Agilent
User Characterization: Electronic Calibration Feature Allows Users to Customize to Specific Needs

White Paper

Agilent Technologies

Abstract

Vector network analyzer (VNA) calibrations have historically been very labor intensive. That story has changed with the release of Agilent's new series of Electronic Calibration Modules (ECal). ECal modules offer calibrations at a fraction of the time it would take to calibrate using mechanical calibrations, and are not just limited to quick accurate calibrations. A new "User Characterization" capability empowers users to characterize the ECal module themselves. Mixed connector, waveguide, and fixture calibrations can all be handled using this feature along with the techniques described in this paper.

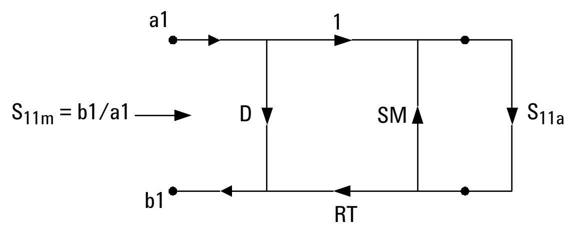
Introduction

ECal has revolutionized the way VNA calibrations are done[1, 2]. The ease and speed at which accurate calibrations are achieved are virtually unheard of with corresponding mechanical calibrations. Supplementing ECal's theme of speed and ease is the addition of "User Characterization" feature. This new feature enhances the versatility of the current line of ECal modules, giving the user the ability to use ECal in several applications where ECal could not be used before, and is supported by the new Agilent PNA and ENA series of vector network analyzers.

Previously, to measure mixed connector devices, a user must use multiple cal kits, and still might have to suffer the uncertainty associated with using an unknown adapter. The User Characterization feature solves this and many other calibration problems. With it, an ECal user may create up to five custom calibrations for an ECal module. These calibrations can be used to account for connector adapters used with the ECal module, to de-embed fixtures and probes, and a variety of other applications.

ECal – How it works

ECal, at its core, consists of several reflective, and at least one transmissive, impedance states that are of known value. Standard one-port error correction on network analyzers follows the signal flow graph and equation shown in Figure 1:



$$S_{11m} = D + \frac{RT \cdot S_{11a}}{1 - SM \cdot S_{11a}} \qquad \text{(Equation 1)}$$

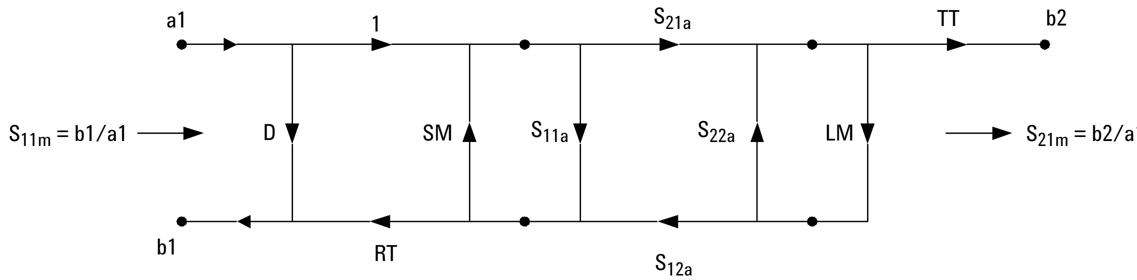
Where

D = Directivity
SM = Source Match
RT = Reflection Tracking

Figure 1. One-port error correction signal flow graph

During one-port calibration the values for Directivity (D), Source Match (SM), and Reflection Tracking (RT) are determined. ECal provides known values of impedance standards (S_{11a}) while the network analyzer provides raw measured values (S_{11m}). Hence, the equation in Figure 1 simplifies to three unknowns (D, SM, RT), which need to be solved for. Three unknowns imply that at least three independent equations are needed to solve for the values. Standard mechanical calibrations use three impedance standards to solve these equations, namely, an *Open, Short, and Load*. This fulfills the minimum requirement to solve the equations. ECal typically provides at least four known reflective impedance standards for one-port error correction. Thus, the solution achieved is considered over-determined and a least squares fit of all four impedance scenarios.

Two-port error correction follows much of the same technique as the one-port error correction. Figure 2 is an equation of the standard two-port error diagram and equation:



$$S_{11m} = D + TT \cdot \frac{\left[S_{11a} \cdot (1 - S_{22a} \cdot LM) + S_{21a}^2 \cdot LM\right]}{\left(1 - S_{11a} \cdot SM - SM \cdot S_{21a}^2 \cdot LM - S_{22a} \cdot LM\right)} \qquad \text{(Equation 2)}$$

$$S_{21m} = \frac{TT \cdot S_{21a}}{1 - S_{11a} \cdot SM - SM \cdot S_{21a}^2 \cdot LM - S_{22a} \cdot LM} \qquad \text{(Equation 3)}$$

Note
The aforementioned error terms pertain to the "forward" configuration. Similar terms can be achieved for the reverse configuration by slightly modifying equations 1 through 3.

Where

D = Directivity
SM = Source Match
RT = Reflection Tracking
TT = Transmission Tracking
LM = Load Match

Figure 2. Two-port error correction signal flow graph.

Note that the Figure 2 diagram assumes that D, SM, and RT have already been solved using the one-port error correction technique. Again, the ECal module provides the known values of S_{11a}, S_{21a}, S_{12a}, S_{22a}, while the network analyzer provides the S_{11m}, S_{21m}. The Load Match (LM) term, and Transmission Tracking (TT) can be solved using equations 2 and 3.

The accuracy of this method relies heavily upon the accuracy of the "actual" values for the impedance standards[3]. The "actual" values are either derived from models or are measured using a network analyzer. ECal impedance standards are measured directly due to their complex structures. The "actual" values contain some degree of uncertainty due to the accuracy of the model or due to the measurement accuracy. The greater the degree of uncertainty in the known values, the larger the error in the calibration produced by the ECal unit. Agilent uses a calibration technique similar to the performance of TRL when measuring ECal modules, thus limiting the amount of uncertainty error. Often, ECal is called a transfer standard because the accuracy of ECal is limited only by the measurement accuracy of the original calibration and the test setup used to measure the ECal impedance standards.

One additional source of error is the stability of the impedance standards. In general, a reference standard implies that something is unmoving or stable. All electronic devices inherently have some degree of instability. ECal modules are designed with that perspective in mind. Only the most stable electrical components are used in the manufacturing of ECal, along with precision connectors to reduce any connector repeatability errors. In addition, thermal compensation is used in the modules to limit performance variations due to environmental temperatures.

User Characterization – How it works

Often users would like to take advantage of the speed and ease of ECal with a connector option or configuration of ECal that is not offered by Agilent. “User Characterization” allows re-characterization of the ECal module by the user. The flash memory in ECal is partitioned into a “Factory Characterized” space, and a “User Characterized” space. This allows “User Characterizations” to be done without affecting the stored data of the “Factory Characterization”. The process for performing a “User Characterization” follows a simple 3-step algorithm:

1. Calibrate analyzer for desired connector configuration
2. Characterize ECal module impedance standards, with adapters if necessary
3. Transfer data to ECal flash memory

This process measures the “actual” values of the impedance standards as described in the section “ECal – How it works”. Hence the accuracy of the calibration done in step 1 directly impacts the calibration quality that the ECal module will re-produce.

Once these steps have been completed, the “User Characterized” ECal module can then be used on any of Agilent’s PNA or ENA series network analyzers. This method can be used in the following scenarios:

- Re-characterization of ECal module with different connector family (i.e. waveguide)
- Re-characterization of ECal module for mixed-connector calibration (i.e. waveguide to coax)
- Re-characterization of ECal module for fixture applications (i.e. wafer probes, antenna)
- Re-characterization of ECal module for re-certification

ECal and Fixturing – The Technique

In some cases, no adapter exists to adapt ECal to a user's test setup. For instance, there is no easily adaptable solution to connect wafer probes to the ECal module. However, using some special techniques, the speed and ease of ECal can still be adapted to fit this situation. The technique described here can apply to any fixturing situation (i.e. wafer probes, antenna, etc.), so long as a calibration can be done on the fixture itself.

A network analyzer is sold with coaxial style connectors. This implies that all test setups have some kind of coaxial connection to their fixture setup. Hence, a connection to the ECal module can be made at this coaxial access point. Examining the generic fixture setup in the diagram in Figure 3, one can quickly see the access point to which the ECal module could be connected.

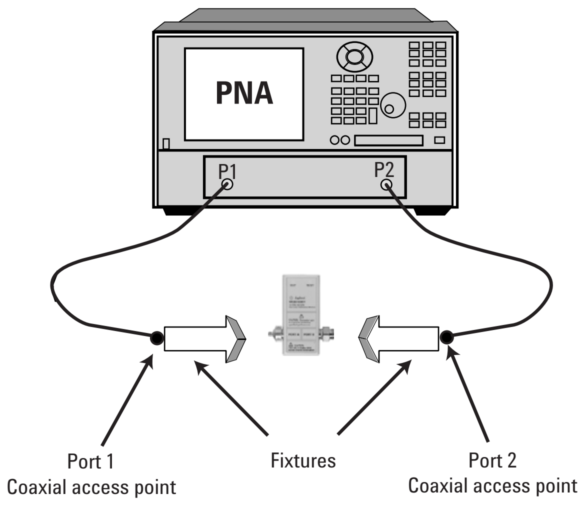


Figure 3. User characterization wafer probe fixturing.

Once the connection point has been established, to characterize the ECal module for a *Fixture Calibration* follows these steps:

1. Calibrate fixture using any desired method (i.e. TRL using wafer probes and standards)
2. Disconnect coaxial connection to fixture and connect to ECal module
3. Characterize ECal module
4. Transfer data to ECal flash memory

Using ECal to calibrate the fixture requires these steps:

1. Disconnect coaxial connection to fixture and connect to ECal module
2. Perform ECal using User Characterization method.
3. Disconnect coaxial connection to ECal and reconnect to fixture.

This methodology allows for the performance of the fixture itself to be embedded or de-embedded from the calibration or characterization process. Hence, this calibration technique only works for the given fixture setup used during the characterization of ECal and is not transferable to another fixture setup. A similar process would need to be done using a different user characterization slot in the ECal module for each subsequent fixture.

One drawback of the previously described method is in the necessity to disconnect the cables to the fixture. In some applications this is a tedious job, or concerns may exist about damaging the fixture from repeated connections. A slightly different configuration could be used to accommodate this situation, with the addition of a few pieces of equipment. The diagram shown in Figure 4 depicts a switch driver in conjunction with two single-pole double-throw (SPDT) switches, and some additional cabling. The cabling is kept to a minimum in order to reduce cable-drift error.

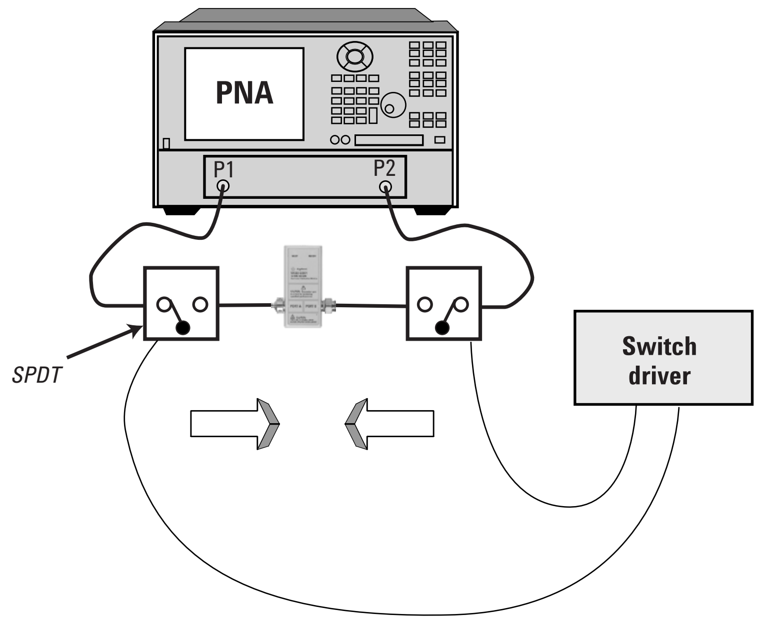


Figure 4. ECal with switches in fixturing application.

The process methodology is still the same with the exception that during an ECal calibration or ECal Characterization, the SPDT must be switched to the ECal module. Conversely, the switches must be set to the fixture when measurements are to be made at the DUT, or when calibrating directly on the fixture. The benefit of this setup is that there is no connector-repeatability error, or cable-movement error introduced into the system. This comes at a cost of the repeatability of the switch. In most high frequency applications the repeatability of the switches is less of an error than the movement of the cables.

ECal and Fixturing – The Theory

Note
In understanding this concept, it will be helpful to understand that calibration plane implies a mathematical representation of a reference plane location, and the measurement plane implies a physical location of a reference plane.

ECal, when used in fixturing application, makes use of a technique that allows measurement to be made with a calibration plane that is different from the physical measurement plane. What follows is mathematical and analytical proof of this concept.

The first step of this process is to perform a calibration at the fixture level. For instance, if the fixture were a wafer probe then one would use wafer TRL, or SOLT calibration. Figure 5 provides a topographical layout of a generic fixturing application.

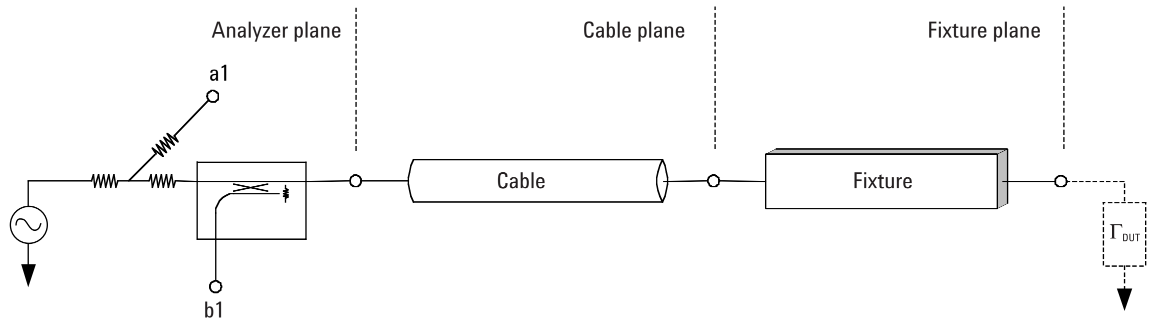


Figure 5. Fixture block diagram.

As a result of the calibration performed at the fixture plane, the error coefficients of the system, looking back from the fixture plane, are determined.

$$\left[\begin{bmatrix} b_1 \\ a_1 \end{bmatrix}\right] = \left[\begin{bmatrix} TE_{11} & TE_{12} \\ TE_{21} & TE_{22} \end{bmatrix}\right] * \left[\begin{bmatrix} \Gamma_{DUT} \\ 1 \end{bmatrix}\right] \quad \text{(Equation 4)}$$

$$[[T_E]] \equiv \left[\begin{bmatrix} TE_{11} & TE_{12} \\ TE_{21} & TE_{22} \end{bmatrix}\right] = [[T_{NA}]] * [[T_C]] * [[T_F]] \quad \text{(Equation 5)}$$

where $[[T_{NA}]] \equiv$ cascade parameter of the VNA error box

$[[T_C]] \equiv$ cascade parameter of the cable,

$[[T_F]] \equiv$ cascade parameter of the fixture

$\frac{b_1}{a_1} \equiv$ network analyzer measured reflection

These error coefficients are applied to all measured data to compute the "actual" characteristics of the device-under-test. If a device is measured at the cable plane, the same error coefficients are used.

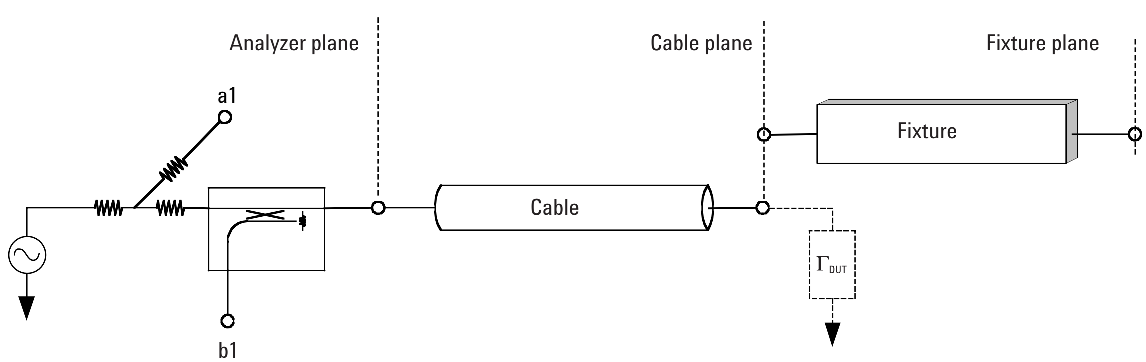


Figure 6. Fixture setup block diagram with fixture removed.

The VNA computed response (Γ_{DUT}') of a device is

$$\begin{bmatrix}\begin{bmatrix}\Gamma_{DUT}' \\ 1\end{bmatrix}\end{bmatrix} = \left[\left[T_E\right]\right]^{-1} * \begin{bmatrix}\begin{bmatrix}b_1 \\ a_1\end{bmatrix}\end{bmatrix} = \left[\left[T_F\right]\right]^{-1} * \left[\left[T_C\right]\right]^{-1} * \left[\left[T_{NA}\right]\right]^{-1} * \begin{bmatrix}\begin{bmatrix}b_1 \\ a_1\end{bmatrix}\end{bmatrix} \quad \text{(Equation 6)}$$

The actual response of a device connected to the cable plane should be

$$\begin{bmatrix}\begin{bmatrix}\Gamma_{DUT} \\ 1\end{bmatrix}\end{bmatrix} = \left[\left[T_C\right]\right]^{-1} * \left[\left[T_{NA}\right]\right]^{-1} * \begin{bmatrix}\begin{bmatrix}b_1 \\ a_1\end{bmatrix}\end{bmatrix} \quad \text{(Equation 7)}$$

Equating the two equations, 6 & 7 –

$$\begin{bmatrix}\begin{bmatrix}\Gamma_{DUT}' \\ 1\end{bmatrix}\end{bmatrix} = \left[\left[T_F\right]\right]^{-1} * \begin{bmatrix}\begin{bmatrix}\Gamma_{DUT} \\ 1\end{bmatrix}\end{bmatrix} \quad \text{(Equation 8)}$$

From the equation above we can now deduce that the corrected response of the network analyzer is the DUT response with the fixture's response de-embedded from it. Hence, the characterization of the ECal modules by the network analyzer in this manner has the effect of the measuring the ECal modules' response with the fixture's response de-embedded from it.

Carrying this a step further, during the calibration process using a "fixture characterized ECal module" the response of the fixture is mathematically embedded onto the measurement plane.

Let

$$\begin{bmatrix}\begin{bmatrix}A & B \\ C & D\end{bmatrix}\end{bmatrix} = \left[\left[T_{NA}\right]\right] * \left[\left[T_C\right]\right] \quad \text{(Equation 9)}$$

$$\begin{bmatrix}\begin{bmatrix}b1_1 & b1_2 & b1_3 & \rightarrow & b1_n \\ a1_1 & a1_2 & a1_3 & \rightarrow & a1_n\end{bmatrix}\end{bmatrix} = \begin{bmatrix}\begin{bmatrix}A & B \\ C & D\end{bmatrix}\end{bmatrix} * \left[\left[T_F\right]\right]^{-1} * \begin{bmatrix}\begin{bmatrix}\Gamma_1 & \Gamma_2 & \Gamma_3 & \rightarrow & \Gamma_n \\ 1 & 1 & 1 & \rightarrow & 1\end{bmatrix}\end{bmatrix} \quad \text{(Equation 10)}$$

To solve for the error correction terms - A, B, C, D:

Let

$$\left[\left[M\right]\right] = \begin{bmatrix}\begin{bmatrix}b1_1 & b1_2 & b1_3 & \rightarrow & b1_n \\ a1_1 & a1_2 & a1_3 & \rightarrow & a1_n\end{bmatrix}\end{bmatrix}; \quad \left[\left[\Gamma\right]\right] = \begin{bmatrix}\begin{bmatrix}\Gamma_1 & \Gamma_2 & \Gamma_3 & \rightarrow & \Gamma_n \\ 1 & 1 & 1 & \rightarrow & 1\end{bmatrix}\end{bmatrix} \quad \text{(Equation 11)}$$

then

$$\left[\left[M\right]\right] * \left[\left[M\right]\right]^T = \begin{bmatrix}\begin{bmatrix}A & B \\ C & D\end{bmatrix}\end{bmatrix} * \left[\left[T_F\right]\right]^{-1} * \left[\left[\Gamma\right]\right] * \left[\left[M\right]\right]^T$$

By inspection, one can see that $[[T_F]]$ is embedded in the solution of $\begin{bmatrix}\begin{bmatrix}A & B \\ C & D\end{bmatrix}\end{bmatrix}$.
Similar arguments can be made for the two-port error terms.

Transfer Accuracy – Verifying the Calibration Transfer

In order to look at the transfer accuracy, or to verify the characterization of an ECal module, one should follow the steps listed below:

1. Calibrate analyzer
2. Store error terms (E1)
3. Characterize ECal module
4. Calibrate analyzer with User Characterized ECal Module
5. Store error terms (E2)

The difference between the two sets of error terms (E1-E2) can then be made to see the amount of error between the ECal module and the original calibration.

Typical graphs are listed below. It is important to note that this is not the residual error of the calibration. It is simply the difference between two calibrations. One can think of this difference as an *additional* error to the residual terms from the source calibration.

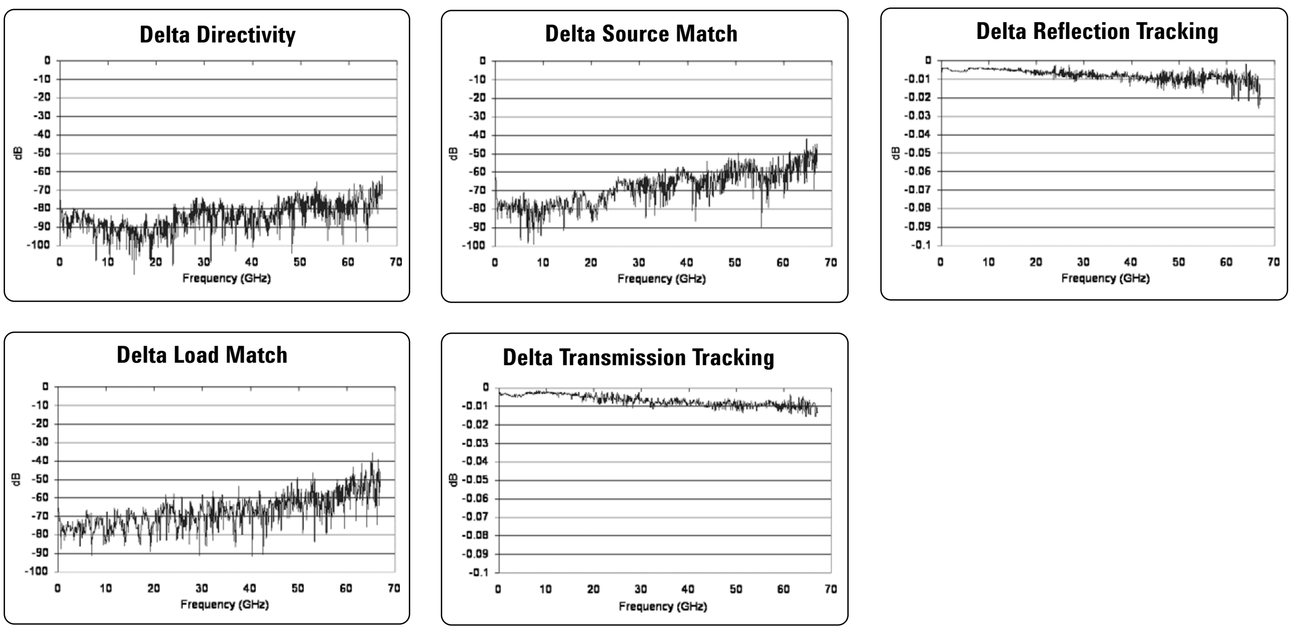


Figure 7. Delta error terms.

User Characterization – Sources of errors

In general, the accuracy of the ECal calibration is derived from the accuracy of the ECal impedance states. The lower the uncertainties, the more accurately an ECal module can be calibrated. These uncertainties are attributed to several factors:

- Measurement accuracy of the system
  - Calibration accuracy
  - Test system stability
- Stability of ECal module
- Interpolation errors

As stated previously ECal is considered a transfer standard, thus the original calibration is one of the fundamental accuracy limitations of ECal. Hence, ECal cannot perform a calibration more accurate than the calibration used to characterize the module.

In addition to the calibration accuracy, test setup stability is just as important in maintaining the highest degree of calibration accuracy. Data listed in Figure 8 shows how cable movement can cause error's in network analyzer measurement.

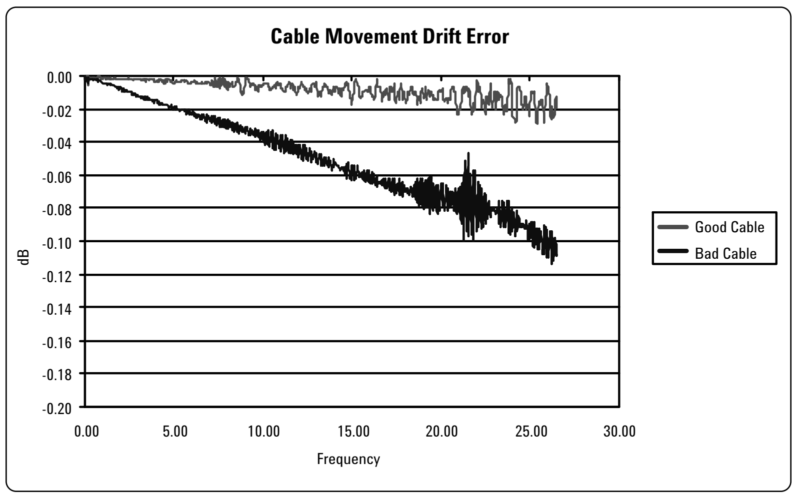


Figure 8. Cable movement drift error.

The two traces show the amount of measurement error that is introduced by moving a cable by 3 inches. The trace labeled *Good Cable* uses high quality cable, while the trace labeled *Bad Cable* uses a poor quality cable. Using a poor quality cable can add as much a 0.1 dB (1%) of measurement error, while using a higher quality cable can reduce this error to roughly 0.02 dB (0.2%). Measurement accuracy is important because it directly relates the calibration transfer quality to the ECal module. Imagine that the 0.1 dB error represented in the graph is the amount of uncertainty in the characterized values of the ECal impedance states. This would imply that the ECal modules could not produce a measurement accuracy greater than 0.1 dB (1%)! The lower the uncertainties in measuring the ECal module, the better the ECal module will perform.

Another potential source of error is the stability of the ECal module. All ECal modules are measured for accuracy and stability parameters before leaving the factory in order to guarantee performance over a given band. “User Characterization” allows the user to characterize the ECal module with adapters and/or cables to the module. The repeatability of the adapters or cables can be an additional source of error to the “User Characterization” calibration. Data shown in Figure 9 shows the connector repeatability error contribution from a good connector and a bad connector.

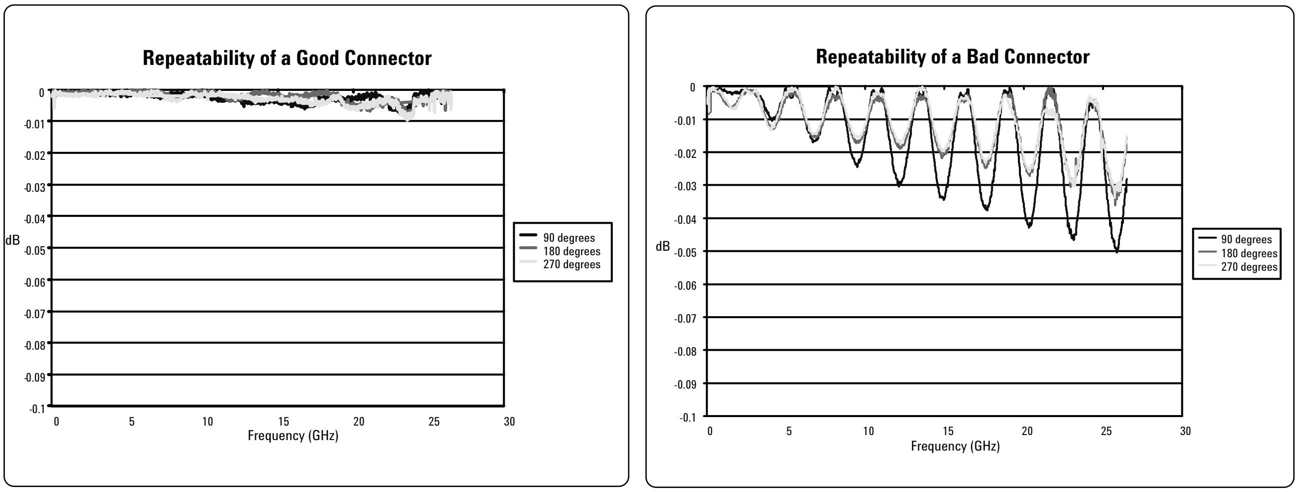


Figure 9. Connector repeatability errors.

Note
Connector repeatability and cable instability will cause additional errors during device measurements.

The described data was taken by measuring an adapter with one end connected to a short and the opposite end connected to the network analyzer. The adapter was then disconnected and rotated by various amounts relative to the original position in 90-degree increments. The logarithmic vector magnitude difference was then calculated for each position relative to the first position.

The difference between a good connector and bad connector is quite obvious. The performance of a dirty or damaged connector can be five times worse than a “good” connector. The amount of connector repeatability will directly effect the uncertainty in the characterization of the ECal module. As stated before this directly impacts the calibration accuracy the ECal module.

One final potential pitfall pertains to the frequency spacing used in the "User Characterization". As stated before, the ECal module's flash memory contains the data of the ECal module's impedance standards as measured by the factory. The data is a set of discrete frequency points spaced at roughly 50 MHz intervals. During normal operation the network analyzer interpolates the data of the ECal module, to the current frequency list of the network analyzer. However, interpolation is only done on the frequency points, which do not match those contained in the ECal module's characterization data. The algorithm for interpolation essentially looks at a few points before and after the frequency of interest to "curve fit" the data. Hence, it is imperative that the frequency spacing, or sampling, is chosen to adequately characterize the full span of the impedance standards.

In order for interpolation to work correctly there must be enough points to accurately describe the behavior of the impedance standard over a given range as shown in Figure 10.

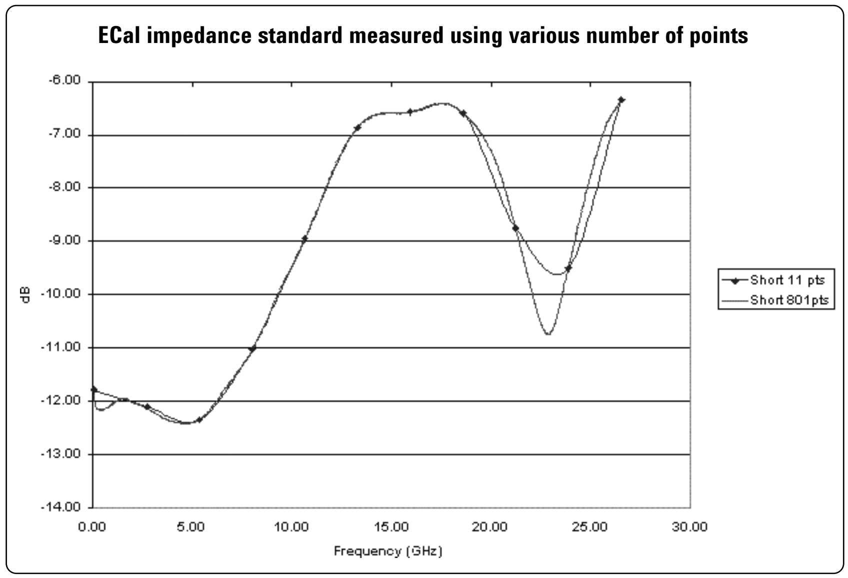


Figure 10. Sampling error.

Here we see two sets of measurements on the same ECal impedance standard using two sets of frequency spacing: 11 points and 801 points. The discrete data points of the 11-point measurement have been highlighted to illustrate the concept of interpolation. As can be seen by the graph in Figure 11, each of the data points themselves are common to both traces. However, the interpolated trace data between the points is significantly different between the graphs. Focusing between 20 to 25 GHz yields another perspective on the data.

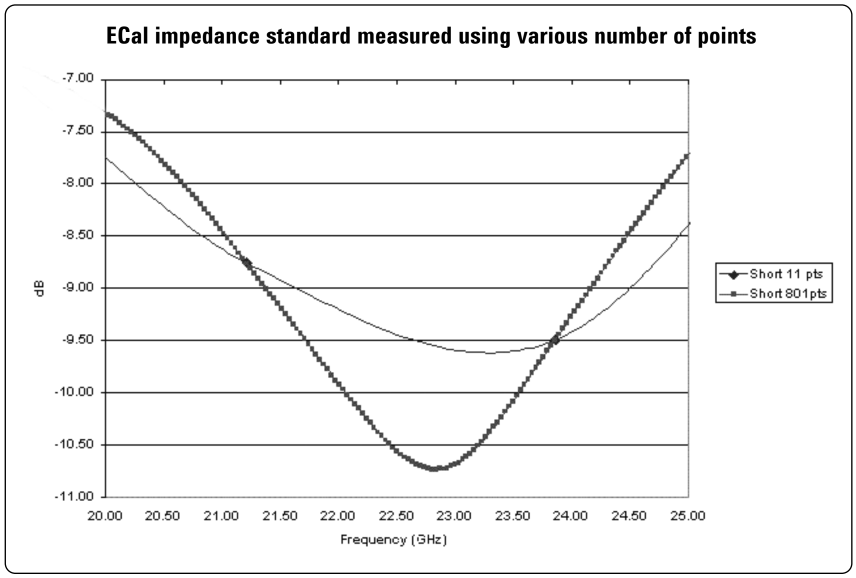


Figure 11. Sampling error (enlarged area).

The point density using 801 points over the 26.5 GHz range is enough to uniquely characterize this particular ECal impedance standard. Looking at only a few data points at a time, the trace looks like a curve or line. Curves and lines can be easily interpolated from the measured data points. In essence, this is how ECal performs interpolation by looking at a few points before and after the frequency point of interest, and interpolating the value based of a line or curve behavior. Failure to have enough points to accurately interpolate leads to an interpolation error, defined as the amount difference between the actual value and the interpolated value.

Conclusion

In recent years, much advancement had been made in the field of electronic calibrations. Coupling "User Characterization", along with superior performing ECal modules and network analyzers opens the door to calibration technology that had not been possible or has been very difficult to perform. Using ECal to simplify the calibration of fixtures and wafer probe stations is now a "dream made real".

References:

[1] V. Adamian, *A Novel Procedure For Network Analyzer Calibration and Verification*, 41st ARFTG Conference Digest, Spring 1993, pp. 8-17.

[2] V. Adamian, *Electronic Calibration of a Vector Network Analyzer for Non-insertable Devices*, 43rd ARFTG Digest, Spring 1994, pp. 1-10.

[3] K. Wong, R.S. Grewal, *Microwave Electronic Calibration: Transferring Standards Lab Accuracy to the Production Floor*, Microwave Journal vol. 37, no. 9, Sept. 1994, pp. 94, 98, 100, 102, 105.

Web Resources

For additional information about the Agilent PNA Series of network analyzers visit:
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Printed in USA May 27, 2004
5988-9478EN

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