On-Line Accuracy Assessment for the Dual Six-Port ANA: Extension to Nonmating Connectors

CLETUS A. HOER, MEMBER, IEEE, AND GLENN F. ENGEN, FELLOW, IEEE

Abstract—A technique is described for calibrating a dual six-port or four-port automatic network analyzer (ANA) so that the scattering parameters of two-port devices having any combination of connectors can be measured. The technique is a generalization of the “thru-reflect-line” (TRL) calibration technique in which the thru is replaced with a second length of precision transmission line. Expressions for errors associated with the second line are derived.

I. INTRODUCTION

THE “thru-reflect-line” (TRL) technique [1] for calibrating a dual six-port or four-port reflectometer has been modified so that the scattering parameters of two-port devices having any combination of connectors can be measured.

The thru, reflect, and line measurements made in the TRL calibration are shown in Fig. 1(a). The complex sidearm ratios w_1 and w_2 are measured for the three measurement conditions shown. The test ports are connected together, then one or more highly reflecting terminations are connected to one test port and then to the other test port. Finally, a length of precision transmission line is connected between the two test ports. For a dual six-port, w_1 and w_2 are each obtained from four power measurements made on the four sidearms of each six-port [1]. For a dual four-port, w_1 and w_2 are each obtained from a detector which measures the complex sidearm ratio directly.

The TRL calibration yields the parameters A_1 , B_1 , and C_1 of four-port A , and A_2 , B_2 , and C_2 of four-port B which relate w_1 and w_2 to Γ_1 and Γ_2 , respectively, as shown in Fig. 1(a). Also obtained from the TRL solution are the reflection coefficients of all the terminations used in the reflect measurements, and γl of the precision transmission line used in the line measurement, where γ is the propagation constant of the line, and l is its physical length. As shown in Fig. 1(a), the TRL technique can be applied only to reflectometers having identical sexless connectors at the test ports. If the requirement for making a thru connection is replaced by a measurement with a short length of line as shown in Fig. 1(b), then the calibration technique can be applied to a pair of reflectometers having identical connectors of any type, not just sexless connectors. This line-reflect-line (LRL) calibration technique is the subject of this paper.

TRL Calibration, Dual 6-port or 4-port

LRL Calibration

Fig. 1. (a) TRL technique for calibrating a dual six-port or four-port reflectometer. (b) LRL calibration technique where the thru is replaced with a short length of line.

II. LRL EXAMPLES

A. Two Pairs of Lines

An example of the LRL calibration technique is shown in Fig. 2(a) where both test port connectors are identical male connectors. When the calibration using two lines and one or more terminations with female connectors is complete, the S -parameters of two-port devices that have female connectors on both ends can be measured.

Fig. 2(b) shows an example where adapters have been added to obtain two female test port connectors. The LRL calibration can be applied to these new test ports using lines and terminations with male connectors. Then two-port devices that have male connectors on both ends can be measured.

To measure two-port devices that have one male and one female connector, adapter C (or D) is removed to obtain the test port configuration shown in Fig. 2(c). The parameters for reflectometer A are known from the calibration in Fig. 2(a), and the parameters for reflectometer configuration F are known from the calibration in Fig. 2(b). The repeatability of the connection between A and

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The authors are with the National Bureau of Standards, Boulder, CO 80303.

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Fig. 2. (a)–(c) Using a set of female standards and a set of male standards to do a complete LRL calibration so that a two-port device with any combination of connectors can be measured.

adapter *C* (or between *B* and *D*) is not important when this sequence of measurements is used.

The connector types used in Fig. 2(a) and (b) can be completely different. For example, those in Fig. 2(a) could be type *N*, while the connectors in Fig. 2(b) could be SMA. Two-ports that have a female type *N* on one end and a male SMA on the other end can be measured as in Fig. 2(c). The LRL calibration technique can also be applied if one set of connectors is waveguide, and the other set is coax.

B. One Pair of Lines

Only one pair of lines is needed to calibrate the two reflectometers if the connectors on the two-port under test are of the same type. For example, to measure two-port devices that have any combination of type-*N* connectors, the reflectometers are first calibrated with type-*N* male connectors as shown in Fig. 3(a). Then a female–female type-*N* adapter *C* is measured as shown in Fig. 3(b), and left connected to one of the reflectometers, say to *A*. Two-port devices that have male–female type-*N* connectors can now be measured between *C* and *B*. To measure two-port devices with two male type-*N* connectors, one may remove adapter *C* and measure the parameters of another similar adapter *D*. As shown in Fig. 3(c), leaving adapter *C* on reflectometer *A*, and reconnecting adapter *D* to reflectometer *B* provides a pair of female test ports between which two-port devices that have male connectors can be measured.

III. LRL CALIBRATION

The computations and software used in the TRL solution can also be used in the LRL solution with only slight

Fig. 3. (a)–(c) Using one set of standards to do a complete LRL calibration when the connectors on the device under test are the same type (but any combination of sexes).

modifications. If a line of length l_1 is used in the TRL calibration instead of a thru ($l_1 = 0$) connection, the following modifications to the four-port parameters are obtained (see Appendix B):

$$B_1 = B_{1t} \quad (1)$$

$$C_1/A_1 = C_{1t}/A_{1t} \quad (2)$$

$$B_2 = B_{2t} \quad (3)$$

$$C_2/A_2 = C_{2t}/A_{2t} \quad (4)$$

$$A_1 = A_{1t} e^{\gamma l_1} \quad (5)$$

$$A_2 = A_{2t} e^{\gamma l_1} \quad (6)$$

$$\gamma_2 l_2 - \gamma_1 l_1 = (\gamma l)_t \quad (7)$$

The terms on the left of each equation are the desired parameters. The corresponding parameters on the right of each equation with a subscript *t* are those obtained from the TRL solution. The first four equations show that the four-port parameters B_1 , C_1/A_1 , B_2 and C_2/A_2 are exactly equal to those obtained from the TRL solution. Equations (5) and (6) show that the four-port parameters A_1 and A_2 are scaled by $e^{\gamma l_1}$.

In the TRL calibration, the optimum electrical length of the line is 90° (or an odd multiple of 90°). Electrical lengths near 0° or 180° (or even multiples of 90°) must be avoided or the solution becomes ill conditioned. Equation (7) shows that when two lines are used, it is the *difference* in the electrical lengths of the two lines that is optimally 90° and that must not be near 0° or 180° .

IV. LRL FOR SEXLESS CONNECTORS

At higher frequencies the optimum length of line for the TRL calibration can become physically too short to be

practical. However, if two lines are used, l_1 can be some convenient length and l_2 slightly longer so that the difference in length is electrically 90° in the center of the frequency band. For this reason, one may want to use the LRL calibration even for sexless connectors at higher frequencies.

V. EQUIVALENT REFERENCE PLANE

Equations (1)–(6) lead to

$$\begin{aligned}\Gamma_1 &= e^{-\gamma_1 l_1} \Gamma_{t_1} \\ \Gamma_2 &= e^{-\gamma_1 l_1} \Gamma_{t_2}\end{aligned}\quad (8)$$

which say that the reflection coefficient of each termination used in the reflect measurements, or any other Γ measurement, will differ from Γ_{t_1} or Γ_{t_2} by the factor $e^{-\gamma_1 l_1}$ where Γ_{t_1} and Γ_{t_2} are the reflection coefficients obtained from A_{1t} , B_{1t} , and C_{1t} at test port 1, or A_{2t} , B_{2t} , and C_{2t} at test port 2.

Equation (8) shows that Γ ratios can be measured at either test port without knowing $\gamma_1 l_1$. If (8) is compared to the following equation for transforming Γ_L through a nonreflecting line of length l

$$\Gamma = e^{-2\gamma l} \Gamma_L \quad (9)$$

we see that the effective reference plane of Γ_t is at $l_1/2$ which is at the center of the line of length l_1 . This location agrees with our intuition as to where the reference plane should be since TRL assumes $l_1 = 0$.

VI. DETERMINING $\gamma_1 l_1$

To complete the LRL calibration, $\gamma_1 l_1$ must be determined. Four methods for determining $\gamma_1 l_1$ are outlined below.

A. From l_1 and l_2

If the lines l_2 and l_1 are made from the same stock and their cross-sectional dimensions are sufficiently the same, we can assume that

$$\gamma_2 = \gamma_1. \quad (10)$$

Then (7) becomes

$$\gamma_1(l_2 - l_1) = (\gamma l)_t \quad (11)$$

which gives

$$\gamma_1 l_1 = K(\gamma l)_t \quad (12)$$

where

$$K \equiv \frac{l_1}{l_2 - l_1}. \quad (13)$$

The physical lengths l_1 and l_2 of the two lines can be measured to obtain a value for K .

The uncertainty in $\gamma_1 l_1$ due to the assumption that $\gamma_2 = \gamma_1$ can be determined as follows. Let

$$\gamma_2 = \gamma_1 + \Delta\gamma. \quad (14)$$

Substituting (14) in (7) and solving for $\gamma_1 l_1$ gives

$$\gamma_1 l_1 = K(\gamma l)_t - K\Delta\gamma l_2 \quad (15)$$

or

$$\gamma_1 l_1 = K'(\gamma l)_t \quad (16)$$

where

$$K' = K \left(1 - \frac{\Delta\gamma l_2}{(\gamma l)_t} \right). \quad (17)$$

Comparing (15)–(17) with (12)–(13) shows that the last term in (15) or (17) represents the error in $\gamma_1 l_1$ when $\gamma_2 \neq \gamma_1$.

B. From a Known Γ

Another way of obtaining $\gamma_1 l_1$ is from (8). If Γ is the known reflection coefficient of a highly reflecting termination connected to either test port 1 or 2, then (8) gives

$$\gamma_1 l_1 = \log_e \frac{\Gamma_t}{\Gamma}. \quad (18)$$

A matched termination cannot be used because if Γ and Γ_t are both zero, $\gamma_1 l_1$ cannot be determined.

C. From ψ of Γ

If the highly reflecting termination is a short or an offset short with a precisely known phase angle ψ_s , then $\gamma_1 l_1$ can be determined from ψ_s alone. $|\Gamma_s|$ need not be known. To show this, define the real and imaginary parts of $(\gamma l)_t$ as

$$(\gamma l)_t = x + jy. \quad (19)$$

Then substituting (16) and (19) in (8) gives

$$|\Gamma_s| e^{j\psi_s} = e^{-K'x} e^{-jK'y} |\Gamma_t| e^{j\psi_t}. \quad (20)$$

From (17) we see that K' is real if $\Delta\gamma = 0$ or if $\Delta\gamma/(\gamma l)_t$ is real. From (14) and (7)

$$\frac{\Delta\gamma}{(\gamma l)_t} = \frac{\gamma_2 - \gamma_1}{\gamma_2 l_2 - \gamma_1 l_1} = \frac{1 - \gamma_1/\gamma_2}{l_2 - l_1 \gamma_1/\gamma_2}. \quad (21)$$

Although γ_1 and γ_2 are complex, the ratio γ_1/γ_2 will be real (or very nearly so) if the two lines are made from the same stock. Then K' is real and (20) expands into the following two equations:

$$|\Gamma_s| = e^{-K'x} |\Gamma_t| \quad (22)$$

$$\psi_s = -K'y + \psi_t. \quad (23)$$

Since $(\gamma l)_t$ is mostly imaginary, y is known much more accurately than x . For this reason we choose (23) to calculate K'

$$K' = \frac{\psi_t - \psi_s}{y}. \quad (24)$$

Then $|\Gamma_s|$ can be calculated from (22). Thus only the phase angle ψ_s of the short needs to be known. For a flat short

$$\psi_s = 180 - 12f\delta \text{ deg} \quad (25)$$

where f is the frequency in gigahertz and δ is the skin depth in centimeters into the face of the short [2]. Equations for the phase angle of an offset short [3] or an open-circuit termination [4] are given in the literature.

D. From Γ Ratio

A fourth way of obtaining $\gamma_1 l_1$ is from the ratio of two Γ measurements. Measure a highly reflecting termination with unknown reflection coefficient Γ_L on one of the test ports of the automatic network analyzer (ANA). Then from (8) the reflection coefficient at that test port can be written

$$\Gamma = \Gamma_L = e^{-\gamma_1 l_1} \Gamma_t. \quad (26)$$

If line l_1 is then inserted between the test port and Γ_L , (8) gives for this second measurement

$$\Gamma' = e^{-2\gamma_1 l_1} \Gamma_L = e^{-\gamma_1 l_1} \Gamma'_t. \quad (27)$$

Taking the ratio of (27) to (26) gives

$$\frac{\Gamma'}{\Gamma} = e^{-2\gamma_1 l_1} = \frac{\Gamma'_t}{\Gamma_t}. \quad (28)$$

Since Γ'_t/Γ_t is known, $\gamma_1 l_1$ can be calculated from this equation.

VII. UNCERTAINTY IN Γ

Elsewhere in this TRANSACTIONS [5], [6] techniques are described for propagating random and systematic errors through the six-port calibration and measurement process when the TRL calibration technique is used. When the LRL calibration technique is used, these errors apply directly to Γ_t but not to Γ . Differentiating (8) leads to the following expression for the worst-case uncertainty $d\Gamma_i$ in Γ_i at test port i .

$$d\Gamma_i = e^{-\gamma_1 l_1} d\Gamma_{ii} - \Gamma_i d(\gamma_1 l_1), \quad i = 1, 2. \quad (29)$$

where $d\Gamma_{ii}$ is the uncertainty in Γ_{ii} obtained from propagating errors through the TRL calibration and the measurement process, and $d(\gamma_1 l_1)$ is the uncertainty in $\gamma_1 l_1$. As Γ approaches zero, the uncertainty in Γ due to $d(\gamma_1 l_1)$ also approaches zero. This means that the error in $\gamma_1 l_1$ causes negligible additional error in the measurement of low reflecting terminations.

Equations for estimating $d(\gamma_1 l_1)$ are given in Appendix A. These equations lead to the conclusion that method d in Section VI is probably the most accurate method for determining $\gamma_1 l_1$.

Once the errors associated with Γ_1 and Γ_2 at both test ports are determined, the errors in the S -parameters of any two-port measured between these test ports are readily calculated [5].

A special case occurs when the two-port being measured is an adapter such as the female-female adapter C in Fig. 3(b). In this case we are not so much interested in the parameters and errors associated with the adapter C , but in the parameters and errors associated with the combination of error box A and adapter C . One way to determine directly the parameters A'_1 , B'_1 , and C'_1 of the combination $A + C$, and the errors associated with these parameters is to consider $A + C$ as a new two-port be-

Fig. 4. Considering adapter C and error box A as a new two-port error box between measurement planes w_1 and Γ_2 to get the parameters A'_1 , B'_1 , and C'_1 of AC directly.

tween measurement planes w_1 and Γ_2 as shown in Fig. 4. The parameters A'_1 , B'_1 , and C'_1 are readily obtained from w_1 and Γ_2 . Since the uncertainties associated with w_1 and Γ_2 have been determined in the TRL calibration, the uncertainties of the parameter A'_1 , B'_1 , and C'_1 are also readily determined in the same way as for a two-port inserted between measurement planes 1 and 2.

VIII. OPTIMUM LINE LENGTHS

The first line of length l_1 can be any convenient length; however, it should not be longer than necessary. As explained in Section III, the length l_2 of the second line should be such that the difference in phase shift $\Delta\phi$ through the two lines is 90° at the center of the operating frequency range f_1 to f_2 . This condition when applied to coaxial lines leads to [7]

$$l_2 - l_1 = \frac{15}{f_1 + f_2} \text{ cm} \quad (30)$$

where f_1 and f_2 are in gigahertz. The corresponding differences in phase shifts $\Delta\phi_{f_1}$ and $\Delta\phi_{f_2}$ at f_1 and f_2 are given by

$$\Delta\phi_{f_1} = 180 - \Delta\phi_{f_2} = \frac{180}{1 + f_2/f_1} \text{ deg.} \quad (31)$$

If the ratio f_2/f_1 is so large that $\Delta\phi_{f_1}$ becomes too small, say less than 20° , then the range f_1 and f_2 may be broken into two ranges f_1 to f_i and f_i to f_2 , where f_i is an intermediate frequency chosen such that

$$\frac{f_2}{f_i} = \frac{f_i}{f_1} = \sqrt{\frac{f_2}{f_1}}. \quad (32)$$

Three lines are required to cover these two ranges. The lengths l_1 , l_2 , and l_3 of the three lines must satisfy

$$l_2 - l_1 = \frac{15}{f_i + f_2} \quad (33)$$

and

$$l_3 - l_1 = \frac{15}{f_1 + f_i} = \sqrt{\frac{f_2}{f_1}} (l_2 - l_1). \quad (34)$$

Lengths l_1 and l_3 are used from f_1 to f_i , and lengths l_1 and l_2 are used from f_i to f_2 . The corresponding differences in phase shift are obtained from (31) using the appropriate frequencies.

Equations similar to (30) and (31) can be derived for a

TABLE I
OPTIMUM LENGTHS FOR RECTANGULAR WAVEGUIDE

WAVEGUIDE SIZE, WR	CUTOFF FREQ	f_1 GHz	f_2 GHz	$l_2 - l_1$ cm	$\Delta\phi_{f1}$ DEG
284	2.078	2.600	3.950	3.048	57.1
187	3.152	3.950	5.850	2.052	58.6
137	4.301	5.850	8.200	1.370	65.2
112	5.259	7.050	10.000	1.136	64.0
90	6.556	8.200	12.400	0.971	57.4
62	9.486	12.400	18.000	0.644	61.7
42	14.047	18.000	26.500	0.445	60.1
28	21.081	26.500	40.000	0.300	57.7
22	26.341	33.000	50.000	0.240	57.4
19	31.357	40.000	60.000	0.197	58.8
15	39.863	50.000	75.000	0.160	58.0
10	59.010	75.000	110.000	0.108	59.9
7	90.840	110.000	170.000	0.073	54.3
4	137.520	170.000	260.000	0.047	56.1
3	173.280	220.000	325.000	0.037	59.4

Optimum difference $l_2 - l_1$ in two lengths of waveguide are calculated from (38) to have a phase difference $\Delta\phi$ (or $180 - \Delta\phi$) equal to or greater than $\Delta\phi_{f1}$ over the complete frequency band from f_1 to f_2 . The shorter length l_1 can be any convenient length including zero.

rectangular waveguide as follows. The phase shift through a rectangular waveguide can be written [8]

$$\phi = 12l\sqrt{f^2 - f_c^2} \text{ deg} \quad (35)$$

where f is the frequency in gigahertz, l is the physical length in centimeters, and f_c is the cutoff frequency in gigahertz. For two lines, the difference in phase is

$$\Delta\phi = 12(l_2 - l_1)\sqrt{f^2 - f_c^2} \text{ deg.} \quad (36)$$

Choose the lengths of line so that the differences in phase shift $\Delta\phi_{f1}$ and $\Delta\phi_{f2}$ at the band edges f_1 and f_2 satisfy

$$\Delta\phi_{f1} = 180 - \Delta\phi_{f2}. \quad (37)$$

This condition keeps the phase differences equally as far from 0° at f_1 as it is from 180° at f_2 . Substituting (36) in (37) and solving for $l_2 - l_1$ gives

$$l_2 - l_1 = \frac{15}{\sqrt{f_1^2 - f_c^2} + \sqrt{f_2^2 - f_c^2}} \text{ cm.} \quad (38)$$

The difference in phase shifts at f_1 and f_2 are obtained by substituting (38) in (36)

$$\Delta\phi_{f1} = 180 - \Delta\phi_{f2} = \frac{180}{1 + \sqrt{\frac{f_2^2 - f_c^2}{f_1^2 - f_c^2}}} \text{ deg.} \quad (39)$$

Table I gives values of $l_2 - l_1$ and $\Delta\phi_{f1}$ for different waveguide sizes.

IX. CONCLUSION

Considerable effort has been expended by the National Bureau of Standards (NBS) to develop the TRL calibration techniques to provide on-line estimates of the random and systematic errors associated with all of the six-port calibration parameters and the measured values of Γ or S -parameters. Currently, this technique has applied only to sexless connectors. By replacing the TRL thru connection

with a short length of line whose $\gamma_1 l_1$ is determined by one of the four methods outlined in this paper, it is possible to use all of the TRL software to calibrate a dual six-port or four-port with any type of connector. Thus only one set of software is needed for any type of connector.

APPENDIX A

The uncertainty $d(\gamma_1 l_1)$ in $\gamma_1 l_1$ depends on how $\gamma_1 l_1$ is determined. The worst-case uncertainties associated with each of the four methods considered in Section VI for determining $\gamma_1 l_1$ are derived in this appendix.

A. From l_1 and l_2

Differentiating (15) and keeping only first-order terms leads to the following expression for the uncertainty in $\gamma_1 l_1$ when $\gamma_1 l_1$ is determined from the physical lengths l_1 and l_2 .

$$d(\gamma_1 l_1) = (\gamma l)_i dK + K d(\gamma l)_i - K l_2 \Delta\gamma. \quad (A1)$$

The uncertainty $d(\gamma l)_i$ in $(\gamma l)_i$ is determined from the TRL solution [5], [6]. From (13)

$$dK = K^2 \frac{l_2}{l_1} \left(\frac{dl_1}{l_1} - \frac{dl_2}{l_2} \right) \quad (A2)$$

where dl_1 and dl_2 are the uncertainties in measuring l_1 and l_2 .

B. From a Known Γ

When a known reflection coefficient is used to obtain $\gamma_1 l_1$, (18) gives

$$d(\gamma_1 l_1) = \frac{d\Gamma_i}{\Gamma_i} - \frac{d\Gamma}{\Gamma}. \quad (A3)$$

In this expression $d\Gamma$ is the total uncertainty with which Γ is known.

C. From ψ of Γ

When $\gamma_1 l_1$ is determined from the known phase angle of a termination using (16) and (24), $d(\gamma_1 l_1)$ is given by differentiating (16) to get

$$d(\gamma_1 l_1) = (\gamma l)_t dK' + K' d(\gamma l)_t \quad (\text{A4})$$

where from (24)

$$dK' = \frac{1}{y} (d\psi_t - d\psi_s - K' dy). \quad (\text{A5})$$

Combining (A4) and (A5)

$$\begin{aligned} d(\gamma_1 l_1) &= \frac{(\gamma l)_t}{y} (d\psi_t - d\psi_s) \\ &+ K' \left(d(\gamma l)_t - (\gamma l)_t \frac{dy}{y} \right). \end{aligned} \quad (\text{A6})$$

Let

$$d(\gamma l)_t = dx + j dy. \quad (\text{A7})$$

Then, since $x \ll y$, (A6) reduces approximately to

$$d(\gamma_1 l_1) \approx K' dx + j(d\psi_t - d\psi_s). \quad (\text{A8})$$

D. From Γ Ratio

If $\gamma_1 l_1$ is obtained by measuring a termination with and without the line l_1 inserted in front of it, the uncertainty in $\gamma_1 l_1$ obtained from (28) is

$$d(\gamma_1 l_1) = \frac{1}{2} \left(\frac{d\Gamma_t}{\Gamma_t} - \frac{d\Gamma'_t}{\Gamma'_t} \right) \quad (\text{A9})$$

$$\approx \frac{d\Gamma_t}{\Gamma_t} = \frac{d|\Gamma_t|}{|\Gamma_t|} + j d\psi_t. \quad (\text{A10})$$

E. Comparing Methods

Assuming that all errors are roughly the same magnitude, (A1), (A3), (A8), and (A10) imply that method D

is more accurate than method B or C. Method A is probably the least accurate, but the easiest to apply.

APPENDIX B

The derivation of (1)–(7) is the same as that given by Engen and Hoer [1] except that the identity matrix which describes the cascading parameters of the thru connection in (20) of that paper is replaced with

$$R_{l_1} = \begin{bmatrix} e^{-\gamma_1 l_1} & 0 \\ 0 & e^{\gamma_1 l_1} \end{bmatrix} \quad (\text{B1})$$

and the cascading matrix for the single line is replaced with

$$R_{l_2} = \begin{bmatrix} e^{-\gamma_2 l_2} & 0 \\ 0 & e^{\gamma_2 l_2} \end{bmatrix} \quad (\text{B2})$$

in (21) and (25) of that paper. The rest of the derivation is the same and leads to (1)–(7) of this paper.

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