Microwave Electronic Calibration: Transferring Standards Lab Accuracy to the Production Floor

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Traditionally, microwave and RF network analyzers require three or more discrete calibration standards to perform systematic error correction. These discrete calibration standards, especially the high precision devices, such as sliding loads and airlines, require well trained operators to obtain the specified performance. Production personnel typically try to avoid them whenever possible. Accuracy and ease of use have been contradictory terms. The recent introduction of electronic calibration standards removes this contradiction. Only a single connection is required. A control unit then takes over the calibration process using stored data provided by a standards laboratory. Accuracy of this calibration closely matches the accuracy of the calibration provided by the standards laboratory. This paper describes the theory behind the electronic calibration and the ways in which a standards laboratory can provide state-of-the-art accuracy on the calibration of the electronic calibration standards. Comparison of measurements made by a standards laboratory's mechanically calibrated system and by an electronically calibrated system are presented.

Introduction

Measurement accuracy of RF and microwave vector network analyzers can be improved by using error correction techniques.[1,2] Traditionally, these error correction techniques require at least three known calibration standards to determine the systematic errors of a network analyzer system. These calibration standards typically consist of discrete devices, such as an open, short, fixed load, sliding load and precision transmission lines (airlines). The precision devices require extreme care and skilled operators to obtain desirable results. New technology finally makes it possible to obtain measurement accuracy without compromising the ease of use.

Traditional Calibration

A one-port error correction is performed using discrete standards of the same calibration procedure that has been used for decades. This procedure consists of individually connecting, measuring and disconnecting an open, a short and a fixed load, and connecting and measuring a sliding load in six positions, then disconnecting the sliding load.

To perform a two-port error correction, twice as many calibration standard connections and disconnections, as well as a thru, must be made. Recent advances in error correction techniques,[3,4] such as TRL, reduced the number of calibration standards required for a two-port calibration to a minimum of three for a 12-term error model. Even with this reduction, a minimum of five connections and disconnections are required. More connections and disconnections present more opportunities for bad connections and damaged parts. Connector repeatability is important because it is the major limiting factor of microwave measurement accuracy today.

Electronic Calibration

Advances in microwave semiconductor, microprocessor and memory chip technologies have made electronically switchable calibration standards feasible. An implementation of the electronic calibrator (ECal) was first publicly demonstrated in spring 1993.[5,6] The ECal system today consists of two pieces of equipment, a control unit and a calibration module. The control unit controls the switching of the calibration module impedance states, interfaces with the network analyzer and calculates the systematic error correction coefficients. It can be programmed and controlled by desk top computers through the GPIB interface. Up to four calibration modules can be connected to the control unit.

The calibration module is a two-port multistate device containing programmable memory that stores the calibration data of each impedance state. These calibration data are produced through S-parameter measurement of all impedance states of the module. The process of measuring the module S-parameters and storing the data in module memory is referred to as characterization. The calibration data are read by the control unit when it calculates the error correction coefficients. Only one connection is needed to perform a one-port calibration. Two connections are needed to perform a complete two-port calibration of a network analyzer system.

To configure a system for ECal, the control unit needs to be connected to the network analyzer by a GPIB interface, and the calibration module and interface cable needs to be connected to the control unit. To calibrate a network analyzer system using the ECal system, the RF connectors of the calibration module are connected to the ANA test ports and the calibration sequence is activated.

ECal Theory

The ECal module has 13 reflective impedance states at each port, and three transmission states, including two thru states and one isolation state. Because there are more impedance states than the minimum needed to determine the systematic error coefficients, the least square fit method is used to take advantage of the overdetermined set of systems equations to reduce calibration errors[5]

$$\begin{bmatrix} \Gamma_1 & 1 & -\Gamma_1\Gamma_{M1} \\ \Gamma_2 & 1 & -\Gamma_2\Gamma_{M2} \\ \vdots & \vdots & \vdots \\ \Gamma_n & 1 & -\Gamma_N\Gamma_{Mn} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \Gamma_{M1} \\ \Gamma_{M2} \\ \vdots \\ \Gamma_{Mn} \end{bmatrix} \rightarrow [A][E] = [M] \qquad (1)$$

where

a, b, c = ANA systematic error coefficients

$\Gamma_1, \Gamma_2 \ldots \Gamma_n$ = characterized reflection of the impedance states

$\Gamma_{M1}, \Gamma_{M2} \ldots \Gamma_{Mn}$ = measured reflection of the impedance states

Four optimum states for each frequency point are used for computation expediency. Using additional states provides minimal accuracy improvement and increases the calibration time. The least square fit solution to the complex systems equations can take many forms. One of the possible forms is the normal equation

$$[E] = \left[[A^H][A]\right]^{-1}[A^H][M] \qquad (2)$$

Ports 1 and 2 of the network analyzer are calibrated by the reflective impedance states. A known thru state is then measured to complete the full two-port calibration of the analyzer.

Traceability

Most of the traditional calibration standards are mechanical standards. Their Γ_1 to Γ_n characteristics can be derived from physical properties.[7] However, the ECal impedance states have complex microwave structures. Accurate modeling of their electrical characteristics is difficult. The frequency responses of the impedance states must be measured, or characterized, with respect to physically traceable standards. Figure 1 shows the traceable path of the most common network analyzer calibration standards.

Advantages and Disadvantages

Using traditional calibration standards has its advantages. The standards are well understood and are accepted techniques. In addition, they have predictable characteristics, are directly traceable to physical properties and are portable. Their disadvantages include the need to make multiple connections and disconnections, making the standards difficult to use, especially when using airlines and sliding loads. They also require high skill levels and entail complex procedures. Their maintenance costs are high due to the wear factor from excessive handling as are the error opportunities due to constant human interaction and complex procedures.

ECal calibration offers fewer connections, a lower required skill level, ease of use, reduction of errors, noninsertable calibration and remote operation. However, ECal

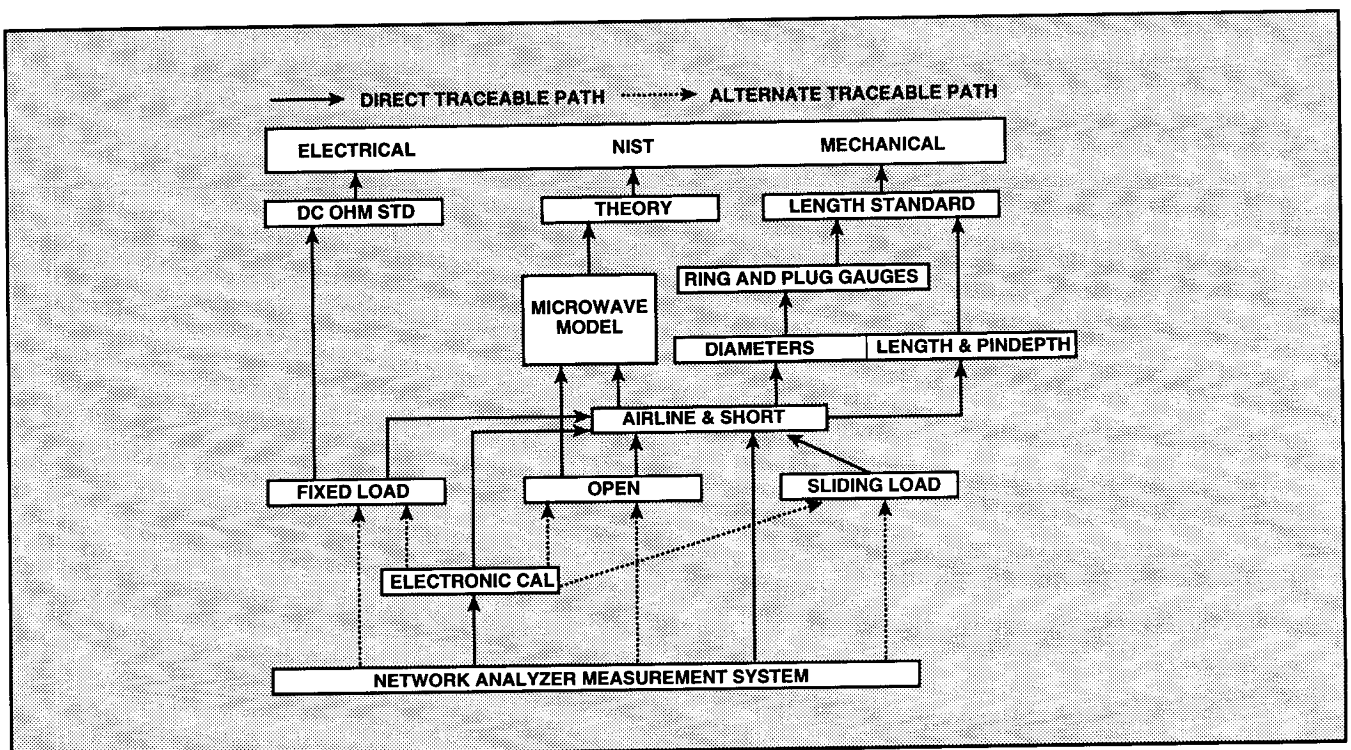

Fig. 1 VANA calibration standard traceability.

has its disadvantages. It is a transfer standard, requires a control unit and its new method creates a level of discomfort.

Standards Laboratory Contributions

Since the ECal module is a transfer standard, its accuracy depends on the accuracy of its characterization process. The more accurately a standards laboratory can characterize the ECal modules, the higher the accuracy of the ECal calibration. Airline standards have the most direct path to a national laboratory. For best results, metrology grade connectors must be used. These precision standards may be difficult and costly to use in a manufacturing environment, however they are reasonable for a standards laboratory environment. Operator skill and care, environmental control, and process control are key success factors in achieving accurate measurements.

Manufacturing the ECal Transfer Standard

Ideally, an ECal module would be factory calibrated using the most accurate calibration and measurement technique available to provide the highest level of accuracy. However, in a manufacturing environment, calibrations such as TRL and LRL, which use primary physical standards, are too complex and time-consuming, driving manufacturing costs up.

To provide the user with a high level of accuracy at a reasonable cost, the ECal modules are factory calibrated using transfer standards. The factory's transfer standards calibration technique is referred to as a characterized device (CD). The CD calibration is a simple short-open-load-thru calibration where each standard has been electrically characterized. The short is calibrated based on physical modeling,[7] the open calibration is based on electrical measurement with reference to physical standards, and the load calibration is based on electrical calibration from a standards laboratory.

The CD calibration carries a large overhead requirement of data disks, external computing and support, but it is fast and flexible, perfect for the factory's manufacturing environment. The CD calibration is well equipped for noninsertible measurements because it employs the reciprocal short-open-load (RSOL) calibration technique, using an arbitrary noninsertible device to make the through connection during calibration. The only requirements of the arbitrary thru are its reciprocity and a rough knowledge of its S_{21}.[8] The measurement uncertainty using the RSOL technique will be slightly degraded due to the uncertainty of calculating the thru's S-parameters based on the one-port error correction coefficients. An ECal module calibrated using the CD technique is traceable to primary physical standards through the calibration of the fixed load and open, and directly through the short.

Measurement Comparison

Experimental measurements of a 3.5 mm 20 dB coaxial attenuator were made on an analyzer using an electronic calibration control unit and kit. S_{11} and S_{21} measurements of the attenuator made on the same system with different calibration techniques show a difference in results.

Figure 2 shows the difference between measurements made with TRL and CD calibrations. The spike at 2 GHz is due to the airline frequency transition of the TRL calibration. The CD standards were not characterized with the TRL calibration. As a result, the TRL and CD calibrations use independent standards and employ different mathematical techniques. With the exception of the 2 GHz transition, the difference is better than –55 dB. This difference shows that there is a minimal loss in accuracy between the primary standard level and the transfer standard level. The CD calibration is a good solution for module characterization.

Figure 3 shows the difference between measurements made with CD and ECal electronic calibrations. ECal was calibrated using the CD calibration. The difference is better than –60 dB, which indicates a good correlation between

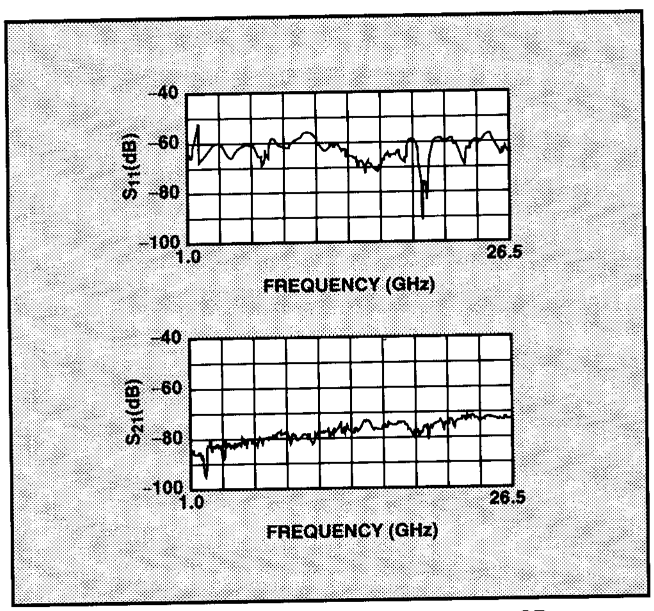

Fig. 2 The vectorial difference between CD and TRL calibrations.

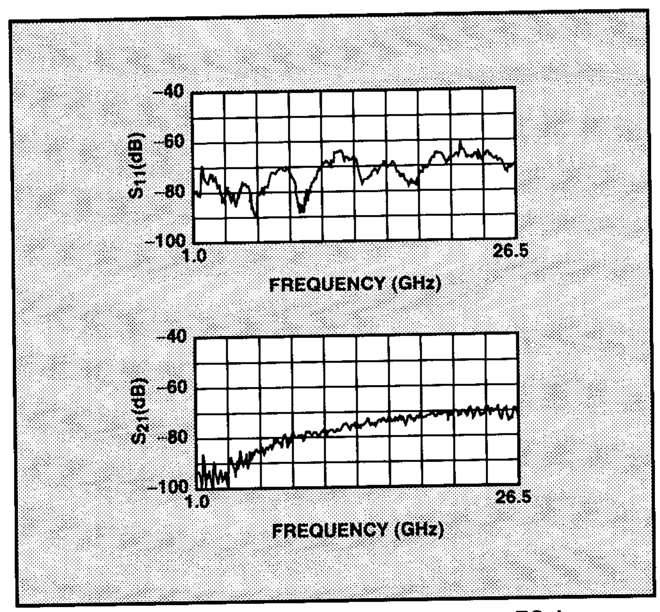

Fig. 3 The vectorial difference between ECal and CD calibrations.

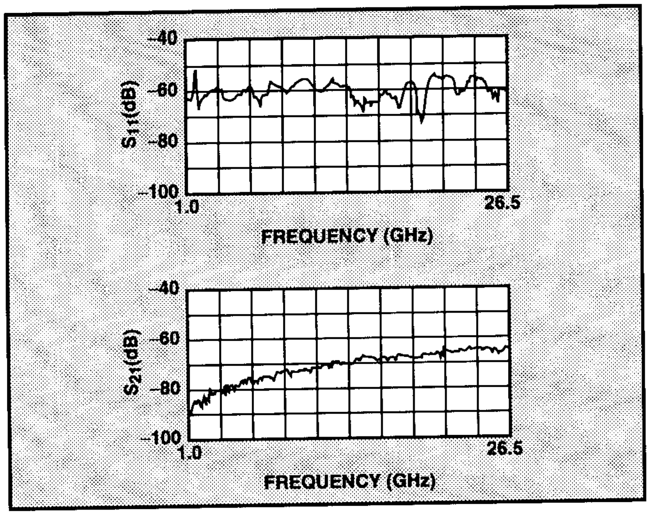

Fig. 4 The vectorial difference between TRL and ECal calibrations.

TABLE I
CALIBRATION COMPARISON

Calibration	Time (min)	Connections	Overhead
TRL	25	10	Small
CD	7	7	Large (computer)
ECal	11	2	Medium (control unit)

measurements made on the ECal calibration and those made on the calibration used to characterize the ECal module.

Figure 4 shows the difference between measurements made with ECal electronic and TRL calibrations. The TRL calibration's airline crossover is at 2 GHz. As expected, the difference is better than –55 dB, confirming the integrity of the ECal calibration when compared with an independent primary standards calibration. Table 1 lists calibration times and number of connections recorded during the described experiment, indicating the required calibration overhead.

Conclusion

Electronic calibration is a breakthrough in RF and microwave measurement technology. ECal reduces calibration complexity, the number of required connections, the opportunity for errors, and most importantly, calibration time.

As a product, ECal provides state-of-the-art external computer-controlled calibration techniques at the factory at a reasonable price. It has been demonstrated that there is extremely small measurement degradation from a primary standards calibration to the ECal calibration. ECal is an easy to use system, shifting the burden for accurate mechanical calibrations from the production floor to the standards laboratory and in return transferring standards lab accuracy to the production floor.

Acknowledgment

The equipment used in the experimental measurements consisted of the HP8493C coaxial attenuator, the HP8510 analyzer, the HP85060C electronic calibration control unit and the HP85062A electronic calibration kit. ■

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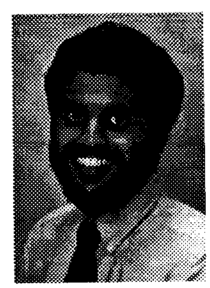

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