Establishing Traceability for SOLT Calibration Kits

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***Abstract* — Establishing traceability for a measurement is very important in that the results of the measurement can be used in a common framework for comparisons and understanding. The standard path of traceability for Short-Open-Load-Thru (SOLT) Vector Network Analyzer (VNA) calibrations has been through empirical models and is tenuous at best. Additionally, the uncertainties do not contain any information about cross-frequency correlations.**

This work describes a technique for establishing traceability for SOLT calibration kits with fully correlated uncertainties. The calibrations performed using calibration kits evaluated with this new approach are traceable back to dimensional standards. This paper describes the new technique and shows the results of measurements based on this technique.

***Index Terms* — Microwave measurements, coaxial connectors, s-parameters, uncertainties, calibration kits**

I. INTRODUCTION

Traceability of a measurement requires two parts: 1) an unbroken chain of measurements and 2) uncertainties for each link of the chain [1]. In general, traceability means showing how, through an unbroken chain, measurements are linked back to fundamental principles or measurements. When a VNA is calibrated, several different error reduction methods (also referred to as calibrations) can be used. The two principle methods are Line-Reflect-Line (LRL) and the SOLT family (**S**hort-**O**pen-**L**oad, **S**hort-**O**pen-**L**oad-**T**hru, **S**hort-**O**pen-**L**oad-**R**eciprocal Thru). The LRL technique has high accuracy, but is difficult to implement; the SOLT technique has lower accuracy, but is much easier to use. The method most people use to calibrate their VNAs is the SOLT technique. The LRL method uses dimensional measurements of the airline standards to establish traceability. SOLT uses empirical models to define the standards [2].

The calibration methods for VNAs are well known [3]. Basically, a raw measurement of a calibration standard (one with no correction) is compared to a response of a model for that device. For LRL the model of the airline standards is developed through first principles and is based on the dimensional measurements of the airlines. For SOLT, empirical models are used that are based on data obtained through other measurement processes (like an LRL calibration).

Traceability is difficult to show for the empirical models used for SOLT. Additionally, the uncertainty analyses for measurements made based on SOLT calibrations do not contain any information on the frequency-to-frequency correlations. These correlations are necessary if transformations are to be made between different realms (for example from the frequency domain to the time domain and vice-versa). Being able to carry uncertainty information through the domain transformations is very important to support advanced measurements (for example, to support the advanced communications community). A new process has been developed that provides a direct-traceability path for the SOLT family of calibrations and determines fully correlated uncertainties and is described in detail in what follows.

II. DEFINING THE NEW PROCESS

The new method will use higher-order calibrations to evaluate the lower-order calibration standards. Simply put, an LRL calibration is used on the VNA, based on airline standards, to measure the responses of the SOLT calibration standards. These responses are then used directly as the models for the SOLT standards, which, in turn are used to calibrate a VNA and make device under test (DUT) measurements. The process can be seen graphically in figure 1.

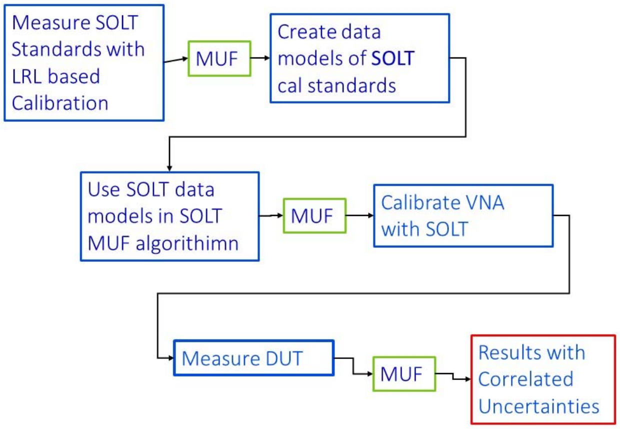


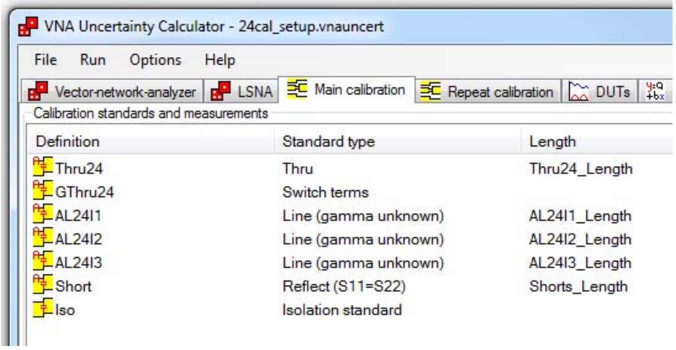
Figure 1. Graphical depiction of the process to create traceable SOLT measurements with correlated uncertainties.

The NIST Microwave Uncertainty Framework (MUF) [4-8] is used to process all of the measurements. The MUF utilizes parallel sensitivity and Monte-Carlo analyses, and enables us to capture and propagate the significant scattering-parameter measurement uncertainties and statistical correlations between them. By identifying and modeling the physical error mechanisms in the calibration standards, we can determine the statistical correlations between both the scattering-parameters at a single frequency and uncertainties at different frequencies [9].

The existing SOLT calibration process uses two different types of loads if frequencies above 2 GHz are being used. A fixed load is used below 2 GHz and a sliding load is used above 2 GHz. For the new method, the sliding load is not necessary. The sliding load was used because the fixed loads do not have a flat response across a broad frequency band. By measuring the response of the fixed load, any deviations from a flat response are accounted for and corrected. For the new technique, the fixed load is used across the entire frequency band.

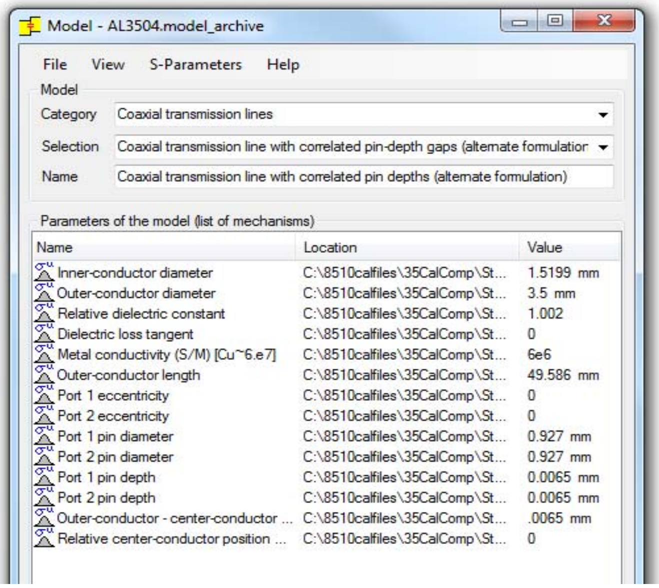
III. IMPLEMENTING THE NEW PROCESS

The airline standards used for this work have dimensional measurements of the inner diameter of the outer conductors, outer diameter of the inner conductors, and airline lengths These dimensional measurements are traceable to gauge blocks and ring gauges calibrated by the NIST Dimensional Laboratory. These measurements are the basis for the traceability of the LRL VNA calibration. Figure 2 shows the calibration setup menu in the MUF for the LRL calibration. Each standard has a definition file, an example of which is shown in figure 3. The definition file contains the various uncertainty components for that standard. One of those files, a parameter file, is shown in figure 4.



Definition	Standard type	Length
Thru24	Thru	Thru24_Length
GThru24	Switch terms	
AL24l1	Line (gamma unknown)	AL24l1_Length
AL24l2	Line (gamma unknown)	AL24l2_Length
AL24l3	Line (gamma unknown)	AL24l3_Length
Short	Reflect (S11=S22)	Shorts_Length
Iso	Isolation standard	

Figure 2. MUF LRL calibration setup showing devices and associated definition files.



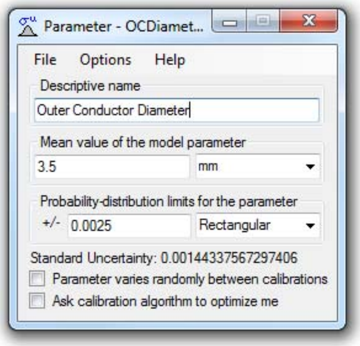
Category: Coaxial transmission lines

Selection: Coaxial transmission line with correlated pin-depth gaps (alternate formulatior

Name: Coaxial transmission line with correlated pin depths (alternate formulation)

Name	Location	Value
Inner-conductor diameter	C:\8510calfiles\35CalComp\St...	1.5199 mm
Outer-conductor diameter	C:\8510calfiles\35CalComp\St...	3.5 mm
Relative dielectric constant	C:\8510calfiles\35CalComp\St...	1.002
Dielectric loss tangent	C:\8510calfiles\35CalComp\St...	0
Metal conductivity (S/M) [Cu~6.e7]	C:\8510calfiles\35CalComp\St...	6e6
Outer-conductor length	C:\8510calfiles\35CalComp\St...	49.586 mm
Port 1 eccentricity	C:\8510calfiles\35CalComp\St...	0
Port 2 eccentricity	C:\8510calfiles\35CalComp\St...	0
Port 1 pin diameter	C:\8510calfiles\35CalComp\St...	0.927 mm
Port 2 pin diameter	C:\8510calfiles\35CalComp\St...	0.927 mm
Port 1 pin depth	C:\8510calfiles\35CalComp\St...	0.0065 mm
Port 2 pin depth	C:\8510calfiles\35CalComp\St...	0.0065 mm
Outer-conductor - center-conductor ...	C:\8510calfiles\35CalComp\St...	.0065 mm
Relative center-conductor position ...	C:\8510calfiles\35CalComp\St...	0

Figure 3. MUF calibration standard definition file.



Descriptive name: Outer Conductor Diameter

Mean value of the model parameter: 3.5 mm

Probability-distribution limits for the parameter: +/- 0.0025 Rectangular

Standard Uncertainty: 0.00144337567297406

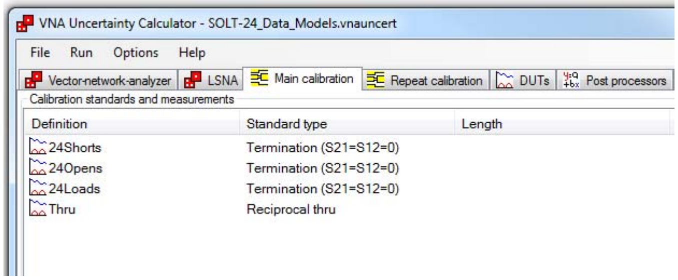
☐ Parameter varies randomly between calibrations

☐ Ask calibration algorithm to optimize me

Figure 4. MUF standard parameter definition file

To test the process outlined in figure 1, we evaluated the standards from a 2.4 mm commercial calibration kit. Based on the measurements of the LRL calibration standards and the 2.4 mm shorts, opens, broadband loads (male and female for all of the standards), and a true thru (the two test ports connected together), the MUF created a measurement-results file (.meas file) for each set of like standards (i.e., male and female shorts in one file). This file essentially contains the corrected, complex results of the measurement and information to create the correlated uncertainty matrix from both a sensitivity analysis (SA) and a Monte-Carlo (MC) analysis [10].

These .meas files can then be used as the definition of the standards in the SOLT MUF algorithm. Figure 5 shows the MUF calibration setup menu for the SOLT calibration. In this setup, instead of the definition and parameter files, as seen in figures 3 and 4, we simply use the .meas file for each standard type which is shown in the left column of figure 5. All of the uncertainty information and the links for traceability are in the .meas files.



Definition	Standard type	Length
24Shorts	Termination (S21=S12=0)	
24Opens	Termination (S21=S12=0)	
24Loads	Termination (S21=S12=0)	
Thru	Reciprocal thru	

Figure 5. MUF SOLT calibration setup

To measure a DUT with the SOLT calibration setup as described, raw measurements (no correction applied to the VNA) of the calibration standards (short, open, loads, and thru) and the DUT are made on the VNA, then we can process all of the raw measurements through the MUF SOLT algorithm and DUT corrected results are obtained.

IV. RESULTS

To test the effectiveness of this process, we made measurements of a DUT based on new measurements of the calibration standards and the DUT over a span of approximately five months. This means that we performed a separate new, SOLT calibration for each DUT measurement. All of these different SOLT calibrations used the same calibration kit and the same .meas definition files for the calibration kit standards. These results are shown in figure 6.

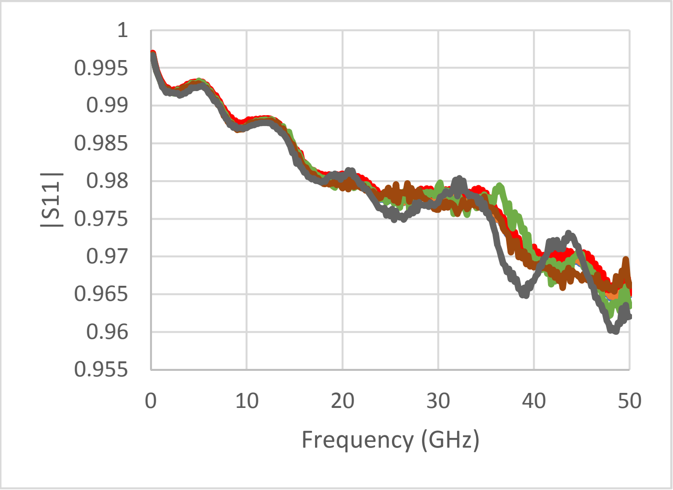


Figure 6. |S11| results from multiple SOLT/DUT measurements. Established NIST measurement process (light blue), MUF LRL calibration (orange), SOLT: 6/23/2017 (red), 6/27/2017(green), 8/3/2017 (brown), and 10/25/2017 (gray).

In figure 6, we show curves not only for the multiple SOLT calibration/measurements, but also for a measurement of the DUT using the established NIST measurement process (multical) [11] and a measurement based on the LRL calibration from the MUF. Figure 7 shows the differences for all of the plots using the multical data as the reference value. Also plotted in figure 7 are the uncertainty bars (k=2) for the established NIST measurement technique.

Figure 8 shows the phase results for the same DUT. With the scale shown, no difference can be seen. In figure 9 the differences between the multical phase measurements and the MUF LRL and several SOLT measurements are shown along with the uncertainty for the multical measurements (k=2). There is very good agreement for the phase measurements. The differences from the reference multical measurement are well within the multical uncertainty.

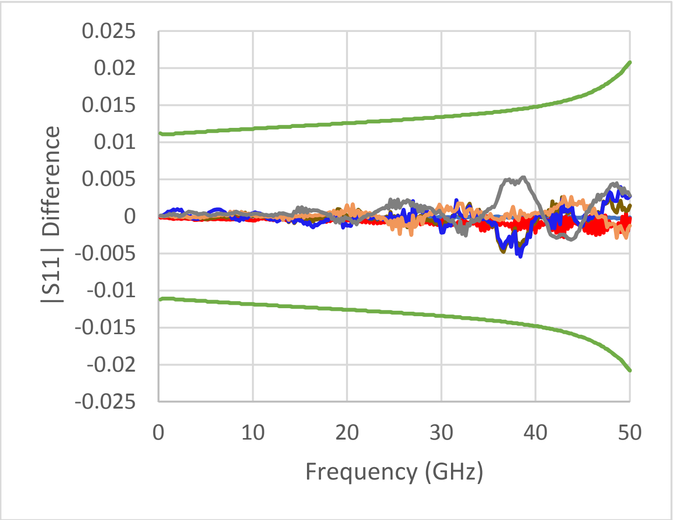


Figure 7. Multical - |S11| results from multiple SOLT/DUT measurements. Multical minus MUF LRL calibration (light blue), minus SOLT: 6/23/2017 (red), 6/27/2017(MUF SA-brown), 6/27/2017(MUF MC-dark blue), 8/3/2017 (orange), multical uncertainties (green), and 10/25/2017 (gray)

Other devices measured at the same time as the one DUT being shown showed similar results: good magnitude and phase agreement. The time span for these measurements was also five months.

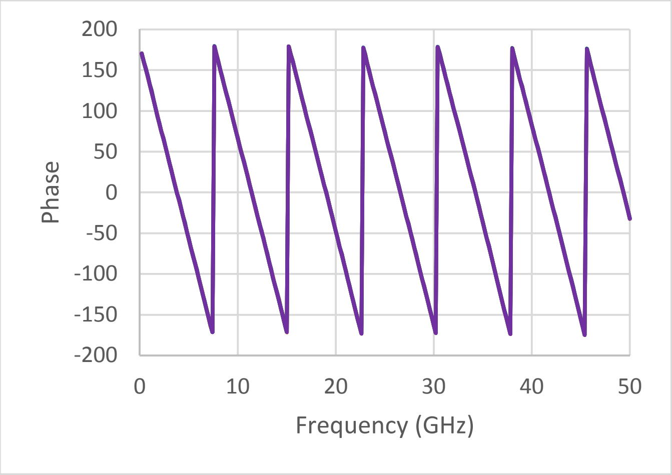


Figure 8. Phase results from multical (green), the MUF LRL calibration (orange), and from multiple SOLT/DUT measurements. 6/23/2017 (dark blue), 6/27/2017(light blue), 8/3/2017 (red), and 10/25/2017 (purple).

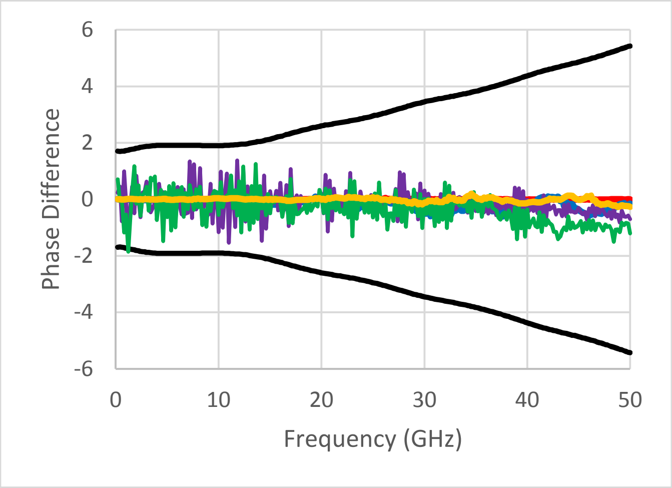


Figure 9. Phase difference plot showing the difference between the multical phase result and multiple SOLT results. The black lines are the multical uncertainty, multical-MUF LRL (red), multical-6/23/2017 (green), multical-6/27/2017 (blue), multical-8/3/2017 (purple), and multical-10/25/2017 (orange).

V. DISCUSSION OF RESULTS

The results shown in figures 6 and 7 show that measurements from multiple calibrations based on the same set of measured definitions for the calibration standards will produce repeatable results. While there are some differences between the different measurements, the differences are much less than the uncertainty from the LRL measurement of the device. The test was performed over a five-month time period; however, more experiments are needed to see if the data definitions of the calibration standards are stable over an even longer time period.

The .meas file for the DUT measurements contains all of the information necessary to establish a traceability path for the device. It also contains the correlation matrix that will allow the uncertainties to be carried through domain transformations.

There are several future plans for this calibration kit evaluation technique. The first will be to extend this to other coaxial connector sizes, then to waveguide connectors. Finally, this will be applied to automatic calibration units.

VI. CONCLUSION

A new technique has been described that uses the NIST Microwave Uncertainty Framework to establish a well-defined traceability path for SOLT calibrations. In addition, measurements results are determined with correlated uncertainties. Repeated passes through the process yielded repeatable magnitude and phase device measurement results.

REFERENCES

[1] “International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM 3rd edition),” BIPM, 2012

[2] “Specifying Calibration Standads and Kits for Keysight Vector Network Analyzers,” KeySight Application Note #5989-4840EN, 2016

[3] “Understanding VNA Calibration,” Anritsu Application Note #111410-00673A, 2012

[4] D. F. Williams, NIST Microwave Uncertainty Framework, Beta Version, http://www.nist.gov/ctl/rf-technology/relatedsoftware.cfm, 2015.

[5] J. A. Jargon, D. F. Williams, T. M. Wallis, D. X. LeGolvan, and P. D. Hale, “Establishing traceability of an electronic calibration unit using the NIST Microwave Uncertainty Framework,” *79th ARFTG Microwave Measurement Conference*, Montreal, CANADA, Jun. 2012.

[6] J. A. Jargon, U. Arz, and D. F. Williams, “Characterizing WR-8 waveguide-to-CPW probes using two methods implemented within the NIST Uncertainty Framework,” *80th ARFTG Microwave Measurement Conference*, San Diego, CA, Nov. 2012.

[7] J. A. Jargon, D. F. Williams, P. D. Hale, and M. D. Janezic, “Characterizing a noninsertable directional device using the NIST Uncertainty Framework,” *83rd ARFTG Microwave Measurement Conference*, Tampa Bay, FL, Jun. 2014.

[8] J. A. Jargon, C. H. Cho, D. F. Williams, and P. D. Hale, “Physical models for 2.4 mm and 3.5 mm coaxial VNA calibration kits developed within the NIST Microwave Uncertainty Framework,” *85th ARFTG Microwave Measurement Conference*, Phoenix, AZ, May 2015.

[9] J. A. Jargon, D. F. Williams, and P. D. Hale, “Developing Models for Type-N Coaxial VNA Calibration Kits within the NIST Microwave Uncertainty Framework,” *87th ARFTG Microwave Measurement Conference,* San Francisco, CA, May 2016

[10] K.A. Remley, D.F. Williams, P.D. Hale, C.M. Wang, J. Jargon, and Y. Park, “Millimeter-Wave Modulated-Signal and Error-Vector-Magnitude Measurement With Uncertainty,” *IEEE Trans. Microwave Theory Tech*., vol.63, no. 5, pp. 1710-1720, May 2015

[11] C.A. Hoer, R.M. Judish, J.R. Juroshek, G.F. Engen “Theory, Uncertainty Analysis, and Statistical Control for the NIST 2-18 GHz Dual 6-Port Automatic Network Analyzer,” unpublished NIST Special Publications Note, 1986