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Understanding VNA Calibration

Table of Contents

In this guide, the concept of calibration is presented and discussed in detail. Specific topics to be covered include how to configure the VNA for calibration, types of calibration and calibration kits. A minimal amount of calibration mathematics and theory will also be covered.

Calibration Overview

Calibration is critical to making good VNA S-parameter measurements. While the VNA is a highly-linear receiver and has sufficient spectral purity in its sources to make good measurements, there are a number of imperfections that limit measurements done without calibrations. These imperfections include:

1. Match—Because the VNA is such a broadband instrument, the raw match is decent but not excellent. Even a 20-dB match, which is physically very good, can lead to errors of greater than 1 dB. Correcting for this raw match greatly reduces the potential error.

2. Directivity—A key component of a VNA is a directional coupler. This device allows the instrument to separate the signal incident on the DUT from the signal reflected back from the DUT. While the couplers used in the VNA are of very high quality, there is a certain amount of coupled signal, even when a perfect termination is connected. This is related to directivity and can impact measurements of very small reflection coefficients.

3. Frequency Response—While the internal frequency response of the VNA could be calibrated at the factory, any cables connected externally will have some frequency response that must be calibrated out for high-quality measurements.

Calibration Summary

Calibration is a tool for correcting for these imperfections, as well as other defects. There are an enormous number of possible calibration algorithms and many of them are implemented within VNAs. The choice between them is largely determined by the media the engineer is working in, the calibration standards available and the desired accuracy/ effort trade off. While these choices will be discussed in detail later in this chapter, they can be categorized according to two distinctions: calibration type (e.g., which ports are being corrected and to what level they are being corrected) and calibration algorithm (e.g., how the correction is being accomplished). A summary of calibration types is provided in Table 1.

Type	Parameters calibrated	Uses
Full 2-port	S_{11}, S_{12}, S_{21}, and S_{22}	Most complete calibration
Full 1-port	S_{11} or S_{22} or S_{11} and S_{22}	Reflection only
1-path 2-port	S_{11} and S_{21} or S_{22} and S_{12}	1-port reflection plus simple transmission (faster, lower transmission accuracy unless DUT very lossy)
Frequency response	Any one parameter (or pairs of symmetric parameters)	Normalization only. fast, lower accuracy

Table 1 - This table summarizes the various types of calibration available to the VNA user

Calibration Algorithms

Calibration algorithms are a forest of acronyms. In literature these acronyms are often times inconsistent. To add further confusion, the letters may represent different things at different times. Table 3-2 shows the acronyms used in Anritsu documentation and is intended to provide a representation of the most common usage of algorithm acronyms.

Calibration Algorithm	Description	Advantages	Disadvantages
SOLT (short-open-load-thru)	Common coaxially	Simple, redundant standards; not band limited	Requires very well-defined standards, poor on-wafer, lower accuracy at high frequency
SSLT (short-short-load-thru), shorts with different offset lengths	Common in waveguide	Same as SOLT	Same as SOLT and band-limited
SSST (Short-short-short-thru), all shorts with different offset lengths	Common in waveguide or high frequency coax	Same as SOLT but better accuracy at high frequency	Requires very well-defined standards, poor on-wafer, band-limited
SOLR/SSLR/SSSR, like above but with 'reciprocal' instead of 'thru'	Like the above but when a good thru is not available	Does not require well-defined thru	Some accuracy degradation, but slightly less definition, other disadvantages of parent calibration
LRL (Line-reflect-line), also called TRL	High performance coax, waveguideor on-wafer	Highest accuracy, minimal standard definition	Requires very good transmission lines, less redundancy so more care is required, band-limited
ALRM* (advanced line-reflect-match), also called TRM	Relatively high performance	High accuracy, only one line length so easier to fixture/on-wafer, not band-limited usually	Requires load definition. Reflect standard setup may require care depending on load model used

Table 2 - This table summarizes the different calibration algorithms available to the VNA user.

**ALRM is an Anritsu enhancement to standard LRM that includes advanced load-modeling techniques and structures. In its basal form of a default-load model, it is conventional LRM. The terms LRM and ALRM are used somewhat interchangeably, except in cases where the load modeling context is important.*

Configuring The VNA

Before discussing calibration further, and some of the alternatives available, it is important to first gain a clear understanding of any VNA setup issues as they will affect calibration performance. In almost all cases, the VNA settings are used during calibration. Therefore, setting up the VNA as desired beforehand can be especially helpful. The settings of interest are:

1. **Frequency Start, Stop and Number of Points** - These settings are obvious. Segmented sweep must also be setup in advance if a more custom frequency list is desired.

2. **IF Bandwidth and Averaging** - These parameters control the digital filtering and post¬processing that determine the effective noise floor, amount of trace noise and, in some special cases, immunity to interfering signals. The trade off for improved noise performance is slower sweep speed.

   Figure 3-1 provides an example of two IF-bandwidth settings. Settings of 1 Hz to 1 MHz are allowed with the root-mean-square (RMS) trace noise ranging from less than 1 mdB at the low end, to a few hundred mdB at the high end for high level signals. The values will be larger for lower level signals. Sweep time is roughly proportional with the reciprocal of IF bandwidth (IFBW) once below 100-kHz IFBW.

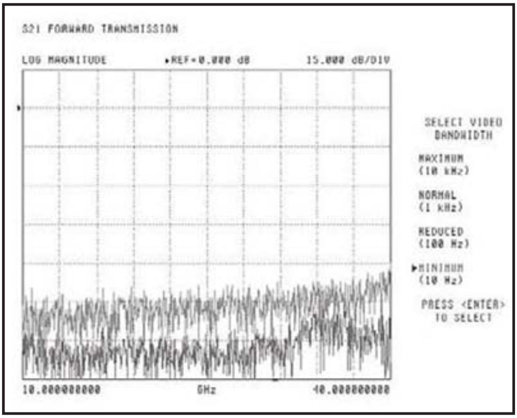


Figure 1. Shown here is the noise floor from a 1 kHz and 10 Hz IF bandwidth setting.

3. **Point-by-Point versus Sweep-by-Sweep Averaging** - Point-by-point averaging incurs additional measurements at each given frequency point and increases sweep time roughly proportionally. Because the additional measurements are taken at once, the effect is similar to the proportional change in IFBW. An additional benefit is that the displayed data is fully optimized during the first sweep.

   Sweep-by-sweep averaging acquires additional measurements on subsequent sweeps. The result is a gradual shift in trace amplitude. Before extracting data, the VNA user must verify that a fully corrected sweep has occurred. Sweep-by-sweep averaging is a rolling average, so the time it takes to fully stabilize from a sudden DUT change is roughly proportional to the average count. Consequently, it offers an alternate way to improve lower-frequency variations.

4. **Power** - Port power in the MS4640A VectorStar VNA is somewhat less critical due to the excellent linearity of the receivers, but any step-attenuator settings must be selected before calibration. Changing the step-attenuator settings alters the RF match in the measurement paths as well as in the insertion loss thus. Therefore, changing them will invalidate the calibration.

An important aspect of test-set power level is the consideration of dynamic range. Setting the port power to the maximum level before receiver compression provides the widest possible signal-to-noise floor ratio and thus dynamic range. Be sure to perform this setting before beginning calibration.

Types of Calibrations

There are several types of calibrations, defined by what ports are involved and what level of correction is accomplished. These calibration types include:

- **Full 2-Port** - This is the most commonly used and most complete calibration involving two ports. All four S-parameters (S_{11}, S_{12}, S_{21}, and S_{22}) are fully corrected.
- **Full 1-Port** - In this case, a single reflection parameter is fully corrected (either S_{11} or S_{22}). Both ports can be covered but only reflection measurements will be corrected. This calibration type is useful for reflection-only measurements, including the possibility of doing two reflection-only measurements at the same time.
- **1-Path 2-Port (forward or reverse)** - In this case, reflection measurements on one port are corrected and one transmission path is partially corrected, but load match is not. Here forward means that S_{11} and S_{21} are covered, while reverse means that S_{12} and S_{22} are covered. This technique may be used when speed is at a premium, only 2 S-parameters are needed and either the accuracy requirements on the transmission parameter are low or the DUT is very lossy (approximately greater than 10 to 20 dB insertion loss).
- **Frequency Response (reflection response and transmission-frequency response)** - This calibration is essentially a normalization and partially corrects one parameter, although two can be covered within the calibration menus. Only the frequency response, or tracking slope, of the parameter is corrected. Directivity and match behaviors are not taken into account. This technique is valuable when accuracy requirements are not at a premium and all that is needed is a quick measurement.

Each of these calibrations has an associated error model that describes what is being corrected. These error models are briefly covered in this chapter. For more detailed information, refer to Anritsu's available application notes on the subject matter.

The error coefficients used in the error models fall into several categories that roughly describe the physical effect that the coefficients are responsible for correcting. To establish a context for these error terms, consider a typical model in which all of the VNA/setup errors are lumped into error boxes that act like S-parameters, between a perfect VNA and the DUT reference planes (Figure 2). Two slightly different error models are used: one where each port is considered to be driving separately and one where both ports are present and no driving distinction is made. In the first error model, one can clearly delineate the source match from the load match. The second model requires some preprocessing to take care of source match-load match differences.

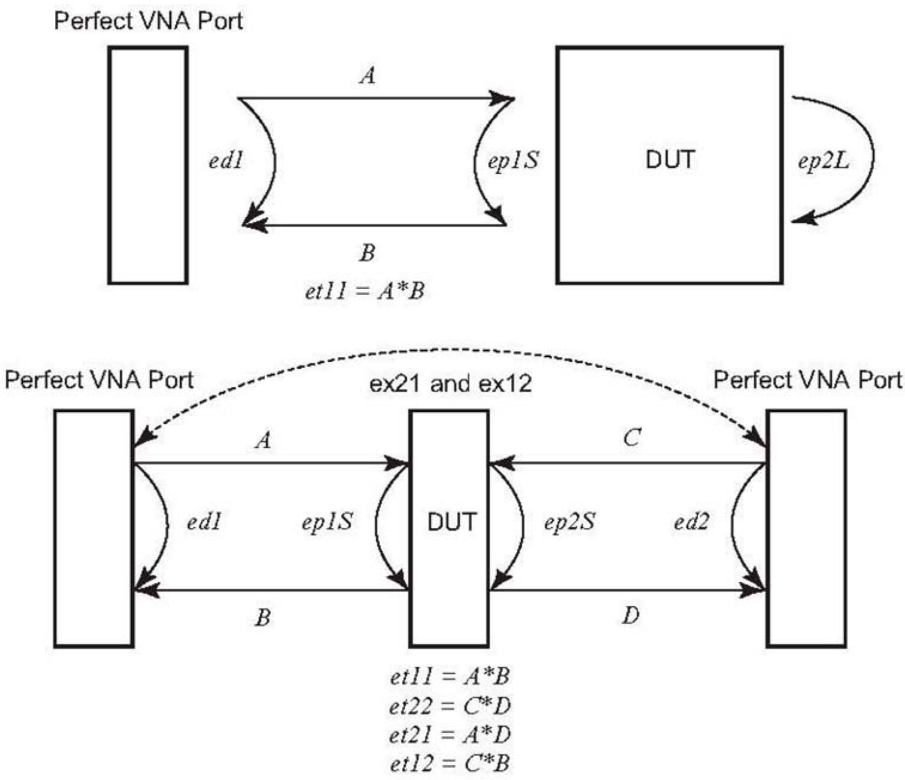


Figure 2 - Classical 1-port and 2-port error models are shown here1.

Using Figure 2 as a reference, the error terms can be defined as follows:

1. **Directivity (ed1 and ed2)** - Describes the finite directivity of the bridges or directional couplers in the system. Partially includes some internal mismatch mechanisms that contribute to effective directivity.

2. **Source Match (ep1S and ep2S)** - Describes the return loss of a driving port.

3. **Load Match (ep1L and ep2L)** - Describes the return loss of a terminating port. In the 8-term error models used as a basis for the LRL/ALRM and other calibration families, load match is treated the same as source match, but the incoming data is pre-corrected to take into account the measured difference in match between driving and terminating states.

4. **Reflection Tracking (et11 and et22)** - Describes the frequency response of a reflect measurement, including loss behaviors due to the couplers, transmission lines, converters, and other components.

5. **Transmission Tracking (et12 and et21)** - Same as above, but for the transmission paths. The tracking terms are not entirely independent and this fact is used in some of the calibration algorithms.

6. **Isolation (ex12 and ex21)** - This term takes into account certain types of internal (e.g., non-DUT dependent) leakages that may be present in hardware. It is largely present for legacy reasons and is rarely used in practice since this type of leakage is typically very small in modern VNAs. These terms are handled somewhat differently from the others and will be covered later in this guide.

Line Types

Part of the calibration definition is the selection of line type or transmission media. The main purpose of this selection process is to assign a dispersion characteristic. Dispersion is the dependence of the phase velocity on the line with frequency. Media such as coax and coplanar waveguides are largely dispersion-free; that is, phase velocity can be defined by a single number:

$$\nu_{ph} = \frac{c}{\sqrt{\varepsilon_r}}$$ phase velocity for coaxial an non-dispersive media

Here c is the speed of light in a vacuum (~2.9978 10^8 m/s) and ε_r is the relative permittivity of the medium involved. Coax has its own selection since it is intrinsic to the instrument, while other non-dispersive media can be selected separately.

One type of dispersive media is the regular waveguide. The phase velocity here is defined by:

$$v_{ph} = \frac{c}{\sqrt{\varepsilon_r}\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} = \frac{c}{\sqrt{\varepsilon_r - \left(\frac{f_{c0}}{f}\right)^2}}$$

phase velocity for waveguide

Here ε_r is the dielectric constant, f_c is the cutoff frequency of the waveguide (with dielectric) and f_{c0} is the cutoff frequency of the waveguide in a vacuum (which is what is entered). The system computes the required values and this information is used for computing distances when in time domain and when adjusting reference planes.

Microstrip lines are another example of dispersive media that can be selected. Here the dimensions of the line, together with the dielectric material, determine the phase-velocity behavior. An intermediate quantity, called the effective dielectric constant ($\varepsilon_{r,eff}$), is used and a suggested value computed by the VNA, but this value can be overridden. At low frequencies, the structure can be considered non-dispersive (like coax) with a phase velocity given by:

$$v_{ph} = \frac{c}{\sqrt{\varepsilon_{r,\,eff}}}$$

low frequency limit

At higher frequencies, when additional mode behavior becomes important, dispersion must be handled. The dielectric constants (media-based and effective), together with a transition frequency f_t, are used to compute this effect which is heavily dependent on the dielectric thickness.

$$\nu_{ph} = \frac{c}{\sqrt{\dfrac{\varepsilon_{r,eff} + \varepsilon_r \bullet \left(\dfrac{f}{f_t}\right)^2}{1 + \left(\dfrac{f}{f_t}\right)^2}}}$$

Where

$$f_t = \frac{Z_c \varepsilon_0 \sqrt{\varepsilon_r c^2}}{2t\sqrt{\varepsilon_{r,eff}}}$$

Here Zc is the characteristic impedance of the microstrip line and t is the dielectric thickness

Calibration Kits

Anritsu and other vendors provide calibration kits for a variety of algorithms and circumstances. In all cases, certain information must be provided to the VNA in order to complete the calibration. The nature of that information varies by kit and application. As an example, consider the following coaxial calibration kits available from Anritsu.

- **SOLT Kits**

These kits are all based on SOLT and require that data describing all of the reflection standards (provided by the factory) be loaded into the VNA on a serial number basis. If this media (e.g., USB key or floppy disk) is not available, average default coefficients are available within the VNA and may suffice for some measurements.

Typically these calibration kits are loaded using the Cal Kit/AutoCal utility menu, but user-defined kits can also be created using the parameters described above. If calibration kits from another manufacturer are used, or if the engineer wants to create a calibration kit, the parameters are typically entered into one of the user-defined kits.

Items required as part of the definition are:

- Open definition (M and F, typically)

- Short definition (M and F, typically)
- Load definition (M and F, typically)

• Kits With Triple-Offset Shorts

Some kits employ multiple algorithms to cover larger frequency ranges. The Anritsu 36_6 110 GHz Calibration Kit uses a triple-offset short scheme for frequencies up to 110 GHz, where it is more difficult to characterize opens and loads. At lower frequencies, an SOLT calibration is used in a banded approach, since the SSST is fundamentally band-limited. Often a merge calibration method is used to combine the triple-offset short and SOLT calibrations. Some additional standards definitions are therefore required, but the general procedure is the same as for an SOLT kit. User-defined kits can be generated for custom kits or for those from another manufacturer.

Items required as part of the definition are:

- Open definition (for low frequency, M and F)
- Load definition (for low frequency, M and F)
- Short 1 definition (M and F)
- Short 2 definition (M and F)
- Short 3 definition (M and F)

• LRL Kits

These airline-based kits use the LRL algorithm so much less definition of components is required. Reflects may be part of the kit, but the only piece of information necessary is an offset length which is used to help with root selection and is hence somewhat non-critical. Line lengths are the other parameters and are mainly used for reference plane placement. All of these parameters must be entered manually since there are a large number of lines in the kit and usually only 2 or 3 will be used per calibration. Details on line selection and the trade offs involved are discussed in the LRL/LRM section later in this chapter.

Items required as part of the definition are:

- Line lengths (at least 2)
- Reflect offset length
- Offset-Short Waveguide Kits

Waveguide calibration kits based on offset-short calibrations are also provided for different waveguide bands. Here two different offset-length shorts (sometimes accomplished with flush shorts and two different insert lengths), loads and a thru must be specified. Some of the standard kits are pre-defined and user-defined kits are possible as usual. Additional pieces of information needed here due to line type are the cutoff frequency and dielectric constant.

Items required as part of the definition are:

- Load definition
- Short 1 definition
- Short 2 definition
- Waveguide cutoff frequency

• Microstrip and Coplanar Waveguide Kits for the Universal Test Fixture

For certain microstrip and coplanar waveguide measurements, the Universal Test Fixture (Anritsu model 3680 Series) can be used as it accommodates a range of substrate sizes and thicknesses. The supplied calibration kits provide opens, shorts, loads, and a variety of transmission-line lengths on alumina that can be used for different calibration algorithms. User-defined kits must be generated based on the information provided with the kits.

• On-Wafer Calibration Kits

A variety of calibration-standard substrates or impedance-standard substrates are available from other vendors that contain opens, shorts, loads, and transmission lines for on-wafer calibrations. A variety of calibration algorithms may be used depending on the application. For the defined-standards calibrations, a user-defined kit will have to be generated.

Automatic Calibration (AutoCal)

In contrast to the mechanical standards approach to calibration, automatic calibration modules can be used to simplify the calibration method. Automatic calibration techniques, such as those performed by the AutoCal modules available from Anritsu, are often the preferred method for calibrating VNAs. AutoCal provides VNA users with the ability to quickly calibrate the network analyzer with the simple push of a button. The AutoCal module incorporates extremely accurate, repeatable solid-state switches to select a variety of impedance standards from just one connection between the VNA and a calibrator module.

Precision AutoCal Calibration Module

Calibrations employing AutoCal modules are consistent, repeatable and provide better accuracy than traditional broadband-termination, 12-term calibrations. In addition, automatic calibrations are much faster than with traditional calibration kits. For example, a 401-point, 12-term AutoCal takes typically 30 seconds when using the VectorStar VNA, as compared to the 10 to 1_ minutes it takes with a traditional calibration kit. In addition, calibrating with the Precision AutoCal module requires only two connections, while a mechanical calibration kit requires 7 to 9 connections for a typical calibration. Note that test-port characteristic specifications require a sliding load-termination calibration, thereby further escalating the complexity of the calibration. Sliding-load terminations require a high level of expertise and care due to their mechanical complexity. If broadband terminations are used, the resultant directivity and port-match performance will suffer.

A further benefit of the Precision AutoCal process stems from the flexibility of the Precision AutoCal characterization process which allows users to measure:

- Non-insertable devices.
- Devices with different connector types on each port.
- Devices with waveguide or coaxial connectors, as well as several other combinations.

The automatic calibrator module also saves wear and tear on traditional calibration components and eliminates operator mistakes, such as incorrect use of calibration coefficients. In addition, it still maintains the accuracy required for critical measurements.

The basic concept in Precision AutoCal is the transfer of known calibration parameters from a traceable VNA to measure the calibration standards within the Precision AutoCal module—a process referred to as Precision AutoCal characterization. A calibrated VNA (using a traceable calibration kit) measures the S-parameter data of each impedance standard throughout the calibrator module's frequency range. The accuracy of the calibrated VNA is thereby transferred to the Precision AutoCal module. The stability and repeatability of the Precision AutoCal impedance standards provides excellent automatic calibrations over a defined time frame. This method of impedance transfer typically results in limited sacrifice of accuracy for simplicity, speed and convenience. But, by combining the Precision AutoCal calibrator with the MS4640A VectorStar VNA, the resulting overall measurement accuracy is better than a mechanical standards calibration, including sliding-load terminations. This accomplishment is reached through the use of ultra-precision LRL/LRM calibration and over-determined algorithms.

The following discussion includes both types of AutoCal modules. In the areas that are unique to the newer AutoCal technology, the term Precision AutoCal will be used.

The AutoCal calibration process represents both a calibration device and an algorithm that can be used to speed up the calibration process with extremely high accuracy and a minimal number of manual connections. Anritsu offers two types of AutoCal modules; the 36_8_X Series Precision AutoCal and the 36_81X Series Standard AutoCal. Both AutoCal series calibrate the VNA by a process known as 'transfer calibration.' There are a number of impedance and transmission states in the module designed to be extremely stable in time and these states are carefully 'characterized,' generally by the Anritsu factory. In certain cases, this characterization can also take place in a customer laboratory. When the same states are re-measured during an actual calibration and the results compared to the characterization data, an accurate picture is generated of the behaviors and error terms of the VNA and setup being calibrated.

Very high calibration accuracy is maintained through the use of certain principles:

- The use of many impedance and transmission states covering as wide a range as possible across the Smith chart.
- The creation of very stable states that are further enhanced with a constant-temperature thermal platform inside the module.
- The use of very reliable and repeatable solid-state switching constructed to provide a great variety of state impedances for better calibration stability.

The resulting accuracy can exceed the performance obtained using a common SOLT mechanical calibration with sliding loads—a process generally performed in a laboratory.

Physical Setup

A RF cable arrangement is shown in Figure 3-3. Here, AutoCal is directly connected to VNA port 1. The cable from AutoCal is connected to VNA port 2. This arrangement can be changed depending on measurement requirements. Different types of cables on both VNA ports may be used. For optimal results, the shortest cable lengths that do not require excessive bending when performing calibration or measurement should be used. Using the most phase- and amplitude-stable cables that are practical will also improve results.

Other AutoCal Topics

Some of the other topics pertaining to AutoCal which may be helpful include:

Thru Type - The term 'internal thru' is used to describe the main transmission state of the AutoCal unit. It is not zero-loss, nor is it perfectly matched, but its characteristics are well-known and, in some sense, de-embedded. This standard AutoCal procedure can yield transmission-tracking values on the scale of .0_ dB. For measurements requiring resolution below that, a true thru option is available where a literal (external) thru connection is made between the port cables in lieu of using the AutoCal thru state. The loss and length of this line must be known for accurate processing. If the external thru is not well-known or is poorly matched (RL< 20 to 2_ dB), the internal thru will produce better results.

AutoCal Assurance - Assurance is a step automatically employed as a means of checking the quality of an AutoCal. Some impedance/transmission states are available within the module that are not central to the calibration, but have been characterized for assurance purposes. The calibration measures these states and the results are compared to existing characterization data. A tolerance band is established, based on the known measurement uncertainties, so that a determination can be made as to whether any deviations are reasonable. A simple pass/fail indication is given after every AutoCal calibration.

Figure 3. A typical AutoCal setup is shown here.

Test-Port Converters - These parts are precision adapters and can sometimes be used to perform an AutoCal calibration with incompatible connector types. They are available in K and GPC-3._ versions. Because the adapters are of precisely the same electrical length, they can be swapped between calibration and measurement steps with minimal degradation to the calibration. As an example, suppose the engineer had a MF

K AutoCal unit, but wanted to have reference planes established at a MM interface. To accomplish this, the engineer could place a FF test-port converter on one of the MM test-port cable connectors, making a MF interface available for the AutoCal. After calibration, the FF converter could then be removed and a MF converter installed so that the MM planes would be established. The typical uncertainty penalty is less than 0.1 dB to 40 GHz, although the residual directivity may be degraded to about 30 dB. If this is unacceptable, consider the adapter removal or related techniques to be discussed later in this chapter.

Characterization

Typically, characterization of auto-calibrators is performed at the factory since the process can be very carefully controlled to achieve maximum accuracy. In certain cases, the customer may wish to perform the characterization themselves. In this case, the customer takes full responsibility for performing an adequate quality characterization.

If re-characterizing the AutoCal module is a necessity, there are procedures available to ensure the characterization process is as accurate as possible. The process involves performance of a calibration check after the VNA is calibrated and requires the use of Anritsu airlines and 20-dB return loss terminations and shorts. Using the components provides a method for measuring the resultant test-port characteristics after a calibration.

After measurement of the actual performance of the corrected VNA, the transfer of accuracy to the AutoCal module is precisely known and therefore can be considered a traceable path. The path is traceable because of the National Institute of Standards and Technology (NIST)-traceable mechanical standards that were used to verify the impedance accuracy of the reference airlines. Thus, re-characterization of the module can be performed without the accuracy of a LRL calibration kit (as performed at the Anritsu factory), and still provide a high level of confidence in the characterization procedure.

Non-Insertable Measurements

Many VNA users have devices which are non-insertable and/or have alternative connector types to the standard K or V connectors used on each AutoCal module. The characterization software built into Anritsu's VNAs allows users to characterize the AutoCal modules with adapters installed specific to their calibration needs. As is the case with a standard characterization, the user must first calibrate the VNA prior to performing the characterization. In this situation, the specific connector type should be calibrated using a traditional calibration kit. In the event of a non-insertable calibration, all Anritsu VNA's offer (as standard) the Adapter Removal calibration feature which utilizes two calibrations to remove the effects of the adapter.

SOLT

One of the more common calibration algorithms is based on SOLT.[1] This is a defined-standards calibration, meaning that each component behavior is specified in advance using data or models. Since the behaviors of all standards are known, measuring them with the VNA provides the opportunity to define all of the error terms. The load behavior largely sets the directivity terms. Together, the short and open largely determine source match and reflection tracking. The thru largely determines transmission tracking and load match.

Shorts - Defined by an S-parameter file or a model consisting of a transmission line length and a frequency-dependent inductance. The inductance is defined as

$$L = L_0 + L_1 \bullet f + L_2 \bullet f^2 + L_3 \bullet f^3$$

Opens - Defined by an S-parameter file or a model consisting of a transmission line length and a frequency-dependent capacitance. The capacitance is defined as

$$C = C_0 + C_1 \bullet f + C_2 \bullet f^2 + C_3 \bullet f^3$$

Loads - Defined by an S-parameter file or a model consisting of a transmission line length, a shunt capacitance, a resistance, and a series inductance, as shown in Figure 4.

Note that a sliding load can be used in lieu of a fixed load. The sliding load is based on a sliding termination embedded in an airline. The transmission line properties of that airline are used to deduce a more nearly perfect synthetic load. Because of the transmission line dependence, a fixed load is also needed at low frequencies (below 4 GHz for V connectors (shorter sliding load), and below 2 GHz otherwise).

Thru - Modeled as a transmission line length with some frequency dependent loss. A root-f frequency dependence of that loss is assumed. If 0 is entered for f_0 (the reference frequency), the loss is assumed to be constant with frequency.

$$\text{Loss}(f) = \text{Loss}(f_0)\sqrt{\frac{f}{f_0}}$$

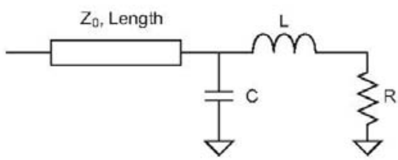


Figure 4 - A graphic representation of the load model

Calibration Model Accuracy

A common question asked is how the coefficients in the above models are determined. In some custom structures (e.g., fixtured), the VNA user could perform electromagnetic modeling of the structures and then use simulation tools to determine the best fit circuit models. For coaxial components, however, the structures are usually sufficiently complex that this process is too difficult. Instead the measurement of an airline, the key to most impedance traceability, is often used to determine the models. A calibration is generated using the components in question and then the models are iterated in a nonlinear least squares fashion. This produces the calibrated result for the airline most closely matching the expected behavior, based on the tight dimensional control of the airline. By using different terminations on the airline, the effects of the various models can be separated, making the problem more soluble. A low-reflectance termination causes the load model to dominate the calibration, while a high-reflectance termination causes the short and open models to dominate. At low frequencies, when an airline may become unfeasibly large to be electrically long, precision-lumped components are used instead. These components can be characterized by other traceable paths including DC and other low-frequency measurements.

For 1-port calibrations, only one of the port definitions (unless reflection-only calibrations are being performed for both ports 1 and 2) will be present. The through line section will not be present. For a 1-path, 2-port calibration, one of the port definition sections will not be present.

For waveguide and microstrip, a few things change:

- Fewer calibration kits are factory-defined and more are user-defined.
- The media must be part of the definition (e.g., cutoff frequency and dielectric constant for waveguide; line width, substrate height, and substrate dielectric constant for microstrip).
- SOLT is not recommended for waveguide due to the difficulty in modeling open standards.

The standards information dialog for SOLT (and SOLR) is shown in Figure 5 using a V-connector as an example.

The standards information for microstrip does not change, but the microstrip media information must be provided either in a user-defined fashion or from selecting the appropriate microstrip calibration kit (Figure 6).

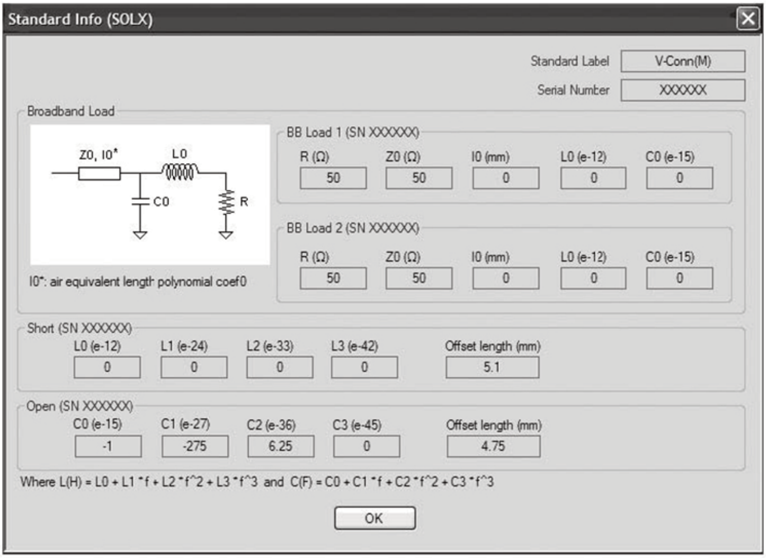


Figure 5 - The standards info dialog box for SOLT (and SOLR) is shown here

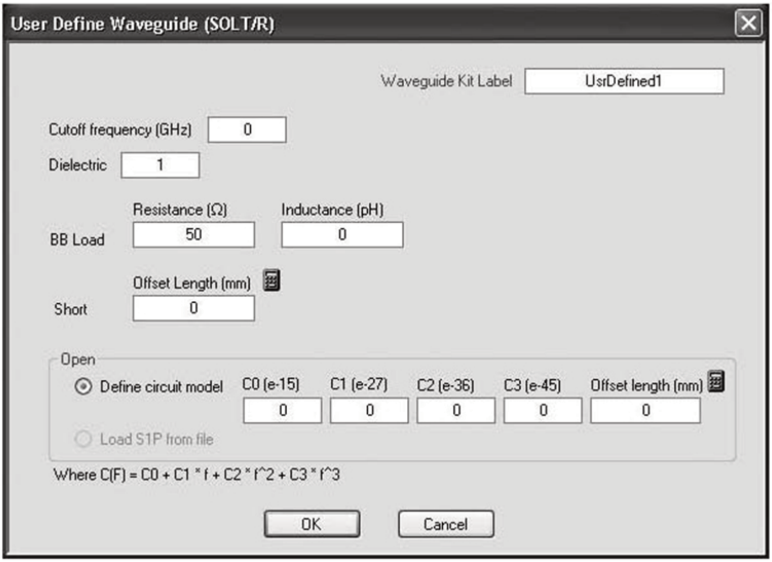


Figure 6 - The waveguide SOLT/SOLR media and standards info dialog is shown here

Offset Short

The prime difference between SSLT and SOLT is that differing offset lengths between two shorts are used to help define reflection behavior instead of an open and short.[2] The frequency range is limited since at DC and higher frequencies, these reflect standards look the same. This method is most commonly used for waveguide problems and in certain coax and board- or wafer-level situations where creating a stable, high-reflection open standard is difficult. The modeling constructs for SSLT are about the same as for SOLT. From an error-term perspective, the only difference is that the two shorts together now largely determine source match and reflection tracking behavior.

Generally, the electrical length difference between the shorts should be between 20 and 160 degrees, over the frequency range of interest. Mathematically, this is stated as:

$$20 < \frac{720 \cdot f \cdot | L_{offset\_short1} - L_{offset\_short2} |}{\nu_{ph}} < 160$$

The top calibration-kit definition dialog for SSLT is identical to the one for SOLT. The standards information dialog is somewhat different and is shown in Figure 7.

Triple Offset Short

The next step in this progression is to remove the load so that the entire reflection space is defined by three shorts of varying offset lengths. The individual short definitions are the same as for SOLT. Together, the three shorts determine all of the reflectometer error terms (directivity, source match and reflection tracking). This calibration is even somewhat more band-limited than the double-offset short method.

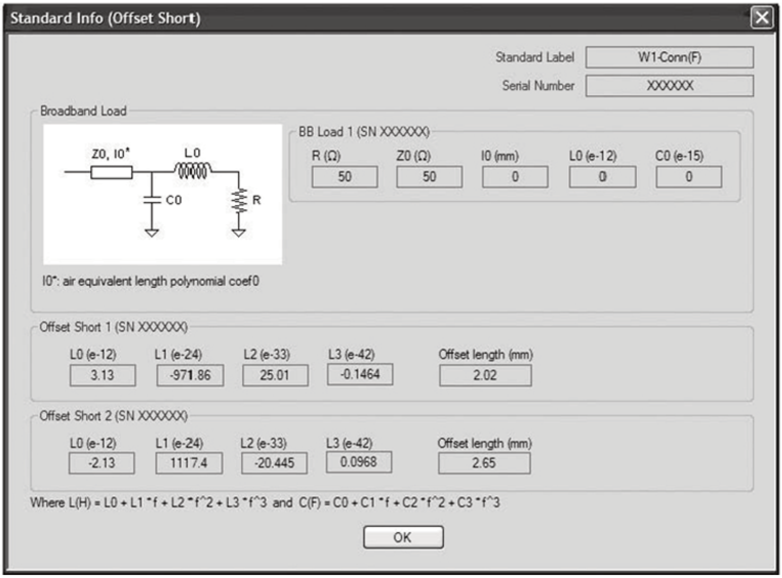


Figure 7 - The standards info dialog box for offset calibrations is shown here

If short 1 is defined as having the smallest offset length and short 3 has the longest offset length, then two variables can be defined as follows:

$$A = L_{offset\_short2} - L_{offset\_short1}$$

$$B = L_{offset\_short3} - L_{offset\_short2}$$

As a general rule of thumb, the electrical-length equivalents of A and B should be between 20 and 8_ degrees over the frequency range of interest. This is not sufficient though as A+B (which represents the difference between short 1 and short 3) must also be constrained according to:

$$20 < \frac{720 \cdot f \cdot A}{\nu_{ph}} < 90$$

$$20 < \frac{720 \cdot f \cdot B}{\nu_{ph}} < 90$$

$$20 < \frac{720 \cdot f \cdot (A+B)}{\nu_{ph}} < 160$$

Since the only standards needed are shorts, this method is attractive for millimeter wave (mm-wave) applications, as well as for certain board and wafer-level calibrations where other types of standards are difficult to manufacture. It should be noted, however, that the impact of inaccuracies in the short offset lengths are more elevated in this calibration since they are used to map the entire reflection space. A good residual directivity (which results from the ability to map the center of the Smith chart accurately) requires very accurate offset-length knowledge. Also, note that the qualities of the connections are critical. With the inclusion of additional short standards, connection quality becomes an even larger issue.

SOLR (Unknown Thru Approach)

The three previous calibration techniques all require a known 'thru' as part of the full 2¬port or 1-path 2-port calibration. The 'thru' is a defined transmission line having known length, known loss and an assumed perfect match (under most conditions). There are certain cases when this is not possible (Figure 3-8). Some examples include:

- Coaxial calibration, when the two ports are different connector types.
- On-wafer, when the 'thru' is a meandering transmission line of imperfect match.
- A calibration that must take place through a test set (e.g., coax or waveguide) with unknown, and highly frequency-dependent, loss and match.

For these cases, and others when the 'thru' is not well-known, there is the reciprocal option, also known as the unknown thru.[3] In this case, the same reflect standards are used, but no assumption is made about the 'thru' except that it is reciprocal (e.g., S_{21}=S_{12}; no assumption made about S_{11} and S_{22}). In practice, there are some limits to this that will be addressed later in the chapter.

The SOLR technique borrows from the LRL family and uses some of the redundancy available with the fully-defined families to reduce the amount of knowledge needed about something; in this case, the thru. The resulting calibration is generally not quite as accurate as the regular thru version, assuming the thru met the conditions described above. Although it is better than using the regular thru version when the thru has unknown loss or match.

A line length estimate (e.g., electrical delay or free-space equivalent length) is needed to help with root choice, but this is not a critical parameter. Typically, the VNA user need only be within a half-wavelength of the correct length at the maximum desired calibration frequency.

If the match of the reciprocal network gets worse than about –8 dB, or the loss exceeds ~20 dB, even the reciprocal treatment will start to degrade slightly, but a calibration will still be possible. Since such a network is at the limits of de-embedding capability, there are few choices except to consider 1-path 2-port processing with scalar de-embedding.

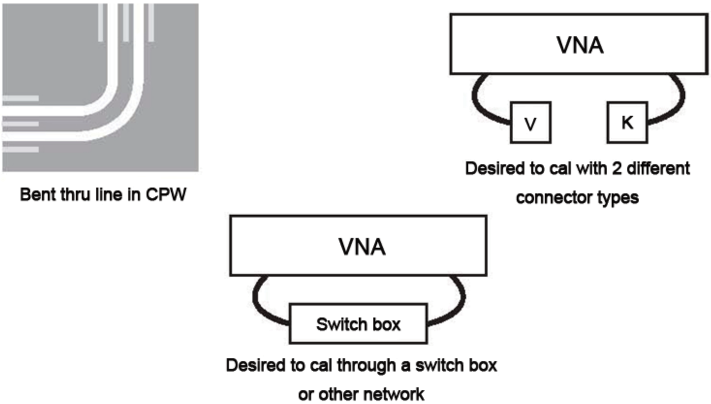


Figure 8: This graphic depicts some examples of situations when the SOLR or 'unknown thru' calibration may be useful

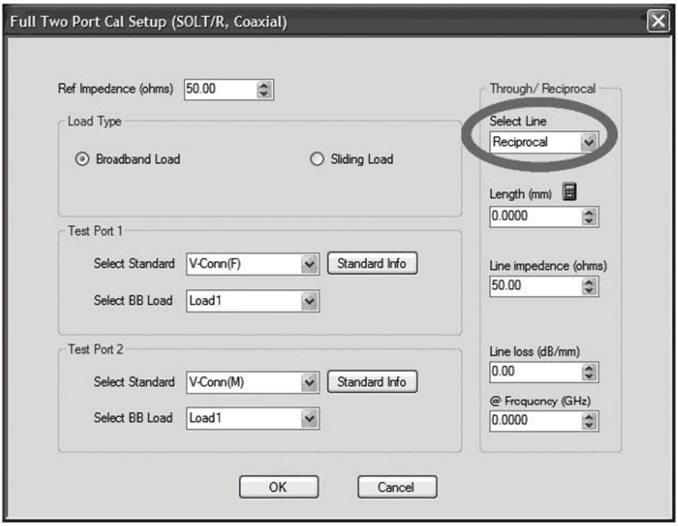


Figure 9: The use of the setup dialog for SOLR is shown here. Note that the same variants are possible fo offset short and triple-offset short calibrations

For SOLR, the ‘select line’ field is chosen as ‘reciprocal’ instead of ‘through.’ The length field is the estimate of length for root choice that was previously discussed (Figure 9).

LRL/LRM/ALRM

The LRL/LRM/ALRM family of calibrations is somewhat different from the previous families. It relies more on the intrinsic behavior of certain components, primarily transmission lines, than it does on characterized/modeled behaviors of components.[4] [_] It also makes less use of redundancy so fewer measurements are needed to complete a calibration. In return though, it is somewhat less tolerant of poor or non-repeatable measurements. Included in this calibration family is:

- **ALRM** - An extension of the LRM algorithm that provides improved performance for on-wafer applications where load symmetry is not ideal. The examples shown apply to the MS4640A series of VectorStar VNAs.
- **LRL** - Uses two or more transmission lines and a reflect standard for each port. The line lengths are important since the lines are required to look electrically distinct at all times. LRL will not work at DC or at a frequency where the difference in length is an integral number of half wavelengths. The reflect standard is not that important as it is only assumed to be symmetric and with not too high of a return loss. Practically speaking, even a 20-dB return loss will usually work. The lines are assumed perfect (e.g., no mismatch) which usually means airlines for coaxial calibrations, although other structures can be used. On-wafer transmission lines are usually very good and therefore, this calibration approach will work well if the required probe movement can be effectively handled.
- **LRM/ALRM** - Here one of the lines above is replaced with a match or load. The load is modeled/characterized (or assumed perfect), so in some sense this calibration drifts back to the concept of the defined standards. Since only one line is involved, it can work down to DC and up to very high frequencies (practically limited by the match knowledge/characterization). Some variations allow one of the match measurements to be traded for a pair of additional reflect measurements, although a second reflect standard is needed. In this case, the requirement that the reflect standards be distinct may force the calibration to become band limited.

In the limiting case of a match that is assumed perfect, or at least assumed symmetric, this calibration reduces to the classical LRM. The added flexibility in the ALRM case is in the ability to define asymmetric load models and to use multiple reflect standards as discussed above. Other extensions are possible elsewhere.[6][7][8] The double-reflect methodology allows the user to feed into a load modeling utility where the load model can be further optimized.

Some parameters to keep in mind include:

Line Lengths - In addition to the LRL frequency limits, the line length is used in all cases for some reference-plane tasks. The fundamental reference plane of an LRL/ALRM calibration is in the middle of the first line. Sometimes it is desirable to have the reference plane at the ends of this line so that the line length (and loss which can also be entered) can be used to rotate the reference planes to the desired place. The line-length delta is also used for some root-choice tasks, although the accuracy required on this entry is less.

As previously mentioned, the usable frequency range for LRL is set by the line-length delta. The electrical length should be between 0 and 180 degrees for all frequencies of interest, although some margin is usually desired to account for line parasitics, spurious mode launches and other problems. One rule-of-thumb is that the delta should be kept between 10 and 170 degrees or 20 and 160 degrees. Practically speaking, the VNA user can usually be more aggressive on the lower number and will likely want to be less aggressive on the upper number.

$$10 < \frac{360 \cdot f \cdot \Delta L}{v_{ph}} < 160$$

Here ΔL is in meters, V_{ph} is the phase velocity on the line (=2.9978 10^8 m/s=c for air dielectric), and f (expressed in Hz) can be any frequency in the range-of-interest.

If this range is too small for the application, multiple lines and multiple bands can be used. Each band uses a line pair covering some range of interest. Also, LRL can be combined with LRM/ALRM to cover the low frequency end within the calibration system. When two bands are used, a frequency break point must be specified to indicate when to switch from one calibration to the other. A suggestion can be calculated and this will be done based on the line lengths entered.

The setup dialog for LRL/LRM/ALRM is quite flexible, with decisions made based on what standards are selected. Several examples of LRL, ALRM and mixed setups are shown in Figure 10A, Figure 10B, Figure 10C, and Figure 10D.

Reflection Offset Length and Reflection Type - Some information is requested about the reflection, although a full characterization is not needed. The information is used in some root-choice activities and it only must be known if the reflect behaves more like an open or a short, since typically opens and shorts are used as the reflect standard. The offset length is used to dynamically move the reference planes around so the algorithm knows what the reflect looks like at any given frequency.

In the double-reflect ALRM methodology it is important that the reflect standards be distinct. More specifically, they must be distinct when rotated to the reference plane at the center of line 1. Since large offset lengths lead to many more degeneracies, the double-reflect option is generally used when offset lengths are smaller (e.g., in on-wafer or fixtured calibrations).

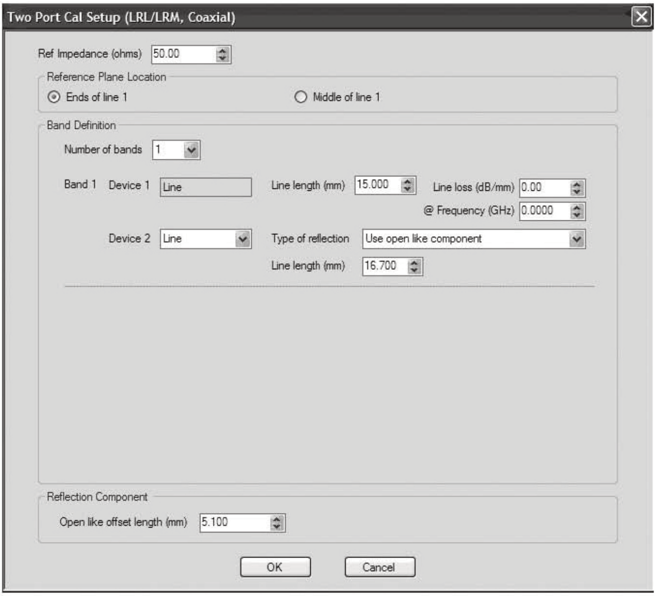


Figure 10A: An example of 1-band LRL

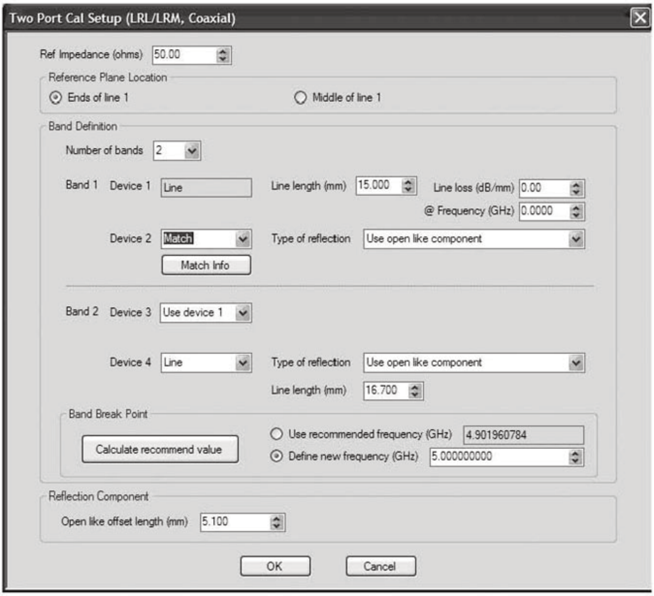


Figure 10B: An example of 2 bands (band 1 LRM/ALRM, band 2 LRL).

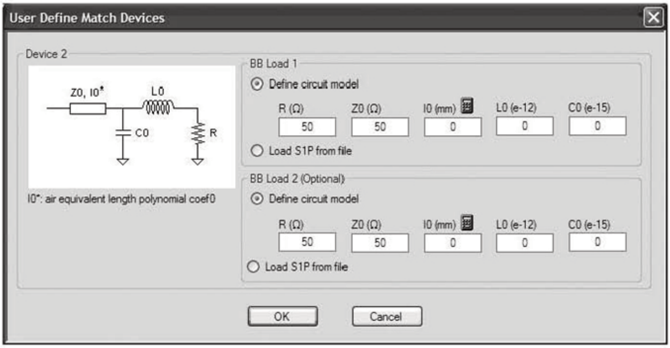


Figure 10C: Defining the load for ALRM (match information)

Load Model/Characterization for ALRM - When a single-reflect approach is taken within ALRM, it behaves like classical LRM. For slightly more advanced use, complete load models can be entered for the two matches independently.

At the highest level, two reflects are measured per port to allow more optimized information to be obtained. When the double-reflect methodology is selected, an optimization routine can be selected which leads to a load model. The structure in Figure 11 is used and is similar to that for the general model except with no capacitance. The resistance element is assumed known, whether from DC measurements or other parametric data. The inductance and transmission line parameters can be optimized over given ranges.

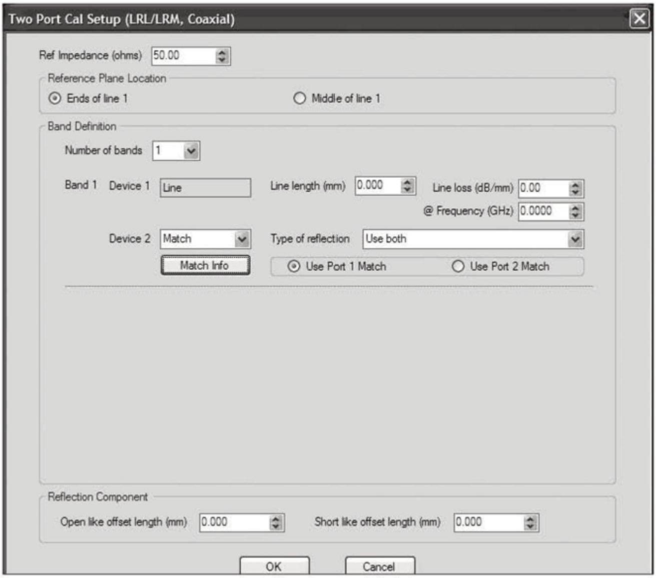
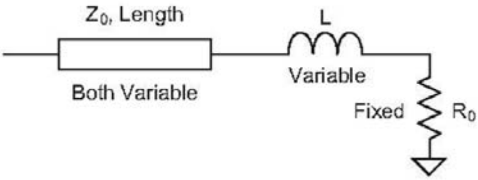


Figure 10D: An example of 1-band ALRM using two reflects

Figure 12 depicts the dialog pertaining to this model. it appears after the main calibration steps are complete. At that point, the fit model can be used (default) or modified values may be entered. Note that the dialogs shown above are for coaxial or non-dispersive line types. For waveguide and microstrip line types, the only change is the addition of cutoff frequency and dielectric constant information to complete the model.

When using the double-reflect ALRM method, the reflections must produce distinct reflection coefficients when rotated to the central reference plane. When the reflect offset lengths start to become large, this gets more difficult over large frequency ranges. In an on-wafer environment when the offset lengths are typically very short, this does not present a problem, but it can be an issue in coax. Since the load modeling is most commonly an issue in high frequency on-wafer measurements, this behavior is usually consistent with the applications.



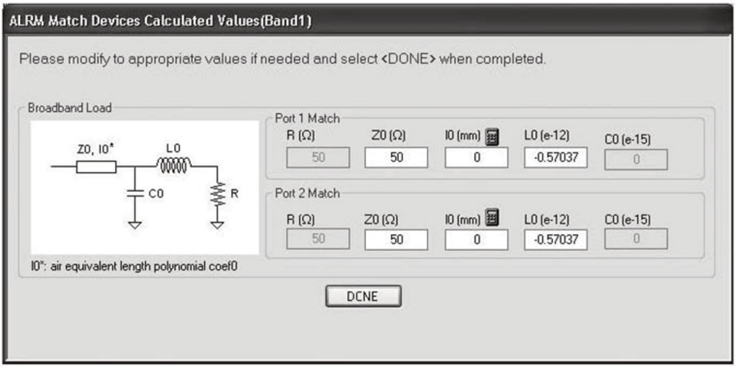


Figure 12: The ALRM load-model selection dialog is shown here. A model will be suggested by the algorithm but can be overridden in this dialog.

Isolation

All of the previously mentioned calibration techniques can take advantage of the isolation error terms (e.g., ex21 and ex12), although they are often not very useful due to the VNA's low internal leakage. With certain external test-set arrangements, however, it can be useful—particularly when reference to test-channel leakage is possibly significant relative to the measurement goals.

This error correction is a very simple vector subtraction that works against the transmission S-parameters. The terms (S21-ex21) and (S12-ex12) literally appear in the error-correction equations. Thus, this correction is only valid if the isolation is truly a scalar-like behavior and not dependent on DUT match. As an example, it will not help if there is test channel¬to-test channel leakage within an external test set.

Adapter Removal

There are a number of situations where the DUT configuration is not entirely compatible with common calibration procedures, such as when:

- The DUT has one connector of some coaxial type and another connector of a coaxial type from a different family (e.g., K and V).
- One port of the DUT is coaxial and the other is waveguide.
- One port of the DUT is coaxial and the other is fixtured (e.g., a transmission line on a board or on wafer)
- The DUT is coaxial with both ports of the same type, but also the same sex and there is a problem creating the thru.

All of these cases share a common problem - it is difficult to generate the thru, or a good transmission line, for the calibration. A number of options exist to address this problem, including:

- Use the SOLR calibration discussed previously. This will work assuming that the VNA user is willing to perform a semi-defined-standards calibration.
- Enter the length and loss of what can be constructed as a thru. Use that information in the calibrations. This can work if the loss is not too great, is well-behaved and the match is still good.
- Use the Phase-Equal-Insertable method (for the case listed above). Here one adapter is used during the calibration and a different adapter of the same electrical length and loss is substituted for the measurement. Note that this is the same as the Test-Port Converter method discussed in the AutoCal section.
- De-embed an adapter. If the VNA user knows enough about the adapting structure (either a good model or .s2p data), the adapter can be de-embedded separately. Acquiring this information is usually the hard part.
- Use the concept of adapter removal.

The concept of adapter removal relies on the existence of two related sets of reference planes: one set on either side of the adapter (Figure 13). Assuming a full calibration is performed at each set of reference planes, there is enough information to extract the behavior of the adapter itself. When the calibration is being performed at the reference planes on the left (between ports 1 and 2'), the adapter behavior is embedded in the characteristics of port 2'. Similarly, when the calibration is being performed between ports 1' and 2, the adapter behavior is embedded in the characteristics of port 1'. Since each of these two calibrations involve mating connector types, they are far easier to perform than the direct 1-2 calibration. The use of the two calibrations provides nearly enough information to extract the parameters of the adapter itself.

There are two caveats to this procedure. First, only the product $S_{21}S_{12}$ of the adapter can be determined from this procedure. The two individual transmission terms can not be determined. Since only product is needed to de-embed the adapter effects, however, this is not much of a problem. Most adapters are passive and reciprocal anyway so the individual terms could probably be determined if necessary. Second, this procedure involves a complex square-root operation so a root determination is necessary. To help this, the user must enter some guess as to the electrical length of the adapter (in picoseconds of delay). The guess need not be very accurate, just within the correct half plane. At 2 GHz, this means that the error in delay entry should be less than 125 ps to ensure the correct root is selected. In general, the error must be less than $1/(4f)$, where f is the highest used frequency. The setup dialog for this procedure is shown in Figure 14.

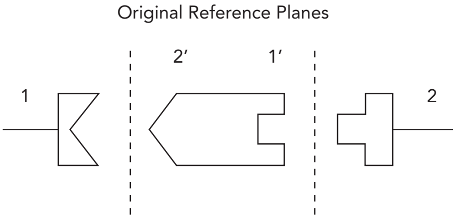


Figure 13: The structure of the adapter removal calibrations is shown here. Two calibrations are performed at the two sets of reference planes shown (between ports 1 and 2′ and between 1′ and 2.) This allows a determination of the adapter behaviour. The resulting calibration, after adapter removal, is between ports 1 and 2.

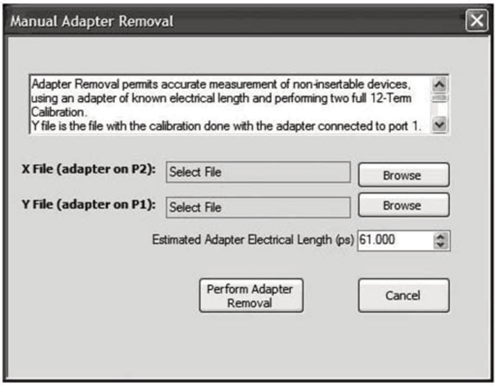


Figure 14: The manual adapter-removal dialog is shown here. The two calibration files, each corresponding to the adapter being connected to a port, must be specified along with a length estimate for the adapter. The resulting calibration resident in memory (after 'perform...' has been selected) will have the adapter removed.

Now consider the special case of adapter removal with AutoCal. In the AutoCal-specialized version, adapter removal primarily refers to the case of a sex incompatibility when the user does not want to use test-port converters (e.g., the user has a MF AutoCal unit and wants to establish MM reference planes). A separate menu item is provided for AutoCal adapter removal. This speeds up the process since fewer manual steps are needed. In this calibration sequence, an adapter that can mate the desired reference-plane connectors is used as part of the calibration. As an example, for the MF AutoCal scenario, the adapter is placed on the desired port and the system is calibrated as before. Then, the AutoCal and adapter pair is rotated between the VNA test ports and the calibration is repeated. The process of reversing the AutoCal provides all the information needed for the internal algorithm to remove the adapter from calibration.

Thru Update

A common question related to calibrations is: How often is it necessary to redo the calibration? The answer depends heavily on the environment, both in terms of temperature stability and in terms of the cabling/fixturing construct that is being used. A recurring theme, however, is that this calibration lifetime is often limited by the stability of the test-port cables through drift or motion. These drift defects directly affect transmission tracking and load match. Therefore, the user might be able to lengthen the time between recalibrations by employing a simple means of refreshing these terms.

The idea is that it is relatively simple to connect just a thru/line and quickly refresh the transmission-tracking and load-match terms without great effort. In a sense, thru update is a one-step calibration that can be used to refresh a current, full 2-port or 1-path 2-port calibration.

Interpolation

Typically, the user calibrates at a specific list of frequencies and then performs measurements over that same list of frequencies. While this is an accurate process, it is not necessarily convenient. If, for example, a variety of narrow-bandpass filters of different center frequencies are being measured, it would be useful to zoom in to look at the passband of each filter, without having to recalibrate. Interpolated calibrations can be useful in these types of situations.

Care must be used when interpolating error coefficients between calibration points to minimize possible error. For the cause of interpolation error, note that the cable running within the instrument and those provided by the user typically result in a large electrical length. As a result, the error coefficient magnitude versus frequency is often periodic in shape. If the interpolation is not performed with care, large errors can result (Figure 15).

As a general rule, the smaller the step size that is used during the calibration, the more successful the interpolation. It is desirable to keep the step size smaller than the ripple period of the coefficients which will typically range from _0 to _00 MHz. A smaller number will be required for setups with very long test-port cables and fully optioned systems, while larger numbers are needed for setups with short test-port cables.

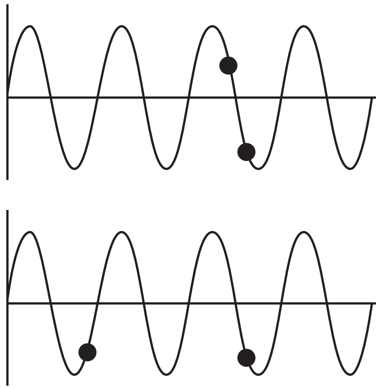


Figure 15: The effect of step size on interpolation is shown here

Calibration Merge

In certain situations, such as the need to cover different frequency ranges, multiple calibration algorithms are needed but the usual calibration approaches are not adequate. In this case, a form of calibration merge procedure may be used to combine the two calibrations. A common example is the broadband coaxial W1 connector, 110 GHz calibration where SOLT is used at low frequencies and SSST is used at high frequencies.

Network Extraction

As a conceptual variant on adapter removal, a pair of calibrations can be used to learn about the networks that are present near the reference planes. Suppose, for example, that the user

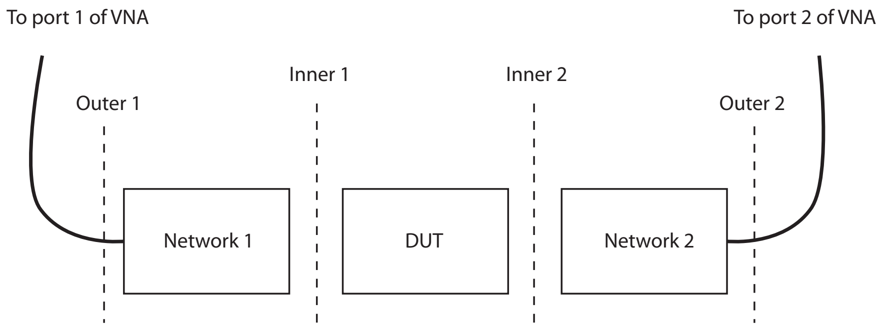


Figure 16: A diagram showing the network extraction process is shown here. Two port calibrations at two different reference plane sets are used to extract the S-parameters of the intervening networks (often test fixtures)

has networks that attach to the ports, the most common of which is a fixture. If a calibration can be performed both inside and outside of those networks, then there is enough information to extract the networks' S-parameters.

Consider the diagram in Figure 16. A calibration is required at the outer reference-plane set and the inner reference-plane set. The outer calibration is usually done coaxially, or with some other well-defined media, depending on the networks involved. The inner calibration is often more complicated and may be board- or wafer-level. Also, it may require the user to create calibration standards. Assuming these calibrations are possible, then the S-parameters of Network 1 and Network 2 can be found.

The dialog for loading the two calibrations is shown in Figure 17. Note the following conditions:

- The two calibrations must be full 2-port calibrations (same type) and must have been performed over the same frequency range with the same number of points.
- The networks are assumed to be reciprocal.

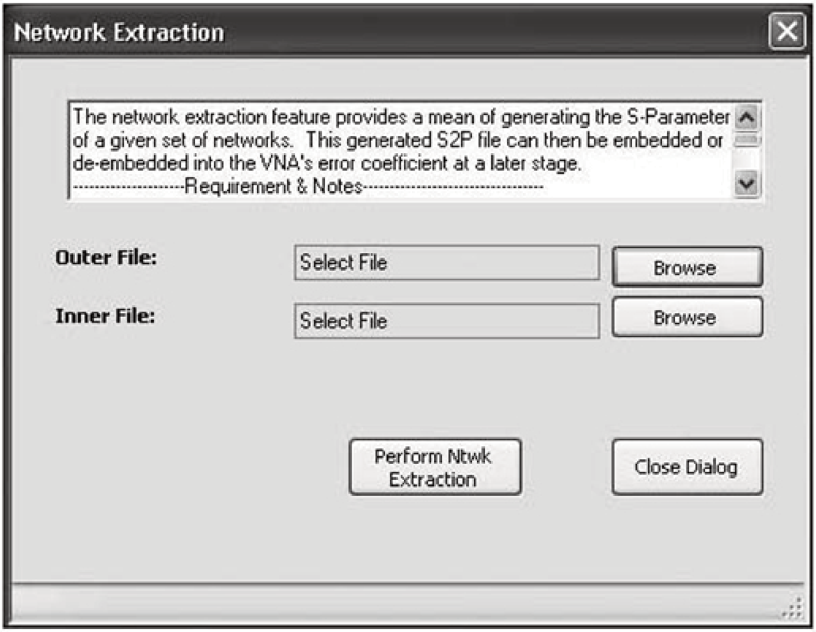


Figure 17: The network extraction dialog is shown here

Summary

The guide introduces the concept of calibration. The various calibration types and calibration algorithms where defined, along with the associated error models that describe what is being corrected.

This chapter also provided details on the selection of line type or transmission media and AutoCal—automatic calibration modules that are used to simplify the calibration method. The concept of adapter removal was also presented as a way to deal with situations where the DUT configuration is not entirely compatible with common calibration procedures. While a minimal amount of calibration mathematics and theory were covered in this chapter, more information is available in Anritsu Application Notes and in readily-available reference literature.[1]-[11]

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