Methods and models of calibration of vector network analyzers

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Abstract: Currently, measurement devices and instruments operating in the microwave range are widespread. Therefore, the problem arises of periodic checks, verifications and calibrations of such devices and instruments. The task of minimizing the systematic measurement error is a key task when performing verification of measuring instruments, measuring systems and devices operating in the microwave range using vector network analyzers. Various methods and models for performing calibrations of a vector network analyzer for determining the scattering parameters of passive microwave devices are described. The analysis of calibration methods is carried out, recommendations for its applications are given.

Keywords: vector network analyzer, reflection coefficient, transmission coefficient, measurement correction, measurement error, one-port device, two-port device.

1. INTRODUCTION

The present stage of modern technological development of production and technologies is characterized by the widespread introduction and use of devices operating in the microwave range [1-10]. To ensure the normal functioning of such devices, it is necessary periodically to verify and calibrate them. The most accurate measuring complexes for calibrations and verifications are Vector Network Analyzers (VNA) [1-10].

The device that we are testing and calibrating hereinafter will be called Device Under Testing (DUT). When we deal with DUT for highly accurate measurements of their scattering parameters (S-parameters) we use VNA. It is very important to minimize the systematic measurement error. As the frequency of the sounding signal increases, as a rule, the properties of the propagation path deteriorate. This is manifested by an increase in Voltage Standing Wave Ratio (VSWR), an increase in the frequency unevenness of the transmission of the elements of the path, the appearance of various parasitic penetrations of signals. All these phenomena contribute to the systematic measurement error.

To determine the components (factors) of the systematic error, the VNA calibration procedure is used. To eliminate errors, the mathematical correction of the measurement results is applied.

When developing a VNA for the frequency range up to 20 GHz, and even more so up to 50 GHz or higher, one cannot ignore how the instrument will be calibrated. In order to properly design the instrument and the calibration means for it, it is necessary to have a clear understanding of the current advances in calibration and correction at the VNA.

The paper summarizes the experience of using the currently most widespread methods and models of
VNA calibration [11-16].

2. BRIEF CLASSIFICATION OF CALIBRATION METHODS AND MODELS

Two-port VNAs are calibrated as follows:
- normalization for measuring the Reflection Coefficient (RC);
- normalization for measuring the Transmission Coefficient (TC);
- one-port vector calibration;
- two-port calibration in one direction;
- full two-port calibration.

All methods involve measuring the complex frequency response of various single-port or dual-port devices.

In addition, to perform high-precision measurements with the VNA, you can use the conversion of the frequency description of the circuits to the time and vice versa. For example, you can test the DUT over ideal lengths of transmission lines and then isolate the DUT response in the time domain. Thus, when the VNA operates up to 50 GHz, the time resolution under certain conditions can reach 6 mm. The problems of performing measurements with the involvement of processing in the time domain and others are not considered in this work. We will focus on the most accurate type of calibration currently used in two-port VNAs - full vector two-port calibration in the frequency domain.

3. VNA MODELS

When we developing a methods and models for calibrating and correcting the results of measurements, we assume that there is an ideal (non-distorting) part of the VNA. It is supposed that all errors are reduced to linear distorting adapters (DA). Obviously, it is supposed that the parameters of the DA should not change over time.

Let us consider two VNA models suitable for deriving calibration algorithms. These models are shown in Fig. 1 and Fig. 2. In the figures, the factors (components) of the systematic error are indicated by \( a_{**} \) (the presence of an additional stroke means a change in the corresponding component for the port, which operates in the mode of receiving the probing signal). VNA receivers measure the complex amplitudes of signals \( a_1, b_1, b_2 \), both for forward sounding (from the first port to the second) \( a_2, b_1, b_2 \) - for the opposite (from the second port to the first). Reference receivers measure signals, and measurement receivers measure signals \( b_{**} \). The obtained amplitudes determine the uncorrected (measurable) S-parameters:

\[
\begin{align*}
S_{11}^M &= \frac{b_{1F}}{a_{1F}}, \\
S_{21}^M &= \frac{b_{2F}}{a_{1F}}, \\
S_{12}^M &= \frac{b_{1R}}{a_{2R}}, \\
S_{22}^M &= \frac{b_{2R}}{a_{2R}},
\end{align*}
\] (1)

The indices F means Forward, indices R means Reverse. Its determine the direction of sounding.
Unknown values in the 10-parameter model are: $e_{00}$, $e_{11}$, $e'_{22}$, $e_{10}e_{01}$, $e'_{10}e'_{32}$, $e_{22}$, $e_{33}$, $e'_{11}$, $e_{32}e_{23}$, $e'_{32}e'_{01}$, and in the 8-parameter model are: $e_{00}$, $e_{11}$, $e_{10}$, $e_{01}$, $e_{22}$, $e_{33}$, $e_{32}$, $e_{23}$.

There exists a model with 16 parameters, which is obtained from an 8-parameter model by adding graph branches describing all kinds of parasitic signal intrusions. For this reason, this model should be used in VNAs as part of probe stations, especially at frequencies around 50 GHz or higher. Obviously, of the mentioned ones, the 16-parameter VNA model is the most complete, since it takes into account the largest number of factors of systematic measurement errors of the four S-parameters of a two-port DUT. This model is not analyzed in detail in this paper.

An 8-parameter model can be converted to a 10-parameter model by invoking additional measurements in a 4-receiver design (forward and reverse). In turn, two main parasitic signal penetrations can be added to the 10 parameters and, as a result, a 12-parameter model, which is basic for modern VNAs, can be obtained. This model is shown in Fig. 3 and is the base for the measurement correction algorithm, which is given below. Table 1 shows the names and designations for all factors of systematic error.

Error factors have a certain physical meaning and simulate reflections and distortions of signals during the passage of circuits inside the device, various cable assemblies and transitions outside it, up to the connector to which the DUT is connected. For example, the frequency unevenness of the paths is formed by the signal transmission circuits between the points of the signal taps to the reference and measuring receivers. Directivity is the sum of the signals arriving at the input of the measuring receiver before they are reflected from the DUT.
**Figure 3.** Graphs of the 12-parameter VNA model: a) – forward sounding; b) - reverse sounding

| Type                        | Name                          | Designation | Model         |
|-----------------------------|-------------------------------|-------------|---------------|
| 1. Parasitic penetration    | Direction                     | ED          | EDF = \( e_{00} \)  
|                             |                               |             | EDR = \( e_{33} \)  |
|                             | Insulation                    | EX          | EXF = \( e_{30} \)  
|                             |                               |             | EXR = \( e_{03} \)  |
| 2. Parasitic reflection     | Signalsourcemismatch          | ES          | ESF = \( e_{11} \)  
|                             |                               |             | ESR = \( e_{22} \)  |
|                             | Load mismatch                  | EL          | ELF = \( e'_{22} \)  
|                             |                               |             | ELR = \( e'_{11} \)  |
| 3. Frequency unevenness     | Uneven path of the reflected signal | ER         | ERF = \( e_{10} e_{01} \)  
|                             | Uneven signal path transmitted from port to port | ETR         | ETF = \( e'_{10} e'_{32} \)  
|                             |                               |             | ETR = \( e'_{23} e'_{01} \)  |

The measured S-parameters (as a solution to the corresponding flow graphs, Fig. 3) are:

\[
s_{11}^M = \frac{EDF + ERF}{1 - ESF \cdot s_{11} - ELF \cdot s_{22} + ESF \cdot ELF \cdot (s_{11}s_{22} - s_{21}s_{22})}, \tag{2}
\]

\[
s_{21}^M = \frac{EXF + ERF}{1 - ESF \cdot s_{11} - ELF \cdot s_{22} + ESF \cdot ELF \cdot (s_{11}s_{22} - s_{21}s_{22})}, \tag{3}
\]

\[
s_{22}^M = \frac{EDR + ERR}{1 - ESR \cdot s_{22} - ELR \cdot s_{11} + ESR \cdot ELR \cdot (s_{11}s_{22} - s_{21}s_{22})}, \tag{4}
\]

\[
s_{12}^M = \frac{EXR + ERF}{1 - ESR \cdot s_{22} - ELR \cdot s_{11} + ESR \cdot ELR \cdot (s_{11}s_{22} - s_{21}s_{22})}, \tag{5}
\]

where \( s_{oo} \) - are the true (real) values of the S-parameters.
To exclude the influence of IA on the results of measurements of S-parameters, it is necessary to carry out a correction, solve (2) - (5) for the true values of the S-parameters. Correction or estimation of the actual values of S-parameters is performed according to the formulas:

\[ S_{11} = \frac{(1 + D \cdot \hat{E}SR)A - \hat{ELF} \cdot B \cdot C}{(1 + A \cdot \hat{ESF})(1 + D \cdot \hat{ESR}) - C \cdot B \cdot \hat{ELR} \cdot \hat{ELF}}, \]

\[ S_{21} = \frac{(1 + D \cdot (\hat{ESR} - \hat{ELF})B}{(1 + A \cdot \hat{ESF})(1 + D \cdot \hat{ESR}) - C \cdot B \cdot \hat{ELR} \cdot \hat{ELF}}, \]

\[ S_{12} = \frac{(1 + A \cdot (\hat{ESF} - \hat{ELR}) \cdot C}{(1 + A \cdot \hat{ESF})(1 + D \cdot \hat{ESR}) - C \cdot B \cdot \hat{ELR} \cdot \hat{ELF}}, \]

\[ S_{22} = \frac{(1 + A \cdot \hat{ESF})D - \hat{ELR} \cdot B \cdot C}{(1 + A \cdot \hat{ESF})(1 + D \cdot \hat{ESR}) - C \cdot B \cdot \hat{ELR} \cdot \hat{ELF}}, \]

where

\[ A = (s_{11}^M - \hat{EDF}) / \hat{ERF}, \quad B = (s_{21}^M - \hat{ESF}) / \hat{ETF}, \]

\[ C = (s_{12}^M - \hat{ESR}) / \hat{ETR}, \quad D = (s_{22}^M - \hat{EDR}) / \hat{ERR}. \]

Factor estimates \( \hat{E}_m \) should be obtained from the calibration results.

In this paper, we will consider two families of complete vector two-port gauges - conditionally SOLT and TRL, which differ in the way of determining the estimates \( \hat{E}_m \) (or \( \hat{E}_s \)). When considering calibration algorithms from these families, at the first stage, we will assume that the output connectors of the VNA ports are such that it is possible to directly connect the ports to each other. The isolation factor estimates \( \hat{e}_{30}, \hat{e}_{03} \) are always either set to zero or measured as parameters \( S_{21} \) and \( S_{12} \) and when matched loads are connected to both VNA ports.

**4. MAIN FAMILIES OF TWO-PORT VNA CALIBRATIONS**

**4.1. Set of calibrations SOLT - Short Open Load Thru.** The relevant 10-parameter model of the VNA is shown in Fig. 1. In order to determine the unknown factors of systematic errors, the calibration procedure is divided into three stages:

a) One-port calibration of the first port (conditionally SOL);

b) Single-port calibration of the second port (conditionally SOL);

c) Calibration for passage (conditionally T).

The following types of one-port calibrations are known, differing in technical details when obtaining data for a measurement vector: using load of short-circuit (SCL), using Idle load (IL) and fixed Matched Load (ML); using SCL, IL and MisMatched Load (MML) with a known RC; using several (three or more) SCL with different known length; using loads of SCL, IL and movable ML; using a SCL and two movable loads with different RC.

Regardless of the type of calibration within the SOLT family under consideration, stage No. 3 is the same. Let us consider the stage No. 3, assuming that one-port calibrations have been performed successfully and the estimates of factors \( e_{00}, e_{11}, e_{10}, e_{01}, e_{22}, e_{33}, e_{32}, e_{23} \) are already known.

It was previously suggested that the VNA ports allow direct connection to each other. The situation where this is not possible is discussed below in chapter 4.
So, according to the results of testing an Ideal Jumper (IJ) or direct connection of ports, it is necessary to determine the estimates of 4 parameters: \( e_{22}', e_{10}'e_{32}', e_{11}', e_{32}'e_{01} \).

The S-parameter matrix for IJ has the form

\[
S_{THRU} = \begin{bmatrix}
    s_{11,T} & s_{12,T} \\
    s_{21,T} & s_{22,T}
\end{bmatrix} = \begin{bmatrix}
    1 & 0 \\
    0 & 1
\end{bmatrix}.
\]

(10)

Matrix \( S_{THRU}^M \) contain systematic errors due to the influence of DA. To write expressions for the desired quantities, it is necessary to consider the flow graph of the VNA model (Fig. 1) for the DUT (10).

Such

\[
\hat{e}_{22}' = \frac{(s_{11,T}^M - \hat{e}_{00})(1 - \hat{e}_{11}s_{11,T}) - \hat{e}_{10}'\hat{e}_{01}'s_{11,T}}{(s_{11,T}^M - \hat{e}_{00})(s_{22,T} - \hat{e}_{11}\det s_{THRU}) - \hat{e}_{10}'\hat{e}_{01}\det s_{THRU}} = \frac{(s_{11,T}^M - \hat{e}_{00})}{\hat{e}_{10}'\hat{e}_{01} + \hat{e}_{11}(s_{11,T}^M - \hat{e}_{00})},
\]

(11)

\[
\hat{e}_{10}'\hat{e}_{22}' = \frac{s_{21,T}(1 - \hat{e}_{11}s_{11,T} - \hat{e}_{22}s_{22,T} + \hat{e}_{11}\hat{e}_{22}\det s_{THRU})}{s_{22,T}} = s_{21,T}(1 - \hat{e}_{11}\hat{e}_{22}) = \frac{s_{21,T}\hat{e}_{10}'\hat{e}_{01}}{\hat{e}_{10}'\hat{e}_{01} + \hat{e}_{11}(s_{11,T}^M - \hat{e}_{00})},
\]

(12)

\[
\hat{e}_{11}' = \frac{(s_{22,T}^M - \hat{e}_{33})(1 - \hat{e}_{22}s_{22,T}) - \hat{e}_{32}'\hat{e}_{23}\det s_{THRU})}{(s_{22,T}^M - \hat{e}_{33})(s_{11,T} - \hat{e}_{22}\det s_{THRU}) - \hat{e}_{32}'\hat{e}_{23}\det s_{THRU}} = \frac{(s_{22,T}^M - \hat{e}_{33})}{\hat{e}_{32}'\hat{e}_{23} + \hat{e}_{22}(s_{22,T}^M - \hat{e}_{33})},
\]

(13)

\[
\hat{e}_{23}'\hat{e}_{01}' = \frac{s_{12,T}(1 - \hat{e}_{22}s_{22,T} - \hat{e}_{11}s_{11,T} + \hat{e}_{22}\hat{e}_{11}\det s_{THRU})}{s_{12,T}} = s_{12,T}(1 - \hat{e}_{22}\hat{e}_{11}) = \frac{s_{12,T}\hat{e}_{23}}{\hat{e}_{32}'\hat{e}_{23} + \hat{e}_{22}(s_{11,T}^M - \hat{e}_{33})},
\]

(14)

where \( \det s_{THRU}^M = s_{11,T}^M s_{22,T}^M - s_{21,T}^M s_{12,T}^M \) is the determinant of the matrix \( S_{THRU}^M \), equal to 1 for (10). As you can see, the calibration algorithm allows the use of a jumper with known S-parameters as a standard, which considers special calibrations, including those from the SOLT family.

The accuracy of SOLT family calibrations essentially depends on the accuracy of the a priori information about the actual values of the S-parameters of the calibration standards, on their stability over time during operation, on the quality of manufacture of loads and connectors. TRL calibration algorithms do not require such a large amount of a priori information.

4.2. Set of calibrations TRL - Thru Reflect Line. This set of calibrations combines two-port VNA calibrations using an 8-parameter model containing factors: \( e_{00} \), \( e_{11} \), \( e_{10} \), \( e_{01} \), \( e_{22} \), \( e_{33} \), \( e_{32} \), \( e_{23} \) (Fig. 2). This 8-parameter VNA model, which, as mentioned earlier, can be converted into a 10-parameter model, is easy to normalize and get 7 unknown parameters.

Knowledge of 7 parameters is sufficient to recover all the factors that are used to perform measurement correction in accordance with (6) - (9). For this, additional measurements must be involved in the VNA circuit with 4 receivers. That is, for a two-port VNA with a common reference receiver, the use of the TRL apparatus is difficult.

To find 7 unknown values of parameters, it is necessary to perform at least 7 measurements. Table 2
summarizes information about almost all calibrations included in the TRL family (in parentheses for each standard, the number of measurements obtained is indicated). The algorithm for finding unknowns depends little on the specific type of calibration from the TRL family. However, it is necessary to correctly specify the initial data to start the calculation at each point in frequency.

Table 2. Brief description of TRL calibrations

| Name    | Standard No. 1                                                                 | Standard No. 2                                                                 | Standard No. 3                                                                 |
|---------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| TRL     | Jumper [T] or line [L] with known S-parameters                                 | Unknown standard for reflection [R] on both ports                              | Line [L] with well-known RC, $S_{11}, S_{22}$                                   |
| LRL     |                                                                                   |                                                                                   |                                                                                   |
| TRM     | Jumper [T] or line [L] with known S-parameters                                 | Unknown standard for reflection [R] on both ports                              | Known ML [M] on both ports                                                     |
| LRM     |                                                                                   |                                                                                   |                                                                                   |
| TRA     | Jumper [T] or line [L] with known S-parameters                                 | Unknown standard for reflection [R] on both ports                              | Attenuator [A] with known RC                                                   |
| LRA     |                                                                                   |                                                                                   |                                                                                   |
| TXYZ    | Jumper [T] or line [L] with known S-parameters                                 | 3 known reflections [X], [Y] and [Z] per port 1 or port 2                      |                                                                                   |
| XYZ     |                                                                                   |                                                                                   |                                                                                   |
| LXYZ    | Jumper [T] or line [L] with known S-parameters                                 | 2 known points [X] and [Y] to port 1                                           | 1 known reflection [X] per port 2                                              |
| XYY     |                                                                                   |                                                                                   |                                                                                   |
| XYX     | Jumper [T] or line [L] with known S-parameters                                 | 2 known [R] and [R] equal reflections to port 1 and port 2                     | Known ML [M] on port 2                                                         |
| LXY     |                                                                                   |                                                                                   |                                                                                   |
| TXYZ    | Jumper [T] or line [L] with known S-parameters                                 | 3 known reflections [X], [Y] and [Z] per port 1                                | 3 known reflections [X], [Y] and [Z] per port 2                                |
| LXYZ    |                                                                                   |                                                                                   |                                                                                   |
| UXYZ    | Unknown line [U] with $S_{11}=S_{12}$                                            | 3 known reflections [X], [Y] and [Z] per port 1                                |                                                                                   |

Overhead lines are standards of wave resistance. The quality of TRL calibration is actually determined by the quality of the overhead line. As a result, TRL algorithms can provide the highest accuracy in determining the systematic error factors, which means the highest measurement accuracy among all known calibration algorithms. Depending on the specifics of the DUT, the available set of measures and the required frequency range, one or another algorithm should be selected from Table 1. It is difficult to provide operation in a wide frequency band with only one overhead line in the calibration set. As a rule, it is necessary to combine methods and even measures, for example, use the TRM algorithm at the beginning of the microwave frequency range, and then the TRL algorithm with two or more different lines. There are calibration methods that involve the use of several lines (multiline) at the same frequencies. The basis of vector measurement metrology is precision overhead lines together with TRL theory. The use of special torque wrenches ensures repeatability and uniformity of measurements.

However, good accuracy can also be achieved from a SOLT type calibration. To do this, it is necessary to exclude errors in the description of measures. If, in addition to the working set of measures (class SOLT), the device contains a reference standard (class TRL), then it is possible to characterize the working measures after calibrating the device to the reference set.

5. METHODS FOR CALIBRATING VNAs WHEN TESTING "NON-INSERTABLE" DEVICES

Let us consider now methods of measuring VNA calibration in the case when it is required to test "non-insertable" devices. "Non-insertable" devices include all two-port devices that have any type of unisex connectors, and various types of hetero or unisex connectors. There are several calibration methods for measuring non-insertable devices. These include: Calibration using equivalent adapters; Calibration with Defined adapter (Defined Thru); Calibration with Adapter Removal; Calibration with an unknown
adapter (Unknown Thru);

The first method assumes that a certain transition is used during the calibration process, which allows direct connection of the VNA ports, and during measurements it is replaced with an equivalent one (in terms of S-parameters). In this case, any calibration algorithm can be used. The second type of calibration is, in fact, a normal SOLT calibration, during which the jumper is not ideal, i.e. its parameters differ from (10). Calibration excluding the adapter is very complex and multi-step, involving four one-port calibrations instead of two. The last type of calibration for testing “non-insertable” DUTs is none other than the UXYZ calibration from the TRL family. This method has one limitation - the unknown adapter must be a mutual device.

We note one important circumstance that must be taken into account both when performing a SOLT type calibration and when performing a TRL type calibration. If the conditions are such that it is necessary to measure the insulation, then after measuring it, before performing the calculations, the obtained values of the TC for each standard per passage (jumper, line, attenuator, transition, etc.) should be replaced with the following:

\[
s^M_{21} = s^M_{21} - \hat{e}_{30}, \quad s^M_{12} = s^M_{12} - \hat{e}_{03}
\]

(15)

6. CONCLUSION

Modern devices of the VNA type allow us to obtain high accuracy of measurements of complex S-parameters of various devices. This is achieved using a variety of calibration methods. To effectively use the capabilities of the devices of VNA type and various calibration kits, it is necessary to understand and navigate the existing variety of algorithms. The paper provides algorithms, methods and models classification and summarizes the experience of the development and use of modern calibration procedures.

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