Application Note

LRL/LRM Calibration

Theory and Methodology

MS4640A Vector Network Analyzer

VectorStar™ VNA

Introduction

Probably the most central concept to making good vector network analyzer (VNA) S-parameter measurements is the calibration. The background on calibration mathematics and theory will only be lightly covered in this application note; more information is available in other Anritsu literature and in the reference literature (e.g., [1]-[11]). This application note will discuss the Line-Reflect-Line (LRL) method of calibration and will include LRM (Line Reflect Match) and a new alternative algorithm providing a more precise termination model developed by Anritsu and designated ALRM (Advanced Line Reflect Match). After a description of the theory and practicalities of an LRL calibration, examples will be provided with emphasis on the Anritsu 3657 LRL Calibration Kit in conjunction with the VectorStar VNA.

Calibration Algorithm Choices

Modern-day VNAs provide a wide range of calibration choices. The choices stem from the different operating and measurement conditions, which present increasing challenges for providing accurate calibration standards. For example, high quality terminations and well-defined opens are difficult to produce at higher frequencies. Alternative calibration choices provide options to the user when attempting to circumvent weaknesses in the calibration kit. The different calibration choices are often defined by acronyms (for example, SOLT, LRL, and so forth) and often these acronyms are not consistent. To add further confusion, the letters may represent different things at different times. The following table shows the acronyms that are used in Anritsu documentation (intended to represent the most common usage).

Cal 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 w/ 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. High sensitivity to connector repeatability errors.
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 due to less defined thru. Other disadvantages of parent cal
LRL (line-reflect-line, also called TRL)	High performance coax, waveguide or 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. Usually not band-limited.	Requires load definition. Reflect standard setup may require care depending on load model used
LRM (line-reflect-match) when one line is a load	High performance coax, waveguide or on-wafer	Highest accuracy. Minimal standard definition	Requires very good transmission lines. Less redundancy so more care is required. Not band-limited due to load.

Line Types (Transmission Media)

As shown in the table, LRL can provide the highest level of accuracy. The accuracy of the calibration is determined by the quality of the transmission line. In a coaxial environment LRL calibration kits incorporating airlines can achieve a very high level of performance with corrected directivity well in the 50 dB range at 40 GHz.

LRL calibration kits can be in the form of coaxial lines, waveguide and microstrip. The VectorStar VNA provides a menu selection for the different line types that are used in the LRL algorithm. The main purpose of this is to automatically assign a dispersion characteristic that will be needed later. Dispersion is the dependence on the phase velocity of the line with frequency. Media such as coax and coplanar waveguide are largely dispersion-free; that is, we can define phase velocity by a single number.

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

Here c is the speed of light in a vacuum (~2.9979 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 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 εr 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 will compute the required values. This information is needed 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 is 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 considered. The dielectric constants (media-based and effective) and a transition frequency f_t are used to compute this effect which is heavily dependent on the dielectric thickness.

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

where

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

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

LRL Calibration kits

Anritsu provides 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, but the nature of that information varies by kit and application.

The Anritsu coaxial air-line-based LRL calibration kits, Models 3657 and 3657-1, use the LRL algorithm, so less definition of components is required when compared to other calibration methods. Accuracy of the reference impedance is determined by the mechanical precision of the airlines. Reflects may be part of the kit but the only piece of information that is needed is an offset length that is used to help with root selection (and is hence somewhat non-critical). The line lengths are the other parameters, and they mainly serve for reference plane placement. All of these parameters must be entered manually because the kit contains a large number of lines 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 to follow.

For certain microstrip and coplanar waveguide measurements, the Anritsu Universal Test Fixture Model 3680 can be used. It will accommodate a range of substrate sizes and thicknesses (see 3680 brochure for more information). The 36804 series of calibration kits provide opens, shorts, loads and a variety of transmission line lengths on alumina that can be used for different calibration algorithms. Careful selection of the line lengths will provide the standards necessary for an LRL calibration.

For on-wafer measurements, a variety of calibration standard substrates or impedance standard substrates are available from vendors that contain opens, shorts, loads, and transmission lines for on-wafer calibrations. Again, careful selection of the proper line length will provide the means of performing an LRL calibration, either by incorporating the vendor software associated with the wafer substrate, or by using the internal LRL algorithm located in VectorStar.

Calibration Choices

LRL/LRM/ALRM

The LRL/LRM/ALRM family of calibrations (e.g., [3]-[4]) is somewhat different from the family of calibrations utilizing well-defined standards. The LRL/LRM/ALRM family relies more on the intrinsic behavior of certain components (primarily transmission lines) than it relies on characterized/modeled behaviors of components. In addition, it makes less use of redundancy so fewer measurements are needed to complete a calibration. However, care must be taken because this method is somewhat less tolerant of poor or non-repeatable measurements.

LRL

Uses two (or more) transmission lines and a reflect standard (for each port). The line lengths are important because the two lines look electrically distinct at all times (meaning it will not work at DC, nor at a frequency where the difference in length is an integral number of half wavelengths). The reflect standard is not too important because it is only assumed to be symmetric (the same at both ports) and not too high a return loss (practically speaking, even 20 dB return loss will usually work). The lines are assumed to be perfect, with no mismatch, which usually means airlines for coaxial calibrations, although other structures can be used. On-wafer transmission lines can usually be very good, and this cal approach will work well if one can handle the required probe movement.

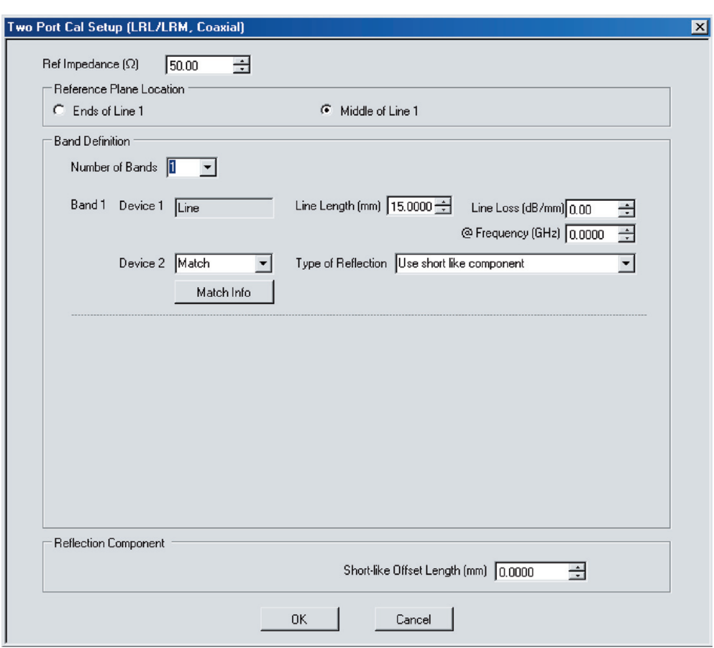


Figure 1. Example of a 1 Band LRL Calibration Setup

LRM

Here one of the lines of the LRL method is replaced with a match (or load). For basic LRM, the match is assumed to be perfect, and thus represents a line of infinite length. For cases where the load is well understood, improvement in accuracy can be achieved by using ALRM and incorporating the load model. So in some sense, this cal relates back to the concept of the defined standards. Because only one line is involved, this calibration can work down to DC and up to very high frequencies (practically limited by the match knowledge/characterization). Some variations allow one to trade one of the match measurements for a pair of additional reflect measurements (a second reflect standard is needed). Because of the requirement (in this case) that the reflect standards be distinct, the calibration may become band limited.

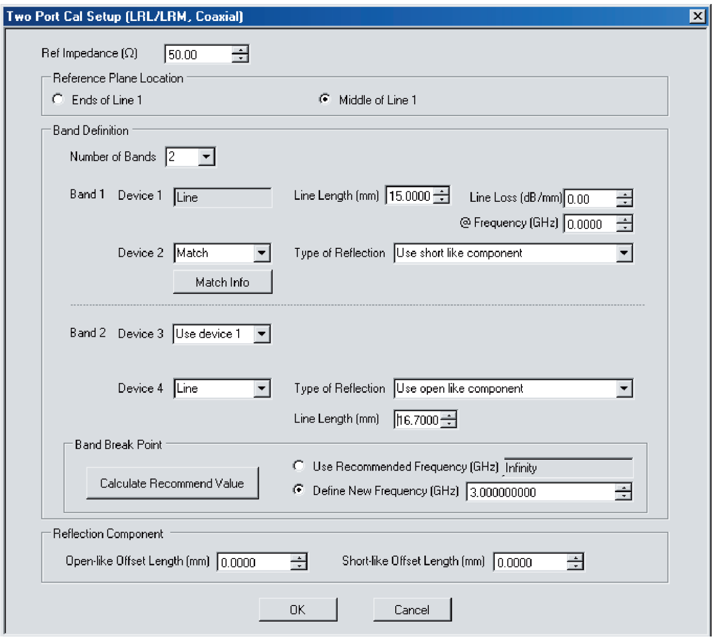


Figure 2. Example of a 2 Band LRL/LRM Calibration Setup

In the limiting case of a match that is assumed to be perfect, or at least assumed to be symmetric, this calibration reduces to the classical LRM. The added flexibility is in the ability to define asymmetric load models and to use multiple reflect standards as discussed above (other extensions are possible elsewhere, e.g., [9]-[11]). The double reflect methodology allows one to feed into a load modeling utility where the load model can be further optimized.

Some parameters to keep in mind:

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 cal is in the middle of the first line. Sometimes one desires the reference plane at the ends of this line, so the line length (and loss that can also be entered) is 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 mentioned above, the usable frequency range for LRL is set by the line length delta. In a pure sense, one could say the electrical length should just 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, one can usually be more aggressive on the lower number and want to be less aggressive on the upper number.

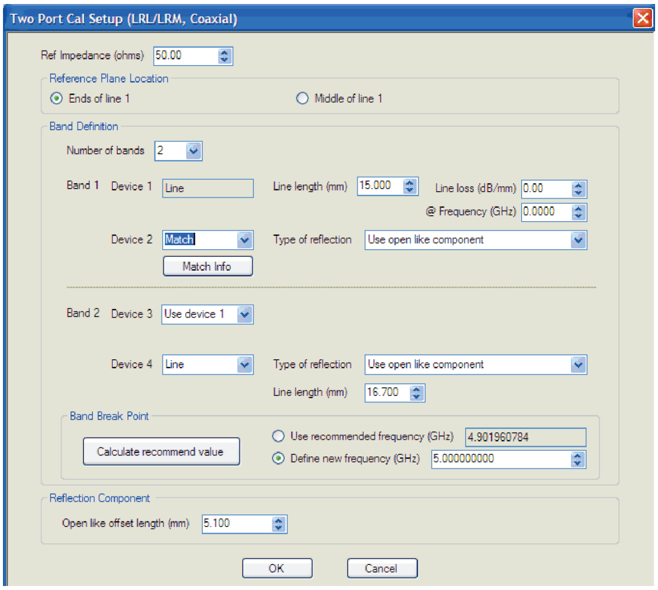
$$10 < \frac{360 \cdot f \cdot \Delta L}{v_{ph}} < 160$$

Where ΔL is in meters, v_{ph} is the phase velocity on the line (=2.9979 10^8 m/s=c for air dielectric) and f can be any frequency in the range of interest.

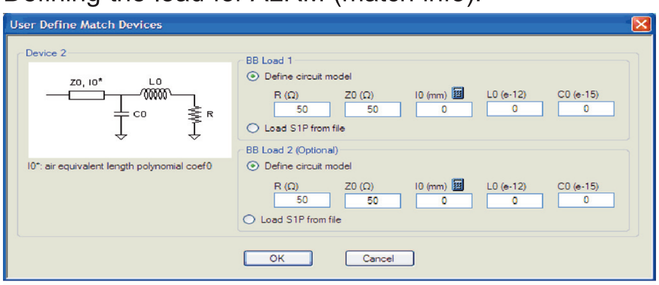
If this range is too small for the application, then multiple lines and multiple bands can be used. Each band will use a line pair covering some range of interest. Also, LRL can be combined with ALRM (ALRM usually covering the low frequency end) within the LRL/ALRM system. When two bands are used, a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

The setup dialog for LRL/ALRM is quite flexible with decisions being made based on what the standards that are selected. Several examples are shown in Figure 3.

2 Band (Band 1 ALRM, Band 2 LRL)



Defining the load for ALRM (match info):



1 Band ALRM using two reflects

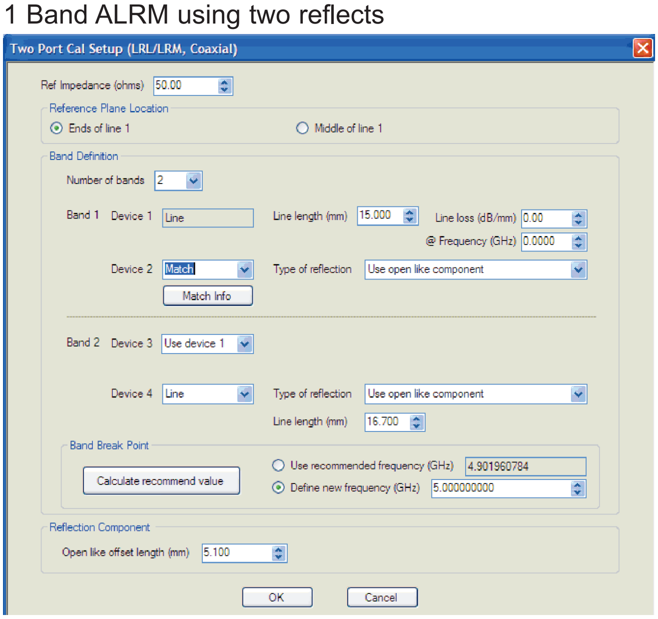


Figure 3. Several examples of LRL, ALRM and mixed setups are shown here.

Reflection offset length and reflection type:

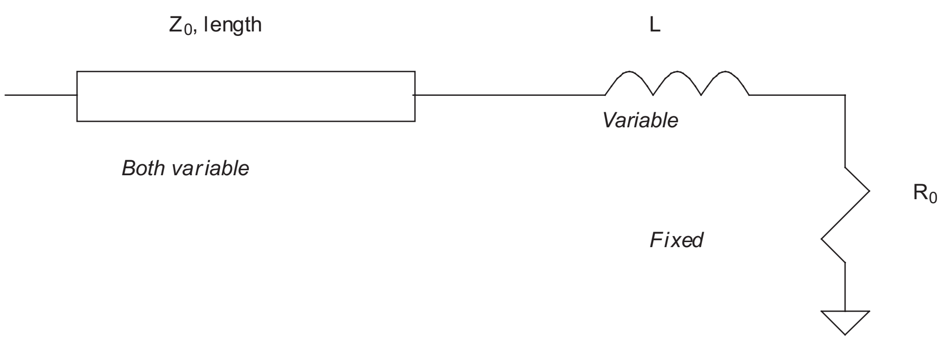
Some information is requested about the reflection, although a full characterization is not needed. The information is used in some root-choice activities, and it must be known only if the reflect behaves more like an open or a short (because typically opens and shorts are used as the reflect standard). The offset length is used to dynamically move the reference planes around so that the algorithm can determine 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. Because large offset lengths will lead to many more degeneracies, this double reflect option will generally be used when offset lengths are smaller (such as in on-wafer or fixtured calibrations).

Load model/characterization for ALRM:

When a single reflect approach is taken within ALRM, it behaves like classical LRM, except complete load models can be entered independently for the two matches. The same model as described for SOLT applies, and .s1p files can be used.

When the double reflect methodology is selected, an optimization routine can be selected which can lead to a load model. The structure below is used (similar to that for the general model, except no capacitance). The resistance element is assumed to be known (whether from DC measurements or other parametric data). The inductance and transmission line parameters can be optimized over given ranges.



The dialogs above were for coaxial or non-dispersive line types. For waveguide and microstrip, the only change is the addition of items at the top of the dialog to specify the media (see Figure 4 and 5).

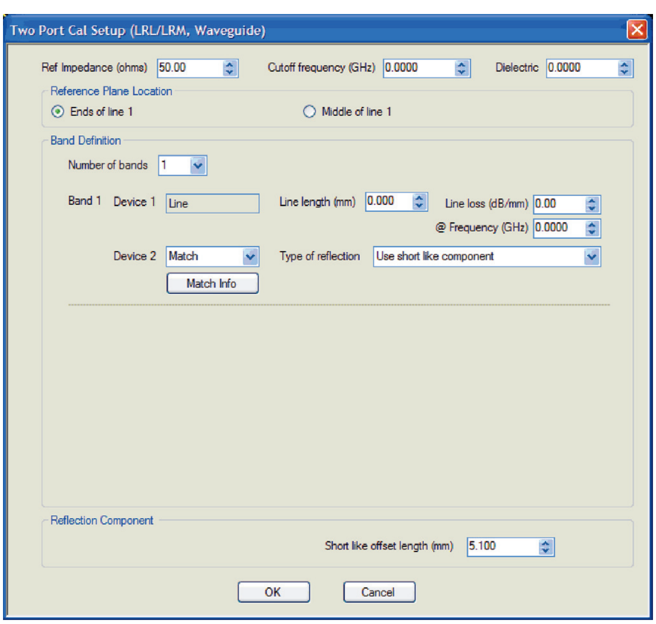


Figure 4. An example LRL/ALRM setup dialog for a waveguide line type is shown here. Note the cutoff and dielectric constant line items that are added.

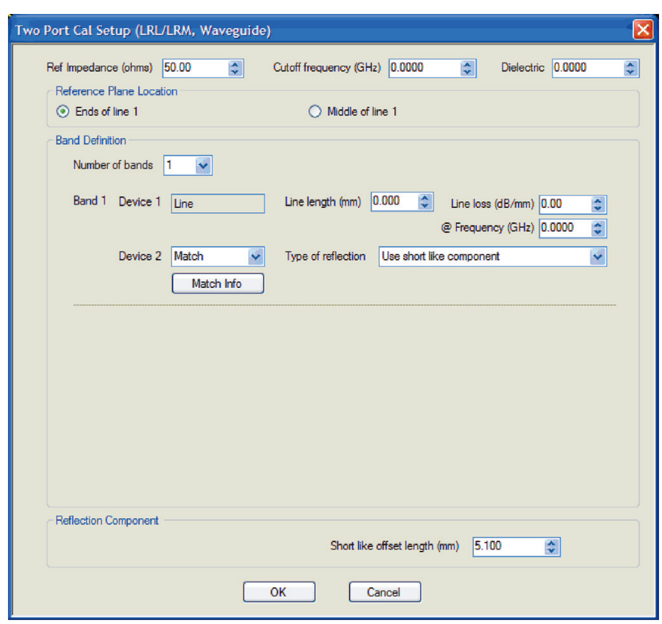


Figure 5. An example LRL/ALRM setup dialog for a microstrip line type is shown here. Note the media line items that have been added (the microstrip info sub-dialog is described earlier).

Techniques on Determining Line Lengths and Breakpoints

As previously mentioned, the line lengths that are used in an LRL calibration need to maintain a phase delta between approximately 10 and 160 degrees. As frequencies decrease, the airline length must increase in order to provide enough phase change and to avoid parasitics. And as airline lengths increase it becomes difficult to maintain proper physical alignment of the center conductor thereby reducing impedance accuracy. For maximum bandwidth, it is therefore best to concatenate LRL with LRM since terminations used for LRM provide excellent performance at lower frequencies. The VectorStar VNA provides a routine that automatically concatenates LRL with LRM for a seamless transition.

Example: Perform an LRL Calibration from 2 GHz to 70 GHz using the Model 3657-1 V Multi-Line Calibration Kit

The Model 3657-1 Multi-Line Calibration Kit consists of one of each of the following 50 Ω airlines:

15.00 mm V (m) to V (m)
16.70 mm V (m) to V (m)
18.40 mm V (m) to V (m)
20.10 mm V (m) to V (m)
21.80 mm V (m) to V (m)
49.84 mm V (m) to V (m)

Considering the 15.00 mm and 16.70 mm airlines, the delta length is 1.70 mm.

Given the boundaries of the delta length from:

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

Where ΔL is in meters, v_{ph} is the phase velocity on the line (=2.9979 10^8 m/s=c for air dielectric) and f can be any frequency in the range of interest in Hz.

At 70 GHz the phase length is:

(360 x 70 10^9 x 1.7 10^{-3})/2.9979 10^8 = 142 degrees. This is within the boundary of 160 degrees.

To determine the lower frequency range limit, with no less than 10 degrees electrical length, we find:

$$f_{low} = \frac{c}{36\Delta L} = 4.89 \text{ GHz}$$

The range covered by the first pair of airlines is 5 to 70 GHz.

To cover the 2 GHz to 5 GHz range, we calculate the coverage using lines 2 (16.70 mm) and 5 (21.80 mm). The delta length between lines 2 and 5 is 5.1 mm. The electrical length at 5 GHz is:

(360 x 5 10^9 x 5.1 10^{-3})/2.9979 10^8 = 30 degrees (within the boundary of the upper limit.)

At 2 GHz, the electrical delay is:

(360 x 2 10^9 x 5.1 10^{-3})/2.9979 10^8 = 12 degrees

Remember that concatenation with LRM provides excellent performance below 2 GHz by using terminations as the low frequency impedance reference. Combining LRL with LRM can provide the highest accuracy calibration over a broad frequency coverage.

Note that when using a three line LRL configuration, the algorithm must be provided with the frequency breakpoint between the two air line pairs. In the VectorStar VNA, a calculator automatically provides a recommended value. Alternatively, a specified value can be entered, usually at a midpoint between the two frequency overlap. In this case, a breakpoint frequency of 4.9 GHz will be used.

Method of Assurance

The Model 3657-1 Multiple Line Calibration Kit uses beadless male-to-male airlines for LRL calibrations. Because the LRL algorithm uses the physical structure of the transmission line as the impedance reference, and the airlines used in the Model 3657-1 calibration kit are high precision mechanical devices, the impedance of the airlines is controlled by the physical relationships between the inner conductor and outer conductor. The physical dimensions of the two components establish the precision of impedance and thus the precision of calibration. Because the physical properties of the inner and outer conductor can be measured using mechanical measurements traceable to a national standards laboratory such as NIST, the impedance of the airlines is traceable.

Summary

A method of calibration using beadless airlines and LRL calibration has been shown to provide excellent results up to 70 GHz. A range of 2 GHz to 70 GHz can be covered using the Model 3657-1 Multi-line Calibration Kit. For lower frequencies, the VectorStar VNA offers automatic concatenation of LRL and LRM calibrations to provide coverage down to 70 kHz.

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