White Paper

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# Vector Network Analyzer (VNA) Calibration: The Basics

**By Michael Hiebel**

Note: VNA calibration has been the subject of hundreds of papers, and when discussed in terms of its mathematical derivation can be quite complex. The goal of this white paper is far less academic, and includes an overview of VNA calibration, a discussion of calibration standards and techniques, along with guidelines that can help designers choose the best calibration technique for specific situations. It also provides tables showing the applicability of the various calibration techniques and the influence of various actions that affect the calibration. A more thorough treatment of the subject can be found in the 420-page book by Rohde & Schwarz author Michael Hiebel entitled "Fundamentals of Vector Network Analysis," which is available from the Book Shop on the Rohde & Schwarz web site (www.rohde-schwarz.com).

The most common measurement task in RF and microwave engineering involves the analysis of circuits using a network analyzer (VNA). This versatile instrument can evaluate nearly all types of devices, from filters and amplifiers to complex multifunction subsystems. The reason the instrument is so widely used is that it can, through the use of scattering (S)-parameters, evaluate the characteristics of the device under test with a high level of precision. S-parameters have long been the chosen method for this because they are relatively easy to derive at high frequencies and are directly related to the measurement parameters of interest to microwave designers, such as gain, return loss, and reflection coefficient. They are also extremely well suited for use by the electronic design automation tools that designers have come to rely on.

A VNA is only as useful as the accuracy with which it makes measurements, and this requires the instrument to be calibrated. The calibration process employs a technique called vector error correction, in which error terms are characterized using known standards so that errors can be removed from actual measurements. The process of removing these errors requires the errors and measured quantities to be measured vectorially (thus the need for a vector network analyzer). In contrast, scalar network analyzers can only record the magnitude of the measured quantities, precluding them from being used to eliminate systematic measurement errors, which unlike random errors, can be mathematically eliminated from the measurement result.

Perhaps the most simplistic analogy to the VNA calibration process is "zeroing out" test-lead resistance from an ohmmeter. This early form of "de-embedding" the test lead resistance from the measurement results is far less complicated but no less relevant than calibration performed on a VNA. Of course, A VNA is a vastly more complex instrument than a simple ohmmeter, as is its error model that includes multiple terms for every frequency at which measurements are made.

The ideal VNA error model includes all possible areas in which systematic inaccuracies can arise, including directivity of the couplers, the match presented by the reflectometer via its test port, the frequency response of the reflectometers and transmission between ports, and crosstalk between ports. A typical VNA error model is shown in Figure 1. Calibration provides accuracy whether the measurement plane resides at the connector on the instrument's front panel or the connectors at the end of test cables.

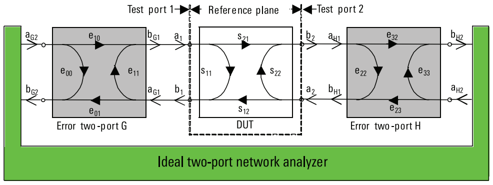

*Figure 1: Typical network analyzer error model*

The preceding simplistic description belies the wide variety of pitfalls that can singly or together degrade or invalidate the calibration process. Some are difficult to conceptualize and require considerable expertise, but others are as simple as making sure measurement setups, such as cables and connectors, are handled with care and that no stresses are placed on them that exceed their specifications. Even the choice of test cable can be extremely important, since cables designed for the VNA environment are generally the most precise. For example, Figures 2a and b show the results of a simple test. Two sets of cables 1 m long were connected to a VNA and their ends connected using a through standard. The first set of test cables was of "commercial grade" and although not specified for use for precision measurements is widely used in microwave systems of many kinds.

The second set was a high-performance type designed for VNA measurements. In the figures, phase and amplitude of the transmission coefficient are displayed. The results of the first measurement were saved, and both sets of cables were reformed to a specific bending radius and angle and measured again. The results show the significant improvement obtained using high-performance test cables – a factor of 10 in phase and 100 in amplitude (note the scaling!) which are designed to maintain their performance within a very narrow range of variance within their specified bending radius. (For more information on the handling of cables and connectors, see "A recipe for cable and connector care," page 9).

Measurement performance also depends on the accuracy and quality of the error model and calibration standards, and the repeatability of the measurement system itself. Even though created to reduce errors to their lowest possible levels, a calibration performed poorly can actually introduce errors that otherwise would not have occurred. In short, a VNA can provide results only as accurate as the information it is provided. For example, the impedance employed in the calibration must be precisely specified, as must information about the calibration standard. Fortunately, the capabilities of modern VNAs as well as optional automatic electronic calibration have made the once-tedious, error-prone process of calibration far less difficult.

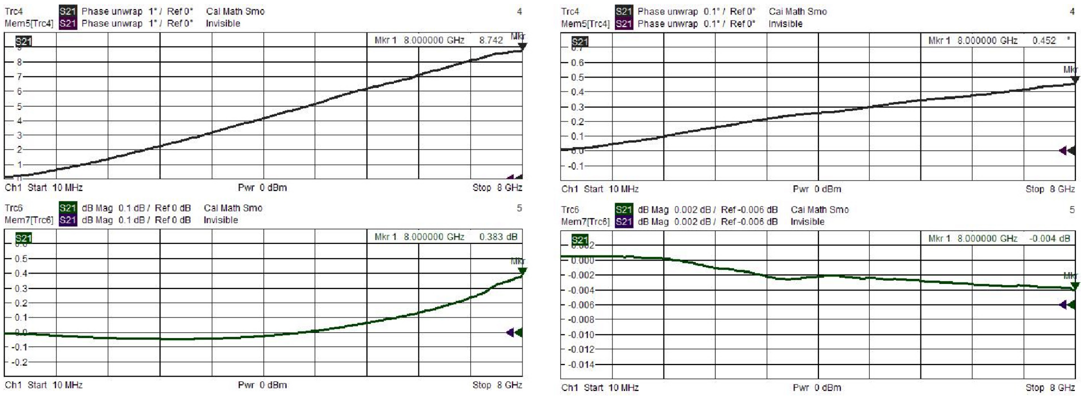

*Figure 2: Deviation caused by bending of two RG400 cables that are 1-m long (a), and for high-performance test port cables (b)*

## THE CALIBRATION PROCESS

Before going further, it is important to keep in mind that every measurement is subject to measurement uncertainly, which is the statistical deviation of the measured values from their true value. In the measurement domain, there are two types of uncertainties – random and systematic. Random errors vary with time and are thus unpredictable. While they can be described, they cannot be removed by calibration. Typical random errors include those caused by instrument noise, and the repeatability of switches, cables, and connectors. In contrast, systematic errors occur in a reproducible manner. They are caused by imperfections in the VNA, can be characterized, and thus can be removed mathematically through calibration. Another type of error called drift occurs after a calibration has been performed because of changes in VNA performance arising from variations in ambient temperature. However, these errors can be removed by performing additional calibrations.

Since random errors cannot be removed through calibration, they must be reduced in severity as much as possible by following prudent measurement practices, such as allowing the instrument to achieve thermal equilibrium, using high-quality cables and connectors, reducing system noise figure by keeping step attenuator values as low as possible, selecting a small IF bandwidth, and possibly using averaging. Finally, as the interface between instrument, cable, DUT, test fixture, and in the case of semiconductors the wafer probe, the connector is a critical element in achieving good measurement results. Connectors may look mundane, but they are fragile, precision-machined components and are highly sensitive to care in handling.

## ERROR TERMS

Each network analyzer can be separated into an error network (or linear error model) and an ideal network analyzer. The parameters of the error network are considered error terms (or correction data), and can be directly interpreted as raw system data. Correcting system errors is the primary goal of calibration, and any remaining errors are expressed by the effective system data and depend on the accuracy of the error terms and the repeatability of the measurement process. An example of raw and corrected system data is shown in Table 1.

| System data | Raw system data | Effective system data |
|---|---|---|
| Reflection tracking | ≤2 dB | ≤0.04 dB |
| Directivity | ≥29 dB | ≥46 dB |
| Source match | ≥22 dB | ≥39 dB |
| Transmission tracking | ≤2 dB | ≤0,06 dB |
| Isolation | ≥130 dB | ≥130 dB |
| Load match | ≥22 dB | ≥44 dB |

*Table 1: Comparison of typical raw and effective system data*

The calibration process determines the error terms, requires a test system consisting of a VNA, cables, and generally a test fixture, and is performed by sequentially making measurements using calibration standards. These calibration standards are one-port and two-port networks that have known characteristics. The chosen calibration process determines the properties of the standards that must be used. It is impossible to manufacture a calibration standard that has ideal properties, so the deviations of the standards are sent to the VNA as characteristic data. This data is provided as data files on digital storage media ranging from a diskette to USB flash drive along with the calibration standards and a printed measurement report (Figure 3).

*Figure 3: The Rohde & Schwarz R&S®ZV-32 3.5-mm calibration kit and calibration data on diskette*

After calibration, the analyzer computes the error terms using the values it measured during the calibration process along with the characteristic data of the standards. It is then possible to correct the raw measured values in later measurements and calculate

S-parameters for the device under test. The interface between the error network and the device under test is called the reference plane. When using coaxial calibration standards, the reference plane is the mating plane of the outer conductor, an example of which is shown in Figure 4.

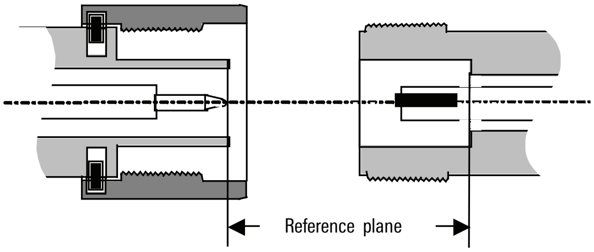

*Figure 4: Location of the reference plane in a Type-N connector*

## CALIBRATION STANDARDS

The process of measuring the characteristic data is called characterization and must be performed in accordance with principles established by various metrological organizations. In the U.S., this organization is the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards). The characterization should ideally be certified at regular intervals by an accredited measurement laboratory to ensure that changes have not occurred that would affect the accuracy of the results.

The standards are described by using special coefficients because they provide a compact solution. Even over a frequency range of DC to 40 GHz, only seven coefficients are required per standard.
The standards are also described using complex S-parameters that can be saved in one of the popular electronic design automation (EDA) file formats, such as Touchstone, which eliminates the need to extract the coefficients manually, which can reduce accuracy. Since the S-parameter data files are generally quite large, they are provided on some form of digital media.

VNA manufacturers also offer electronic (automatic) calibration, which has greatly simplified the calibration process and eliminates the time-consuming, error-prone process of switching manually between various calibration standards. Characteristic data is stored in the electronic calibration equipment, which eliminates the need to transfer all the data using a separate storage medium.

### Coaxial calibration standards

### Short (S)

A coaxial short (Figure 5) can be constructed that has near ideal characteristics, with a total reflection of magnitude 1. The reflection coefficient of the short is dependent only on its length offset, which represents the length between the reference plane and the short. The loss occurring over this length can generally be ignored. Modeling the short in a VNA requires that only its electrical length be entered into the instrument, but in some cases the model can be extended using the polynomial coefficients $L_0$ to $L_3$ to account for parasitic inductance.

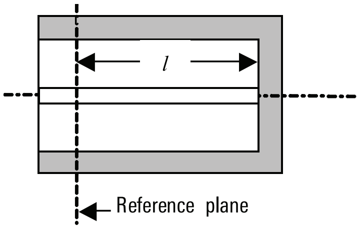

*Figure 5: Short calibration standard.*

### Open (O)

A coaxial open standard (Figure 6) is constructed using a closed design to avoid effects caused by entry of stray electromagnetic energy. At the open end of the inner conductor, a frequency-dependent fringing capacitance is formed. Even if an open standard could physically be constructed with a length of 0, fringing capacitances would result in a negative imaginary part for $S_{11}$ at higher frequencies.

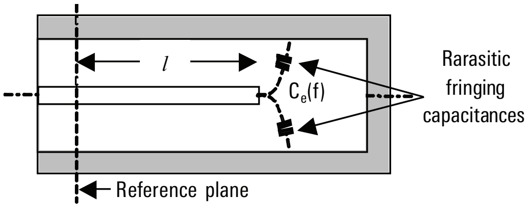

*Figure 6: Open calibration standard.*

### Match (M)

A match is a precision broadband impedance that has a value corresponding to the system impedance. An implementation in which the inner conductor terminates into a resistively-coated substrate is shown in Figure 7. Using trimming holes created by a laser, it is possible to optimize the impedance value so that return loss of 45 dB is achievable up to about 4 GHz. It was standard practice for many years to assume an ideal match in the calibration process. However, VNAs now include the non-ideal properties of a match as well.

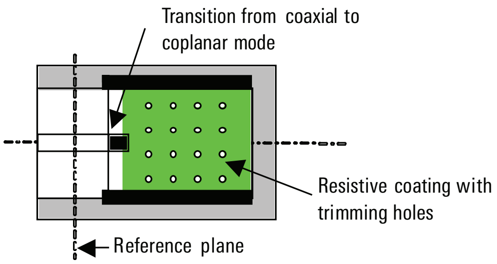

*Figure 7: Match standard, implemented as a terminating load.*

**Sliding Match** (also called a sliding load or sliding termination)

A sliding match cannot be used at frequencies below 2 GHz. However, almost all calibration techniques can be performed using a sliding match and a fixed match to circumvent this low-end frequency-range restriction. At frequencies above about 8 GHz, a sliding match is considerably more accurate than a match. The TOM-X calibration technique cannot be performed using a sliding match. An air line sliding match (Figure 8) that has a specified characteristic impedance can be manufactured much more accurately than the match shown in Figure 7.

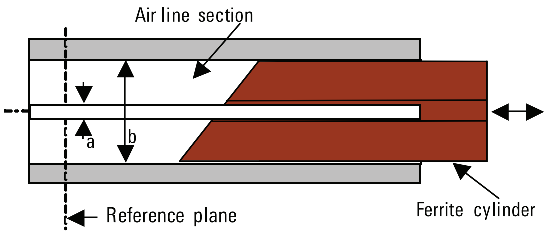

*Figure 8: Sliding match*

The characteristic impedance $Z_c$ of the air line is calculated from the diameter *a* of the inner conductor and the inner diameter *b* of the outer conductor as follows:

$$Z_0 = \frac{60\,\Omega}{\sqrt{\varepsilon_r}} \ln\left(\frac{b}{a}\right) \approx 60\,\Omega \cdot \ln\left(\frac{b}{a}\right)$$

*(Equation 1)*

Because the formula contains the ratio values *a* and *b* and not their absolute values, it is possible to match the mechanical properties of the air line to the type of connector being used. As a result, the transition from the connector to the air line is quite free of discontinuities. A cylindrical ferrite rod is introduced into the air line that absorbs a considerable portion of the electromagnetic energy at frequencies of 2 GHz and above. At the input of the sliding match there is return loss of about 20 dB, and if the rod is moved along the line, the length offset changes as does the phase of the reflection coefficient at the line input.

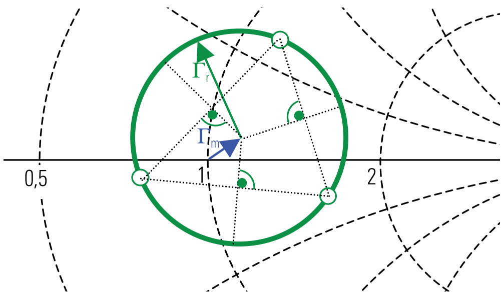

*Figure 9: Excerpt from the Smith chart for determining characteristic impedance*

At a constant frequency, the reflection coefficient of the sliding match lies at a different point on the circle of a Smith chart shown in green in Figure 9, depending on the length offset. Three points on the circle are sufficient to construct the center point $\Gamma_m$, which corresponds to the characteristic impedance of the air line section as measured by the VNA. For calibration purposes, this quantity is used instead of the impedance of the match in Figure 7. The circle radius is determined by the return loss of the ferrite rod.

In practice, frequency sweeps are performed instead of fixed-frequency measurements, so it is no longer acceptable to measure just three positions of the ferrite rod. If the frequency is increased, the three points move along the circumference of the circle. However, frequency dependence of the points is not identical so they move at different speeds, and at certain frequencies two or three points will overtake one another and merge into a single point. In constructing the center point, at least three separate points are required, distributed over the circumference of the circle. To ensure this occurs in the frequency range of the sliding match, six positions are selected on the match.

It is not necessary to approach a specific position on the Smith chart with exceptional accuracy. Instead, it is acceptable to orient the calibration procedure toward the marks on the sliding match (points 1 to 6 on Figure 10). Using the pin and fastening nut (points 7 and 8), the offset of the inner conductor can be adjusted with respect to the reference plane for the connector using a pin-depth gage. The “0” point on the gage is generally aligned with a gage master before using the device. If the inner conductor of the sliding match protrudes too far the connectors can be damaged when connecting the match to the test port. If the inner conductor is seated too low, an unnecessary air gap will be produced, which reduces accuracy. It’s important to note that a pin depth gage, like all measurement instruments, has measurement uncertainty. Consequently, it is quite risky to adjust the pin depth to an exact “0” with the gage. In practice, a clearance of about 0.010 mm (depending on the connector system and the gage used) is desirable.

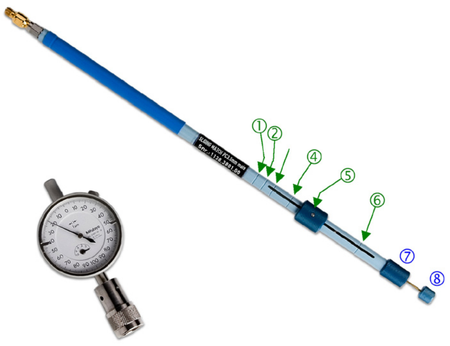

*Figure 10: Sliding match and pin depth gage key points noted*

**Through (T)**

A through (Figure 11) is a two-port standard that allows direct connection of two test ports with low loss. The characteristic quantities of a through are insertion loss and electrical insertion length. In most common calibration techniques, the through is assumed to be ideally matched. If connectors of the same type but of a different gender are used, the two test ports can be directly connected to produce a through connection. This special case of a through has an electrical insertion length of 0 mm. If connectors of the same type and gender are used, a through will consist of a small line section, making a good electrical connection between the two test ports. The characteristic impedance of the connection should match the reference impedance as closely as possible.

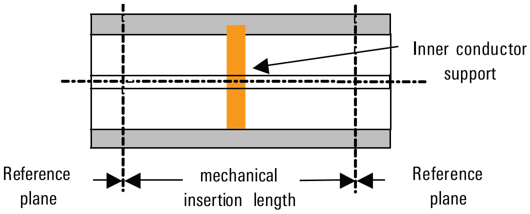

*Figure 11: Through calibration standard*

**Standards with Partially-Unknown Parameters for Seven-Term Calibration Techniques**

**Reflect (R)**

This one-port standard, which like all of the standards within this section has only partially-known S-parameters, shows a reflection coefficient of magnitude 1. The exact reflection is not required for the TRL calibration technique but must be identical at both test ports. The reflect standard is used for self-calibration techniques in which the known information for the standards is used to determine their unknown properties. The phase of the reflect standard must be known to within +/-90 deg. To characterize this type of standard, its behavior at lower frequencies is considered to be either more capacitive or more inductive. If the length offset of the standard causes the phase to reside outside the interval 0 deg to -90 deg. or 0 deg. to +90 deg., the length offset must also be approximately known.

### Line (L)

The line is a two-port standard and in coaxial systems is implemented as an air line. The critical quantity of the line is its characteristic impedance, which is matched as precisely as possible to the reference impedance using a proven mechanical design as in Equation 1. The electrical length of the line must be different than the length of the through being used. The difference in length between the through and the line must not be equal to an integral multiple of half the wavelength because the calibration techniques would produce a singularity. The frequency range for calibration using the line standard is restricted by the fact that the phase difference between transmission coefficients of the through and line must be sufficiently different form 0 deg. and 180 deg. That is, it must be between 20 deg. and 160 deg. or the ratio of the stop and start frequencies may have a maximum ratio of 8:1.

To extend this frequency range, two lines with different lengths can be measured. The lower frequency dictated by the longer of the two lines can be extended down to 0 Hz by measuring the fixed match. Since air lines do not have supports, the standard should be held vertically. This is especially true for longer air lines because the suspended weight would displace the inner conductor from its central position.

### Symmetrical Network (N)

This is a two-port standard that has symmetrical reflection coefficients $S_{11}$ and $S_{22}$ for its two ports. They may have any value but $S_{11} = S_{22} = 0$. It is necessary to know if the reflection coefficients are more like an open or like a short. The transmission coefficient $S_{21}$, $S_{12}$ of the standard is irrelevant and can have any value, even 0 and 1.

### Attenuator Standard (A)

This two-port standard must be well matched on both sides, and unlike the through standard its insertion loss need not be precisely known. The attenuation difference compared to the through should be at least 10 dB and the insertion loss of the attenuator should not be more than 55 dB.

### Unknown Through (U)

Any two-port network whose S-parameters fulfill the reciprocity conditions $S_{21} = S_{12}$ can be used as an unknown through when the UOSM calibration technique is used. The phase shift of the unknown through must be known to some degree. If a two-port device under test fulfills the reciprocity requirement, it too can be used as an unknown through. However, an isolating network or $S_{21} = S_{12} \approx 0$ cannot serve as an unknown through.

## LINEAR ERROR MODELS AND CALIBRATION TECHNIQUES

In the last four decades, a very large number of calibration techniques have been described. Consequently, for purposes of this white paper, four different error models will be used to group and describe the most important ones to allow designers to choose the best ones for specific situations. Table 2 (page 8) lists the calibration techniques described below along with their features and applicability for use in specific situations.

### **OSM** (full one-port calibration)

The OSM technique employs an open, short, and match, and is the most popular for one-port calibration. It uses the three standards connected one after the other to the test port and the relations occurring for wave-quantities a1 to b1 are determined. The behavior of the individual standards is assumed to be known. The corresponding descriptive models are stored in the vector network analyzer. Based on the three derived values, the three unknown quantities (source match, directivity, and reflection tracking) can be calculated.

### TOM

This technique employs fully-characterized standards and together the two, one-port standards open and match produce four equations that are supplemented by four additional equations for the through standard. Connection of incorrect or defective standards as well as faulty electrical connections can be detected immediately after this calibration technique is complete.

**TRM**

In the TRM technique, a reflect standard is used instead of the open. The same reflect standard must be use for all of the test ports.

**TRL**

The TRL technique uses a line with a corresponding characteristic impedance as its reference impedance, replacing the match, and is ideally an air line. It is possible to manufacture an air line with characteristic impedance more precise than that of a fixed match, so the technique delivers higher effective directivity, improving the test port match.

**TNA**

The reflection standard used in the techniques just mentioned is replaced in the TNA technique with a two-port symmetrical network. Instead of the line standard, an attenuator standard is used with very good matching, but having arbitrary attenuation.

**UOSM**

In this technique, a complete one-port calibration is performed with the open, short, and match standards on each of the test ports used in the calibration process. Individual one-port standards can be

| CALIBRATION TECHNIQUE | OSM | TOM | TRM | TRL | TNA | UOSM | TOSM | TOM-X |
|---|---|---|---|---|---|---|---|---|
| Error model (terms) | 5 | 7 | 7 | 7 | 7 | 7 | 12 | 15 |
| Suitable for transmission measurements | | • | • | • | • | • | • | • |
| No band limitation due to singularities | • | • | • | | • | • | • | • |
| Indirect plausibility check | | • | | | | | | |
| Partially unknown standards | | | • | • | • | • | | |
| Consideration of DUT depended cross talk | | | | | | | | • |
| Usage of standards with different gender | | • | •1) | •1) | •1) | • | • | • |
| Suitable for non-insertable DUTs | | | | | | • | | |
| Possible usage of sliding match | • | • | • | | | • | • | |
| Well-suited for on- waver measurements | | | • | • | • | • | | • |
| Effective directivity attained | + | + | + | +++ | + | + | + | + |
| Number of receivers in N-port VNA | N+1 | 2N | 2N | 2N | 2N | 2N | N+1 | 2N |
| Minimum number of calibration standards | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 5 |
| Contacts 2) in two port VNA | 3 | 6 | 6 | 6 | 6 | 8 | 8 | 10 |

1) Assuming the standards produce symmetrical reflections.

2) The number of "contacts" is used to assess the amount of work involved in the calibration procedure. By contact, we mean setting up an electrical connection. For example, mounting a one-port standard requires one contact. Mounting a two-port standard requires two contacts.

*Table 2: Properties of the various error models and calibration techniques*

used for each test port depending on the connector type and gender (and the characteristic data must be considered). An unknown through replaces the though in the TOM technique. Since (for example), a conventional adapter meets the requirements of an unknown through, the UOSM technique is particularly well suited for calibration involving different connector types at the test ports.

### TOSM

To determine the 10 unknown error terms required for the TOSM technique, the open, short, and match one-port standards must be measured on both ports of the analyzer, and the through must be measured as well. It is also possible to determine crosstalk parameters with this technique, which requires a measurement in the forward and reverse directions in which both test ports have a match. This forces $S_{21} = S_{12} = 0$. Measurement of the quantity $b_{H2}/a_{G2}$ or $b_{G2}/a_{H2}$ thus leads directly to the crosstalk parameter $e_x$ and $e_x'$.

### TOM-X

This technique is based on the 15-term error model, from which it can be derived. Its name reflects the standards used in the calibration process. The letter "X" stands for the ability to eliminate crosstalk. Determination of the 15 parameters requires a significantly higher number of calibration measurements than needed when using a seven-term technique. With a two-port network analyzer, a through, two opens, and two matches are required. Contact with the one-port standards is always made in pairs as open-open, open-match, and match-match. All standards must be fully known.

### CALIBRATION OF NON-INSERTABLE DEVICES

Many devices use different connectors on their RF ports, such as a female Type-N connector on Port 1 and a female PC 3.5 connector on Port 2. The test ports of the VNA must be equipped with suitable adapters such as those in Figure 12. To avoid reducing measurement accuracy, the adapters must be introduced into the test setup before the calibration process is performed. This means a suitable calibration kit is required for each of the different types of connectors.

*Figure 12: Calibration standards and adapters for a noninsertable device*

At a minimum, the calibration kit must include the standards required for one-port calibration. The through connection between test ports that use different connector types must be made using adapters. However, unlike through standards the adapters are usually not characterized. Nevertheless, conventional adapters fulfill the requirements for an unknown through, but the VNA must allow use of unknown throughs as calibration standards. A vital prerequisite is that the reference channel be measured separately on each measurement port. In some VNAs, a multistep procedure called adapter removal is performed instead of the procedure just described. It is based on the 12-term error model so that it can also be implemented with vector network analyzers using a common reference channel for all measurement ports.

### A Recipe for Cable and Connector Care

The connection assembly can, if proper care is not taken, significantly degrade calibration effectiveness or even render calibration invalid. Consequently, it is essential that the following steps be taken to minimize the possibility that these adverse consequences will occur.

First, a connector's interfaces should be kept clean and free of dirt. Never use water, acids, or abrasives, but rather a cotton swab moistened with isopropyl alcohol, which will adequately clean the surfaces. The swab should not be saturated with alcohol, and make sure that none of the cotton remains on the connector after cleaning. Pure low-pressure compressed air or nitrogen also works well.

One of the most common causes of connector failure is over tightening the connecting nut. Use a torque wrench designed for this connector type, and tighten only the nut. The connector should not be rotated, which will cause unnecessary stress to the inner and outer contacts of the connectors, leading to excessive wear.

| Influence Action | No influence | Interpolation | Loss of validity |
|---|---|---|---|
| Modification of the test port output level | X1) | | |
| Modification of the IF bandwidth | X1) | | |
| Loosening and retightening of the connections | X2) | | |
| Modification of the trace format | X | | |
| Change in the measured quantity to S, Y, X parameters or µ1, µ2, k coefficients | X | | |
| Modification of the scaling of the axes | X | | |
| Reduction in the frequency range to be displayed or increase in the number of measurement points | | X | |
| Switchover to logarithmic sweep | | X | |
| Exchange or extension of test port cables | | | X |
| Increase in the frequency range to be displayed | | | X |
| Change to wave quantities or wave ratios or usage of frequency conversion capabilities | | | X |
| Switching the step attenuator | X3) | | X3) |

1) Assuming that the network analyzer and DUT show a linear behavior.
2) Depending on the repeatability of the connectors.
3) Switching a receiver step attenuator always results in a loss of validity. In the case of a generator step attenuator, we must distinguish between the implementation with the step attenuator prior or after coupling out the reference channel signal.

*Table 3: Influence of actions on calibration*

## SOME FINAL THOUGHTS

As must be obvious, the calibration process is by no means simple, and measurement accuracy can be compromised in many ways. Table 3 shows activities performed after calibration that will affect the validly or precision of the calibrated system. The following are some general guidelines that should always be followed:

- A calibration kit should be available for every connector type used.
- As mechanical components, calibration standards are subject to wear so their properties should be regularly verified. As an alternative, their condition can be checked when verifying the measurement uncertainty of the calibrated VNA.
- Calibration should be performed regularly according to schedule that is always followed. The frequency of calibration depends on the desired measurement accuracy as well as the temperature stability of the environment in which measurements are performed, along with cable quality.

Finally, a pin depth gage should be used to regularly check the offset of the inner conductor with respect to the reference plane. This is important before new test equipment, cables, and accessories