Three-Port Vector-Network-Analyzer Calibrations using the NIST Microwave Uncertainty Framework

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***Abstract* — We have implemented methods for calibrating three-port vector network analyzers (VNAs) and propagating correlated uncertainties using the NIST Microwave Uncertainty Framework. We describe our calibration procedures, which utilize measured wave-parameters rather than scattering parameters to account for switch-term corrections, and present results for a three-port power splitter. We compare our calibrated measurements with those performed using the firmware of a commercial VNA, and show the results agree to within our confidence intervals at most frequencies.**

***Index Terms* — calibration, coaxial, power splitter, physical models, three-port, uncertainty, vector network analyzer.**

I. Introduction

Numerous commercial vector network analyzers (VNAs) are available for measuring scattering-parameters (*S*-parameters) of multiport devices such as circulators, coupled transmission lines, directional couplers, power dividers, and power splitters, to name just a few.

In this paper, we focus on three-port *S*-parameter measurements, utilizing the NIST Microwave Uncertainty Framework (MUF) [1] to perform calibrations and propagate correlated uncertainties. The MUF utilizes parallel sensitivity and Monte-Carlo analyses, and allows us to capture and propagate the significant *S*-parameter measurement uncertainties and statistical correlations between them [2]. By identifying and modeling the physical error mechanisms in the calibration standards, we can determine the statistical correlations between both the *S*-parameter uncertainties at a single frequency and uncertainties at different frequencies. These uncertainties can then be propagated to measurements of the devices under test (DUTs).

In the following sections, we describe how our three-port calibration methods are implemented in the MUF and compare our calibrated measurements of a resistive power splitter to those using a calibration performed with the firmware of a commercial VNA.

II. Three-Port Calibrations

Figure 1 illustrates a model of the systematic errors to be calibrated in a three-port VNA. The DUT is embedded within the error boxes X, Y, and Z, which represent impedance mismatches, losses in the test cables and connectors, and frequency response errors in the sources and receivers. For linear networks, the VNA supplies measurements of uncalibrated *S*-parameters at ports 1, 2, and 3. In the MUF, the error boxes, X, Y, and Z, are arranged into "s6p" files, with the following port nomenclature: ports 1, 2, and 3 correspond to the physical ports of the VNA, and ports 4, 5, and 6 correspond to the ports between the error boxes and the DUT. There are numerous ways to solve for the error boxes [3-4], but in the current version of the MUF software, they can be determined either with two separate short-open-load-thru (SOLT) calibrations or three one-port SOL calibrations in conjunction with two reciprocal connections, commonly referred to as SOLR. Both calibrations assume no crosstalk, so 24 of the 36 error terms are zero.

The SOLR calibration [5-6] is akin to the SOLT calibration [7] in that it is relatively easy to perform, is inherently broadband, and makes use of three characterized standards (open, short, and load) connected to each port of the VNA. The SOLR calibration is an attractive alternative to the SOLT when a zero-length thru is unavailable or difficult to implement, such as when measuring non-insertable or multiport devices. Here, the thru need not be characterized. The only knowledge required is the standard must be reciprocal.

The SOLT and SOLR calibrations are realized with eight-term error models in the MUF. Furthermore, in the case of multiport measurements, the software makes use of measured wave-parameters (a_i and b_i), and then converts them to *S*-parameters prior to calibration to avoid measuring and correcting for the switch-terms of each port [8]. The short, open, and load measurements, along with their respective definitions, allow us to determine the two reflection terms for each of the error boxes. This leaves the transmission terms.

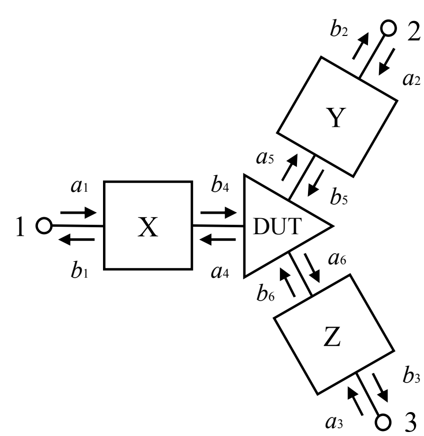

Fig. 1. Model of systematic errors in a three-port VNA.

The SOL-family of calibrations determines the product of the transmission-terms ($S_{ij} \cdot S_{ji}$) of each one-port error box [7]. In the MUF, the two individual terms are arbitrarily set equal by taking the square root of the product. Then, a sequential method is used to adjust the ratios of the Y and Z error boxes' transmission-terms by setting complex constants α and β so the calibration is consistent with measurements of the reciprocal or thru standard, as illustrated in Figure 2. Error box X contains two identical transmission-terms (S_{41}=S_{14}). After error box Y is determined, its transmission-terms, which are initially identical (S_{52}=S_{25}), are adjusted to be consistent with error box X by multiplying and dividing the terms by α so the product of the two ($\alpha S_{52} \cdot \alpha^{-1} S_{25}$) remains unchanged. Likewise, after error box Z is determined, its transmission terms, which are initially identical (S_{63}=S_{36}), are adjusted to be consistent with error box X by multiplying and dividing the terms by β so the product of the two ($\beta S_{63} \cdot \beta^{-1} S_{36}$) remains unchanged.

For the SOLT case, the definition of the thru is constrained to be ideal, while for the SOLR case, the thru is merely assumed to be reciprocal. In the case of large-signal calibrations, the transmission terms are adjusted again to account for amplitude and phase corrections.

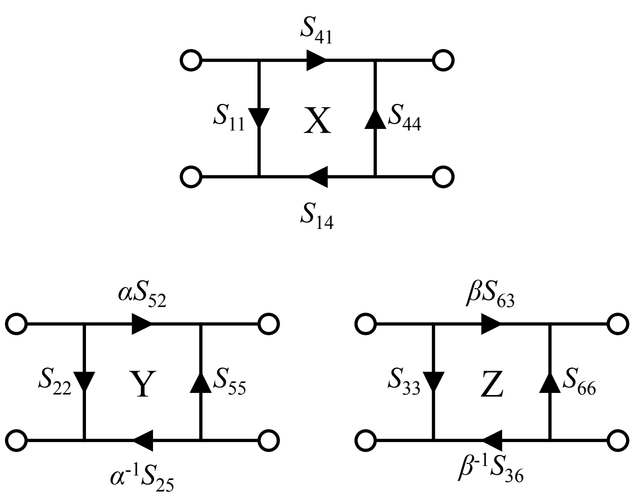

Fig. 2. Model of consistent error boxes in a three-port VNA.

III. Three-Port Measurements

We measured a resistive power splitter, shown in Figure 3. Such a device has *S*-parameters with the following nominal values: $S_{31} = S_{21}$ = 0.50 (-6 dB); $S_{23} = S_{32}$ = 0.25 (-12 dB); $S_{22} = S_{33}$ = 0.25 (-12 dB); and S_{11} = 0. Our power splitter was equipped with 3.5 mm connectors, a female on port 1 and males on ports 2 and 3, as shown in Figure 4. For the SOLT case, we performed an insertable calibration between port 1 (male) and port 2 (female), and another insertable calibration between port 1 (male) and port 3 (female). For the SOLR case, we performed one-port SOL calibrations on ports 1, 2, and 3, and connected our insertable, reciprocal thru between ports 1 and 2, and 1 and 3. Thus, both types of calibrations made use of identical connections. Our calibration standards were modeled with closed-form expressions for coaxial lines of finite metal conductivity [9, 10].

All measurements were performed with 3.5 mm coaxial connectors between 0.2 – 18.0 GHz, and an IF bandwidth of 20 Hz with no averaging. We measured wave-parameters of each device, and then converted them to uniquely-defined *S*-parameters, rather than measuring the switch-terms separately and then correcting the measured *S*-parameters.

The MUF contains a program called the 'VNA Uncertainty Calculator' for performing both covariance-based and Monte-Carlo uncertainty analyses using general connector models and common calibration engines. Figures 5 and 6 illustrate the menus for our three-port SOLT and SOLR calibrations, respectively. The first column of each menu contains the filenames of the standard definitions; the second column refers to the standard types; the third column contains the measurement filenames; and columns 4 and 5 refer to the ports of the VNA to which the devices were connected. For example, in row 1 of Figure 5, the open standards were simultaneously connected to ports 1 and 3.

In addition to performing the SOLT and SOLR calibrations with the MUF, we also performed a calibration using the firmware of our commercial VNA with the same calibration kit. We compared the calibrated measurements of the power splitter using the three methods. Figures 7-10 plot the magnitudes of S_{31}, S_{23}, S_{33}, and S_{11}, respectively, along with the 95% confidence intervals of our SOLT and SOLR calibrations. Figure 11 plots the differences in phase of S_{31}. The nominal values and associated uncertainties agree almost perfectly for the two calibrations processed by the MUF; in part since they were performed using identical measurements and calibration standard definitions. The small variations can be attributed to differences in the calibration algorithms. The variations between the two MUF calibrations and the VNA's firmware calibration are more noticeable but lie within the confidence intervals of the MUF calibrations at most frequencies. Here, some of discrepancies may be attributed to repeatability of the connections, different calibration algorithms, and different definitions of the calibration standards. In our case, we developed physical models for the standards, while the VNA firmware utilized polynomial models.

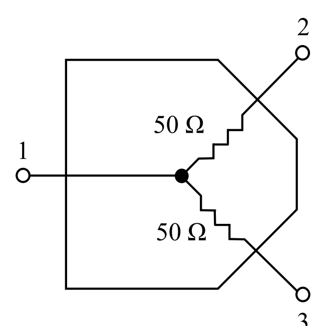

Fig. 3. Simplified schematic of a three-port power splitter.

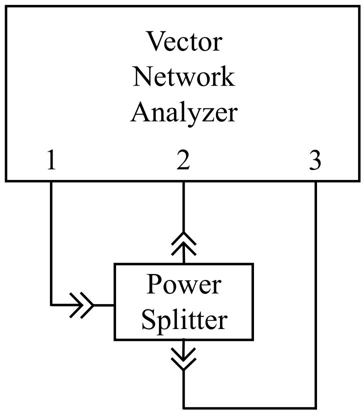

Fig. 4. Simplified schematic of a three-port measurement setup.

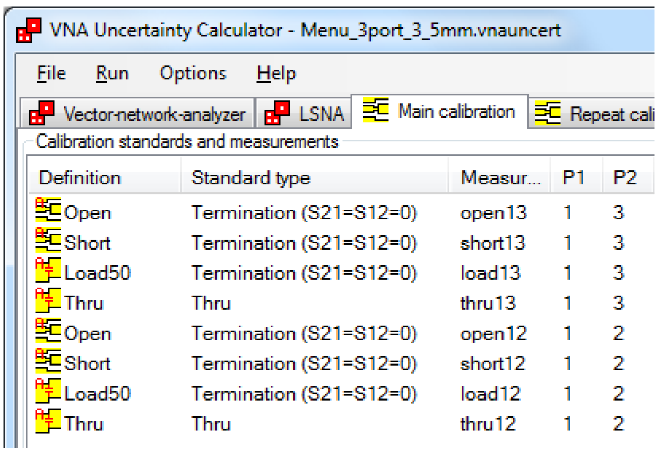

Fig. 5. Calibration menu for the three-port SOLT calibration utilized by the NIST Microwave Uncertainty Framework.

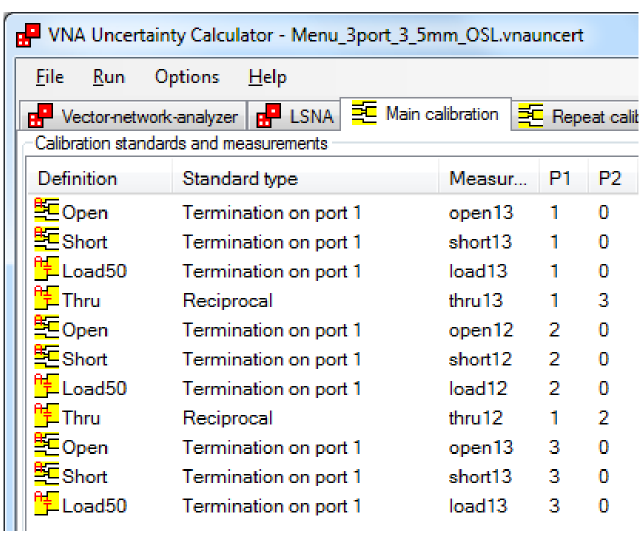

Fig. 6. Calibration menu for the three-port SOLR calibration utilized by the NIST Microwave Uncertainty Framework.

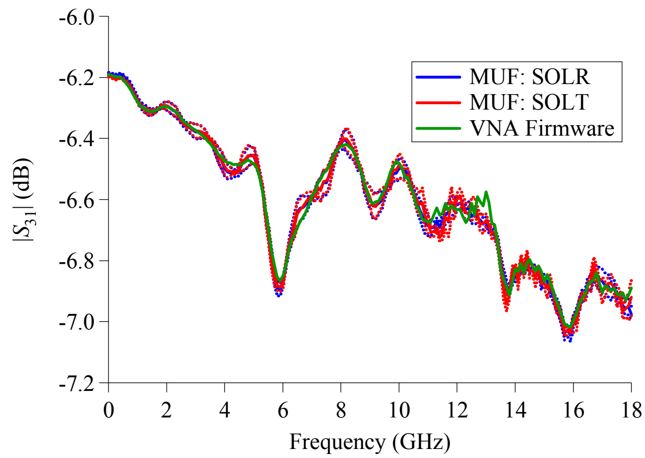

Fig. 7. Comparing magnitudes and 95% confidence intervals (dotted lines) of the power splitter's S_{31} measurements.

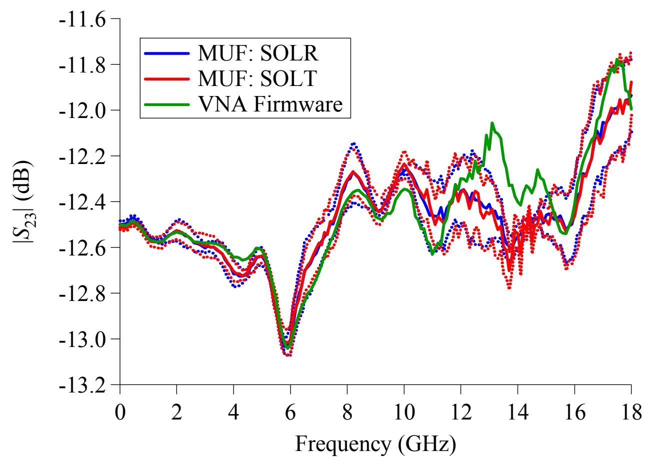

Fig. 8. Comparing magnitudes and 95% confidence intervals (dotted lines) of the power splitter's S_{23} measurements.

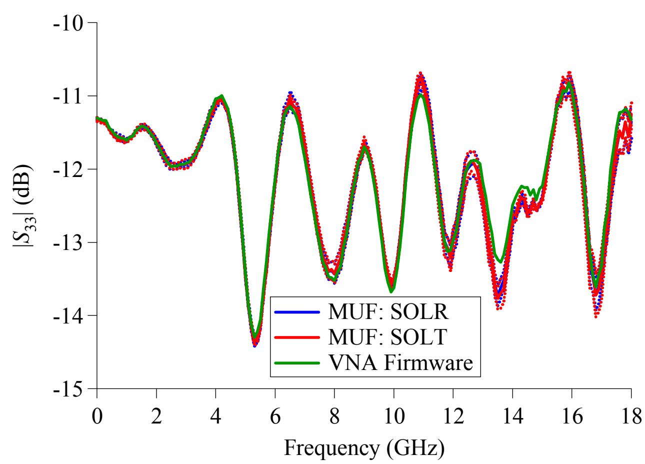

Fig. 9. Comparing magnitudes and 95% confidence intervals (dotted lines) of the power splitter's S_{33} measurements.

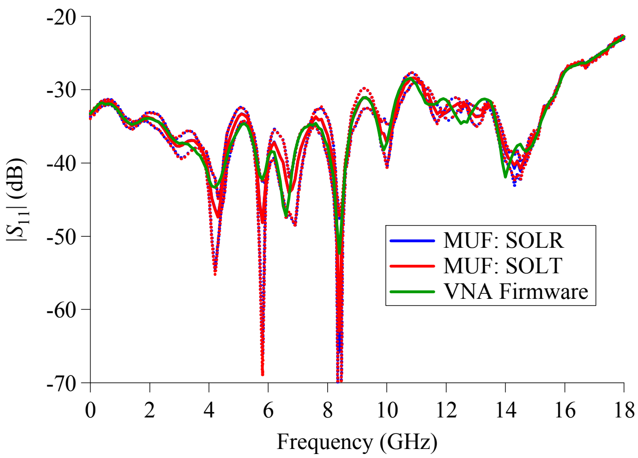

Fig. 10. Comparing magnitudes and 95% confidence intervals (dotted lines) of the power splitter's S_{11} measurements.

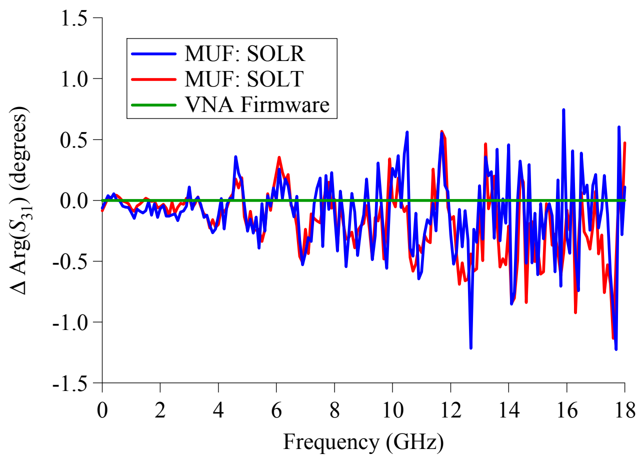

Fig. 11. Comparing differences in phase (MUF – VNA firmware) of the power splitter's S_{31} measurements.

IV. Conclusions

We have developed the capability for characterizing three-port DUTs and propagating correlated uncertainties using the MUF. Our calibration procedures, which utilize measured wave-parameters, provide results that compare well with those performed by the firmware of a commercial VNA.

Acknowledgement

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