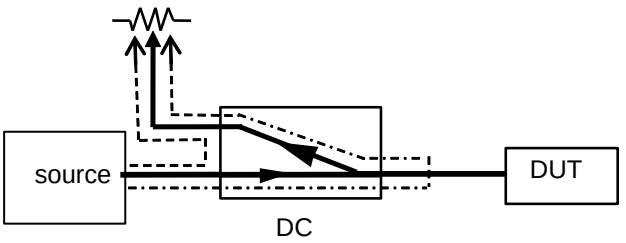
Network Analyzer Calibration

Uncertainty

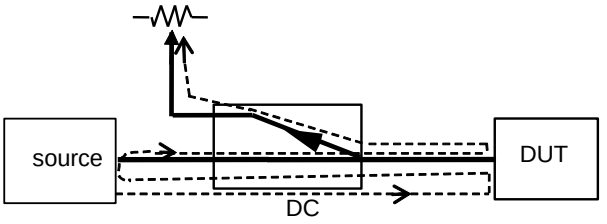
- **Random uncertainties**: due to the noise sources present in the system components (signal sources, local oscillators, detectors, receivers). As they vary in time in a random way they can be reduced with an average procedure.
- **Systematic uncertainties** (systematic errors): due to the non idealities of the components of the measurement system, these uncertainties do not change over time and can therefore be evaluated and reduced with calibration. The residual uncertainties that persist after calibration are due to imperfections in the calibration standards used.
- **Drift errors**: due to changes in the analyzer produced by changes in temperature in humidity and environmental pressure after calibration has been performed.

Error Network

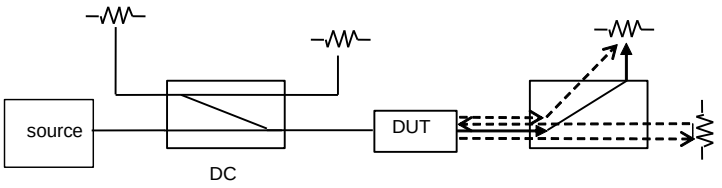
Directivity Error (D)



Source Mismatch Error (MS)



Load Mismatch Error (ML)



Other Errors

- *Frequency response error in reflection (FR)*
- *Frequency response error in transmission (FT)*
- *Crosstalk (C)*

Flow Graphs

Given a network with fixed variables (incident and reflected waves) defined at various points (ports)

Each of these variables is associated with a node (symbol •)

The nodes are connected to each other by lines oriented in the direction of the power flow (branches) (•$\xrightarrow[S_{11}]{}$•).

Each branch is associated with a value which represents the multiplicative factor it correlates the two variables at the ends of the branch (nodes).

Mason Formula

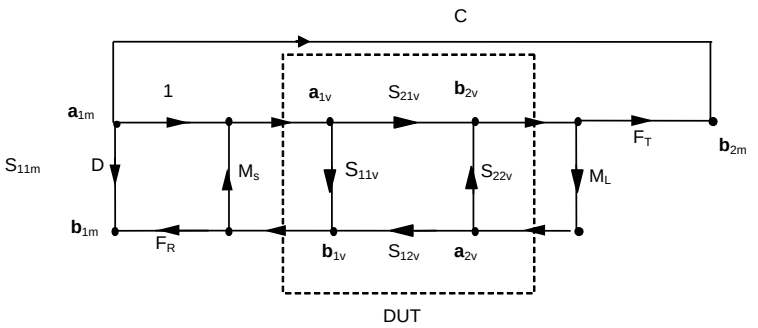
$$T_{12} = \frac{P_1\left[1-\Sigma^{(1)}L(1)+\Sigma^{(1)}L(2)-\Sigma^{(1)}L(3)+\ldots\right]+P_2\left[1-\Sigma^{(2)}L(1)+\Sigma^{(2)}L(2)-\ldots\right]+P_3[\ldots]}{1-\Sigma L(1)+\Sigma L(2)-\Sigma L(3)+\ldots}$$

Pi = value of the i-th path possible between the two nodes under examination.

ΣL (i) = sum of all possible i-th order rings

Σ (k) L (i) = sum of all possible i-th order rings no points in common with the k-th path.

Network Analyzers with Manual DUT Rotation

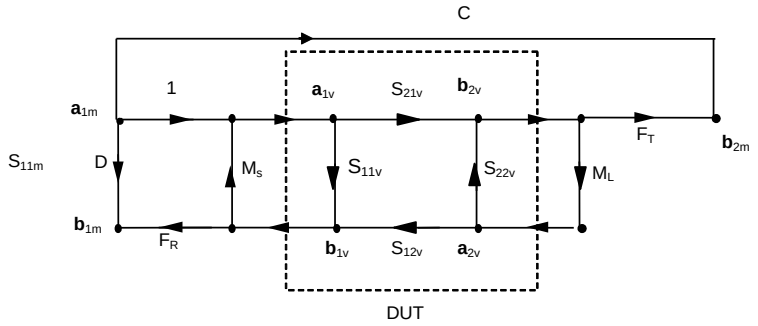


$P_1 => D \quad P_2 => F_R S_{11v} \quad P_3 => F_R S_{21v} S_{12v} M_L$

$L_1 => M_S S_{11v} \quad L_2 => M_L S_{22v} \quad L_3 => M_L S_{21v} S_{12v} M_S$

$L_2 => M_S S_{11v} M_L S_{22v}$

Network Analyzers with Manual DUT Rotation



$$S_{11m} = \frac{\mathbf{b}_{1m}}{\mathbf{a}_{1m}} = D + \frac{F_R S_{11v}(1 - M_L S_{22v}) + F_R S_{21v} S_{12v} M_L}{1 - M_S S_{11v} - M_L S_{22v} - M_L S_{21v} S_{12v} M_S + S_{11v} M_S S_{22v} M_L}$$

6 Error Parameters

$$S_{11m} = \frac{\mathbf{b}_{1m}}{\mathbf{a}_{1m}} = D + \frac{F_R S_{11v}(1 - M_L S_{22v}) + F_R S_{21v} S_{12v} M_L}{1 - M_S S_{11v} - M_L S_{22v} - M_L S_{21v} S_{12v} M_S + S_{11v} M_S S_{22v} M_L}$$

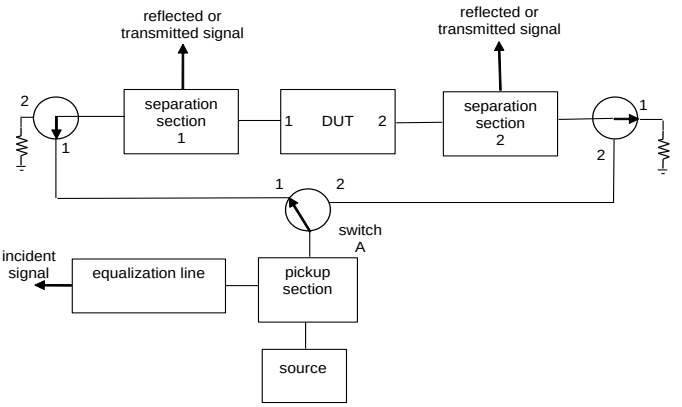
$$S_{21m} = \frac{\mathbf{b}_{2m}}{\mathbf{a}_{1m}} = C + \frac{F_T S_{21v}}{1 - M_S S_{11v} - M_L S_{22v} - M_L S_{21v} S_{12v} M_S + S_{11v} M_S S_{22v} M_L}$$

$$S_{22m} = \frac{\mathbf{b}_{2m}}{\mathbf{a}_{2m}} = D + \frac{F_R S_{22v}(1 - M_L S_{11v}) + F_R S_{21v} S_{12v} M_L}{1 - M_S S_{22v} - M_L S_{11v} - M_L S_{21v} S_{12v} M_S + S_{11v} M_S S_{22v} M_L}$$

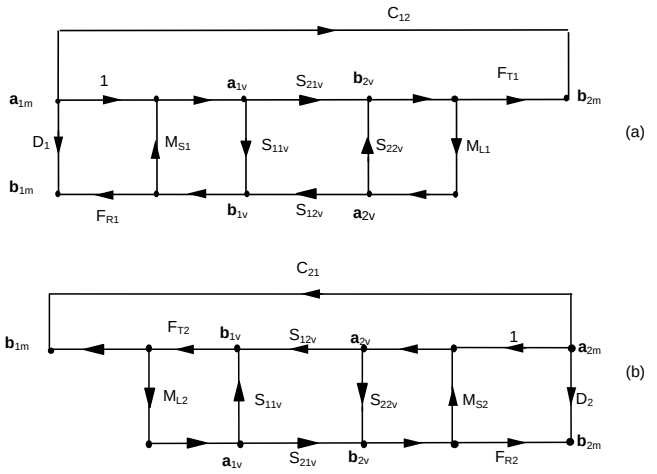
$$S_{12m} = \frac{\mathbf{b}_{1m}}{\mathbf{a}_{2m}} = C + \frac{F_T S_{12v}}{1 - M_S S_{22v} - M_L S_{11v} - M_L S_{21v} S_{12v} M_S + S_{11v} M_S S_{22v} M_L}$$

Inverting the system we get $S_{ijv} = f(S_{ijm}$, Error Par.)

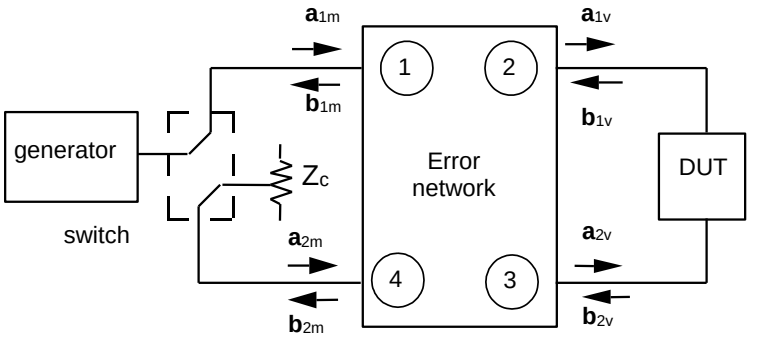
Network Analyzers with Automatic DUT Rotation



12 Error Parameters

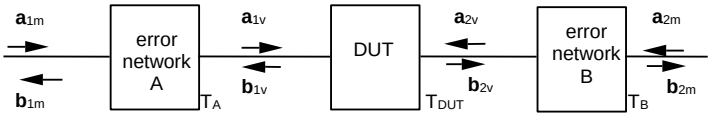


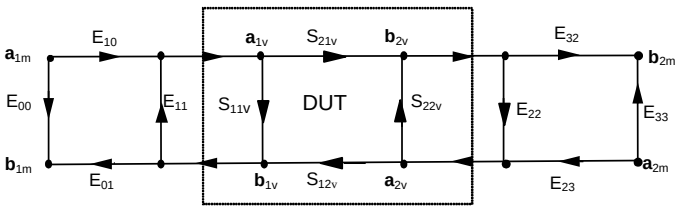
16 Error Network



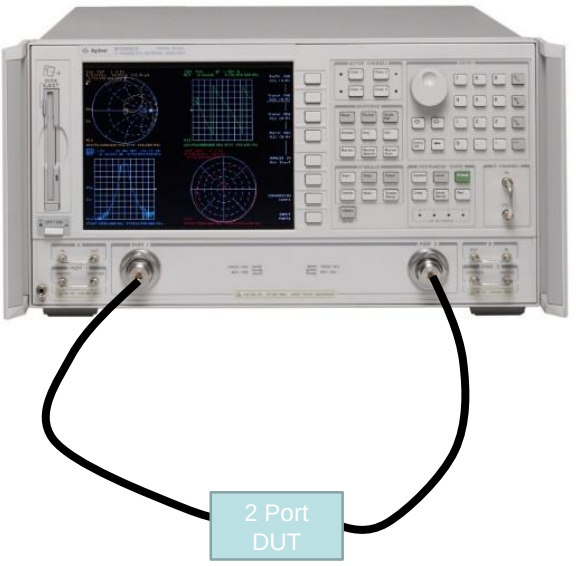
$$\begin{pmatrix} b_{1m} \\ a_{1v} \\ a_{2v} \\ b_{2m} \end{pmatrix} = \begin{bmatrix} E_{00} & E_{01} & E_{02} & E_{03} \\ E_{10} & E_{11} & E_{12} & E_{13} \\ E_{20} & E_{21} & E_{22} & E_{23} \\ E_{30} & E_{31} & E_{32} & E_{33} \end{bmatrix} \begin{pmatrix} a_{1m} \\ b_{1v} \\ b_{2v} \\ a_{2m} \end{pmatrix}$$

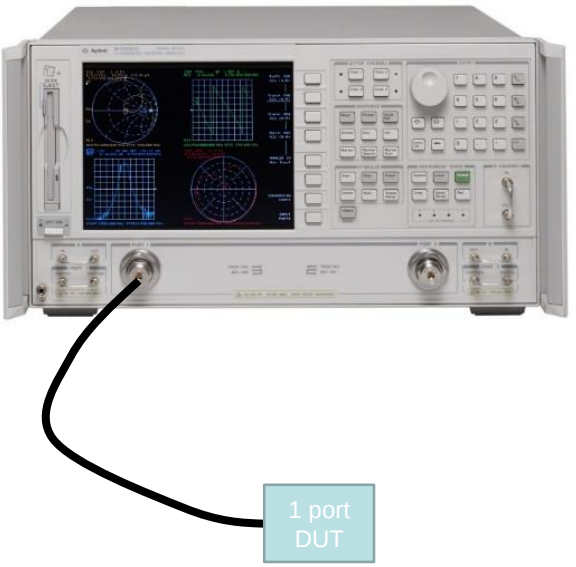
8 Error Network



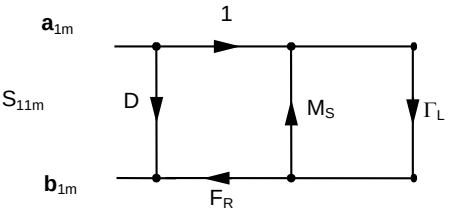


Calibration Procedure





SOLT Technique
(Short, Open, Load, Thru)



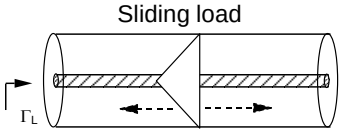
$$S_{11m} = \frac{\mathbf{b}_{1m}}{\mathbf{a}_{1m}} = D + \frac{F_R \Gamma_L}{1 - \Gamma_L M_S}$$

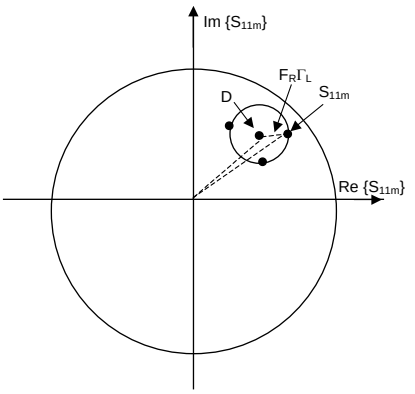
Short, Open, Load

$$S_{11m}^{(1)} = D - \frac{F_R}{1+M_S} \qquad S_{11m}^{(2)} = D + \frac{F_R}{1-M_S} \qquad S_{11m}^{(3)} = D$$

difficult to do a load perfectly matched

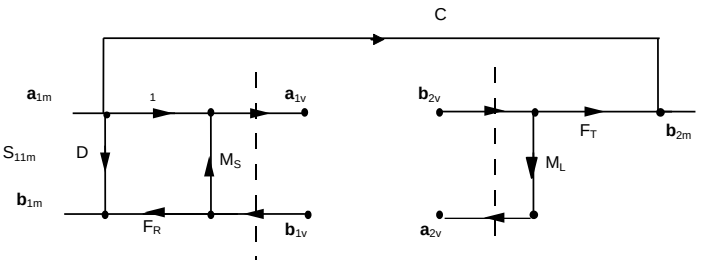
Sliding load





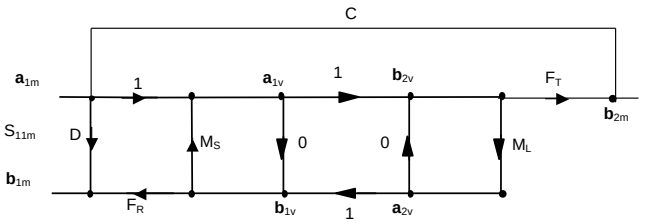
$$S_{11m}^{(1)} = D + F_R \Gamma_L$$

No load



$$S_{21m}^{(4)} = \frac{\mathbf{b}_{2m}}{\mathbf{a}_{2m}} = C$$

Thru



$$S_{21m}^{(5)} = \frac{\mathbf{b}_{2m}}{\mathbf{a}_{1m}} = C + \frac{F_T}{1 - M_L M_S}$$

$$S_{11m}^{(6)} = \frac{\mathbf{b}_{1m}}{\mathbf{a}_{1m}} = D + \frac{F_R M_L}{1 - M_L M_S}$$

8 Parameter Calibration Techniques

$$T_m = T_A T_{DUT} T_B$$

$$T_m = \left(\frac{1}{E_{10}E_{32}}\right)\begin{pmatrix} E_{10}E_{01} - E_{00}E_{11} & E_{00} \\ -E_{11} & 1 \end{pmatrix} T_{DUT} \begin{pmatrix} E_{32}E_{23} - E_{22}E_{33} & E_{22} \\ -E_{33} & 1 \end{pmatrix}$$

$$T_{M1} = T_A T_{C1} T_B \qquad T_{M2} = T_A T_{C2} T_B \qquad T_{M3} = T_A T_{C3} T_B$$

Three partially known DUTs are used

Txx Techniques

$$T_{c1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$ direct link

Through-Reflect-Line = TRL

Through-Delay-Line = TDL

Lxx Techniques

$$T_{c1} = \begin{bmatrix} \cosh\gamma l & z_0 \operatorname{senh}\gamma l \\ y_0 \operatorname{senh}\gamma l & \cosh\gamma l \end{bmatrix}$$ Transmission line

Line-Reflected-Line = LRL

Line-Reflected-Match = LRM

Conclusions

- In conclusion, the most widely used techniques are SOLT and TRL.
- The SOLT is usually preferred when measurements are to be made at low frequency and in coaxial cables, ie with components or devices accessible via coaxial connectors. In fact, in coaxial technology, and at low frequencies, it is quite simple to realize opens, shorts and mobile adapted loads.
- TRL is preferred for devices not in coaxial and at millimetric frequencies. The advantage of the TRL in these cases is related to the fact that the TRL standards are generally simpler to implement than those of SOLT. In particular, the matched load, which is difficult to accurately achieve in particular at high frequencies, is not required.

Reference technique

- A calibration technique used in some cases is that of "normalization" (reference) which consists in making a measurement with a short or an open (to calibrate reflection measurements) and with a through termination (for transmission measurements). These reference tracks are stored in the analyzer memory.
- For the short we have $|S11| = 1$ and then S11dB = 0, while with the through termination we have $|S21| = 1$ and therefore S21dB = 0.
- When the measurement is made, the DUT is inserted and the measurement of S11 and S22 is compared to that in memory. With this technique only errors related to the frequency response are corrected. There is also an improved version of this technique which consists in using as a reference for reflection the average of the measurements between a short and an open.

SOLR Technique

- Another solution for calibrating devices is to use the SOLR technique.
- This technique uses the usual short, open and matched loads for calibration, but instead of a direct connection, it uses a reciprocal component (reciprocal thru - R).
- In practice, instead of the direct connection a two-port component is used which may also be unknown (unknown thru) and which must have the only characteristic of being reciprocal and having an input-output phase shift known within 90 ° at the highest analyzed frequency, ie the group delay must be known within a quarter of a period always at the highest working frequency (an EM field in air covers about 3 mm in 10 ps).
- Although SOLR is a variant of SOLT it is based on the 8-term error model that was seen for TRL. So, like the TRL technique, it can be applied only on network analyzers with automatic DUT rotation and with 4 receivers.

Electronic Calibration Kit

- The calibration kits used in SOLT or TRL are mechanical kits, consisting of loads that must be successively tightened and disconnected from the network analyzer access connectors.
- This procedure is slow and laborious and, to guarantee a certain repeatability in the connections, it also requires the use of torque wrenches. These problems have been solved with the introduction of electronic calibration kits.
- These kits consist of a single DUT that is connected to the analyzer's ports. The DUT typically allows to select, with electronic switches, one of four standard reflective loads, and a load in transmission. The four reflective loads are connected to the two inputs of the analyzer and are used to calculate the three independent parameters of the input error network.
- In this way we have more equations than unknowns and we use a least squares fit to solve the system. Finally, it is important to remember that to ensure repeatability of the calibration the calibration DUT is thermostated.

Measurement Uncertainty

Sistematic Error on S_{11}

$$\Delta_{11} = S_{11m} - S_{11v}$$

$$\Delta_{11} \cong D + \frac{F_R S_{11v}(1 - M_L S_{22v}) + F_R S_{21v} S_{12v} M_L}{(1 - M_L S_{22v} - M_S S_{11v})} - S_{11v}$$

$$\Delta_{11} \cong D + (F_R - 1) S_{11v} + M_L S_{12v} S_{21v} + M_S S_{11v}^2$$

Sistematic Error on S_{21}

$$\Delta_{21} = S_{21m} - S_{21v}$$

$$\Delta_{21} \cong C + \frac{F_T S_{21v} - S_{21v} F_T (1 - M_L S_{22v} - M_S S_{11v})}{(1 - M_L S_{22v} - M_S S_{11v})}$$

$$\Delta_{21} \cong C + (F_T - 1) S_{21v} + M_S S_{21v} S_{11v} + M_L S_{21v} S_{22v}$$

EXAMPLE: No Calibration

- Typical values for an uncalibrated network analyzer are:
- D = 30 dB (0.03); MS = 20 dB (0.1); ML = 20 dB (0.1); FR = 1.5 dB (1.19); FT = 0.2 dB (1.023); C = 90 dB (3·10-5).

- If we consider a one-port device with S11v = -12 dB (0.25); S21v = S12v = S12v = 0 dB. In the worst case scenario in which all the errors add up you will have:

$$\Delta 11 = 0.03 + 0.19 \cdot 0.25 + 0.1 \cdot 0.25 \cdot 0.25 = \pm 0.084$$

- So S11m can vary between S11v + Δ 11 = 0.334 (-9.5 dB) to S11m - Δ 11 = 0.166 (-16 dB).

D (dB) = 20 LOG10 (1 / D)
MS (dB) = 20 LOG10 (1 / MS)
FR (dB) = 20 LOG10 (FR)

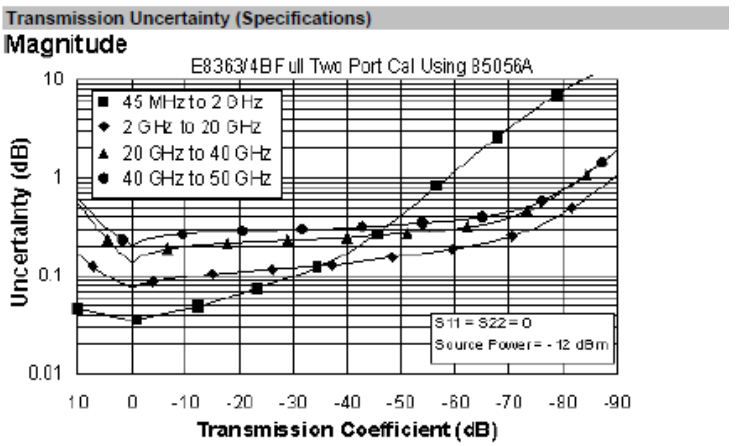
EXAMPLE: with calibration

- Typical values for a calibrated network analyzer are:
  D = 50 dB (0.0032); MS = 40 dB (0.01);
  ML = 40 dB (0.01); FR = 0.05 dB (1.006);
  FT = 0.08 dB (1.069); C = 100 dB (10-5).
- Assuming the worst case in which all the errors add up you will have:

$$\Delta 11 = \pm 0.005$$

- So after the calibration S11m varies between 0.255 (-11.87 dB) and 0.245 (-12.22 dB).
- As you can see there has been a noticeable improvement in the uncertainty of the measure. In general, improvements in uncertainty can be obtained even by 99% depending on this factor also from the absolute value of the parameter under examination.

Uncertainty Graph



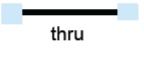
Calibration and error correction

Errors and Calibration Standards

UNCORRECTED

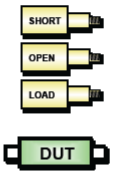
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



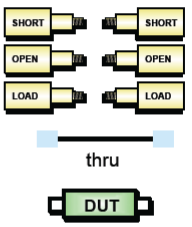
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

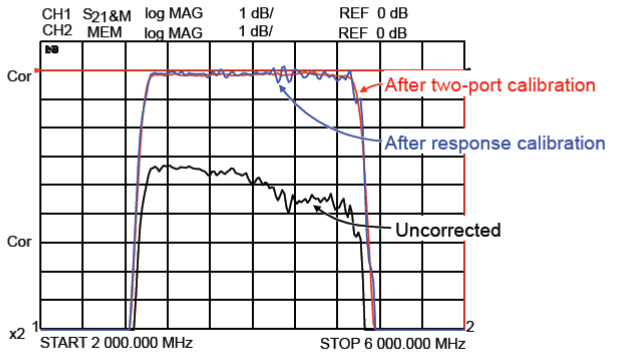
ENHANCED-RESPONSE

- Combines response and 1-port
- Corrects source match for transmission measurements

Agilent Technologies

Response versus Two-Port Calibration

Measuring filter insertion loss



Agilent Technologies

Network Analyzers
FUNCTIONS

STIMULUS

- **Frequency (grid with 10 divisions)**
  - START (Value , Unit of measure)
  - STOP (Value , Unit of measure)
  - CENTER (Value , Unit of measure)
  - SPAN (Value , Unit of measure)
- **Power**
  - dBm (Source power i.e. -10 dBm)
  - Start – Stop (For measurements with power on the x axis)
- **Sweep**
  - Number of Points (i.e. 1601)
  - Time

RESPONSE

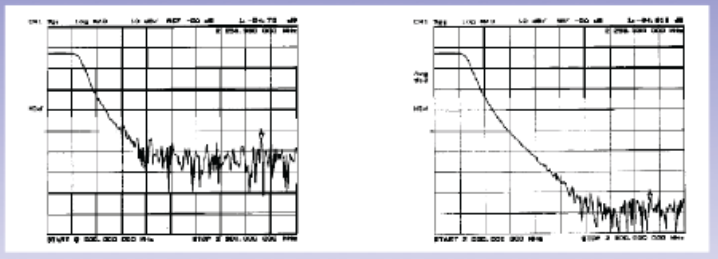
- **Measure**
  - S11, S21, S12, S22
- **Format**
  - (LogMag, Phase, Unwrapped, Smith Chart, LinMag, Real, Imaginary)
- **Scale (grid with 10 divisions)**
  - Autoscale
  - Per division (i.e. 10 dB/div)
  - Reference
    - Level (i.e. 0 dB)
    - Position (i.e. 5 div)
  - Electrical delay (secondi)
  - Phase offset (deg)

RESPONSE

- **Average**
  - Averaging Factor (i.e. 10, 20, etc)
  - Smoothing
    - % of point (i.e. 5%)
    - Points (5, 10 etc)
  - IF Bandwidth (i.e. 1 Hz – 40 kHz)

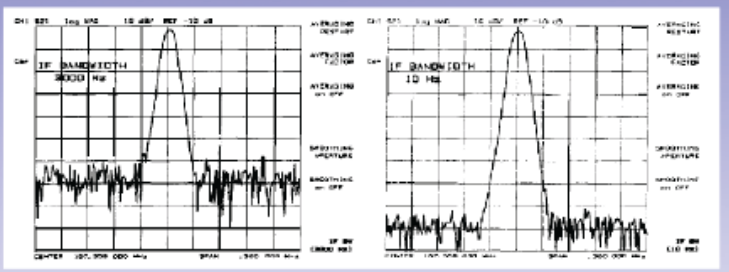
- **Data Memory**
  - Data
  - Memory
  - Data and Memory

Averaging trace



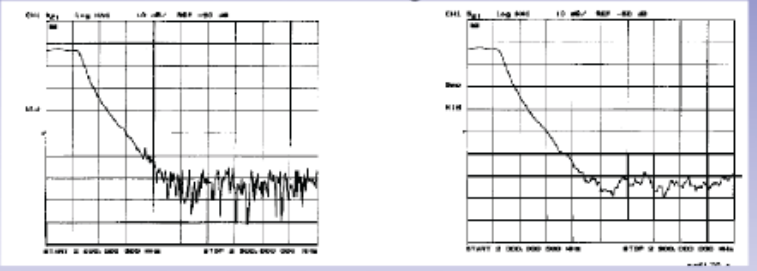
Averaging computes each data point based on an exponential average of consecutive sweeps weighted by a user-specified averaging factor. Each new sweep is averaged into the trace until the total number of sweeps is equal to the averaging factor, for a fully averaged trace. Each point on the trace is the vector sum of the current trace data and the data from the previous sweep. A high averaging factor gives the best signal-to-noise ratio, but slows the trace update time. Doubling the averaging factor reduces the noise by 3 dB.

IF BW reduction



IF bandwidth reduction lowers the noise floor by digitally reducing the receiver input bandwidth. It works in all ratio and non-ratio modes. It has an advantage over averaging as it reliably filters out unwanted responses such as spurs, odd harmonics, higher frequency spectral noise, and line-related noise. Sweep-to-sweep averaging, however, is better at filtering out very low frequency noise. A tenfold reduction in IF bandwidth lowers the measurement noise floor by about 10 dB. Bandwidths less than 300 Hz provide better harmonic rejection than higher bandwidths.

Smoothing trace



Smoothing (similar to video filtering) averages the formatted active channel data over a portion of the displayed trace. Smoothing computes each displayed data point based on one sweep only, using a moving average of several adjacent data points for the current sweep. The smoothing aperture is a percent of the swept stimulus span, up to a maximum of 20%.

Rather than lowering the noise floor, smoothing finds the mid-value of the data. Use it to reduce relatively small peak-to-peak noise values on broadband measured data. Use a sufficiently high number of display points to avoid misleading results. Do not use smoothing for measurements of high resonance devices or other devices with wide trace variations, as it will introduce errors into the measurement.

Cal (Calibration)

- **Calibration**
  - **Before calibrating, check that the correct kit is selected**
  - Response
  - 1 Port
  - 2 Port
    When connecting loads, we must also say the sex (male or female)
  - Once the calibration is done, you must save the file
    - Check that Correction ON is displayed
    - Interpolation ON / OFF

Marker

- **Marker**
  - Marker 1, Marker 2, etc.
    - You can make one REF markers and others give variations
- **Marker function**
  - Marker center, start stop , etc.
    - change the x scale to bring the marker where selected
- **Marker Search**
  - Max, Min, Next Peak, Bandwidth, etc..

Transform

- **Modality**
  - Low pass impulse
  - Low pass STEP
  - Bandpass
- **Set frequency low pass**
  - For the two Low pass modes you must set the stop and the number of points and select ‘set frequency low pass’ so the system chooses the equidistant frequency points
- **Window**
  - maximum, normal, minimum
- **Gating**
  - Star, stop, center, span

Conversion

- **Conversion Equation**
  - Select or write the conversion equation