ELEC 411 - Antennas and Propagation

# Module 1A
# RF Test & Measurement

## Introduction to VNAs





- During these lectures, the instructor will bring up many points and details not given on these slides. Accordingly, it is expected that the student will annotate these notes during the lecture.
- The lecture only introduces the subject matter. Students must complete the reading assignments and problems if they are to master the material.

# Introduction

- After an antenna has been designed and constructed, we usually need to evaluate its performance.
- On one hand, we may need to determine the input impedance of the antenna over its operating range.
- On the other hand, we may need to determine the power transmitted from one antenna to another, either to measure the antenna's radiation pattern or to characterize the propagation environment.
- In both cases, the *Vector Network Analyzer* is often the instrument of choice.





# Objectives

Upon completion of this module, the ELEC 411 student will be able:

- to recount the differences between signal analysis and system characterization.
- to describe and explain the function, architecture, and operation of VNAs.
- to describe and explain alternative ways to interpret VNA response data.
- to describe and explain how calibration and error correction can improve measurement accuracy.
- to describe and explain typical application of VNAs in antennas and propagation.

# Outline

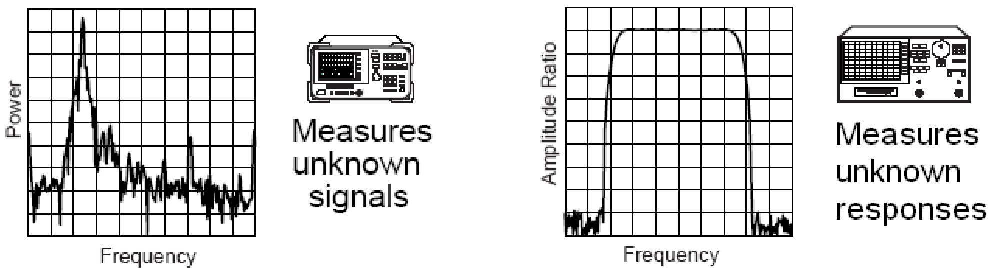
1. Spectrum Analyzers vs. Network Analyzers
2. The Vector Network Analyzer Concept
3. S-parameters
4. Interpreting Vector Network Analyzer Response Data
5. Vector Network Analyzer Calibration
6. Applications of VNAs in Antennas and Propagation





# 1. Spectrum Analyzers vs. Network Analyzers

- One broad class of RF/microwave test and measurement equipment includes instruments designed to measure the properties of signals, *e.g.*,
  - power meter
  - spectrum analyzer
  - vector signal analyzer
- Another broad class includes "stimulus-response" test sets designed to measure the properties of systems, *e.g.*,
  - spectrum analyzer with tracking generator
  - **vector network analyzer**
  - noise figure meter
  - distortion analyzer




**Spectrum analyzers:**
- measure signal amplitude characteristics (carrier level, sidebands, harmonics, etc.)
- can demodulate (& measure) complex signals
- are receivers only (single channel)
- can be used for scalar component test (no phase) with tracking gen. or ext. source(s)

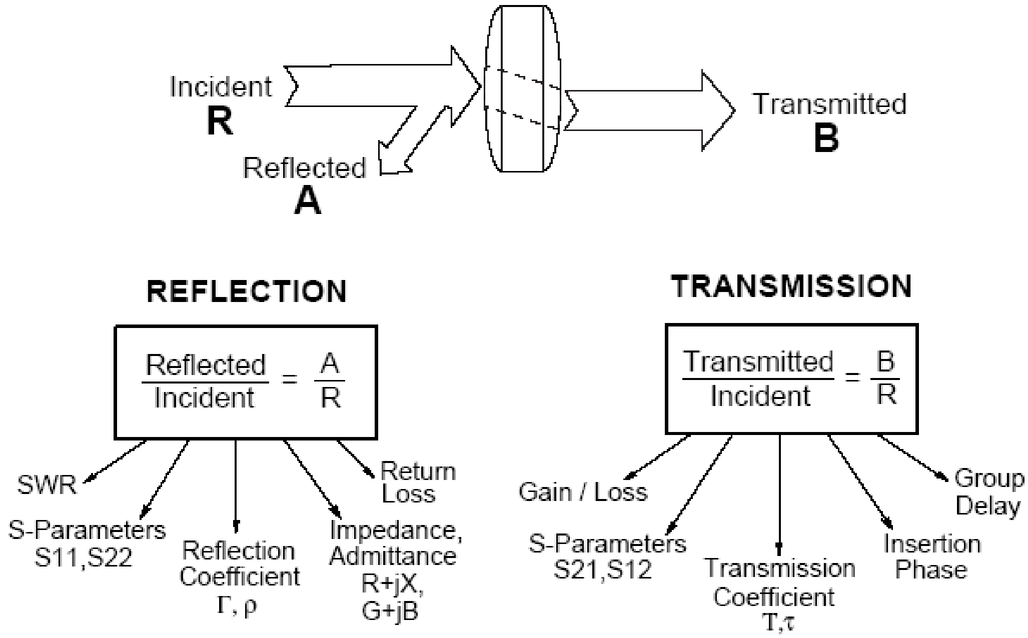
**Network analyzers:**
- measure components, devices, circuits, sub-assemblies
- contain source and receiver
- display ratioed amplitude and phase (frequency or power sweeps)
- offer advanced error correction





# 2. The Vector Network Analyzer Concept

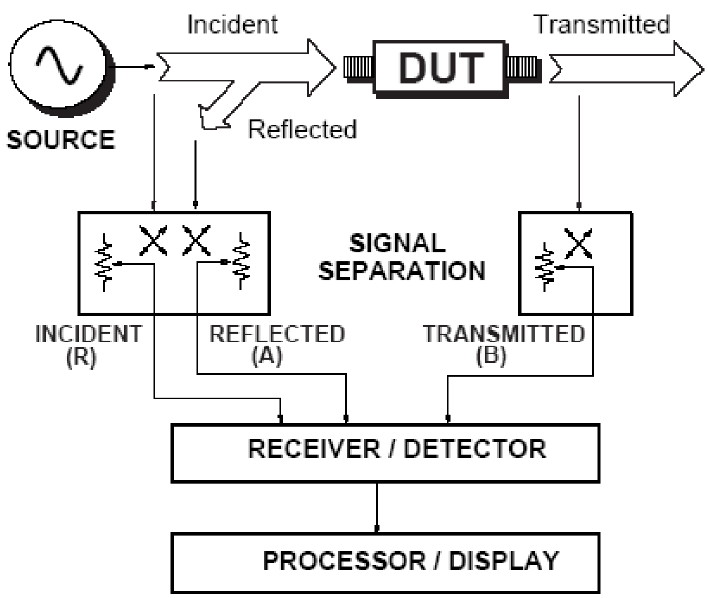
- Vector network analyzers characterize a two-port network by applying a test signal to a device and measuring the amplitude and phase of a signal reflected from or transmitted through the device over a specified range of frequencies.
- *cf.* spectrum analyzer with tracking generator (transmission only, no phase) and scalar network analyzer (transmission and reflection but no phase)








# Architecture of a Vector Network Analyzer



# Vector Network Analyzer Response Data

A vector network analyzer returns the following response data as a function of frequency:

- $A$ - signal on channel $A$ (reflection), usually expressed in dBm
- $B$ - signal on channel $B$ (transmission), usually expressed in dBm
- $B/R$ - return loss of channel $A$, usually expressed in dB
- $A/R$ - gain of channel $A$, usually expressed in dB

In order to completely characterize the response of the DUT, we need to insert a module that contains two-way switches that allow these parameters to be measured in both directions. Such a module is referred to as an S-parameter test set.





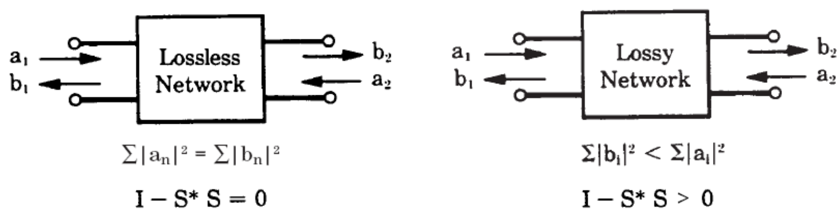
# Vector Network Analyzer Settings

Some of a VNA's instrument setting are similar to those of a spectrum analyzer, but some are different:

- start and stop frequency
- output power
- S-parameter to display - $S_{11}$, $S_{12}$, $S_{21}$, $S_{22}$
- derived quantity to display - Gain, Gain(dB), Phase, VSWR, *etc.*
- type of plot - rectangular, polar, Smith chart
- scale and reference level

# 3. S-Parameters

- S-parameters are yet another way to characterize linear time-invariant two-ports; *cf.* z, y, g and h-parameters.
- Because they are expressed in terms of the amplitude and phase of the voltage of travelling waves incident upon, reflected from, and emitted by each of the ports, they are compatible with the transmission line approach and well suited for use at RF and microwave frequencies.
- If we know the characteristic impedance of the line, we can convert the voltages to power.








- If $a$ and $b$ are complex numbers that give the amplitude and phase of the incident and reflected waves, the S-parameters are formally defined as:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$\begin{aligned} S_{11} &= \frac{b_1}{a_1}|_{a_2=0} = \Gamma_1, \text{the input reflection coefficient} \\ S_{21} &= \frac{b_2}{a_1}|_{a_2=0} = \tau_{21}, \text{the forward transmission coefficient} \\ S_{22} &= \frac{b_2}{a_2}|_{a_1=0} = \Gamma_2, \text{the output reflection coefficient} \\ S_{12} &= \frac{b_1}{a_2}|_{a_1=0} = \tau_{12}, \text{the reverse transmission coefficient} \end{aligned}$$

- In all cases, the opposite port of the device must be properly terminated (attached to a load with $Z_L$ equal to the complex conjugate of its output impedance) when its S-parameters are measured.

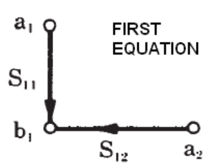
## Representation of S-Parameters Using Signal Flow Graphs

- It is convenient to use signal flow graphs to follow incident and reflected waves throughout a network:
  - Each variable, *e.g.*, $a_1$, $a_2$, $b_1$, and $b_2$, will be designated as a node.
  - Branches enter dependent variable nodes and emenate from independent variable nodes.
  - Each node is equal to the sum of the branches entering it.
- Such a representation is applicable to many aspects of RF/microwave analysis, including amplifier design, network design, and modelling of sources of error in VNAs.
- Signal flow graphs are particularly useful as one cascades networks or adds feedback paths.

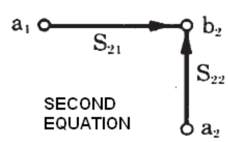




## Example: Representation of an S-Matrix Using Signal Flow Graphs

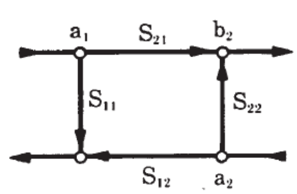



$b_1 = S_{11}\, a_1 + S_{12}\, a_2$




$b_2 = S_{21}\, a_1 + S_{22}\, a_2$

COMPLETE FLOW GRAPH




$b_1 = S_{11}\, a_1 + S_{12}\, a_2$
$b_2 = S_{21}\, a_1 + S_{22}\, a_2$

# S-parameters of Standard One and Two-Port Devices

- a matched load: $S_{11} = 0$
- a short circuit: $S_{11} = -1$
- an open circuit: $S_{11} = 1$
- an ideal transmission line of zero length:

$$[S] = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

- Exercise: Draw their signal flow graph representations.





# Changes in the Reference Plane

- S-parameters are transformed as one moves the measurement plane away from or towards the device under test.
- If we add a length of transmission line $\ell_1$ to port 1 and a length $\ell_2$ to port 2, then

$$[S'] = [\Phi][S][\Phi]$$

where

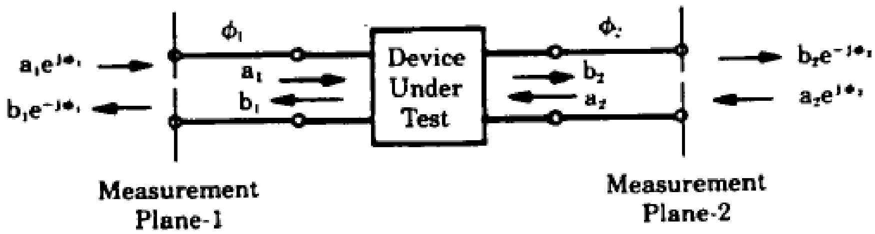
$$[\Phi] = \begin{bmatrix} e^{-j\beta\ell_1} & 0 \\ 0 & e^{-j\beta\ell_2} \end{bmatrix} = \begin{bmatrix} e^{-j\phi_1} & 0 \\ 0 & e^{-j\phi_2} \end{bmatrix}$$

- Note that $[\Phi]$ is *not* an S-matrix. It is a *distortion matrix*.
- Exercise: If you multiply through, you'll re-discover some familiar transmission line relationships!

# Effect of Changes in Reference Plane on the S-matrix

- Exercise: What value of $[S']$ would one measure at the end of the transmission lines in terms of the value $[S]$ as measured at the device ports?

- Exercise: Given the measured value $[S']$, how would one recover the value of $[S]$ that would be seen at the device ports?

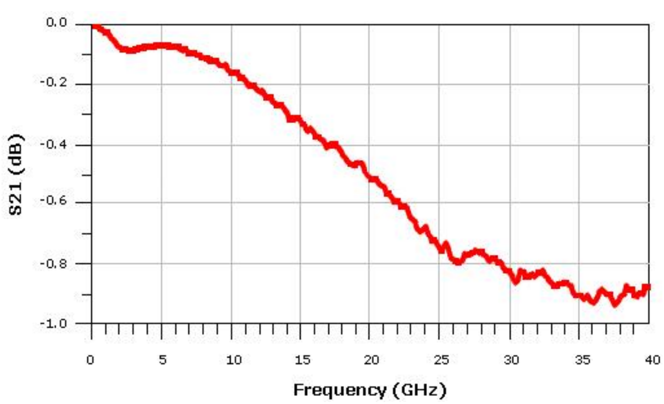







# 4. Interpreting Network Analyzer Response Data

- Interpreting transmission response data is fairly straightforward.
- We usually present such data as a rectangular plot of magnitude (in dB) or phase (in deg) *vs.* frequency.



# Group Delay

- Most network analyzer also allow one to display the *group delay* associated with transmission response.
- Group delay is a measure of how long it takes a signal, *e.g.,* a pulse, to traverse a network. It may be regarded as the transit time of the signal.
- Group delay through a device or transmission medium is defined as the rate of change of the total phase shift with respect to angular frequency, $d\theta/d\omega$.
- While the group delay of a TEM transmission line is constant with frequency, the group delay of a waveguide or filter is not.
- If different frequency components have different group delays, the network is said to be *dispersive.* This leads to distortion of pulses (or other signals) that travel through the network.





# Time Domain Characterization

- Because VNAs measure the frequency response of the DUT (in discrete steps), it should be possible to determine the impulse response simply by taking the IDFT. (In other cases, we might use an IFFT. Here, the chirp-Z transform is most often used. Why?)
- There's a catch: a frequency response of finite width is actually the entire frequency response multiplied by a rect function of appropriate span and centre frequency.
- This implies that the impulse response that we calculate is actually the true impulse response convolved with the sinc function obtained by taking the IDFT of the rect function.
- In order to yield the true impulse response, one must deconvolve the sinc function from the "measured" impulse response. (How do we do this?)

# Time Domain Gating

- Sometimes, the frequency response that we measure, *e.g.*, on a non-ideal antenna range, is frequency selective due to the presence of unwanted echos and reflections in the transmission path. These can often be removed by *time domain gating.*
- First, we transform the frequency response into an impulse response by taking the IDFT. Because we're going to transform the result back into the frequency domain later, we can skip the deconvolution step.
- Next, we set all portions of the impulse response after the initial spike to zero.
- Finally, we DFT the impulse response to yield a time-gated frequency response in which unwanted echoes and reflections have been suppressed.





# Reflection Data

- One can plot the voltage reflection coefficient, $|\Gamma|$; the return loss, $1-|\Gamma|^2$; or the voltage standing wave ratio, $s = \dfrac{1+|\Gamma|}{1-|\Gamma|}$ on a rectangular plot *vs.* frequency.
- Because phase information is particularly helpful when interpreting response data, it's often useful to plot complex $\Gamma$ on a polar plot. Although we lose an explicit frequency scale in the process, one can use markers to good advantage here.
- If one superimposes a Smith chart onto the $\Gamma$ plane, one can read the value of the load impedance directly off the display.

# The Smith Chart

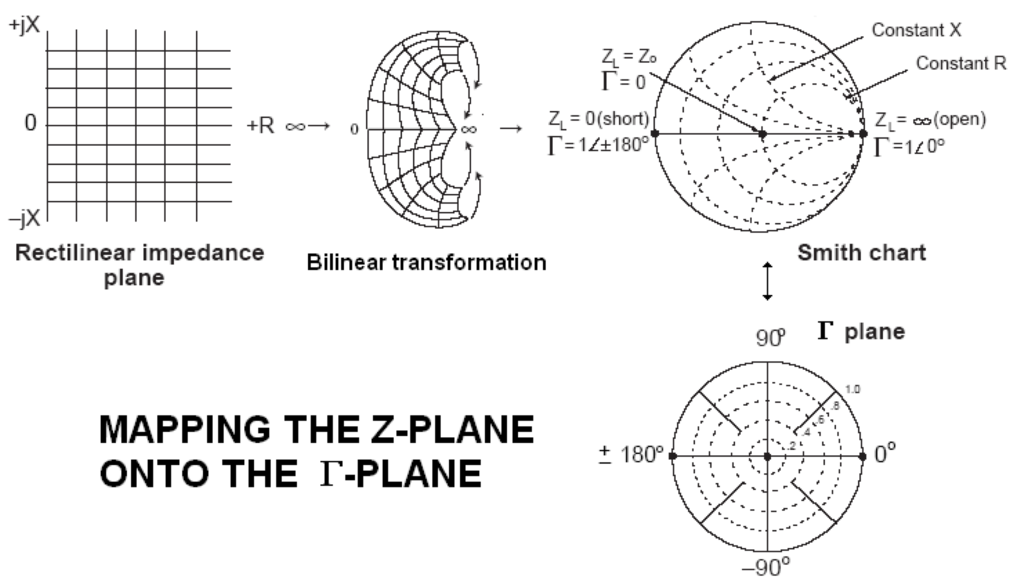
- The Smith chart was developed in the 1930's by Phillip Smith, a Bell Labs engineer.
- The Smith chart is simply a mapping from the Z (or impedance) plane onto the $\Gamma$ (or reflection coefficient) plane.
- Any given value of (normalized) load impedance on the chart is at the location that gives the corresponding complex reflection coefficient, *i.e.*,

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\hat{Z}_L - 1}{\hat{Z}_L + 1}, \ \ \hat{Z} = Z/Z_0$$

- This conformal mapping is immediately recognized as a *bilinear transformation*.





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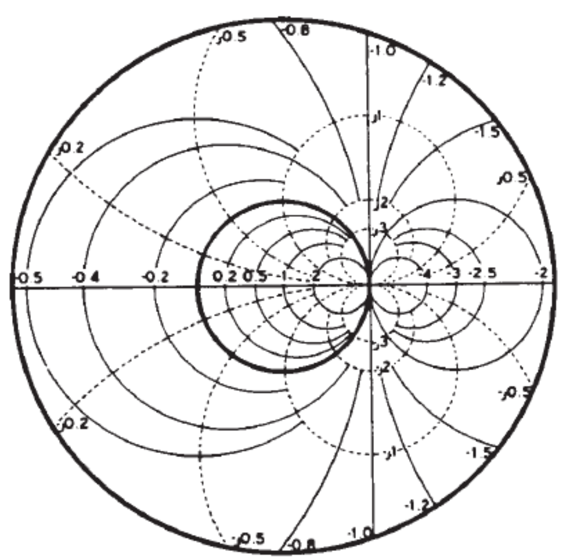
- Because the mapping is a bilinear transformation, lines of constant resistance and reactance in the $z$-plane are transformed into circles of different radii in the $\Gamma$-plane.
- Because the mapping is conformal, resistance circles and reactance circles are everywhere orthogonal to each other.
- Because $\Gamma(\ell)$ describes a circle with constant radius, the Smith chart permits one to easily visualize the manner in which $Z$ is transformed as one moves either forward or backward along a transmission line.
- As a consequence of Foster's reactance theorem, $Z$ tends to traverse the reflection plane in a clockwise direction as frequency increases.
- The conventional Smith chart lies within the circle defined by $|\Gamma| = 1$ or $R = 0$. The region beyond $|\Gamma| = 1$ corresponds to cases where resistance is negative.





# The Smith Chart beyond $|\Gamma| = 1$



# 5. Vector Network Analyzer Calibration

- All measurement systems, including vector network analyzers, may be affected by three types of measurement errors.
  - systematic errors
  - random errors
  - drift errors
- Systematic errors can be characterized through calibration and removed mathematically.
- Random errors cannot be removed through calibration, but can be reduced by improving SNR and employing averaging techniques.
- Drift errors are mostly due to temperature-related effects and can be often be controlled through: (1) attention to the environment, (2) use of temperature controlling or compensating mechanisms, and, possibly, (3) through specialized calibration and error correction.





# Systematic Errors

Systematic errors in the response of a VNA:

- are caused by imperfections in the test equipment, cables and adapters
- are related to signal leakage, signal reflections, and frequency response:
  - directivity and cross-talk
  - source and load impedance mismatch
  - frequency response errors (reflection and transmission)
- can be removed through calibration and error correction.

# Random Errors

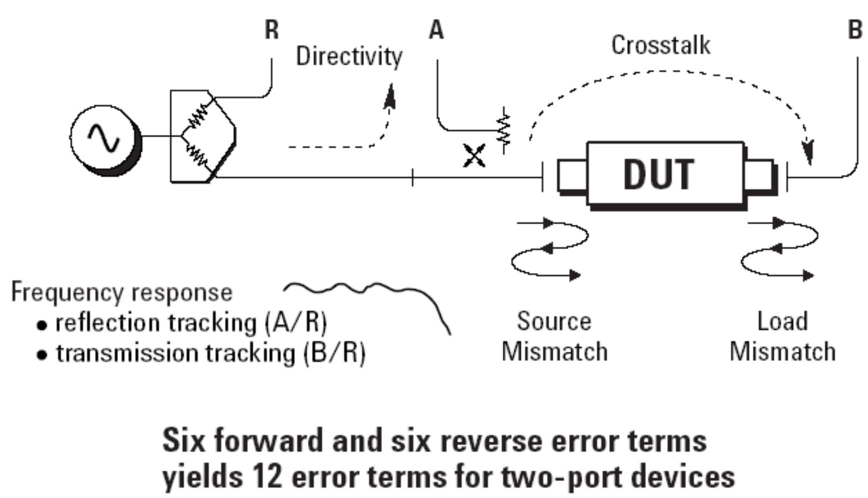
Random errors in the response of a VNA:

- are mostly caused by instrument noise, switch repeatibility and connector repeatability
- can often be reduced by: (1) increasing source power, (2) narrowing the IF bandwidth, or (3) by using trace averaging over multiple sweeps;
- cannot be removed through calibration and error correction.





# Sources of Error in Network Analyzer Measurement



# A Simplified Model for Vector Error Correction

- The effect of non-ideal directional coupler directivity, source match, reflection tracking, load match, and transmission tracking can be accounted for by pre- and post multiplying [S] by distortion matrices.
- If

$$[S_m] = [R][S][T]$$

then

$$[R]^{-1}[S_m][T]^{-1} = [R]^{-1}[R][S][T][T]^{-1}$$

and

$$[S] = [R]^{-1}[S_m][T]^{-1}$$

- How to determine $[R]$ and $[T]$?
- If $[S]$ is known because the device is a standard and $[S_m]$ is known through measurement, we can solve for the elements of $[R]$ and $[T]$.





# Alternative Calibration Methods

- It is not sufficient to measure a single calibration standard because there are too many unknowns.
- Typically, four standards are measured: short, open, matched load, and through-line, hence the moniker SOLT method.
- It is fairly easy to calibrate to a coaxial connector, but much more difficult to calibrate to a wafer probe or other non-standard test fixtures.
- Accordingly, development of error models, calibration standards, and algorithms for determing the coefficients of error models appropriate for use with different test fixtures was an area of particularly intense activity during the 1970's and 80's.

# Calibration Options

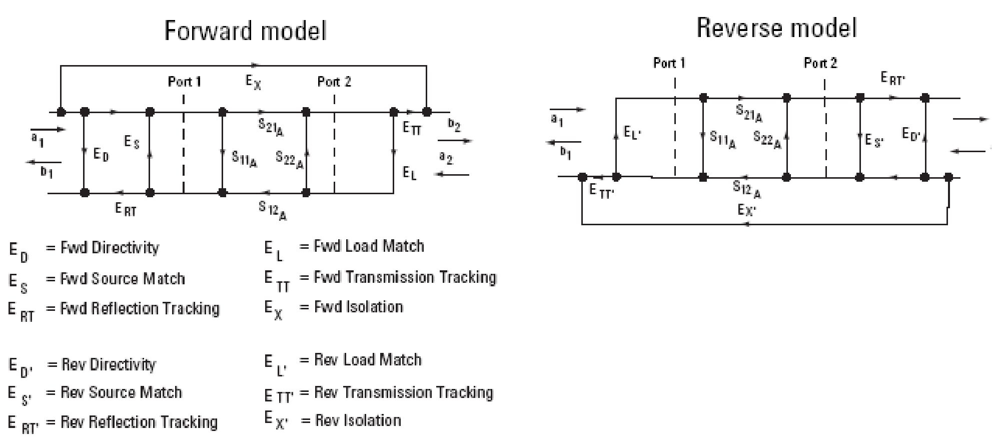
- In practice, one typically has three calibration options:
  - full twelve-term error model
  - frequency response only
  - reflection only.
- Full twelve-term error model: measure the response of: (1) a short and open on ports 1 and 2, respectively; (2) an open and short on ports 1 and 2, (3) a matched load on both, and finally, (4) the through response.
- Frequency response: measure the through response only.
- Reflection only: measure (in sequence) the response of a short, open, and matched load.





# The Twelve-Term Error Model

- The twelve-term error model has emerged as a standard method for calibrating VNAs. The closed form expressions for recovering $[S_a]$ given $[S_m]$ are given on the next slide.



$$S_{11_a} = \frac{\left(\frac{S_{11m} - E_D}{E_{RT}}\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

$$S_{21_a} = \frac{\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} (E_S' - E_L)\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

$$S_{12_a} = \frac{\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)\left(1 + \frac{S_{11m} - E_D}{E_{RT}} (E_S - E_L')\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

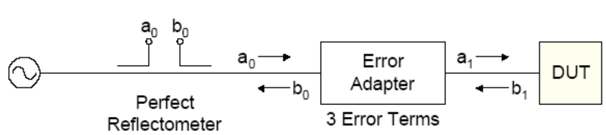
$$S_{22_a} = \frac{\left(\frac{S_{22m} - E_D'}{E_{RT}'}\right)\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right) - E_L' \left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

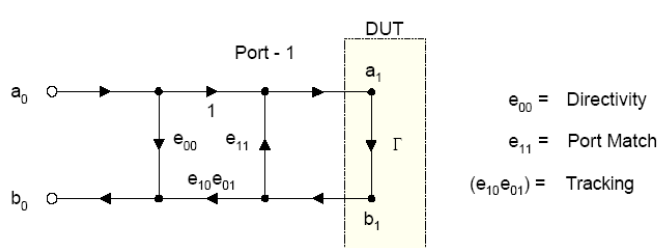




# One Port Calibration

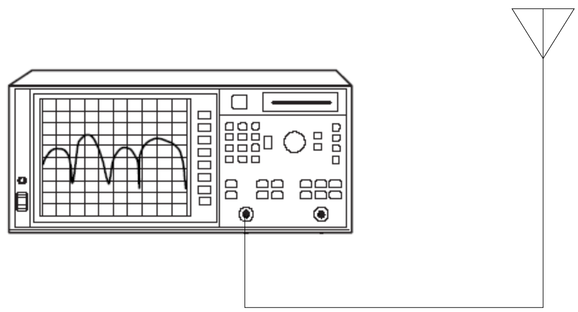
- In the problem set, we'll consider a subset of the twelve-term error model that applies to reflection (impedance) measurements only.



# 6. Applications of VNAs in Antennas and Propagation

- Measurement of input impedance is often the critical first step in assessing the performance of an antenna.
- During measurement, there must be adequate clearance to ensure that the antenna is not affected by objects impinging of the reactive near field or reflections from nearby structures.



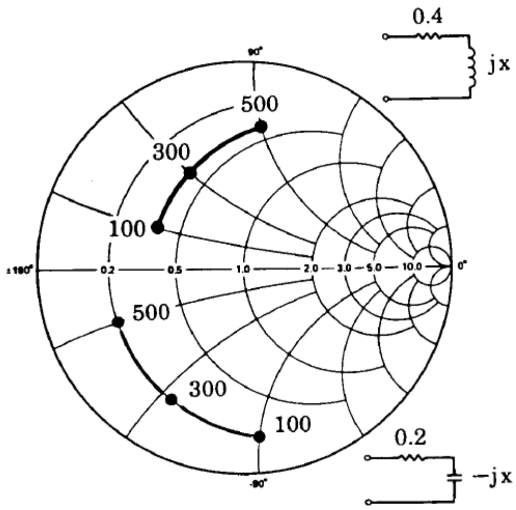


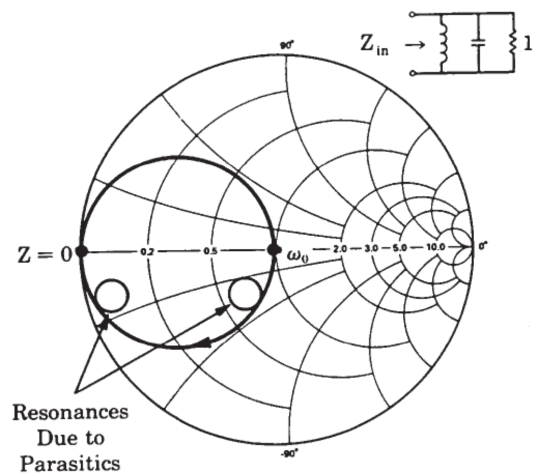


# Interpreting the Response

- Obvious results: input impedance and return loss/VSWR/reflection coefficient at each frequency.
- Derived parameters: bandwidth, Q-factor, coupling coefficient.
- As noted earlier, the driving point impedance of a network generally shifts clockwise around the Smith Chart as frequency increases. This is a consequence of Foster's reactance theorem.
- Lossy resonant circuits describe loops that encircle prime ($Z = 1$) (overcoupled), touch prime (critically coupled), or fall short of prime (undercoupled)

# $Z_{\mathbf{in}}$ of Reactive and Resonant Circuits



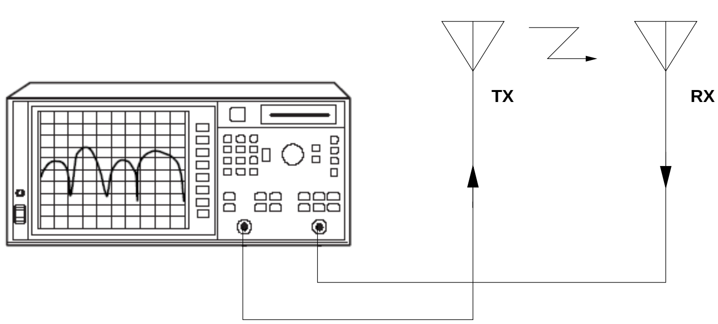








# Measurement of Path Loss Between Two Antennas

- The frequency response gives the loss (or gain) between the transmission and reception measurement planes.
- The technique is usually limited to fairly short distances (10's of metres) because the transmitter and receiver must be connected by cable (although extraordinary steps, such as use of "RF over fibre optics" technology, can be taken to extend the range).



# Intepreting the Response

- If the gains of both antennas are known, the frequency response can be averaged so that the broadband pathloss (or, if more appropriate, the isolation between the antennas) can be estimated.
- If the separation between the antennas is known, the channel is free from multipath, and the gain of one of the antennas is known, the gain of the other antenna can be estimated.
- The frequency response can be processed using Fourier techniques to yield the impulse response of the channel.
- This may be of interest in its own right (channel modelling) or may be used to eliminate unwanted multipath scatter (time domain gating).





# Summary

- The vector network analyzer (VNA) has been an essential tool for RF, microwave, and antenna engineers for over three decades.
- Formally described as stimulus-response test set, it allows one to apply a test signal to a device and measure the amplitude and phase of a signal reflected from or transmitted through the device over a specified range of frequencies.
- This allows one to derive a multiplicity of useful parameters, including return loss, VSWR, input impedance, gain, loss, frequency response, phase response, *etc.*
- Whether one is measuring the input impedance of an antenna, the radiation pattern of an antenna, coupling between two antennas, characteristics of an indoor propagation channel, or properties of materials, the VNA is an essential tool.

# References


[1] "RF Network Analysis Basics - A Computer-based Tutorial," Agilent.

[2] R. Nelson, "How does a Smith Chart work?" *Test and Measurement World,* Jul. 2001.

[3] "S-Parameter Design," Agilent AN 154, chap. 1-2.

[4] "Understanding the Fundamental Principles of Vector Network Analysis," Agilent AN 1287-1.

[5] "Exploring the Architecture of Network Analyzers," Agilent AN 1287-2.

[6] "Applying Error Correction to Network Analyzer Measurements," Agilent AN 1287-3.

[7] "Network Analyzer Measurements: Filter and Amplifier Examples," Agilent AN 1287-4.