IEEE SW Test Workshop

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Comparison of Various RF Calibration Techniques in Production: Which is Right for You?

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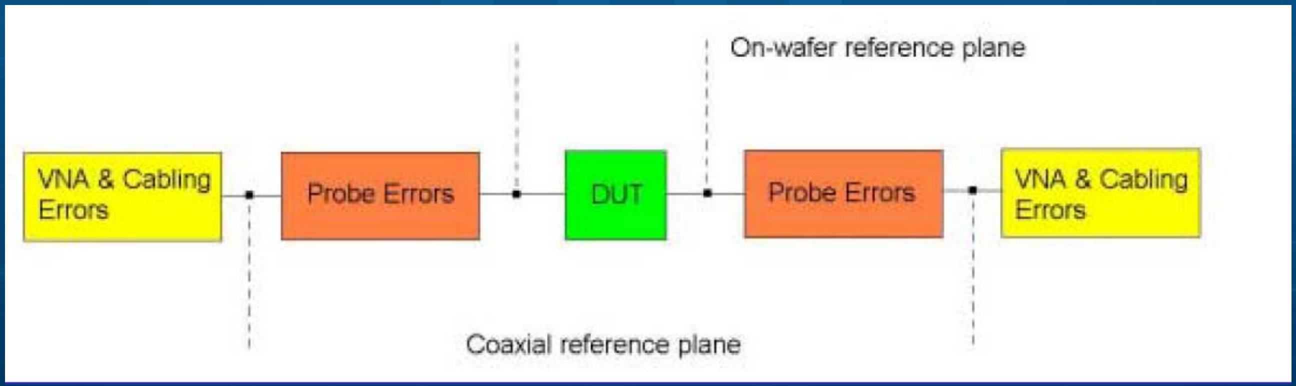
Overview

- Introduction
- How does Calibration Work
- Types of Calibrations
- Comparison of Calibration Types
- Summary

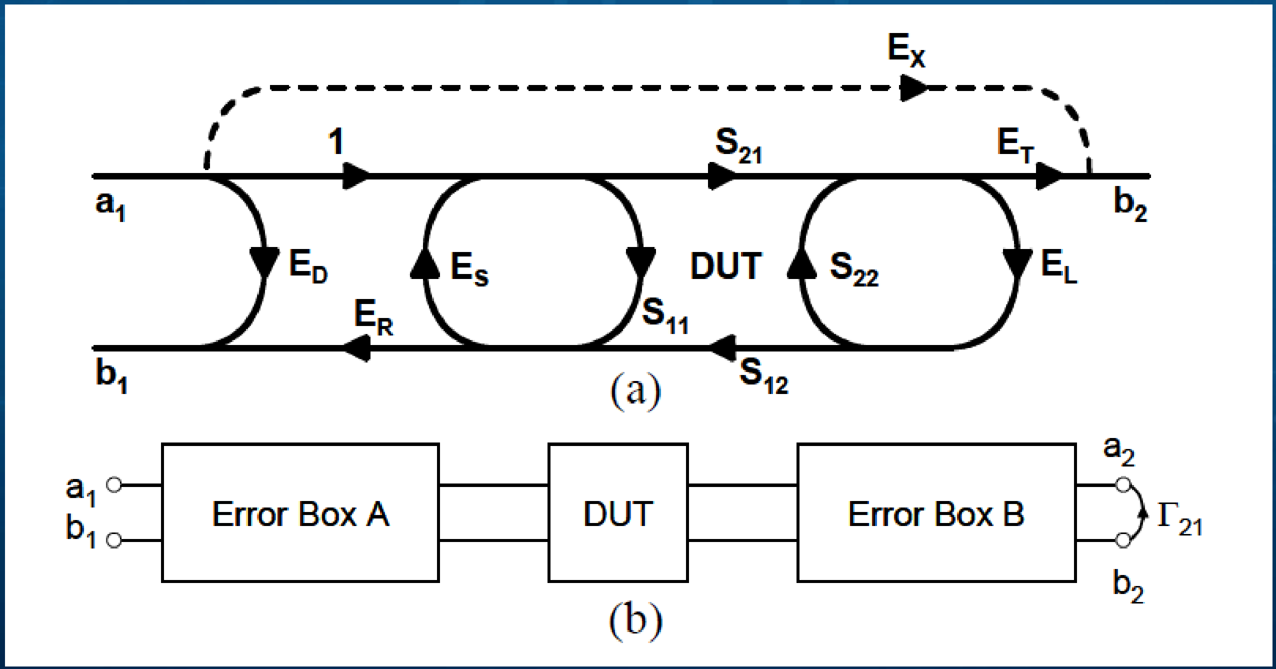
Why do you need Calibration?

- **You want a guarantee that you are measuring your DUT and NOT you test equipment**
  - The Probes and cabling introduces errors
  - However, Calibration is able to remove those errors



How does Calibration Work

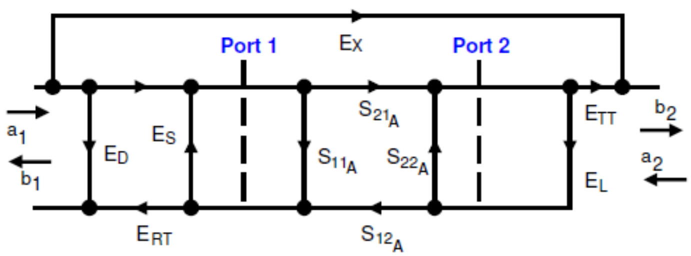
- In characterizes the RF performance parameters of your test hardware
- Then mathematically remove the parameters



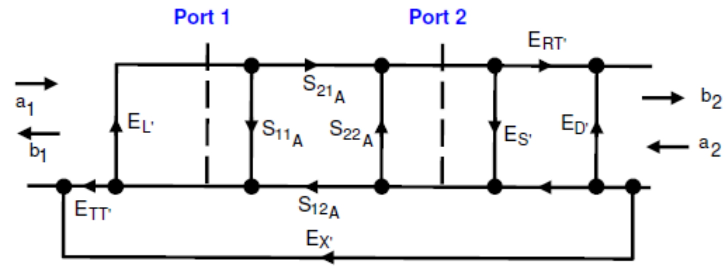
A Little Math….

Two-Port Error Correction

Forward model



Reverse model



E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to ***use*** network analyzers!!!

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

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

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

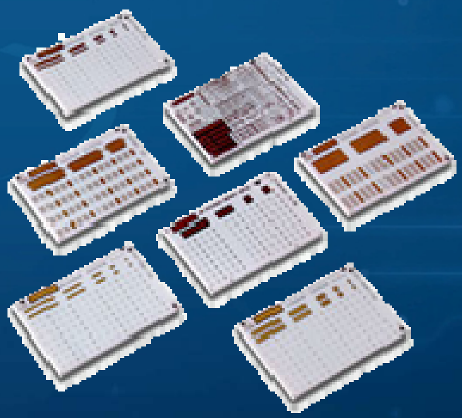
$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{RT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)-E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\r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

How to get to the measurement system error terms

- **One characterizes the RF parameters of your system by measuring some 'known' RF structures**
  - Open
  - Short
  - Load
  - Thru
- **Calibration can be various combinations of these standards based on your needs**

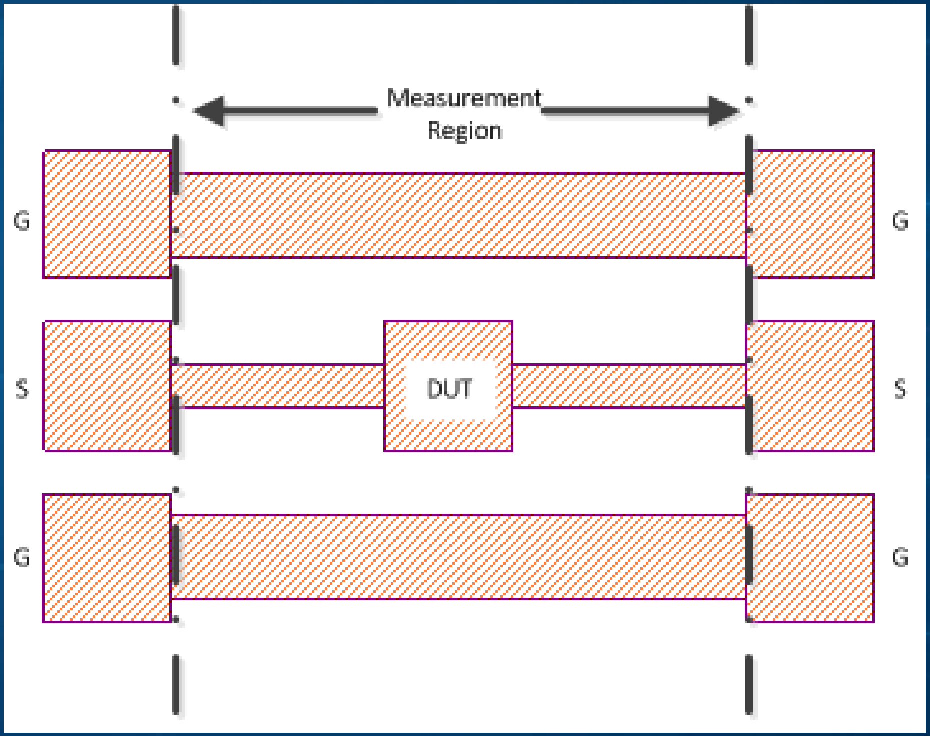
Calibration Substrates

- **The choice of the calibration substrate is important based on what you want to do:**
  - Edge of pad
  - End of transmission line
  - Type of Calibration
  - Frequency Range
  - Tip Pitch



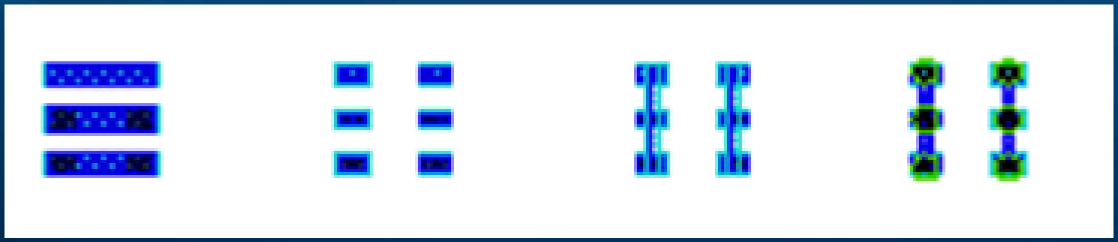
More about the Reference Plane…

- **The reference plane can be placed ALMOST anywhere in the RF signal path**
  - Can located at the:
    - Edge of the Pad
    - End of a transmission line to the DUT



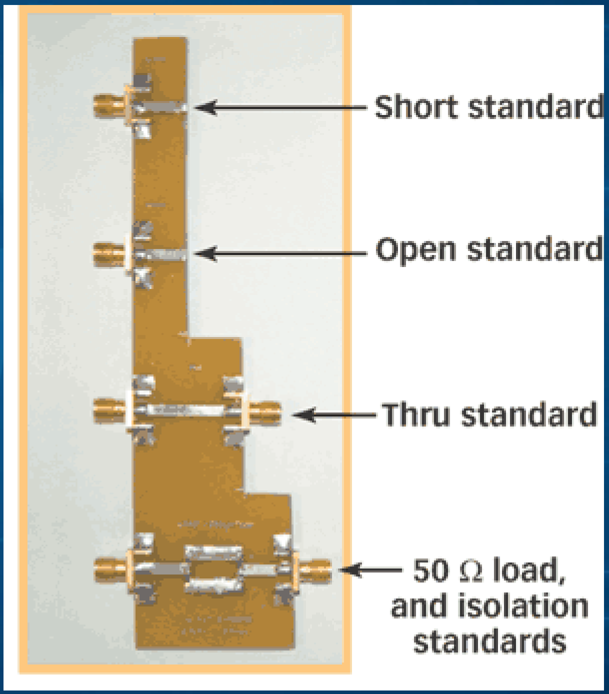
Calibration to edge of Pads

- **Place standards connected to pads**
  - Allows for removal of the full contact area
  - For high frequency, requires accurate Probe-To-Pad-Alignment to be successful
  - Highest accuracy by using standards on wafer, but good accuracy for can be achieved using ISS standards, especially in KGD applications



Calibration to end of Xline

- **This will generally require the use of on wafer standards**
  - Make a transmission line like that connected to the DUT, and then place your calibration standards



Cal Coefficients

- **Cal Coefficients are values that characterize the RF performance of the standards**
  - They are never ideal Opens, Short, Loads, and the Thru has a characteristic length
  - These are input into the previous equations as the known terms using the reflection coefficient

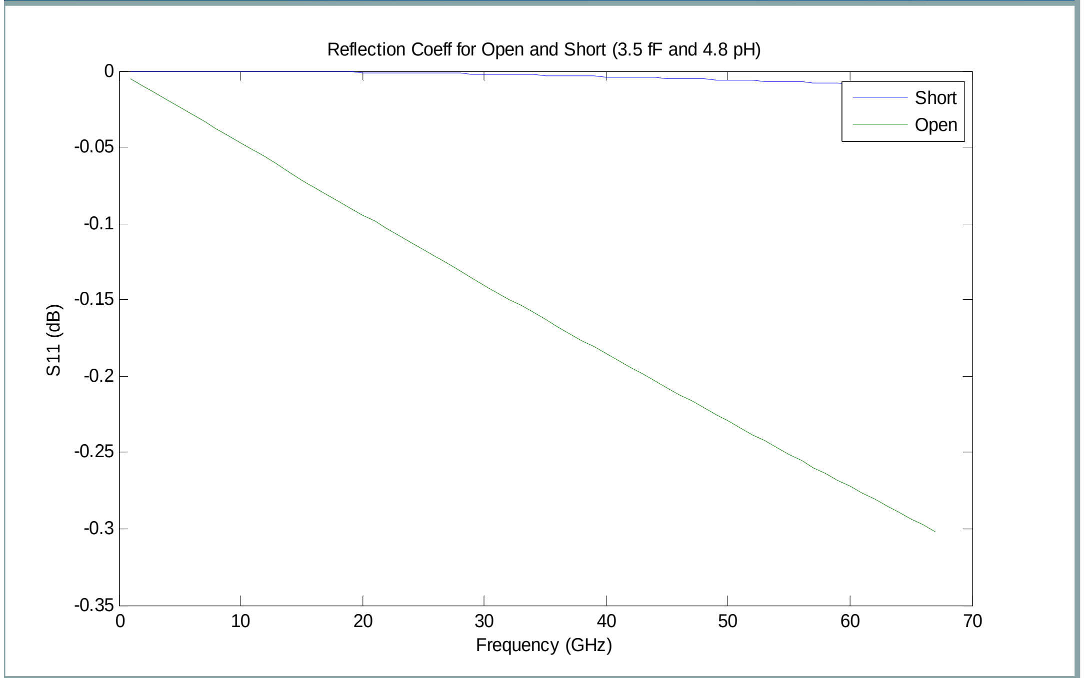
$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S}$$

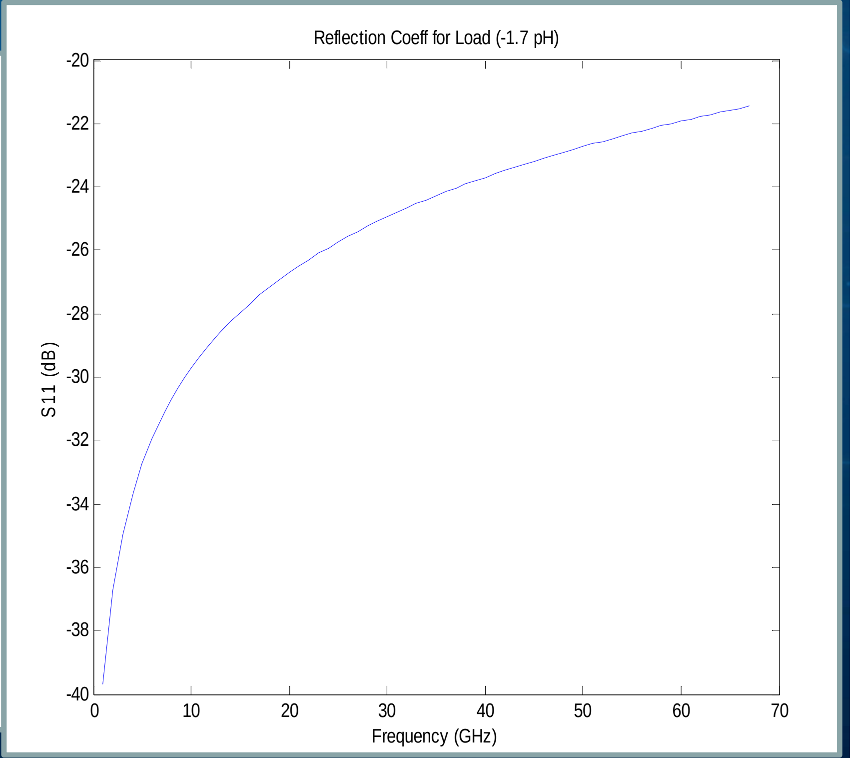
But… Do you need Cal Coeff?

- **In some situations, you can actually ignore the Cal Coeff.**
  - Depends upon Max Frequency and value of Cal Coeff.
  - Evaluated for 150 µm GSG for the model
    - C_open = 3.5 fF
    - L_load = -1.7 pH
    - L_short = 4.8 pH

Plot of Variation of Open and Short

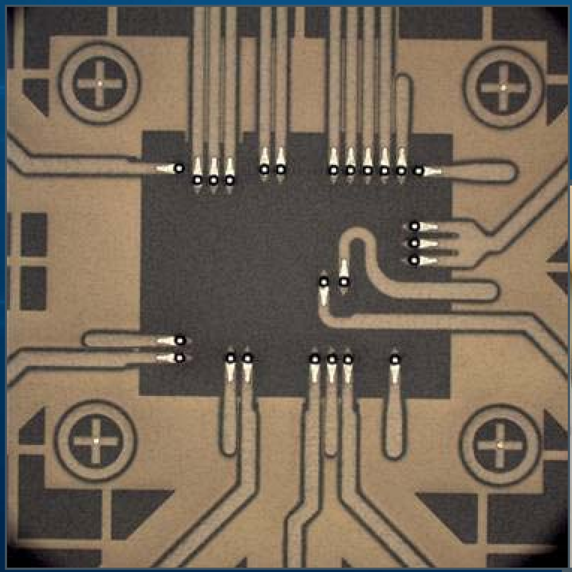
- **The varition is dominated by the Short**
  - At less than 20 GHz, it is less than 0.1 dB off from ideal

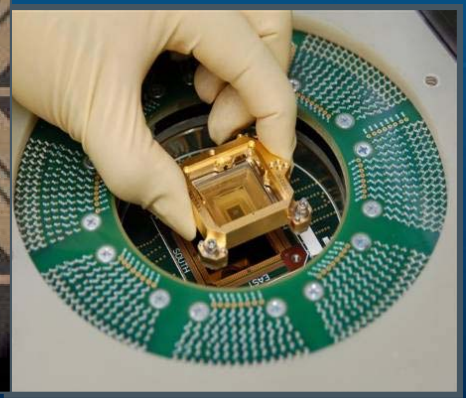


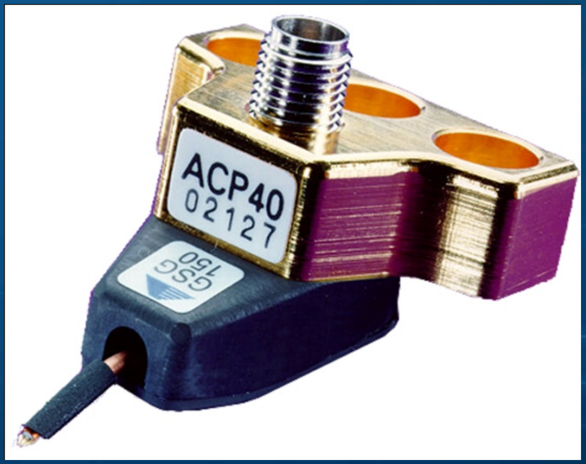


Calibration Options

- There are several options available on the test floor to calibrate your probe card
- The selection depends upon several factors
  - Accuracy needed
  - Type of Probe Card





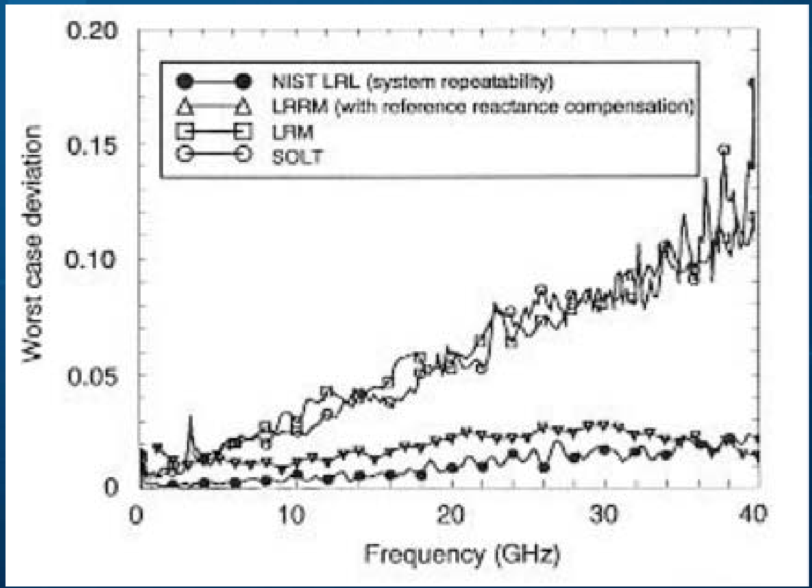


TRL

- **NIST traceable standard Calibration technique**
  - Mulit-line TRL (Thru-Reflect-Line)
  - Uses multiple transmission lines as the standards
  - Measurements referenced to the line impedance
  - Limited frequency range
    - 3 lines for 2-18 GHz
  - Requires multiple probe spacing
  - Not suitable for fixed spacing probes

Thru-Reflect-Reflect- Match (LRRM)

- **Compares favorably to TRL**
- **In Cascade's Wincal**
- **Does not need well defined standards other than the thru**
  - Known length and impedance



SOLT

- **Short-Open-Load-Thru**
  - Needs well defined standards
  - L-short, C-open, L-load, and Thru length
  - Uses off wafer standards
  - Sensitive to the probe placement

SOLR

- **SOLR is similar to SOLT**
  - Needs well defined Load, Short, and Open
  - The thru does not need to be well defined, just approximate length
  - Convenient for use with probe cards
    - Fixed probe spacing and are usually not inline with eachother

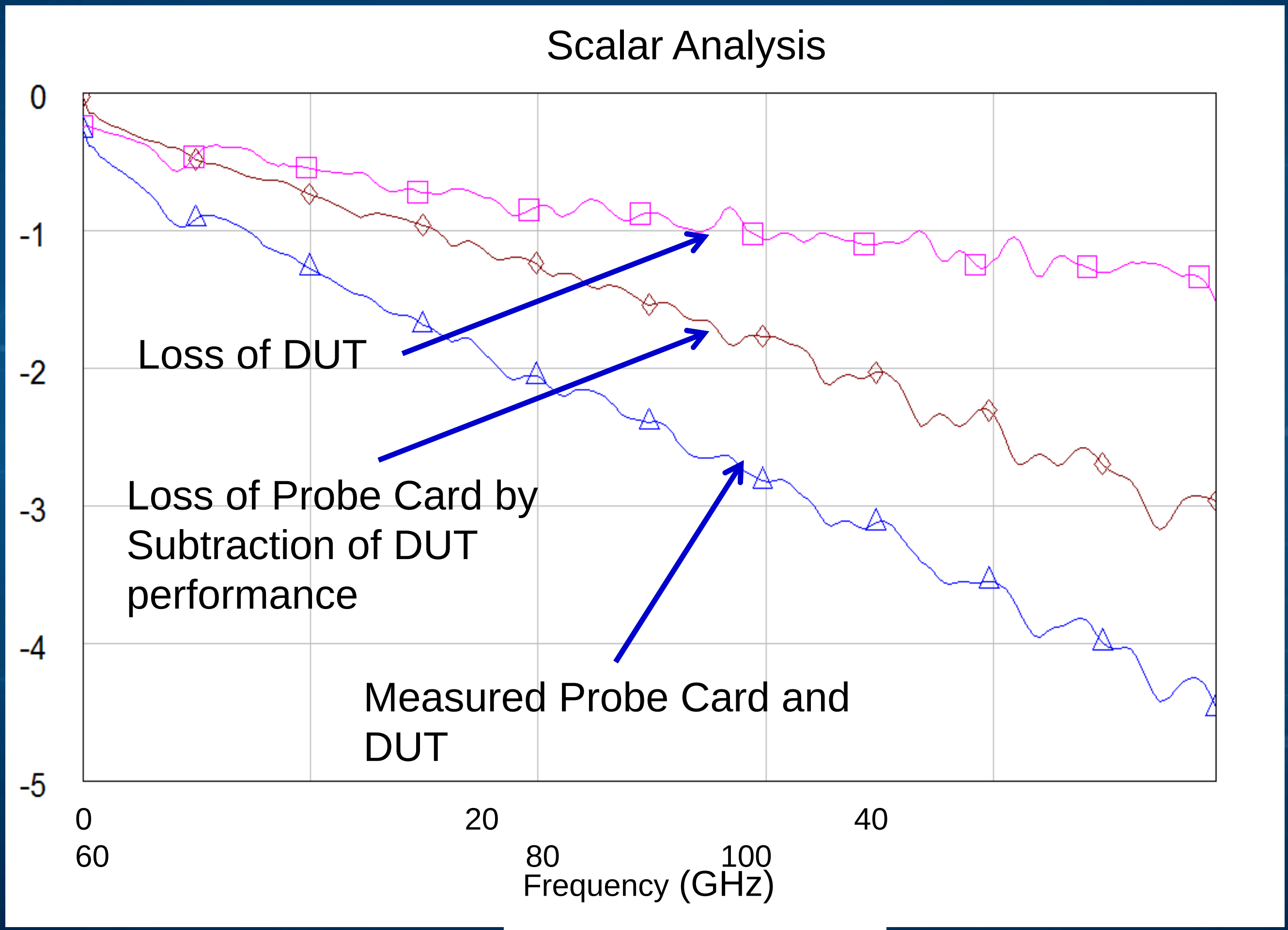
2nd Tier Calibration with SOL

- **What is 2nd Tier?**
  1. Calibrate to the end of the cable using standards
  2. Measure SOL to generate 2 port parameters
     - Requires reciprocal probe card (which is true for Pyramid Probes)
  3. The 2-port parameters are then combined with the first calibration
- **Does not require a thru for calibration**
- **Can be compared favorably to SOLR calibration in terms of accuracy**
- **WinCal and most VNAs have this programmed into them**

SO

- **Only needs Short-Open**
- **Can be done with:**
  - Probe card in air for open
  - Probe card in contact with a metal wafer
- **Assumes that ALL losses are due insertion losses, IE, no RL**
  - Works well down to probe cards with -12 dB RL or better

SO



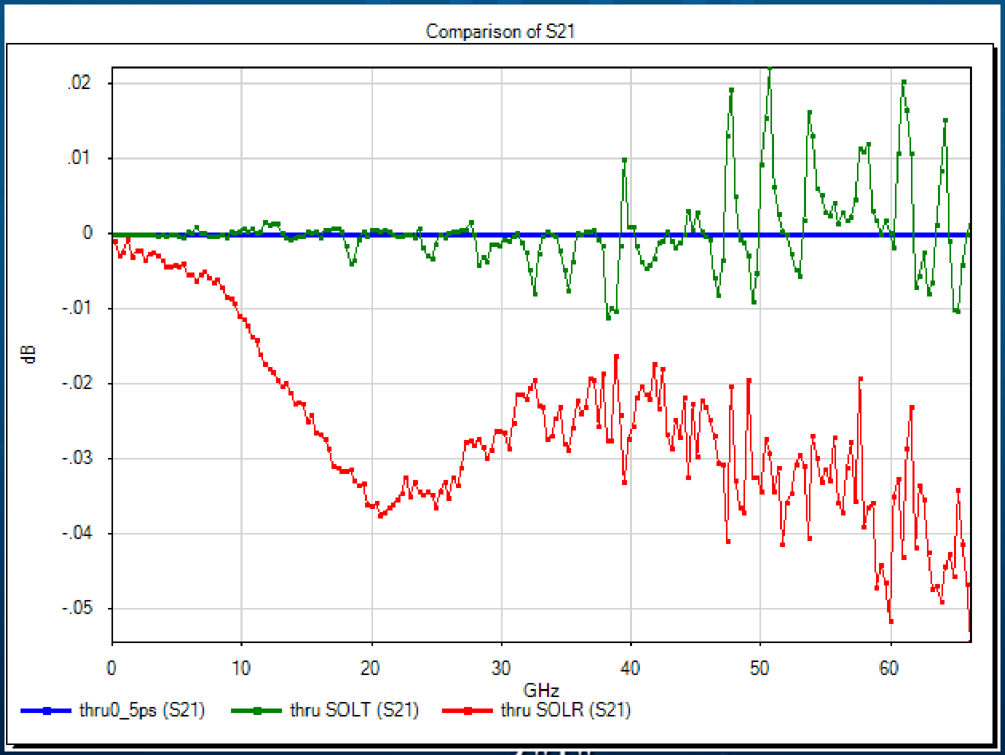
Scalar Analysis
0
-1
-2
-3
-4
-5
Loss of DUT
Loss of Probe Card by Subtraction of DUT performance
Measured Probe Card and DUT
0
20
40
60
80
100
Frequency (GHz)

SO

- Can be done a few ways:
  - Using S-parameters provided, use the loss factors as a correction term at specific frequencies
  - Measure golden die that have been characterized using a different method (such as Infinity) that is calibrated to the tips
    - Comparing the two measurements, the loss of the probe card is known
    - Measurements show that the loss is repeatable and does not change much when a new core is placed in the PCB
- However, this is the least accurate
  - No phase correction
  - Is done at only a few frequencies
- Easiest to implement of the calibration options

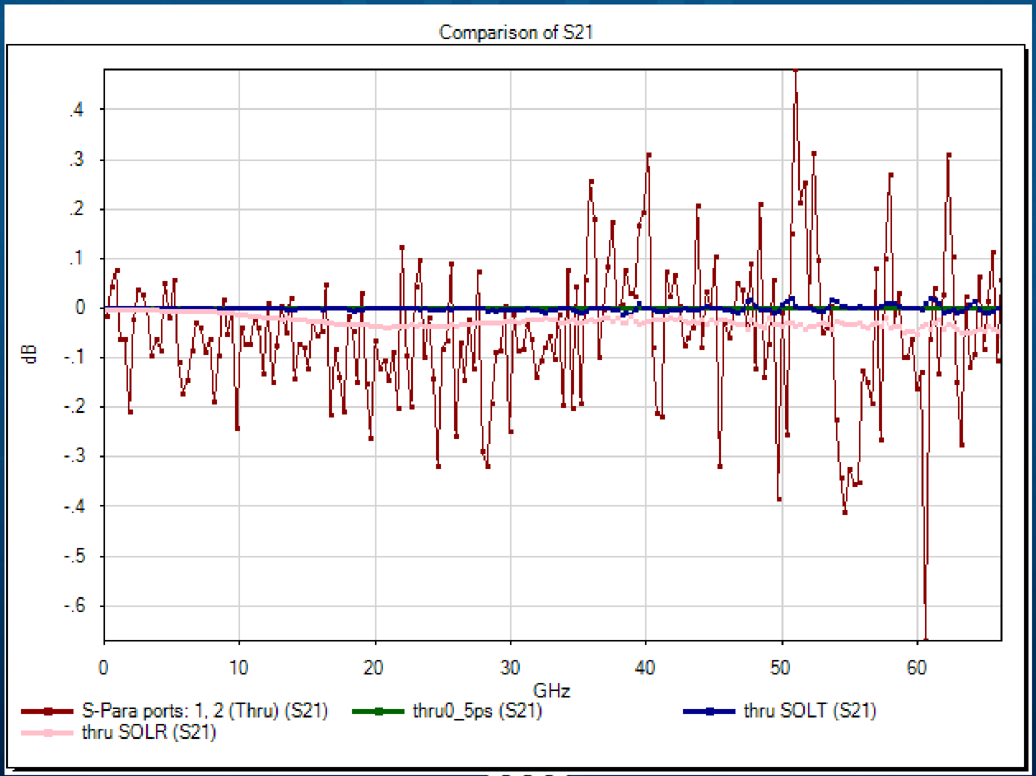
Comparison of Methods using Thrus - Magnitude

- **SOLT, SOLR, and LRRM are all very good**
  - Within 0.05 dB of each other using the same calibration files up to 67 GHz



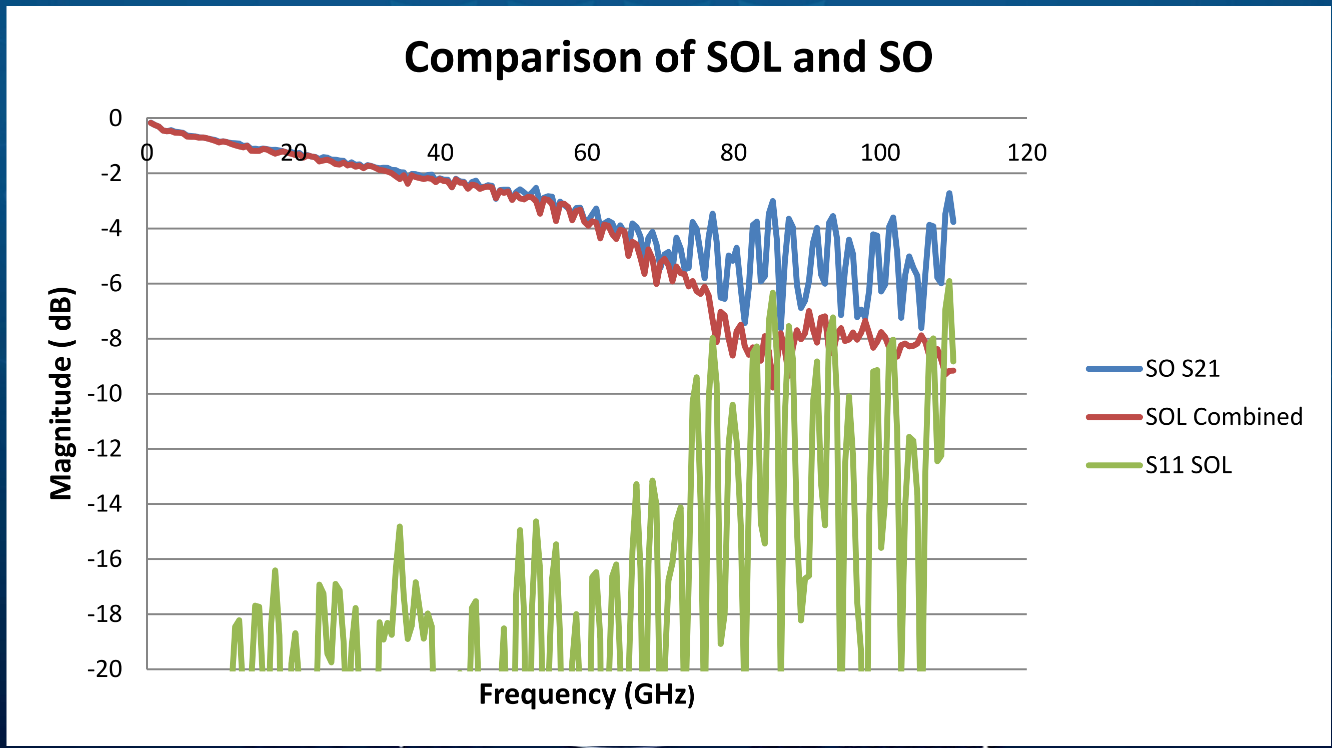
SOL Compared to LRRM

- SOL is reasonable for KGD testing, being within +/- 0.5 dB out to 50 GHz when compared to LRRM



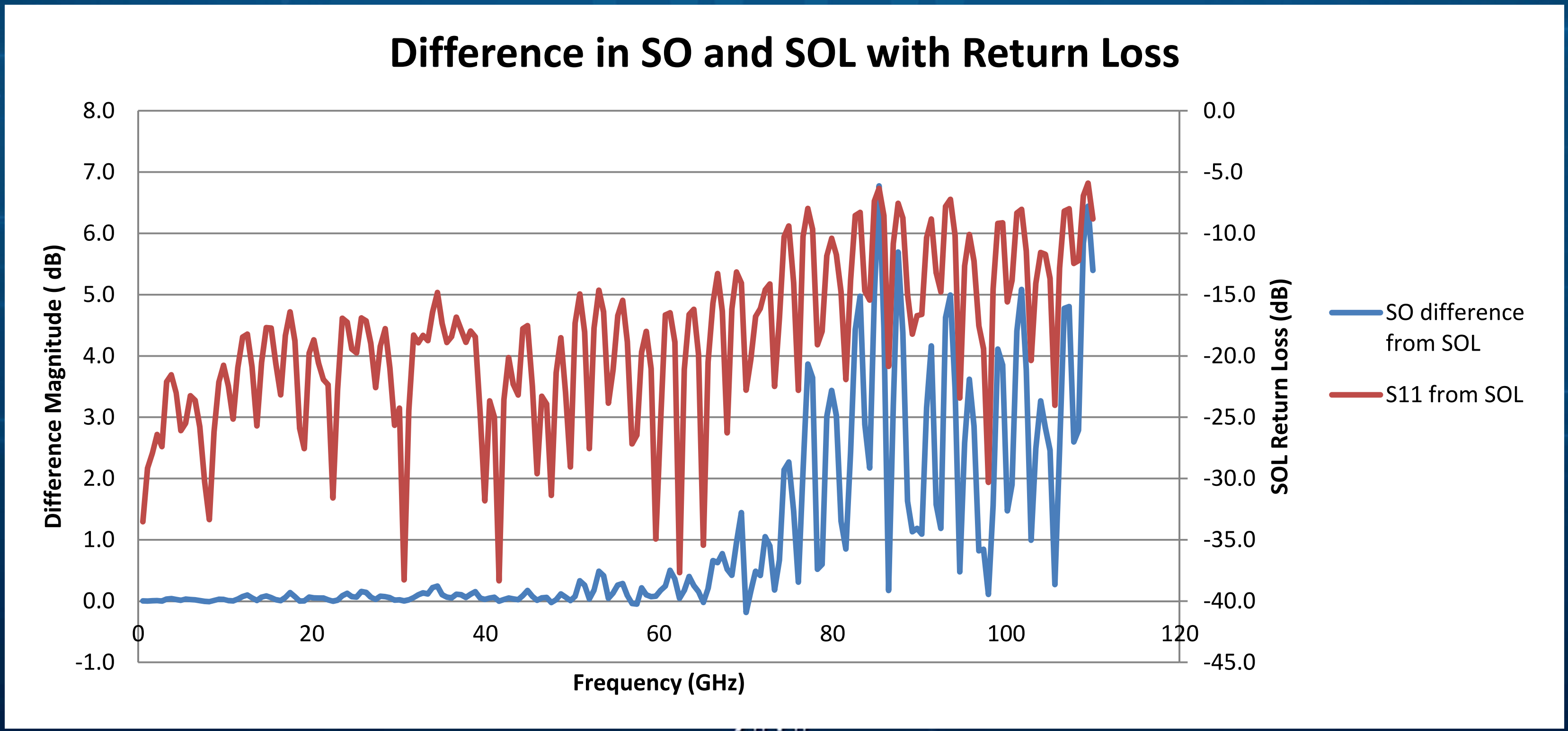
SO Comparison to SOL

- **Short-Open works well as long as the RL is better than -12 dB**
  - Because of the assumption that ALL losses are due to insertion loss



Difference in SO and SOL with RL

- Comparing SO and SOL, as long as RL is less than -12 dB, then SO is within 1 dB of SOL



Comparsion of Calibration Options

Calibration Method	Absolute Accuracy	Probe Card Support
SOLT	Fair	Fair -due to usually not having straight thrus
TRL	Best	Poor -due to inability to have variable length thrus
LRM/LRRM	Good	Fair -due to usually not having straight thrus
SOLR	Good	Best -works best with bends in thrus
SOL	Fair	Fair Works well of KGD test
SO	Low	Fair to Poor (Depending upon RL) Ease of use due to not needing precise alignment

How to Verify your Calibration? Trust me.....

- **This depends upon the type of calibration, and how accurate**
- **For more accurate measurements**
  - SOLT, SOLR, SOL, SO
    - Use thru
    - Do not use short, open, or load – user defined
  - LRRM, TRL
    - Use open or short
    - Do not use thru – user defined

Now Really Trust Me….

- **For lower accuracy applications, you can consider**
  - Remeasure your standards (even if using SOLT, SOLR, and SOL)
    - If some measurement was wrong (bad alignment;bad contact), it will appear immediately as excessive loss or gain
    - Compare to previous measurement for system drift

Summary

- Calibration has a lot of different considerations
- The best option depends upon your needs and ease of setup

Questions?