LRL CALIBRATION OF VECTOR NETWORK ANALYZERS

Ever since the introduction of vector network analyzers (VNAs) for the characterization of RF and microwave circuits through scattering parameter measurements, the need was recognized for automated procedures for system calibration. These were expected to be capable of providing an accurate representation of the repeatable system errors and, as such, were expected to be usable for correcting uncalibrated measurements.

VNA Calibration

To date, a wide variety of error models and VNA calibration procedures have been formulated, all differing in their degree of complexity and effectiveness. A common feature, however, of nearly all of the proposed error models is the attempt at representing the repeatable system errors by means of an error-two-port network. The error network is assumed to exist between the measurement interface and an ideal, error-free VNA system, (**Figure 1**). The various error models differ in the assumed configurations of the error networks and in the number of independent, complex parameters required for their complete characterization. A common two-port error model is obtained by simply mirror-image duplicating the aforementioned one-port model (including the error-two-port) and introducing a second measurement port for connection of the Device Under Test (DUT).

A feature common to all proposed calibration procedures is their reliance upon simple, idealized standards for which the scattering response is assumed to be known. The various calibration procedures differ, in the number, type and complexity of the idealized standards, and in the types of measurements that must be performed upon them.

As mentioned above, the most common single-port error model is an error-two-port assumed to be inserted between the measurement port of an ideal,error-free reflectometer and the physical test port at which the unknown reflection is to be measured. This model requires the specification of three independent, complex parameters at each frequency. These parameters usually are identified with elements S_{11} and S_{22} with the product $S_{12} S_{21}$ of the 2 x 2 error-two-port scattering matrix. At least three reflection standards and three calibration measurements are required to determine these parameters. Occa-

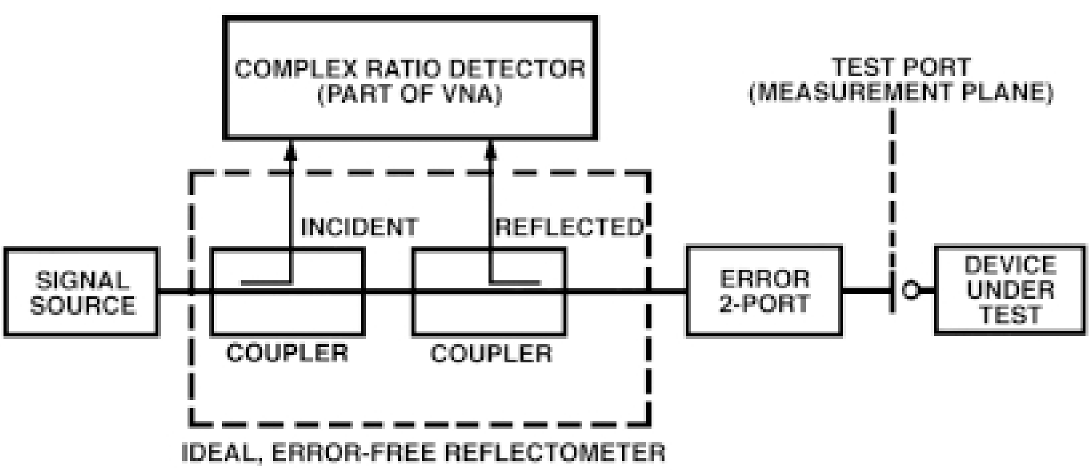

Figure 1: One-port measurement with error model.

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sionally, more than three calibration measurements are performed, e.g. when a sliding load is measured at multiple settings.

OSL — The Traditional Technique

The most widely used one-port calibration technique[1] uses two high reflection coefficient standards of widely separated reflection phase, typically an open-circuit and a short-circuit, and an extremely low reflection matched termination. This constitutes the conventional OSL (Open-Short-Load) calibration method. For improved accuracy at higher microwave frequencies, a sliding termination, such as one of those shown in **Figure 2**, is normally used in lieu of the fixed termination. For a complete two-port calibration, additional measurements must be performed with the two test ports connected directly together, i.e. a thru connection.

Figure 2: Sliding loads used in VNA calibration.

Enter TSD

Similar to earlier techniques, the Thru-Short-Delay (TSD) calibration procedure[2] also provides an explicit, non-iterative solution to the set of calibration equations. In contrast to OSL, the TSD method requires only two calibration standards in the case of sexless connectors, such as 7mm, to completely specify the assumed error-two-port model and perform a full two-port calibration. The TSD calibration procedure is represented in **Figure 3**. Note that all of the TSD calibration standards are "simple" components having no moving parts. Also, the TSD procedure does not assume negligible measurement-port mismatch or negligible response distortion by the introduction of the individual calibration devices.

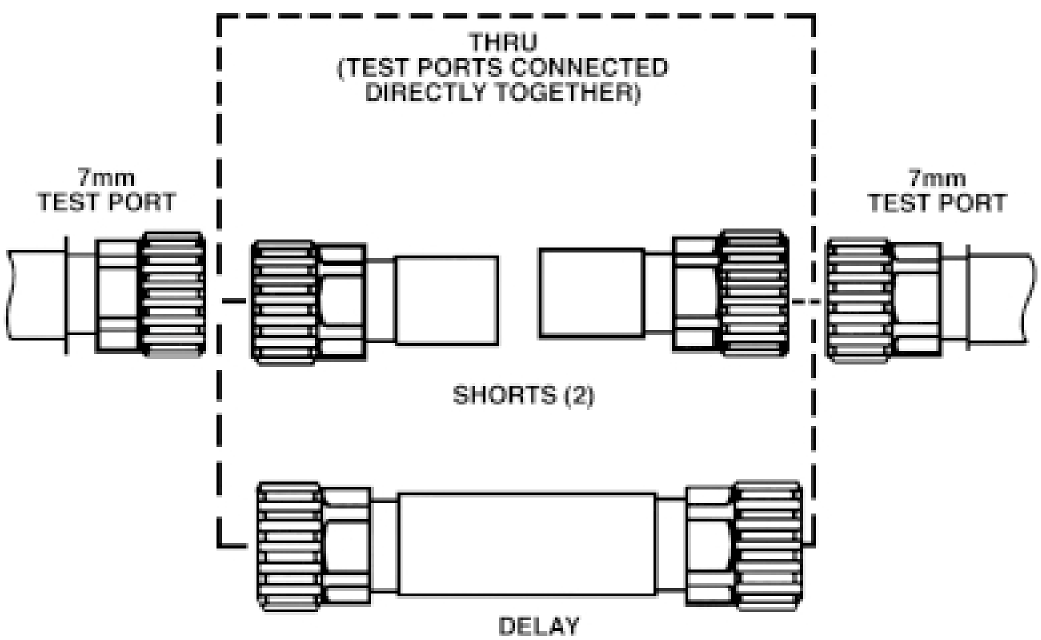

Figure 3: TSD calibration procedure using 7mm connectors.

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In the TSD technique, the error-two-ports become the key components in three fictitious two-port networks. The first of these is formed simply by connecting the two measurement planes together (Thru). The second two-port is a degenerate one and results from terminating the measurement planes with short-circuits (Short). The third two-port results from the insertion of an unknown length of nonreflecting transmission line, such as a precision air line (Delay), between the measurement planes. From the scattering parameters of these three two-ports, it is possible to solve the closed-form expressions for the individual scattering parameters of the error-two-ports. These, in turn, are used in explicit parameter transformations to correct the subsequent uncalibrated measurements.

Instead of a collection of offset shorts, or a single short-circuit and an open-circuit used in conjunction with a termination, the only items required by TSD to calibrate the VNA are a section of precision coaxial line or waveguide, plus a short-circuit. The line section should match the impedance to which the measurements are to be referenced.

TRL — Generalizing TSD

In 1979, Engen and Hoer[3] presented a new calibration procedure, TRL, in which the requirement for using a short-circuit termination has been eliminated. In its place, a termination of unknown reflection (Reflect), which must be other than zero, is used. While a nominal short-circuit is a convenient choice for the Reflect calibration standard, the actual magnitude of its reflection coefficient need not be known. Instead, this is obtained as a by-product of the TRL (Thru-Reflect-Line) calibration procedure. In addition, Engen and Hoer have substituted the word *Line* in place of *Delay*, the former being more descriptive of the technique.

In common with the TSD technique, the length of the precision section of transmission line can be arbitrary and unknown, as long as it differs from one-half of the guide wavelength. Additionally, it does not have to be dissipation-free. As with TSD, the scattering parameters of the error-two-ports are conveniently solved from closed-form equations.

LRL — Extending TRL

Just as TRL may be considered an extension of the TSD technique, LRL (Line-Reflect-Line) may be viewed as a generalization of the TRL calibration procedure in which the Thru is replaced by a second length of precision transmission line, coaxial or waveguide[4]. LRL is represented pictorially in **Figures 4(a) and 4(b)**.

The beauty of current LRL implementations is that after the proper calibration is performed, the scattering parameters of two-port networks with *any*

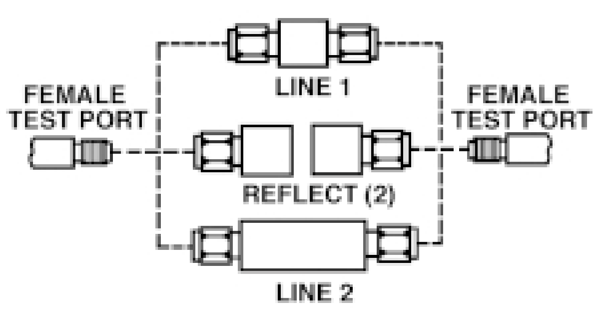

Figure 4(a): Basic LRL calibration procedure.

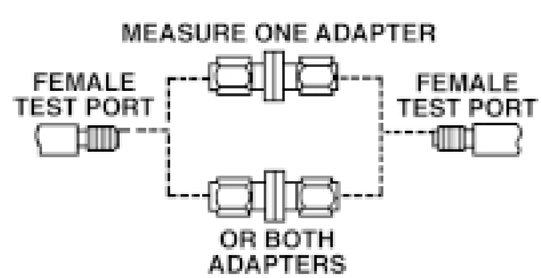

Figure 4(b): Extending the LRL technique for changing test port sex.

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combination of connectors can be measured accurately. In contrast, the TSD or TRL technique can be applied only to VNAs having directly matable connectors at the measurement ports. By replacing the Thru connection with a short length of precision Line, the calibration technique can be applied to test ports having identical connectors of any type, not just sexless connectors (waveguide, APC7 or 14mm).

With the LRL calibration technique and the proper software, the sex of the test port can be changed following the measurement of one or two adapters, (**Figure 4(b)**). If the sex of only one test port needs to be converted, then only one adapter has to be measured. To change the sex of both test ports, a pair of adapters must be tested. After performing the LRL calibration and measuring adapters, if required, devices of any sex can be measured, (**Figure 5**).

Furthermore, one test port could be an APC3.5 female and the second one could be waveguide if the proper sets of calibration standards were first employed in performing the required calibration procedures. To accomplish this, an LRL calibration is first performed in APC3.5, (**Figure 4(a)**). This is followed by a second calibration, this time in waveguide, (**Figure 6**). After both LRL calibrations are finished, normally non-insertable devices (without the aid of additional adapters) now can be measured directly, (**Figure 7**). Thus, a two-port having male APC3.5 on one end and waveguide on the other could be measured directly. Typical waveguide and APC3.5 calibration kits for the LRL technique (**Figures 8(a) and 8(b)**).

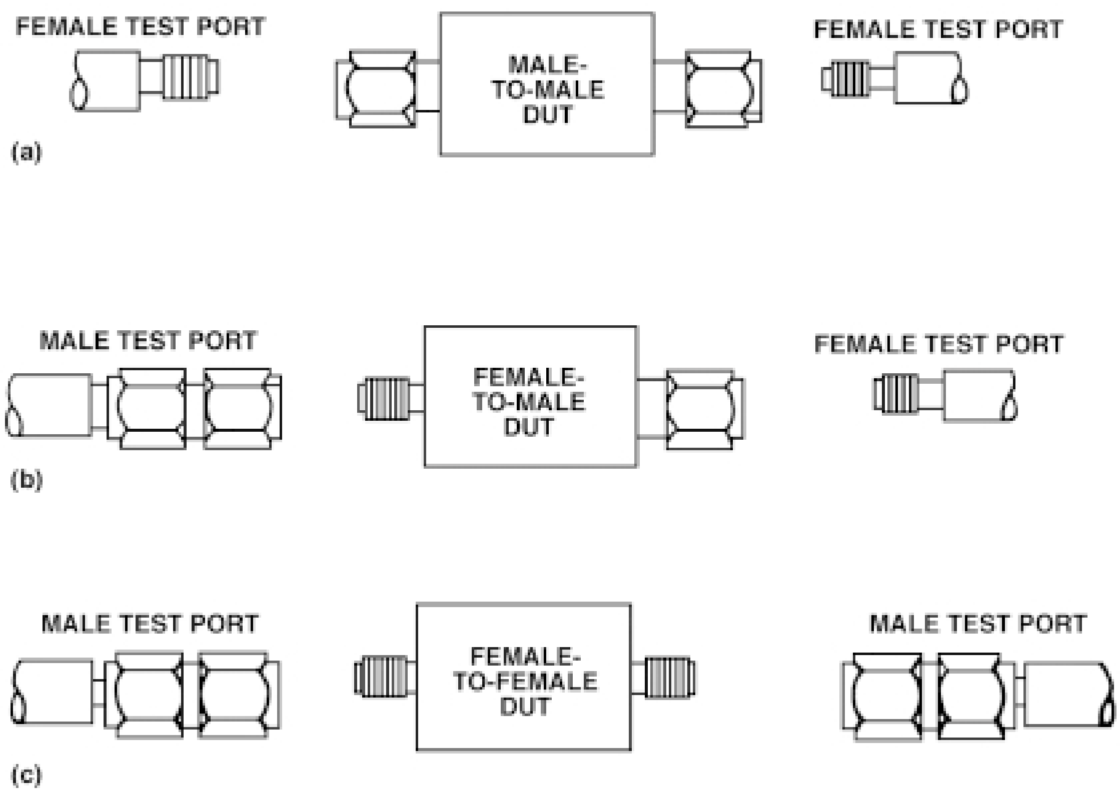

Figure 5: Measuring a DUT after LRL calibration and adapter measurement: (a) male-to-male DUT; (b) female-to-male DUT; (c) female-to-female DUT.

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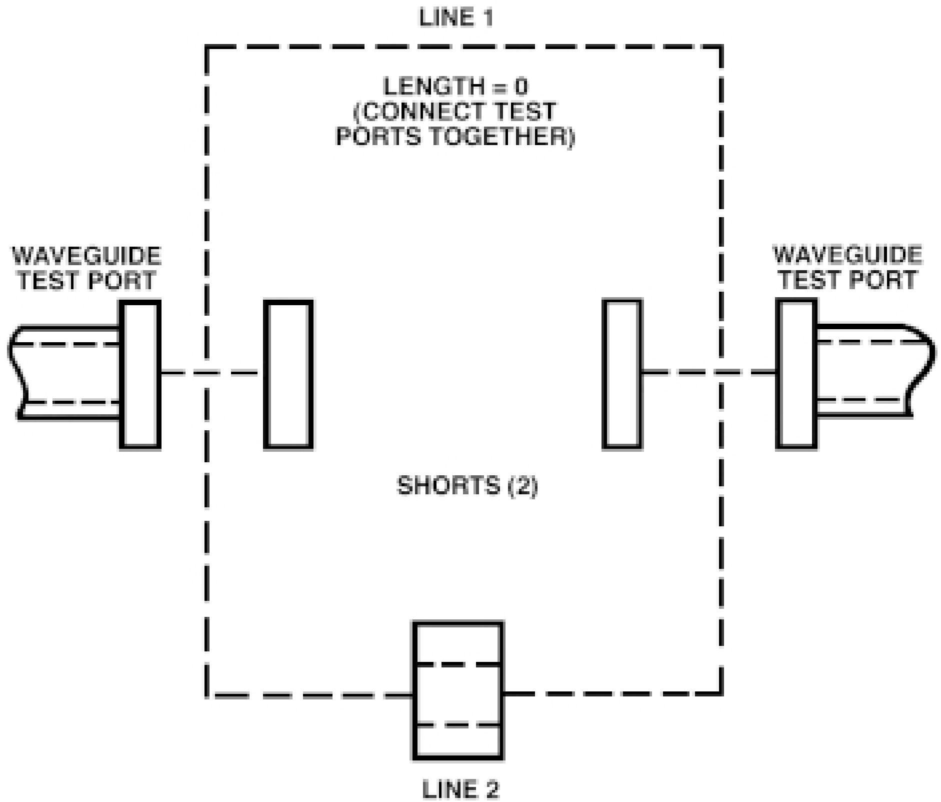

Figure 6: Basic LRL calibration in waveguide.

Line Lengths for LRL

In the TRL calibration technique, the optimum electrical length of the "Line" is 90° or an odd-multiple of a quarter-wavelength. Electrical lengths near 0° or even multiples of 90° must be avoided or the solution of the closed-form equations becomes ill-conditioned. In the LRL procedure, it is the difference in the electrical length of the two Lines that is optimally 90° and must not be near 0° or 180°. In reality, a phase difference between 30°[5] and 150° is recommended by NIST and Hewlett Packard to provide the most accurate, reliable calibrations.

Because of the freedom in choosing the lengths of the two Lines, the LRL calibration technique is often preferable to the TRL calibration (when the length of Line 1 is zero, LRL=TRL), even for sexless connectors. This becomes evident when higher microwave frequencies are considered. In this case, the optimum length of the single Line used in TRL can be

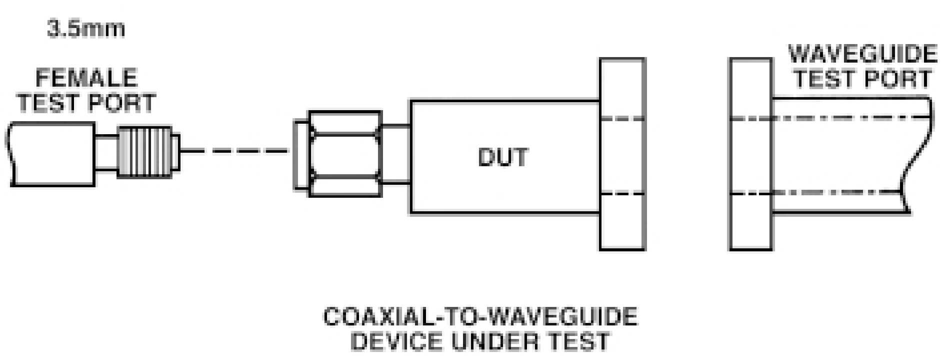

Figure 7: Measurement after two-stage LRL calibration.

Figure 8(a): **Components in a coaxial LRL calibration kit.**

Figure 8(b): **Components in a waveguide LRL calibration kit.**

physically too short to be practical. However, if two Lines are used, Line 1 can be some convenient length and Line 2 can be physically longer so that the difference in electrical length is 90° in the center of the frequency band of interest.

As an example, suppose that it was desired to configure an LRL calibration kit for the frequency range of 0.5 to 34 GHz. In this case, three offset Lines are necessary to properly cover the complete frequency range. With geometrically equally spaced center frequencies of 1.270, 5.185, and 21.165 GHz, and using 1.000649 as the relative permittivity of air, the Lines would have quarter-wave lengths of 5.989cm, 1.445cm, and 0.354cm, plus the length of the reference Line. A set of air lines developed using this concept is shown in **Figure 9**.

In contrast, one reference Line, one offset Line (slightly longer), and two short-circuits are all that are required for performing an LRL calibration for the 2.0 to 10.0 GHz range.

Other Considerations

The test port shown in the various figures should not be confused with the test set connectors which are integral to the vector network analyzers.

It is good practice *never* to use the test set connectors as the measurement test ports, as test ports do wear and, on occasion, require servicing. Instead, the recommended practice is to use special test port adapters which are removable, replaceable and serviceable. Calibration is then performed with the test port adapters in place and the test port adapters remain affixed to the test set connectors during subsequent measurements. Several types of test port adapters are shown in **Figure 10**.

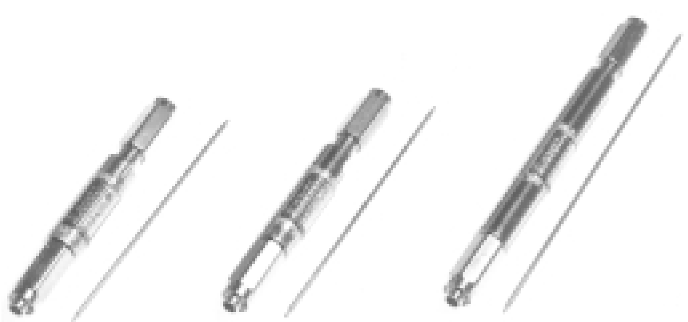

Figure 9: **3.5mm air lines used in VNA calibration procedures.**

Figure 10: **Various VNA test port adapters.**

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Air lines, as calibration standards, are particularly susceptible to errors due to the test ports being used for calibration and measurements. These precision air lines rely completely on the test ports for proper alignment and interface control. The accuracy achieved is thus a function of both the air lines and the test ports.

Remember that calibration kits, just like test ports, are subject to wear and possible damage. For this reason, the recommended practice is to establish a hierarchy of standards. A laboratory-grade calibration kit should be retained in pristine condition in order to corroborate any suspicious calibrations and to perform periodic verifications of the components contained in the working calibration kits which are used for daily calibrations.

Acknowledgments

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Notes

[1] J. Fitzpatrick, "Error Models for Systems Measurement," ***Microwave Journal***, Vol. 21, May 1978, pp. 63-66.

[2] N. R. Franzen and R. A. Speciale, "Accurate Scattering Parameter Measurements on Nonconnectable Microwave Networks," Proc. 6th European Microwave Conference, September 1976, pp. 210-214.

[3] G. F. Engen and C. A. Hoer, "Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-27, December 1979, pp. 987-993.

[4] C. A. Hoer and G. F. Engen, "Calibrating a Dual Six-Port or Four-Port for Measuring Two-Ports with Any Connectors," 1986 IEEE MTT-S International Microwave Symposium Digest, June 1986, pp. 665-668.

[5] When this article was first published in 1987, NIST (U. S. National Institute of Standards and Technology) recommended keeping the phase between 18° and 162°. Further study since then has led NIST to recommend reducing the phase variation to between 30° and 150°.

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