

Correcting For Systematic Errors In One-Port Calibration-Standards

by

John R. Juroshek and Denis X. LeGolvan

Abstract:

This paper describes how to correct for systematic errors in one-port vector network analyzer calibrations that are caused by modeling errors in the one-port calibration standards. The paper shows how to correct an open-short-load calibration that was made with a broadband load whose reflection coefficient is not zero. The method can also be used to correct for modeling errors in the open and short reflects if those errors are known. The method is demonstrated by performing an open-short-load calibration with a broadband load whose reflection coefficient is as large as 0.035 at 50 GHz, and then correcting that calibration to produce measurement accuracies comparable to those from a thru-reflect-line calibration.

1.0 Background:

Vector network analyzers (VNA) are often calibrated with techniques such as open-short-load (OSL) and open-short-sliding-load (OSSL) where the calibration errors can be sizeable [1]. These errors are typically systematic and are caused by imperfections in the calibration standards and/or the software models that are used to model those standards. For example, it is difficult to manufacture a broadband load whose reflection coefficient is zero over a wide frequency range or to model its variation as a function of frequency. Even if the reflection coefficient's variation with frequency is known, the procedures for correcting those variations are not obvious. Systematic errors also occur in OSL and OSSL calibrations due to imperfections in the open and short models that are used for those devices. Thus, calibration techniques such as OSL and OSSL are typically used where less accurate measurements are acceptable, or at the lower-frequency ranges where the load's reflection coefficient is acceptable. This paper describes how to correct for modeling imperfections in the open, short, and load if they are known.

Currently the most accurate method for calibrating a VNA is the thru-reflect-line (TRL) method. This paper shows how to correct a conventional OSL or OSSL calibration to produce measurement accuracies comparable to those from TRL. The correction method described here is applicable only to 1-port measurements. The theory is presented, and results are shown where a 1-port OSL calibration is corrected to make its measurement accuracy comparable to that from a TRL calibration. The technique can be used to transfer measurement accuracy from a high accuracy laboratory where TRL is used to other laboratories where OSL and OSSL are commonly used.

2. Theory:

The publication “Sensitivity analysis of one-port characterized devices in vector network analyzer calibrations: theory and computational analysis” by Godfrey Kwan analyzes the sensitivity of VNA measurements to errors in the open, short, and load models [2]. That paper describes a Monte Carlo method for studying the VNA measurement errors caused by imperfect calibration standards. However the theory described in that paper can also be extended to correct those errors. This paper describes that correction procedure. As will be seen, the correction procedure is similar to the two-tier correction that is used to correct for probe heads in on-wafer measurements [3-4].

We begin by assuming that a VNA is calibrated with a calibration procedure such as OSL and that this calibration produces the three complex one-port error terms E_D (raw directivity), E_S (raw source match), and E_T (raw reflection tracking). The error corrected measurements made with this calibration are defined as Γ_M , and the raw or uncorrected measurements are defined as Γ_U . The OSL calibration is called the first-tier calibration and is assumed to have significant systematic calibration errors. The errors in the first-tier calibration are determined by performing a more accurate calibration with a technique such as TRL and comparing the measurements made by the two different techniques. The measurements made with the more accurate calibration are called the reference measurements, and are denoted by Γ_R . If the same device is measured with both calibrations, then from linear network theory

$$\Gamma_M = \varepsilon_D + \frac{\varepsilon_T \Gamma_R}{1 - \varepsilon_S \Gamma_R}. \quad (1)$$

The error terms ε_D , ε_S , and ε_T are often referred to as the residual or second-tier error terms. The error model for these measurements is shown in Figure 1.

Assume that three devices such as an open, short, and load are measured with both calibrations yielding Γ_{MO} , Γ_{MS} , Γ_{ML} , Γ_{RO} , Γ_{RS} , and Γ_{RL} , where the M subscript designates measurements made with the first-tier calibration, and the R subscript denotes measurements made with the more accurate calibration. Equation (1) can then be solved for ε_D , ε_S , and ε_T by the matrix equation

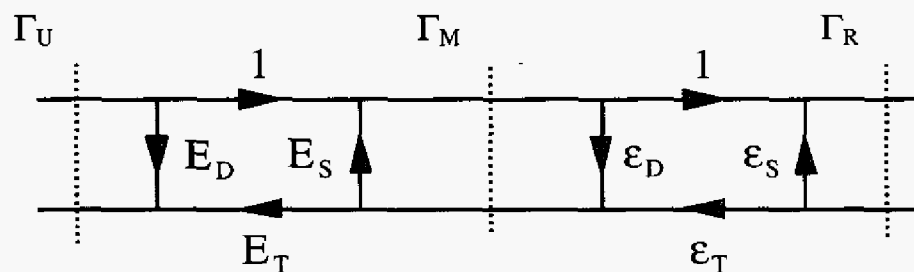


Figure 1: Error model showing first-tier and residual or second-tier error terms.

$$\begin{bmatrix} \epsilon_D \\ \epsilon_T - \epsilon_D \epsilon_S \\ \epsilon_S \end{bmatrix} = \begin{bmatrix} 1 & \Gamma_{RO} & \Gamma_{RO} \Gamma_{MO} \\ 1 & \Gamma_{RS} & \Gamma_{RS} \Gamma_{MS} \\ 1 & \Gamma_{RL} & \Gamma_{RL} \Gamma_{ML} \end{bmatrix}^{-1} \begin{bmatrix} \Gamma_{MO} \\ \Gamma_{MS} \\ \Gamma_{ML} \end{bmatrix}. \quad (2)$$

The discussion so far has assumed that the three devices used to solve (2) are an open, short, and load. However, any number of other devices can also be used. These three devices may or may not be the ones used in the first-tier calibration. The only restriction on them are those typically imposed on one-port calibration standards. For example, three offset shorts could be used, as long as their phase angles remain separated by approximately 120 degrees. However, caution must be exercised in the choice of these devices to be sure that solution is not ill-conditioned and therefore unduly sensitive to additive noise.

3. Experimental Results:

To demonstrate the technique, a VNA was calibrated with a 2.4 mm OSL calibration that uses a broadband load. This calibration is the first-tier calibration. The reflection coefficient of the broadband load is as large as 0.035 at 50 GHz, which introduces a significant systematic calibration error. There are also significant errors in this calibration due to the imperfect models that are used for the short and open. The phase errors in the short and open models are as large as 2% at 50 GHz. The VNA was then calibrated with a TRL reference calibration. Measurements were then made using these two calibrations on an offset short, a 0.5 mismatch and a matched load. None of these devices were used in either the first-tier or the TRL calibrations. From these measurements, equation (2) was solved for ϵ_D , ϵ_S , and ϵ_T .

Figure 2 shows the magnitude of the reflection coefficient for the offset short with and without the second-tier corrections applied. Also shown on this graph are the TRL measurements. As can be seen, the differences in the magnitude of the reflection coefficient between the TRL and first-tier OSL are as large as 0.05. After the second-tier corrections are applied the differences are typically less than 0.006. Figure 3 shows the results for the phase of the offset short. Plotted in Figure 3 is $\phi_{TRL} - \phi_{OSL}$ and $\phi_{TRL} - \phi_{Corrected\ OSL}$, where ϕ_{TRL} is the phase from the TRL measurements, ϕ_{OSL} is the phase from the first-tier OSL measurements, and $\phi_{Corrected\ OSL}$ is the phase after the second-tier corrections have been applied. The phase difference between TRL and OSL is as large as 5.5% before the second-tier corrections are applied, and less than 0.8% after they are applied.

Figure 4 shows the magnitude of the reflection coefficient for the 0.5 mismatch, with and without the second-tier corrections. The difference between the first-tier OSL measurements and TRL is as large as 0.026. After the second-tier corrections are applied, the difference is typically less than 0.004. Figure 5 shows similar measurements for the matched load. In this case, the difference in the magnitude of the reflection coefficient between the first-tier and TRL measurements is as large as 0.025. After the second-tier corrections are applied, the difference is typically less than 0.004.

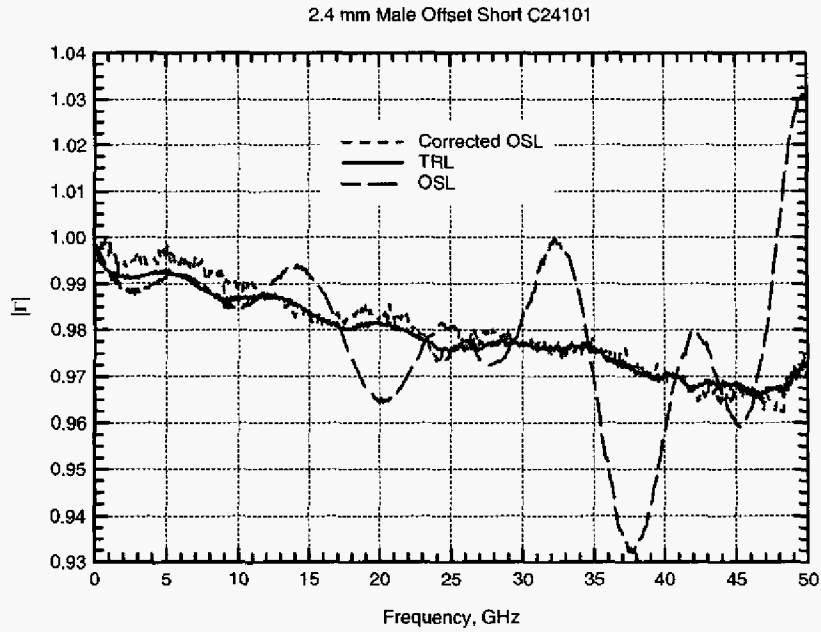


Figure 2: Measurements of $|\Gamma|$ for the offset short with first-tier OSL, second-tier corrected OSL, and TRL.

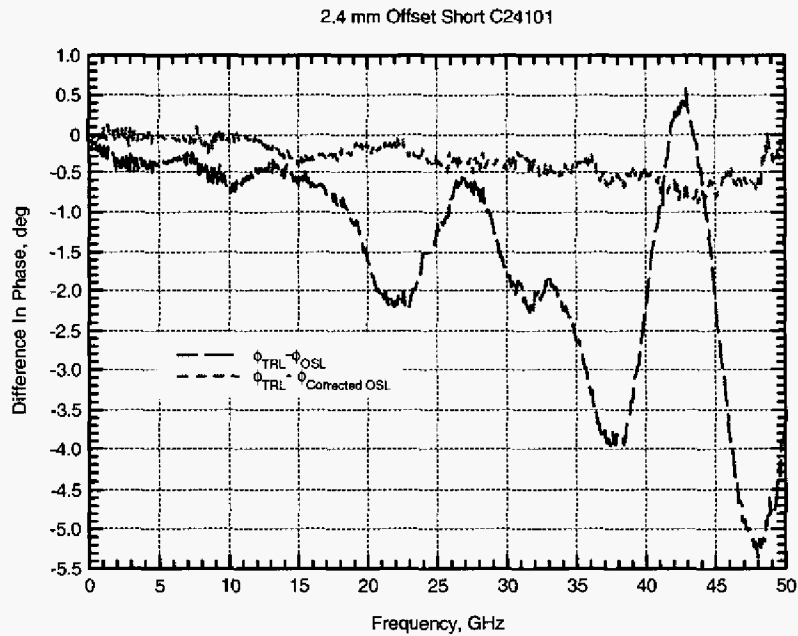


Figure 3: Measurements of the phase of Γ for the offset short with first-tier OSL, second-tier corrected OSL, and TRL.

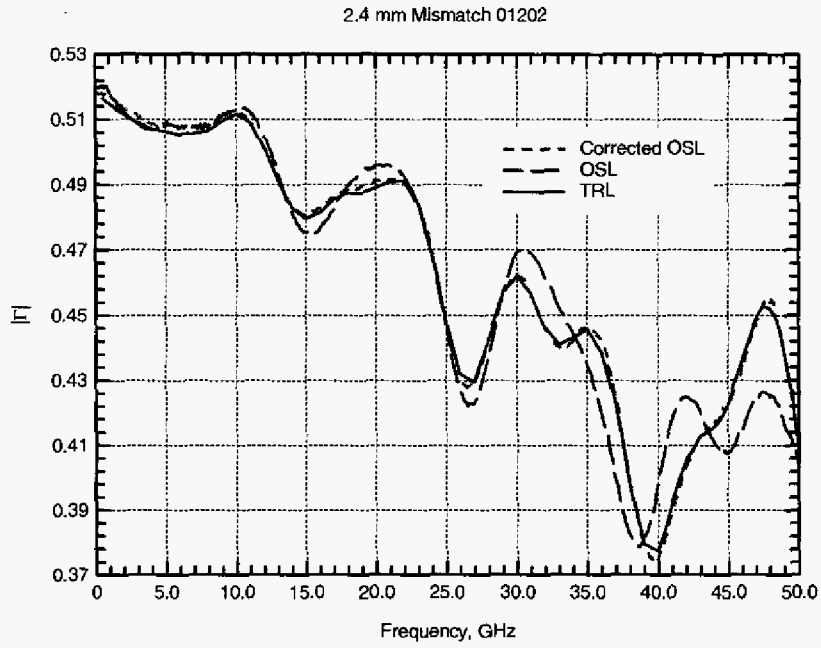


Figure 4: Measurements of $|\Gamma|$ for the 0.5 mismatch with first-tier OSL, second-tier corrected OSL, and TRL.

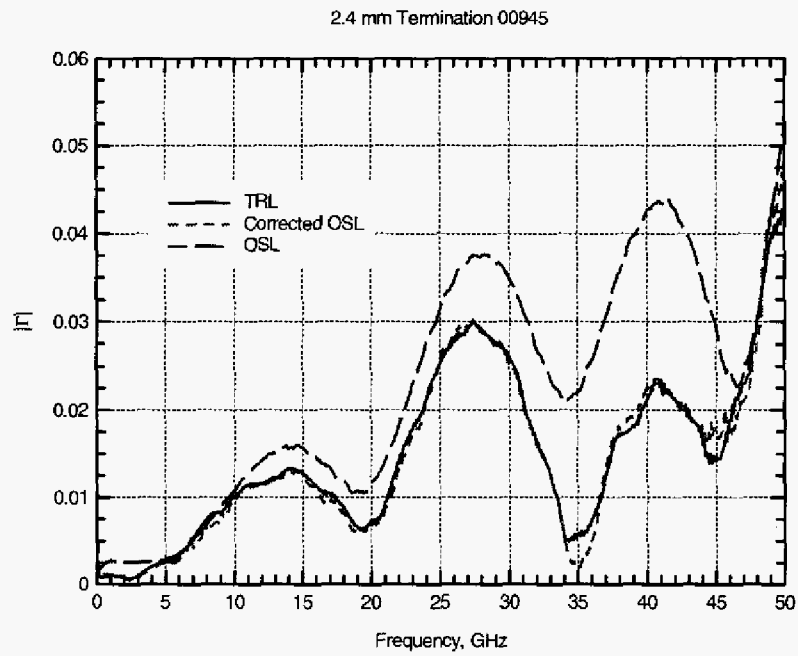


Figure 5: Measurements of $|\Gamma|$ for the matched load with first-tier OSL, second-tier corrected OSL, and TRL.

The next set of tests was made with a 2.4 mm open, short, sliding-load (OSSL) calibration. This calibration uses a sliding load for frequencies above 4 GHz, and a broadband load for frequencies below 4 GHz. The major source of systematic error in this calibration is the errors in the models for the open and short. Figure 6 shows the magnitude of the reflection coefficient for the offset short with and without the second-level corrections applied. The difference in the magnitude of the reflection coefficient between the first-tier OSSL calibration and TRL is as large as 0.025. However, after the second-tier corrections are applied, the difference is less than 0.004. Figure 7 shows measurements of the magnitude of the reflection coefficient for the matched load. In this case, the difference between the first-tier OSSL calibration and TRL is as large as 0.004. However, after the second-tier corrections are applied, the difference is typically less than 0.001.

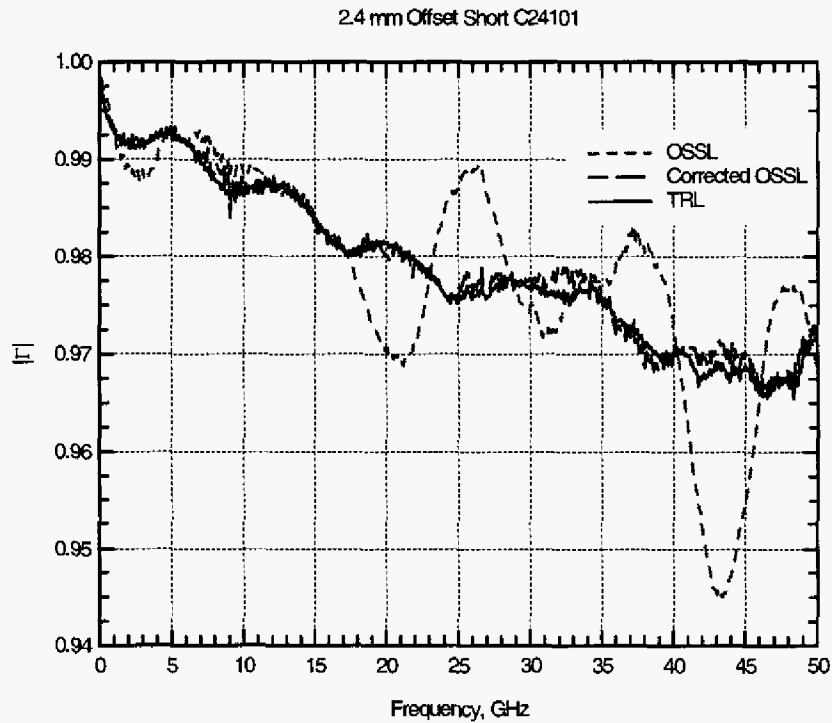


Figure 6: Measurements of $|\Gamma|$ for the offset short with first-tier OSSL, second-tier corrected OSSL, and TRL.

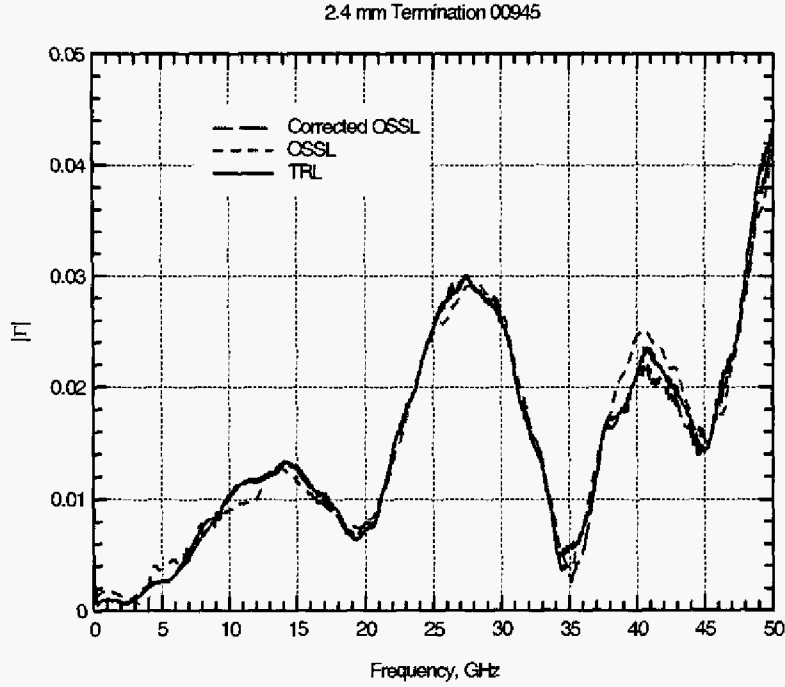


Figure 7: Measurements of $|\Gamma|$ for the matched load with first-tier OSSL, second-tier corrected OSSL, and TRL.

4. Approximations:

In general, the solutions for ε_D , ε_S , and ε_T , as given in (2), are a complicated nonlinear function of the all of the unknowns. However, there are a few special cases that add insight into these correction terms. For example, assume that there are no errors in the open or short ($\Gamma_{MO} = \Gamma_{RO}$ and $\Gamma_{MS} = \Gamma_{RS}$) and that all of the error is due to the calibration load ($\Gamma_{RL} - \Gamma_{ML} = \Delta_L$). Also assume, as in the OSL calibration, that $\Gamma_{ML} = 0$. Given these assumptions, it can be shown that

$$\varepsilon_D = -\Delta_L, \quad (3)$$

$$\varepsilon_S = \frac{\Delta_L}{\Gamma_{MS} \Gamma_{MO}}, \quad (4)$$

$$\varepsilon_T \approx 1 + \frac{\Delta_L^2}{\Gamma_{MS} \Gamma_{MO}}. \quad (5)$$

As can be seen, ε_D and ε_S are a function of Δ_L , while ε_T is a function of Δ_L^2 .

The other special case of interest is where the calibration error is due to errors in either the open or short. For example, assume that all of the calibration error is due to the open circuit. In this instance $\Gamma_{MS} = \Gamma_{RS}$ and $\Gamma_{ML} = \Gamma_{RL}$ and $\Gamma_{RO} - \Gamma_{MO} = \Delta_O$. Also assume as in the previous case that $\Gamma_{ML} = 0$. For this case it can be shown that

$$\varepsilon_D = 0, \quad (6)$$

$$|\varepsilon_S| \approx \frac{|\Delta_O|}{2}, \quad (7)$$

and

$$|\varepsilon_T| \approx \left| 1 - \frac{\Delta_O}{2} \right|. \quad (8)$$

Thus, $\varepsilon_D = 0$ while ε_S and ε_T are both a function of $\Delta_O/2$.

5. Summary and Conclusions:

A method is described for correcting for systematic errors in one-port calibrations. The method, which is similar to the two-tier technique that is used to correct for probe heads in on-wafer measurements, can be used to correct for imperfect loads and for imperfect open and short models in OSL and OSSL calibrations. The method is demonstrated by correcting a broadband OSL and a conventional OSSL calibration. In both cases, the systematic errors in the measurements were reduced to a level comparable to those from a TRL calibration. With the technique, the systematic errors in the measurements of offset shorts were reduced by nearly an order of magnitude.

6. References:

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- [4] Williams, D.F., "De-embedding and unterminating microwave test fixtures with nonlinear least squares," IEEE Trans. Microwave Theory Tech., vol 38, no 6, pp. 787-791, June 1990.