IMPROVED RF HARDWARE AND CALIBRATION METHODS FOR NETWORK ANALYZERS

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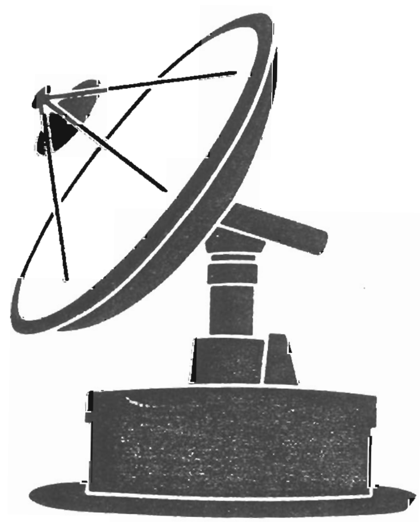

ABSTRACT

The degree to which measurement accuracy in a vector network analyzer can be improved through error correction is dependent on a number of factors. Modern error correction methods have improved the system accuracy and simplified the calibration procedure. Methods are in place to determine the accuracy of error corrected measurements. And the quality of the calibration standards is key to system performance. One significant factor is the "uncorrected" RF performance at the system test port (directivity, port match, path losses, etc.). The amount of time calibration remains valid is greatly dependent on the performance of the system before error correction is applied. This paper, authored by a leading authority of vector error correction, discusses the advantages of modern error correction methods, the resultant error correction accuracy, and the advantage of having excellent uncorrected RF performance. A number of criteria for selecting the best calibration method will be described.

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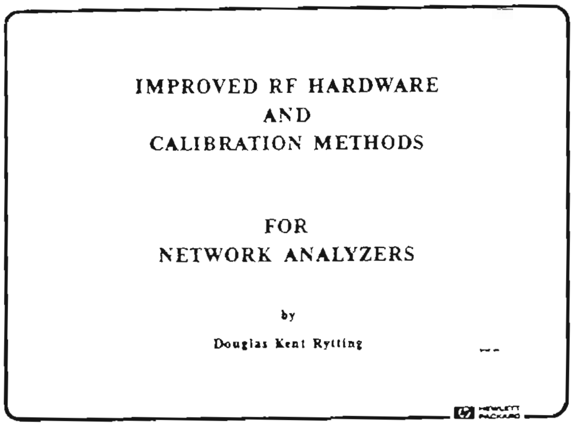
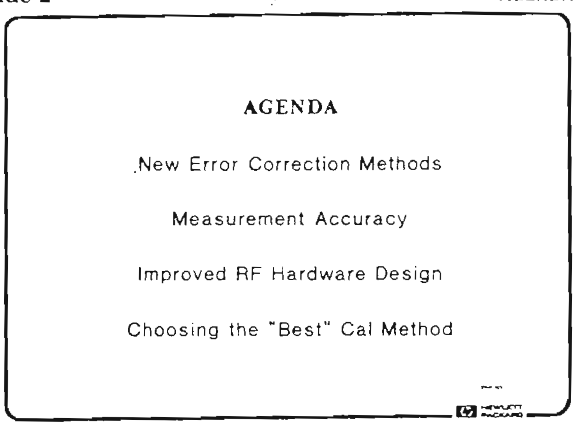
Slide 1 IMPROVED RF HARDWARE AND CALIBRATION METHODS FOR NETWORK ANALYZERS



Modern network analyzers have greatly enhanced the productivity of the microwave industry. Error-correction techniques have made it possible to use non-perfect hardware and still achieve very good performance. A significant question is, "what really contributes to the accuracy and performance of a network analyzer?" Certainly, the error-correction concept of mathematically removing hardware errors has made a significant impact. New error-correction methods like TRL, LRL, TRM, and LRM have simplified the calibration process and also provided better accuracy. Through refined machining, the quality of the calibration standards has improved the error-correction accuracy. Also the modeling of standards has significantly improved. However, one overlooked fact is uncorrected "raw" hardware performance and its effect on the system accuracy.

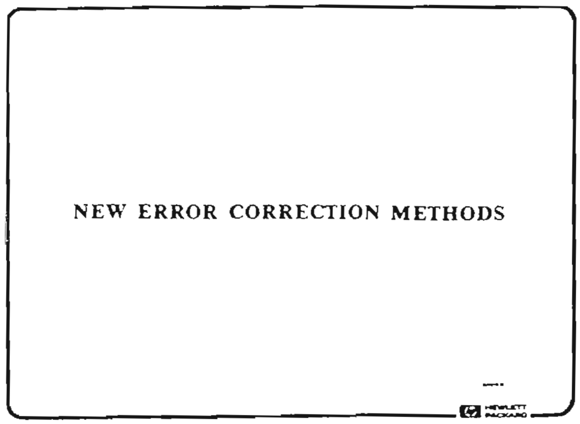
A common misconception is that error correction "does it all," and that it can calibrate out, or quantify, any level of uncorrected performance. It is clear that the more stable the hardware, the better the calibration process can correct the errors. The calibration will then remain stable as a function of time and temperature, and calibrations will not need to be updated as often.

Slide 2 AGENDA



The new error correction methods will be reviewed. Then the measurement accuracy will be defined and measurement assurance will be established. The design requirements for the hardware will than be described that is necessary for good error corrected performance. The last issue is selecting the best calibration method for various applications.

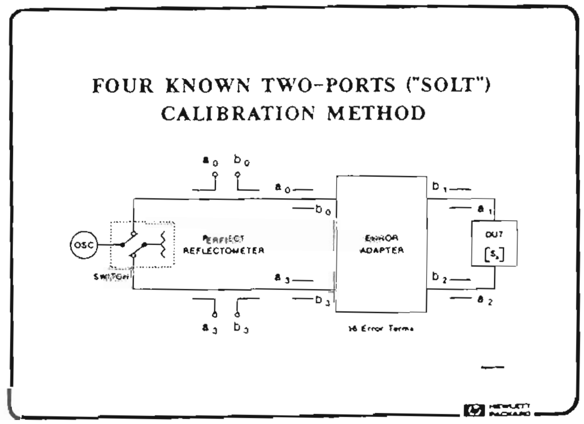
Slide 3 NEW ERROR CORRECTION METHODS



There are two basic methods used widely in the industry today. The first method uses known calibration artifacts to determine the system error terms. There must be as many know characteristics of the calibration standards as there are error terms.

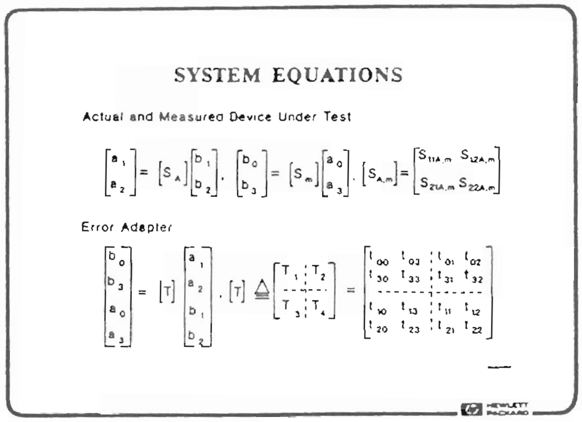
The second method uses the redundancies that exist in the system equations to determine the system error terms as well as some of the characteristics of the calibrations standards.

Slide 4 FOUR KNOWN TWO-PORTS



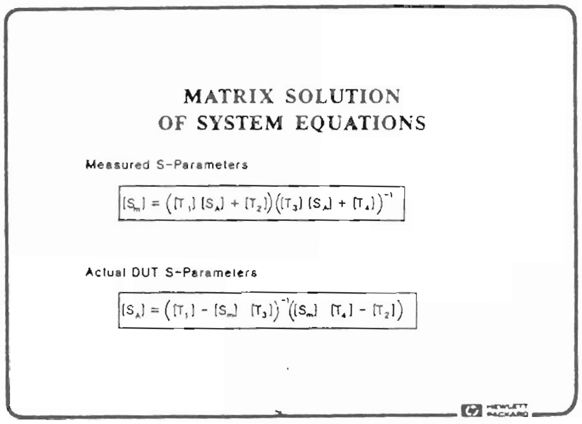
All the linear errors of the imperfect reflectometer can be combined into an error adapter yielding a system model with a perfect reflectometer combined with a fictitious error adapter. In this case, the fictitious error adapter must be a four-port. This error adapter has 16 error terms. The number of error terms is the square of the number of ports. The errors of the switch can be removed as long as we can measure all four waves at the coupler ports at the same time. There are 2 directivity terms, 2 port-match terms, 2 reflection tracking terms, and 2 transmission tracking terms. Eight of the error terms are leakage between the various ports.

Slide 5 SYSTEM EQUATIONS



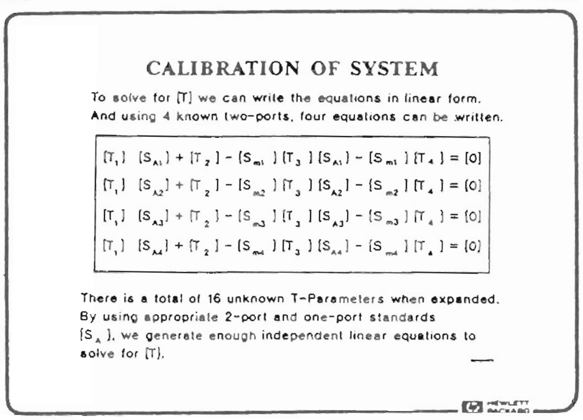
The equations for the device under test and the measured results are described in terms of s-parameters. However it is better to describe the system error adapter in terms of the cascading t-parameters. The t-parameters describe the input wave as a function of the output waves. The t-parameter solution yields a much more compact result.

Slide 6 MATRIX SOLUTION



With the t-parameter formulation, the solution for the measured s-parameters is the matrix form of the bilinear transformation. This is easily solved for the actual s-parameters.

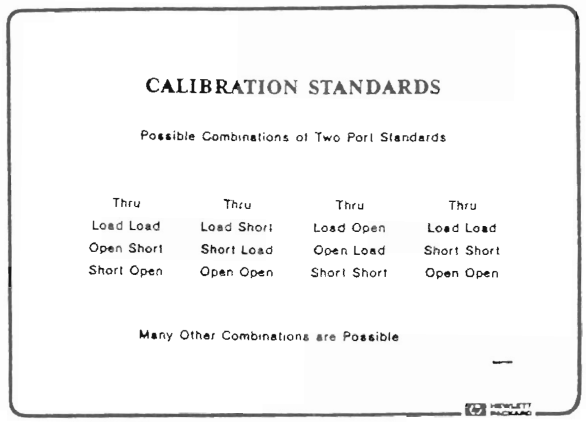
Slide 7 CALIBRATION OF SYSTEM



The real benefit of the t-parameter is in the solution for the error term. The matrix bilinear transformations can be easily written in linear equation form. Since there are four 2x2 matrix error terms, four known two-ports can be used as calibration standards. The system of four linear matrix equations can then be solved for the 16 system error terms. The solution is not as easy as it seems since this set of equations is homogeneous. Numerically the solution to the t-parameters would be the trivial one, that is [T]=0. This requires reducing the rank of the matrix by one and normalizing the values of all the coefficients with respect to one of the t-parameters. This procedure is valid as long as we are calibrating for ratio measurements.

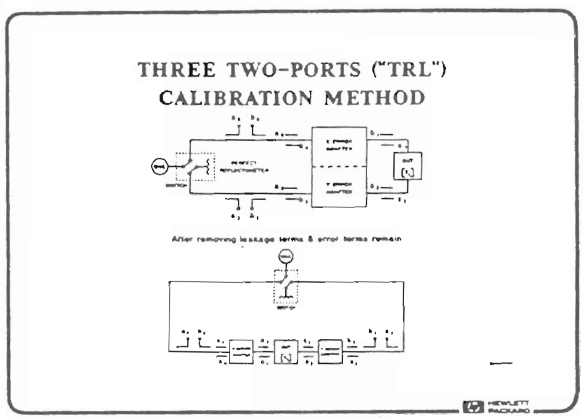
Many practical measurement systems in coax and waveguide do not to use all 16 error terms. 8 of the error terms are leakage terms and are not significant. The most common method neglects 6 of the leakage terms resulting in only 10 unknown error terms. This simplifies the math a little, but the method of solution is the same. However, in wafer probing systems or fixtures, the other error terms are more significant and could be considered.

Slide 8 CALIBRATION STANDARDS



There are four combinations of common two-port standards that will give the required 16 linear equations that are needed to solve the 16 unknowns. Any known standard can be used as long as each is used only once on each port.

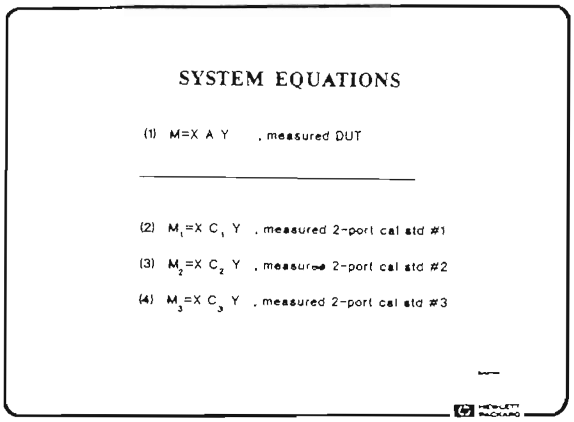
Slide 9 THREE TWO-PORTS



Further development of the TRL calibration concepts has led to a more generalized method that overcomes the major limitations of TRL. This generalized method also ties together the traditional techniques with the new techniques in a unified manner.

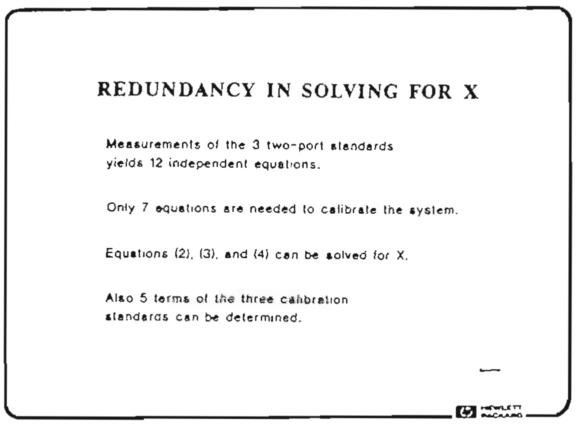
The first step involves separating the system into a perfect reflectometer followed be a 4-port error adapter. This error adapter represents all the errors in the system that can be corrected. It can be split into two 2-port error adapters, X (at port 1) and Y (at port 2), after removing the leakage (crosstalk) terms as a first step in the calibration. Since X and Y are 2-ports it would appear there are 8 unknowns to find, however since all measurements are made as ratios of the b's and a's, there are actually only 7 error terms to calculate.

Slide 10 SYSTEM EQUATIONS



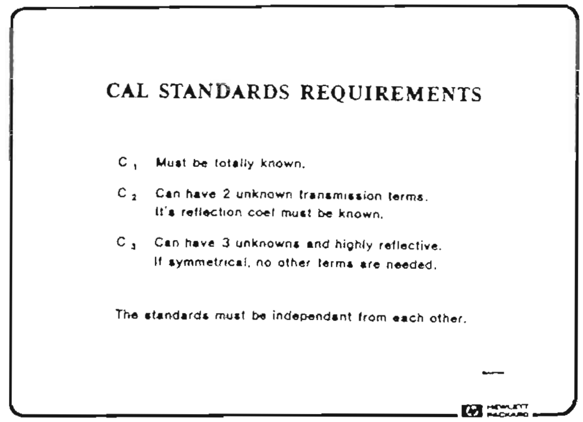
It is most convenient to use t-parameters instead of s-parameters because it allows one to represent the overall measurement, M, of the DUT, A, as corrupted by the error adapters as a simple product of the matrixes, M=XAY. In a similar manner, each measurement of three 2-port standards, C_1, C_2, and C_3 can be represented as M_1, M_2, and M_3.

Slide 11 REDUNDANCY IN SOLVING FOR X



While there are 7 unknowns, measuring three 2-port standards yields a set of 12 equations. Due to this redundancy, it is not necessary to know all the parameters of all the standards. X and Y can be solved for directly plus 5 characteristics of the calibration standards.

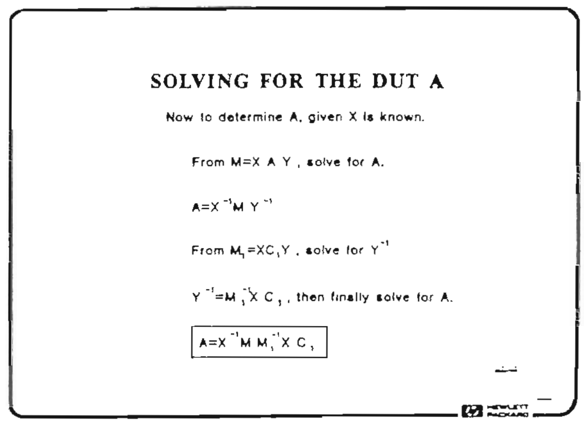
Slide 12 CAL STANDARDS REQUIREMENTS



All 4 parameters of C_1 must be known but only 2 parameters for C_2 and none for C_3 if it is symmetric. The simplest of all standards is a throughline, so let C_1 be a thru and C_2 a Z_0 matched device. If needed, impedance renormalization can be used to shift to a different impedance base. The other parameters of C_2 and C_3 can be solved from the data.

For this calibration method there are several combinations of standards that fit the requirements. However, there are also choices that generate ill-conditioned solutions or singularities. In choosing appropriate standards, one standard needs to be Z_0 based, one needs to present a high mismatch reflection. In addition, all three standards need to be sufficiently different as to be three independent measurements.

Slide 13 SOLVING FOR THE DUT A



The unknown device characteristics can be easily calculated by knowing the parameters of the X error adapter, the known standard C_1, and the measured data of the test device and measured data for C_1. The Y error adapter does not need to be solved for directly.

Slide 14 — CALIBRATION STANDARDS

CALIBRATION STANDARDS

Possible Combinations of Two Port Standards

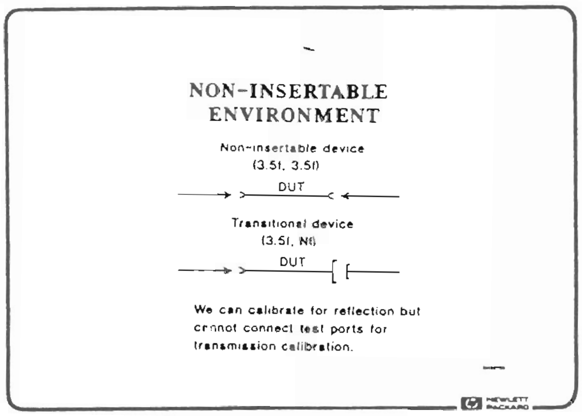
Cal Type	Std C_1 Thru	Std C_1 Line	Std C_3 Sym Reflect	Std C_2 Line	Std C_2 Match	Std C_2 Atten
TRL	X		X	X		
TRM	X		X		X	
TRA	X		X			X
TSD	X		$\Gamma = -1$	X		
LRL		X	X	X		
LRM		X	X		X	
LRA		X	X			X

Many Other Combinations are Possible

There are several possible strategies in choosing standards. The use of a zero length thru is an obvious selection but a non-zero length thru is also acceptable if its characteristics are known or the desired reference plane is in the center of the non-zero length thru. A second standard needs to be a Z_0 reference. In this solution, only the match of this standard needs to be of concern. Its S_{21} and S_{12} can be any value and do not need to be known. In fact, they will be found during the calibration process. This opens up the choices to a wide range of 2-port components, such as a pair of matched loads or and attenuator. For the final standard only one piece of information is needed. This could be a known reflection value of symmetrical reflections. Since the other standards have been well matched, this standard must be a high mismatch.

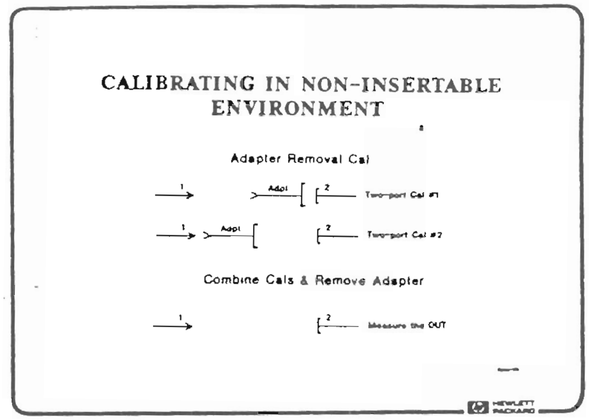
The table shows a partial list of possible calibration configurations with appropriate three letter acronyms. Many are familiar combinations but there are some new ones of significant usefulness, such as TRM and LRM. There are other possibilities not yet tried and therefore not listed.

Slide 15 — NON-INSERTABLE



There are many times when a device with female or male connectors on both ends needs to be measured The problem is that you can not connect the two test ports together for the transmission calibration. The same problem exists if the device has different connectors at both ends, like type N and waveguide.

Slide 16 — CALIBRATION IN NON-INSERTABLE



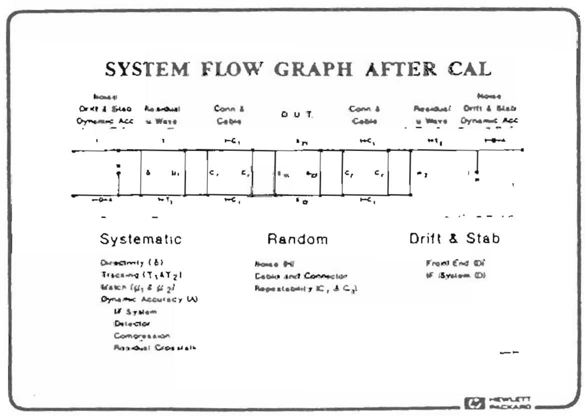
There is a mathematical method to calibrate in these difficult environments. The first step is to locate an adapter that mates the two test ports. The process is to first do a two-port calibration at test port 1 then do a two-port calibration at test port 2. These two calibrations can then be combined to remove the adapter and provide a complete non insertable calibration. The redundant data gathered by this method is used to improve the final calibration results.

Slide 17 — MEASUREMENT ACCURACY

MEASUREMENT ACCURACY

Error correction theory is of limited value if the final measurement accuracy is unknown. A method that accounts for the errors is a simple and complete manner is a key desired feature.

Slide 18 — SYSTEM FLOW GRAPH AFTER CAL

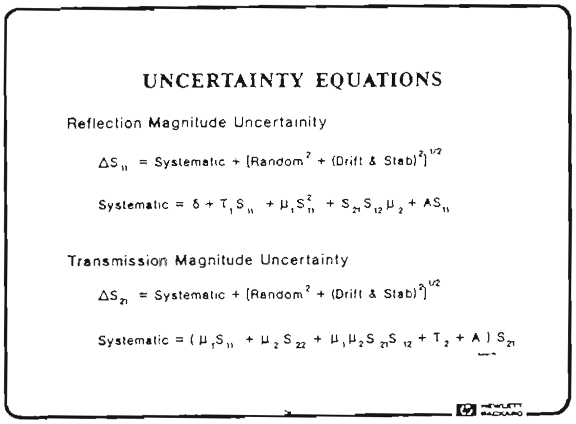


The error corrected measurement system can be nicely described using flow graphs. The device under test measurements will be degraded by the following hardware issues.

There is a cable and connector interface with characteristics that will change after calibration. The cable will remain calibrated if it is not moved but this is not the case and C_t and C_r describe the change in the cable characteristics. C_t and C_r also characterize the connector repeatability between calibration and measurement. C_r is defined as the change of the reflection coefficient and C_t is defined as the transmission coefficient change. The residual microwave errors (δ, τ_1, and μ_1) characterize the fact that the calibration standards are not perfect and even after calibration there are residual errors still present. There is noise (N) in the system that sets the sensitivity of the system and the amount of noise on the measurement data. The hardware will also drift with time, temperature, and use as characterized by the front end and IF drift and stability terms (D). The nonlinearities of the system with measurement level are described by the dynamic accuracy (A).

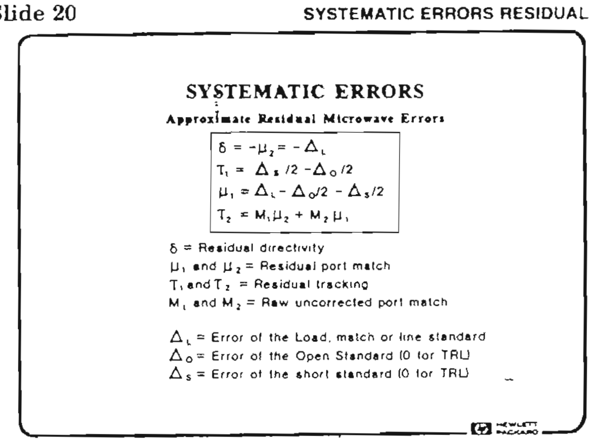
These errors can also be viewed from a different perspective. Systematic errors are those errors that don't change after calibration and have a bias. The random errors have a zero mean and random distribution and can be reduced by averaging or multiple measurements. Drift and stability errors characterize the system changes with time, temperature, and use.

Slide 19 UNCERTAINTY EQUATIONS



The flow graph can be solved to show the total system uncertainty. These equations calculate the magnitude uncertainty with each error term defined by it's absolute magnitude. The first part of the equation describes the systematic errors and these errors typically add up is a worst case manner. The random, drift and stability errors are typically characterized in an RSS fashion in the second part. The phase error is usually determined by taking the arcsin and adding any phase drift that is uncorrelated with the magnitude.

Slide 20 SYSTEMATIC ERRORS RESIDUAL



The reflection residual microwave errors are mainly determined by the quality of the calibration standards. If the assumed values of the standards and their measured value (assumed plus error) are known, then the residual errors can be calculated. This is done by using the invariance of the cross-ratio principle of the bilinear transformation.

Assuming that three reflection standards are employed, then define

$\Gamma_1, \Gamma_2, \Gamma_3$ = assumed reflection coefficients of standards
$\Delta_1, \Delta_2, \Delta_3$ = errors in standards $\Gamma_1, \Gamma_2, \Gamma_3$
$\Gamma_1', \Gamma_2', \Gamma_3'$ = measured values (Γ_m) with standards connected

Using the invariance property of the cross-ratio of complex numbers, the measurements Γ_m of an unknown Γ can be written as

(1) $$\frac{(\Gamma_m - \Gamma_1')(\Gamma_2' - \Gamma_3')}{(\Gamma_m - \Gamma_2')(\Gamma_1' - \Gamma_3')} = \frac{(\Gamma - \Gamma_1)(\Gamma_2 - \Gamma_3)}{(\Gamma - \Gamma_2)(\Gamma_1 - \Gamma_3)}$$

Noting that, in fact, the perceived value of the device under test is in error

(2) $\Gamma' = \Gamma + \Delta\Gamma$

If the true reflection coefficient is required it can be obtained by substituting Equation 2 in Equation 1. After a page of so of math the final result can be put in the following form.

(3) $\Delta\Gamma = \delta + \tau_1\Gamma + \mu_1\Gamma^2$
Total reflection error

(4) $\delta = -\mu_2 = -(D_1\Gamma_2\Gamma_3 + D_2\Gamma_1\Gamma_3 + D_3\Gamma_1\Gamma_2)$
Residual directivity & port-2 match

(5) $\tau_1 = D1(\Gamma_2 + \Gamma_3) + D_2(\Gamma_1 + \Gamma_3) + D_3(\Gamma_1 + \Gamma_2)$
Residual reflection tracking

(6) $\mu_1 = -(D_1 + D_2 + D_3)/\tau_1$
Residual port-1 match

where

$D_1 = \Delta_1/[(\Gamma_1 - \Gamma_2)(\Gamma_1 - \Gamma_3)]$
$D_2 = \Delta_2/[(\Gamma_2 - \Gamma_3)(\Gamma_2 - \Gamma_1)]$
$D_3 = \Delta_3/[(\Gamma_3 - \Gamma_1)(\Gamma_3 - \Gamma_2)]$

The $\Delta_{1,2,3}$ terms of the calibration standards are determined from primary electrical standards that are carefully modeled from precision mechanical measurements.

The slide shows the simplified results when using an open ($\Gamma_1 = 1, \Delta_1 = \Delta o$), short ($\Gamma_2 = -1, \Delta_2 = \Delta_s$), and load ($\Gamma_3 = 0, \Delta_3 = \Delta_L$) calibration standards.

The transmission residual error term (τ_2) is calculated by a different method. The raw port match causes an error in the error corrected transmission tracking. This is true even if the port match is stable and never changes. To calculate the residual transmission tracking (τ_2) the two test ports are connected together. The resultant measurement yields:

(7) $$S_{21m} = \frac{(1+T_2)}{(1-M_1M_2)}$$

where M_1 and M_2 are the raw test port matches and $(1+T_2)$ is the raw transmission tracking term. The calculated $(1+T_{2c})$ is solved for from Equation 7 where the calculated values for M_1 and M_2 (defined as M_{1c} and M_{2c}) are used.

(8) $$1+T_{2c} = S_{21m}(1-M_{1c}M_{2c}) = (1+T_2)\,\frac{1-M_{1c}M_{2c}}{1-M_1M_2}$$

where the calculated terms are defined as

(9) $M_{1c} = M_1 + \mu_1$, μ_1 = residual port-1 match.
(10) $M_{2c} = M_2 + \mu2$, μ_2 = residual port-2 match.

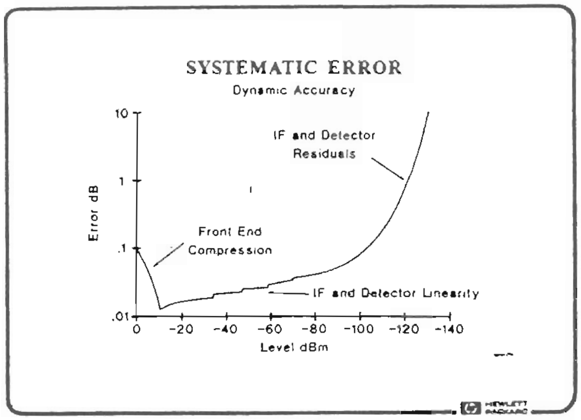
The final result after substituting Equations 9 and 10 into 8 and simplifying yields.

(11) $1+T_{2c} = (1+T_2)(1 - M_1\mu_2 - M_2\mu_1)$

And the residual transmission tracking error is

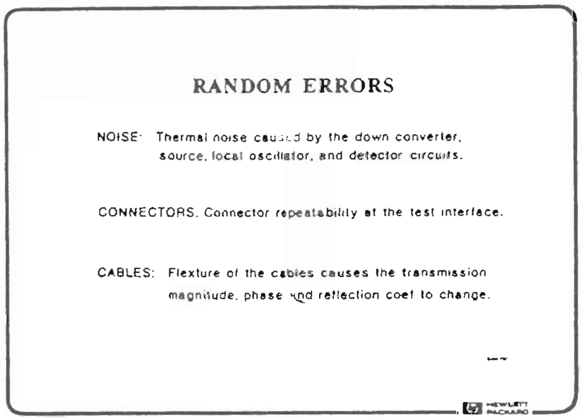
(12) $\tau_2 = M_1\mu_2 + M_2\mu_1$

Slide 21 SYSTEMATIC ERROR DYNAMIC ACCURACY



The dynamic accuracy describes the system errors as a function of level and phase shift. At high measurement levels the main error is caused by the front end compression. In the middle ranges the errors are caused by the autoranging attenuators, xtal filter non-linearity and the accuracy of the detectors as the phase is changed. At the low levels the residuals are caused by DC drift, A/D bit resolution, and coherent IF leakage signals caused by various clocks. The dynamic accuracy does not include any noise or microwave errors.

Slide 22 RANDOM ERRORS

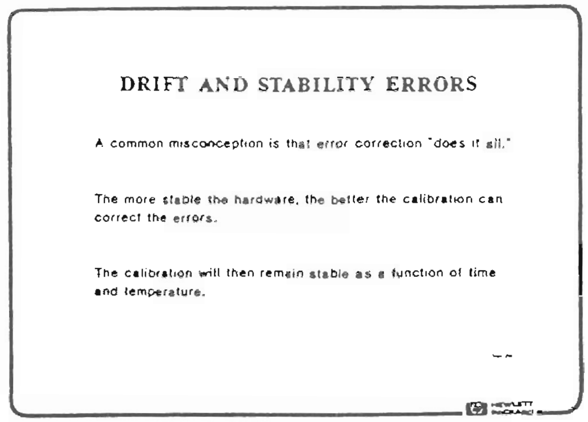


There are a number of noise sources. The system sensitivity is determined by the noise Figure of the front end converter and LO noise leakage through the converter. Noise on the data is caused by the system sensitivity plus noise from the LO close to the carrier. The higher the harmonic of the LO the more this noise will increase and dominate. There is also noise added to the data by the detector circuits and the RF source, but these are usually smaller.

Connector repeatability is characterized by making multiple connections and measuring the vector difference in the data. This is done over a large sample and characterized statistically.

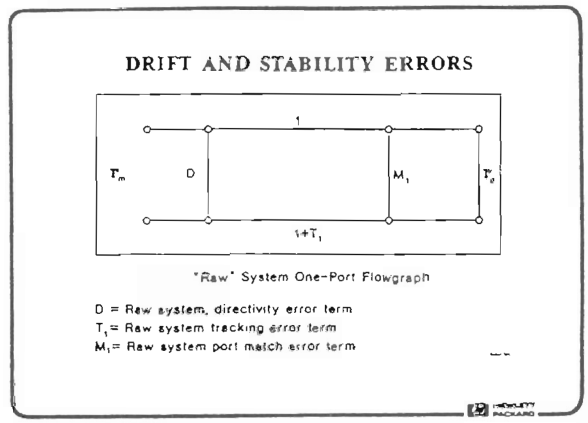
Cables are a major source of error. If they are not moved after calibration the error can be very small but this is not the typical use of the system. The port match and transmission characteristics of the cable will change with use. Typically the transmission phase error will be larger that the magnitude error. Hard line cable tend to be more stable if the measurement requires very little movement. But if the cables must be moved often then a high quality flexible cable is a must. Also the phase shift of cables with temperature is mainly a function of the dielectric and can be very different from cable to cable.

Slide 23 DRIFT AND STABILITY ERRORS



As calibration methods have improved and the frequency range has increased, the quality of the RF hardware has become the limit in measurement accuracy. A major step forward in stable high performance hardware is a must. Because of the importance of system stability in an error corrected system, a detailed analysis of the hardware is required.

Slide 24 DRIFT AND STABILITY ERRORS FLOWGRAPH



The flow graph of a one-port measurement system is shown, where D=system directivity error term, T_1=system reflection tracking error term, and M_1=system port match error term. These error terms correspond directly to the uncorrected "raw" hardware performance. The system directivity is mainly determined by the directional coupler. The system tracking error is determined by how well the reference and test channels track each other as a function of frequency. The system port match consists of the match terms of all the components in the system, including the coupler, bias network, step attenuators, splitters and switches.

Slide 25 DRIFT AND STABILITY ERRORS MATH

(1) $\Gamma_m = D + (1+T_1)\frac{\Gamma_a}{1-M_1\Gamma_a}$, and (2) $\Gamma_{ac} = \frac{\Gamma_m - D_c}{(1+T_{1c})+M_{1c}(\Gamma_m-D_c)}$

Substituting for Γ_m from Equation 1 into 2, and deleting second order terms yields:

$$\Gamma_{ac} \doteq \frac{D-D_c}{1+T_{1c}} + (1+\frac{T_1-T_{1c}}{1+T_{1c}})\Gamma_a + (M_1-M_{1c})\Gamma_a^2$$

and taking partial derivatives yields the Drift & Stab. error.

$$d\,\Gamma_{ac} = \frac{1}{1+T_1}dD + \frac{\Gamma_a}{1+T_1}dT_1 + \Gamma_a^2\,dM_1$$

The measured Γ_m can be calculated in terms of the actual test device Γ_a and the error terms from the flow graph.

$$(1) \quad \Gamma_m = D + (1+T_1)\frac{\Gamma_a}{(1-M_1\Gamma_a)}$$

From Equation 1, and from the use of a calibration procedure, the calculated error terms (D_c, T_{1c}, and M_{1c}) can be determined. Equation 1 can then be solved for the calculated return loss Γ_{ac} of the test device:

$$(2) \quad \Gamma_{ac} = \frac{(\Gamma_m-D_c)}{(1+T_{1c})+M_{1c}(\Gamma_m-D_c)}$$

Substituting for Γ_m from Equation 1, and deleting second order terms yields:

$$(3) \quad \Gamma_{ac} \cong \frac{(D-D_c)}{(1+T_{1c})} + (1+\frac{(T_1-T_{1c})}{(1+T_{1c})})\Gamma_a + (M_1-M_{1c})\,\Gamma_a^2$$

Residual error terms (after error correction) can now be defined in a different manner than in the earlier development:

(4) $\delta = \frac{D-D_c}{1+T_{1c}}$, residual system directivity

(5) $\tau_1 = \frac{T_1-T_{1c}}{1+T_{1c}}$, residual system reflection tracking

(6) $\mu_1 = M_1-M_{1c}$, residual system port-1 match.

Hopefully, the calculated error terms (D_c, T_{1c}, and M_{1c}) are equal to the actual error terms (D, T_1, and M_1), and will cancel. But, they are not equal due to an imperfect system and imperfect calibration standards. Typical values after error correction for the residual directivity (δ) are in the 35 to 60 dB range; and typical values for the residual port match ($\mu1$) are from 30 to 60 dB return loss. The tracking term $(1+\tau_1)$ normally varies from 0 to $\pm$-0.1 dB. The wide range of error-corrected performance is determined by the connector size, frequency, calibration method, and the quality of the calibration standards.

The sensitivity of Γ_{ac} to the uncorrected error terms (D, T_1, and M_1) is determined by taking the partial derivative of Γ_{ac} that is defined in Equation 3. Note that the calculated error terms (D_c, T_{1c}, and M_{1c}) are stationary and don't change after error correction. The partial derivative is defined in Equation 8.

$$(8) \quad d\Gamma_{ac} = \frac{\partial \Gamma_{ac}}{\partial D}dD + \frac{\partial \Gamma_{ac}}{\partial T_1}dT_1 + \frac{\partial \Gamma_{ac}}{\partial M_1}dM_1$$

Taking the partial derivative of Equation 3 and dropping second order terms yields:

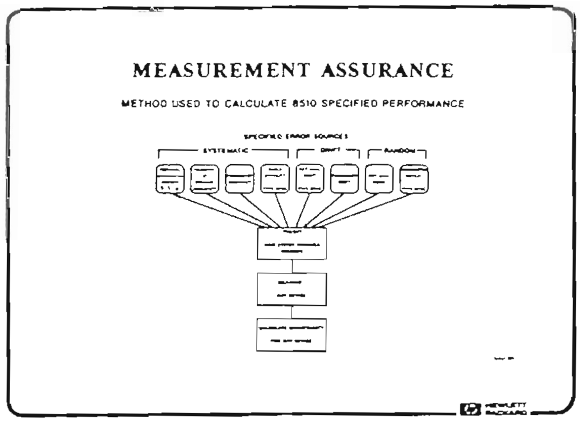
$$(9) \quad d\Gamma_{ac} \cong \frac{1}{1+T_{1c}}dD + \frac{\Gamma_a}{1+T_{1c}}dT_1 + \Gamma_a^2 dM_1$$

and using the safe assumption that $T_{1c} \cong T_1$

$$(10) \quad d\Gamma_{ac} = \frac{1}{1+T_1}dD + \frac{\Gamma_a}{1+T_1}dT_1 + \Gamma_a^2 dM_1$$

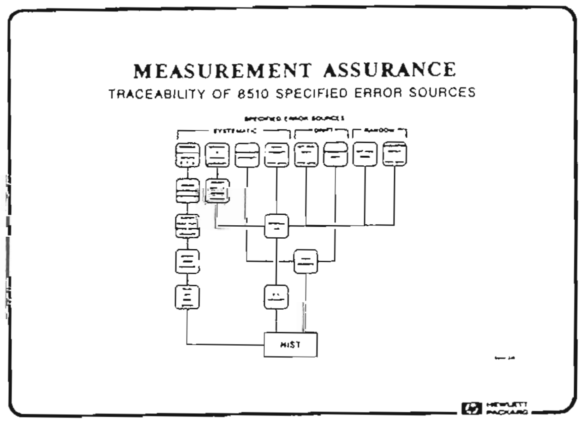
Equation 10 shows clearly the effect of changes in directivity, tracking, and match on the resultant error-corrected measurement. Note that both the stability of the error terms (dD, dT_1, and dM_1) and the absolute value of $(1+T_1)$ both contribute to the stability. Also the stability will change as a function of the test device Γ_a.

Slide 26 MEASUREMENT ASSURANCE SPECS



The 8510 specifications are developed by combining the effects of the specified error sources. As long as each of the error sources can be determined, the final result is assured. The resultant uncertainties are not only a function of the measurement system but must include the parameters of the device under test.

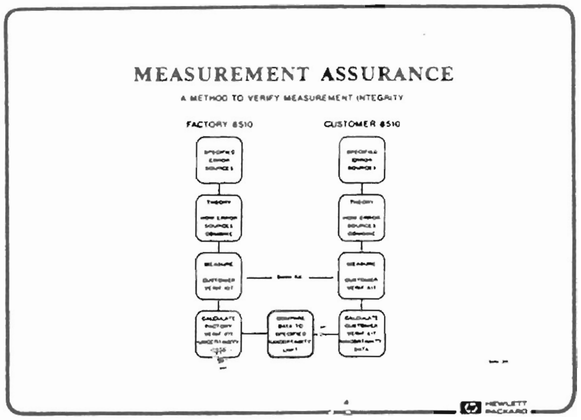
Slide 27 MEASUREMENT ASSURANCE TRACEABILITY



Each one of the specified error sources has a traceable path back to NIST. The residual microwave error terms are tested with precision airlines or low frequency resistance. The resistance is than directly traced back to NIST. The airline electrical characteristics are developed from mechanical measurements. The mechanical measurements and material properties are carefully modeled to give a very accurate electrical representation. The mechanical measurements are then traced back to NIST through various plug and ring gages and other mechanical measurements.

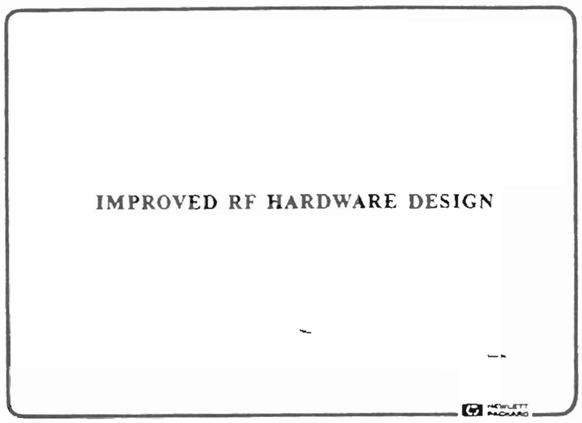
The residual IF dynamic accuracy is determined be measuring the individual IF and A/D error terms. These errors include the front end compression and the other IF and detector errors described earlier. These IF errors are then combined together in an IF model to calculate the complete dynamic accuracy. The frequency errors and various A/D measurements are easily traced back to NIST.

Slide 28 MEASUREMENT ASSURANCE VERIFICATION



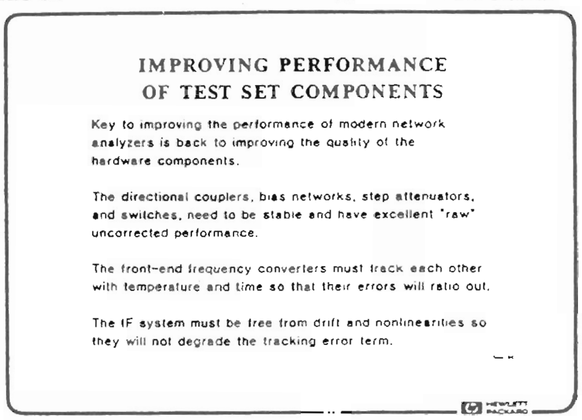
The actual system specs are generated as explained in the past two slides but an additional method is provided to verify measurement integrity. A verification kit made up of airlines and pads is measured on a factory system and the uncertainty is calculated and documented. This same verification kit can then be measured in the field on the customers system and the results compared. The process does not verify the individual error sources but provides an excellent final system performance check.

Slide 29 IMPROVED RF HARDWARE DESIGN



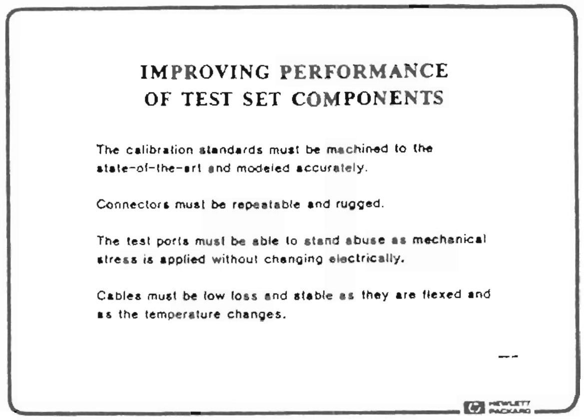
Many improvements in the RF hardware have occurred over the past few years. Sometimes these advances get lost in the fervor over error correction. The key advances will now be discussed.

Slide 30 IMPROVING PERFORMANCE



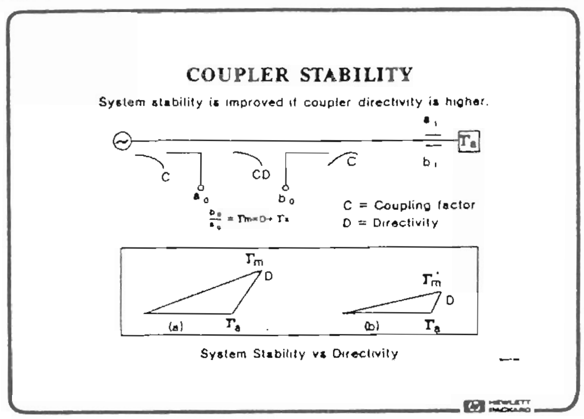
After years of improvements in the performance of calibration standards and the development of more powerful calibration algorithms, the key now to improving the performance of modern network analyzers is back to improving the quality of hardware components. The front-end test set components, such as the directional couplers, bias networks, step attenuators, and switches, need to be stable and have excellent "raw" uncorrected performance. The front-end mixers and samplers must track each other with temperature and time so that their errors are ratioed out. The IF system must be free from drift and nonlinearities so they will not degrade the tracking error term.

Slide 31 IMPROVING PERFORMANCE CONTINUED



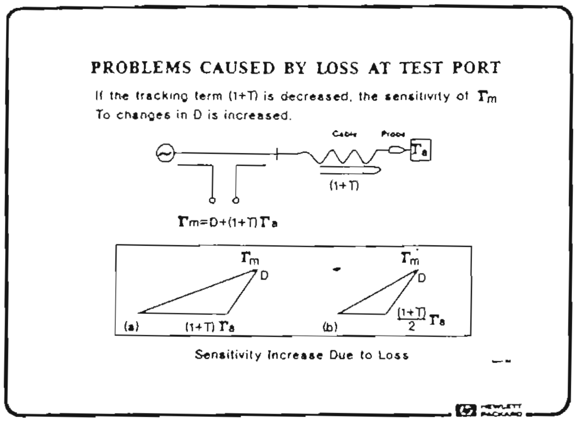
The calibration standards must be machined to the state-of-the-art and modeled accurately. Connectors must be repeatable and rugged. The test ports must be able to stand abuse as mechanical stress is applied without changing electrically. Cables must be low loss and stable as they are flexed and as the temperature changes.

Slide 32 COUPLER STABILITY



If the test set components do not have good, inherent, uncorrected performance, the stability is typically degraded. For example, a directional coupler cannot have good broadband performance if the coupler hardware is unstable, or, conversely, if the coupler is typically unstable, it does not have good broadband performance. To illustrate further, consider the vector diagram shown. If the system directivity error (D) caused by the coupler is reduced as shown in Figure b, then, for the same percentage instability in the coupler, the change in the measured reflection coefficient (Γ_m) is decreased. As the test frequency continues to increase, these stability issues and uncorrected hardware performance will determine the final outcome of the measurements.

Slide 33 PROBLEMS CAUSED BY LOSS



A problem exists if there is loss caused by adapters, cables, or fixtures after the directional device. This can be illustrated by referring to the vector diagram showing that changes in the system directivity is more critical if there is loss. Note in Figure b that if the tracking term $(1+T_1)$ is decreased, that the sensitivity of Γ_m is increased to changes in the directivity error term (D).

This sensitivity increase is a particular problem at higher frequencies where the losses are the greatest from coax cables, probes, and other components. The necessity for stability of the directivity term is even more important at higher frequencies. The test port of the network analyzer needs to be as close as possible to the test device. Obviously the losses due to components and test port cables need to be kept as low as possible.

Slide 34 RAW PORT MATCH

RAW PORT MATCH

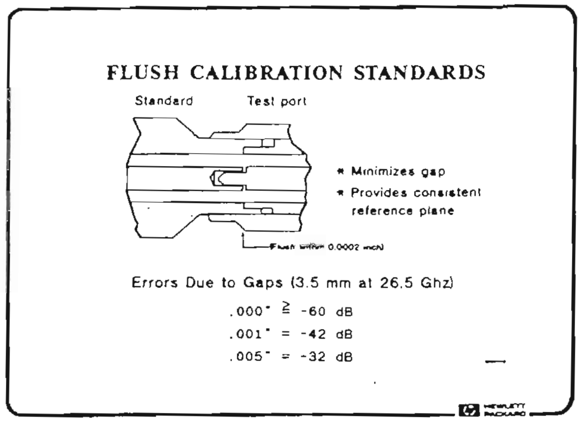
The error in the transmission tracking term is $(M_1\mu_2+M_2\mu_1)$.

If the raw port match (M_1 and M_2) reflection coefficient is 0.316 (10 dB return loss) and the residual error corrected port match (μ_1 and μ_2) is 0.02 (34 dB return loss), the error, in linear terms, will be ±0.0126 (±0.11 dB).

Two ways to reduce this error are to achieve a better residual port match using higher quality standards and error-correction methods, or to improve the uncorrected "raw" performance of the test ports.

The error in the transmission tracking term is $M_1\mu_2 + M_2\mu_1$. To see the effect of this analysis let's consider a system where the raw port match (M_1 and M_2) reflection coefficient is 0.316 (10 dB return loss) and the residual error corrected port match (μ1 and μ2) reflection coefficient is 0.02 (34 dB return loss). The error, in linear terms, will be ±0.0126 (±0.11 dB), which is very significant for precision, low-loss measurements. Two ways to reduce this error are to achieve a better residual port match using higher quality standards and error-correction methods, or to improve the uncorrected "raw" performance of the test ports.

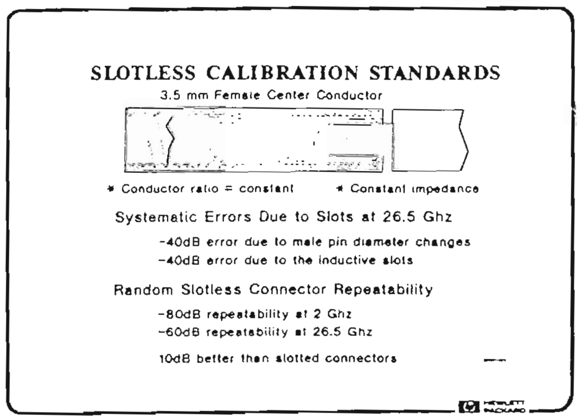
Slide 35 FLUSH CALIBRATION STANDARDS



If the standards were perfect, the only errors would be due to the network analyzer. Unfortunately there are numerous errors that potentially can cause difficulties. Many of these are due to mechanical issues involving tight tolerances. Others are due to modeling errors. The basic definition of the connector interface is also an issue. For example, how do you model slots and gaps in connectors. It there is not a clean definition of the connector interface it is very difficult to cascade devices s-parameters accurately. Skin loss also affects the characteristic impedance of the airline. And connector repeatability determines an absolute performance floor.

A major improvement is to define standards that are flush with no gaps. IF each of the standards does not have a consistent flush reference plane the resultant calibration will not calibrate out the test port gaps. These gaps can have significant error contributions. A 1 to 5 mil gap is not uncommon is normal 3.5 mm or SMA connectors. with a 5 mil gap the error is only down 32 dB.

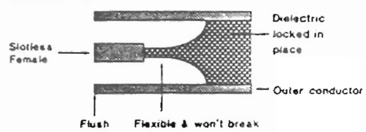
Slide 36 SLOTLESS CALIBRATION STANDARDS



The slotless contact is an inner contact that does not change the mechanical outer detail as connection is made. It is a very high life low impedance contact. The resultant simple mechanical structure is easy to trace to primary national mehanical standards and the measurement system calibrated with these standards can be certified. The error due to slots changes as the male pin diameter changes over it's tolerance range. The slots also add an inductive component that can be partially compensated, but still remains a major error. Connector repeatability is better since there are no center conductor fingers to change as the male pin is rotated during reconnection.

Slide 37 — OPEN CALIBRATION STANDARD

OPEN CALIBRATION STANDARD



3.5 mm at 26.5 Ghz

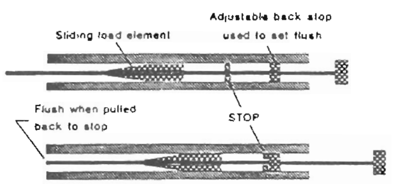
Open Error	Eff Match
2.0 deg	- 35 dB
1.0 deg	- 41 dB
0.5 deg	- 47 dB
0.2 deg	- 55 dB

The open circuit calibration standard is flush, slotless and very rugged. The open center conductor is extended beyond the reference plane to hide the difficult to model male pin. The outer conductor extends beyond the center conductor to provide shielding so there is no radiation. This simple structure is easier to model accurately. Note that even if the phase model of the open is in error less than a degree that there is still significant reduction in the performance of the calibrated test port match.

Slide 38 — SLIDING LOAD STANDARD

SLIDING LOAD STANDARD

Pull-Back Sliding Load



* Better connection
* Easier to use

The sliding load also incorporates the slotless and flush contact. Plus the ability to easily connect the load by pushing the center conductor forward to make contact. Then the back stop allows the center conductor to return to the flush position after connection.

Slide 39 — MECHANICAL TOLERANCES

MECHANICAL TOLERANCES

(7 mm Example)

O.D. Tolerance Center Cond. (micro-inches)	O.D. Tolerance Center Cond. (micro-inches)	Mechanical Zo (Ohms)	Mechanical Return Loss (dB)
±20	±40	50.02	-74
±35	±80	50.05	-69
±70	±160	50.07	-63
±150	±250	50.13	-58

Additional errors due to concentricity and eccentricity.

Note: 40 micro inches = 1 micron

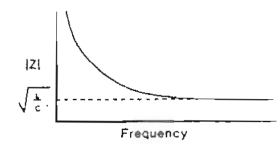
This table illustrates the tight tolerances required to achieve high performance for airlines used in sliding loads or TRL line standards. In addition to the errors listed in the table there are additional errors caused by concentricity and eccentricity. It should be noted that 40 micro-inches is about one micron. The mechanical tolerances require the same dimensional control as state of the art microwave FET gate widths.

Slide 40 — LOSSY LINE IMPEDANCE STANDARD

LOSSY LINE IMPEDANCE STANDARD

Varies With Frequency, Non-Resistive

$$Z = \sqrt{\frac{R_{skin} + jwL}{jwC}}, \quad R_{skin} \propto \frac{1}{\sqrt{F}}$$



Skin loss in non perfect conductors cause the characteristic impedance to change. Pure gold 7 mm airlines at 100 Mhz have a theoretical return loss limit of 55 dB.

Slide 41 — CHOOSING THE BEST CAL METHOD

CHOOSING THE "BEST" CAL METHOD

There are a number of different calibration methods.

Four Known Two-Port Standards Methods:

- OSL_f = Open, Short, and Fixed Load.
- OSL_s = Open, Short, and Sliding Load.
- SSL_o = Offset short, Short, and Offset Load used mainly in wavequide.
- SSL_s = Offset Short, Short, and Sliding Load used mainly in waveguide.
- SSS = Three Different Offset Shorts.

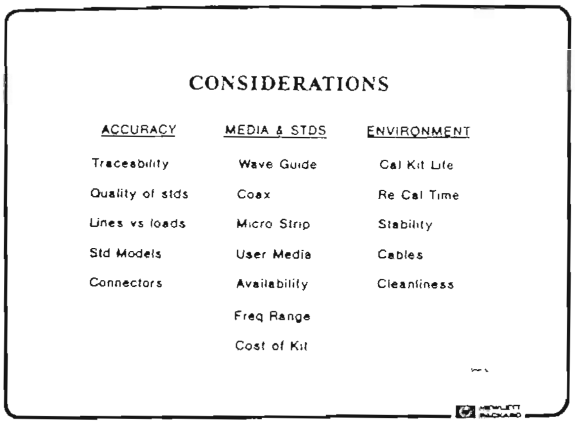
Three Two-Port Standards Methods:

- TRL = Thru Reflect, and Line.
- LRL = Thru Line, Reflect, and Line.
- TRM = Thru, Reflect, and Matched Load.
- LRM = Thru Line, Reflect, and Matched Load.

De Embed = Characterizing a fixture and mathematically removing it.

This is just a sample listing of the most often used methods. There are numerous other techniques that are used in the industry. What is the best method to use? When should it be applied? These questions depend on many factors and considerations that will now be discussed.

Slide 42 CONSIDERATIONS



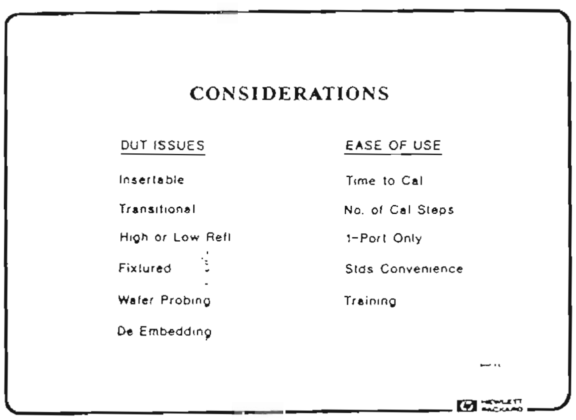
There are many considerations to balance when selecting a particular calibration method.

Accuracy: What accuracy a particular measurement require varies a great deal depending on the application. If high accuracy is not needed the calibration standards can cost less and may be easier to use. Do the measurements need to be traceable? What connector family is being used? Some utility type connectors do not have well defined calibration kits. Can fixed loads be used as impedance standards or do is the higher quality sliding loads or transmission line standards required? How accurate do the standards models need to be?

Media and Standards: Is the transmission media in waveguide, coax, or some type of microstrip structure? Perhaps it is some special media that is unique. What frequency range is being used? Low frequency calibrations are easier use and more accurate. What is the cost of a calibration kit? Are there calibration kits available for this media?

Environment: Is the temperature stable? The calibration will hold much better if the temperature is controlled. Also if the environment is stable the cal will hold longer and the cal kit will last longer. The calibration time is much faster for some calibration methods than for others. Cables present a unique situation because they are not always stable as flexed and as the temperature changes. The connectors need to be kept clean and in good repair for best results.

Slide 43 CONSIDERATIONS CONTINUED

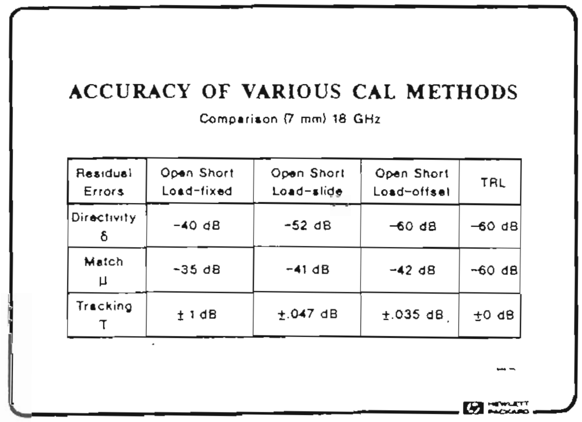


DUT Issues: If the test device is non-insertable or transitional then special calibration steps need to be taken. Different calibration methods work better for measuring high reflections than they do for low reflections. Special considerations arise when making fixtured or wafer probing measurements. Also de-embedding techniques can be used to remove previously characterized fixture errors.

Ease of Use: One of the most important questions is how easy is the calibration method to use? How long does it take to calibrate? How many steps are involved in the process? If only 1-port measurements are being made only certain calibration methods will work. What is the training investment?

All these questions can seem overwhelming! But there is really an optimum choice for most of the measurements being made today. These choices will now be discussed.

Slide 44 ACCURACY OF VARIOUS CAL METHODS



Residual Errors	Open Short Load-fixed	Open Short Load-slide	Open Short Load-offset	TRL
Directivity δ	-40 dB	-52 dB	-60 dB	-60 dB
Match µ	-35 dB	-41 dB	-42 dB	-60 dB
Tracking T	± 1 dB	±.047 dB	±.035 dB	±0 dB

This table gives a tradeoff in accuracy for various calibration methods in Coax. The example is for 7mm but can be scaled to other connector types. The relative differences stay the same. The OSL_f (open, short, load-fixed) cal is the least expensive and usually the easiest to use. The tradeoff is that it has the lowest accuracy, but this may be fine for many measurements. The OSL_s (open, short, load-sliding) is the traditional calibration that has been used for many years for accurate calibrations. It is fairly expensive and sometimes the sliding load is not as easy to use. The SSL_o (offset short, short, offset-load) provides better directivity than the sliding load but is not available in all connector types. All of the previous methods will work for one-port calibrations. The short and open determine most of the match and tracking error and this error does not change dramatically with the improved directivity values. TRL provides the best accuracy and particularly for the match and tracking terms. It is fairly easy to use but reasonably expensive. The TRL calibration method needs a two port system in order to calibrate.

Slide 45 CALIBRATION METHOD COMPARISONS

CALIBRATION METHOD COMPARISONS

Method	Coax	Wafer	WR-10	Ease	High Γ	Cost	Comments
OSL_f	C	C		A	C-	A	Simple
OSL_s	B			C	C	C	Traditional
SSL_o	B+	C	A-	B-	C	B	WG One-Port
SSL_s	B	B	B+	C	B+	C	Traditional WG
SSS	B	C	C	B+	C+	A	One Std.
TRL/LRL	A	B	A	B	A	A/C	Accurate
TRM/LRM	B	B	B	A	B	A	Easy to Use
De Embed	B	C+	C	A/C	B-	A/C	Modeling

This table is an attempt at grading various calibration methods for different applications.

A quick and to the point summary is next. The best method for low cost, easy to use coaxial calibration is the OSL_f (open, short, load-fixed) method! The most accurate calibration for coax is TRL! The best low cost and accurate method for waveguide is TRL! For one port waveguide calibration use the SSL_o (offset short, short, offset load) method. For fixtured or wafer probe systems the most accurate methods are either LRL or LRM! LRL if the desired reference impedance is the transmission line and LRM is the desired reference impedance is a resistor! The easiest method to use for fixtured of wafer probe systems is LRM!

Slide 46 CONCLUSION

CONCLUSION

Error correction methods have been refined to a high degree. And the accuracy of the various methods is understood.

HOWEVER

The hardware must be designed to be accurate and stable in order to achieve the full potential possible.

There are some very nice calibration methods that exist today. And the measurement accuracy is well understood for coax and waveguide. The most important criteria for improved performance and ease of use is RF hardware that is designed and optimized for todays measurement needs. The test equipment must be stable and have good uncorrected performance. The standards need to have mechanical precision and accurately modeled. With this combination excellent results are obtained. Then the question is to select the best calibration method to meet the measurement needs.

I would like to acknowledge the contributions of the following peers from Hewlett-Packard: Dr. Roger Pollard (also of Leeds University, U.K.) and John Barr, program manager of the 8510 Network Analyzer family.

ERROR CORRECTION GLOSSARY

ERROR CORRECTION: A complex mathematical computational process built into most network analyzers introduced since 1984 which "corrects" for imperfect hardware. Examples of imperfect hardware include couplers with less than infinite directivity and test ports that are not matched exactly to 50 ohms. Most microwave network analyzer measurements would simply not be possible without these computational procedures. Error correction is also called accuracy enhancement.

MEASUREMENT CALIBRATION: A process performed on a network analyzer once a measurement setup (cables, test fixture, frequency range) is defined. The process computes the "error coefficients" which are subsequently used to "error correct" measured data.

ERROR COEFFICIENTS: A mathematical array of complex (magnitude and phase) numbers stored within a network analyzer. One set of numbers (typically 24 coefficients) is required for each measurement frequency.

OSLT: An abbreviation for a two-port error-correction calibration procedure that determines the "error coefficients" with subsequent measurements of precisely known Open, Short, Load, and Thru calibration standards.

TRL: An alternative calibration procedure to OSLT using a thru connection, arbitrary identical reflection, and arbitrary length transmission line of known Z_o appropriate for the frequency range (Thru, Reflect Line). This calibration type is particularity suited to calibration in non-coaxial mediums. It provides the best accuracy for metrology grade measurements in coax and waveguide.

LRM: A calibration procedure using a transmission line, arbitrary identical reflection and a known load (Line, Reflect, Match). This calibration type is particularity suited to very broadband wafer-probing measurements.

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