ABSTRACT

CEL uses a variety of methods to accurately measure and characterize RF and microwave devices in support of customer’s designs. The most important part of measuring these high frequency devices is to use appropriate fixtures and calibration methods. One of the calibration methods often used to calibrate the HP8510 network analyzer is Through-Reflect-Line (TRL). Like other calibration methods, TRL will introduce a twelve term error correction vector for each frequency point. To calculate these terms, some standards for which S-parameters must be measured. These standards can be a short, an open, a through or a delay line with known electrical delay. A TRL calibration uses a through, a reflect which could be either an open or a short, and a delay line.

The TRL calibration corrects phase and magnitude errors introduced by the sliding of reference planes and the insertion loss of cables, fixtures and connectors. Calibration standards should be as close as possible to the theoretical performance because each defect in a standard will be transformed into error during the calibration.

This application note explains how to characterize and build a proficient TRL calibration kit for the HP8510 Network Analyzer. An explanation of how to characterize a TRL calibration kit is given and methods to improve the calibration kit using the measurements made on it are demonstrated.

CALIBRATION OF A NETWORK ANALYZER

In any measurement, there are systematic error sources, which will completely change the response of a Device Under Test (DUT). In order to annul the response of cables, connectors and miscellaneous loss (in couplers, cables, connectors, mismatched lines, etc.) it is possible to calibrate the network analyzer. That calibration will provide a correction term vector for each frequency point. If a sweep in frequency has been implemented, this vector will become a matrix. The two main correction vectors are the eight term correction vector and the twelve terms correction vector.

The twelve-term error correction

The twelve-term error correction theory permits correction of six terms in forward and six in reverse mode. These six terms are:

- $E_d$: The directivity term
- $E_r$: The reflection tracking term
- $E_l$: The load match term
- $E_t$: The transmission tracking term
- $E_s$: The source match term
- $E_i$: The isolation term

They can be seen in the below flow graph (Figure 1) representing the forward error terms:

![Figure 1. Flow graph of the forward path twelve-term error correction.](image)

This correction is the most efficient and is only available on the most expensive network analyzer and corrects all systematic errors provided by the network analyzer. The eight-term calibration is implemented in cheaper network analyzers. It is simpler but does not correct all the systematic errors such as the errors introduced when switching to an alternate measurement direction.

The eight-term error correction

The eight-term error correction models each access by a quadripole defined by its S-parameters. There are four terms per port and two ports. In some network analyzers, it is possible to also correct the isolation, which is not included in the eight-term correction. That kind of correction can be modeled by the below flow graph (Figure 2):

![Figure 2. Flow graph of the eight-term error correction.](image)

The TRL calibration

The TRL calibration uses the through, the delay line and a reflection standard, either an open or a short. Each of the four S-parameters is calculated for each standard. Thus
twelve parameters are measured and it is then possible with a system of equations to find ten of the twelve error terms. The two missing terms are the forward and reverse isolation terms that cannot be extracted from that set of equations. If the user also wants to calibrate these parameters, isolation calibration will need to be performed with two $Z_0$ loads as in the OSLT calibration.

The flow graph of each TRL standard can be defined as shown in Figure 3.

```
0 1 0
THROUGH

0 e^{j\phi} 0
DELAY

0 \Gamma 0
REFLECT
```

Figure 3. Flow graphs of TRL standards.

CHARACTERIZATION OF A TRL CALIBRATION KIT

Errors sources

Errors appear when the standard used for the calibration is different from the fixture of the device under test. For example, if the fixture microstrip does not have the same board thickness as the through standard, its frequency response will not be the same as the standard. Systematic error will not be the same as the standard and the correction will not remove this error. The difference between such standard and the fixture strip response will be added to the component response, biasing the results. Therefore, one critical factor when building a calibration kit is the repeatability of each standard and test fixture. Each standard must only differ by that aspect of the electrical characteristic which was intended to change. For example, the only desirable difference between a through and a delay line is the phase. All other parameters (including insertion loss) should be identical. In reality this is impossible, but differences should be minimized. Differences between standards and fixtures are numerous. The biggest difference is often the soldering of the connector because it is a human process. Other defaults such as strip thickness, line width and metal thickness are negligible because processes are very repeatable. Therefore, it is very important to test each connector and to measure each return loss. These measurements can be done with the time domain measurement explained below.

The fact that standards are not perfect is an error source. The network analyzer assumes that standards are perfect during the calibration. For example, the reflect standard does not have a reflection coefficient equal to one (see Figure 4). Some of the incident signal radiates. The higher the frequency, the more radiation there is. The correction vector becomes less and less precise as the frequency increases. The non-perfect aspect of the open can be modeled with a nonlinear capacitance and return loss in the calibration kit definition of the HP8510 network analyzer. Nonlinear modeling and implementation on the HP8510 is explained below.

A good calibration kit standard can also provide bad results if it is not well implemented in the HP8510. The electrical delay of each delay line is a significant parameter that should be measured with good precision. If the effective delay line is not the same as the parameter implemented in the HP8510, there will be a linear frequency dependent systematic phase error (see Figure 5). The measurement of delay lines is a very substantial part of the calibration definition. This measurement is explained below.

```
0 \Gamma 0
REFLECT
```

Figure 4. Response of a reflect line (S22).

```
0 1 0
THROUGH

0 e^{j\phi} 0
DELAY

0 \Gamma 0
REFLECT
```

Figure 5. S12 phase

Left : with perfect offset definition.
Right : with 10 ps delay offset error.

The difference between a perfect open, a perfect through and a perfect line can be defined on the Smith chart simply by a phase shifting. To avoid having several standards too close on the Smith chart, the phases of delay lines have to respect some rules. The S12 differential phase of the delay line has to be within a 20 - 160 degree limit, when compared to the through line.
It is easy to measure the frequency corresponding to these 20 and 160 degree limits by performing an electrical delay measurement explained below.

**Time domain measurement**

A good way to find the physical location of a defect on a fixture is to use time domain measurement on the HP8510 network analyzer. To figure out the defect at a precise point on the circuit, frequency domain measurements can not be used. Time domain can be achieved through a Fast Fourrier Transform (FFT) of the frequency domain. It typically is an option available on a UNA. Assuming that speed of an electrical impulse is constant, time becomes proportional to distance and viewing a time domain signal is equivalent to viewing a “distance domain” signal. Looking at S11, which refers to reflection coefficient on port 1, or S22, which refers to reflection coefficient on port 2 is like viewing the reflection coefficient versus distance. The transition from frequency to time domain is assured by a Fast Fourier Transform (FFT). Because there is only a mathematical relation between frequency and time domain, the user has to set up the frequency domain with appropriate values to have good results in the time domain.

First of all the calibration should be done at the highest frequency where good measurements can be attained and with the greatest number of points. The wider the bandwidth, the more precise the time domain conversion will be. The step between two discrete time points will be small when the frequency domain bandwidth is large.

The reference planes should be located right on the connectors so the connector will be located at zero seconds in the time domain. The user can use a Short-Open-Load (SOL) calibration from 45 MHz to 24 GHz using a 50 MHz step (479 points) with a good calibration standard such as 3.5 mm SMA or a 2.6 mm calibration kit.

When the calibration is done, the user needs to switch the network analyzer into “time domain” mode.

→ Press Domain Button
→ Select “Time band pass” on menu

The network analyzer is now in time domain. The user needs to change the scale to have an appropriate curve displayed. A typical curve for a transmission line (delay line or through) is two peaks spaced with a quasi-null flat part. The two peaks refer to the connectors return loss, the flat part between deals with the insertion loss of the matched line (see Figure 6). Both peaks and flat null part should be as small as possible. Typically a peak less than 50 mV is considered good. A typical curve for a reflection line is also two peaks. The first one deals with the connector insertion loss and should be as small as possible, the second one refers to the reflection on the reference plan of the fixture (short or open). It should be as close as possible to an open or short (reflection of N1).

![Figure 6. Time domain measurement of a delay line.](image)

**Frequency domain measurement**

It is possible to measure the S-parameter of fixtures in frequency domain with the HP8510 network analyzer. This kind of measurement can provide some useful information on S-parameter versus frequency. It is used to model lines, open and short (with respectively nonlinear resistor, capacitance and inductor) and can also provide information about the maximum usable frequency. It also supplies information about the electrical delay of lines. This kind of measurement will be developed in paragraph.

To characterize a fixture in frequency domain with the HP8510, you first need to calibrate the network analyzer, using for example an SOL calibration. You can then view S11, S12, S21 and S22 in magnitude, angle or on a Smith chart.

For a transmission line (through or delay) the insertion loss (S12 and S21) should be very small (under 0.5 dB). Insertion loss varies as the square root of frequency, so the insertion loss rises quickly as the frequency increases. Depending on the desired precision, the user will be able to assign a maximum usable frequency for the transmission line fixture with this curve. If that maximum usable frequency is not high enough, it is possible to introduce a nonlinear offset loss in the network analyzer which will take into account a modeled loss varying with the square root of frequency. This will be explained in the following paragraph. S11 and S22 have to be less than -20 dB meanings that the reflection coefficient is very small (under 0.01).

For a reflection line (open or short), the transmission coefficient (S12, S21) should be very small, less than -30 dB. That means there is hardly any coupling between the two reflection lines (one for port 1, the other for port 2) and good isolation between the two ports. The reflection coefficient (S11, S22) should be as close as possible to 0 dB so there is virtually no insertion loss. Like the transmission lines, it is possible to introduce a nonlinear model made of a resistor and a capacitor for the open and a resistor and an inductor for the short. The modeling aspect...
is explained below in paragraph.

**Electrical delay measurement**

The TRL kit uses different lengths transmission lines so it is necessary to be able to measure very precisely the difference between the through and the delay lines electrical length. By definition, the through has a null electrical delay. That means the two reference planes of the fixture are overlapped.

The through can then be used as a reference for the electrical delay measurement. The user needs to calibrate the network analyzer with the calibration kit through standard. As there is only one standard for the calibration, the user has to display the phase of S12 or S21, so that it will be the corrected value after calibration. After completing the calibration with the through standard, the user should see a flat null phase response versus frequency. This means that the standard measured is now the phase - or electrical delay - reference. The user can now insert the delay line. As the length is different, the phase will no longer be flat. It is now easy to measure the differential phase versus frequency to obtain the frequency range of the delay line. It is also possible to measure the differential electrical length of the delay line. The network analyzer can automatically give the electrical length. The user just has to press electrical delay in the response menu and turn the control knob until the phase response becomes flat again. To have good precision, it is recommended to change the Y axis scale while the phase curve comes close to a flat null curve. When the curve is flat again, the user can just read the electrical delay displayed.

**IMPROVEMENT OF A TRL CALIBRATION KIT**

**Physical error correction**

Even if it is possible to compensate for physical errors by introducing basic nonlinear error modeling on the HP8510 network analyzer, the fixtures have to be as perfect as possible. There are a few points to check to be sure that the fixture is adequate.

**Connectors**

The connectors have to be as consistent as possible on all standards and fixtures. They should come from the same manufacturer, and be assembled the same way. The pin of each connector has to be in contact with the substrate strip to assure a smooth transition from the connector to the strip and reduce the coax to microstrip discontinuities. There should be just a little wet solder to keep the pin in contact with the strip (Figure 7). The ground connection has to be as big as possible, so that the impedance between the connector and the fixture ground is null. Each transition reflection coefficient should be the same for all connectors of all fixtures (standards and component fixtures). It is easy to test each connector with the time domain measurement.

**Figure 7. Schematic of a well-built connector.**

**Line and substrate**

The substrate should be, of course, the same for all fixtures. The line should be 50Ω. If it is long enough, it is easy to check if the impedance is close to 50Ω with the time domain measurement. The part of the time domain curve dealing with the line has to be as close as possible to 0. It is also possible to calculate the impedance of the line with, for example, Linecal from ADS. There should be no solder on the strip, otherwise the thickness and conductivity of the line will be changed and the impedance will no longer be 50Ω.

**Modeling standard errors**

If standards are not good enough up to the desired frequency, it is possible to include a nonlinear model in the calibration kit definition of the network analyzer. This modeling is summarized in Table 1.

<table>
<thead>
<tr>
<th>LINE</th>
<th>( R = \alpha_{lin} f^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN</td>
<td>( R = \alpha_{lin} f )</td>
</tr>
<tr>
<td>SHORT</td>
<td>( R = \alpha_{lin} f^2 )</td>
</tr>
</tbody>
</table>

*Table 1. TRL Standards modelization.*

**Dimensions:**

\[
R[\Omega], C[F], L[H], \alpha[H], L_0[H]
\]

The nonlinear modeling of a line is a series nonlinear frequency dependant resistor. The model assumes that insertion loss varies as square root of frequency therefore, equivalent resistor varies as square of frequency.

\[
R = \alpha_{lin} f^2
\]  

*(Equation 1)*
To calculate the proportional factor $\alpha_{\text{loss}}$, the equivalent resistor at one frequency needs to be known. The frequency chosen is 1 GHz. When that value is known, equation 2 provides $\alpha_{\text{loss}}$:

\[ \alpha_{\text{loss}} = \frac{R_{\text{equiv}} \log_{10} f}{10^{14}} \]  

At 1 GHz, these equations provides $R=\text{Requ}$.

The offset loss that will be implemented in the HP8510 is:

\[ \text{Offset} - \text{Loss} = \text{R} - \frac{\text{Electrical} - \text{Length}}{\text{s}} \]  

(Equation 3)

The nonlinear modeling of an open is a series resistor followed by a parallel nonlinear frequency dependent capacitor. The total impedance of the model in harmonic domain is:

\[ Z_{\text{equiv}} = R + \frac{1}{j \omega C \alpha} \]  

(Equation 4)

where:

\[ R = \alpha_{\text{loss}} f^2 \]

\[ C = C_0 + C_1 f + C_2 f^2 + C_3 f^3 \]

so:

\[ Z_{\text{equiv}} = \frac{1 + j 2 \pi \alpha_{\text{loss}} f (C_0 + C_1 f + C_2 f^2 + C_3 f^3)}{j (C_0 + C_1 f + C_2 f^2 + C_3 f^3) 2 \pi f} \]  

(Equation 5)

Values for $C_0$, $C_1$, $C_2$, $C_3$ have to be within the following limits (Table 2):

<table>
<thead>
<tr>
<th>Minimum value</th>
<th>Variable</th>
<th>Maximum value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-10^{-11}$</td>
<td>$C_0$</td>
<td>$10^{-11}$</td>
<td>F</td>
</tr>
<tr>
<td>$-10^{-23}$</td>
<td>$C_1$</td>
<td>$10^{-23}$</td>
<td>F/Hz</td>
</tr>
<tr>
<td>$-10^{-32}$</td>
<td>$C_2$</td>
<td>$10^{-32}$</td>
<td>F/Hz^2</td>
</tr>
<tr>
<td>$-10^{-41}$</td>
<td>$C_3$</td>
<td>$10^{-41}$</td>
<td>F/Hz^3</td>
</tr>
</tbody>
</table>

Table 2. Limit values for coefficient of the nonlinear capacitor on a HP8510 network analyzer

As with the open, the equivalent resistor must be divided by two for one-way path insertion loss. The values of $R$, $L_1$, $L_2$, $L_3$ and $L_4$ can also be determined via optimization.

Optimization with ADS

The aim of optimization is to make the model converge to the real physical response of the device. This can be obtained with a simple comparison of the model and the measured fixture response.

First, the user must measure the fixture in frequency domain and acquire the data in s2p format as explained above. When the s2p file is saved, the response of the fixture can be read by ADS using a 2 port S parameter box (Menu data item → 2 port S parameter box). That box terminated by a 50 $\Omega$ load on both port and the reference is the ground (see Figure 8).

The nonlinear model has to be implemented in a 1 port SDD (Symbolically Defined Device - Menu Equation - NonLinear). The user needs to define the current-voltage equation. As it is forbidden to use frequency dependent insertion loss. That calculation assumes that the insertion loss is the same for the forward and for the reverse path. The values of $R$, $C_0$, $C_1$, $C_2$, $C_3$ can be found with an optimization engine (included in Agilent’s ADS). The way to do such an optimization is explained below.
values in the current-voltage, it is necessary to use a weighting function.

If I is the current, V the voltage and H the weighting function, the model is made as below:

\[ I = H \cdot f(V) \]  

(Equation 8)

As it is impossible to use a frequency dependent variable in \( f(V) \), it is more simple to use \( f(V) = V \) and \( -1/V = Z \cdot I - H = 1/Z \). Finally the equation is:

\[ I = H \cdot \frac{1}{Z} \]  

(Equation 9)

Using the equivalent impedance found above, the result is a frequency dependent nonlinear block. For some equivalent impedances which are null when \( f=0 \), it is necessary to add a small constant negligible at the lowest simulated frequency so that the DC analysis does not provide a divide-by-zero error.

The optimization variables have to be included in a VarEqu block. The simulation engine used is the S parameter engine. Last thing to do is to implement the optimization engine and the goals. The two parameters to optimize are included in Table 4:

<table>
<thead>
<tr>
<th>Standard</th>
<th>Parameters to optimize</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line</td>
<td>Phase and magnitude of S12 or S21</td>
<td>( \text{Phase}(S12)&lt;wedge&gt;\text{Phase}(S12) \cdot 1 &lt; \text{MaxError } \text{phase} ) [ \text{Mag}(S12) \cdot \text{Mag}(S12) \cdot 1 &lt; \text{MaxError } \text{magnitude} ]</td>
</tr>
<tr>
<td>Open</td>
<td>Phase and magnitude of S11 or S22</td>
<td>( \text{Phase}(S11) \cdot \text{Phase}(S11) \cdot 1 &lt; \text{MaxError } \text{phase} ) [ \text{Mag}(S11) \cdot \text{Mag}(S11) \cdot 1 &lt; \text{MaxError } \text{magnitude} ]</td>
</tr>
<tr>
<td>Short</td>
<td>Phase and magnitude of S11 or S22</td>
<td>( \text{Phase}(S11) \cdot \text{Phase}(S11) \cdot 1 &lt; \text{MaxError } \text{phase} ) [ \text{Mag}(S11) \cdot \text{Mag}(S11) \cdot 1 &lt; \text{MaxError } \text{magnitude} ]</td>
</tr>
</tbody>
</table>

Table 4. Optimization equations for TRL standards.

Where MaxErrorphase is the maximum absolute phase error tolerated and MaxErrormag is the maximum absolute magnitude error tolerated. When all these equation are implemented, it is possible to optimize the values. To have the best results, the user has to use a random algorithm with a high number of points (several hundred) so that ADS can find out roughly the minimum of the error function in valid parameter values limit. When that is done, using a Gradient algorithm on about 30 points permits the simulator to obtain the local minimum of the error function which should be, if the random optimization has been made efficiently, the absolute minimum of the error function. The values obtained are the most accurate values within the limits depending on the norm used. Best physical results are obtained with a quadratic norm (L2). Figure 9 illustrates the results of the optimization performed in Figure 8.

Figure 8. Example of a short nonlinear model optimization with ADS.
BUILDING OF A TRL CALIBRATION KIT ON HP8510 NETWORK ANALYZER

Several parameters have to be known to build a TRL calibration kit. These are summarized in Table 5:

<table>
<thead>
<tr>
<th></th>
<th>Offset loss (optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THRU</td>
<td></td>
</tr>
<tr>
<td>LINE</td>
<td>For each delay line:</td>
</tr>
<tr>
<td></td>
<td>Offset delay</td>
</tr>
<tr>
<td></td>
<td>Frequency bandwidth of validity of the line</td>
</tr>
<tr>
<td></td>
<td>Offset loss (optional)</td>
</tr>
<tr>
<td>REFLECT</td>
<td>Type of reflect (open or short)</td>
</tr>
<tr>
<td></td>
<td>Non linear coefficient (optional)</td>
</tr>
<tr>
<td></td>
<td>Offset loss (optional)</td>
</tr>
</tbody>
</table>

Table 5. Parameters to be known to build a TRL calibration kit.

There are some optional fields for setting up a calibration kit. These optional fields define the nonlinear model of the standards. If the user does not want to include a nonlinear model in the calibration kit, these fields should be set to zero.

Once all the needed parameters are known, the user has to implement them in the HP8510. The way to do that can be simplified in a block diagram (Figure 10):

The HP8510 memorizes the standard parameter in its memory addresses from #1 to #2; therefore the user can define 20 standards for each calibration kit.

The first step in implementing a calibration kit is to assign the standard addresses for each class. One or several standard memory numbers have to be attributed for each class (there are three for TRL calibration kit - through, reflect and delay lines). To do so, the user has to go to the Specify class menu. The menu that appears the specification of class for the reflect standard of the 2 port and 1 port calibration. These standards are not used in a TRL calibration kit. After pressing more, the menu becomes the specification of class for the transmission standards of the 2 port and 1 port calibration. These standards are also not needed. After pressing more, the menu becomes the response and TRL calibration standard specification. The different choices are:

- Response
- TRL thru
- TRL reflect
- TRL line
- Adapter

The user now has to attribute one or several standard addresses for each of the three TRL classes. To do this, select the standard and enter the address number on the HP8510 numeric panel separated by the x1 button. For example, to implement a three delay lines TRL cal kit, the procedure could be:
• Press TRL THRU
• Press 1 followed by x1
• Press TRL REFLECT
• Press 2 followed by x1
• Press TRL LINE
• Press 3, x1, 4, x1, 5, x1

If the user wants to implement the response calibration kit too, the addresses wanted for the response calibration must be defined. It is advised to use the thru and/or the delay lines. In the example above, if the user wants to implement the through and the delay lines in the response calibration kit:

• Press RESPONSE
• Press 1, x1, 3, x1, 4, x1, 5, x1

At this point, the addresses of the standards are implemented for each class. The user needs now to modify the label of the three classes (Thru, reflect and line). That can be done in the label class menu. This menu is exactly the same as the specified class menu but instead of entering the addresses of the standard, the user will enter the label of the standard. Assuming that the reflect in the example above is a short, the label could be:

• TRL THRU → “Through”
• TRL REFLECT → “Short”
• TRL LINE → “Delay_lines”

The classes are defined, addressed and labeled. The user now enters the parameter of the standard. This is done in the define standard menu. The user enters the address of the standard to define. The standard choices are:

• Short
• Open
• Load
• Line/Thru

In the example above, if the user is defining the standard implemented in address #1, #3, #4 or #5 - which are the through and the lines - select Line/Thru. If defining the standard implemented in address #2 - which is the reflect standard - select short.

For each address corresponding to a standard, the user will have to enter all the parameters included in the table above. More precisely, the parameters are:

**Short:**
• Nonlinear coefficients $L_0$, $L_1$, $L_2$, $L_3$.
  If the user does not want nonlinear modeling, enter 0 (zero).
• Offset delay. Including : Offset delay. Should be zero in most cases, if the short is right on the reference plane. Otherwise, the user needs to measure the electrical delay between the reference plane and the short plane and enter it.
• Offset loss. Should be zero if the user does not want a frequency dependent model. Otherwise enter the calculated or simulated value.
• Offset Z0. Should be 50 in most case.
• Minimum frequency. There is no frequency compliance for the reflect standard. The user can enter 10 MHz which is less than the smallest frequency that the HP8510 can generate.
• Maximum frequency. There is no frequency compliance for the reflect standard. The user can enter 100 GHz which is more than the biggest frequency that the HP8510 can generate.
• Coax/Waveguide. The user enters the type of cable used. Most often it is Coax.
• Label Std. The user enters the name of the standard.

**Open:**
• Nonlinear coefficients $C_0$, $C_1$, $C_2$, $C_3$. If the user does not want nonlinear modeling, enter 0 (zero).
• Offset delay. Including : Offset delay. Should be zero in most case, if the open is right on the reference plane. Otherwise, the user needs to measure the electrical delay between the reference plane and the open plane and enter it.
• Offset loss. Should be zero if the user does not want a frequency dependant model. Otherwise enter the calculated or simulated value.
• Offset Z0. Should be 50 in most case.
• Minimum frequency. There is no frequency compliance for the reflect standard. The user can enter 10 MHz which is less than the smallest frequency that the HP8510 can generate.
• Maximum frequency. There is no frequency compliance for the reflect standard. The user can enter 100 GHz which is more than the biggest frequency that the HP8510 can generate.
• Coax/Waveguide. The user enters the type of cable used. Most often it is Coax.
• Label Std. The user enters the name of the standard.

**Load:**
• Fixed/Sliding/Offset. Enter the kind of load used. Most often, the load is a fixed type.
• Offset delay. Including : Offset delay. Should be zero in most case, if the load is right on the reference plane. Otherwise, the user needs to measure the electrical delay between the reference plane and the load plane...
and enter it.
- Offset loss. Should be zero if the user does not want a frequency dependant model. Otherwise enter the calculated or simulated value.
- Offset Z0. Should be 50 in most case.
- Minimum frequency. The user enters there the minimum frequency of validity of the load.
- Maximum frequency. The user enters there the maximum frequency of validity of the load.
- Coax/Waveguide. The user enters the type of cable used. Most often it is Coax.
- Label Std. The user enters the name of the standard.

**Line/Thru:**
- Offset delay. Including:
  - Offset delay. Is zero for the through standard by definition. The user enters the measured offset for the different delay lines.
  - Offset loss. Should be zero if the user does not want a frequency dependant model. Otherwise enter the calculated or simulated value.
  - Offset Z0. Should be 50 in most case.
  - Minimum frequency. The user enters there the minimum frequency of validity of the delay line. There is no minimum frequency for the through (enter a value < 45 MHz).
  - Maximum frequency. The user enters there the maximum frequency of validity of the delay line. There is no maximum frequency for the through (enter a value > 50 GHz).
  - Coax/Waveguide. The user enters the type of cable used. Most often it is Coax.
  - Label Std. The user enters the name of the standard.

The calibration kit is now nearly entirely defined. The user needs to program the TRL options in the TRL options menu. The user will then select LineZ0 in the Cal Z0 menu and Thru in the Set Ref menu. The lowband frequency will be set to 45 MHz.

When measuring very high insertion loss devices, it is necessary to do an isolation calibration with the TRL calibration. To do so, the user needs to define the forward and reverse isolation with the method explained above and associate the reverse and forward isolation with the address #6. In the define standard menu, the address #6 will be a load type.

The user needs now to label the calibration kit in the Label Kit menu and press CalKit done.

The calibration kit implementation is now finished. The example above is summarized in Table 6. Figure 11 is an example of a calibration kit standard and Figure 12 shows measured data on a DUT with these standards used to calibrate the HP8510.

<table>
<thead>
<tr>
<th>CalKit</th>
<th>Class Label</th>
<th>#</th>
<th>Type</th>
<th>Label</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL THRU Through</td>
<td>Thru Delay</td>
<td>1</td>
<td>Thru</td>
<td>Through</td>
<td>Offset Delay ~ 0 No min/max frequencies</td>
</tr>
<tr>
<td>TRL REFLECT Short</td>
<td>Short</td>
<td>2</td>
<td>Short</td>
<td>Offset Delay ~ 0 No min/max frequencies</td>
<td></td>
</tr>
<tr>
<td>TRL LINE Delay Line</td>
<td>Thru Delay</td>
<td>3</td>
<td>Delay_low</td>
<td>Offset delay ≠ 0</td>
<td></td>
</tr>
<tr>
<td>TRL LINE Delay Line</td>
<td>Thru Delay</td>
<td>4</td>
<td>Delay_mid</td>
<td>Offset delay ≠ 0 &lt; Delay_low</td>
<td></td>
</tr>
<tr>
<td>TRL LINE Delay Line</td>
<td>Thru Delay</td>
<td>5</td>
<td>Delay_high</td>
<td>Offset delay ≠ 0 &lt; Delay_mid</td>
<td></td>
</tr>
<tr>
<td>FWD ISOL. Pad_iso</td>
<td>Load</td>
<td>6</td>
<td>Pad_iso</td>
<td>Offset: fixed type</td>
<td></td>
</tr>
<tr>
<td>REV ISOL. Rev_iso</td>
<td>Load</td>
<td>6</td>
<td>Rev_iso</td>
<td>Offset: fixed type</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Outlook of the organization of a TRL calibration kit in a HP8510 network analyzer.

Figure 11. TRL calibration kit using two delay lines and a short
CONCLUSION

Use of the TRL fixture calibration requires a good calibration kit and a thorough understanding of calibration techniques. This method permits the deletion of systematic errors, a most important first step in making accurate measurements of microwave devices. These measurements are the foundation for the creation of precise device characteristics and nonlinear models. Errors introduced in models propagate throughout the simulations of higher level circuit designs causing mismatch between computer aided and measured results. This mismatch requires detailed analysis to correct. Efficient system design begins with well-defined components.

References

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