# Qualitative Multidimensional Calibration Comparison

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***Abstract* — We present a technique for the visual comparison of any two vector network analyzer calibrations. This method visualizes the comparative action of the calibrations for multiple complex scattering parameters. This method is independent of the calibration model. This comparative visualization of the two calibrations facilitates quick assessment of different calibration and error models, guides the choice of verification standards for later comparison, creates an easy way to monitor instrument stability over time, and can help guide the development of new on wafer calibration schemes.**

***Index Terms* — calibration comparison, scattering parameters, impedance, synthetic DUTs, microwave measurements.**

## I. Introduction

Vector network analyzer (VNA) calibrations for scattering parameters vary in complexity and uncertainty. Each type of calibration is generated by the measurement of a set of well-understood artifacts, calculated, and then applied to subsequent measurements. Frequently, by comparing two of these calibrations, we gain insight into fundamental questions about the algorithm or measurement. While comparison techniques that create bounds for the worst-case difference of two calibrations [1]-[2] have been previously reported on, these techniques simplify the problem into a single frequency-dependent metric. These techniques have the advantage of being easy to interpret, but have the disadvantage that more nuanced questions are left unanswered. For example, when two methods of on-wafer calibration are compared, we are not presented with any information that identifies calibrations that are identical for certain devices, while widely different for others. Without this information, measurements on a limited set of devices, by use of a specialized calibration techniques, might be disregarded although they are of high quality. In addition, other methods do not give information pertaining to the device types most likely to show differences between calibrations, and hence give little to no direction as to the best choice of verification standards. In order to provide a more complete, easy-to-interpret, qualitative comparison of two calibrations, we have developed an easy-to-apply visual technique.

## II. Method

Given two calibrations C1 and C2 that we desire to compare, we construct a plot of the relative action of the two calibrations. We assume that the corrections apply to the same frequency points. This is not a strict requirement, but prevents complications from interpolated data sets.

To create the visual comparison, we:

1) Create a series of synthetic device under tests (DUTs) in the calibrated measurement plane. These standards are constant complex scattering parameters grouped around multiple amplitudes with different phases. For Figs. 1-8, we have chosen three reflection amplitudes of 0.98, 0.60 and 0.20 for ease of viewing. The standards are created such that they are reciprocal and conserve energy. This leads to the constraint that transmission is symmetric (S21 = S12) and their amplitudes are 0.20, 0.80 and 0.98 respectively [3]. In Fig. 1, we show the complex scattering parameters of 20 synthetic DUTs, four with the reflection amplitude of 0.20, eight each with the reflection amplitudes of 0.80 and 0.98.

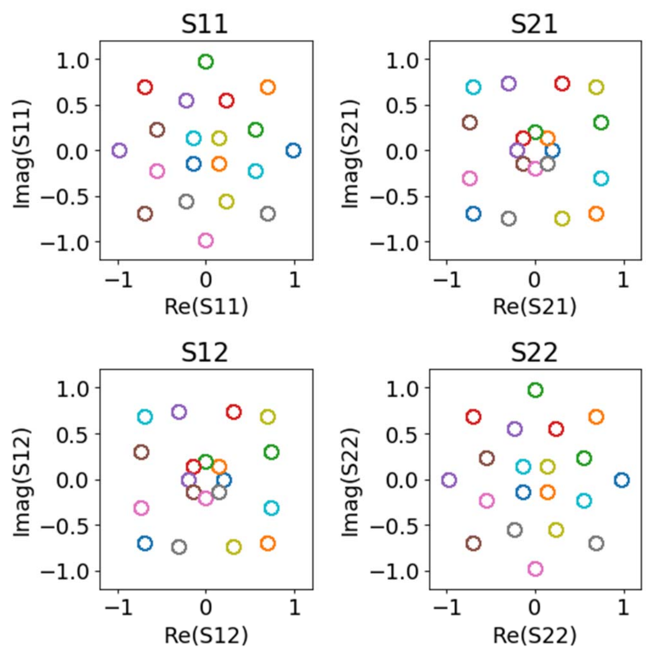


Fig. 1. The Synthetic DUTs' Scattering Parameters. The scattering parameters are plotted at the calibrated plane with all frequencies being simultaneously shown. The standards are constant in frequency, reciprocal and conserve energy, the phase is chosen to provide the most coverage of the plane. Here each symbol on the plot represents a single standard.

2) Apply the inverse calibration ($C1^{-1}$) to the standards. This maps the synthetic DUTs to the uncorrected reference plane. In Fig. 2 the result of applying the inverse calibration $C1^{-1}$, is shown for a test thru-line-reflect (TRL) calibration. In the raw or uncorrected reference plane, our synthetic DUTs have scattering parameters that depend on the inverse of the specific correction.

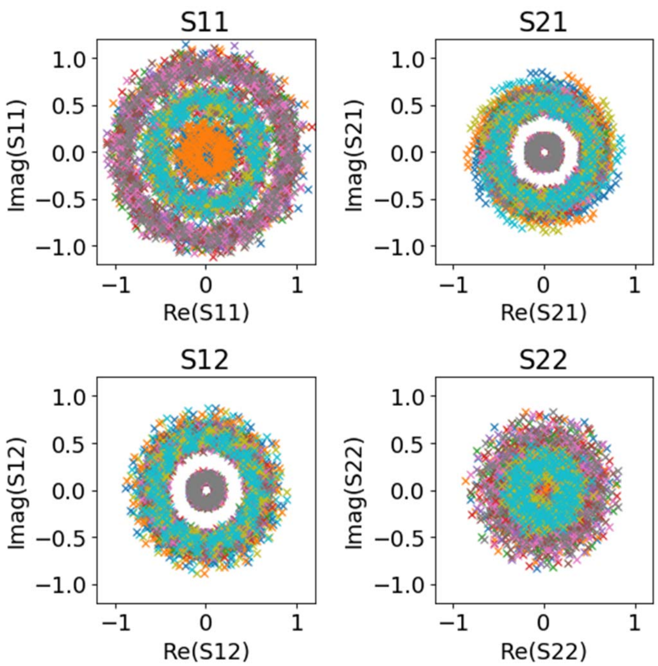


Fig. 2. The Synthetic DUTs' Uncalibrated Under C1 Scattering Parameters. After applying the inverse of the first calibration, the synthetic DUTs have a pattern that is controlled by the nature of the calibration. Since the calibration has a rich frequency dependence of amplitude and phase, the constants will now typically follow a different pattern in the uncorrected plane.

3) Calibrate the resulting uncorrected standards with the calibration (C2) that is to be compared. In Fig. 3 the result of applying another test calibration to the data in Fig. 2 is plotted. Once the comparison correction (C2) is applied the resulting pattern displays the comparative action of the two calibrations. In cases where the calibrations are similar, the plots will be nearly identical.

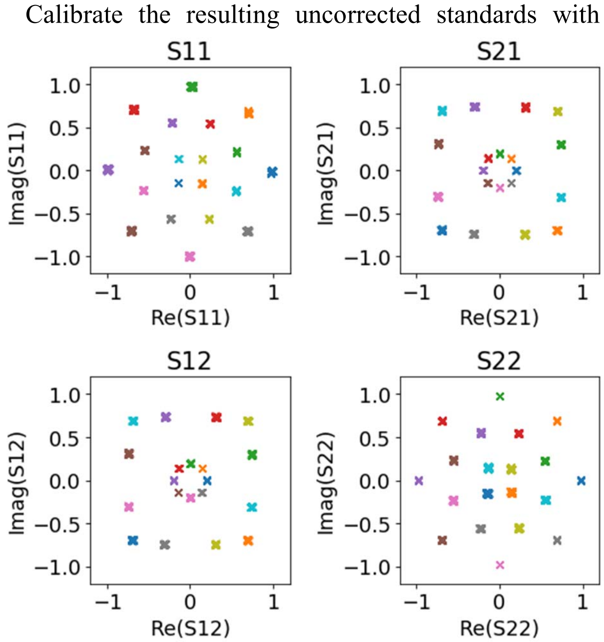


Fig. 3. The Standards' Scattering Parameters Under the Comparison Calibration. Once the synthetic DUTs have been mapped to the raw or uncalibrated plane, they are calibrated with the comparison calibration (C2). Each symbol represents the DUTs after calibrating with C2.

4) Overlay the original plot of the synthetic DUTs and the resulting calibrated standards on the complex plane (see Fig 4.). This resulting plot can be all frequencies or a sub set of frequencies of interest. If the calibrations are equivalent, the resulting plot will be identical to one another, otherwise the new location of the resulting calibrated standards will show the comparative action. The choice of complementing symbols emphasizes this relationship. In Figs. 4-8. the original location of the synthetic DUTs are indicated by circles, while the comparative action on the synthetic DUTs are indicated by the symbol x. If the calibrations are close but not exact, the comparative action will appear to blur and move slightly from center. If the calibrations deviate significantly, the resultant scattering parameters will be in different locations from the original synthetic DUTs. For calibrations that correct measurements to the same amplitude but vary in phase, a series of arcs will appear at the amplitudes chosen for the original synthetic DUTs.

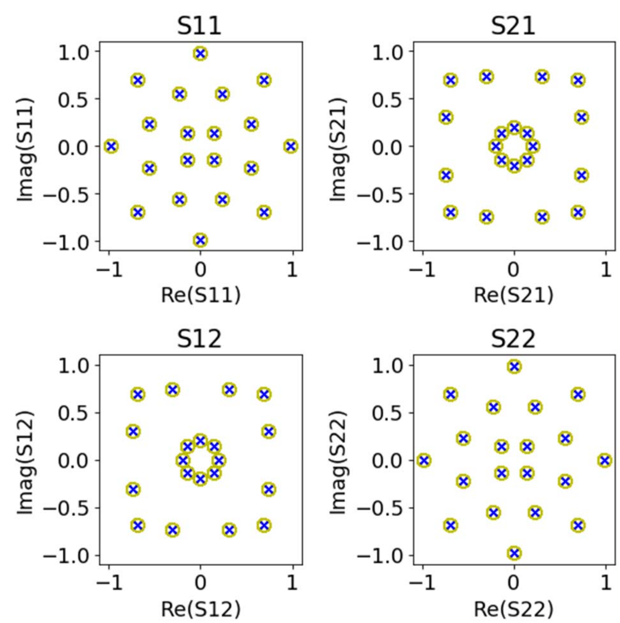


Fig. 4. Comparison of C1 = Synthetic DUTs with the C2 = Uncalibrated-Calibrated Synthetic DUTs. This is a plot of identical calibrations for clarity. The circles are chosen, original synthetic DUT locations to be the same size as the comparative action markers (x). Subsequent plots conserve space by following the convention that the vertical axis is always imaginary.

## III. TRL VS OSLT

Once the method of visualization is understood, we can use it to compare different calibration techniques or how the same calibration changes over time. For instance, two calibration techniques of interest are the multiline thru-reflect-line (TRL) and the open-short-load-thru (OSLT). The TRL provides high accuracy, and the OSLT makes use of simple standard artifacts and is less time consuming. In Fig. 5 we compare an OSLT calibration with a TRL calibration within the same measurement session. In this specific instance, we have replaced the simple definitions describing the calibration standards in the OSLT by higher accuracy measurements of the standards. The typical way to compare different calibration error models like these is to use a correspondence of the error coefficients [4] which is unnecessary in this case. In addition to showing that the calibrations are close to the same, Fig. 5

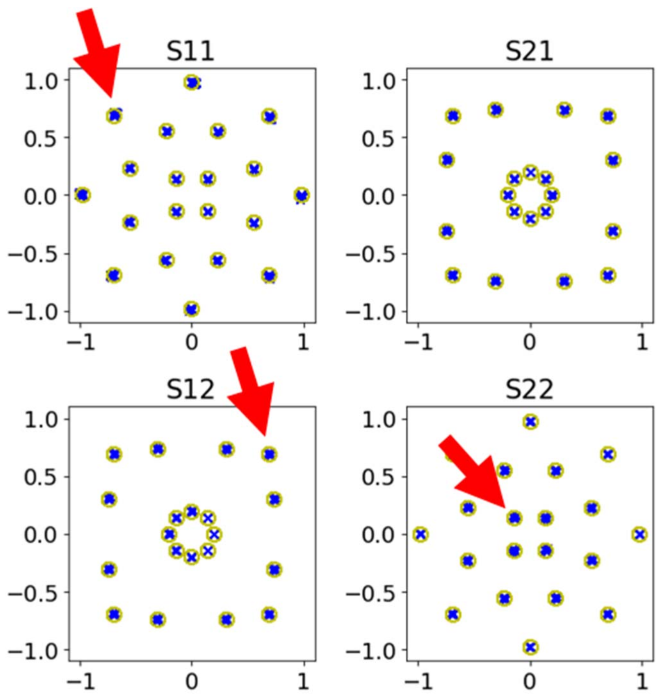


Fig. 5. Comparison of C1 = TRL and C2 = Data Defined OSLT. The arrows mark points were disparities are easily noticeable, potentially guiding the selection of future verification standards. Circles are of the unprocessed synthetic DUTs, while the symbol x represents those standards transformed first using

can give us insight into which verification standards to choose from. Specifically, by plotting the scattering parameters that have the largest difference between the two calibrations, it allows us to choose verification standards that have similar scattering parameters. This choice exploits places of highest variation in order to put the most stringent conformance criteria on subsequent calibrations, and hence achieve the highest degree of calibration algorithm agreement. By comparing calibrations in different measurement on different days, it also gives us a qualitative tool for investigating instrument stability. For example, close examination of the comparison plot in Fig. 5 reveals that the complex impedance points close to a reflectance of 1 (0.98) for S11, show the most disparity. If we desire a verification standard to compare measurements later, we should choose a high-reflect standard for the S11 verification process. In comparison, the points of highest transmission, or closest to the origin for the S21 and S12 plot show the highest discrepancy. Taken together with the fact that the S22 points close to the origin show a large discrepancy, this indicates a low-loss line should also be chosen to provide verification of subsequent calibrated measurements.

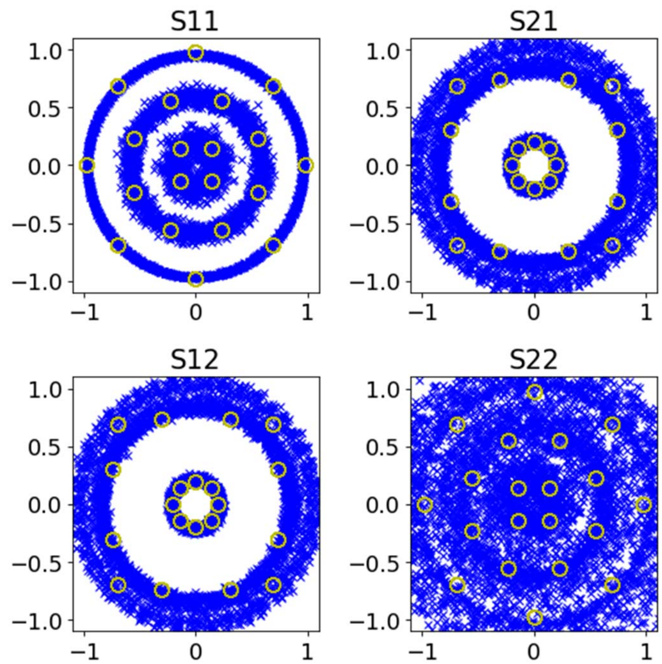


Fig. 6. Comparison of C1 = TRL and C2 = OSLT, 42 Days Later. The amplitude of S11 for DUTs at 0.98 remains relatively constant overtime. However, the phase does not. The test port with longer cables attached (port 2) is seen to be more variable.

Additionally, this type of visualization allows us to appraise the stability of calibrations over time. Consider Fig. 5 that shows the comparison of a TRL and OSLT. If we repeat the OSLT at some much later date, we can observe how the calibration changes over time. In Fig. 6, we see when the OSLT standards used in Fig. 5, are measured using the same experimental configuration 42 days later. In this case, Fig. 6 shows that the corrected amplitude of S11 remains close, but the phase has changed significantly. This type of similar correction that differs greatly in phase creates a particular pattern of arcs and can indicate an abrupt change in measurement conditions; we are still investigating the causes of the pattern in Fig. 6.

## IV. On-Wafer TRL vs Series Resistor

In contrast to connectorized calibrations, those for use in an on-wafer environment are often more complex and can have multiple tiers. Each tier moves the reference plane, and if we are comparing calibrations at the same reference plane, we can also investigate by use of this visualization method. For example, consider an on-wafer TRL method, compared to an on-wafer series resistor method [5]-[6]. The TRL method provides a small uncertainty, but is incompatible with very-low frequencies (< 200 MHz) while the series resistor calibration makes use of more compact standards and provides a convenient way to calibrate to very low frequencies. In Figs. 7 and 8 comparing these calibrations at different frequencies gives insight into the range over which the calibrations perform essentially the same and where they differ significantly. Here, we compare broad-band calibrations calculated over the range 1-110 GHz via measurement of a large set of thin-film standards.

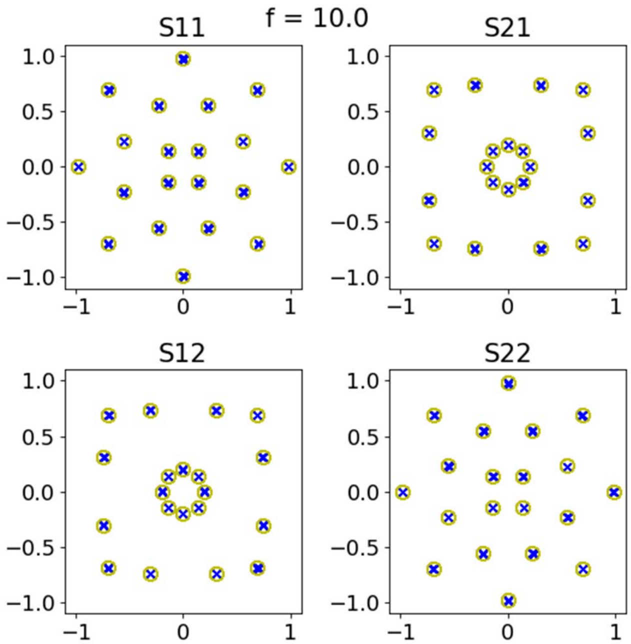


Fig. 7. Comparison of C1 = On-wafer TRL and C2 = Series Resistor, Over the Range of 1-10 GHz. The calibrations are close to identical over this range

In Fig. 7, which covers the range of 1-10 GHz, we see that the calibrations are almost identical, with little distortion in phase or amplitude. In contrast, over the full range of the measurement 1-110 GHz, displayed in Fig. 8, we see that the calibrations have significant disagreement. In particular, for all scattering parameters not on the real axis there is notable amplitude distortion at the higher frequencies. This is indicative of the series resistor calibration not performing to the same accuracy as the TRL at the higher frequency range.

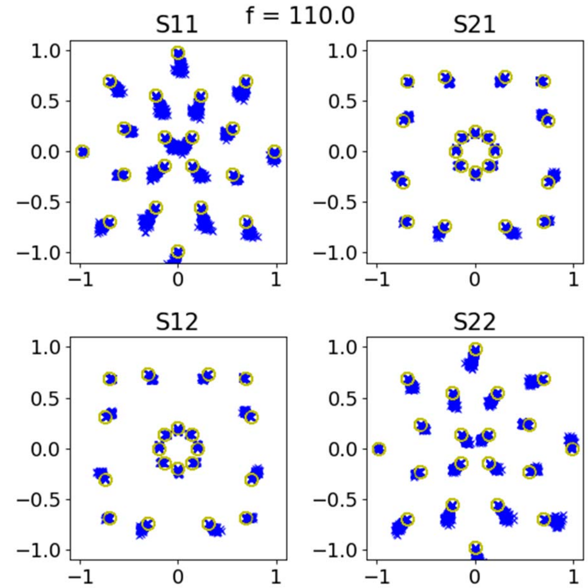


Fig. 8. Comparison of C1 = On-wafer TRL and C2 = Series Resistor, Over the Range of 1-110 GHz. As frequency increases differences in the calibrations become more evident. For synthetic standards along the negative real axis (short-like), we see agreement at even these frequencies.

## V. Conclusion

We presented a method for the visual comparison of two calibrations. This comparison technique yields qualitative information about the comparative action on synthetic DUTs with scattering parameters distributed in the complex plane. This qualitative information is used to identify potential verification standards, inspect the stability of calibrations over time, and determine the frequencies over which two calibration algorithms coincide.

## Acknowledgement

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