

TRL calibration for SMT devices using the PicoVNA 108



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1. Introduction

The TRL (Thru-Reflect-Line) calibration technique [\(1\)](#) was originally developed as a way of enhancing calibration accuracy in coaxial lines. The improvement is based on the fact that the impedance reference is a coaxial air line, which can be manufactured very accurately to provide a precise known impedance. The other calibration Standards required are a zero-length through (very simple to implement) and a pair of high-reflection mismatches. The latter do not need to be known accurately but need to provide the same value of reflection.

The air line reference is required to provide a phase shift of significantly greater than 0° and significantly less than 180° . This gives rise to the key difficulty with TRL. At lower frequencies (i.e. longer wavelengths) it is not possible to obtain air lines that are long enough to provide sufficient phase shift. In addition, the characteristic impedance of the line becomes appreciably complex and frequency-dependent, due to skin depth effects. In general, these problems start to become significant below approximately 1 GHz so the easiest solution is to restrict the TRL technique to frequencies above 2 GHz, say.

TRL calibration lends itself well to characterizing surface mount devices. The air line is replaced with a microstrip line whose characteristic impedance can be controlled and also reasonably well measured at microwave frequencies. The Reflect Standards can be either open circuits or short circuits, both easily implemented in surface mount technology.

2. TRL on a printed circuit board

As mentioned already, the TRL technique is well suited for implementing on a surface mount printed circuit board. The Standards are easy to define and implement. Fig. 1 shows the various components required, laid out on PCB. There are four 2-port circuit blocks.

- Through line
- Reflect Standards (Shorts)
- Reference line (Delay)
- DUT (device under test)

Connections to each of the circuit blocks is by means of edge connectors. These must all be identical and with complete soldering underneath to provide the best grounding. The microstrip length, L , is not significant. It is chosen to be a convenient length to handle and populate the board with the edge connectors. The short circuits are simply via-holes to the ground plane.

As an aid to clarity, Fig.1 includes the equivalent connections for TRL using coaxial components. It is instructive to note where the measurement plane(s) is for each of the Standard measurements illustrated in Fig. 1. Note particularly that the 'Through' is zero length and equivalent to the coaxial 'insertable' Through connection which is zero length and zero loss. For all calibration and DUT measurement steps, the measurement plane of each of the instrument's ports is on the PCB and, for this technique to work well, it is critically important that all L/2 sections illustrated in Fig. 1 are made identical and that the L/2 sections lengths are precisely half the length L of the Through.

Reference line length

It is generally recommended that the line length, ΔL , is selected to provide no less than 20° and no more than 160° of phase shift with respect to the thru length over the band of operation. In practice, best results are achieved by restricting the range to around 30° to 150° .

The required reference line length can be calculated as follows.

$$\Delta L = \frac{\emptyset}{360} \left(\frac{c}{f \sqrt{\epsilon_{\text{eff}}}} \right)$$

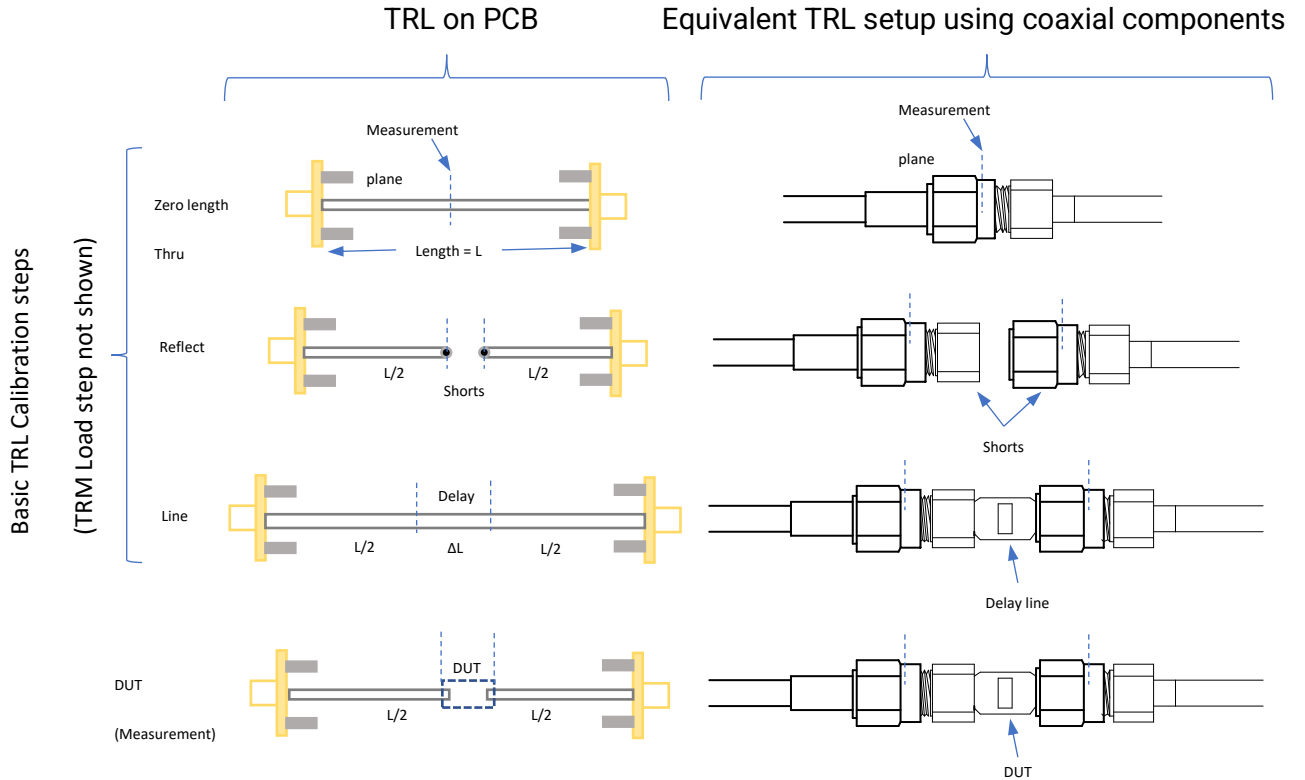
\emptyset = phase shift in degrees

f = frequency

c = speed of light

ϵ_{eff} = effective dielectric constant

Further, as mentioned already, it is sensible to avoid lower microwave frequencies in order to avoid skin depth effects. So, keeping to 1.5 or 2 GHz and above may be a good idea.



Note: The absolute value of L is not important.
 However, all L/2 sections shown must be identical and be exactly half the value of L.

Figure 1: PCB circuit blocks for TRL calibration and measurement

For example, assuming a nominal 50 Ω line with resulting effective dielectric constant of 3.35, to achieve 30° phase shift at, say, 1.5 GHz, we find that:

$$\Delta L = 9.1 \text{ mm}$$

This reference line length of 9.1 mm would in turn provide 150° of phase shift at 7.5 GHz. So, the useable bandwidth for this line, as a TRL line standard, is 1.5 GHz to 7.5 GHz.

Test PCB

A test board made to illustrate the operation of the TRL technique with the PicoVNA is shown below in Fig. 2. This includes an additional DUT and a pair of matched loads. These loads are used by the software to perform a TRM (Thru-Reflect-Match) calibration at frequencies below the lowest frequency of the TRL calibration (set by the length of the TRL reference line).

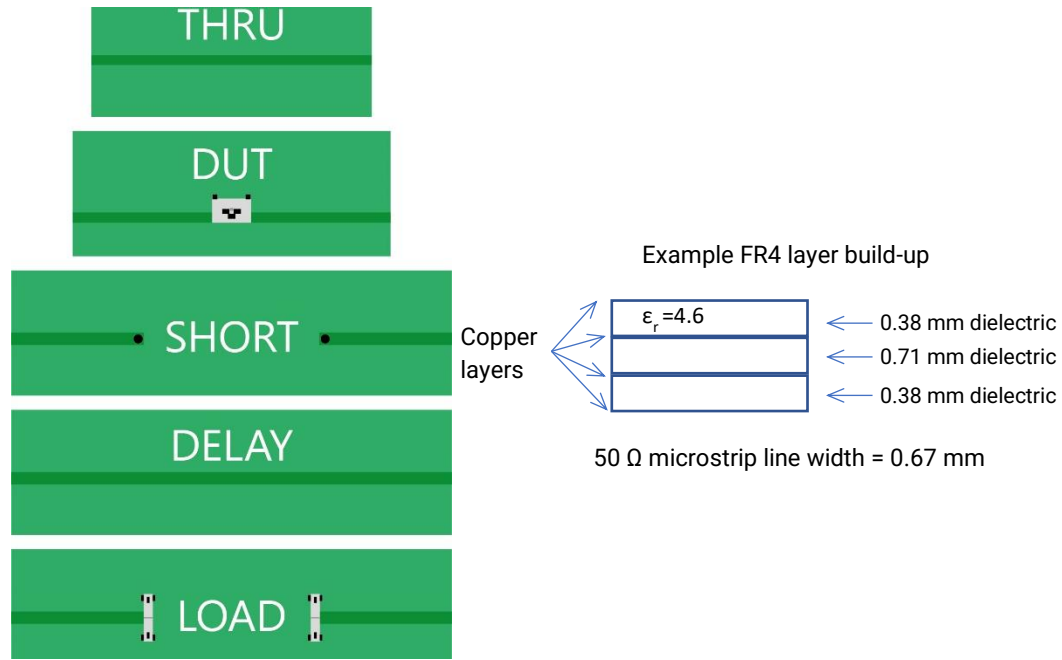


Figure 2: Test board for TRL calibration and measurement

Lower frequencies

The PicoVNA 108 automatically switches to TRM at frequencies below those supported by the TRL reference line. The TRM technique relies on matched loads to set the reference impedance. This approach works well since good matched loads can easily be implemented at lower microwave frequencies (< 2 GHz). The frequency range of the TRL reference line is set in the calibration kit definition and is described in the following section.

TRL calibration kit

In order to perform a TRL calibration with the PicoVNA 108, a calibration kit file needs to be created. This can be done very easily using the calibration kit editor (Tools > Calibration kit > Cal Kit Editor).

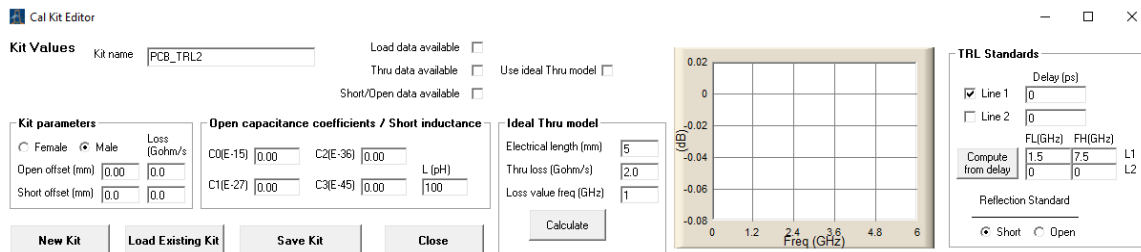


Figure 3: Use the calibration kit editor to create the TRL cal kit file

TRL calibration kit – entering the reference line information

In our test board (Fig.2) there is only one reference line ('Delay') so we check just the box next to 'Line 1' to indicate that the cal kit has only one reference line. The Line 2 box is left unchecked as shown in Fig. 3.

Now, we can either enter the electrical delay in ps and click the button 'Compute from delay' to set the frequency range of the line, or preferably, enter directly the frequency range we wish to assign to the reference line. The low frequency is entered into the box labelled 'FL' and the high frequency into the box 'FH'. Both values are in GHz.

TRL calibration kit – entering the Reflect Standard information

The next step is to select whether the Reflect Standard is going to be a short or an open circuit. Click on the appropriate radio button as required. Note that it is only necessary to know approximately the value of the reflection coefficient of the Reflect Standard. So, in the case of our test PCB, we will use short circuits implemented with vias to ground. For this, we can enter 100 pH as an approximate value of the inductance into the box labelled 'L (pH)'.

Finally, we enter the desired Kit name in the top left box and click on 'Save Kit' to save the file to disk.

3. Performing the TRL/TRM calibration and measured results

Performing the TRL/TRM Calibration is simple. The first step is to load the TRL calibration kit file created for the test PCB. This is done using the calibration kit form (Tools > Calibration kit) which is shown below.

The cal kit files for the test PCB are loaded for both port 1 and port 2 by clicking on the 'Load P1 kit' and 'Load P2 kit' in turn. Thereafter, click on 'Apply' and close the form.

Calibration Kit Parameters

Port 1 Kit name: Load data available Thru data available Short and Open data available

Kit parameters
 Female Male Loss (Gohm/s)
 Open offset (mm)
 Short offset (mm)

Open capacitance coefficients
 C0(10⁻¹⁵) C2(10⁻³⁶)
 C1(10⁻²⁷) C3(10⁻⁴⁵)

Short inductance
 L (pH)

Thru length (mm)

TRL Standards
 Line 1 Line 2
 FL(GHz)
 FH(GHz)
 Reflect Standard

Port 2 Kit name: Load data available Short and Open data available

Kit parameters
 Female Male Loss (Gohm/s)
 Open offset (mm)
 Short offset (mm)

Open capacitance coefficients
 C0(10⁻¹⁵) C2(10⁻³⁶)
 C1(10⁻²⁷) C3(10⁻⁴⁵)

Short inductance
 L (pH)

TRL Standards
 Line 1 Line 2
 FL(GHz)
 FH(GHz)
 Reflect Standard

Figure 4: Load the TRL calibration kit files for ports 1 and 2

Once the calibration kit files have been loaded, the sweep plan can be set (if needed) and the calibration completed using the Calibration Form. See Fig. 5.

Once the Measurement is set to 'Insertable DUT (TRL/TRM)' proceed to connect to each of the PCB calibration Standards (see Fig. 6) and then click on the corresponding button on the Calibration form. So, for example, after connecting to the Short circuits, click on the Reflect button on the form to measure these Standards.

Once all the Standards have been measured, click on the 'Apply Cal' button to complete the calibration. The Calibration form will close and the DUT can then be connected and measured.

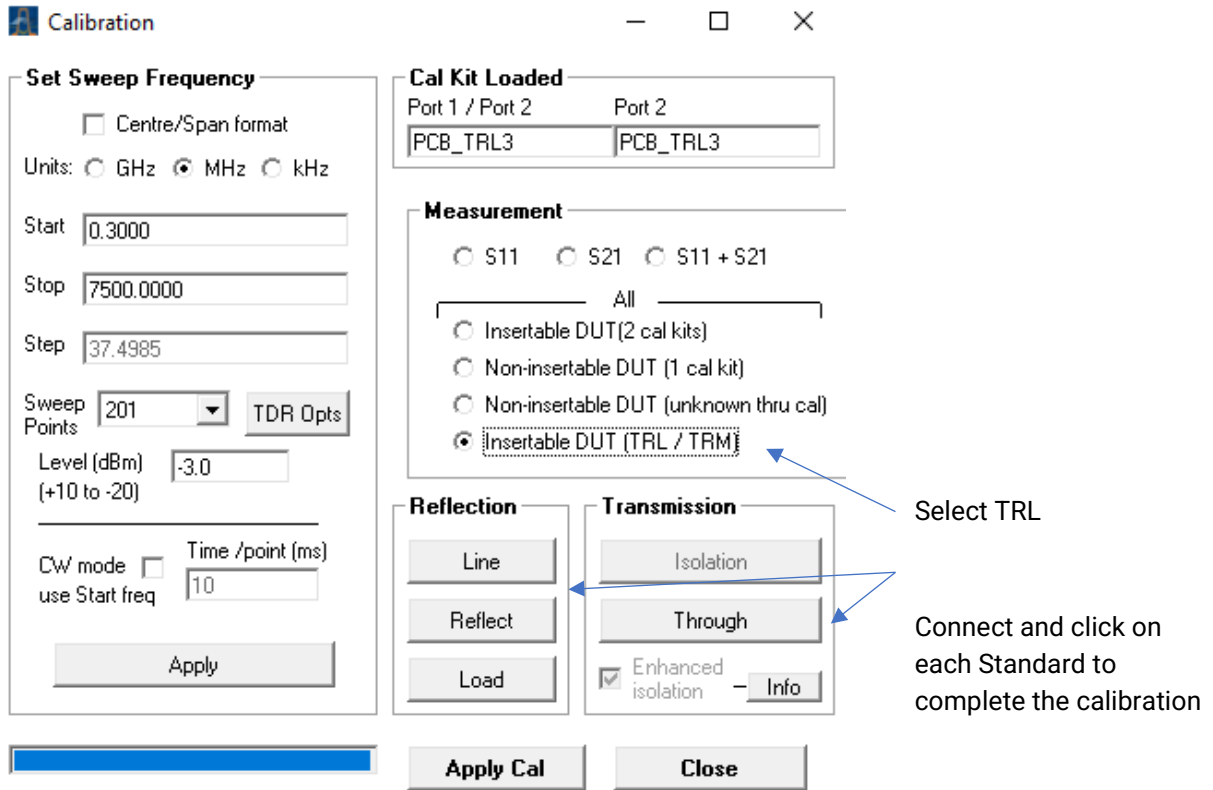


Figure 5: The calibration form is used to set the sweep plan and carry out the calibration

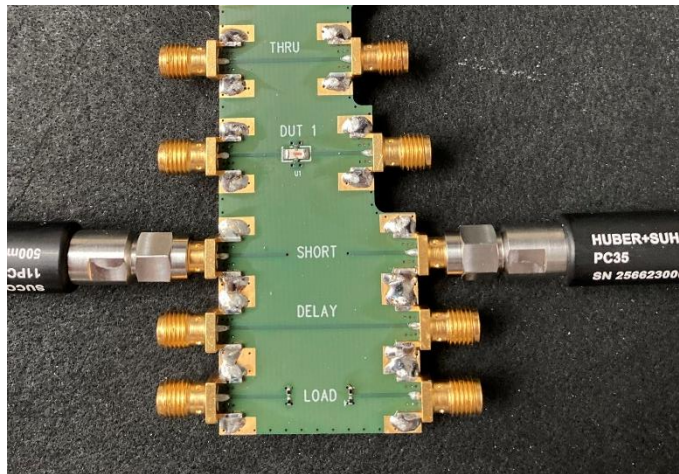


Figure 6: Connect to each Standard in turn to complete the calibration

Example measurement results

DUT 1: Mini-Circuits BFCN-2700+ bandpass filter

The first DUT on the test PCB is a LTCC (Low Temperature Co-fired Ceramic) bandpass filter manufactured by Mini-Circuits. This device has a nominal pass band 200 MHz wide centred on 2.7 GHz.

Figure 7a shows the measured value of S21 compared to the data published by the manufacturer. It can be seen that the measurement taken using the PicoVNA 108 is in good agreement with the manufacturer's data. It is not known how the manufacturer data was taken but it does show some apparent measurement anomalies above 4 GHz. It is interesting to see that the measurements from the PicoVNA 108 show somewhat lower loss and deeper sidelobe responses.

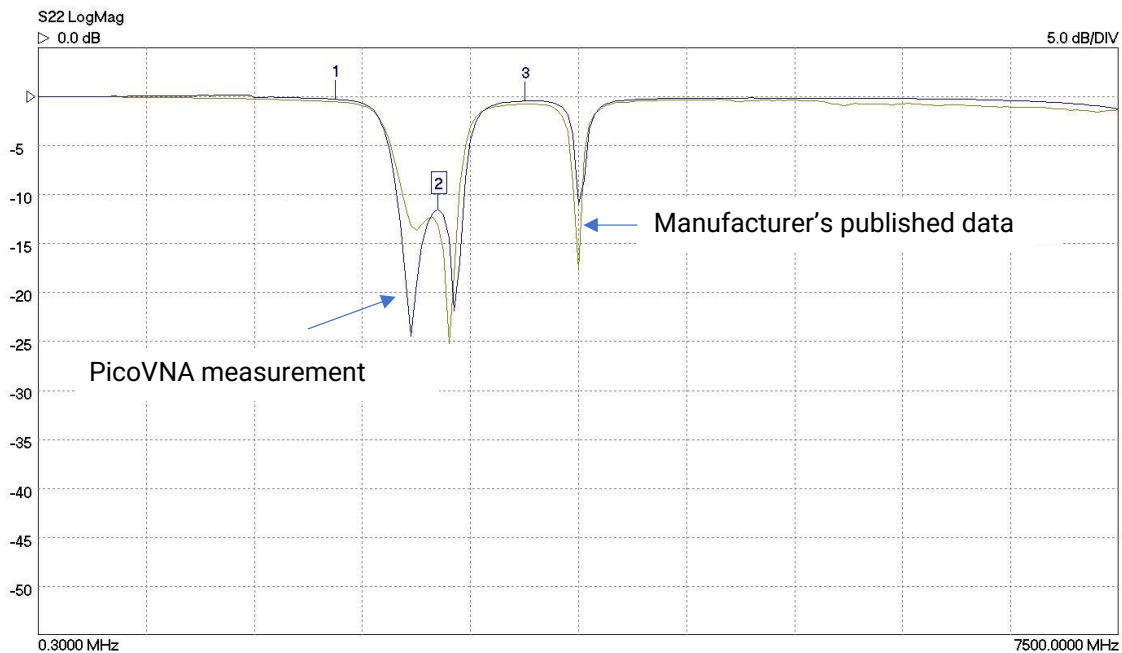


Figure 7a: Bandpass filter (BFCN-2700+) S21 measurement

Figure 7b shows the measured value of S22 compared to the data published by the manufacturer. As before there is general good agreement, including the presence of an out-of-band resonance at about 3.8 GHz.

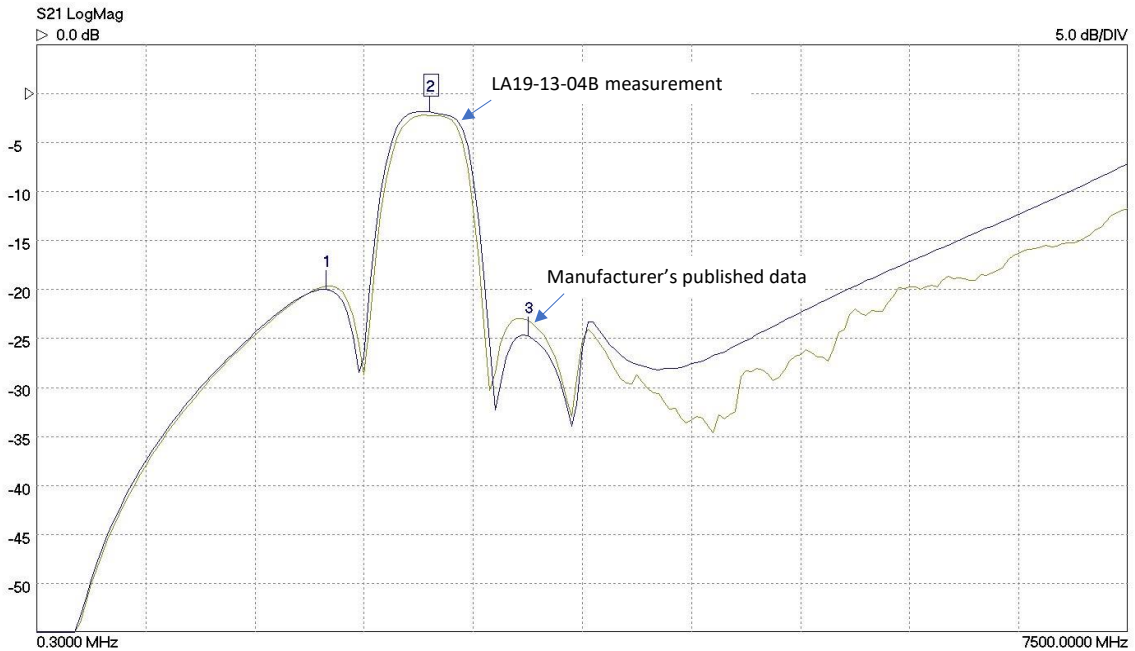


Figure 7b: Bandpass filter (BFCN-2700+) S22 measurement

Reference line impedance correction

It is very likely that using low-cost FR4 boards for this kind of evaluation leads to an error in the characteristic impedance of the TRL reference line. This can be measured using the TDR facility in the PicoVNA 108. The result, in terms of the line's linear reflection coefficient, is shown below in Fig. 8. Marker 2 indicates a value of Z_0 of 52.2 Ω .

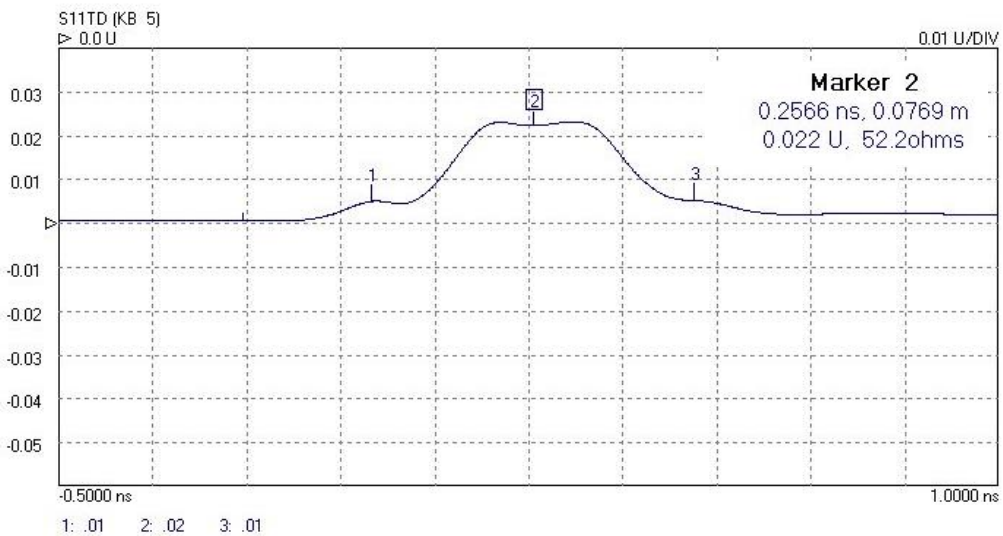


Figure 8: Reference line Z_0 can be determined from the reflection coefficient, measured using TDR

In order to be able to carry out a TDR measurement of the reference line, it is important to bear in mind the available time resolution (or effective rise time) of the VNA TDR measurement. This is equivalent to the inverse of the frequency span (stop frequency minus the start frequency) used. By selecting the widest available span, we end up with a time resolution value of around 118 ps. Therefore, it is sensible to ensure that the overall length of the reference line, plus the interconnecting lines to the edge connectors, amounts to at least 2.5×118 ps. This will allow an unambiguous TDR impedance measurement to be made as shown in Fig. 8.

Once the impedance of the reference line has been determined as described, the value can be entered in the Enhancement Set Up form as shown in Fig. 9. Once the value is entered and the box next to the corresponding line is checked, all TRL measurements will be corrected using impedance conversion back to the system impedance, typically 50Ω . Note that the correction will only be applied over the frequency range applicable to the line selected.

The screenshot shows the 'Enhancement Set Up' dialog box with the following settings:

- Set Values:** Averages (1-255): 1; Smoothing (0-10%): 3; Smoothing (pts): 5; Bandwidth: 1kHz; Port 1 Lev (dBm) (-20 to +10): -3.0; CW mode time (0.5 - 60 ms/pt): 10; Extra synth settling time (ms): 0.
- Ref Plane (applies to active channel):** Select Units: mm; Auto Ref: Enhanced (unchecked); Enter Value: 0; Loss (dB), 1 GHz: 0.00; Eff dielectric: 1.00; Velocity factor: 1.0.
- TRL Line impedance correction:** Line 1: checked, Z0: 52.2, i: 0.0; Line 2: unchecked, Z0: 50.0, i: 0.0.
- Current active channel:** Ch 1, measuring S11.
- De-embedding:** Port 1 network (unchecked); Port 2 network (unchecked); De-embed on (unchecked); De-embed off (checked); Convert to System Zo (unchecked); External Zo match (unchecked); Value: 50; Help button.

Enter TRL Reference line Z_0 value to allow live correction of measurement

Figure 9: TRL Measurement can be corrected using known Reference line Z_0

Reference line impedance correction example

DUT2: Mini-Circuits 0805 6 dB chip attenuator

The second DUT on the test board (see Fig.2) is a 6 dB chip attenuator. It provides broadband performance from DC to beyond 7 GHz. Figs. 10a and 10b show the measured S11 and S21 of the attenuator.

The measured data show a step at 2 GHz. This is the frequency chosen where the calibration switches between TRM and TRL. As a reminder, this frequency is set in the TRL calibration kit file. In particular, it is the lowest frequency where the reference line is used as a standard, which was chosen to be 2 GHz for this measurement.

The effect of applying the impedance correction is evident in Figs. 10a and 10b. In particular, the reduction in the step size in S11 is clear to see. The residual error may be likely to be associated with the imperfect 50 Ω loads used on the board for the TRM calibration. Although a small error of around 1 dB it is nevertheless clearly evident.

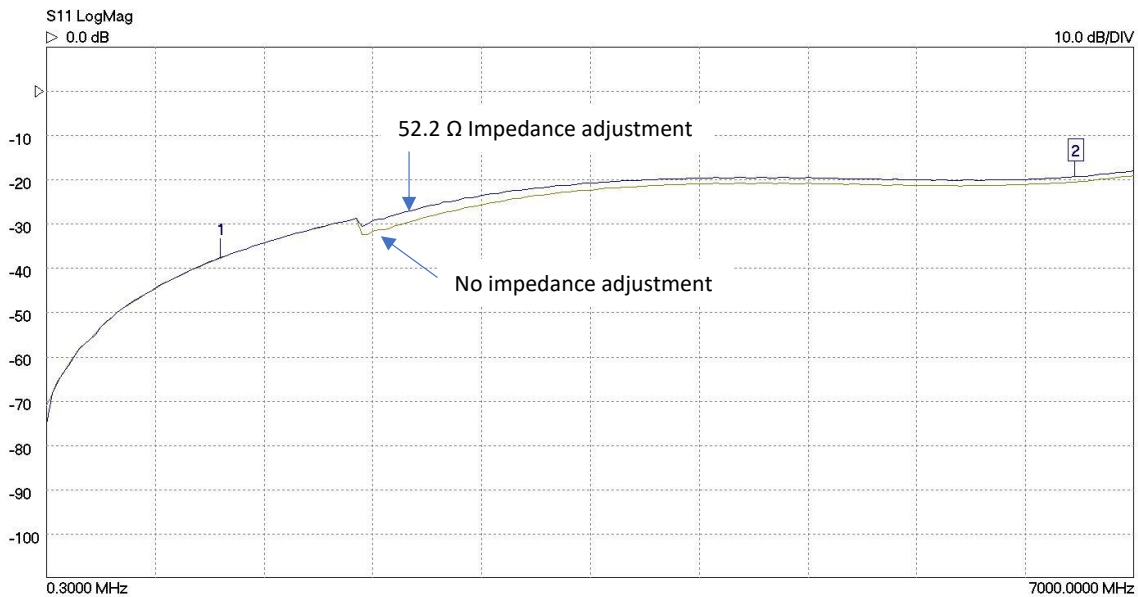


Figure 10a: 0805 6 dB attenuator S11 measurement

It is worth commenting that reducing the transition frequency below 2 GHz to reduce the error introduced by the 50 Ω loads in turn leads to other sources of errors, in particular skin depth effects [\(2\)](#) that are likely to begin affecting the characteristic impedance (making Z_0 complex) of the microstrip reference line.

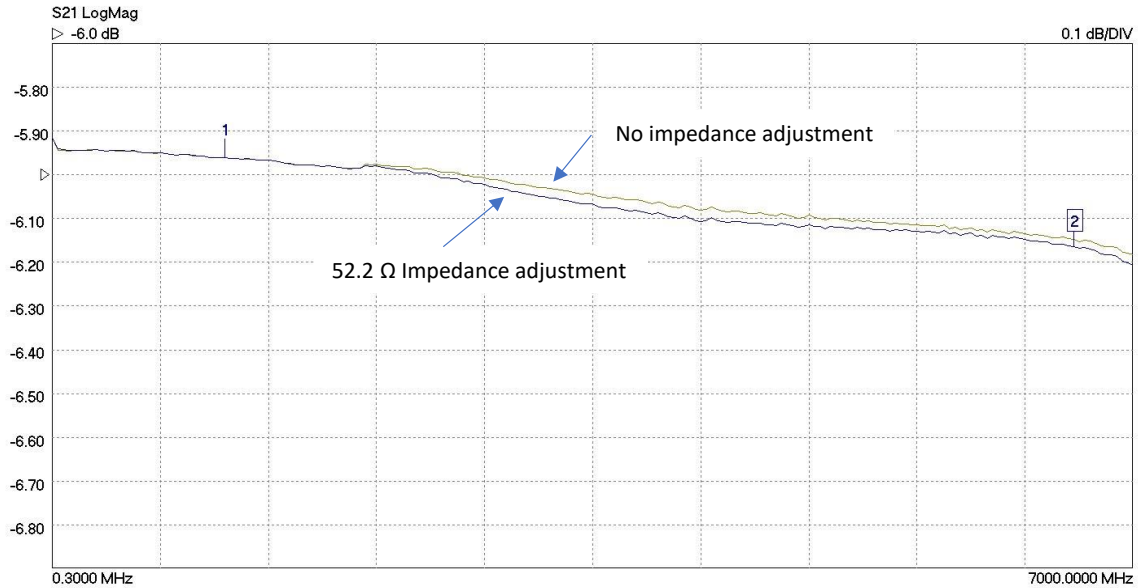


Figure 10b: 0805 6 dB attenuator S21 measurement

4. Conclusions

This application note has described how to use the TRL/TRM calibration technique available on the PicoVNA 108 to characterize SMT components. In particular, it details how a suitable test PCB can be designed and used to measure components over the operating bandwidth of the VNA.

A way to reduce measurement errors arising from incorrect characteristic impedance of the reference line has been described and details of two measurement examples have been given.

Overall, the TRL/TRM feature on the PicoVNA 108 provides another useful option for accurately characterizing SMT components on low-cost PCBs.

5. References

1. **Engen, Glenn F. and Hoer, Cletus A.** *“Thru-Reflect-Line”: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer*, *IEEE Transactions Microwave Theory and Techniques*, Vol MTT-27, No.12, Dec 1979. New York, NY, USA : IEEE, 1979. Electronic ISSN: 1557-9670.

2. **Johnson, Howard W. and Graham, Martin.** *High-Speed Signal Propagation: Advanced Black Magic*. Hoboken, NJ, USA : Prentice Hall, 2005. ISBN 013084408X.