

Microwave S-parameter VNA calibration techniques and associated uncertainty

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Abstract — This paper discusses calibration techniques for S-parameter measurements using a vector network analyzer and uncertainties associated with the measurements due to random errors. A number of calibration methods have been used to compare scattering parameters (S-parameters) for a number of different devices and the measured results are presented. The investigation has been carried out at frequencies from 100 MHz to 26 GHz, which covers many of today's RF/microwave applications. Six different types of calibrations have been investigated on a number of one-port and two-port devices. The evaluated uncertainty due to random errors is also compared with results produced by NPL's Primary Impedance Microwave Measurement System (PIMMS).

Index Terms — Network Analyser, S-parameters, Microwave, Calibration.

I. INTRODUCTION

The performance of a high frequency device or component is usually measured using a Vector Network Analyzer (VNA), which measures the complex-valued scattering parameters (or S-parameters) of the component i.e. the magnitudes and phases of its reflection and transmission coefficients.

Before a device under test (DUT) can be measured using a VNA, the VNA and the associated cables, adaptors, etc. need to be calibrated to remove the known systematic errors. In this paper, six different VNA calibration methods are compared by measuring various passive DUTs with a wide range of reflection and transmission coefficient characteristics.

The VNA calibration methods were:

- TRL calibration implemented using NPL's PIMMS [1]
- TRL calibration implemented using the VNA firmware
- SOLT calibration
- SOLR calibration with a zero length (flush) thru
- SOLR calibration with a non-zero length (Reciprocal) thru
- ECal calibration

The DUTs measured in this investigation were:

- Two offset open-circuits (male and female with different offset lengths)
- Two offset short-circuits (male and female with different offset lengths)
- A 50 Ω load (male)
- Two reflection check standards (male and female 1-port devices with well characterized reflection coefficients)
- A thru connection (direct connection of the VNA test ports)

- A Beatty line
- A 3 dB fixed attenuator
- A 20 dB fixed attenuator
- A 40 dB fixed attenuator

II. EXPERIMENTAL SETUP

For each of the calibration method, six sets of measurements were made where each set of measurements consisted of a calibration of the VNA followed by measurement of the S-parameters of each DUT.

The DUTs used for the investigation were one-port and two-port devices fitted with 3.5 mm coaxial connectors. According to [2], 3.5 mm connectors operate mode-free up to at least 33 GHz. However, 3.5 mm calibration kits from most vendors such as Keysight, Maury Microwaves etc. are only characterized and supported to 26.5 GHz. Therefore, all investigations in this work were done between 0.1 GHz and 26 GHz.

Further details of the VNA calibration methods and DUTs are given in Sections III.

The measurements were made using a four-port Keysight N5247A PNA-X VNA which has a frequency range of 10 MHz to 67 GHz and is fitted with 1.85 mm coaxial connectors. To allow the DUTs to be connected to the VNA, 1.85 mm to 3.5 mm adaptors were used on VNA test ports 1 and 2. A flexible test port extender cable with good amplitude and phase stability was used on VNA test port 2. Port 1 of the VNA consisted of a 3.5 mm male test port and port 2 consisted of a 3.5 mm female test port.

The VNA settings used during the measurements were as follows:

- Frequency: 100 MHz to 26 GHz
- Frequency step: 50 MHz, below 1 GHz; and 0.2 GHz, above 1 GHz
- Power: -5 dBm
- IF Bandwidth: 10 Hz
- Averaging Factor: 2

The measurements were carried out in a temperature-controlled laboratory at a temperature of 23 \pm 2 $^{\circ}$ C. The measurement set-up is shown in Fig. 1.

III. VNA CALIBRATION METHODS

In a VNA measurement, components such as the measuring instrument, the cables and the connectors can introduce errors into the measurement. For example, impedance mismatches within the test setup cause errors that appear as ripples superimposed on the measured transmission and reflection coefficients. These systematic errors make it difficult to determine the actual S-parameters of the DUT as reflections from the DUT and from other sources are combined. To evaluate the systematic errors, a calibration of the setup is carried out prior to the measurement of the DUT. After calibration, the systematic errors can be de-embedded from the DUT measurements.

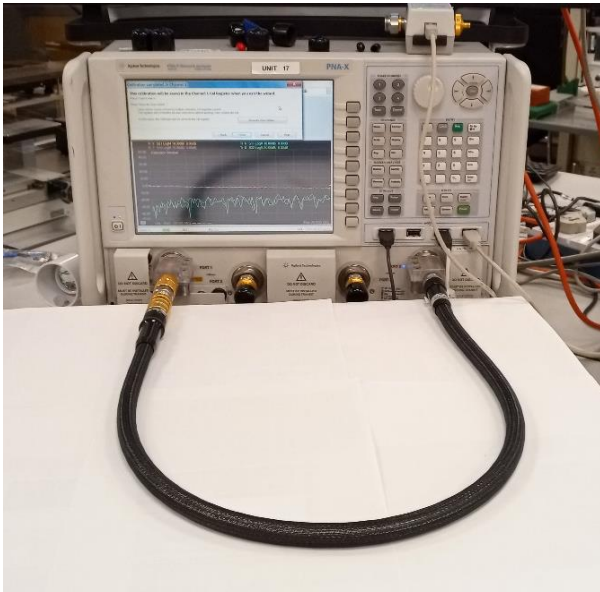


Fig. 1. VNA measurement set-up.

From the many different methods of VNA calibration available, the following were chosen for investigation in this study:

1. PIMMS – Thru-Reflect-Line implemented using NPL’s PIMMS [1];
2. TRL – Thru-Reflect-Line implemented using the VNA firmware;
3. SOLT – Short-Open-Load-Thru;
4. SOLR 0 mm – Short-Open-Load-Reciprocal (unknown thru) using zero length thru;
5. SOLR Reci – Short-Open-Load-Reciprocal (unknown thru) using non-zero length thru;
6. ECal – Calibration using Keysight Electronic Calibration module.

The above list includes the methods most commonly used for coaxial measurements. Apart from PIMMS, all the calibration methods investigated in this work relied on the VNA firmware to perform the calibration and correct the DUT measurements.

Other VNA calibration methods include relative calibrations, reflect response (using either a short or an open), transmission response and QSOLT. These are all low accuracy calibrations and are usually used for quick instrument setup where the user may be interested in only a subset of the two-port S-parameters. None of these calibration methods were part of the investigation reported in this work.

The following sub-sections give a brief overview of the calibration methods.

A. PIMMS

PIMMS (Primary Impedance Microwave Measurement System) [1] is NPL’s primary method for S-parameters measurement at microwave frequencies. It is based on the use of precision coaxial air lines as impedance standards in a TRL calibration. Systematic errors in the air lines and in the VNA are assessed in separate experiments. Several repeat calibration and measurements are performed to assess the random errors in the measurements. In this work, for each repeat measurement of the DUTs, the VNA was calibrated using PIMMS based TRL calibration, i.e. without using VNA firmware TRL calibration.

B. TRL

Thru-Reflect-Line (TRL) [3] is a very accurate calibration method. However, very few calibration kits contain TRL standards. TRL is a “self calibration” technique which means that the calibration standards do not need to be fully characterised. The calibration algorithm itself estimates certain parameters of the line and the reflect standards. The characteristic impedance of the line standard sets the reference impedance for the measured S-parameters. The reflect standard is usually a short-circuit or an open-circuit and, for coaxial measurements, the line standard is an unsupported air dielectric coaxial line. The number of lines required depends on the frequency range since each line standard is only useable over an 8:1 frequency range. Line length usually limits the lowest frequency at which TRL can be used since the long lines which would be required at low frequency are not practical to use.

In this investigation, three TRL line standards were used to cover the frequency range 100 MHz to 26 GHz. The same calibration standards were used for both the PIMMS and TRL calibrations and these are listed in Table 1.

C. SOLT

Short-Open-Load-Thru (SOLT) [4] is a calibration method often used in industry to calibrate VNAs and can provide high accuracy measurements. SOLT does not suffer from frequency bandwidth restrictions like TRL. Unlike TRL, the calibration standards for SOLT need to be fully characterized; the accuracy of the measured S-parameters of the DUT depends on the accuracy of the characterization of the calibration standards. The manufacturer usually provides calibration standard definitions which can be used by the VNA.

The calibration standards used to perform the SOLT calibration in this investigation were from NPL’s 3.5 mm calibration kit, Model 8050C from Maury Microwave Corp (NPL reference number CIS/C/306). The thru used for the SOLT calibration was a zero length (flush) thru.

Table 1: Calibration standards used for PIMMS and VNA firmware TRL calibrations

| Calibration standard | Description |
|--|--|
| Zero-length Thru | Two VNA test ports connected together |
| Reflect (short-circuit) | Two short-circuits (one male and one female) with assumed identical reflection coefficients for connection to the two VNA test ports |
| Line #1 (frequency range 0.1 to 1.5 GHz) | 74.93 mm coaxial air line |
| Line #2 (frequency range 1.5 to 7.0 GHz) | 16.17 mm coaxial air line |
| Line #3 (frequency range 7.0 to 26 GHz) | 3.90 mm coaxial air line |

D. SOLR

Short-Open-Load-Reciprocal (SOLR), also known as the “unknown thru” calibration method [5], is like SOLT except that the S-parameters of the thru standard do not need to be known. The only assumption is that the thru is reciprocal, i.e. $S_{12} = S_{21}$. Like TRL, SOLR is a “self-calibration” method. This calibration works well provided the thru line is well matched (S_{11} and $S_{22} < -10$ dB) with low insertion loss (< -20 dB).

In this investigation, two SOLR calibrations were performed: SOLR #1 with a zero length (flush) thru and SOLR #2 with a non-zero length thru (approximately 15 mm line length). The same calibration kit that was used for the SOLT calibration was used for the SOLR calibrations.

E. ECAL

Most VNA vendors offer Electronic Calibration (ECal) modules [6] to make the calibration process fast and easy. The ECal has all the required terminations embedded in the module and these can be switched in sequence to provide highly repeatable reflection states. The ECal module is directly controlled by the VNA firmware through a USB cable and requires a single connection to the test ports to calibrate the test setup.

ECal module N4691D-60004 (S/N 11728) from Keysight was used in this investigation. In our calibration, the internal ECal terminations were used together with an external flush thru to give a higher calibration accuracy.

IV. MEASURED RESULTS

The sequence of calibration investigations followed a set procedure: (i) after performing each calibration, the calibration data (i.e. the coefficients in the error terms) was saved to the VNA and used for correction; (ii) each DUT was then connected to the VNA and measured. This was repeated 6 times to achieve a complete set of data. This procedure was adopted in order to include any errors due to DUT connection repeatability. This sequence was repeated for all calibration methods. The measurement results for transmission and reflection coefficients are presented using a linear scale and angles in degrees.

The experimental standard deviation [7] was used to quantify the variability in the measurement results. The measured S-parameters are complex-valued quantities and so the standard deviation was computed separately for the magnitude and phase component of each S-parameter, S . For n repeat measurements, the experimental standard deviation in the magnitude of S can be expressed as follows:

$$s(S) = \sqrt{\frac{1}{n-1} \sum_{k=1}^n (S_k - \bar{S})^2} \quad (1)$$

Where \bar{S} is the magnitude and phase means, for all S-parameters. The experimental standard deviation, $s(S)$, of both magnitude and phase of S-parameters were calculated using equation (1).

The experimental standard deviation was averaged over the measured frequency range and plotted together as a summary. The averaged experimental standard deviation of reflection coefficient (S_{11}) for one-port DUTs is plotted in

Fig. 2 and averaged experimental standard deviation of transmission coefficient (S_{21}) for two-port DUTs is plotted in Fig. 3. The results show that the reflection averaged experimental standard deviation is less than 0.8 mU for magnitude and less than 0.25° for phase. The experimental standard deviation for the phase of very low reflecting devices (such as the Load in this investigation) can be ignored as this can vary widely. For two-port devices, the averaged experimental standard deviation of transmission coefficient is 1.2 mU for magnitude and less than 0.16° for phase.

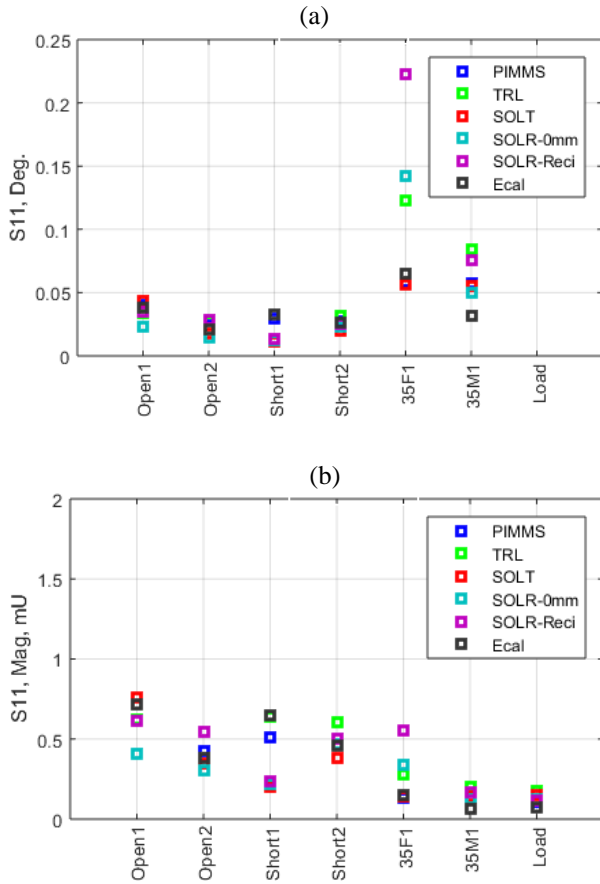


Fig. 2. Measured average experimental standard deviation of S_{11} for one-port DUTs; (a) Phase and (b) Magnitude.

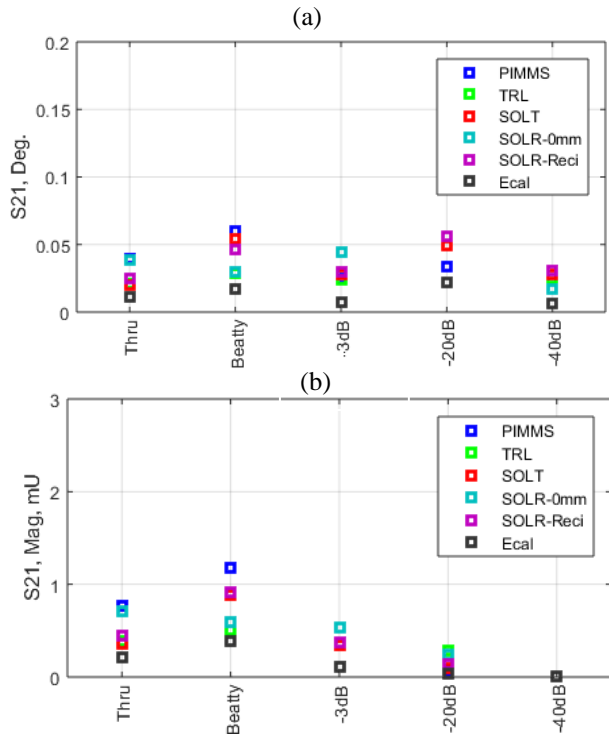


Fig. 3. Measured average experimental standard deviation of S_{21} for two-port DUTs; (a) Phase and (b) Magnitude.

V. CONCLUSIONS

The results showed relatively good agreement between the different calibration techniques for the experimental standard deviation due to random errors in the S-parameter measurements. Seven one-port DUTs were used in the calibration repeatability investigation: two offset short-circuits, two offset open-circuits, two reflection check standards and a 50Ω termination. Five two-port DUTs were used in the investigation: a thru, a Beatty line, a 3 dB attenuator, a 20 dB attenuator and a 40 dB attenuator. Six calibration types were investigated: PIMMS TRL, VNA firmware TRL, SOLT, SOLR-Flush Thru, SOLR-Reciprocal Thru, and ECAL. The repeatability analysis was based on calculations of the experimental standard deviation of six repeated measurements at each frequency for each DUT and for each calibration type to establish the variability in the measurement data.

The results from the investigation are applicable to generic S-parameters measurements and give a very good indication of expected random errors for a wide range of components.

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