TRL Calibration for Microstrip Planar Circuits on the HP 8753D Vector Network Analyzer*

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Introduction

The purpose of vector network analyzer (VNA) calibration is to establish a reference plane for subsequent VNA *S*-parameter measurements. The reference plane typically corresponds to the input and output ports of the device under test (DUT), such that the calibration enables microprocessor correction for the effects of cables, connectors, microstrip feedlines, and the interior circuitry of the VNA. One technique, the TRL, provides an accurate method of achieving calibrations at frequencies above 500 MHz. The TRL technique is preferred over other calibration methods because well-characterized opens, shorts, and loads are not required; and a reference plane can be easily established (by setting the length of the feedlines) at any distance from the edge of the board.

It is not possible to perform a true TRL calibration on the HP8753D VNA. All required error-correction parameters cannot be determined due to limitations in the VNA architecture. Since the HP8753D contains only three internal samplers, the switching terms[1] of the calibration cannot be calculated. The resultant calibration is termed TRL* calibration, a term used to emphasize the absence of the switching terms in the VNA's internal calibration calculations [1].

Designing TRL standards

To properly design a set of TRL standards, it is necessary to know the substrate parameters, the desired characteristic impedance of the transmission lines, and a desired "center" frequency. Three standards are then created, a thru line, an open line and a delay line. The measurement reference plane is set by the lengths of the thru line and the open line; specifically the reference plane is established at the midpoint of the thru line. For this reason, the open line is often designed to be half as long as the thru line[2]. Let the length of the thru line be l_{thru}, then the nominal length of the delay line is given by

$$l_{delay} = l_{thru} + l_{\lambda/4} \tag{1}$$

where $l_{\lambda/4}$ is a quarter guide wavelength at the center frequency.

For an EM wave propagating down a microstrip transmission line, part of the electric field is the substrate (dielectric) and the other part is in air. This disparity in dielectric constant values requires the use of an effective dielectric constant, which can be approximated by

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \tag{2}$$

where ε_r is the substrate relative dielectric. We can now define the equation for the wavelength of the wave propagating on the transmission line (guide wavelength)

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{eff}}} \tag{3}$$

where c is the speed of light in a vacuum and f is the design frequency. The result from (3) is then divided by four to yield the quarter guide wavelength.

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[1] The switching terms represent corrections for the imperfect terminations that forward and reverse mode signals see.

[2] In general, the open line does not have to be half the length of the thru line. Design of an open standard that is not half the length of the thru line requires the specification of an offset (time delay).

Modifying the Standards Kit

The HP 8753 is factory programmed with several calibration kits. The machine also contains a user defined custom calibration kit, called the User Kit. The TRL* standards represent custom calibration standards, and thus the calibration kit used by the machine must be specified as User Kit. The User Kit must then be programmed according to the desired TRL* standards.

Press the CAL key to enter the calibration menu. Enter the following: CAL KIT | User Kit | More | Modify [*Standard kit name*]. The calibration standards used by the 8753D are specified by numbers, with the numbers 1 - 4 reserved for factory preset standards. To modify the standards for the designed TRL standards, a number higher than 4 must be selected. The numbers 6, 7, and 8 have already been labeled for the TRL calibration according to Table 1.

Number	Standard
6	Thru
7	Delay (Line)
8	Reflect (Open)

Table 1. Standard Designations.

Defining the Standards

Select DEFINE STANDARD. The machine will prompt for a numeric entry. Enter a number greater than 4 (the designations defined in Table 1 are suggested). Next, select Standard Type (Open, Thru, Load, Delay/Thru). Once the standard type has been entered, an offset for the standard must be defined. For both the thru and the open, the offset is zero[3]. The delay line has an offset which must be calculated (in nanoseconds) and entered. The offset time can be calculated from the following formula:

$$t_{offset} = \frac{l_{\lambda/4}\sqrt{\varepsilon_{eff}}}{c} \qquad (4)$$

Entry of offset information follows the selection of SPECIFY OFFSET. Also defined within this menu are the offset loss and offset characteristic impedance corresponding to the designed standards, as well as the frequency range of the intended measurements and choice of cable type (for the connecting cables). Coaxial cable is the most common cable type currently available in the microwave lab, so this setting should be set to *coax*. For each of the standards, all fields must be filled. Note the open standard SPECIFY OFFSET menu has one extra set of fields. These fields (C_0, C_1, C_2, C_3) correspond to capacitances which the VNA uses in its error correction model. These can all be set to zero. A summary of the SPECIFY OFFSET entries is given in the following Tables. The recommended numerical designation for the standards is also given.

Thru (Standard #6)	
Offset Delay	0 s
Offset Loss	0
Offset Z_0	50 Ω
Minimum Frequency	Minimum frequency for desired measurement sweep
Maximum Frequency	Maximum frequency for desired measurement sweep
Cable Type	Coax

Table 2. Summary of Through Offset Specifications.

[3] The offset for the open is nonzero if the length of the open is not exactly half the length of the thru.

Delay Line (Standard #7)	
Offset Delay	Calculated from Equation (4)
Offset Loss	0
Offset Z_0	50 Ω
Minimum Frequency	Minimum frequency for desired measurement sweep
Maximum Frequency	Maximum frequency for desired measurement sweep
Cable Type	Coax

Table 3. Summary of Delay Line Offset Specifications.

Open (Reflect) (Standard #8)	
C_0	0
C_1	0
C_2	0
C_3	0
Offset Delay	0 s
Offset Loss	0
Offset Z_0	50 Ω
Minimum Frequency	Minimum frequency for desired measurement sweep
Maximum Frequency	Maximum frequency for desired measurement sweep
Cable Type	Coax

Table 4. Summary of Open Offset Specifications.

Once all offset information has been entered, the standards may be assigned alphanumeric labels (for convenience) from the LABEL STD menu.
When all information has been properly entered, select STD DONE (DEFINED) to exit.

Standard Class Assignment

Once the offsets have been specified, the new standards must be assigned to their respective classes. Recall that the open standard (number 8) defines a reflect measurement, the delay standard (number 7) defines a line measurement, and the through (number 6) defines a transmission measurement. The standard classes are therefore defined as summarized in Table 5.
Notice that the Response and Response & Isolation fields are both zero. The user must make sure to enter something into these fields, and as the response is normally not a concern - a zero should be entered into both fields (*Note:* a zero entry into the Isolation and Response & Isolation fields will cause a "1" to appear as the designated standard).

Standard Class Entries and Labels		
S11A RE FW MTCH	8	Open (Reflect)
S11B LN FW MTCH	7	Delay
S11C LN FW TRAN	7	Delay
S22A RE RV MTCH	8	Open (Reflect)
S22B LN RV MTCH	7	Delay
S22C LN RV TRAN	7	Delay
FWD TRANS	6	Thru
REV TRANS	6	Thru
FWD MATCH	6	Thru
REV MATCH	6	Thru
RESPONSE	0	
RESPONSE & ISOLATION	0	

Table 5. Summary of Standard Class Entries.

Select SPECIFY CLASS to accomplish the class assignments. Note that there are two pages of menus which contain fields which must be filled. When done, choose SPECIFY CLASS DONE.

Standard Class Labeling

The specified classes may now be assigned alphanumeric labels (for convenience) from within the LABEL CLASS menu. The third column of Table 5 gives suggested Class Labels. The labels assigned to the standard classes will be the labels which appear on the VNA screen during the calibration sequence.

Calibration Kit Labeling

The user-defined calibration kit may be assigned an alphanumeric title by entering the LABEL KIT menu. The Standard name entered here will appear in the calibration kit menu as the User Kit.

Calibration Kit Saving

Once the standards have been defined, assigned to classes, and labeled, the calibration kit modification has been completed. Choose KIT DONE (MODIFIED), then SAVE USER KIT.

Calibration

Now that the standards have been defined and entered, the calibration can be implemented. Select the CAL button, then choose the CALIBRATE MENU. Select TRL*/LRM* 2-PORT. Table 6 summarizes the calibration procedure.

- Choose THRU first. Connect the thru line then press each key to measure. Four measurements are required from within this menu.
- Choose REFLECT AND LINE. Both the open and the delay line will be calibrated from within this menu. The REFLECT calibrations will be done with the open connected[4], the DELAY calibrations will be done with the delay line connected. A total of six measurements are required within this menu.
- Choose ISOLATION. Then select OMIT ISOLATION.

Selection from TRL*/LRM* 2-Port Menu	Standard to connect and measure
Thru	Through (Thru Line)
Reflect and Line	
Forward Reflect	Open (Reflect Line)
Reverse Reflect	Open (Reflect Line)
Forward Delay	Delay Line
Forward Delay	Delay Line
Reverse Delay	Delay Line
Reverse Delay	Delay Line
Isolation	Omit Isolation measurement

Table 6. Summary of Calibration Procedure.

The TRL calibration has now been completed on the custom standards. Measurements of the device under test (DUT) may now be conducted.

Calibration Data

The uncertainty inherent in any set of microwave measurements is determined by the accuracy of the calibration. For this reason, the calibration procedure is of critical importance to subsequent measurement. To better characterize a set of measured data, the calibration procedures are typically documented [1]. Table 7 summarizes the criteria for an acceptable TRL* calibration.

TRL Standard	Measured data	Nominal Result
Thru	Amplitude of S_{11}, S_{22}	Less than -40 dB across band
Thru	Phase of S_{21}, S_{12}	0 degrees across band
Delay	Amplitude of S_{11}, S_{22}	Less than -40 dB across band
Delay	Amplitude of S_{21}, S_{12}	Monotonic decrease across band

Table 7. TRL calibration criteria. From Weller* et al. *[1].*

It is important to note that measurements can still be made even if the calibration data does not meet the Table 7 criteria. Such measurements will have greater error due to the inaccuracy of the calibration.

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[4] Note that the forward reflect measurement is made with the open standard connected to the VNA RF out port and the reverse reflect measurements is made with the open standard connected to the VNA RF in port.

Reference

[1] T.M. Weller, H.C. Gordon, B. Lakshminarayanan, E. Grimes. "Development of Simulation, Modeling, and Extraction Techniques for Passive (R, L, C) Components." May 1998.

Appendix

Sample TRL Calibration*

The following example illustrates the design and measurement of a set of TRL* calibration standards fabricated on FR-4 substrate. Calibration standards were designed with a nominal center frequency of 2.4 GHz. The range for measurement (and therefore also for calibration) was set at 30 kHz - 3.2 GHz. Table A-1 gives the substrate parameters for the FR4 board.

Relative dielectric, ε_r	4.7
Substrate height, t	1.575 mm

Table A-1. FR4 substrate parameters.

The line widths (2.82 mm) for a 50 Ω characteristic impedance microstrip transmission lines were determined using Linecalc™. Table A-2 summarizes the standard dimensions used for the TRL* calibration.

Through Line	20 mm
Reflect Line	10 mm
Delay Line	36.59 mm

Table A-2. TRL standard length dimensions.*

Calibration data were saved, so that the accuracy of the calibration could be verified. Figure A-1 shows amplitude of S_{11} for the through line, which should be less than -40 dB across the entire frequency band.

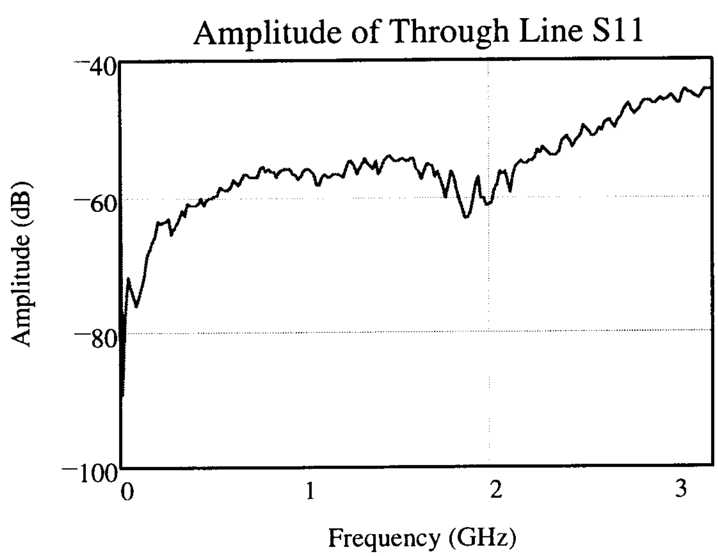

Figure A-1. Amplitude of through line S_{11}.

Figure A-2 shows the phase of the through line S_{21}.

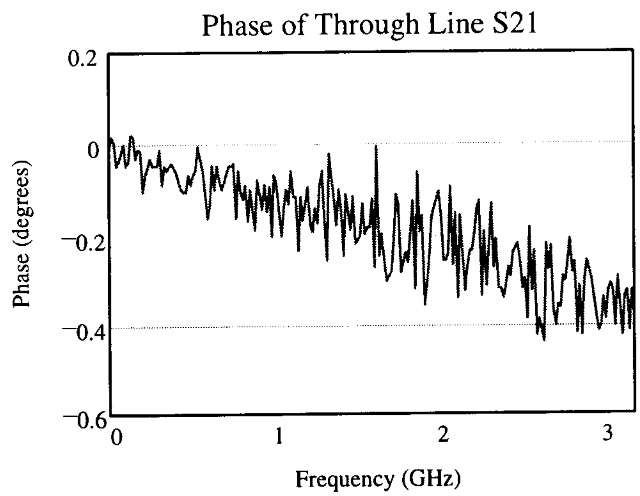

Figure A-2. Phase of through line S_{21}.

The phase of S_{21} should be nominally zero across the frequency band (corresponding to a zero length transmission line). The approximately 0.5 dB ripple in the phase can be attributed to the imperfections in the TRL* calibration.

Figure A-3 shows the amplitude of the delay line S_{11}, which should be less than -40 dB across the band.

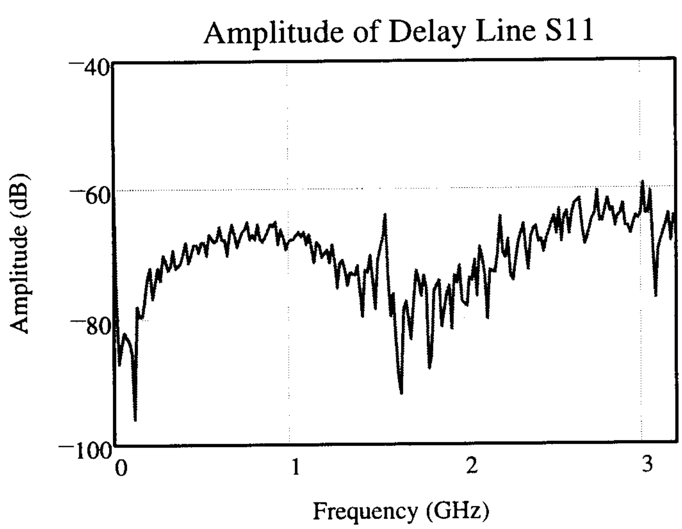

Figure A-3. Amplitude of delay line S_{11}.

Figure A-4 shows the amplitude of the delay line S_{21}, which should show a monotonic decrease across the frequency band.

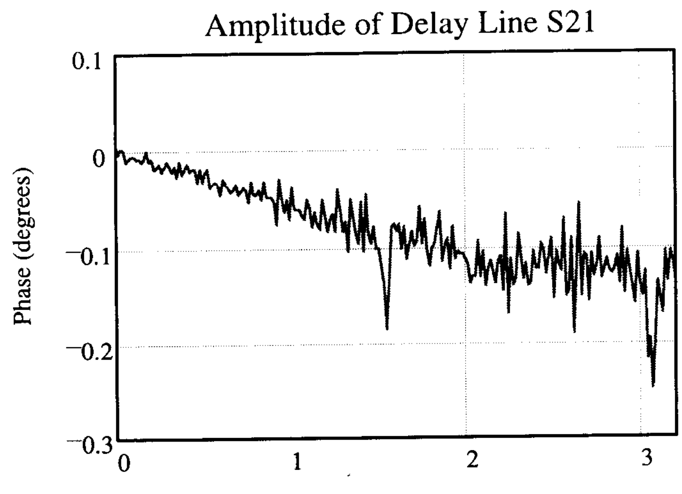

Figure A-4. Amplitude of delay line S_{21}.

The reciprocal nature of the standards allows the S_{12} and S_{22} values of the measured standards to be nearly identical to S_{21} and S_{11}, respectively. An examination of the measured standard data reveals that the accuracy of the TRL* calibration was adequate for the degree of accuracy for the desired measurements.