APPLICATION NOTE

Specifying Calibration Standards and Kits for Keysight Vector Network Analyzers

Provides guidance in creating calibration kits for use with Keysight Vector Network Analyzers

KEYSIGHT

This application note provides guidance in creating calibration kits for use with Keysight Vector Network Analyzers. It includes detailed information including insight into the derivation for each type of calibration standard model to enable users to define their own calibration standards with confidence. It also shows how to define the interaction between calibration standards and the various calibration algorithms included in Keysight Vector Network Analyzers.

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Introduction

Measurement errors in network analysis can be separated into two categories: random and systematic errors. Both random and systematic errors are vector quantities. Random errors are non-repeatable measurement variations and are usually unpredictable. Systematic errors are repeatable measurement variations in the test setup.

Measurement errors

Systematic errors include impedance mismatch, system frequency response and leakage signals in the test setup. In most microwave measurements, systematic errors are the most significant source of measurement uncertainty. The source of these errors can be attributed to the signal separation scheme used. Vector error correction is the process of mathematically compensating for the systematic errors. There are two parts of vector error correction, characterization of the errors through measurement calibration and subsequent measurement correction using the characterization of the systematic errors. This application note focuses on the measurement calibration portion of vector error correction.

Numerous publications are available on vector network analyzer (VNA) calibration techniques. References [1], [2], [3], [4], [5], [6], and [7] are just some of the published work. Keysight Technologies, Inc. application notes also provide insights on VNAs and VNA error correction see [8], [9], and [10]. It is recommended that a user be familiar with these calibration techniques and terminologies to get the maximum understanding from this application note.

Measurement calibration

A measurement calibration is a process which mathematically derives the systematic error model for the VNA. This error model is an array of vector error coefficients used to establish a fixed reference plane of zero phase shift, zero reflection magnitude, lossless transmission magnitude and known impedance. The array of coefficients is computed by measuring a set of “known” devices or calibration standards connected at a fixed measurement plane.

Different calibration techniques can be used to solve for the VNA error models. The VNA error models include but are not limited to one-port correction and multiport correction. The definition of calibration standards and types are set up differently for the applicable calibration techniques. Solving the full 2-port twelve term error model using the short/open/ load/ thru (SOLT) calibration method is an example of only one of the many measurement calibration methods available.

The type of measurement calibration selected by the user depends on the device to be measured (i.e., 1-port, 2-port, or multiport device), the calibration standards available and the extent of accuracy enhancement desired. The accuracy of subsequent device measurements depends on the accuracy and stability of the test equipment, the accuracy of the calibration standard model, and the calibration method used in conjunction with the error correction model.

This application note covers calibration standard definitions, calibration kit content and its structure requirements for Keysight’s vector network analyzers. It also provides some examples of how to set up a new calibration kit and how to modify an existing calibration kit definition file.

Calibration Kits

A mechanical calibration kit consists of a set of physical devices called standards. Each standard has a precisely known magnitude and phase response as a function of frequency. The calibration standards are organized into calibration kit classes which are a group of standards identified for specific uses by the calibration methods. Calibration methods access the various types of calibration standards required for the calibration algorithm via one or more calibration kit classes. Keysight currently supplies mechanical calibration kits with 1 mm, 1.85 mm, 2.4 mm, 3.5 mm, 7 mm, Type-N $50\,\Omega$, Type-N $75\,\Omega$, Type-F $75\,\Omega$, and 7-16 coaxial connectors. Rectangular waveguide calibration kits include WR-90 (X band), WR-62 (P band), WR-42 (K band), WR-28 (R band), WR-22 (Q band), WR-19 (U band), WR-15 (V band), and WR-10 (W band). Calibration for microstrip and other non-coaxial media is described in references [11], [12], and [13]. A calibration kit may support multiple calibration methods.

Connector definitions

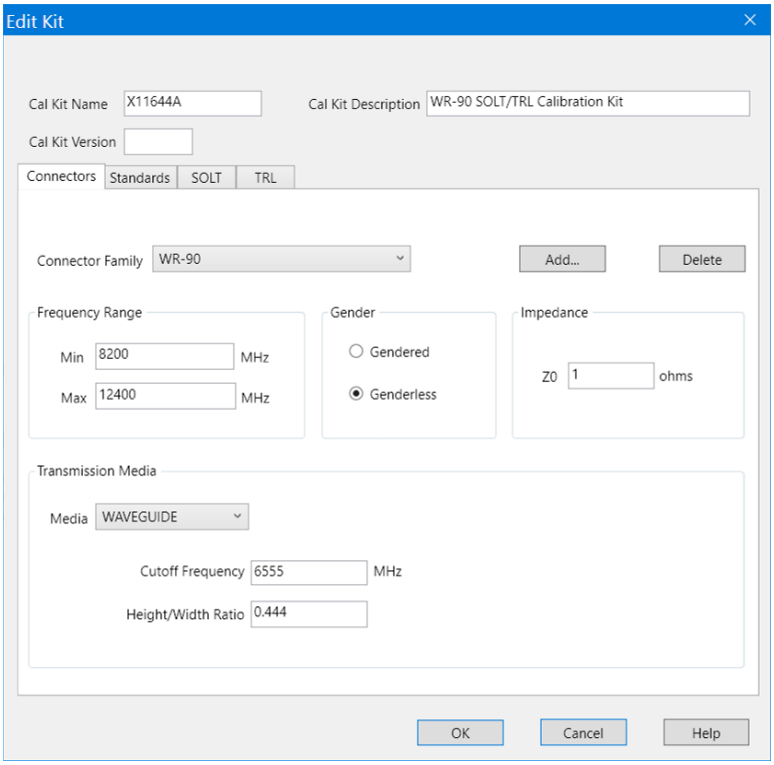


Figure 1. VNA connector entry screen

In addition to calibration standard definitions and calibration kit class assignments, calibration kits also provide definitions of connectors. Keysight's vector network analyzer (VNA) products use the connector definition to define the following connector properties (Figure 1):

- Frequency Range
- Gender (male, female, no gender)
- Impedance (Connector Z_0 is the reference impedance Z_{ref})
- Media (coax, waveguide, etc)
- Cutoff Frequency (waveguide)
- Height/Width Ratio (waveguide)

A calibration kit may be defined with multiple connectors. Each 1-port calibration standard must be associated with a single connector. Two port standards, such as thrus and adapters, are associated with two connectors.

Calibration standards definition

The S-parameters of VNA calibration standards must be defined sufficiently and accurately to satisfy the requirements of the calibration methods for which they will be used. Calibration standards may be defined in various ways. Keysight's VNAs support two types of calibration standard definitions: calibration coefficient model and data-based model.

Transmission line model

Most VNAs support calibration standards defined using a parameterized transmission line model for 2-port standards. (See Figure 2.) The transmission line model shown in Figure 2 can be represented by signal flowgraph sections representing the input impedance discontinuity, the delay and the output impedance discontinuity as shown in figure 3 (see references [14] and [15]).

- Z_c is the characteristic impedance of the line
- Z_{in} is the input impedance
- Z_{out} is the output impedance

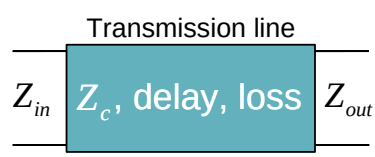


Figure 2. Transmission line model

The difference in the offset characteristic impedance Z_c, the input impedance Z_{in}, and the output impedance Z_{out} leads to reflection coefficients Γ_1 and Γ_2 at the input and output of the offset delay section.

$$\Gamma_1 = \frac{Z_c - Z_{in}}{Z_c + Z_{in}}; \quad \Gamma_2 = \frac{Z_{out} - Z_c}{Z_{out} + Z_c} \qquad (1)$$

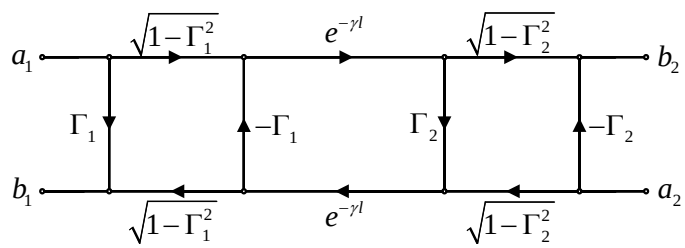


Figure 3. Flowgraph representation of the transmission line model

The cascade parameter representation of the transmission line model can be represented by cascaded sections representing the input impedance discontinuity ($\mathbf{T_{XI}}$), the offset delay ($\mathbf{T_L}$), and the output impedance discontinuity ($\mathbf{T_{XO}}$) as shown in Figure 4.

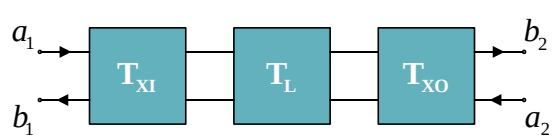


Figure 4. Cascade parameter representation of the transmission line model

The cascade parameters for the input impedance discontinuity is given as:

$$\mathbf{T_{XI}} = \frac{1}{\sqrt{1-\Gamma_1^2}} \begin{bmatrix} 1 & \Gamma_1 \\ \Gamma_1 & 1 \end{bmatrix} \qquad (2)$$

The cascade parameters for the offset delay is given as:

$$\mathbf{T_L} = \begin{bmatrix} e^{-\gamma l} & 0 \\ 0 & e^{\gamma l} \end{bmatrix} \tag{3}$$

The cascade parameters for the output impedance discontinuity is given as:

$$\mathbf{T_{XO}} = \frac{1}{\sqrt{1-\Gamma_2^2}} \begin{bmatrix} 1 & \Gamma_2 \\ \Gamma_2 & 1 \end{bmatrix} \tag{4}$$

where:

- l is the length of the line
- α is the propagation loss constant of the line
- $\gamma = \alpha + j\beta$ is the propagation constant of the line
- β is the propagation phase constant of the line

The S-parameters of the non terminated offset are computed from the cascaded parameters $\mathbf{T_{TOT}}$ where:

$$\mathbf{T_{TOT}} = \mathbf{T_{XI}} \cdot \mathbf{T_L} \cdot \mathbf{T_{XO}} \tag{5}$$

For the standards that use the transmission line model **Connector $\mathbf{Z_0}$** defines a common reference impedance (Z_{ref}) with $Z_{in} = Z_{out} = Z_{ref}$. In this case $\Gamma_2 = -\Gamma_1$ resulting in:

$$S_{11} = S_{22} = \frac{\Gamma_1\left(e^{-2\gamma l} - 1\right)}{\Gamma_1^2 e^{-2\gamma l} - 1} \tag{6}$$

$$S_{21} = S_{12} = \frac{\left(\Gamma_1^2 - 1\right)e^{-\gamma l}}{\Gamma_1^2 e^{-2\gamma l} - 1} \tag{7}$$

Transmission line characteristic impedance and propagation constants can be derived from the line's physical properties [16], [17].

Terminated transmission line model

A variety of one port calibration standards are defined as a terminated transmission line model. The termination impedance Z_T defines the standard type. The signal flow graph representation of the terminated transmission line is shown in Figure 5.

It can be used to compute the response of the one-port standard (Γ_i).

$$\Gamma_i = S_{11} + \frac{S_{21}S_{12}\Gamma_T}{1 - S_{22}\Gamma_T} \tag{8}$$

where

$$\Gamma_T = \frac{Z_T - Z_{ref}}{Z_T + Z_{ref}} \tag{9}$$

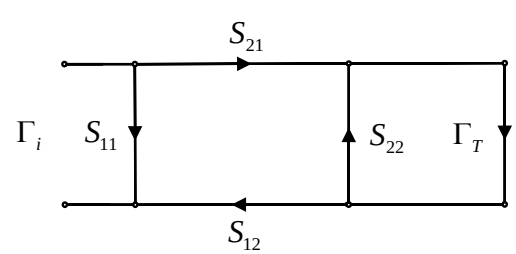


Figure 5. Signal flow graph of terminated transmission line model

Substituting equations 6 and 7 into equation 8 yields:

$$\Gamma_i = \frac{\Gamma_1\left(1 - e^{-2\gamma l} - \Gamma_1\Gamma_T\right) + \Gamma_T e^{-2\gamma l}}{1 - \Gamma_1\left(\Gamma_1 e^{-2\gamma l} + \Gamma_T\left(1 - e^{-2\gamma l}\right)\right)} \tag{10}$$

Keysight VNAs use **Offset delay**, **Offset loss** and **Offset $\mathbf{Z_0}$** instead of Z_c, and γl to model the transmission line. With these "offset" definitions, the VNA can compute the transmission line's characteristic impedance as well as propagation phase and loss constants of the calibration standard without defining the dielectric constant of the calibration standard's transmission medium which may be different from that of the device under test. This assumes that the offset loss and offset delay values were derived using the same dielectric constant.

Offset delay

Offset delay is the dispersion free, TEM mode, electrical delay in seconds defined by:

$$\textbf{Offset delay} = \frac{l}{v} \tag{11}$$

where

- l = physical offset length from reference plane in cm
- $v = \frac{c}{\sqrt{\varepsilon_r}}$ is speed of light in transmission medium
- ε_r = relative permittivity (dielectric constant) of transmission medium = $1.000\,649$ in air @ sea level and $50\,\%$ humidity
- For many transmission line configurations $\varepsilon_r = \varepsilon_e$
- ε_e = effective relative permittivity
- c = speed of light in vacuum = $2.997\,924\,58 \times 10^{10}\,\mathrm{cm/s}$

> The effective relative permittivity (ε_e) provides a single value to represent the interaction of the electric field with multiple regions of differing relative permittivity values. An example would be a microstrip structure where the electric field is in both the substrate and air. In those cases ε_e is used in place of ε_r.

Note that the reference plane of coaxial connectors is defined as the mating plane of the outer conductors. Appendix A on page 52 illustrates the physical offset length definition of certain coaxial connector types.

Offset loss

Offset loss is in $\mathrm{G\Omega/s}$. It is the propagation loss per unit length of the transmission line at a normalization frequency of $1\,\mathrm{GHz}$ multiplied by the speed of light in the transmission medium. For most coaxial devices, it can be estimated from the loss magnitude data at $1\,\mathrm{GHz}$.

Using S_{21} linear magnitude data at $1\,\mathrm{GHz}$:

$$\textbf{Offset loss} = -2\ln\left(|S_{21lin}|\right)\left(\frac{\textbf{Offset Z}_0}{\textbf{Offset delay}}\right) \tag{12}$$

Using S_{21} log magnitude data at $1\,\mathrm{GHz}$:

$$\textbf{Offset loss} = -\frac{\ln(10)\,S_{21dB}}{10}\left(\frac{\textbf{Offset Z}_0}{\textbf{Offset delay}}\right) \tag{13}$$

Using S_{11} linear magnitude data at $1\,\mathrm{GHz}$:

$$\textbf{Offset loss} = -\ln\left(|S_{11lin}|\right)\left(\frac{\textbf{Offset Z}_0}{\textbf{Offset delay}}\right) \tag{14}$$

Using S_{11} log magnitude data at $1\,\mathrm{GHz}$:

$$\textbf{Offset loss} = -\frac{\ln(10)\,S_{11dB}}{20}\left(\frac{\textbf{Offset Z}_0}{\textbf{Offset delay}}\right) \tag{15}$$

For best results, curve fit the measured data to the $\sqrt{f/1\,\mathrm{GHz}}$ function.

A TRL calibration is a good choice if a calibration is part of the characterization process because it avoids dependencies on loss values defined for the calibration standards.

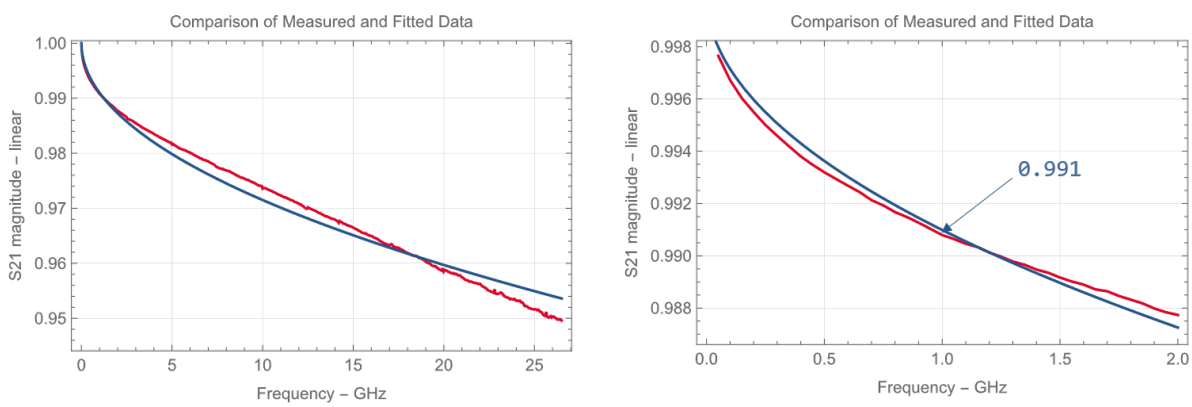


Figure 6. Fitting measured S_{21} magnitude to $\sqrt{f/1\,\mathrm{GHz}}$

See Appendix B on page 54 for details of the coaxial loss model.

Keysight's vector network analyzers include a waveguide loss model. See Appendices C and D starting on page 59.

$$\textbf{Offset loss} = -\frac{\ln\left(|S_{21lin}|_{@f}\right)}{\textbf{Offset delay}}\left(\sqrt{\frac{\mu_r}{\varepsilon_r}}\right)\sqrt{\frac{f_c}{f}}\left(\frac{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}{1+\frac{2h}{w}\left(\frac{f_c}{f}\right)^2}\right) \tag{16}$$

Offset Z_0

Offset $\mathbf{Z_0}$ is the lossless characteristic impedance of the transmission line. For coaxial transmission lines, the lossless characteristic impedance is

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}\ln\left(\frac{D}{d}\right) = \frac{\mu_0 c}{2\pi}\sqrt{\frac{\mu_r}{\varepsilon_r}}\ln\left(\frac{D}{d}\right) \tag{17}$$

where

- μ_r = relative permeability constant of the transmission medium
- D = outer conductor inner diameter
- d = center conductor outer diameter

The transmission line characteristic impedance Z_c including skin loss effects is derived from the **Offset $\mathbf{Z_0}$** and **Offset loss** terms.

Waveguide impedance varies as a function of frequency. In such cases, normalized impedance measurements are typically made. When calibrating in waveguide, the impedance of a "matched" load is used as the impedance reference. The impedance of this load is matched to that of the waveguide characteristic impedance across the guide's frequency bandwidth. Normalized impedance is achieved by setting **Offset $\mathbf{Z_0}$** to $1\,\Omega$ for each standard and setting the **Connector** Z_0 to $1\,\Omega$.

Transmission line alternate parameters

Alternate parameters facilitate creating Keysight calibration kit definitions using parameters specified by other vendors. In all cases, the fundamental representation in the calibration $*$.xkt file will remain unchanged. The CalKit editor is modified to permit representation in multiple forms. This has the benefit that the standalone version of the CalKit editor can be used to create calibration kit files that are compatible with older versions of firmware.

All of the differences are simply a scale factor with the exception of the offset loss term used in the alternate parameters. The Keysight parameters are orthogonal which permits a single loss term to be computed and used for multiple lengths of line. The alternate offset characteristics are not orthogonal as the alternate loss term ($L_{\mathrm{dB\,GHz^{-1}}}$) is impacted by both offset length and offset Z_0. Conversion from the Keysight offset loss term ($L_{\mathrm{G\Omega\,s^{-1}}}$) to the alternate loss term for one-port standards is given as:

$$L_{\mathrm{dB\,GHz^{-1}}} = \frac{20\log_{10}(e)\,d_{\mathrm{ps}}L_{\mathrm{G\Omega\,s^{-1}}}}{Z_0\times 10^3} \simeq 0.00868589\frac{d_{\mathrm{ps}}L_{\mathrm{G\Omega\,s^{-1}}}}{Z_0} \tag{18}$$

where $e \simeq 2.718\,281\,828\,459$ is the base of the natural logarithm and d_{ps} is the offset delay in ps. Conversion in the opposite direction for one-port standards yields:

$$L_{\mathrm{G\Omega\,s^{-1}}} = \frac{L_{\mathrm{dB\,GHz^{-1}}}Z_0\times 10^3}{20\log_{10}(e)\,d_{\mathrm{ps}}} \simeq 115.12925465\frac{L_{\mathrm{dB\,GHz^{-1}}}Z_0}{d_{\mathrm{ps}}} \tag{19}$$

Conversion from the Keysight offset loss term ($L_{\mathrm{G\Omega\,s^{-1}}}$) to the alternate loss term for two-port standards is given

as:

$$L_{\mathrm{dB\,GHz^{-1}}} = \frac{10\log_{10}(e)\,d_{\mathrm{ps}}L_{\mathrm{G\Omega s^{-1}}}}{Z_0 \times 10^3} \simeq 0.004342945\frac{d_{\mathrm{ps}}L_{\mathrm{G\Omega s^{-1}}}}{Z_0} \tag{20}$$

Conversion in the opposite direction for two-port standards yields:

$$L_{\mathrm{G\Omega s^{-1}}} = \frac{L_{\mathrm{dB\,GHz^{-1}}}Z_0 \times 10^3}{10\log_{10}(e)\,d_{\mathrm{ps}}} \simeq 230.2585093\frac{L_{\mathrm{dB\,GHz^{-1}}}Z_0}{d_{\mathrm{ps}}} \tag{21}$$

The alternate offset term ($L_{\mathrm{dB\,GHz^{-1}}}$) accounts for the loss along the forward and the reverse path for one-port standards while the Keysight offset loss term ($L_{\mathrm{G\Omega s^{-1}}}$) represents the one-way loss for both one-port and two-port standards.

The conversion between the Keysight offset delay term and the alternate offset length term is defined by

$$\textbf{Offset Delay} = \frac{\textbf{Offset Length}}{c} \tag{22}$$

This implies the alternate **Offset Length** is an electrical length related to the physical length l by

$$\textbf{Offset length} = l\sqrt{\varepsilon_r{}'} \tag{23}$$

Standard types

Calibration standards are assigned to the following standard types (Figure 7): OPEN, SHORT, LOAD, THRU (ADAPTER), DATA-BASED, and ISOLATION.

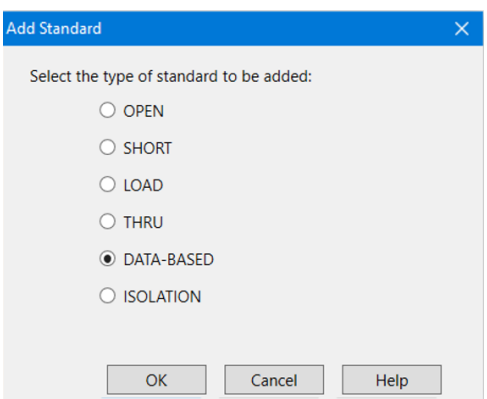


Figure 7. Calibration standard selections

Maximum/minimum frequency

The maximum and minimum frequency entries apply to all of the standard types. They define the applicable frequency range of the calibration standard which helps determine which standard is used for each frequency during the calibration. The applicable range may be limited by the model data, accuracy of the model or the physical dimensions of the calibration standard. A fixed load, for example, may be used at low frequencies while a sliding load may be used at high frequencies.

Open

An OPEN calibration standard is based on the terminated transmission line model where the termination impedance Z_T is defined by polynomial coefficients that represent a capacitance model. The reflection coefficient values are computed using equations 9 through 10.

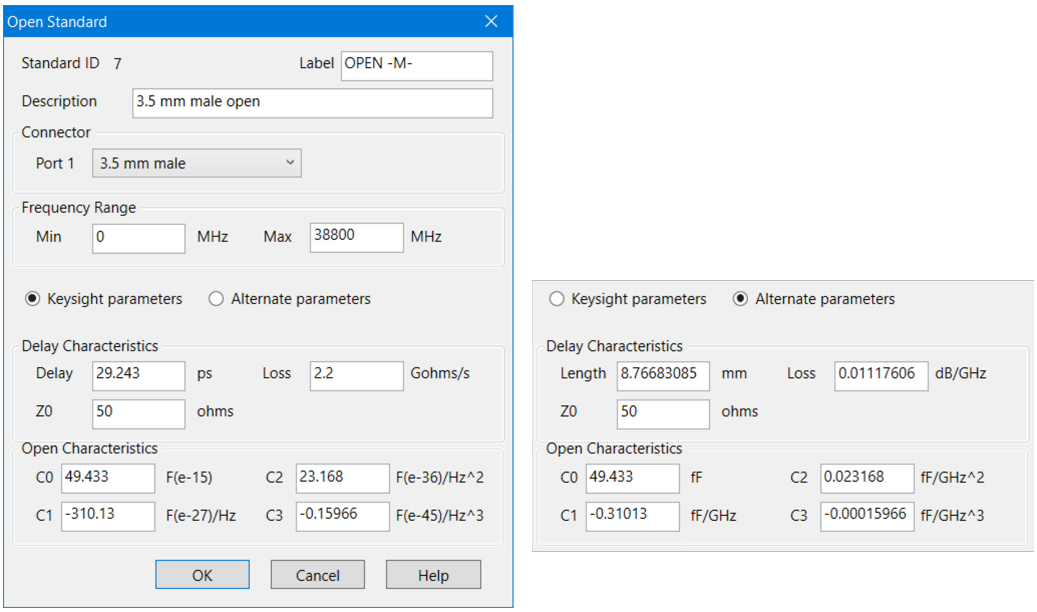


Figure 8. Open entry screen

Open circuits radiate at high frequencies. This effectively increases the electrical length of the device and can be modeled as a frequency dependent capacitor, C_{open}, (also known as fringing capacitance). At low frequencies, a fixed capacitance value may be sufficient; this would use only the $\mathrm{C0}$ term. Most network analyzers use a third order polynomial capacitance model. Radiation loss is assumed to be insignificant.

$$C_{open} = (\mathrm{C0}) + (\mathrm{C1})\,f + (\mathrm{C2})\,f^2 + (\mathrm{C3})\,f^3$$
$$Z_T = \frac{1}{j2\pi f C_{open}} \tag{24}$$

Keysight parameters

- $\mathrm{C0}$ is in units of 10^{-15} F
- $\mathrm{C1}$ is in units of 10^{-27} F/Hz
- $\mathrm{C2}$ is in units of 10^{-36} F/Hz^2
- $\mathrm{C3}$ is in units of 10^{-45} F/Hz^3

Alternate parameters

- $\mathrm{C0}$ is in units of fF
- $\mathrm{C1}$ is in units of fF/GHz
- $\mathrm{C2}$ is in units of fF/GHz^2
- $\mathrm{C3}$ is in units of fF/GHz^3

Short

A SHORT calibration standard is based on the terminated transmission line model where the termination impedance Z_T is defined by polynomial coefficients that represent an inductance model.The reflection coefficient values are computed using equations 9 through 10.

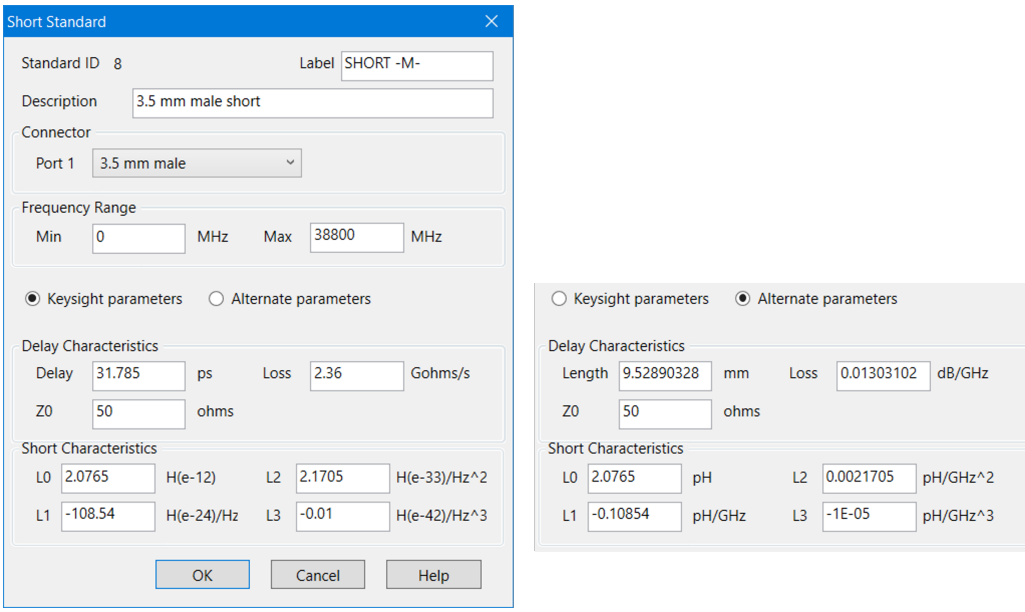


Figure 9. Short entry screen

Many vector network analyzers assume that the short is an ideal short and has a reflection coefficient of –1. This may be adequate at low frequencies and for large connector sizes, such as 7 mm and larger. However, at higher frequencies and for smaller connectors, 3.5 mm and smaller, at least a third order polynomial inductance model, L_{short}, is required. Loss of the short circuit is assumed to be insignificant.

$$\begin{aligned} L_{short} &= (\mathrm{L0}) + (\mathrm{L1})\,f + (\mathrm{L2})\,f^2 + (\mathrm{L3})\,f^3 \\ Z_T &= j2\pi f L_{short} \end{aligned} \tag{25}$$

Keysight parameters

- $\mathrm{L0}$ is in units of 10^{-12} H
- $\mathrm{L1}$ is in units of 10^{-24} $\mathrm{H/Hz}$
- $\mathrm{L2}$ is in units of 10^{-33} $\mathrm{H/Hz^2}$
- $\mathrm{L3}$ is in units of 10^{-42} $\mathrm{H/Hz^3}$

Alternate parameters

- $\mathrm{L0}$ is in units of pH
- $\mathrm{L1}$ is in units of $\mathrm{pH/GHz}$
- $\mathrm{L2}$ is in units of $\mathrm{pH/GHz^2}$
- $\mathrm{L3}$ is in units of $\mathrm{pH/GHz^3}$

Load

Four types of LOAD standards are available: a fixed load, sliding load, arbitrary impedance and offset load. The fixed load and arbitrary impedance load are based on the terminated transmission line model.

Fixed load

The default setting for fixed load is **Offset delay**$= 0$, **Offset loss**$= 0$, and **Offset** $\mathbf{Z_0} = Z_{ref}$; i.e. a perfect termination, $\Gamma_T = 0$. However, if an offset transmission line with a finite delay and loss is specified, and an **Offset** $\mathbf{Z_0}$ is not equal to the reference impedance (Z_{ref}), the total reflection is NOT zero. This is as defined in equation 10.

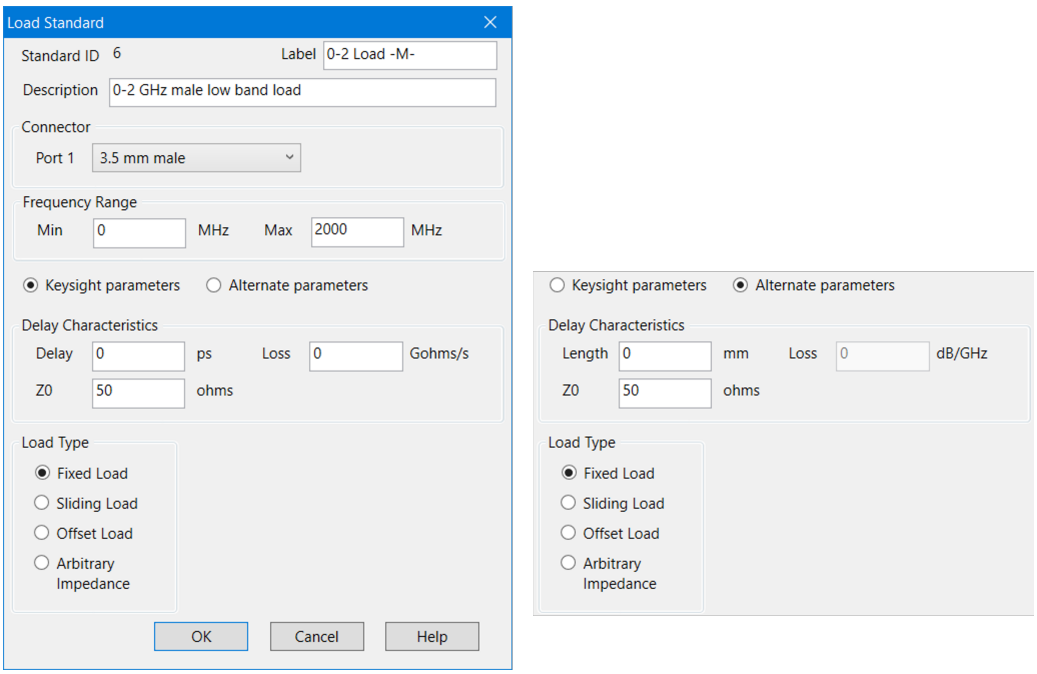


Figure 10. Fixed load entry screen

Sliding load

A sliding load is defined by making multiple measurements of the device with the sliding load element positioned at various marked positions of a long transmission line. The transmission line is assumed to have zero reflections and the load element has a finite reflection that can be mathematically removed, using a least-squares-circle-fitting method. For best results, move the load element in the same direction. Also, slide in non-uniform increments. A sliding load triggers prompts for multiple slide positioning and measurements. A minimum of 6 slide positions is recommended.

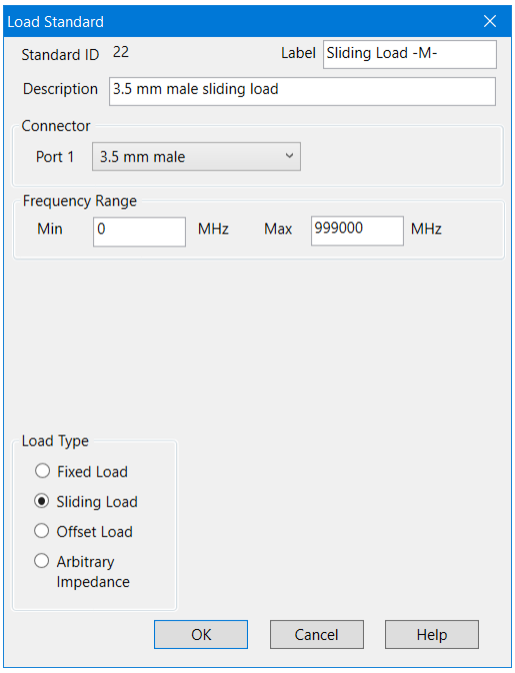


Figure 11. Sliding load entry screen

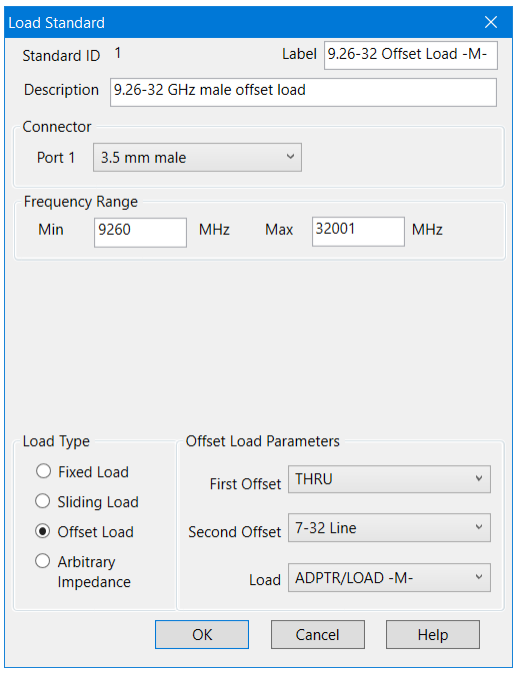


Figure 12. Offset load entry screen

Offset load

An offset load can be considered a compound standard consisting of 2 known offsets (transmission lines) of different lengths and a load element (Figure 12). The definition of the offsets is the same as all offset transmission lines. The shorter of the two offsets can be a zero length offset. The load element is defined as a one-port reflection standard. An offset load standard is used when the response of the offset standards are known more precisely than the response of the load element.

Measurement of an offset load standard consists of two measurements, one with each offset terminated by the load element. The frequency range of the offset load standard should be set so that there will be at least a $20°$ separation between the expected response of each measurement. In cases where more than two offsets are used the frequency range may be extended as the internal algorithm at each frequency will search through all of the possible combinations of offsets to find the pair with the widest expected separation (to use in determining the actual response of the load element.)

When specifying more than two offsets, the user should define multiple offset load standards. When assigning multiple offset load standards to SOLT classes for the VNA. it is usually beneficial to specify “use expanded math when possible”. See the Expanded calibration subsection on page 23.

Arbitrary impedance

An arbitrary impedance device is similar to a fixed load except that the load impedance is NOT perfect.

> It is possible to combine the arbitrary impedance with offset parameters to simulate an inductance in series with the arbitrary impedance. See the derivation of a transmission model to represent a lumped reactance model on page 57 for details. Alternatively a Data-based standard can be used.

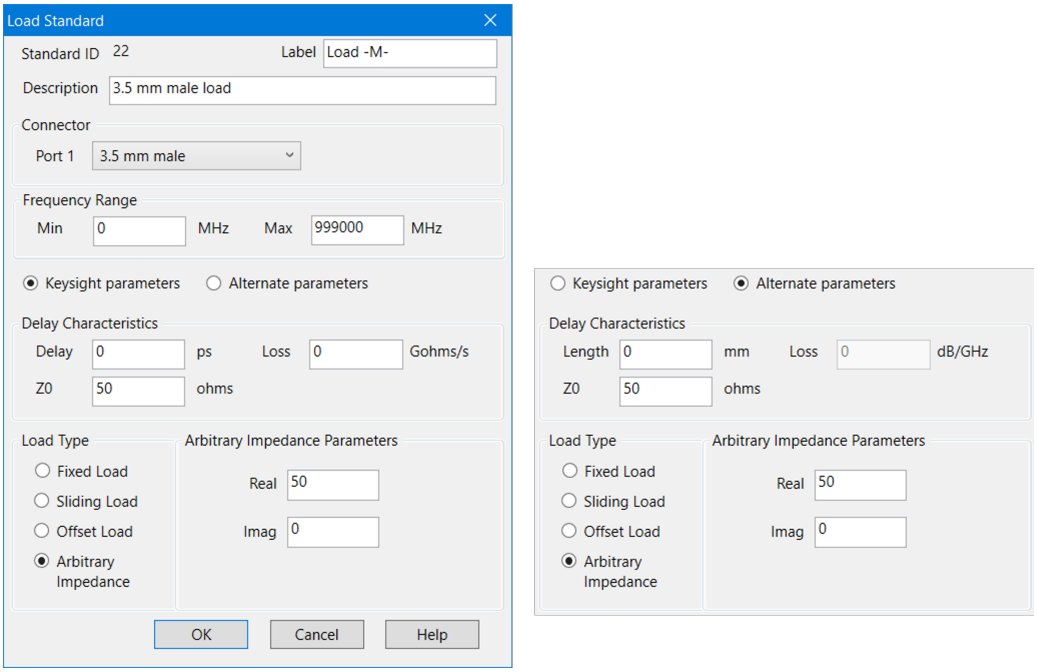


Figure 13. Arbitrary impedance load entry screen

$$
\begin{aligned}
Z_T &= R + jI \\
\Gamma_T &= \frac{Z_T - Z_r}{Z_T + Z_r}
\end{aligned}
\tag{26}
$$

Thru standard

The thru standard is based on the transmission line model

Figure 14 shows the parameters associated with the thru standard. The **Virtual Device** checkbox is set to indicate that the standard being modeled doesn't include a physical device. An example of a virtual device is the flush thru standard where the VNA testports are directly connected to each other. This signals the calibration software to create the appropriate descriptions of the calibration topology. For the flush thru standard checking **Virtual Device** causes the prompt to be **PORT 1** | **PORT 2** rather than **PORT 1** | **THRU** | **PORT 2**.

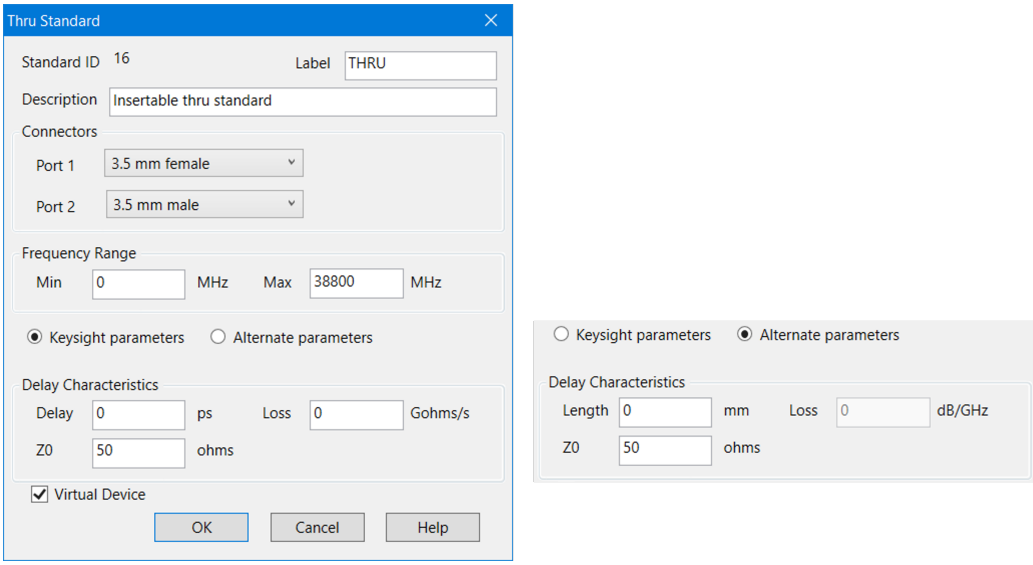


Figure 14. Thru entry screen

Data-based standard

The data-based standard model allows a calibration standard to be defined by a data file that contains frequency data, S-parameter data and confidence factor data. The confidence factor helps prioritize standards used during Expanded calibration and is usually related to the standard model uncertainty. See the Expanded calibration subsection on page 23. The data file may be created using actual measured data from a reference metrology laboratory, modeled data from device modeling software or combinations of both.

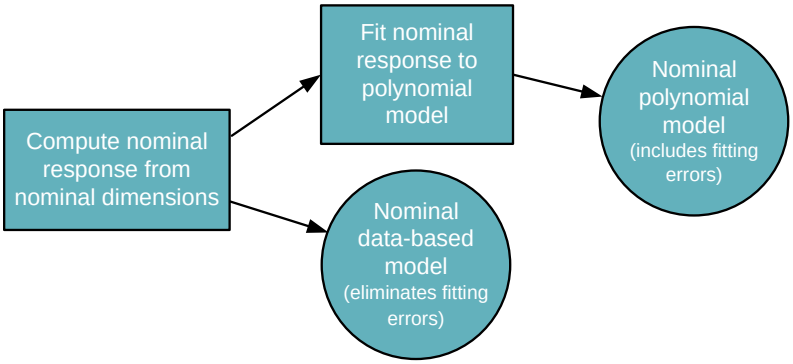


Figure 15. Data-based vs. polynomial model

Figure 15 shows how the data-based standard bypasses the fitting process and eliminates any errors that may have been associated with the fitting. Fitting errors are usually negligible for frequencies below 30 GHz. However, at higher frequencies multiple frequency banded models for the same standard have been used to avoid errors due to fitting. The data-based standard avoids this problem altogether by interpolating on the data directly.

The data-based calibration standard also eliminates shortcomings of fitting non-coaxial or waveguide standards to the models based on a coaxial or waveguide structure. This increased flexibility also enables the user to more easily define custom calibration standards that do not accurately fit existing calibration coefficient models. This

can be especially useful for dispersive transmission line structures. The data may be obtained by device modeling based on physical dimensions or from accurate measurements.

The factory data-based models are similar to polynomial models in that they are a generic nominal model for a particular part number. Thus, a replacement calibration standard can be ordered for a calibration kit and used without having to modify the data-based model.

Data-based standards also open the opportunity of enhancing the accuracy of a particular calibration kit. For example, calibration with a broadband load calibration kit is usually less accurate than calibration with either a TRL calibration kit or sliding load calibration kit.

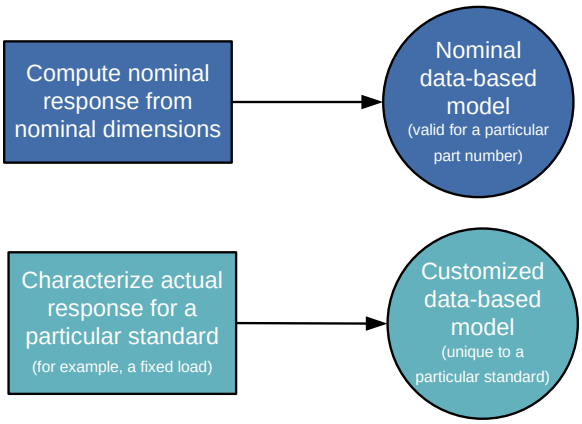


Figure 16. Nominal vs. customized data-based model

Figure 16 shows how data-based standards can be used to represent the response of all standards for a particular model number or it can be used to represent the response unique to a particular standard. Customized data-based models are useful when creating calibration kit with characterized devices; this can lead to a more accurate calibration as the actual response of the standard is used. Using a customized data-based model for a fixed load can significantly enhance the calibration rather than using a model that assumes the load is ideal. When replacing a calibration standard defined as a customized data-based model, it is important to remember to update the definition for the standard in the associated calibration kit file. Figure 17 shows the data entry screen for data-based standards. Calibrations using the fixed load and its associated data-based model will have an accuracy approaching the accuracy of the system that characterized the fixed load. The residual directivity error now depends on the uncertainty of the characterization rather than the specification of the load.

Data-based standard supported file types:

- Data-Based Cal Standard (*.dat) where a single file specifies both the s-parameter data and the confidence factors to define data-based model
- Citifile (*.cti, *.cit, *.citi) separate files are used to specify the s-parameter data and the confidence factors to define data-based model
- Snp file (*.s1p, *.s2p) separate files are used to specify the s-parameter data and the confidence factors to define data-based model

See Appendix E for details on the data-based cal standard (*.dat) file format.

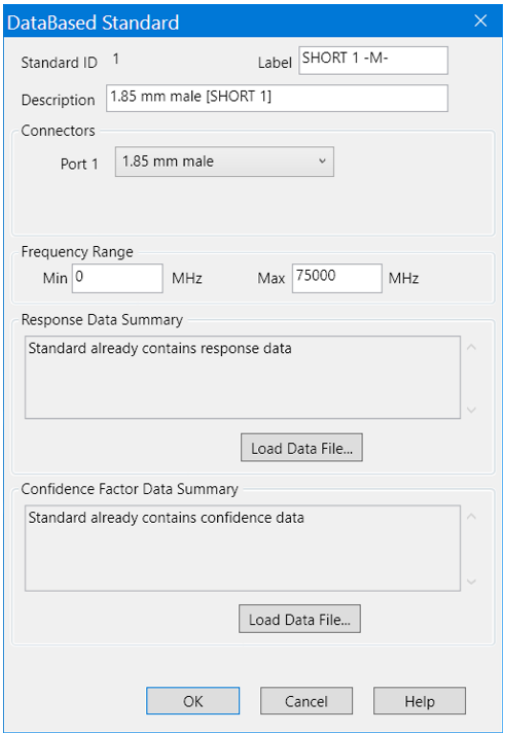


Figure 17. Data-based standard setup screen

Isolation standard

The isolation standard is a two port standard that is made of two one port standards. Figure 18 shows the use of two loads to specify the isolation standard.

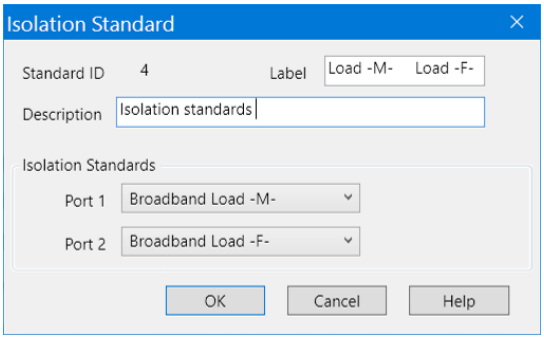


Figure 18. Isolation standard setup screen

Calibrations and class assignments

Calibration kits can be created to support the SOLT family of calibrations,

> The SOLT family includes, SOLT, SOLR, QSOLT and Oneport calibrations.

the TRL family of calibrations, or both. Class assignments are a way for the calibration kit file to guide the selection of standards during the calibration process.

When assigning standards to a class the order in which the standards appear indicates the default preference for the calibration kit. As the internal VNA firmware searches for the appropriate calibration standard to use at a given frequency it starts at the top of the list and searches until it finds a standard that can be used at that frequency. For this reason it is important to list the preferred standards first. For example,

> The TRL family includes, TRL, LRL, TRM, LRM, TRA, LRA, TSD, and LSD calibrations. It also includes multiline TRL.

a calibration kit that includes a sliding load usually also includes a broadband load—if the broadband load is listed before the sliding load, the sliding load will not come up as a default selection.

Multiport calibrations use a series of one-port and two-port calibration standards and are comprised of a series of one-port and two port calibration methods.

Calibration kit class assignments organize calibration standards into a format which is compatible with the error models used in measurement calibration. Some standards may have multiple different standard definitions. This was done to optimize the accuracy of the standard model for a given frequency band and/or calibration requirement when using polynomial models to fit the standard response. This is not necessary when using data-based standards to model the response.

There is no limit on the number of standards that can be defined in a calibration kit. The required number of standards will depend on frequency coverage and calibration methods supported.

A single standard class is a standard or group of standards that comprise a single calibration step. It is important to note that each and every class must be defined over the entire frequency range for which the calibration is made, even though several separate standards may be required to cover the full measurement frequency range.

Not all VNAs support the same set of calibration methods and calibration kits. Check the instrument's documentation for its capabilities. The following sections provide detailed descriptions of the various VNA class assignment structures.

SOLT class assignment

In the simplest case, an SOLT calibration consists of two one-port calibrations followed by forward and reverse transmission and reflection measurements on a thru standard. The thru standard can be a defined thru or an "unknown thru". The simplest thru standard is a zero-length thru which is simply the connection of port *i* to port *j*. Selecting the radio button corresponding to a particular class enables modification of both the standards

included in the class, and a user-defined label associated with the class. The user-defined class label is visible during calibration on the VNA when there is the possibility of selecting multiple standards for the class.

Each one-port calibration requires reflection measurements on at least three known and distinct standards. SA, SB, and SC represent the three reflection standard classes. The standards assigned to each class may have different connector definitions, different frequency coverage, and different standard types. Some calibration kits, such as the Keysight 85058B 1.85 mm precision calibration kit, use a combination of open, short, load, and offset short standards to calibrate over a very wide frequency range. Both shorts and opens are assigned to the SA class as illustrated by Figure 19. Label is just a name assigned to that class. This label is used for on-screen prompts or soft-key labels during the calibration measurement process.

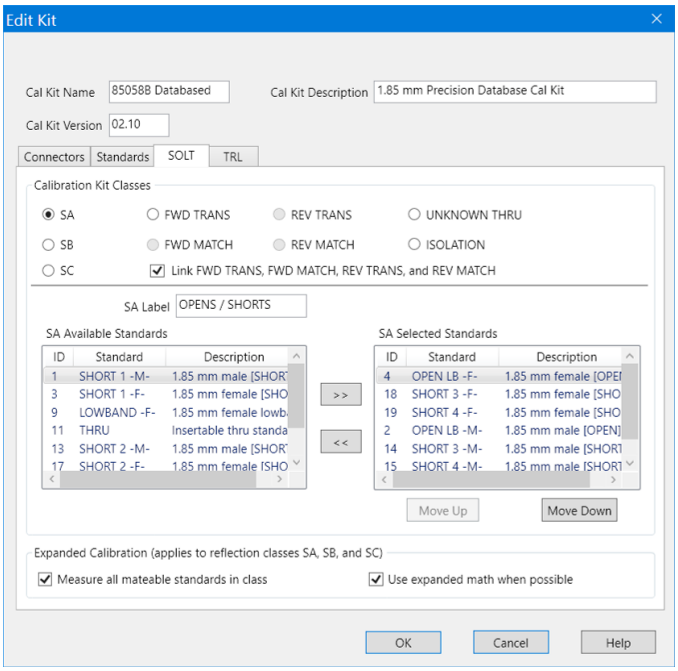


Figure 19. Calibration Kit Class edit screen showing opens and shorts in same class

Four calibration classes are associated with the thru standard measurements, namely: FWD TRANS, FWD MATCH, REV TRANS, and REV MATCH. Except for rare occasions, these classes will all contain the same standards; the **LINK FWD TRANS, FWD MATCH, REV TRANS, and REV MATCH** checkbox facilitates the common manipulation for these classes.

☑ Link FWD TRANS, FWD MATCH, REV TRANS, and REV MATCH

Unchecking the “Link” option provides the ability to define different standards for each of these classes. This option would be used in the rare case where an external testset may require manipulation between the various measurements of the thru standard. In this case assigning different standards for each class will result in a separate prompt during calibration. For example, one thru standard would be assigned to the FWD TRANS and FWD MATCH classes and a different thru standard, with an identical model, would be assigned to the REV TRANS and REV MATCH classes. This would result in two separate prompts during the calibration sequence.

The unknown thru calibration is one of the thru calibration methods of the VNA. It does not require a thru standard definition. Any two port passive reciprocal device can be used as the “unknown thru” device. A low-loss device, less than -20 dB loss, is recommended. Unknown thru and adapter removal calibrations require an approximate estimate for the transmission phase response of the unknown thru adapter in order to select the correct root during the computation of the calibration error coefficients. Adding adapters to the unknown thru calibration kit class allows the VNA firmware an ability to search through the list and find one that appears to match the measurement of the “unknown thru” device.

A class assignment table is a useful tool to help organize calibration standard assignments for data entry. All calibration kit operating and service manuals provide examples and blank forms of assignment tables. Compare the SOLT class assignment table (Table 1) with the VNA’s cal kit editor SOLT class assignment edit screen (Figure 20) to see the mapping relationships.

Table 1. SOLT class assignment table for the 85052D kit

Standard class	Standard numbers	Class label
SA	2, 15	Open
SB	1, 7	Short
SC	3, 14	Load
FWD TRANS	4	Thru
FWD MATCH	4	Thru
REV TRANS	4	Thru
REV MATCH	4	Thru

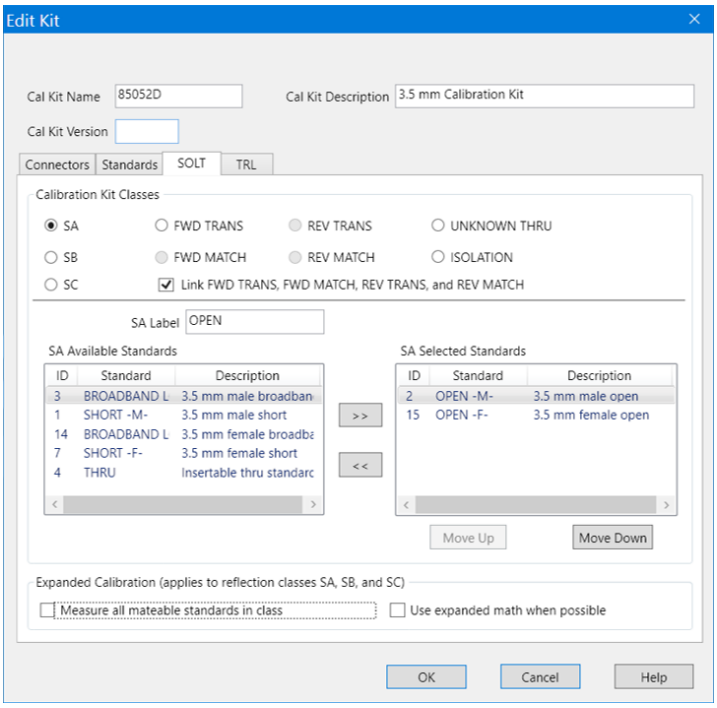


Figure 20. VNA’s cal kit editor modify SOLT class screen for 85052D kit

Traditionally, reflection calibrations have been computed using the measured response of three calibration standards at each frequency. For each port, three standards are selected, one each from SA, SB, and SC calibration kit classes and used to compute the systematic error terms associated with the port. Each class may include more than one standard, the specified minimum and maximum frequency of each standard in the class is used to determine which standard to use for a particular frequency.

Usually, when multiple standards are listed in a class their frequency ranges have a finite overlap. For the 8510 and unguided calibration on older Keysight VNAs, the last standard measured is used in the overlap region. Usually the load classes for a sliding load kit are defined with three load standards–a low band load, a sliding load and a broadband load. Often the low band load and the broadband load are the same physical device. The low band load has a reduced frequency range and is intended to be paired with the sliding load to cover the full frequency range of the kit. For users who desire a quicker, less accurate calibration, the broadband load is

defined to cover the full frequency range. In the 8510, if a user measured a sliding load then measured a broadband load, the calibration would be computed using only the broadband load ignoring the sliding load altogether. SmartCal (guided cal) avoids this problem by selecting the standards based on the order they are listed in the class, thus a sliding load will always have priority over a broadband load when it is listed before the broadband load. The current version of the Keysight VNA firmware uses the order of the standards in the calibration kit classes when resolving frequency overlaps.

Expanded calibration

Expanded Calibration (applies to reflection classes SA, SB, and SC)

☑ Measure all mateable standards in class ☑ Use expanded math when possible

Expanded calibration uses a weighted least squares solution for one-port calibrations that use the measurement of more than three standards[18]. The least squares solution works well when all observations are trusted to the same degree. That is to say the actual response of each standard is known with the same confidence so the weighting factors will be equal. This is a reasonable assumption for ECal, but may not be valid when a least squares approach is applied to calibrations using other calibration kits due to the differences in the confidence in the models for the standards.

Expanded math is a weighted least squares solution to handle the case where the observations are not all trusted to the same degree[19]. If the observations are all independent but not equally trusted, an optimal solution is best obtained by multiplying each equation by a combined factor that includes both the confidence factor of the standard and the proximity of the standard's response to the response of the other measured calibration standards. The confidence factor of the standard model is explicitly defined for data-based standards, for the other standards a nominal confidence factor is assigned to provide a relative weighting for the weighted least squares solution see Table 2. The measurement of a standard is included in the weighted least squares solution over the frequency range where the confidence factor of the standard is defined; this frequency range is greater than or equal to the frequency range where the standard is selected specified by the min/max frequencies. F_{min} in Table 2 corresponds to the minimum frequency specified for the standard. $\hat{F}_{min}$ and $\hat{F}_{max}$ correspond to the minimum and maximum frequency where confidence is specified. $F_{conn_{min}}$ and $F_{conn_{max}}$ correspond to the minimum and maximum frequency range of the connector. Also in Table 2 endpoints are given; a nominal confidence factor at a given frequency is computed as a linear interpolation between the appropriate endpoints.

For the Open, Short, and Fixed Load standards the confidence factor at U_{max} is limited to be greater than or equal to the confidence factor at U_{min} and less than or equal to 1. F_X is the crossover frequency between the fixed load and the sliding load. For the fixed load $F_X = F_{max}$. For the sliding load $F_X = F_{min}$.

Table 2. Default relative confidence factor of cal standards types

	Frequency range		Nominal confidence factor		
Standard type	$\hat{F}_{min}$	$\hat{F}_{max}$	U_{min}	U_{F_X}	U_{max}
Open	$F_{conn_{min}}$	$F_{conn_{max}}$	0.01		$\frac{U_{max}}{10^{12}}$
Short	$F_{conn_{min}}$	$F_{conn_{max}}$	0.005		$\frac{U_{max}}{10^{13}}$
Fixed Load	$F_{conn_{min}}$	$F_{conn_{max}}$	0.003	0.003	$\frac{3U_{max}}{10^{12}}$
Sliding Load	$\frac{F_X}{2}$	$F_{conn_{max}}$	0.01	0.003	0.003

When **Use expanded math when possible** is checked, the solution (on a frequency by frequency basis) includes all of the one-port standards that fall between their U_{min} and U_{max} values. For example, consider a sliding load calibration that includes frequencies in both the low band load and sliding load frequency ranges. The open, short, low band load and sliding load will be measured. The sliding load will be included when the frequency falls between U_{min} and U_{max} associated with the sliding load. Using expanded math in this case will blend the transition between the low band load frequency range and the sliding load frequency range. As another example, the 85058B 1.85 mm calibration kit has a low-band load, an open and a series of short standards with varying offsets. There is a minimal set of standards defined that would insure calibration with three standards is possible at each frequency. The minimum and maximum frequency ranges for each standard combined with the class assignments will determine a set of three standards for each frequency resulting in a series of frequency ranges where only three standards would be required. If the VNA spans more that one of these frequency ranges there will be more than three reflection standards connected. In the case of the 85058B, in addition to blending the transitions between the frequency ranges, the overall accuracy of the calibration improves when using expanded math. **Measure all mateable standards in class** can be checked which adds all of the mateable standards in the SA, SB and SC calibration kit classes without considering the specified frequency range for the standards. Measuring all of the standards results in the best accuracy for kits like the 85058B and the 85059B.

It is advantageous to measure all of the standards for some calibration kits, but not for others. For example, in the case of the sliding load kit discussed earlier, selecting measure all standards in class would result in measuring the low-band load, the sliding load and the broadband load. There is no advantage to measuring two fixed loads when doing a sliding load calibration.

TRL class assignment

The TRL/TRM family of calibration is defined by the TRL THRU, REFLECT and LINE classes plus TRL options. Table 3 shows the TRL portion of a typical VNA class assignment table. Current Keysight VNAs include the Multiline TRL algorithm which is based on the NIST Multiline TRL calibration algorithm called MultiCal[20][21]. It provides an over-determined solution when multiple *line* standards are used.

> TRL does not support the use of data-based standards for *thru* or *line* standards. Data-based standards can be used for *match* or *reflect* standards.

TRL is a generic name that represents a class of calibrations that allow partially known calibration standards to be used. In general, the *thru* standard is assumed to be fully known with perfect match; the reflect standard is assumed to have a high reflection with unknown amplitude and partially known phase. The *line* standard is assumed to have the same propagation characteristics as the *thru* standard with partially known phase. Table 4 provides a mapping of specific calibration types to the TRL class.

The **Calibration Reference $\mathbf{Z_0}$** option allows for adjustments to the calibration to account for small perturbations between **Connector $\mathbf{Z_0}$** and the line characteristic impedance Z_c which is derived from the defined **Offset delay**, **Offset loss** and **Offset $\mathbf{Z_0}$** terms. See equation 43 in Appendix B on page 54. If **Line $\mathbf{Z_0}$** is selected, no adjustments are made.

Table 3. TRL class assignment table

Standard class	Standard numbers	Class label
TRL THRU	15	Thru
TRL REFLECT	7, 14	Shorts
TRL LINE/MATCH	16, 17, 2, 9	Lines
ISOLATION		Isolation

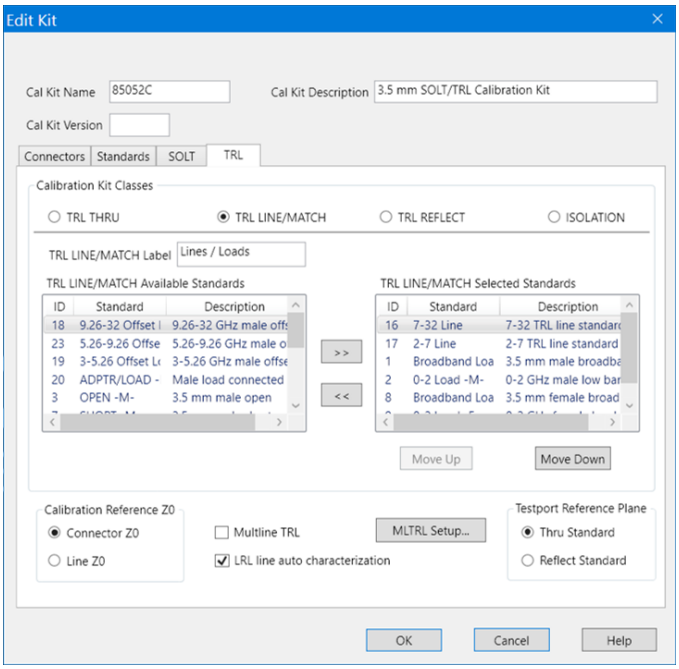


Figure 21. TRL class edit screen for 85052C kit

Caution: Do not select **Connector Z_0** *if* **Offset Z_0** *of the line or match standard is very different from* **Connector Z_0**. **Connector Z_0** is the Impedance associated with the testport connector. See the connector definitions section on page 5.

TRL calibration is computed initially at a reference plane that corresponds to the middle of the *thru*. In this case, the *line* standard can be assumed to be the portion of the *line* standard left over after subtracting a length equal to the length of the *thru* standard. After the error coefficients are computed, they are adjusted to establish the **Testport Reference Plane** based on either the model of the *thru* standard or the model of the *reflect* standard. When selecting the **Reflect Standard** to set the **Testport Reference Plane**, the assumption is that the *reflect* standard is precisely known as both magnitude and phase of the *reflect* standard will be used to compute the error term adjustments. Selecting the **Thru Standard** to set the reference plane obviously works for a zero length *thru*. In the case when the *thru* standard is a line with non-zero length, the model of the *thru* standard is used to compute the error term adjustments.

The generalized TRL algorithm assumes the characteristic impedance of the *thru* and *line* standards are equal. In the case of coax or waveguide, using the model of the *thru* standard will provide excellent results. In the case of other dispersive media such as microstrip, the *thru* standard may not model the dispersion with sufficient accuracy and therefore could yield sub-optimal results. One option would be to design the test fixture and calibration standards so that the testport would be located in the middle of the *thru*. Another alternative would be to select **LRL line auto characterization**. One of the by-products of the TRL algorithm is a computed value for the *line* standard propagation constant. This would include any dispersive effects of the transmission medium. When **LRL line auto characterization** is set the propagation characteristics of the *thru* standard are computed from the computed propagation characteristics of the *line* standard and the defined delays for both the *thru* and *line* standards. Note, **LRL line auto characterization** will only be used at frequencies where both the *thru* and *line* standards are delay lines and where the offset impedance of the *thru* and *line* standards are equal.

Table 4. Mapping TRL standards to TRL class

	Thru class	Reflect class	Line class
TRL (thru/reflect/line)	Zero length thru with $S_{11} = S_{22} = 0$, $S_{21} = S_{12} = 1$	Unknown equal reflect on port i and port j. Phase approximately known.	Line with $S_{11} = S_{22} = 0$ phase approximately known. Bandwidth limited to avoid phase of $\pm$ 20°.
LRL (line/reflect/line)	Line 1 with $S_{11} = S_{22} = 0$, S_{21} and S_{12} both known with same propagation characteristics as Line 2.	Unknown equal reflect on port i and port j. Phase approximately known.	Line 2 with $S_{11} = S_{22} = 0$ phase approximately known. Bandwidth limited so phase is at least $\pm$ 20° different from phase of Line 1.
TRM (thru/reflect/match)	Zero length thru with $S_{11} = S_{22} = 0$, $S_{21} = S_{12} = 1$	Unknown equal reflect on port i and port j. Phase approximately known.	Can be defined as fixed loads on ports i and j $\Gamma_{Li} = \Gamma_{Lj}$ and known. Can also be defined as very long lossy line.
LRM (line/reflect/match)	Line with $S_{11} = S_{22} = 0$, S_{21} and S_{12} both known.	Unknown equal reflect on port i and port j. Phase approximately known.	Can be defined as fixed loads on ports i and j $\Gamma_{Li} = \Gamma_{Lj}$ and known. Can also be defined as very long lossy line.
TRA (line/reflect/attenuator)	Zero length thru with $S_{11} = S_{22} = 0$, $S_{21} = S_{12} = 1$	Unknown equal reflect on port i and port j. Phase approximately known.	Attenuator between ports i and j $S_{11} = S_{22} = 0$. Defined as lossy line.
LRA (line/reflect/attenuator)	Line with $S_{11} = S_{22} = 0$, S_{21} and S_{12} both known.	Unknown equal reflect on port i and port j. Phase approximately known.	Attenuator between ports i and j $S_{11} = S_{22} = 0$. Defined as lossy line.
TSD (thru/short/delay)	Zero length thru with $S_{11} = S_{22} = 0$, $S_{21} = S_{12} = 1$	Single known reflect on port i or port j.	Delay (line) standards with $S_{11} = S_{22} = 0$ phase approximately known. Only available with Multiline TRL.
LSD (line/short/delay)	Line with $S_{11} = S_{22} = 0$, S_{21} and S_{12} both known.	Single known reflect on port i or port j.	Delay (line) standards with $S_{11} = S_{22} = 0$ phase approximately known. Only available with Multiline TRL.

Multiline TRL

The TRL algorithm (Legacy TRL) that existed prior to Multiline TRL being added is still available for use. If the **Multiline TRL** check box is selected, then the Multiline TRL algorithm will be used when the defined calibration kit is used for TRL calibration. The Legacy TRL algorithm allowed multiple *line* standards to be used, but for any given frequency only one *line* standard is used with the *thru* and *reflect* standards. Figure 22 is the TRL tab that comes up when editing the class definitions of the calibration kit. It's purpose is to define which standards are to be used for during the TRL calibration.

Both Legacy TRL or Multiline TRL automatically use a Thru Reflect Match (TRM) calibration when the frequency is below the lowest start frequency of the *line* standards defined in the calibration kit if there are *match* standards defined.

In addition to Multiline TRL there is also an option to select Multiline TSD see Figure 23. The Multiline TSD algorithm differs from the Multiline TRL in how the algorithm uses the *short*/*reflect* standard. For Multiline TSD the *short* standard is assumed to be fully known and only connected to one port. For Multiline TRL the *reflect* only needs to be partially known but has to be connected to both ports. For both Multiline TSD and Multiline TRL the *line* and *delay* standards are equivalent.

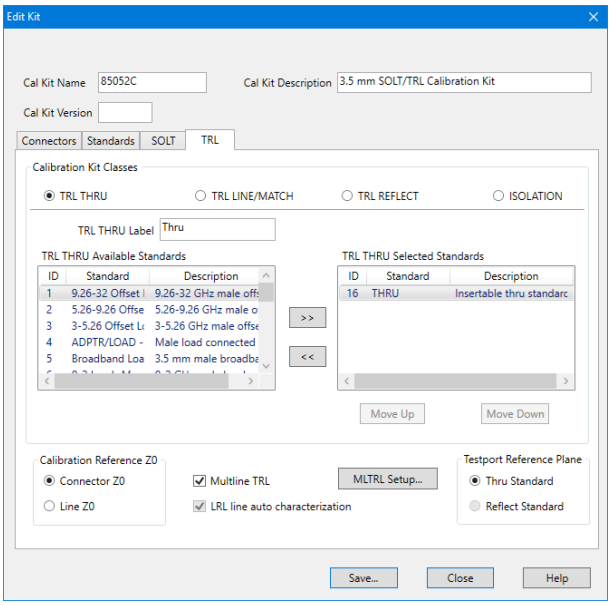


Figure 22. TRL tab in cal kit editor.

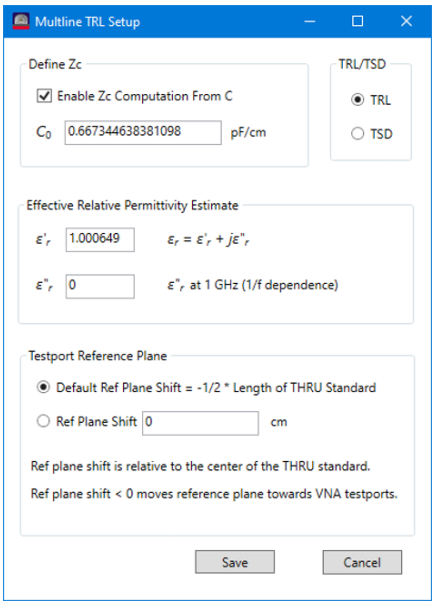


Figure 23. Multiline TRL setup dialog.

Multiline TRL Kit Classes

For TRL there are four categories of standards called Calibration Kit Classes. They are TRL THRU, TRL LINE/MATCH, TRL REFLECT and ISOLATION. The ISOLATION class is optional.

TRL THRU class when Multiline TRL is selected

The TRL THRU class should be setup so that only a single standard is defined for a given pair of port connectors. Generally this means that for Multiline TRL calibrations there will only be one standard defined in the TRL THRU class that is intended to be used over the entire frequency range. It should be noted that the legacy TRL algorithm still may benefit from using multiple *thru* standards in order to provide the best phase margin over different frequency ranges.

TRL LINE/MATCH class when Multiline TRL is selected

This actually represents two classes that share a similar purpose during calibration. A *line* standard needs to have a distinct response from the *thru* standard. Typically the *line* standard is chosen such that the phase of $S_{21_{line}}$ is different from the phase response of $S_{21_{thru}}$ by at least $20°$. This becomes prohibitive at low frequencies so *match* standards are used with a TRM calibration at frequencies where it is impractical to create *line* standards. Both the Legacy TRL and Multiline TRL calibrations use *match* standards and TRM calibration to cover the low frequency portion as needed. In those cases, the calibration is actually a mix of TRM and TRL.

The TRM portion of the calibration is not over-determined when Multiline TRL is selected. A fundamental assumption of the TRL algorithm is that the characteristic impedance of the *thru* standard is the same as the characteristic impedance of each of the *line* standards. The match standard is often defined as an idealized fixed load standard with reflection coefficient = 0, but it can be defined as a non-ideal standard; for example, by using a data-based standard which can be used to adjust for the actual reflection coefficient of the standard. Both Legacy TRL and Multiline TRL assume the data-based standards have the same reflection coefficient applied to both ports.

TRL REFLECT

When doing a TRL calibration there is a fundamental assumption that the *reflect* standard is the same on both ports. It doesn't have to be fully known, but should be approximately known to permit the correct root selection during the calibration process. For gendered connectors, multiple *reflect* standards need to be created, one for each connector gender, each standard should have the same model.

The Multiline TRL algorithm has the option to do a TSD calibration instead of TRL calibration. In that case, only one *reflect* standard is used; but it has to be fully known. When doing a TSD calibration, one has the option of deciding which *reflect* standard to be used. In general, the order of the calibration standards in a Calibration Kit Class is important as the calibration algorithms step through the standards from top to bottom selecting standards until it accumulates enough standards to satisfy all of the frequency requirements for each port. In the case of TSD, the order of the *reflect* standards is significant because as the TSD portion of the algorithm steps through the standards listed in the TRL REFLECT class it will use the first *reflect* standard it finds that will mate with either of the testports. The user specifies which algorithm to use Multiline TRL or Multiline TSD on a kit by kit basis by making the desired selection in the Multiline TRL Setup dialog (see Figure 23).

A data-based standard can be used for the *reflect* standard. In general there is no advantage to using a data-based standard for Legacy TRL and Multiline TRL calibrations since only an approximate value for the reflect is required. There are a couple of instances where using a data-based standard might provide benefit. In the Legacy TRL when the **Reflect Standard** is used to define the **Testport Reference Plane**, the actual value

of the *reflect* standard obtained from the standard model is used to set the reference planes. In the Multiline TSD calibration, the actual value of the standard model is also used to compute the error terms.

Relationship between delay and physical length with Multiline TRL

The NIST MultiCal software defines the calibration standards using physical lengths and relative permittivity. The Keysight implementation also defines the same standards but uses an offset delay term to be consistent with existing calibration standard definitions. Traditionally, the offset delay model used by both *thru* and *line* standards has the offset defined by a delay parameter. The delay specified for the standard offset is assumed to be equivalent to the delay a TEM mode would face for a given physical length. The Keysight Multiline TRL algorithm assumes the physical length is constant and computes that value from the offset delay parameter defined in the standard's model. The physical length is obtained using the real part of the relative permittivity estimate (see Figure 23) and then held constant even while the Multiline TRL algorithm adjusts the relative permittivity during subsequent computations.

Calibration Reference Z_0

Both Legacy TRL and Multiline TRL algorithms assume the characteristic impedance for the *thru* and *line* standards are the same. The computations optimize the error terms for the characteristic impedance of the standards. There are multiple impedance terms that are used by both the Legacy TRL and Multiline TRL algorithms. There is an additional impedance term Z_{line} that is not defined in the calibration kit but is computed by the TRL algorithms. It is inherently subject to the assumptions that all of the *thru* and *line* standards have the same characteristic impedance. When **Line $\mathbf{Z_0}$** is selected as the **Calibration Reference $\mathbf{Z_0}$** setting, the characteristic impedance of the measurement system after calibration is simply Z_{line}.

For Legacy TRL, when **Connector $\mathbf{Z_0}$** is selected an impedance transformation is applied which assumes that characteristic impedance of the *line* standard is equal to Z_c as computed using equation 43 and the math to transform from Z_c of the *line* standard to **Connector $\mathbf{Z_0}$** is applied (see Figure 24).

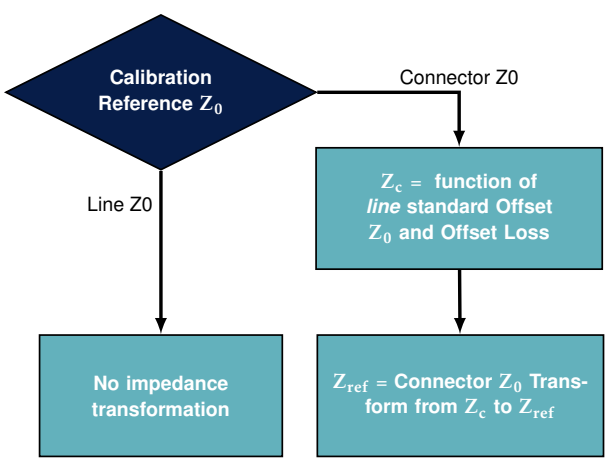


Figure 24. Calibration kit settings for Legacy TRL impedance transformations.

The impedance transform process for Multiline TRL has differences in how Z_c is computed as shown in Figure 25.

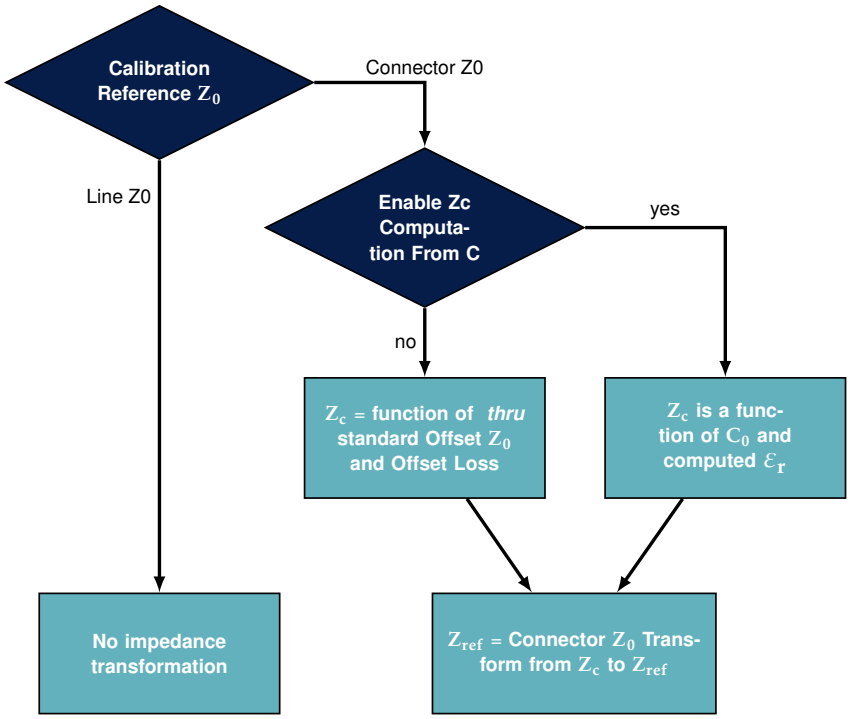


Figure 25. Calibration kit settings for Multiline TRL impedance transformations.

Line Z_0

If the user selects **Line Z_0** in the **Calibration Reference Z_0** section (see Figure 22) the computed error terms are used without any additional impedance transform. Additionally, when the user selects **Line Z_0** , the **Define Zc** section in the Multiline TRL setup dialog is disabled (see Figure 23).

Connector Z_0

There is a slight difference in behavior between Legacy TRL and Multiline TRL due to the additional **Define Zc** section in the Multiline TRL setup dialog (see Figure 23).

Legacy TRL uses the definition of **Offset Z_0** and **Offset Loss** specified in the *line* standard model. If this is not equal to the **Connector Z_0** specified on the Connectors tab (see Figure 26) an impedance transform is applied to the error terms.

Multiline TRL uses the definition of **Offset Z_0** specified in the *thru* standard model. If **Enable Zc computation from C** is checked in the Multiline TRL setup dialog an additional impedance transform is done to account for the low frequency dispersion specified by C_0. This additional impedance transform uses the complex relative permittivity of the line (ϵ_r) that is characterized during the calibration process. There are papers published to explain details for determining the low frequency dispersion from the characterization of the propagation constant and an estimate of C_0[22][23][24]. This also uses the characterization of the relative permittivity which covers the full frequency range of the Multiline TRL algorithm. The transmission line capacitance can also be characterized by additional measurements[25]. If the **Offset Z_0** specified in the *thru* standard model is different from the **Connector Z_0** specified on the Connectors tab the error terms are modified by an impedance transform. A default value for C_0 is computed using characteristic impedance specified by **Offset Z_0** for the *thru*

standard model. Inputting a negative value for C_0 will cause the default value to be reinserted. There is also an interaction between the real part of the line's relative permittivity (ε'_r) and C_0. If C_0 is equal to the default value changes to ε'_r will update C_0. If a user has specified a different value for C_0 no change to C_0 will be made when changes to ε'_r are made. The default value for C_0 is computed as

$$C_0 = \frac{\sqrt{\varepsilon'_r}}{(\textbf{Connector } \mathbf{Z_0})\, c} \tag{27}$$

where c is the free space speed of light.

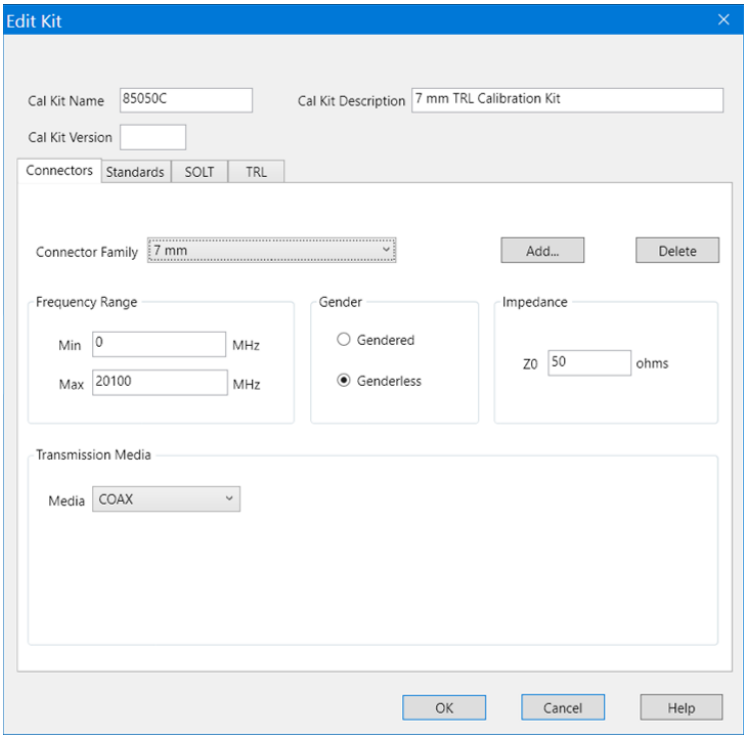


Figure 26. Connectors tab in cal kit editor.

Testport Reference Plane

The **Testport Reference Plane** options differ between the Legacy TRL and Multiline TRL options. The initial calibrations for both Legacy TRL and Multiline TRL both assume the reference plane is in the middle of the *thru* standard. This becomes significant for the LRL case where the delay of the *thru* standard is greater than zero.

Testport Reference Plane for legacy TRL

Legacy TRL has the option to use either **Thru Standard** or **Reflect Standard** to set the reference plane after calibration. If the *thru* standard is selected the reference plane for each testport will be rotated towards the VNA testport by half the delay of the *thru* standard. If **LRL line auto characterization** is checked, the propagation constant computed during the TRL calibration will be used to estimate the rotation based on the delays specified by the *thru* and *line* standards; otherwise, the modeled behavior of the *thru* standard will be used.

Testport Reference Plane for Multiline TRL

When Multiline TRL is selected the ability to select **LRL line auto characterization** is disabled because Multiline TRL always uses LRL line auto characterization. The ability to select **Reflect Standard** to define the testport is not an option with Multiline TRL but Multiline TSD uses the **Reflect Standard** on one of the ports to set the reference plane for both ports. There is an additional option of defining an arbitrary reference plane. A negative number input for the reference plane shifts the testport towards the VNA testports.

The default behavior is to shift the **Testport Reference Plane** to the edge of the *thru* standard with behavior similar to the Legacy TRL behavior having the **Testport Reference Plane** set by the *thru* standard and having **LRL line auto characterization** active.

Considerations when creating and using calibration kits

It is important to remember the fundamental assumptions for VNA calibration when creating and evaluating any user defined calibration kit.

- Vector error correction inherently assumes that there is a single propagating mode at the calibration and measurement reference planes. This can lead to challenges particularly for PC board and on-wafer calibrations at higher frequencies. Careful design of calibration standards can minimize the impact of this.
- It is assumed that the systematic errors that are characterized are constant during the calibration and measurement processes. Selecting high quality cables and minimizing cable movement during calibration and measurement can help avoid changes to the systematic errors that will degrade the vector error correction process.
- Test fixtures that add significant loss make the measurement system more sensitive to instrument drift. It is always important to evaluate the performance over time in order to estimate the quality of the measurements.
- It is important to understand the assumptions of the calibration method being used. It is important to know which standards are fully defined; if you remeasure a fully defined calibration standard after the calibration process it will match it's definition. Many people make the mistake of assuming that it is possible to gain insight into the quality of the calibration by remeasuring one or more of the calibration standards after calibration. If the standard is a fully defined standard it can give insight into the connector repeatability and drift of the system since calibration but it provides no indication in the overall quality of the calibration.
  - TRL family calibrations: Table 4 lists the assumptions for TRL standards. In general, the Thru class standard is a known standard it is fully defined with perfect match. The Reflect class standards is partially known but equal on both ports; the reflect standard shifts to be fully defined if the reflect standard is used to define the Testport Reference Plane. The Line class standard is partially known; it is assumed to have perfect match with the same propagation characteristics as the Thru standard. Deviations from the assumptions will lead to errors in the characterization of systematic error terms. For example, when different physical standards are used as Reflect standards, the characterization of systematic error terms will degrade proportionally to the difference between them. Also, for

on-wafer or PC board calibration kits using a meander line, the Line standard will degrade the calibration as the bends in the line will change both the return loss and propagation characteristics of the line.

  - SOLT family calibrations (excluding SOLR):

    > SOLR and Unknown Thru are often used interchangeably.

    All of the standards are assumed to be fully known.

  - Unknown Thru calibration: The unknown thru standard is the least constrained standard. The only assumption about the unknown thru standard is that it is reciprocal. This makes it a very useful calibration as the unknown thru adapter can have non-ideal match. It is often useful to have the same testport topology as the devices to be measured after the calibration in order to help minimize cable movement. If the devices to be measured are reciprocal, they can often be used as the unknown thru device. In theory the unknown thru device can be lossy; however, it is good practice to minimize the loss particularly if the device is going to be characterized and used as a known device in another portion of the calibration. Measurement of the unknown thru device can provide more insight into the overall quality of the calibration since the only assumption is that it is reciprocal.

- Connector repeatability is the term that represents the variation in the standard response due to the connection process. It provides a random deviation to measurements both of the calibration standards and the DUTs resulting in measurement degradation. There are things that can be done to minimize the impact of connector repeatability.
  - Use high quality connectors and cables.
  - PC board calibration kits often define the calibration interface somewhere on the PC board. Even in these cases, the connection to the VNA is usually through a coaxial connector. An inherent assumption is that the coaxial connection is similar for each of the standards. The deviation between connectors is a form of connector repeatability. Better quality connectors will have better consistency; in general, end launches are better than right angle launches. Time domain reflectometry (TDR) is a useful tool to help evaluate the consistency of PC board connectors. Some precision cases have actually used the same physical coaxial connector and moved it from standard to standard in an effort to minimize the variation introduced when using the coaxial connector launches.
  - Use proper connector inspection, cleaning methods and torque.
  - For waveguide connectors use the precision alignment pins.
- PC boards are not always homogeneous. Keep thru and lines in the same orientation with respect to the grain of the PC board.
- PC board and on-wafer calibration kits often have a fixed topology for the standards on the calibration card. When creating a calibration kit it may be useful to assign separate connector families to each position such as Probe1, Probe2, etc. When doing so, it is possible to only assign straight lines to defined standards. Bent lines are often useful as unknown thru adapters.

Calibration kit editing procedure

Calibration kit modification provides the capability to adjust the calibration standards selected and how they are used for various calibration types. Editing the calibration standards affects the models of the standards. Adding the calibration standards to various calibration kit classes determines how they will be used during calibration and the ordering of the calibration standards in calibration kit classes determines their prioritization. The process to edit or create a cal kit consists of the following steps:

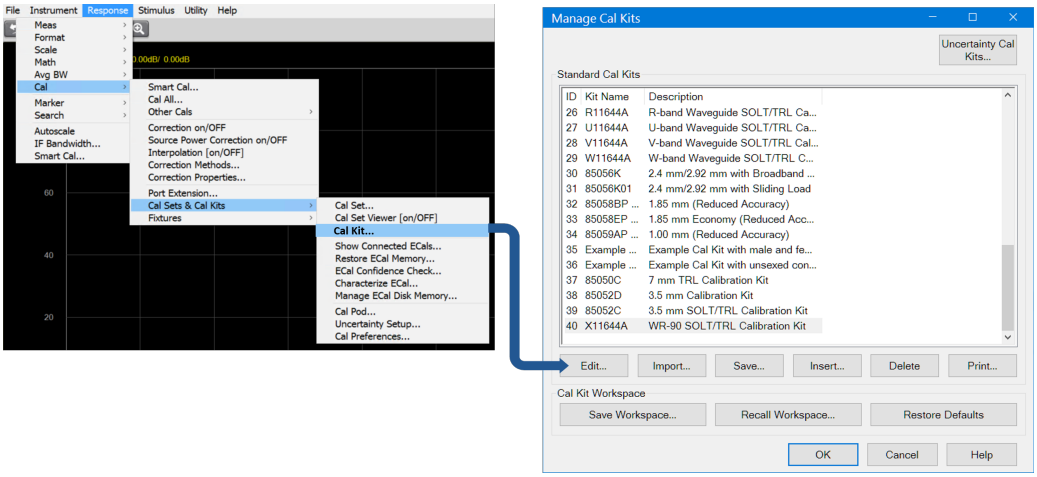
1. Launch the Cal Kit Editor
2. Select the calibration kit to edit or create a new kit
3. Edit Cal Kit Name, Description and optionally Version
4. Define the Connectors (COAX or WAVEGUIDE)
5. Select Standards
6. Add or edit the Standard definitions
7. Assign Standards to calibration kit classes (SOLT and/or TRL)
8. Save the edited calibration kit

The steps for creating a new calibration kit for the X11644A calibration kit are shown below.

Launch the Cal Kit Editor

The Cal Kit Editor is available in the VNA or a standalone version is available online at https://www.keysight.com/us/en/lib/software-detail/computer-software/pna-service-applications.html. The Cal Kit Editor in the VNA deals with multiple calibration kits while the standalone version deals with a single calibration kit at a time.

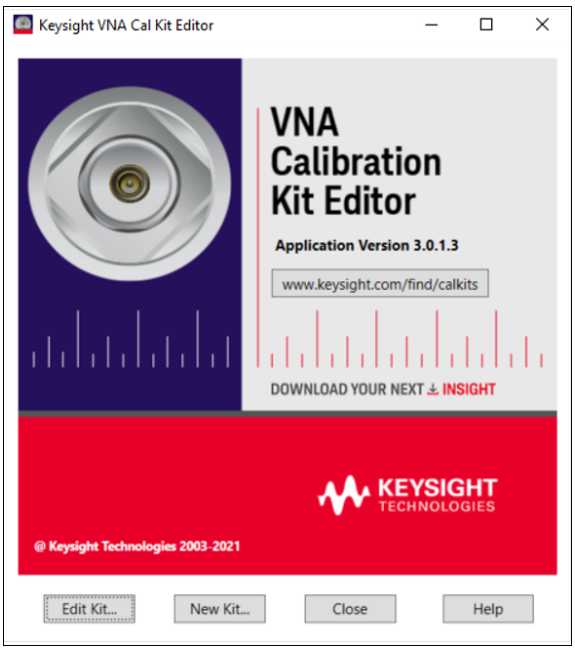
Launch from VNA



Select **Response** → **Cal** → **Cal Sets & Cal Kits** → **Cal Kit...** The Manage Cal Kits dialog shows a list of calibration kits installed in the VNA. There are several options for editing or creating a calibration kit.

- To edit an installed calibration kit, highlight the desired kit then press Edit...
- To load an existing calibration kit file select Import...
- To create an new calibration kit select Insert...

Launch standalone version



The standalone editor deals with cal kit files.

- To load an existing calibration kit file select Edit Kit...
- To create an new calibration kit select New Kit...

Edit cal kit name and description

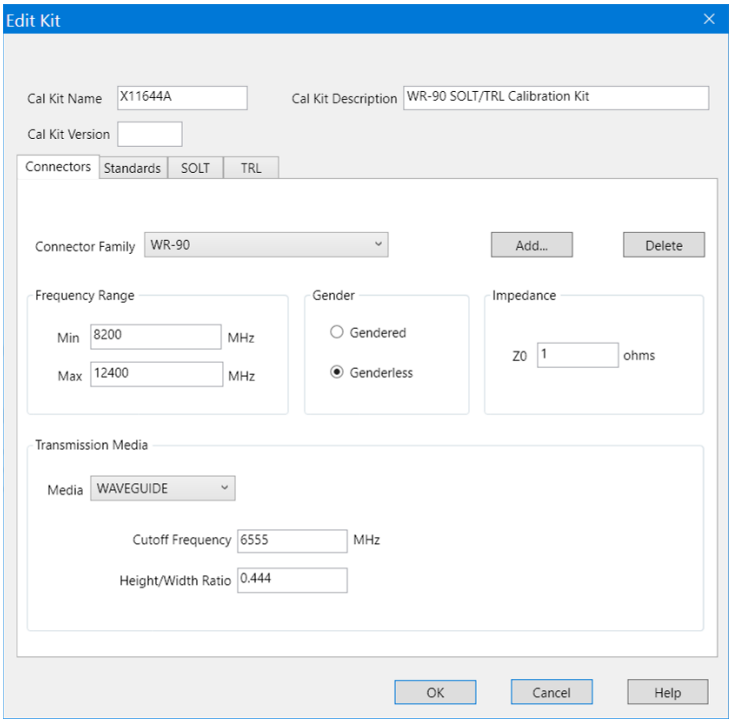
For this step and subsequent steps the calibration kit editor launched from the VNA and the standalone calibration kit editor behave the same. The X11644A calibration kit contains standards with WR-90 rectangular waveguide connectors.

1. Enter **X11644A** in the **Cal Kit Name** field
2. Enter **WR-90 SOLT/TRL calibration kit** in the **Cal Kit Description** field

Add Connector definition

The WR-90 connector has the following properties:

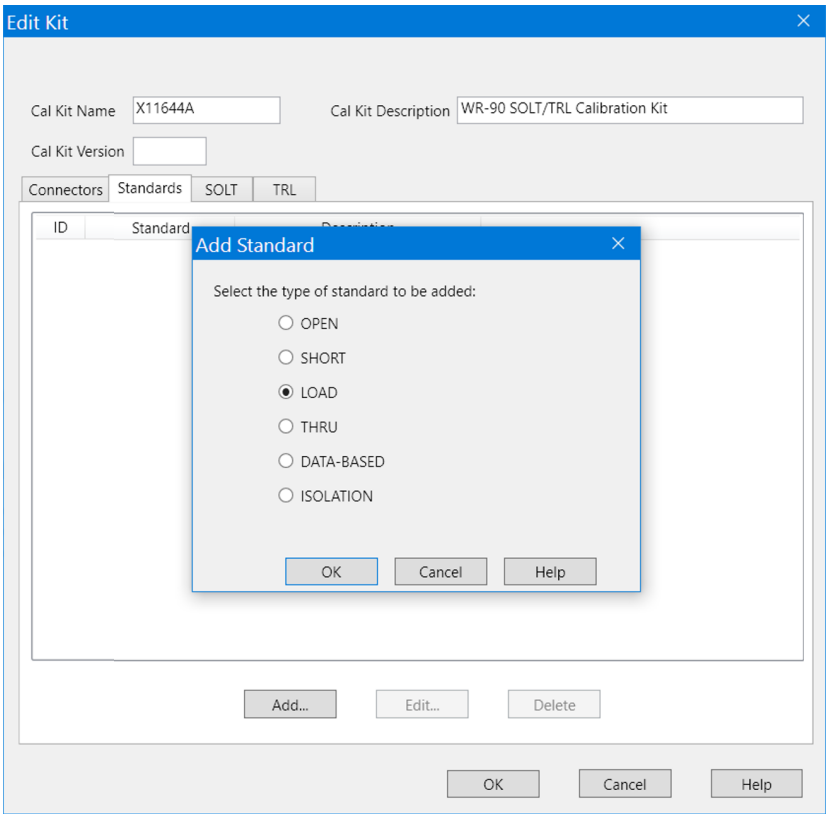
- Frequency range $8.2\,\mathrm{GHz}$ to $12.4\,\mathrm{GHz}$
- Cutoff frequency $6.557\,\mathrm{GHz}$
- Height $1.016\,\mathrm{cm}$
- Width $2.286\,\mathrm{cm}$



1. Make sure the **Connectors** tab is selected
2. Press Add... to create a new connector
3. Input **WR-90** in the **Connector family** field
4. Set **Frequency Range Min** to $8200\,\mathrm{MHz}$
5. Set **Frequency Range Max** to $12\,400\,\mathrm{MHz}$
6. Select **Genderless**
7. Set **Z0** to 1
8. Use the **Media** drop down box to select **WAVEGUIDE**
9. Set the **Cutoff frequency** to $6557\,\mathrm{MHz}$
10. Set the **Height/Width Ratio** to 0.444

Add Standard definitions

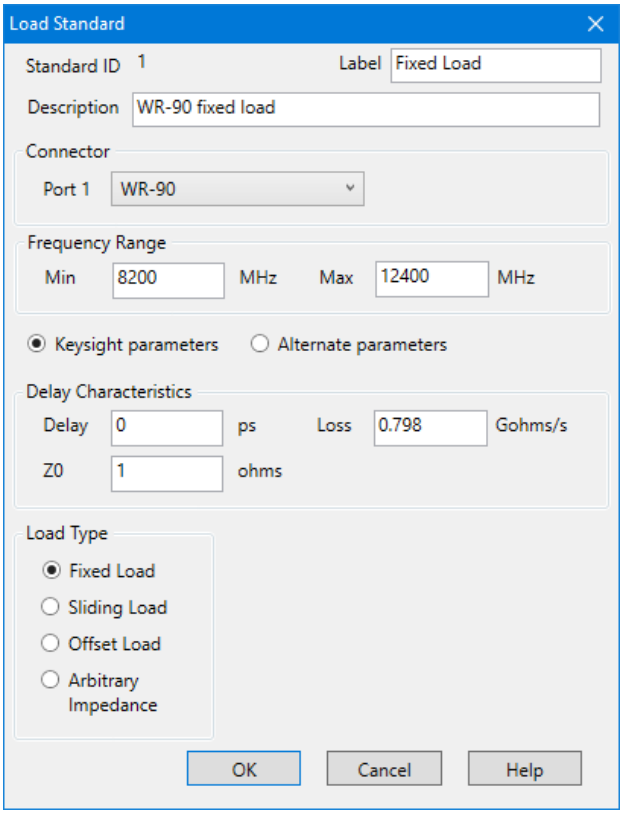
We will be adding six standards to the calibration kit. A fixed load, a short, an offset short, a thru, a quarter wavelength line, and an offset load.



For each of the standards to be added do the following:

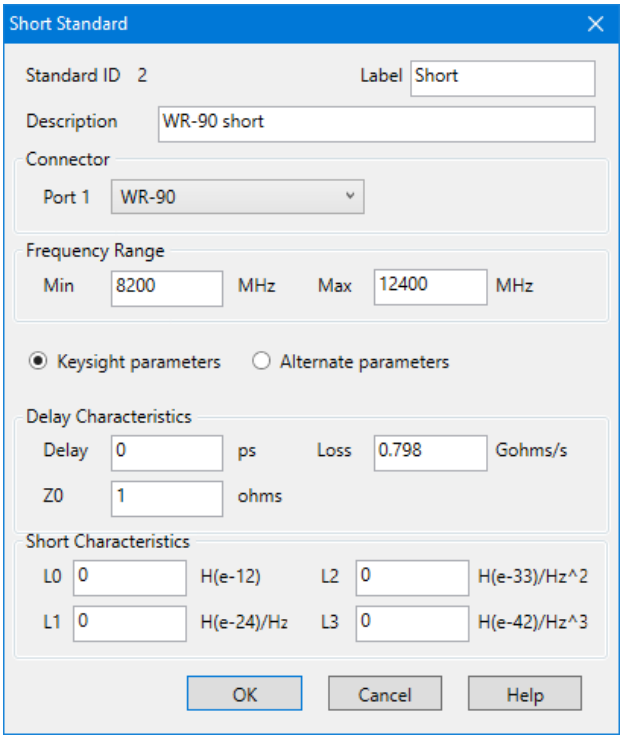
1. Make sure the **Standards** tab is selected
2. Press Add... to bring up the **Add Standard** dialog
3. Select the desired standard type then press OK

Fixed load



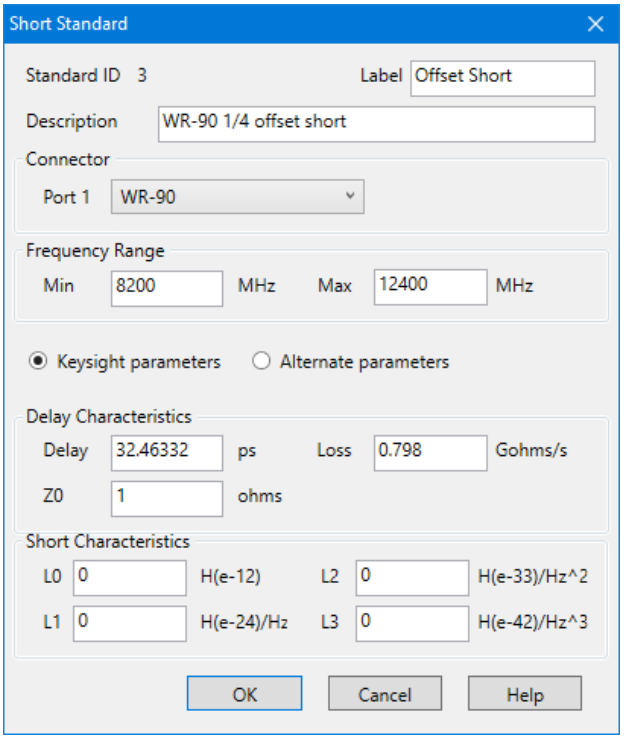
1. Select **Fixed Load** for **Load Type**
2. Input Fixed Load in the **Label** field
3. Input WR-90 fixed load in the **Description** field
4. Set **Frequency Range Min** to $8200\,\mathrm{MHz}$
5. Set **Frequency Range Max** to $12\,400\,\mathrm{MHz}$
6. Set **Delay** to $0\,\mathrm{ps}$
7. Set **Z0** to $1\,\Omega$
8. Set **Loss** to $0.798\,\mathrm{G\Omega/s}$
9. Press OK

Short



1. Input **Short** in the **Label** field
2. Input **WR-90 short** in the **Description** field
3. Set **Frequency Range Min** to $8200\,\mathrm{MHz}$
4. Set **Frequency Range Max** to $12\,400\,\mathrm{MHz}$
5. Set **Delay** to $0\,\mathrm{ps}$
6. Set **Z0** to $1\,\Omega$
7. Set **Loss** to $0.798\,\mathrm{G\Omega/s}$
8. Set **L0** to 0
9. Set **L1** to 0
10. Set **L2** to 0
11. Set **L3** to 0
12. Press OK

Offset short

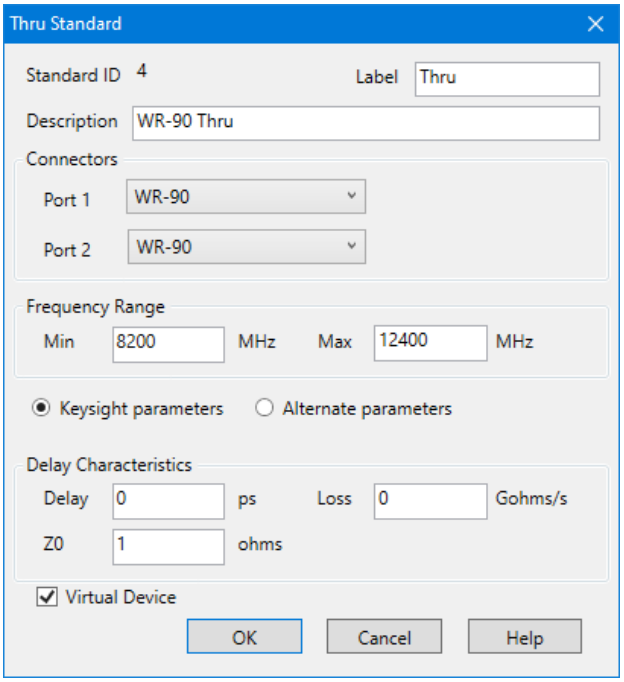


The offset short is a fully defined standard where both the terminating impedance (short) and the delay are fully known.

The offset short standard is specified using the Short type of standard.

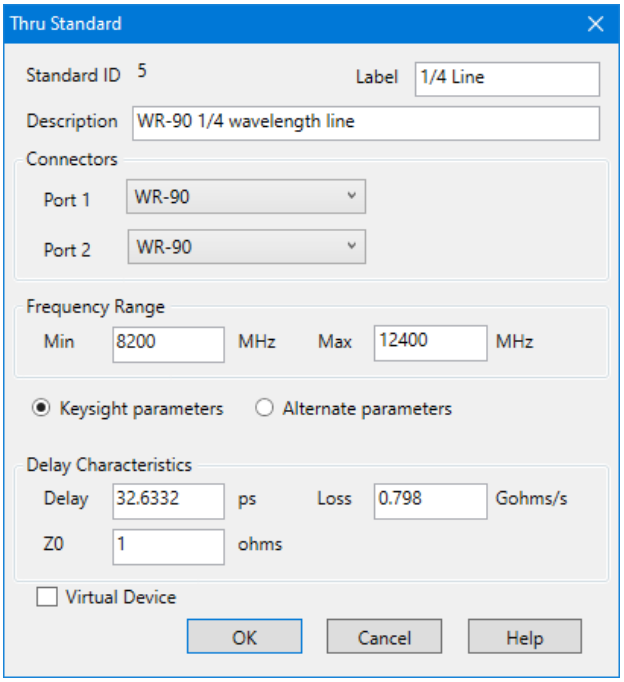
1. Input **Offset Short** in the **Label** field
2. Input **WR-90 1/4 offset short** in the **Description** field
3. Set **Frequency Range Min** to $8200\,\mathrm{MHz}$
4. Set **Frequency Range Max** to $12\,400\,\mathrm{MHz}$
5. Set **Delay** to $32.463\,32\,\mathrm{ps}$
6. Set **Z0** to $1\,\Omega$
7. Set **Loss** to $0.798\,\mathrm{G\Omega/s}$
8. Set **L0** to 0
9. Set **L1** to 0
10. Set **L2** to 0
11. Set **L3** to 0
12. Press OK

Thru



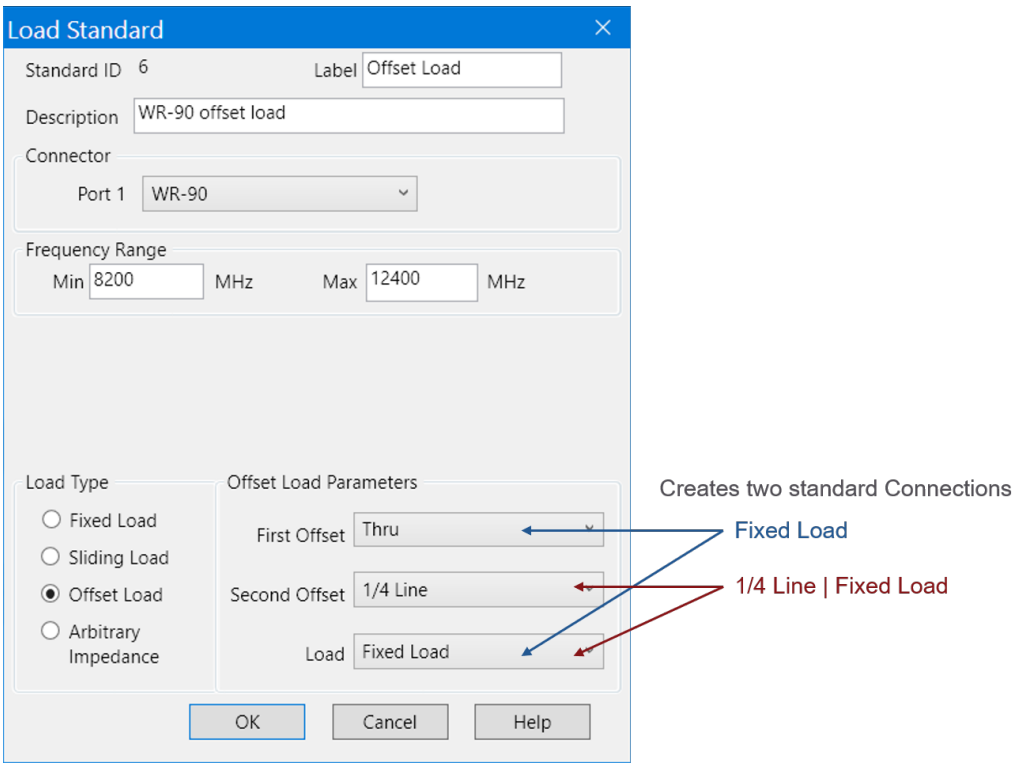
1. Input **Thru** in the **Label** field
2. Input **WR-90 thru** in the **Description** field
3. Set **Frequency Range Min** to $8200\,\mathrm{MHz}$
4. Set **Frequency Range Max** to $12\,400\,\mathrm{MHz}$
5. Set **Delay** to $0\,\mathrm{ps}$
6. Set **Z0** to $1\,\Omega$
7. Set **Loss** to $0.798\,\mathrm{G\Omega/s}$
8. Make sure **Virtual Device** is checked
9. Press OK

1/4 Line



1. Input **1/4 Line** in the **Label** field
2. Input **WR-90 1/4 wavelength line** in the **Description** field
3. Set **Frequency Range Min** to $8200\,\mathrm{MHz}$
4. Set **Frequency Range Max** to $12\,400\,\mathrm{MHz}$
5. Set **Delay** to $32.463\,32\,\mathrm{ps}$
6. Set **Z0** to $1\,\Omega$
7. Set **Loss** to $0.798\,\mathrm{G\Omega/s}$
8. Make sure **Virtual Device** is unchecked
9. Press OK

Offset load



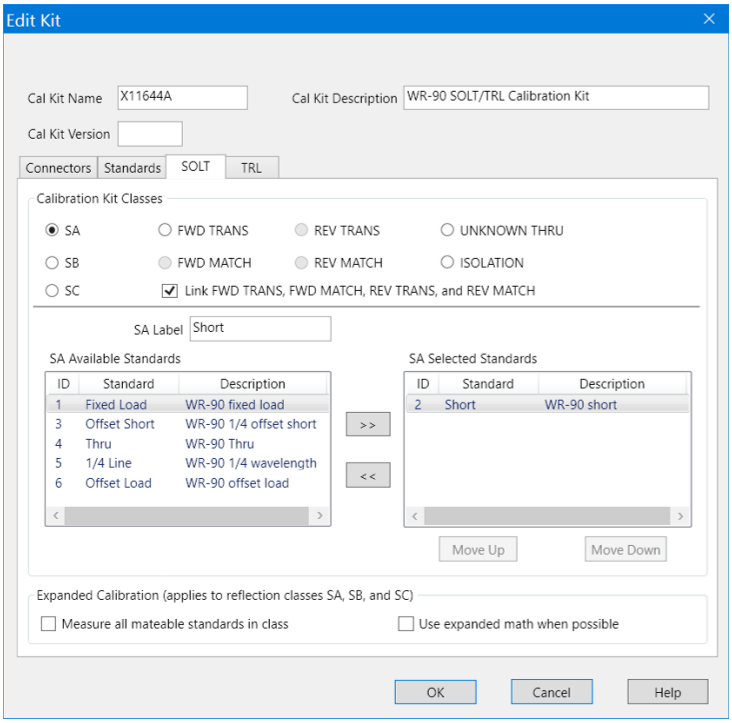
The offset load is a combination of multiple calibration standards. The Load doesn't need to be fully known. It creates two calibration standard connections to be measured,
Fixed Load and
1/4 Line | Fixed Load.
Note, the Thru doesn't appear in the connection prompt because it is specified as virtual.

1. Select **Offset Load** for **Load Type**
2. Input **Offset Load** in the **Label** field
3. Input **WR-90 offset load** in the **Description** field
4. Set **Frequency Range Min** to $8200\,\mathrm{MHz}$
5. Set **Frequency Range Max** to $12\,400\,\mathrm{MHz}$
6. Select **Thru** from the drop down menu for the **First Offset**
7. Select **1/4 line** from the drop down menu for the **Second Offset**
8. Select **Fixed Load** from the drop down menu for the **Load**
9. Press OK

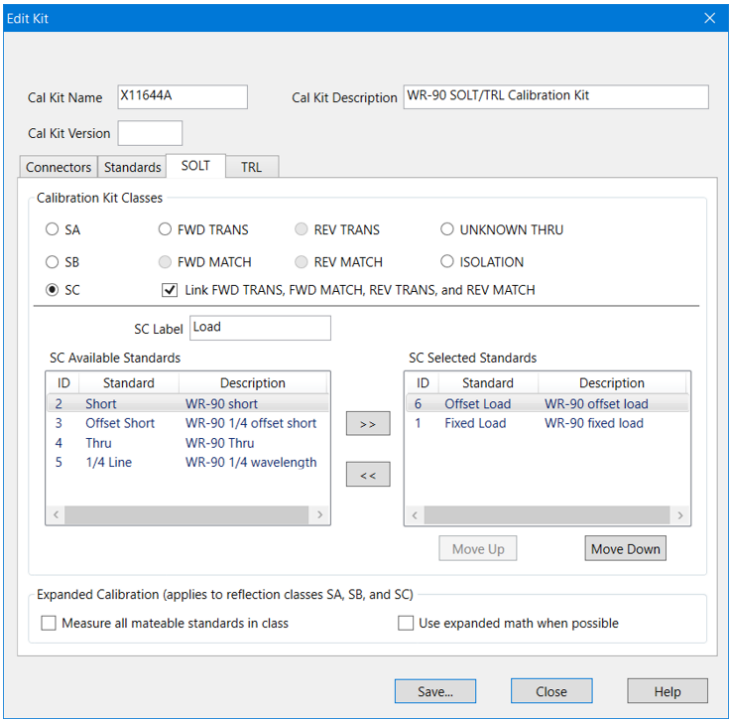
Edit calibration kit classes

The X11644A calibration kit supports both SOLT and TRL calibrations.

Edit SOLT kit classes



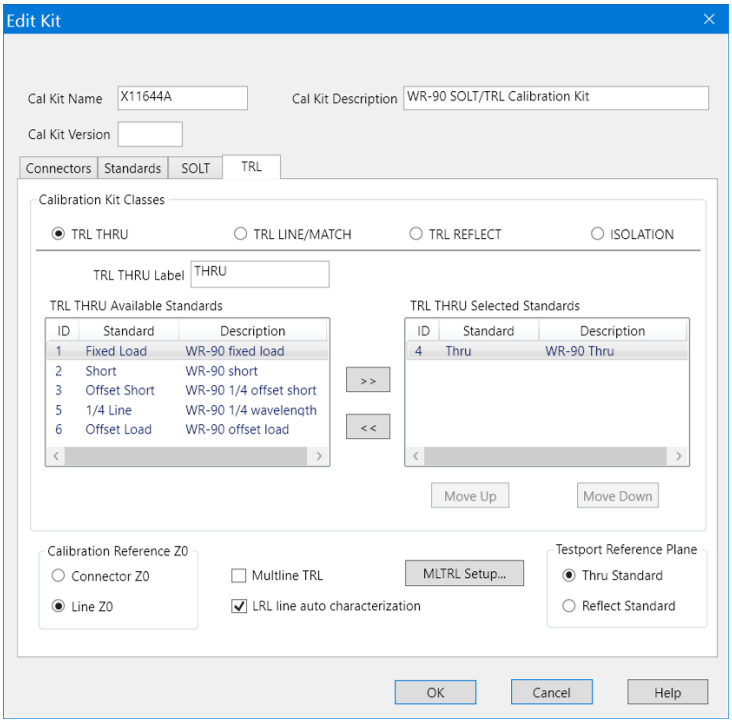
1. Make sure the **SOLT** tab is selected
2. Add standard to **SA** Calibration Kit Class
   (a) Select **SA** radio button
   (b) Input **Short** in the **SA Label** field
   (c) Select **Short** from **SA Available Standards**
   (d) Move **Short** to **SA Selected Standards** using >>
3. Add standard to **SB** Calibration Kit Class
   (a) Select **SB** radio button
   (b) Input **Offset Short** in the **SB Label** field
   (c) Select **Offset Short** from **SB Available Standards**
   (d) Move **Offset Short** to **SB Selected Standards** using >>



There are two standards selected for the SC calibration kit class. They both cover the same frequency range. The **Offset Load** standard has priority over the **Fixed Load** so it will be chosen by SmartCal. If the **Fixed Load** standard were moved to the top position it would be the default choice.

4. Add standards to **SC** Calibration Kit Class
   (a) Select **SC** radio button
   (b) Input **Loads** in the **Sc Label** field
   (c) Select **Offset Load** from **Sc Available Standards**
   (d) Move **Offset Load** to **Sc Selected Standards** using >>
   (e) Select **Fixed Load** from **Sc Available Standards**
   (f) Move **Fixed Load** to **Sc Selected Standards** using >>
5. Add standard to **FWD TRANS**, **FWD MATCH**, **REV TRANS** and **REV MATCH** Calibration Kit Classes
   (a) Make sure **Link FWD TRANS, FWD MATCH, REV TRANS, and REV MATCH** is checked
   (b) Select **FWD TRANS** radio button
   (c) Input **Thru** in the **FWD TRANS Label** field
   (d) Select **Thru** from **FWD TRANS Available Standards**
   (e) Move **Thru** to **FWD TRANS Selected Standards** using >>

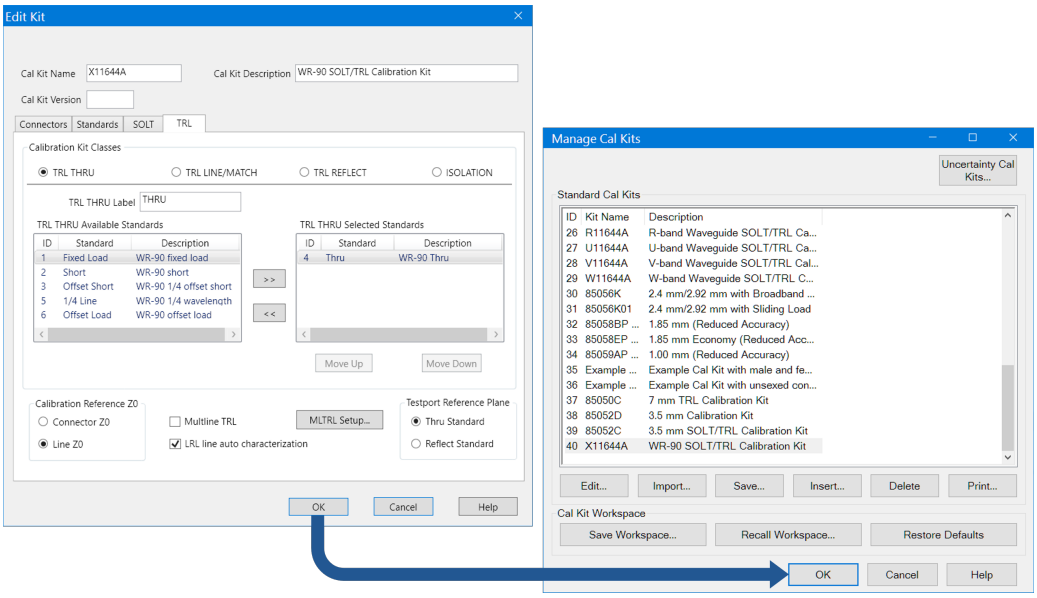
Edit TRL kit classes



1. Make sure the **TRL** tab is selected
2. Add standard to **TRL THRU** Calibration Kit Class
   (a) Select **TRL THRU** radio button
   (b) Input **THRU** in the **TRL THRU Label** field
   (c) Select **Thru** from **TRL THRU Available Standards**
   (d) Move **Thru** to **TRL THRU Selected Standards** using >>
3. Add standard to **TRL LINE/MATCH** Calibration Kit Class
   (a) Select **TRL LINE/MATCH** radio button
   (b) Input **LINE** in the **TRL LINE/MATCH Label** field
   (c) Select **1/4 Line** from **TRL LINE/MATCH Available Standards**
   (d) Move **1/4 Line** to **TRL LINE/MATCH Selected Standards** using >>
4. Add standards to **TRL REFLECT** Calibration Kit Class
   (a) Select **TRL REFLECT** radio button
   (b) Input **SHORT** in the **TRL REFLECT Label** field
   (c) Select **1/4 Line** from **TRL REFLECT Available Standards**
   (d) Move **1/4 Line** to **TRL REFLECT Selected Standards** using >>

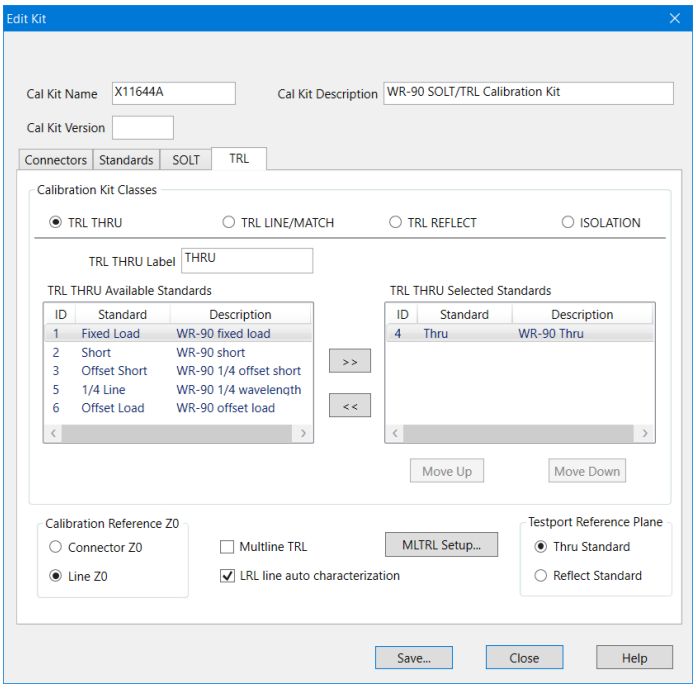
Save calibration kit

Save using VNA calibration kit editor



1. Select OK from the **Edit Kit** dialog
2. Select OK from the **Manage Cal Kits** dialog

Save using standalone calibration kit editor



1. Select Save... from the **Edit Kit** dialog

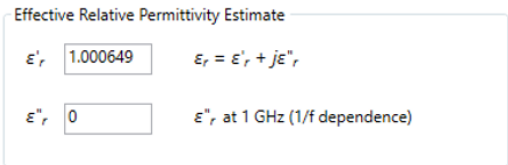
Procedure to define a calibration kit for Multiline TRL

The following steps are recommended when creating a new calibration kit to be used with Multiport TRL calibrations.

1. Determine the relative permittivity. If using a substrate or PC board, this should account for both the effect of the substrate relative permittivity and air.

   > Keysight's Advanced Design System (ADS) includes an electromagnetic field simulator that can determine the effective relative permittivity associated with a transmission line on a substrate or PC board.

   This is the number that should be input for the **Effective Relative Permittivity Estimate** shown in Figure 23.

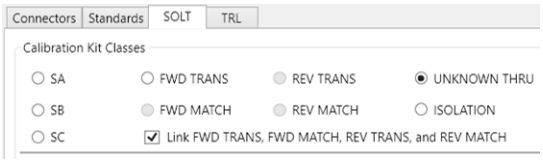
   It will be used when estimating the Offset Delay of the calibration standards. All devices in the calibration kit are assumed to use the same relative permittivity estimate.

2. Define the connectors. It can be beneficial to define multiple connectors when the topology of the calibration kit is intended to have a particular standard be used only with a probe in a fixed location. In that case it could be beneficial to provide unique connector names to be associated with that probe. For example, you might end up with Probe A, Probe B, Probe C, etc.

3. Define the characteristic impedance of the connectors. This is the final system impedance desired after calibration. Generally, all of the connectors in the calibration kit would have the same characteristic impedance.

4. Avoid using meander lines or bent lines for standards intended to be used as either the *thru* standard or a *line* standard. It is possible to include bent lines needed during a multiport calibration but the bent lines would be included in the UNKNOWN THRU kit class under the SOLT tab in the Edit kit dialog.

   The SOLT tab is next to the TRL tab shown in Figure 22.

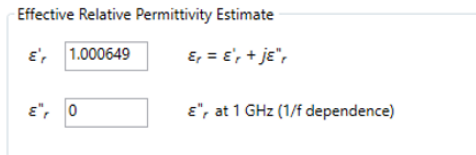
   

5. Measure the physical lengths of the standards in cm. This would include the standard to be used as a *thru*. All of the *thru* and *line* standards should be defined using the *thru* standard model. Specify the parameters for each standard:

   - Specify the Label and Description.
   - Select the connectors.
   - Specify the frequency range. The *thru* standard should be specified over the full frequency range of the calibration. The *line* standards should have a minimum frequency selected to ensure a minimum

phase difference from the *thru* standard of approximately $20°$.

- The offset delay should be computed using the real part of the relative permittivity estimate (ε'_r) defined on the Multiline TRL setup (see Figure 23).

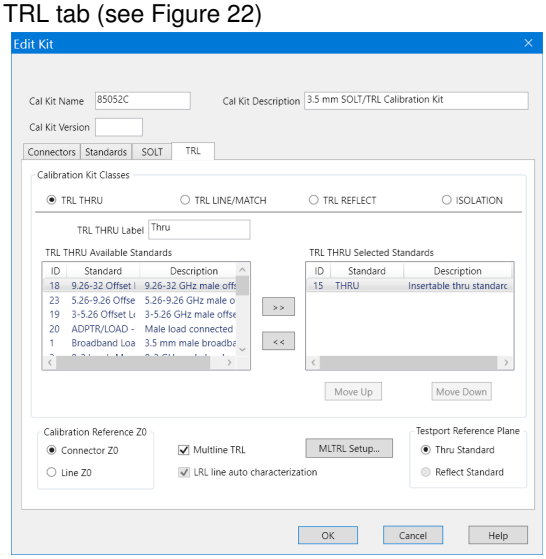


  The delay in picoseconds (ps) for the ith standard with length L_i in cm is computed as $D_i = \frac{L_i \sqrt{\varepsilon'_r}}{c}$ where $c = 2.997\,924\,58 \times 10^{-2}$ cm/ps.

- **Offset Z_0** should be the nominal characteristic impedance of the *thru* and *line* standards. They should all be set to the same value. In many cases, it will be the same value as the characteristic impedance defined for the connectors.
- **Offset loss** can be specified. It is not critical to specify this accurately since the Multiline TRL calibration will estimate the loss of the propagation independent of this estimate.
- If **Offset delay** is specified as 0 ps it makes sense to check the **Virtual Device** box. This causes the calibration prompts to indicate connecting the testports directly to each other rather than including the device label and description.

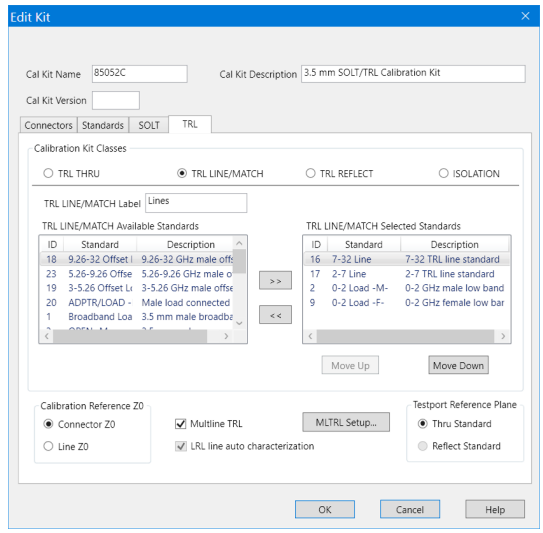
6. Assign calibration kit class definitions by selecting the TRL tab (see Figure 22)

- A single *thru* standard should be selected for a given pair of ports involved in the TRL calibration. If it is a multiport calibration additional *thru* standards can be added provided there is only a single *thru* standard selected for each port pair.

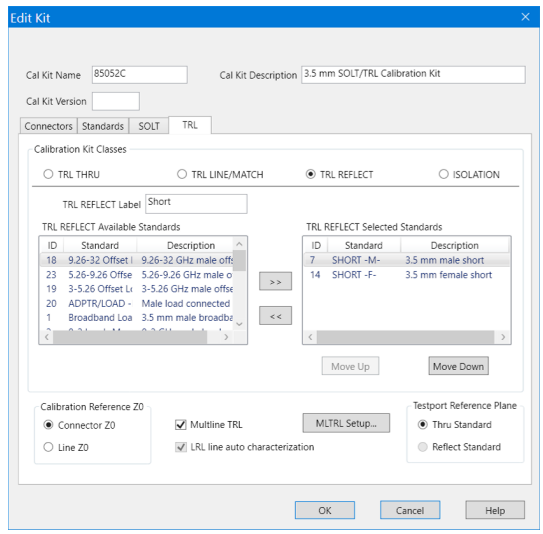


- Multiple *line* standards can be selected.

- If the frequency range of usage is lower than the lowest frequency for the *line* standards add *match* standards. There should be a single *match* standard for each port connector. The model for each *match* standard should be the same.



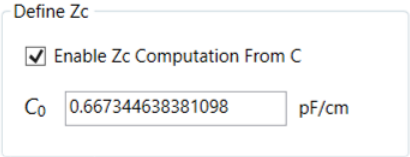
- Add the *reflect* standards. There should be a *reflect* standard for each port connector. If the calibration kit is intended for Multiline TRL calibrations the *reflect* standards should all match the same model. If the calibration kit is intended for Multiline TSD the *reflect* standards do not have to match the same model.



For Multiline TSD calibrations only the first standard listed that matches the connectors required during the calibration will be used.

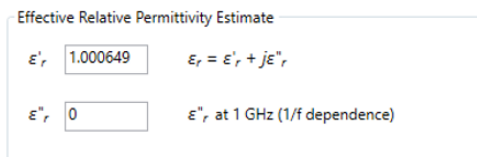
7. Check the **Multiline TRL** checkbox.
8. Specify **Calibration Reference Z0** Usually **Connector Z_0** is selected which includes the impedance transform between the **Offset Z_0** defined and the Connector Z_0. It also includes the transform for Z_c defined in the Multiline TRL setup dialog box.
9. Press MLTRL Setup... to open the Multiline TRL setup dialog box (Figure 23)

- Define Z_c. Check the **Enable Z_c Computation from C** checkbox to account for low frequency dispersion.

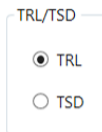


When setting up a calibration kit for waveguide, uncheck the **Enable Z_c Computation from C** checkbox as the cutoff frequency is used instead.

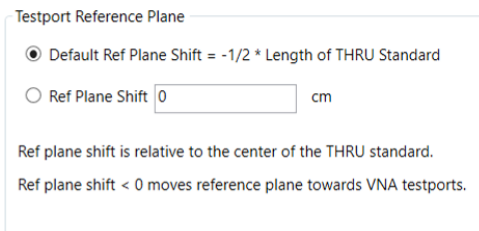
- Specify C_0. If defining a coaxial calibration kit, the default value is usually adequate. If the value has been modified, the default value can be automatically re-entered by inputting a negative number in the C_0 field. For other transmission media (exclusive of waveguide) the value for C_0 needs to be determined, often by an iterative process. There are papers published that explain details for determining the low frequency dispersion from the characterization of the propagation constant and an estimate of C_0[22][23][24].
- Make sure the values input for the relative permittivity estimate match the value used to estimate the offset delay for the *thru* and *line* standards.



- Specify either TRL or TSD.



- Specify the **Testport Reference Plane** as desired.



10. If doing a multiport calibration, add additional *thru* standards with offset delays specified. These standards are usually loop-back *thru* standards or bent in order to connect ports that are not directly opposing each other. Add these standards to the UNKNOWN THRU class.

Appendix A Dimensional Considerations in Coaxial Connectors

This appendix describes dimensional considerations and required conventions used to determine the physical offset length of calibration standards in gendered coaxial connector families.

Precise measurement of the physical offset length is required to determine the **Offset delay** of a given calibration standard. The physical offset length of one and two-port standards is as follows.

1. One-port standard – Distance between “calibration plane” and terminating impedance.
2. Two- port standard – Distance between the Port 1 and Port 2 “calibration planes.”

The definition (location) of the “calibration plane” in a calibration standard is dependent on the geometry and gender of the connector type. The “calibration plane” is defined as a plane which is perpendicular to the axis of the conductor coincident with the outer conductor mating surface. This mating surface is located at the contact points of the outer conductors of the test port and the calibration standard. To illustrate this, consider the following connector type interfaces:

7 mm coaxial connector interface

The “calibration plane” is located coincident to the outer conductor mating surface as shown in Figure 27. Unique to this connector type is the fact that the inner and outer conductor mating surfaces are nominally coincident as well as having hermaphroditic (genderless) connectors. In most other coaxial connector families this is not the case.

3.5 mm, 2.4 mm, 1.85 mm, and 1 mm coaxial connector interfaces

The location of the “calibration plane” in these connector standards, both genders, is at the outer conductor mating surface as shown in Figure 27.

Type-N coaxial connector interface

The location of the “calibration plane” in Type-N standards is the outer conductor mating surfaces as shown in Figure 28.

For current Keysight VNAs, the device label uses –M– or –F– to indicate the gender of the calibration standard instead of the test port.

Gap effects

It was originally thought that minimizing the pin depth gap was important for the best measurements when using coaxial connectors. Studies have shown that better measurements are made when there is an intentional gap introduced. The gap minimizes repeatability due to variations in coupling and higher order modes that can degrade measurement results. Coaxial calibration standards and testport adapters are now designed with an intentional gap to provide more repeatable and accurate measurements (see reference [26]).

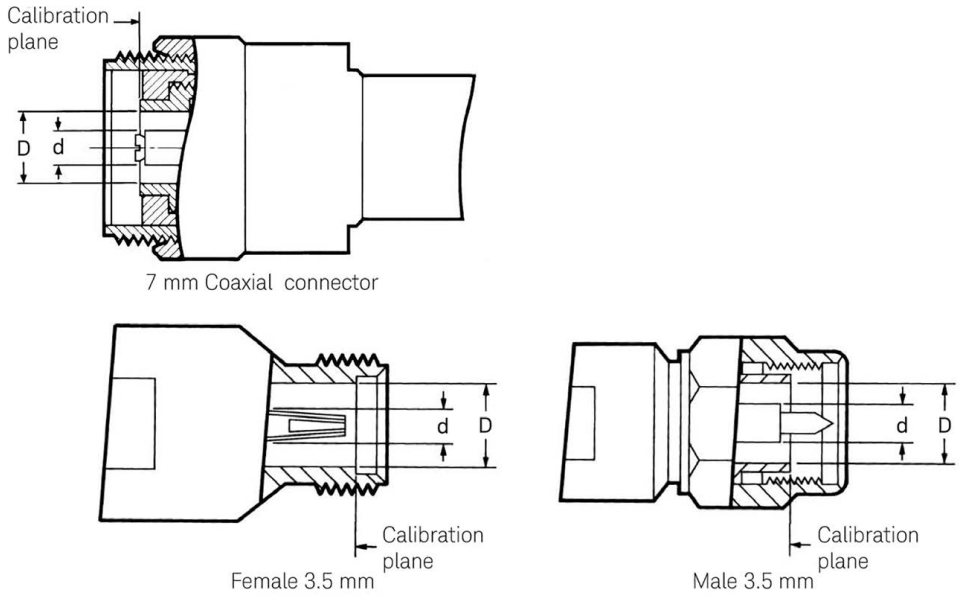


Figure 27. Location of coaxial connector calibration plane

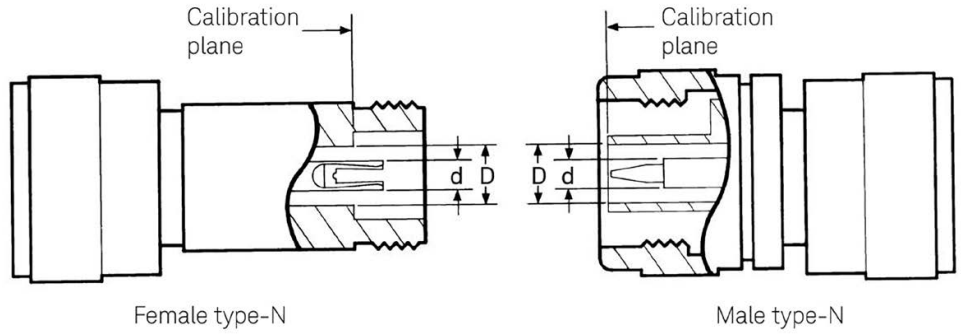


Figure 28. Type-N connector calibration plane

Appendix B Derivation of Coaxial Calibration Coefficient Model

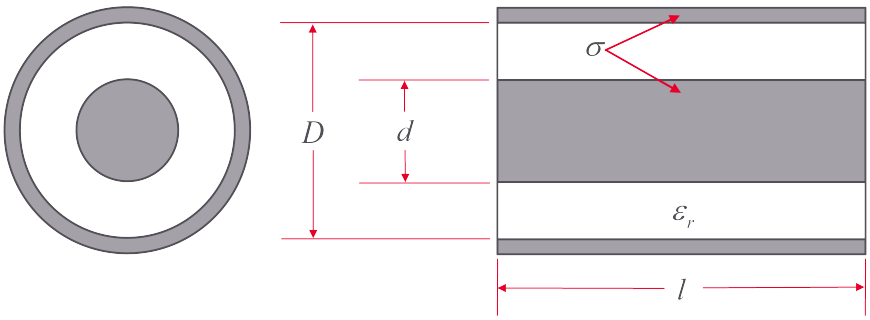


Figure 29. Coaxial transmission line characteristics

All transmission lines may be defined by their characteristic impedance (Z_c), propagation loss constant (α), propagation phase constant (β), and length (l). They are related to the calibration coefficients **Offset delay**, **Offset loss** and **Offset Z_0** as follows:

Recall that:

$$\text{Transmission loss and phase} = e^{-\gamma l}$$

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{28}$$

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{29}$$

where:

- R is the distributed resistance of the offset line
- L is the distributed inductance of the offset line
- G is the distributed conductance of the offset line $G = 0$ for air dielectric
- C is the distributed capacitance of the offset line
- f is the frequency in Hz
- $\omega = 2\pi f$ is the radian frequency
- l is the length of the physical length of the offset

For coaxial transmission lines with finite conductivity. the distributed inductance L includes a distributed self inductance term L_i. The overall distributed inductance can be represented as:

$$L = L_o + L_i = L_o + \frac{R}{\omega} \tag{30}$$

The propagation constant γ and characteristic impedance Z_c are impacted by the self inductance refereed to as the skin effect.

Propagation constant

For $G = 0$ and small R the propagation constant can be computed as:

$$\gamma = \sqrt{(R + j\omega L)\, j\omega C} \tag{31}$$

substitute 30 into 31

$$\gamma = \sqrt{(R + j\omega L_o + jR)\, j\omega C} \tag{32}$$

Apply a few manipulations to 32

$$\gamma = \sqrt{j\omega L_o \left(1 + \frac{R + jR}{j\omega L_o}\right) j\omega C}$$

$$\gamma = j\omega \sqrt{L_o C} \sqrt{\left(1 + \frac{(1+j)}{j} \frac{R}{\omega L_o}\right)} \tag{33}$$

$$\gamma = j\omega \sqrt{L_o C} \sqrt{\left(1 + (1-j) \frac{R}{\omega L_o}\right)} \tag{34}$$

Equation 34 can be rewritten using a series expansion.

$$\gamma = j\omega \sqrt{L_o C} \left(1 + (1-j) \frac{R}{2\omega L_o} + \frac{j}{4}\left(\frac{R}{\omega L_o}\right)^2 + \cdots\right) \tag{35}$$

When $R \ll \omega L_o$ we get:

$$\gamma \approx j\omega \sqrt{L_o C} \left(1 + (1-j) \frac{R}{2\omega L_o}\right) \tag{36}$$

Offset impedance

The offset impedance Z_c when $G = 0$ is given as:

$$Z_c = \sqrt{\frac{R + j\omega L}{j\omega C}} \tag{37}$$

Substitute equation 30 into 37

$$Z_c = \sqrt{\frac{R + j\omega\left(L_o + \frac{R}{\omega}\right)}{j\omega C}} \tag{38}$$

$$Z_c = \sqrt{\frac{L_o}{C}} \sqrt{\left(1 + (1-j) \frac{R}{\omega L_o}\right)} \tag{39}$$

When $R \ll \omega L_o$ we end up with:

$$Z_c \approx \sqrt{\frac{L_o}{C}} \left(1 + (1-j) \frac{R}{2\omega L_o}\right) \tag{40}$$

Offset definitions

For coaxial transmission lines, let:

$$\begin{aligned}
\textbf{Offset Loss} &= \frac{R\nu}{\sqrt{\frac{f}{10^9}}} \\
\textbf{Offset Delay} &= \frac{l}{\nu} = \sqrt{L_o C} \\
\textbf{Offset Z}_\mathbf{0} &= \sqrt{\frac{L_o}{C}} = \frac{\mu_0 \nu}{2\pi} \ln\left(\frac{D}{d}\right)
\end{aligned} \tag{41}$$

- ν is the speed of light in the media between the inner and outer conductors computed as $\nu = \frac{c}{\sqrt{\varepsilon_r}}$
- the media between the inner and outer conductors is assumed to be non-magnetic with $\mu = \mu_0$ and $\varepsilon = \varepsilon_r \varepsilon_0$.
- $R = \sqrt{\frac{\pi f \mu_0}{\sigma_c}} \left(\frac{1}{\pi d} + \frac{1}{\pi D}\right)$
- $\nu^2 = \frac{1}{\varepsilon \mu}$
- $L_o = \left(\frac{\mu_0}{2\pi}\right) \ln\left(\frac{D}{d}\right)$
- $C = \frac{2\pi\varepsilon}{\ln\left(\frac{D}{d}\right)}$

Substituting the offset definitions (equations 41) back to the transmission line equations (34 and 38):

$$\begin{aligned}
\frac{R}{\omega L_o} &= \frac{(\textbf{Offset loss})}{2\pi f\,(\textbf{Offset Z}_\mathbf{0})} \sqrt{\frac{f}{10^9}} \\
\gamma l &= j2\pi f\,(\textbf{Offset delay}) \sqrt{1 + (1-j)\frac{(\textbf{Offset loss})}{2\pi\sqrt{f}\,\sqrt{10^9}\,(\textbf{Offset Z}_\mathbf{0})}} \\
Z_c &= (\textbf{Offset Z}_\mathbf{0}) \sqrt{1 + (1-j)\frac{(\textbf{Offset loss})}{2\pi\sqrt{f}\,\sqrt{10^9}\,(\textbf{Offset Z}_\mathbf{0})}}
\end{aligned} \tag{42}$$

The traditional computations are obtained by substituting the offset definitions (equations 41) back to the transmission line equations (36 and 40):

$$\begin{aligned}
\frac{R}{2\omega L_o} &= \frac{(\textbf{Offset loss})}{4\pi f\,(\textbf{Offset Z}_\mathbf{0})} \sqrt{\frac{f}{10^9}} \\
\alpha l &= \left(\frac{(\textbf{Offset loss})\,(\textbf{Offset delay})}{2\,(\textbf{Offset Z}_\mathbf{0})}\right) \sqrt{\frac{f}{10^9}} \\
\beta l &= 2\pi f\,(\textbf{Offset delay}) + \alpha l \\
Z_c &= (\textbf{Offset Z}_\mathbf{0}) + (1-j)\left(\frac{\textbf{Offset loss}}{4\pi f}\right) \sqrt{\frac{f}{10^9}}
\end{aligned} \tag{43}$$

The short's inductance may be determined from physical properties of the shorting plane, as presented in

reference [17]. The computed results are then curve fitted to a third order polynomial function.

$$\begin{aligned} Z_T &= j\omega L_T \\ L_T &= L_0 + L_1 f + L_2 f^2 + L_3 f^3 \\ \Gamma_T &\approx (-1)\, e^{-2j \arctan\left(\frac{\omega L_T}{Z_{ref}}\right)} \end{aligned} \tag{44}$$

At low frequencies where the inductance is reasonably linear, it may be modeled as an extra delay term.

$$\Delta\varphi = 2\arctan\left(\frac{2\pi f L_T}{Z_{ref}}\right) = 2\pi f\,(\Delta\textbf{delay}) \tag{45}$$

The open's fringing capacitance may be determined using three dimensional microwave structure simulators. However, the mechanical structure of the open assembly can be quite complex and can cause simulation problems. It may be more realistic to measure the open's response using TRL or offset short calibration techniques where opens are not employed as calibration standards. The measured results are then curve fitted to a third order polynomial capacitance model.

$$\begin{aligned} Z_T &= \frac{1}{j\omega C_T} \\ C_T &= C_0 + C_1 f + C_2 f^2 + C_3 f^3 \\ \Gamma_T &\approx (1)\, e^{-2j \arctan\left(\omega C_T Z_{ref}\right)} \end{aligned} \tag{46}$$

At low frequencies where the capacitance is reasonably linear, it may be modeled as an extra delay term.

$$\Delta\varphi = 2\arctan\left(2\pi f C_T Z_{ref}\right) = 2\pi f\,(\Delta\textbf{delay}) \tag{47}$$

Derivation of a transmission model to represent a lumped reactance model

For a lossless transmission line equation 39 becomes

$$Z_c = \sqrt{\frac{L_0}{C}} \tag{48}$$

and equation 34 becomes

$$\gamma = j\beta = j\omega\sqrt{L_o C} \tag{49}$$

The input impedance of a transmission line of length l with characteristic impedance Z_c terminated by Z_L is given as

$$Z_{in} = Z_c\left(\frac{1 + \Gamma_L e^{-2j\beta l}}{1 - \Gamma_L e^{-2j\beta l}}\right) \tag{50}$$

where

$$\Gamma_L = \frac{Z_L - Z_c}{Z_L + Z_c} \tag{51}$$

Euler's formula will allow the real and imaginary portions of Z_{in} to be separated.

$$e^{-2j\beta l} = \cos(-2\beta l) + j\sin(-2\beta l) \tag{52}$$

Substituting equations 51 and 52 into equation 50 and simplifying yields:

$$Z_{in} = \frac{Z_c(Z_L\cos(\beta l) + jZ_c\sin(\beta l))}{Z_c\cos(\beta l) + jZ_L\sin(\beta l)} \tag{53}$$

$$\begin{aligned} Z_{in} &= \frac{Z_c(Z_L\cos(\beta l) + jZ_c\sin(\beta l))}{Z_c\cos(\beta l) + jZ_L\sin(\beta l)}\frac{(Z_c\cos(\beta l) - jZ_L\sin(\beta l))}{(Z_c\cos(\beta l) - jZ_L\sin(\beta l))} \\ &= \frac{Z_c^2 Z_L + j\sin(\beta l)\cos(\beta l)Z_c\left(Z_c^2 - Z_L^2\right)}{Z_c^2\cos^2(\beta l) + Z_L^2\sin^2(\beta l)} \end{aligned} \tag{54}$$

When $Z_c \gg Z_L$ equation 54 becomes

$$Z_{in} \approx \frac{Z_L + j\sin(\beta l)\cos(\beta l)Z_c}{\cos^2(\beta l)} \tag{55}$$

When $\beta l \ll 1$ equation 55 becomes

$$Z_{in} \approx Z_L + j\beta l Z_c = Z_L + j\omega(\textbf{Offset delay})(\textbf{Offset } \mathbf{Z_0}) \tag{56}$$

An inductive load $Z_L + j\omega L$ can be modeled with the arbitrary impedance and appropriate choices of the offset parameters.

- $(\textbf{Offset loss}) = 0$
- $(\textbf{Offset } \mathbf{Z_0}) \gg Z_L$ Choose $(\textbf{Offset } \mathbf{Z_0})$ to be at least an order of magnitude greater than Z_L. Older network analyzers sometimes had an upper limit on $(\textbf{Offset } \mathbf{Z_0})$ such as $500\,\Omega$; in those cases use the upper limit.
- $(\textbf{Offset delay}) = \frac{L}{(\textbf{Offset } \mathbf{Z_0})}$

Appendix C Derivation of Waveguide Calibration Coefficient Model

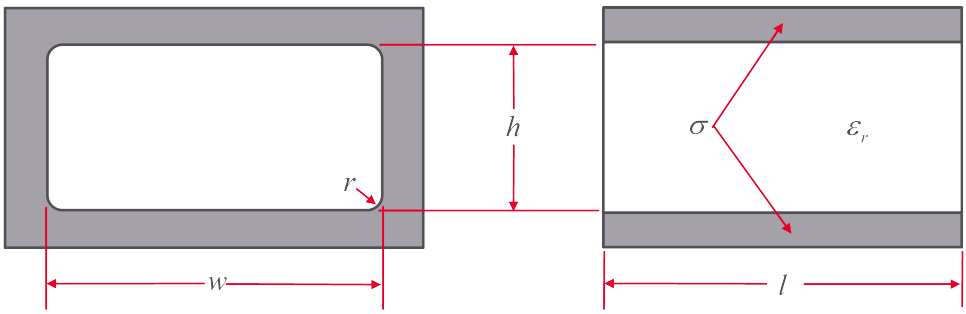


Figure 30. Rectangular waveguide dimensions and properties.

The physical properties of a rectangular waveguide are illustrated in Figure 30.

$$\beta = \frac{2\pi f}{v}\sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2} \tag{57}$$

where:

- the guide medium is assumed to be non-magnetic with $\mu_r = 1$
- v is the speed of light in the medium computed as $v = \frac{c}{\sqrt{\varepsilon_r}}$
- ε_r = relative permittivity (dielectric constant) of transmission medium = $1.000\,649$ in air @ sea level and $50\,\%$ humidity
- λ is the TEM wavelength in the guide medium computed as $\lambda = \frac{v}{f}$
- w_e is the effective guide width computed as $w_e = w - \frac{(4-\pi)r^2}{h}$ (see reference [27])
- λ_c is the guide cutoff wavelength with $\lambda_c = 2w_e$
- Note, the cutoff frequency (f_c) is computed as $f_c = \frac{v}{\lambda_c}$

Assuming the guide medium is low loss permits the attenuation coefficient to be defined by the conductive losses give as:

$$\alpha \approx \frac{\sqrt{\pi f \mu_0 \rho}}{h}\sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}}\frac{\left(1+\frac{2h}{w_e}\left(\frac{\lambda}{\lambda_c}\right)^2\right)}{\sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2}} \tag{58}$$

where:

- ε_0 is the free space permittivity = $8.854\,187\,812\,8 \times 10^{-12}\,\mathrm{F/m}$
- μ_0 is the free space permeability = $1.256\,637\,062\,12 \times 10^{-6}\,\mathrm{N/A^2}$
- ρ is the resistivity of the conductor computed as the inverse of the conductivity $\rho = \frac{1}{\sigma}$
- l = physical offset length from reference plane in meters

To structure the waveguide loss equation in calibration coefficient format for the VNA,offset loss must be in $\mathrm{G\Omega/s}$. The equation may be reformulated as follows:

$$\alpha l \approx \frac{\sqrt{\pi f_c \mu_0 \rho}}{h} l \sqrt{\frac{f}{f_c}} \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}} \frac{\left(1 + \frac{2h}{w_e}\left(\frac{f_c}{f}\right)^2\right)}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \tag{59}$$

Offset definitions

For waveguide transmission lines it is assumed that **Offset** $\mathbf{Z_0}$ = **Connector** $\mathbf{Z_0}$, let the other offset parameters be defined as:

> At frequencies below 50 GHz, offset loss is primarily a function of the metal wall conductivity. Above 50 GHz, surface roughness starts to have a significant impact related to the wavelength and skin depth. The offset loss constant should be determined from transmission measurements which includes all of the effects.

$$\begin{aligned} \textbf{Offset Loss} &= \nu \frac{\sqrt{\pi f_c \mu_0 \rho}}{h} \\ \textbf{Offset Delay} &= \frac{l}{\nu} \end{aligned} \tag{60}$$

Substituting 60 into 59 yields:

$$\alpha l \approx (\textbf{Offset Loss})(\textbf{Offset Delay}) \sqrt{\frac{f}{f_c}} \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}} \frac{\left(1 + \frac{2h}{w_e}\left(\frac{f_c}{f}\right)^2\right)}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \tag{61}$$

The combined propagation constant is given as:

$$\begin{aligned} \gamma l &= (\alpha + j\beta) l \\ \gamma l &\approx \left((\textbf{Offset Loss}) \sqrt{\frac{f}{f_c}} \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}} \frac{\left(1 + \frac{2h}{w_e}\left(\frac{f_c}{f}\right)^2\right)}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} + j2\pi f \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \right) (\textbf{Offset Delay}) \end{aligned} \tag{62}$$

Appendix D Derivation of Circular Waveguide Calibration Coefficient Model

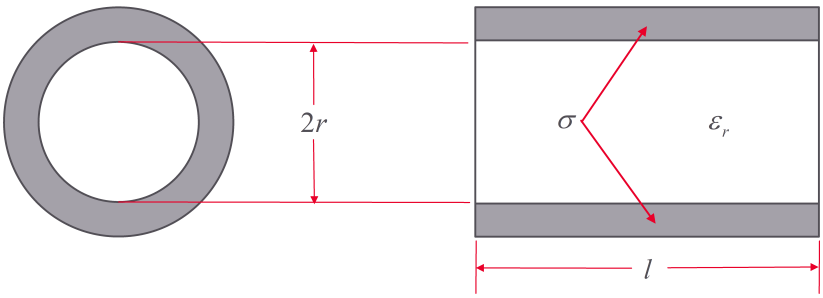


Figure 31. Circular waveguide dimensions and properties.

The physical properties of a circular waveguide are illustrated in Figure 31. The propagation properties are described by Marcuvitz[28].

$$\beta_{mn} = \frac{2\pi f}{v}\sqrt{1-\left(\frac{\lambda}{\lambda_{c,mn}}\right)^2} \tag{63}$$

where:

- the guide medium is assumed to be non-magnetic with $\mu_r = 1$
- v is the speed of light in the medium computed as $v = \frac{c}{\sqrt{\varepsilon_r}}$
- λ is the TEM wavelength in the guide medium computed as $\lambda = \frac{v}{f}$
- $\lambda_{c,mn}$ is the circular guide cutoff wavelength computed as $\lambda_{c,mn} = \frac{2\pi r}{\chi_{mn}}\sqrt{\varepsilon_r}$
- for the H_{11} mode $\chi_{11} = 1.841$

Assuming the guide medium is low loss permits the attenuation coefficient to be defined by the conductive losses give as:

$$\alpha \approx \frac{\sqrt{\pi f \mu_0 \rho}}{r}\kappa\sqrt{\frac{\varepsilon_0\varepsilon_r}{\mu_0}}\frac{\left(1+\frac{1}{\kappa}\left(\frac{\lambda}{\lambda_{c,mn}}\right)^2\right)}{\sqrt{1-\left(\frac{\lambda}{\lambda_{c,mn}}\right)^2}} \tag{64}$$

where:

- ρ is the resistivity of the conductor computed as the inverse of the conductivity $\rho = \frac{1}{\sigma}$
- $\kappa = \frac{m^2}{\chi_{mn}^2 - m^2}$
- For H_{11} mode $\kappa = 0.4185$
- The relationship between frequency and wavelength leads to $\frac{f_{c,mn}}{f} = \frac{\lambda}{\lambda_{c,mn}}$

To structure the waveguide loss equation in calibration coefficient format for the VNA,offset loss must be in

$\mathrm{G\Omega/s}$. The equation may be reformulated as follows:

$$\alpha l \approx \frac{\sqrt{\pi f_{c,mn} \mu_0 \rho}}{r} \sqrt{\frac{f}{f_{c,mn}}} \kappa \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}} \frac{\left(1 + 2\left(\frac{1}{2\kappa}\right)\left(\frac{f_{c,mn}}{f}\right)^2\right)}{\sqrt{1 - \left(\frac{f_{c,mn}}{f}\right)^2}} \tag{65}$$

Offset definitions

For waveguide transmission lines it is assumed that **Offset** $\mathbf{Z_0}$ = **Connector** $\mathbf{Z_0}$, let the other offset parameters be defined as:

$$\begin{aligned} \textbf{Offset Loss} &= \nu \frac{\sqrt{\pi f_{c,mn} \mu_0 \rho}}{r} \kappa \\ \textbf{Offset Delay} &= \frac{l}{\nu} \end{aligned} \tag{66}$$

Substituting 66 into 65 yields:

$$\alpha l \approx (\textbf{Offset Loss})(\textbf{Offset Delay}) \sqrt{\frac{f}{f_{c,mn}}} \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}} \frac{\left(1 + 2\left(\frac{1}{2\kappa}\right)\left(\frac{f_{c,mn}}{f}\right)^2\right)}{\sqrt{1 - \left(\frac{f_{c,mn}}{f}\right)^2}} \tag{67}$$

The combined propagation constant is given as:

$$\begin{aligned} \gamma l &= (\alpha + j\beta) l \\ \gamma l &\approx \left((\textbf{Offset Loss}) \sqrt{\frac{f}{f_{c,mn}}} \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}} \frac{\left(1 + 2\left(\frac{1}{2\kappa}\right)\left(\frac{f_{c,mn}}{f}\right)^2\right)}{\sqrt{1 - \left(\frac{f_{c,mn}}{f}\right)^2}} + j2\pi f \sqrt{1 - \left(\frac{f_{c,mn}}{f}\right)^2} \right) (\textbf{Offset Delay}) \end{aligned} \tag{68}$$

Note that the $\left(\frac{1}{2\kappa}\right)$ term in equation 68 is equivalent to the height/width ratio $\left(\frac{h}{w_e}\right)$ for rectangular waveguides in equation 62.

Appendix E Data-based Calibration Standard Definition File Format

A standalone version of the calibration kit editor is available online at https://www.keysight.com/us/en/lib/software-detail/computer-software/pna-service-applications.html. This editor can create kits that include data-based standards. Data-based standards are described by a data list. A data-based standard should include a list of frequencies, the actual response for each s-parameter at each frequency and an estimate of the confidence factor for the actual response; this is part of what is used to determine the weighting factor when the standard is used during an weighted least squares over-determined solution.

Example file:

```
CITIFILE A.01.01
COMMENT Rev A.01.00
COMMENT STDTYPE DATABASED
COMMENT MODEL: 85058-60101
COMMENT SERIAL NUMBER: NOMINAL
NAME DATA
COMMENT This section describes the s parameter data and confidence
COMMENT factor for the calibration standard
COMMENT S[i,j] is sij for the standard. Supported formats: RI
COMMENT U[i,j] is the confidence factor for sij.
COMMENT Supported U[i,j] formats: RI, MAG
COMMENT note number of points is 509 below
VAR Freq MAG 509
DATA S[1,1] RI
DATA U[1,1] MAG
VAR_LIST_BEGIN
0
10000000
15000000
...
70000000000
VAR_LIST_END
BEGIN
-1,0
-0.99976354927,0.00249289367
-0.99970950119,0.00367766097
...
0.9772034982,-0.14575300423
END
BEGIN
0.00028
0.00028
0.00028
...
0.005
END
```

Appendix F 8510 Calibration kit modification/entry procedure

Calibration kit specifications can be entered into the Keysight 8510 vector network analyzer using the disk drive, a disk drive connected to the system bus, by front panel entry, or through program control by an external controller. Table 5 provides the standard definitions and Table 6 provides the calibration class assignments.

Table 5. 8510 standard definitions table

STANDARD		Fixed or	Offset			Frequency GHz		Coax or	Standard
Num	Type	Sliding	Delay ps	Z_0 Ω	Loss $G\Omega s^{-1}$	Min	Max	Waveguide	Label
1	SHORT		10.8309	1	0	9.487	18.974	W/G	PSHORT 1
2	SHORT		32.4925	1	0	9.487	18.974	W/G	PSHORT 2
3	LOAD	FIXED	0	1	0	9.487	18.974	W/G	PLOAD
4	THRU		0	1	0	9.487	18.974	W/G	PTHRU

Table 6. 8510 class assignment table

Standard class	Standard numbers	Class label
S11A	1	PSHORT 1
S11B	2	PSHORT 2
S11C	3	PLOAD
S22A	1	PSHORT 1
S22B	2	PSHORT 2
S22C	3	PLOAD
FWD TRANS	4	THRU
FWD MATCH	4	THRU
REV TRANS	4	THRU
REV MATCH	4	THRU
RESPONSE	1,2,4	RESPONSE

Disk procedure

This is an important feature since the 8510 can only store two calibration kits internally at one time, while multiple calibration kits can be stored on a single disk.

Below is the generic procedure to load or store calibration kits from and to the disk drive or disk interface.

To load calibration kits from disk into the Keysight 8510

1. Insert the calibration data disk into the network analyzer (or connect compatible disk drive to the system bus).
2. Press the DISC key; select STORAGE IS: INTERNAL or EXTERNAL; then press the following display soft keys: LOAD CAL KIT 1-2 CAL KIT 1 or CAL KIT 2 (This selection determines which of the non-volatile registers that the calibration kit will be loaded into.) FILE #_ or FILE NAME (Select the calibration kit data to load.) LOAD FILE.

3. To verify that the correct calibration kit was loaded into the instrument, press the CAL key. If properly loaded, the calibration kit label will be shown under “CAL 1” or “CAL 2” on the CRT display.

To store calibration kits from the Keysight 8510 onto a disk

1. Insert an initialized calibration data disk into the network analyzer or connect compatible disk drive to the system bus.
2. Press the DISC key; select STORAGE IS: INTERNAL or EXTERNAL; then press the following CRT displayed soft keys: STORE CAL KIT 1-2 CAL KIT 1 or CAL KIT 2 (This selection determines which of the non-volatile calibration kit registers is to be stored.) FILE #_ or FILE NAME (Enter the calibration kit data file name.) STORE FILE.
3. Examine directory to verify that file has been stored. This completes the sequence to store a calibration kit onto a disk.

To generate a new cal kit or modify an existing one, either front panel or program controlled entry can be used.

In this guide, procedures have been given to define standards and assign classes. This section will list the steps required for front panel entry of the standards and appropriate labels.

Front panel procedure: (P-band waveguide example)

1. Prior to modifying or generating a cal kit, store one or both of the cal kits in the ’s non-volatile memory to a disk
2. Select **CAL** menu >**MORE**
3. Prepare to modify cal kit 2: press **MODIFY 2**
4. To define a standard: press **DEFINE STANDARD**
5. Enable standard no. 1 to be modified: press 1, x1
6. Select standard type: **SHORT**
7. Specify an offset: **SPECIFY OFFSETS**
8. Enter the delay from Table 1: **OFFSET DELAY**, 0.0108309 G/n
9. Enter the loss from Table 1: **OFFSET LOSS**, 0, x1
10. Enter the Z0 from Table 1: **OFFSET Z0**, 1, x1
11. Enter the lower cutoff frequency: **MINIMUM FREQUENCY**, 9.487 G/n
12. Enter the upper frequency: **MAXIMUM FREQUENCY**, 18.97 G/n
13. Select **WAVEGUIDE**
14. Prepare to label the new standard: press **PRIOR MENU** >**LABEL STANDARD** >**ERASE TITLE**
15. Enter PSHORT 1 by using the knob, **SELECT** >**LETTER soft key and SPACE soft key**
16. Complete the title entry by pressing **TITLE DONE**

17. Complete the standard modification by pressing **STANDARD DONE (DEFINED)**

Standard #1 has now been defined for a 1/8 λ P-band waveguide offset short. To define the remaining standards, refer to Table 5 and repeat steps 4-17. To define standard #3, a matched load, specify "fixed."

The front panel procedure to implement the class assignments of Table 2 for the P-band waveguide cal kit are as follows:

1. Prepare to specify a class: **SPECIFY CLASS**
2. Select standard class **S11A**
3. Direct the network analyzer to use standard no. 1 for the **S11A** class of calibration: **1**, x1 , **CLASS DONE (SPECIFIED)**

Change the class label for **S11A**:

1. **LABEL CLASS**, **S11A**, **ERASE TITLE**
2. Enter the label of **PSHORT 1** by using the knob, the **SELECT** soft key and the **SPACE** soft key
3. Complete the label entry procedure: **TITLE DONE** >**LABEL DONE**

Follow a similar procedure to enter the remaining standard classes and labels as shown in Table 6.

Finally, change the cal kit label as follows:

1. Press **LABEL KIT** >**ERASE TITLE**
2. Enter the title **"P BAND"**
3. Press **TITLE DONE** >**KIT DONE (MODIFIED).** The message **"CAL KIT SAVED"** should appear

This completes the entire cal kit modification for front panel entry. An example of programmed modification over the GPIB bus through an external controller is shown in the *"Introduction To Programming" section of the 8510 Network Analyzer Operating and Service Manual (section III).*

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