Establishing Traceability of an Electronic Calibration Unit Using the NIST Microwave Uncertainty Framework

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***Abstract* — We present a method for establishing traceability of a commercial electronic calibration unit for vector network analyzers by characterizing the scattering parameters of its internal states with repeated multiline thru-reflect-line (TRL) calibrations and utilizing the NIST Microwave Uncertainty Framework to propagate uncertainties. With the electronic calibration unit characterized, we use it to calibrate a network analyzer, and characterize a number of verification devices with corresponding uncertainties. We also characterize the same verification devices using one of the previous multiline TRL calibrations, and compare results.**

***Index Terms* — Electronic calibration unit, traceability, uncertainty, vector network analyzer.**

I. Introduction

The multiline thru-reflect-line (TRL) calibration [1] is perhaps the most accurate vector network analyzer (VNA) calibration for coaxial circuits. Multiline TRL measures the propagation constant of the line standards so that the reference impedance can be set, and offers high bandwidth and accuracy through the use of multiple transmission line standards. However, a set of coaxial lines, some relatively long, is required to obtain a wide-band measurement. Coaxial airlines also require considerable care to ensure a good connection without damaging the standard. Furthermore, a set of lines can be costly, and measurements are time-consuming.

Other types of VNA calibrations make use of compact, lumped-element standards. The most common of these calibrations are the open-short-load-thru (OSLT) and the line-reflect-match (LRM) methods [2]. These methods provide calibration procedures that are easier to perform at the cost of lower accuracy. Over the years, electronic calibration units have become a viable alternative to the aforementioned methods. First proposed in 1993 [3], these units provide the advantage of requiring only one connection and are capable of rapidly switching among a large variety of reflection coefficients and low-loss transmission coefficients. Recently, newer commercial units have been shown to be stable enough to be used in place of mechanical verification artifacts [4, 5].

In this paper, we create a traceability path for a commercial electronic calibration unit by characterizing it with repeated multiline TRL calibrations and utilizing the NIST Microwave Uncertainty Framework [6] to propagate uncertainties. This approach is based on parallel sensitivity and Monte-Carlo analyses that enable us to capture and propagate the significant S-parameter measurement uncertainties and statistical correlations between them [7]. By identifying and modeling the physical error mechanisms in the multiline TRL standards, we can determine the statistical correlations between both the scattering parameters at a single frequency and uncertainties at different frequencies. These uncertainties can then be propagated into the uncertainties for the electronic calibration unit, as well as the measurements of the verification devices measured using a calibration based on that unit. In the following sections, we describe our methodology in further detail and present our results.

II. Methodology

In order to establish traceability of an electronic calibration unit, we begin by measuring the multiline TRL standards. Using these measurements, along with their respective definitions (i.e. lengths, diameters, etc.) and associated uncertainties, we calibrate the VNA using the NIST Microwave Uncertainty Framework [6], which results in a set of calibration coefficients along with uncertainties. With this multiline TRL calibration in place, we make measurements of the electronic calibration unit and calibrate its response with corresponding uncertainties. We repeat the previous steps two additional times, giving us three sets of data characterizing the electronic calibration unit. Next, we use a post-processor to combine the data from the three calibrations to give us means and combined uncertainties of the characterized electronic calibration unit's scattering parameters. During each of the three multiline TRL calibrations, we also measure a set of verification devices, including a thru connection, a short, a matched load, and a Beatty line.

With the electronic calibration unit characterized, we can then use it to calibrate the VNA at a later date, which gives a new set of calibration coefficients along with uncertainties for that particular instrument/calibration. With this calibration in place, we measure the same verification devices, calibrate the measurements, and determine the corresponding uncertainties. We then compare our measurements to results from an earlier multiline TRL calibration to establish traceability of the electronic calibration unit. A flowchart describing this method is illustrated in Figure 1.

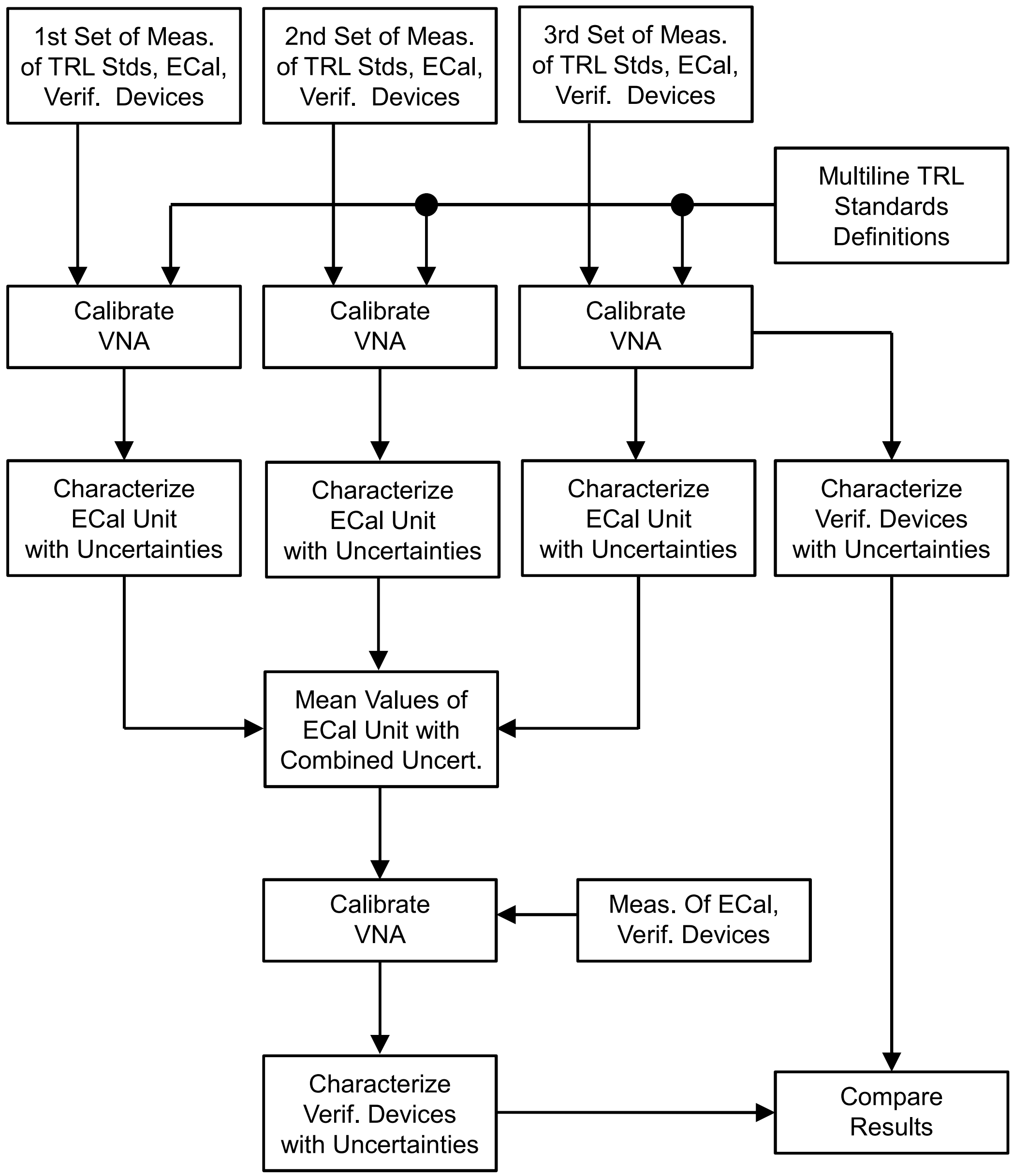

Fig. 1. Flowchart for establishing traceability of an electronic calibration unit using repeated multiline TRL calibrations.

To illustrate our technique, we performed measurements in a 1.85 mm coaxial environment. Table 1 lists the line lengths and associated uncertainties for the multiline TRL standards, and Table 2 lists the other sources of uncertainty for the standards. Our values and distributions of the uncertainties come from a variety of sources, including previous publications [8], manufacturers' specifications, and an IEEE standard [9]. We assumed an infinite number of degrees of freedom for all of these mechanical uncertainties.

The NIST Microwave Uncertainty Framework is employed to construct models for the calibration standards. The airline and offset short standards are modeled using closed-form expressions for coaxial lines with finite metal conductivity [8]. The framework is also used for automatically propagating the uncertainties to the calibrated verification devices in conjunction with the calibration engine, StatistiCAL™ [10, 11], which accommodates most coaxial and on-wafer standards, and enables a "mix-and-match" philosophy to VNA calibrations.

Table I. Line lengths and uncertainties for the TRL standards.

Line Designation	Length (mm) ± Uncertainty (Probability Distribution)
Thru	0 ± 0
Line 1	14.999 ± 0.009 (Rectangular)
Line 2	16.337 ± 0.009 (Rectangular)
Line 3	18.573 ± 0.009 (Rectangular)
Line 4	23.066 ± 0.009 (Rectangular)
Line 5	29.981 ± 0.009 (Rectangular)
Offset Short	5.1 ± 0.009 (Rectangular)

Table II. Sources of uncertainty for the TRL standards.

Mechanism (units)	Value ± Uncertainty (Distribution)
Inner Conductor Diameter (mm)	0.8036 ± 0.002 (Rectangular)
Outer Conductor Diameter (mm)	1.85 ± 0.0025 (Rectangular)
Port 1 Pin Diameter (mm)	0.511 ± 0.005 (Rectangular)
Port 2 Pin Diameter (mm)	0.511 ± 0.005 (Rectangular)
Port 1 Pin Depth (mm)	0.006 ± 0.006 (Rectangular)
Port 2 Pin Depth (mm)	0.006 ± 0.006 (Rectangular)
Port 1 Eccentricity (mm)	0 ± 0.0125 (Gaussian)
Port 2 Eccentricity (mm)	0 ± 0.0125 (Gaussian)
Metal Conductivity (S/m)	$7.9\times10^6 \pm 4.0\times10^6$ (Rectangular)
Outer – Inner-Cond. Length (mm)	0.006 ± 0.006 (Rectangular)
Relative Inner-Conductor Position	0 ± 1 (Bernoulli)
Relative Dielectric Constant	1.000535 ± 0
Dielectric Loss Tangent	0 ± 0

III. Results

Figures 2-9 show calibrated S-parameters and corresponding 95% confidence bounds calculated from the sensitivity analysis performed by the NIST Microwave Uncertainty Framework for a thru, short, load, and Beatty line using two calibrations – one with the characterized electronic calibration unit and one using multiline TRL. The S-parameters of the devices calibrated with the electronic calibration unit tend to be noisier than those of the multiline TRL calibration. Nevertheless, for each device, we see that the magnitudes and phases of the two calibrations agree within the 95% confidence bounds for the vast majority of the data points. These results provide credence that our method for establishing traceability of a commercial electronic calibration unit by characterizing its scattering parameters with repeated multiline (TRL) calibrations is reasonable.

IV. Conclusion

The principle advantage of characterizing an electronic calibration unit and providing uncertainties is that the unit can be used as a working set of standards that requires only a single connection to calibrate the VNA, saving both time and wear-and-tear on the VNA test ports and TRL standards. In the near future, we plan to characterize additional units with other connector sizes, and utilize these traceable units for adapter characterization.

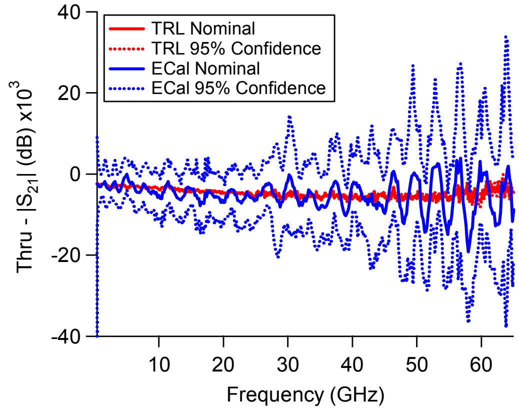

Fig. 2. Magnitude of S_{21} for a thru calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

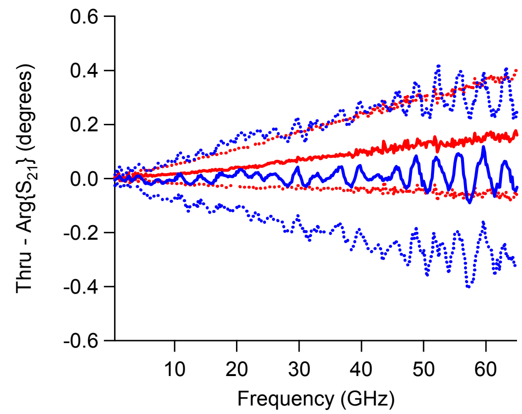

Fig. 3. Phase of S_{21} for a thru calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

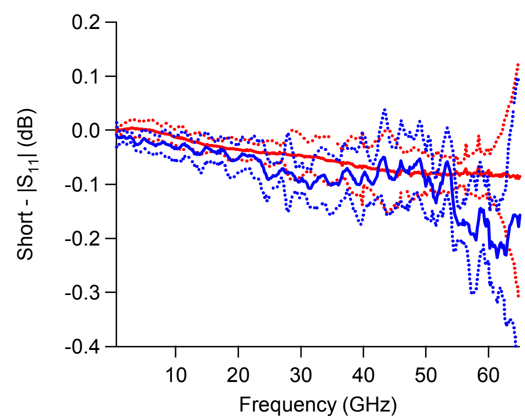

Fig. 4. Magnitude of S_{11} for a short calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

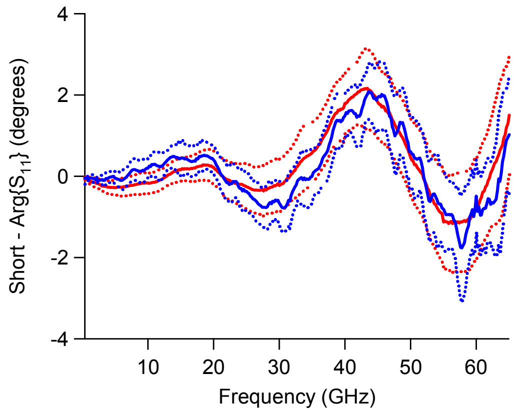

Fig. 5. Unwrapped and de-trended phase of S_{11} for a short calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

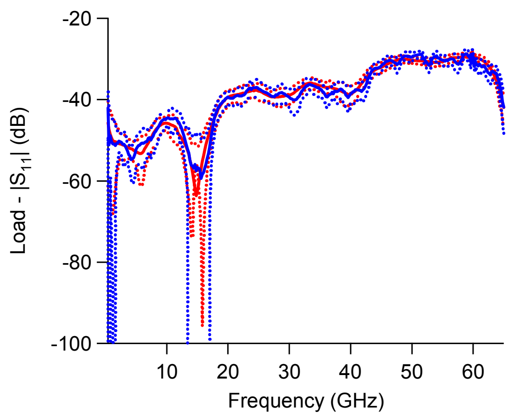

Fig. 6. Magnitude of S_{11} for a load calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

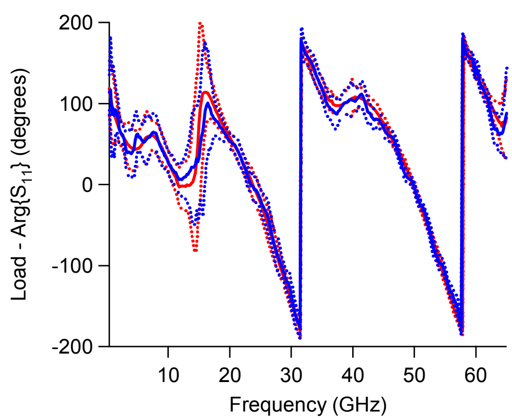

Fig. 7. Phase of S_{11} for a load calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

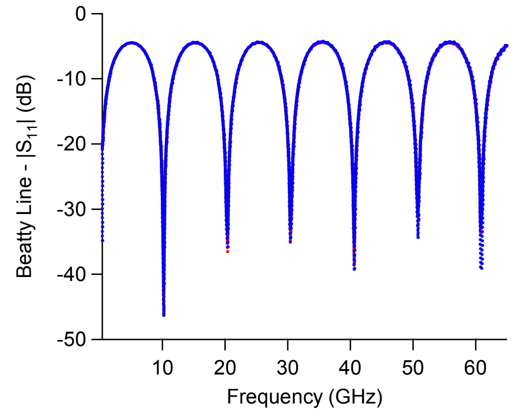

Fig. 8. Magnitude of S_{11} for a Beatty line calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

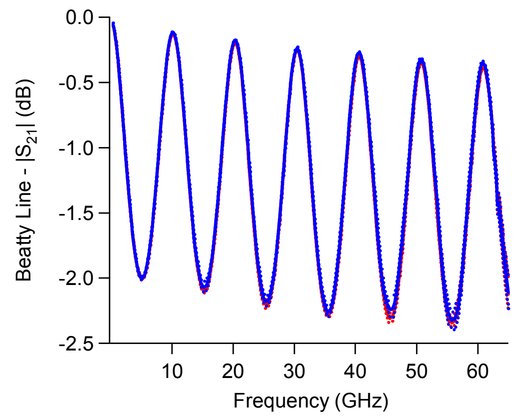

Fig. 9. Magnitude of S_{21} for a Beatty line calibrated by multiline TRL and by a traceable electronic calibration unit, along with 95% confidence bounds.

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