extension should be a positive value and the signal should move in a counter clockwise direction towards zero degrees phase if the know is being rotated in the correct direction. Measure S22 with the test fixture installed and repeat this process for the port extension on port 2. Re-save the instrument state to retain these settings. The signal should appear similar to that shown in Figure 9. Notice that the phase across the entire band is 0 degrees for the “open” condition that exists at the end of the test fixture launch.

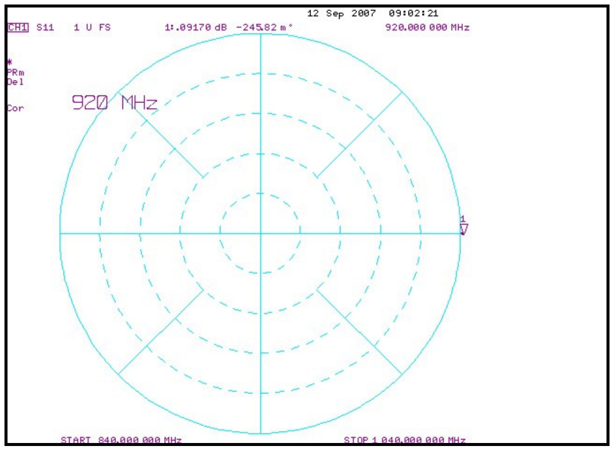

Figure 9 – Port 1 (S11) port extension after setting.

The last step in the calibration process is verification using a “Gold” standard. This is a model specific device that has been set aside to verify that the calibration is acceptable and that correlation between engineering and manufacturing is at an acceptable level. As designs are completed by engineering, “Gold” standards are built and saved at each design center as well as provided to manufacturing in Shanghai. The correlation should be within ±0.03dB and 0.3° (100MHz – 3GHz) for the insertion loss (transmission or S21) while the values for the return loss (reflection or S11 / S22) are shown in Table 3 below.

Measured Reflection Value (dB)	Reflection Uncertainty (dB)	Reflection Uncertainty (degrees)
-20	±1.0	±3.5°
-30	±2 - 3	±10°
-40	±5-7	Undetermined (>10° possible)

Table 3: Uncertainty at various magnitudes

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For consistency throughout the company the format of our plotted data should be consistent. This allows for easy visual comparison of data taken at one facility vs. another. Figure 10 shows the preferred S-parameter formats, positions, scales and reference values that should allow most circulator / isolators to be evaluated.

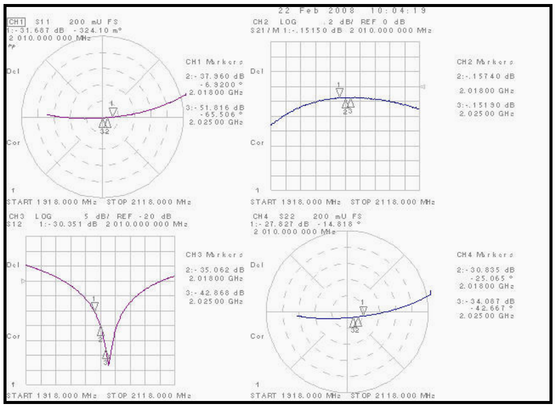

Figure 10
Typical S-parameter positions, scales, reference settings for Polar.

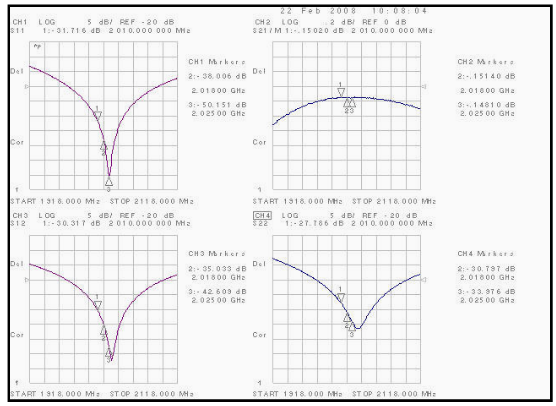

Figure 11
Typical S-parameter positions, scales, reference settings for Log

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