ACCURACY OF LUMPED-ELEMENT CALIBRATIONS FOR FOUR-SAMPLER VECTOR NETWORK ANALYZERS

R. B. Marks[1], J. A. Jargon[1], and D. K. Rytting[2]

[1] *National Institute of Standards and Technology*
325 Broadway, Mail Code 813.06, Boulder, CO 80303 USA
marks@nist.gov
[2] *Hewlett-Packard Company, Santa Rosa, CA*

Abstract - Several lumped-element calibrations have been proposed for four-sampler vector network analyzers. This paper offers the first assessment of their accuracy in the face of imperfectly defined standards. We discover significant error and introduce a new calibration that offers demonstrably improved accuracy.

INTRODUCTION

The original applications of the SOLT ("short-open-load-thru") calibration to vector network analyzers (VNAs) presumed a three-sampler architecture. The method is commonly applied even to *four*-sampler VNAs, with the data available from the fourth sampler simply ignored. Early in this decade, two papers considered variations of the SOLT method that presumed switch-corrected data as input [1,2] and were therefore appropriate to four-sampler VNAs. If the data from the fourth sampler is used, the number of measurements in the calibration can be reduced, as compared to conventional SOLT. In principle, many options are possible.

As noted by one of these papers [2],"the methods are not equally sensitive to measurement errors and calibration standard accuracy... thus, measurement errors and error progression mainly depend on the quality of the test equipment and the standards used. More detailed investigations will have to be undertaken in this field." Such an investigation is the subject of this paper. The results are essential if VNA users are to have confidence in some of the faster calibration methods.

Instead of reducing the number of standards, we can try to use the data from the fourth sampler to improve the accuracy of the calibration, making it more robust with respect to errors in the definitions of the standards. Based on the results shown below, we will introduce a new method based on such an approach.

SOLT AND ITS VARIATIONS

The SOLT calibration (here using the algorithm of [3]) makes use of a "thru" connection of the two VNA ports as well as the measurement (on both ports) of three one-port standards, typically a nominal open, nominal short, and nominally matched load. None of these needs to be ideal, but we must know their reflection coefficients. In practice, our "definition" of those values is typically drawn from a model of the standard.

One variation of SOLT for four-sampler VNAs [1] has been dubbed "QSOLT." The "Q" (for "quick") signifies that the method is faster than SOLT since the three one-ports need only be connected to *one* of the VNA ports. Reference [2] included a number of variations in which the one-ports were connected to only one of the two VNA ports or in some cases need not be measured at all.

Although both [1] and [2] demonstrated the basic functionality of their proposals, neither studied the robustness of the proposed methods in the face of the inevitable discrepancy between the reflection coefficients of the standards and our definition of those values.

In addition to QSOLT, Table 1 lists the nine combinations for which two standards are connected to Port 1 and one to Port 2. An additional ten combinations are possible by swapping the ports. In the table, each calibration is given a designation referring to the standards and the ports to which they are connected.

In Table 1, we have categorized the calibrations as:

- Category A: Three unique standards measured on Port 1 (QSOLT).
- Category B: Three unique standards, one of which is measured on Port 2.
- Category C: Open and short measured on Port 1; one remeasured on Port 2. No load.
- Category D: Load measured on both ports, open or short measured on Port 1.
- Category E: Open or short measured on both ports, load measured on Port 1.

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Table 1. Lumped element calibration combinations.

Port 1	Port 2	Designation	Category
O S L	O S L		
1 1 1	0 0 0	$O_1S_1L_1T$	A
1 1 0	0 0 1	$O_1S_1L_2T$	B
1 0 1	0 1 0	$O_1L_1S_2T$	
0 1 1	1 0 0	$S_1L_1O_2T$	
1 1 0	0 1 0	$O_1S_1S_2T$	C
1 1 0	1 0 0	$O_1S_1O_2T$	
1 0 1	0 0 1	$O_1L_1L_2T$	D
0 1 1	0 0 1	$S_1L_1L_2T$	
1 0 1	1 0 0	$O_1L_1O_2T$	E
0 1 1	0 1 0	$S_1L_1S_2T$	

THE SIMULATOR

Our accuracy study makes use of a measurement simulator which simulates "raw" VNA output from input that represents the actual scattering parameters of several physical standards and test devices. After calibrating with the raw measurements of the standards, we apply error correction schemes to raw data for the test devices. Since we have access to the true scattering parameters of each test device, we can explicitly determine the error introduced by each calibration. Other approaches that simply compare the measurement results produced by two calibrations cannot determine the accuracy of either or even say definitively which is better.

In our studies, the input data was measured using a VNA calibrated using multiline TRL ("thru-reflect-line") carried out with MultiCal® software [4]. We provide to the simulator the VNA calibration coefficients determined in that process; with these, it simulates the raw VNA measurements. The simulator operates on calibrated data for a thru and for pairs of nominal opens, shorts, and loads. In addition, we include measurements of a 19 mm transmission line, which serves as a device under test (DUT). All of the measured devices were implemented in coplanar waveguide on GaAs.

CALIBRATION PROCEDURE

Several published mathematical procedures [2,6,7] allow calibration using the measurements described in Table 1. Here we have applied an alternative formulation [3] in which we create a 7x7 complex linear system. Four of the equations are generated using the (simulated) measurements of the scattering parameters of the thru. The other three use the reflection coefficient measurements of the three one-port standards. Solution of the linear system yields the seven error coefficients that describe the four-sampler VNA (ignoring crosstalk errors). We also tried alternative algorithms [1], but saw no significant effect.

RESULTS OF ACCURACY ASSESSMENT

Construction of the 7x7 system requires the "true" reflection coefficients Γ of the standards. When the simulator used these data, all of the calibration procedures proved functional.

However, we would normally have no access to this information in practice. Instead, we would need to model the standards. The essence of this study is to determine the sensitivity of the calibration methods to errors in these models. We tested the calibrations in three cases: simplistic open (Γ = +1 for the open); simplistic short (Γ = -1 for the short); and simplistic load (Γ = 0 for the load). In each case, we used the "true" Γ of the other two lumped-element standards. As an example, Figure 1 illustrates the actual Γ of the open, along with its simplistic model. For illustration, we offset the open.

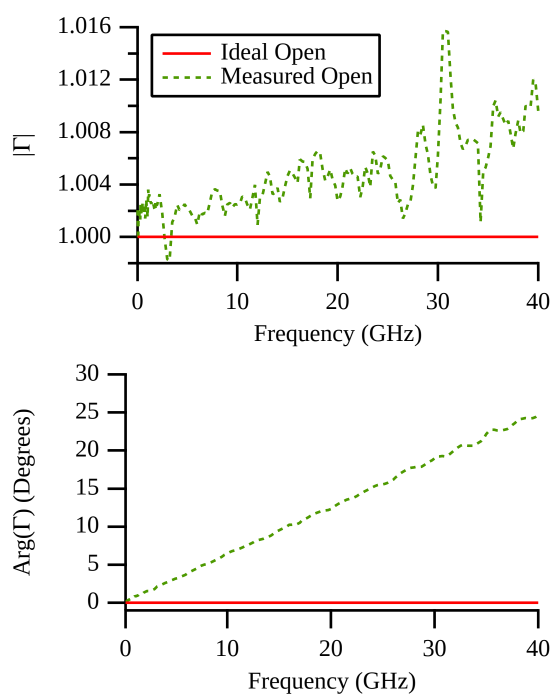

Fig.1. Corrected reflection coefficient of the measured open circuit.

In the case of Category A (QSOLT), we found that the effect of a simplistic model was qualitatively similar for any standard. Figure 2 illustrates the effect of the simplistic open model on QSOLT and SOLT. QSOLT provides significantly improved accuracy in transmission measurement with respect to SOLT, with a slight accuracy gain in S_{11}. However, QSOLT could not accurately obtain S_{22}. This performance can be explained by the fact the QSOLT uses no standards on Port 2. However, the result is not apparent from prior publications. Reference [1] suggested that QSOLT appeared to provide somewhat better accuracy than SOLT in S_{12} and S_{21} and "seems to be reasonably better" for S_{22}. This can be explained by the limited data available. Reference [2] did not show data for S_{22}. Its transmission data were not compared to other measurements and were inconclusive.

In the Category B calibrations, one of the three unique standards is measured on Port 2. When one of the standards was simplistically modeled, the Category B calibrations still provided improved transmission accuracy with respect to SOLT. We found that a simplistic load model gave reflection results comparable to SOLT. With a simplistically modeled reflect instead, we found S_{11} to be comparable to SOLT and S_{22} to be less accurate if the load was on Port 1, and the opposite to be true if the load was on Port 2.

As expected, Category C, which included no load, performed poorly. When the reflect measured on one port was simplistically modeled, the Category C calibrations provided better transmission accuracy than SOLT, although with very poor reflection accuracy. When the reflect measured on both ports was simplistically modeled, the results were disastrous for all scattering parameters, presumably because that standard is used twice.

Clearly, lumped-element calibration will fail when all of the standards have reflection coefficients of +1 or -1, for these reflection coefficients are invariant to reference impedance. To fully understand the capabilities of Category C calibrations, we would need to study their performance using reflects that avoid these two critical points (for example, offset opens and shorts). The resulting reflection coefficients would be more difficult to model. The advantage of the Category C calibrations, however, is that they do not require a load and are therefore free of errors due to inaccuracy in the load definition.

Category D calibrations ignore either the open or short but measure the load on both ports. This may be advantageous if only one well-characterized high-reflection standard is available. We found that a simplistic load model gave reflection results comparable to SOLT but better transmission results. With a simplistically modeled reflect instead, we found much better transmission results, but the reflection results were slightly less accurate.

Category E calibrations also ignore either the open or short, but they remeasure the reflect, rather than the load. For a simplistically modeled load, these calibrations provide good transmission accuracy and reflection accuracy comparable to SOLT. When the reflect present on both ports was simplistically modeled, however, these calibrations proved to be disastrous. Again, this is not surprising, since it means that two of the three standards are simplistically modeled.

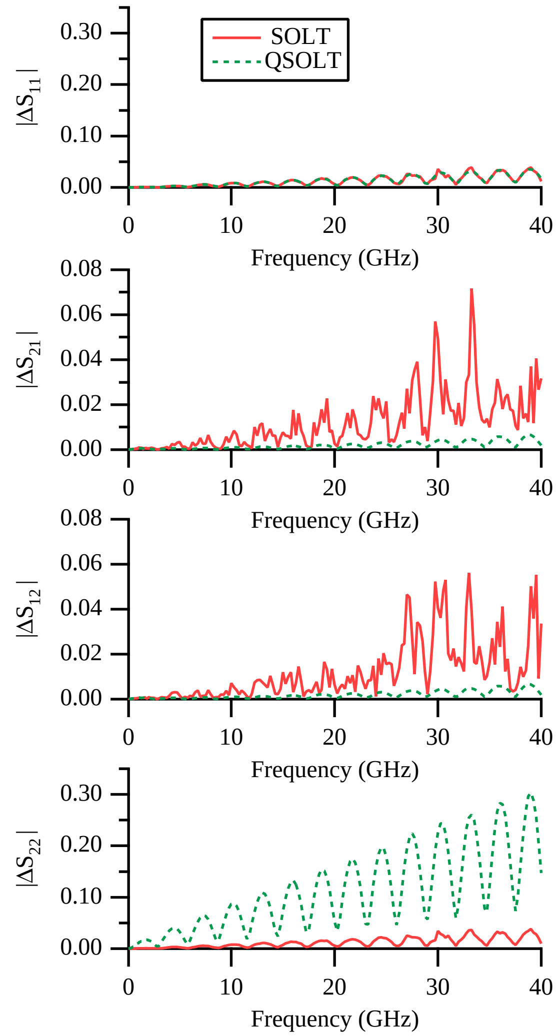

Fig. 2. Magnitude of S-parameter errors ($|\Delta S_{ij}|$) using SOLT and QSOLT to measure a 19 mm coplanar waveguide transmission line. The open standard is defined by the simplest model. QSOLT standards are measured on Port 1 only.

ROBUST SOLT

We have seen that QSOLT provides significantly better accuracy than SOLT in the transmission terms with slight improvement in the accuracy of S_{11}. However, S_{22} is quite inaccurate. On the other hand, there is a simple way to get good accuracy for S_{22}: we simply repeat QSOLT using the one-port standards on Port 2. The estimates of S_{12} and S_{21} turn out to be identical whether we measure the standards on Port 1 or Port 2. Making use of *both* calibrations, we have a new robust SOLT that provides good measurements of all four scattering parameters.

To demonstrate the effectiveness of this method, Figure 3 compares SOLT and robust SOLT measurements to those using MultiCal® [4]. We used the simplistic model of the open of Figure 1. The robust SOLT clearly outperforms traditional SOLT. The performance of both is limited by the increasing phase of the offset open as it traverses the Smith chart.

This new robust SOLT provides greater accuracy than SOLT but is no more difficult in terms of standards or calculations. Each calibration, however, uses *two* twelve-term calibration sets, which doubles the memory requirements. It may be possible to merge the two calibration sets without loss of accuracy, but we have not found a way to do so.

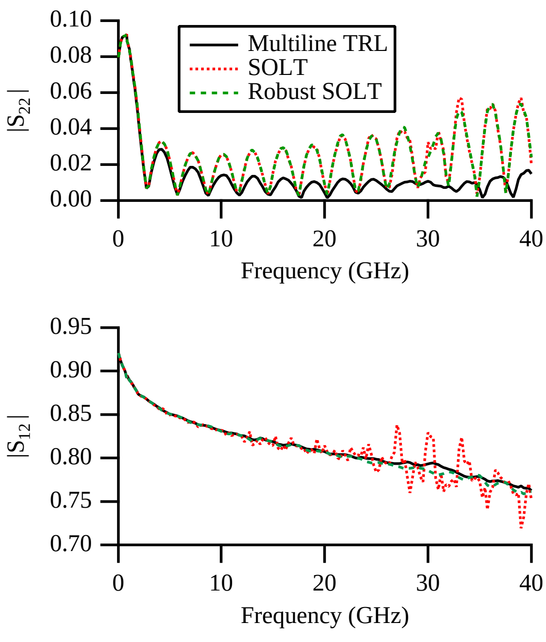

Fig. 3. Magnitude of S_{22} and S_{12} using Multiline TRL, SOLT, and Robust SOLT to measure a 19 mm coplanar waveguide transmission line. The open standard is defined by the simplest model. S_{11} and S_{21} are nearly identical to S_{22} and S_{12}, respectively.

CONCLUSIONS

SOLT is susceptible to significant errors in the measurement of transmission coefficients when the model of the lumped element standards is imperfect. QSOLT provides much more accurate measurement of transmission coefficients but offers poor accuracy of reflection coefficient on the port at which no one-port standards are measured.

A new robust SOLT requires the same measurement and computational effort as SOLT. This robust SOLT provides much better accuracy in transmission measurements and slightly better accuracy in reflection measurements.

The only drawback to the robust SOLT is the doubled memory requirements. It may be possible to merge the two calibration sets into one and thereby eliminate this minor deficiency.

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