Kicking the Tires of the NIST Microwave Uncertainty Framework, Part 2

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Abstract — **Traceability of a measurement requires two parts: 1) an unbroken chain of measurements and 2) uncertainties for each link of the chain. The NIST Microwave Uncertainty Framework (MUF) can provide both the required parts for a single link in the chain or for multiple links. In Part 1 of this work [1] the scattering-parameter measurement results determined by the MUF were compared to the established technique used at NIST. In this Part 2, the comparison of the uncertainties calculated with the different approaches will be examined and discussed.**

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

I. Introduction

The NIST Microwave Uncertainty Framework (MUF) is a recently-developed tool for producing measurement results and uncertainties [2-6]. The ability of the MUF to produce accurate results and uncertainties must be verified and this will be done through a comparison of the MUF results against the existing technique used at NIST. This is “checking the viability of an unknown system by a quick test” or “kicking the tires”.

The established technique used at NIST for s-parameter measurements is the multiline method for network analyzer calibration [7]. The multiline method is applied in a NIST software package titled “Multical.” Data is taken from the Vector Network Analyzer (VNA) and analyzed using other NIST software packages.

II. The Experimental setup

The measurement setup is the same as that used in Part 1[1]. As a quick refresher, all of the devices measured, calibration standards and DUTs, had 3.5 mm connectors and the frequencies measured were from 0.2 to 33.0 GHz by 0.1 GHz steps. The specifics of the actual measurement process steps are as follows:

1) Uncertainty models were established in the MUF for the devices used in the VNA calibration
2) Raw measurements (no VNA correction applied) were taken of the devices used for the VNA calibration
3) The identical data was used in both Multical and the MUF to form the error correction matrices for the VNA
4) Starting with the VNA correction turned off, raw measurements were taken of one of the DUTs.
5) Without touching the DUT, the VNA correction from Multical was applied and corrected data of the DUT was taken using the NIST measurement software (a program called MeaslpX was used to take the corrected data from the VNA and another program called Calrep was used to analyze the data taken by MeaslpX)
6) All DUTs were measured by use of the process of 4) and 5)
7) The raw calibration standards data and the raw DUT data were processed through the MUF to arrive at the corrected response for each DUT
8) The corrected MUF responses were compared to the results from the Multical and NIST measurement software process[1].

Throughout this comparison, we have tried to keep the two measurement paths as similar as possible. Because of the differences in the two measurement paths, we needed to take both the uncorrected and corrected measurements of the DUTs.

III. Discussion of uncertainty components

To have a legitimate comparison of uncertainties we needed to make sure that we are comparing the same essential components. The established NIST technique has uncertainty components from three major sources, which are instrumentation, systematic effects and random effects [8]. Instrumentation uncertainties come from the hardware of the system including signal generation, signal processing, signal detection, and other general electronics errors. The random components of uncertainty include long-term variation in the error reduction parameters and short-term connector non-repeatability. Systematic components of uncertainty are generally associated with the connectors and calibration standards. The systematic components included in the analysis for the established NIST technique (also called the Calrep technique) are:

1. Test Port Connectors
   a. More than one mode present at the reference plane
   b. Eccentricity of center conductor relative to outer conductor
   c. Discontinuity capacitance due to misalignment of conductors
   d. Gap in center conductor when mated to airline
2. Standard Airlines
   a. Specifications
   b. Dimensions of lines; Z_{00} of lossless line
   c. Conductivity of lines; skin depth correction
   d. Outer Diameter and Inner Diameter not equal to specified dimensions
   e. Non-uniformity of inner and outer conductor diameters
   f. Uncertainty in Z_0
   g. Step capacitance due to line diameters not equal to specified diameters
   h. Electrical length of line too close to $n\pi$ (n=0,1,…)
   i. Length of inner conductor not equal to length of outer conductor

3. Reflect Termination
   a. Reflect connectors are not some as line connectors causing $\Gamma_1 \neq \Gamma_2$
   b. Coupling between test port and terminations

For the MUF, the uncertainty model for an airline standard is shown in figure 1. Similar, but simpler models are also used for the reflects. An identity matrix is used for the isolation terms.

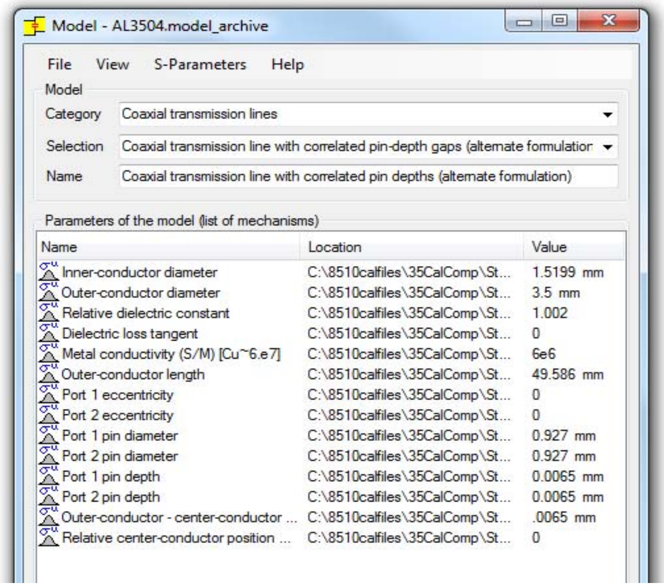


Figure 1. Airline uncertainty model used in the MUF

The most significant uncertainty sources are included in both the established technique and the MUF model. A rectangular probability distribution was used for all of the uncertainty components used in the MUF. Figure 2 shows the parameter definition for one of the uncertainty components.

A difficult part of the comparison process is to make sure that we are comparing as similar as possible combinations of uncertainty components. It should be noted that the MUF directly handles only the uncertainty due to systematic effects (other type of components can be added using post-processors). Because of this, for the comparison, the instrumentation and components of uncertainty due to random effects will be deconvoluted from the Calrep uncertainty.

There is not an exact one-to-one matching between all of the components of the two different models. The Calrep model has a few more minor terms than the MUF model. These should not have a significant effect on the comparison.

The MUF provides two different calculations of the uncertainty. One is through a sensitivity analysis (SA) where the uncertainty is calculated from a compilation of varying one uncertainty component at a time and a Monte-Carlo analysis (MC) where all uncertainty components are randomly varied at once [9]. Both results will be examined in the comparison.

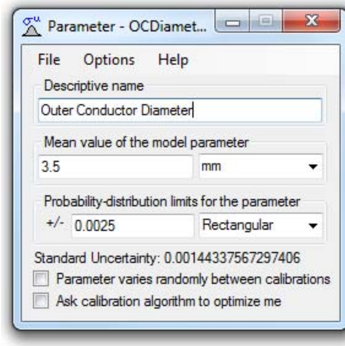


Figure 2. Uncertainty parameter dialog box from the MUF

IV. Results of the Comparison

In figure 3 we show the results of the measurements of a matched termination. There is very little difference between the three curves. The same data is plotted in figure 4, but now the curves show the difference between the Calrep response and the MUF sensitivity analysis and the MUF Monte-Carlo results respectively. Also shown in figure 4 is the expanded Calrep uncertainty (k=2). The takeaway from figure 4 is that the differences between the responses of the established technique and the MUF are very small and well under the Calrep uncertainty.

Figure 5 again shows the difference curves, but this time only the systematic component of the Calrep uncertainty (k=1) and the MUF SA and MC uncertainty estimates (equivalent k=1). Uncertainty results similar to those shown in Figure 5 are shown for high reflect, low loss, and 20 dB devices in Figures 6, 7, and 8 respectively. It should be noted that the phase results of the devices in figures 7 and 8 are very similar to those shown in figure 6b and will not be shown.

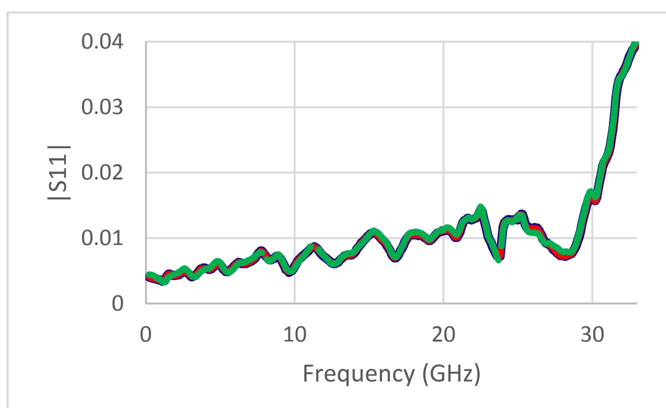


Figure 3. Measurement results for a matched termination showing the Calrep response (blue), the MUF SA response (red) and the MUF MC response (green).

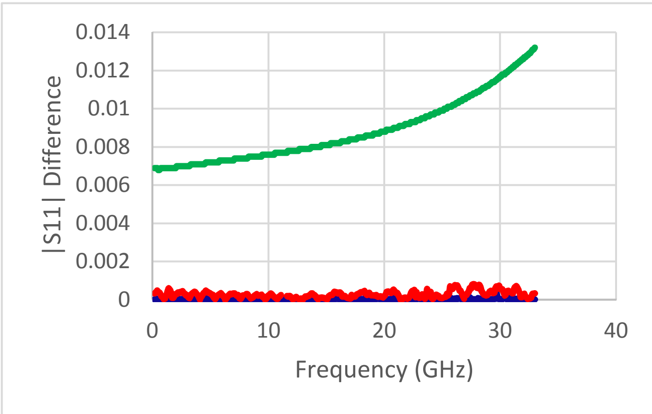


Figure 4. Difference plot for $|S_{11}|$ of a matched termination. Calrep – MUF SA (blue), Calrep – MUF MC (red), and the expanded Calrep uncertainty (k=2) (green).

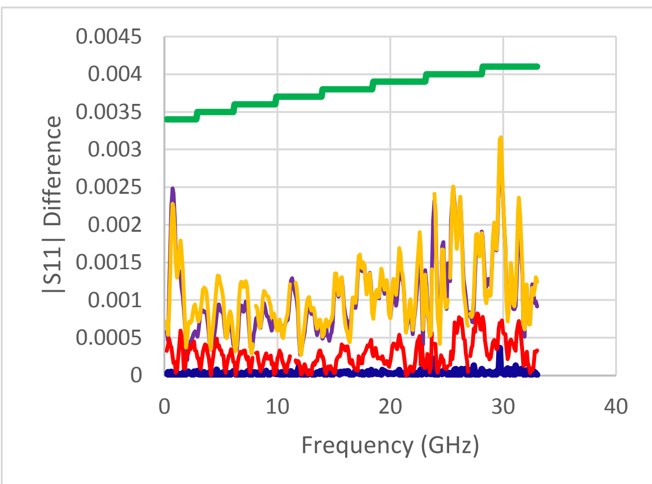
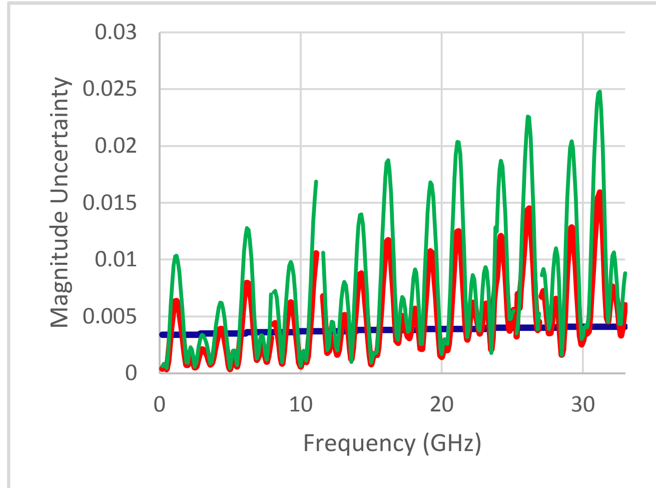
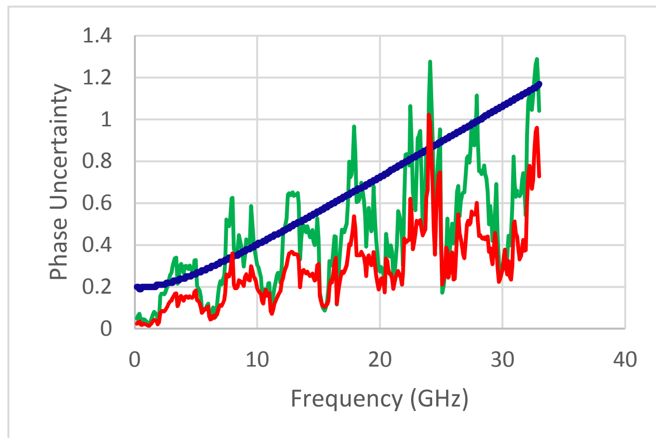


Figure 5. Difference plot for $|S_{11}|$ of a matched termination (blue, red) and Calrep systematic (k=1) (green), MUF SA (purple), and MUF MC (orange) uncertainty values.



(6a)



(6b)

Figure 6. Uncertainties for S_{11} of a high-reflect device. Magnitude data (6a), phase (6b). Calrep systematic uncertainty (blue), MUF SA uncertainty(red), and MUF MC uncertainty (green).

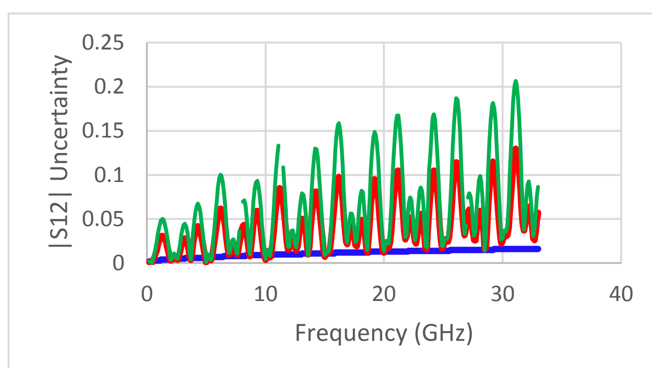


Figure 7. Uncertainties for the $|S_{21}|$ of a low loss device (~0.3 dB). Calrep systematic uncertainty (blue), MUF SA uncertainty(red), and MUF MC uncertainty (green).

and for future comparison, are truly comparable between the established technique and the MUF.

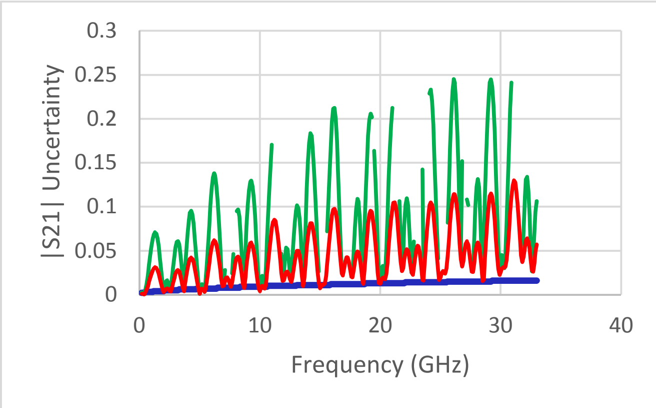


Figure 8. Uncertainties for the $|S_{21}|$ of a high loss device (~50 dB). Calrep systematic uncertainty (blue), MUF SA uncertainty(red), and MUF MC uncertainty (green).

V. Discussion of Results

There are several general trends that can be seen in figures 5 through 8. The uncertainty from the established technique and the uncertainties generated from the MUF are of the same order of magnitude. The Calrep uncertainties have a very structured nature. The MUF uncertainties have a more random nature with some structure.

For a matched termination, figure 5 shows that the MUF uncertainty (SA or MC) is smaller than the Calrep uncertainty due to systematic effects. This was seen in the S_{11} data for the two-ports as well. For a high reflect device the uncertainties are more comparable for both magnitude and phase (figure 6). For both of the two-port devices, for magnitude results, the MUF uncertainties are larger than the Calrep uncertainties (figure 7 and 8) and the MUF phase uncertainties (not shown) are slightly smaller than those from Calrep.

The Calrep uncertainties have well defined shapes which is not surprising due to the formulaic approach used to determine the uncertainties. The MUF uncertainties have a more random nature which is also expected due to their statistical determination. While the expectation is that the MUF uncertainties should be totally random in nature, the uncertainties are dependent on the value of the parameter that they correspond to and this causes the more structured form. This can be seen in all of the results. Changing the number of Monte-Carlo iterations from 100 to 1000 or 10000 does not change the structures that are seen in the Monte-Carlo uncertainties.

As was stated earlier, it is very difficult to make sure that we are comparing similar uncertainty quantities. There likely are still differences in how the uncertainty components from the different techniques are assigned values. As an experiment, all of the uncertainty component distribution limits for all of the calibration standards were halved and the same calibration standard data and DUT data were again processed through the MUF. The results are shown in figure 9. The resulting uncertainty still shows the same structure, but the overall magnitude has been reduced by over half. The take-away from this is that care must be taken in describing the uncertainty distributions. Further work may be needed to make sure the uncertainty components are fully understood and evaluated,

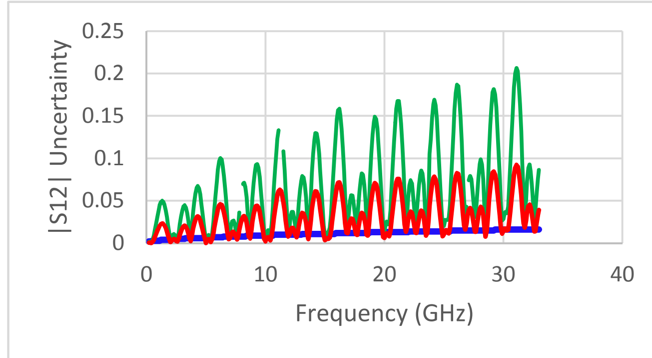


Figure 9. Comparison of uncertainties using different uncertainty distribution limits for the S_{12} magnitude of a low loss device. Calrep systematic uncertainty (blue), MUF MC uncertainty(green), and MUF MC uncertainty half limits (red).

VI. Conclusions

The uncertainty results from the NIST Microwave Uncertainty Framework agree to the same order of magnitude with our established method. The results depend on the type of s-parameter being measured. These conclusions apply to both magnitude and phase uncertainties, although the phase uncertainties from the established technique tend to be more conservative. It was also seen that care must be used in setting the distribution limits for the uncertainty components.

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