Why TRL Is the Recommended VNA Calibration for Load Pull

Microwaves and RF

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I can't recall how many times I've been asked the simple question, do we really need TRL to characterize tuners or can we get by with SOLT? My answer, and that of my colleagues, has always been that TRL is the more accurate method with regards to highly reflective devices like tuners, but there has never been a specific document proving this. This blog entry will hopefully remedy the situation.

Before we start, I first need to clarify that SOLT is more than adequate for the majority of applications out there. But TRL is preferred with highly reflective devices such as tuners or transistors.

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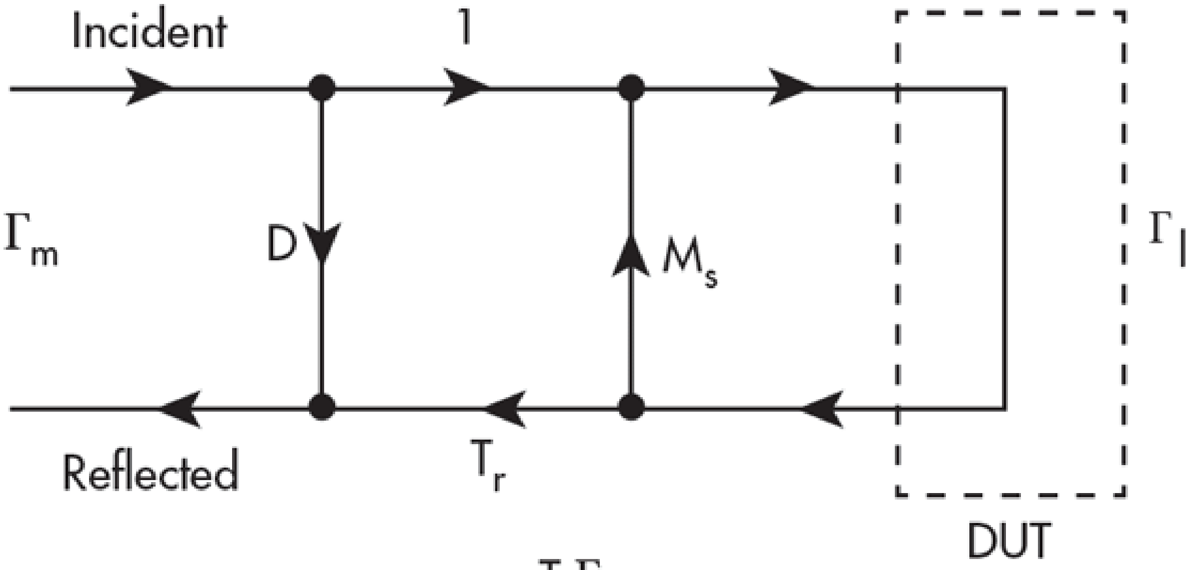
Impedance Tuning 101

The slide-screw impedance tuner is a two-port device, so we need a two-port VNA calibration to measure it. The VNA uses a 12-term error model to correct the measurement and give accurate data at our specific reference planes. The calibration process consists of connecting known standards in order to determine the 12 error terms at each frequency.

The 12-term error model includes two one-port error models, one for each port. The accuracy of each one-port model has the biggest impact on the accuracy of the impedance presented by the tuner, and this is where the TRL method generally has an advantage over the SOLT method. To understand why, let's look at a diagram of a VNA one-port error model (*Fig.1*).

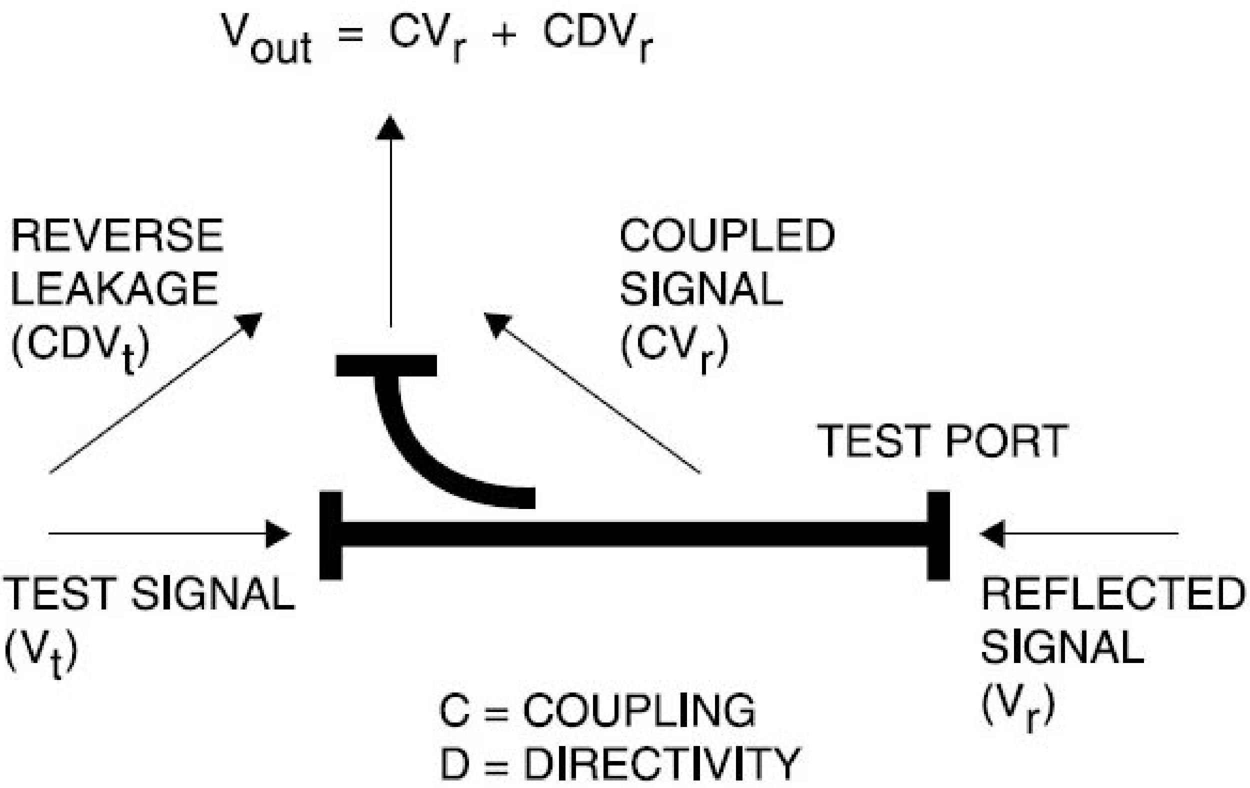


$$\Gamma_m = D + \frac{T_r \Gamma_l}{1 - M_S \Gamma_l}$$

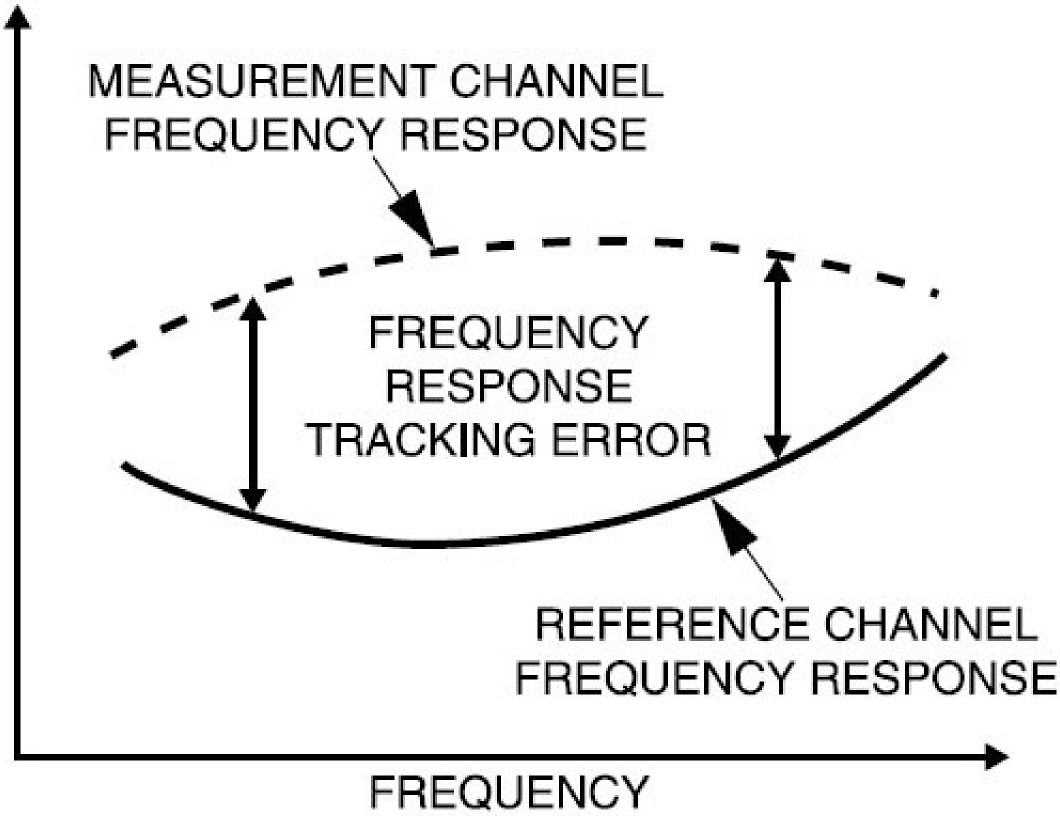
The impedance (in form of Γ) read from the calibration-corrected VNA is dependent on the three terms of the one-port error model, including directivity (D), reflection frequency response tracking (Tr), source match (Ms), and the magnitude of reflection being measured (also in form of Γ).

Let’s first understand what each of these components refers to.

Directivity is a measure of the ability of a directional coupler to discriminate against signals traveling opposite to the coupled direction. At Port 1, for example, a small amount of power traveling toward the DUT will appear in the coupled arm causing an error in the reflected signal measurement. This signal will be below an equal signal traveling from the DUT by an amount equal to the directivity. The principle of Directivity is shown in *Fig. 2*.

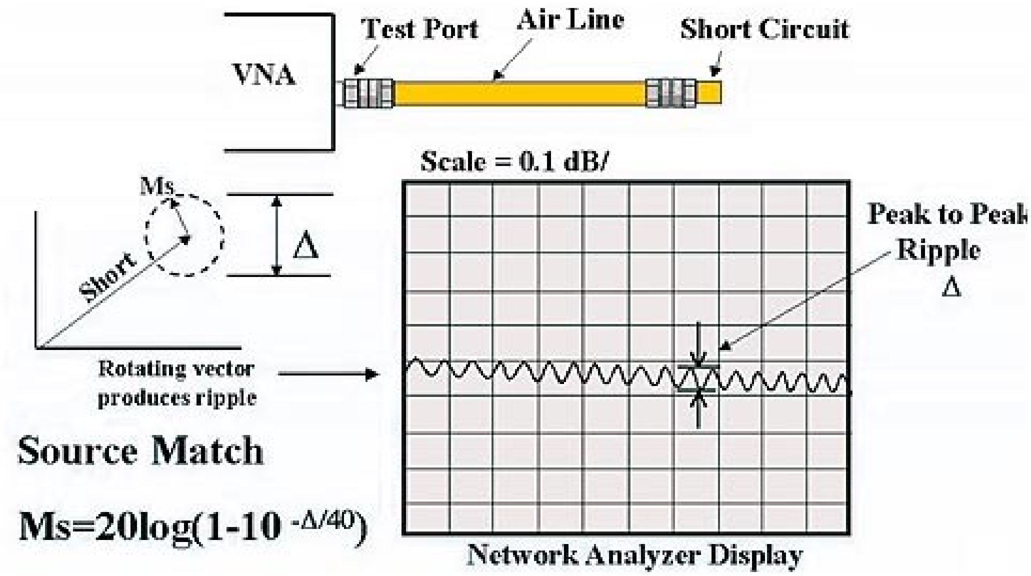


Reflection Frequency Response Tracking is the error arising from response differences between the reference and measurement paths, shown in *Fig. 3*.



Source Match is the mismatch between the source test port and the system characteristic impedance.

Measurement errors can occur as a result of source test port reflections being re-reflected back into the system by the DUT. Source Match can be viewed as the post-calibration peak-to-peak ripple measured on an offset short and is shown in *Fig. 4*.



A SOLT calibration uses two high-reflection coefficient standards of widely separated reflection phase, typically an open-circuit and a short-circuit, and an extremely low-reflection matched termination, or load. For improved accuracy, a sliding termination is normally used in lieu of the fixed termination. For a complete two-port calibration, additional measurements must be performed with the two test ports connected directly together, i.e., a through connection. It is important to note that the characteristics of the short, open and load must be perfectly known and that any deviation from the parameters entered into the network analyzer will lead to additional errors.

A TRL calibration comprises of a THRU, two REFLECTs and a LINE measurement. The THRU is obtained by connecting the two measurement planes together. The REFLECT is obtained by connecting a termination of unknown reflection in the input and output measurement planes; both reflect standards used must have identical reflection coefficients. A short-circuit is often used for coaxial structures, while an open-circuit is more convenient for microstrip or coplanar calibrations standards. The LINE is an additional THRU measurement with some delay. Compared to the SOLT method, TRL is simpler in that the calibration kit standards do not need to be characterized; only the characteristic impedance of the LINE (delay) standard is critical. The LINE length must be selected such that a phase shift between 30 and 150 degrees occurs in the calibration frequency range. Multiple LINE standards with varying lengths may be used for wideband calibrations.

A main point is that measurement accuracy of high reflections for a SOLT calibration is degraded by any errors in characterizing the high-reflection standards, where the TRL calibration accuracy does not need the reflect standards to be known. This is why the TRL method is generally more accurate at high reflections.

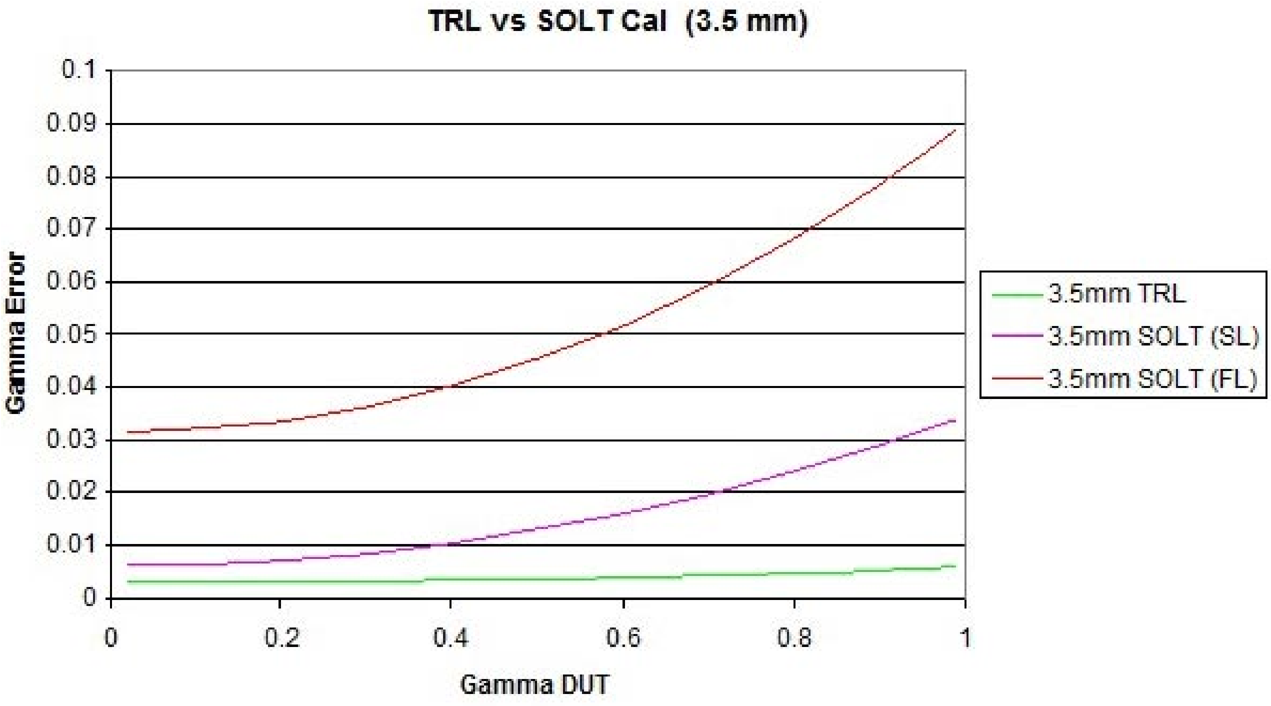
The measurement accuracy of a calibrated VNA can be evaluated by analyzing the residual error terms for Directivity, Tracking, and Source match. The residual error terms are the post-calibration errors associated with each calibration component.

The graph below shows exemplary 3.5 mm calibration kits and the corresponding values of residual error terms D, Tr, and Ms for different calibration techniques.

	Typical SOLT kit with fixed load	Typical SOLT kit with sliding load	Typical TRL kit
D (dB)	-30	-44	-50
Tr (dB)	-0.011	-0.006	-0.003
Ms (dB)	-25	-31	-50

Remember to convert from dB to linear if you plan on solving the equation yourself.

A typical impedance tuner can vary ΓL between 0 (representing VSWR of 1:1, or 50Ω in most load pull setups) and 0.9 (representing VSWR of 20:1, or 2.5Ω). Specialized high gamma tuners can achieve ΓL up to 0.99 (or VSWR of 200:1). Using the values of D, Tr and Ms above, we can plot Γm as a function of ΓL for each calibration type, as shown in *Fig. 5*.



From the equation in Figure 1, it is clear that the directivity of the calibration has the largest effect for low values of Γ. Ms and Tr play larger roles as Γ increases. It is clearly visible that the TRL calibration resulted in the smallest errors for higher Γs.

In conclusion, when measuring a highly reflective device such as an impedance tuner, it is critical to minimize errors by using a calibration technique suited for mismatch, such as TRL.

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