Calibration and De-Embedding Techniques in the Frequency Domain

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Agenda

- Calibration and De-Embedding Concepts
- Selecting a Suitable Measurement Approach
- Examples
  - SOLT measurements
  - TRL measurements
- Creating a TRL calibration kit, step-by-step
- Measures of Calibration accuracy
- Examples of 3D field solver measure-based correspondence

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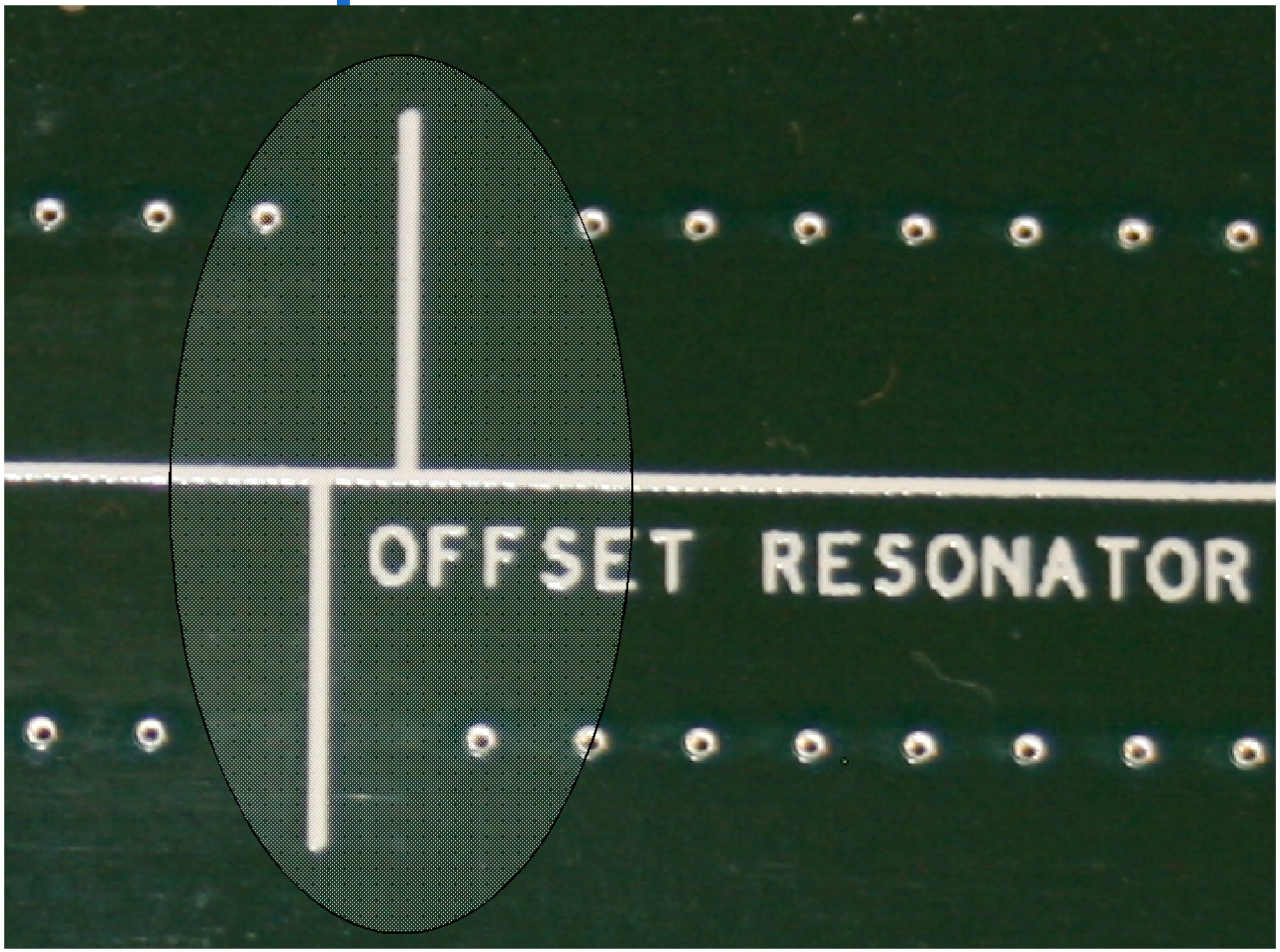
Typical Measurement Objective: Measure S-parameters of a Very Specific Structure



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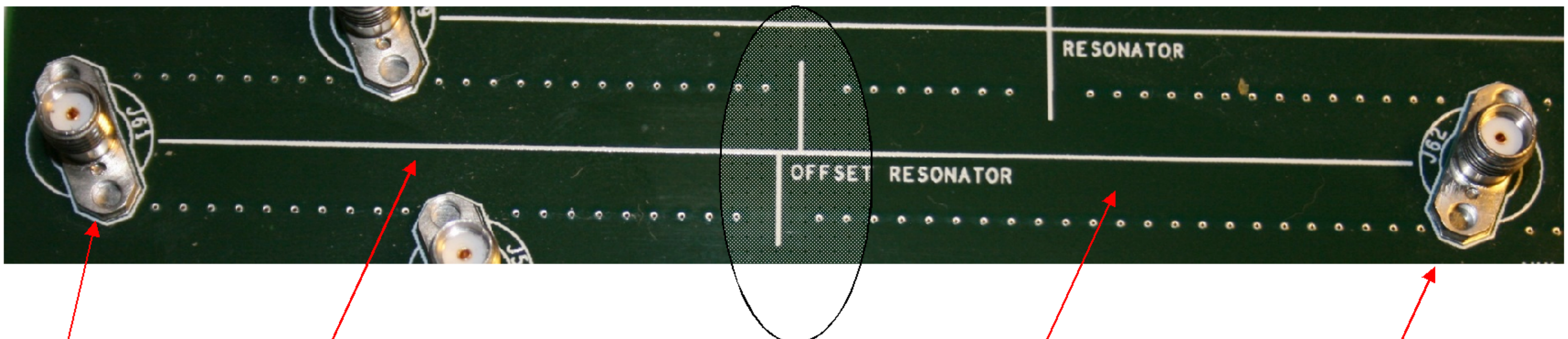
Reality is that there is more to the picture – The Fixture



Launch

Lossey Transmission Line

Lossey Transmission Line

Launch

We only want to measure this structure

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Methods of Removing the Fixture

- Calibration – Removal of unwanted measurement portion using known standards
  - SOLT Short-Open-Load-Thru
  - TRL   Thru-Reflect-Line
- De-Embedding – post process removal by mathematically removing fixture artifact with known response of fixture
  - T-matrix de-embedding (will not deal with here)
- Error Correction
  - Normalization, gating

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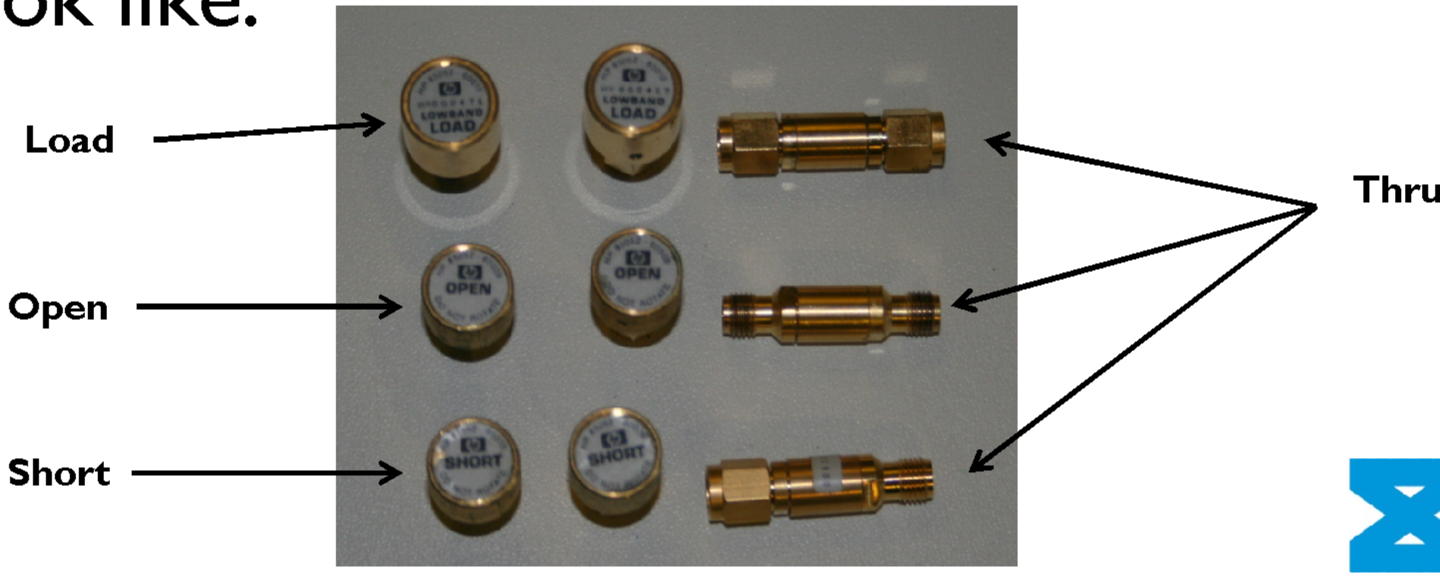
Calibration Standards

- In both SOLT and TRL standards are required
- In the Case of SOLT, the standards often look like:



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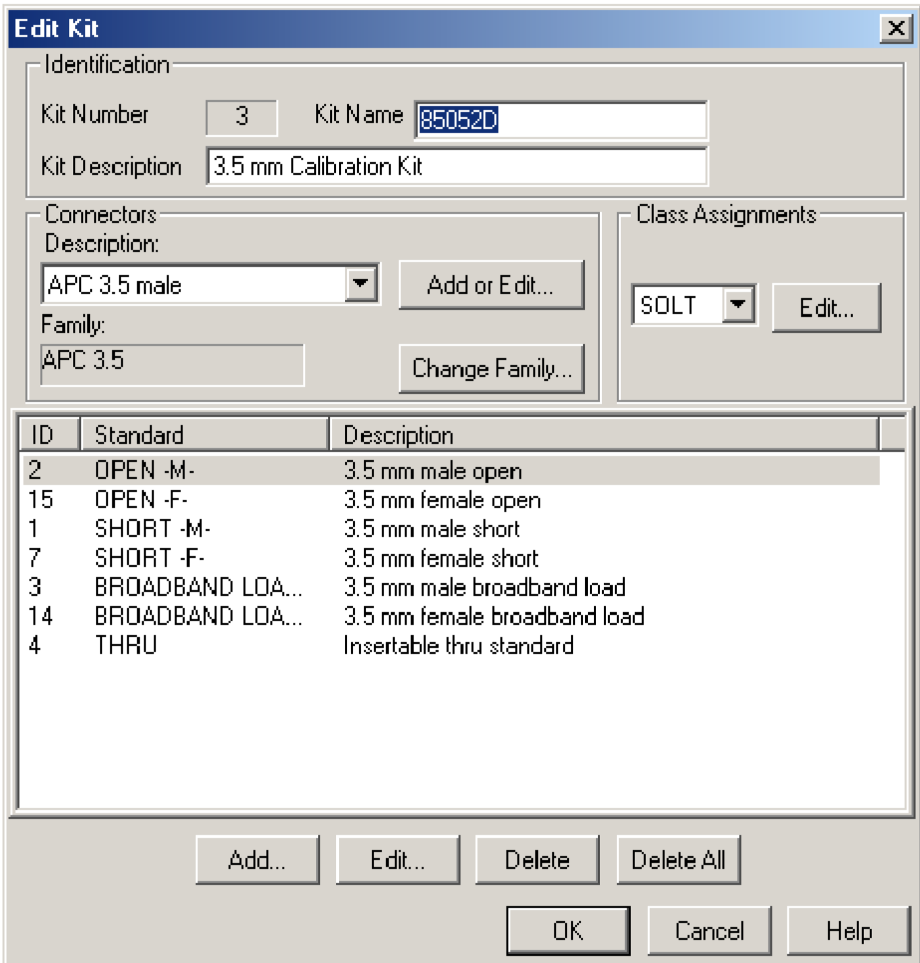
For SOLT calibration each standards needs to be carefully modeled



Establishing a SOLT cal kit is tough in that it requires very careful modeling of each structure to BW of interest using polynomial functions

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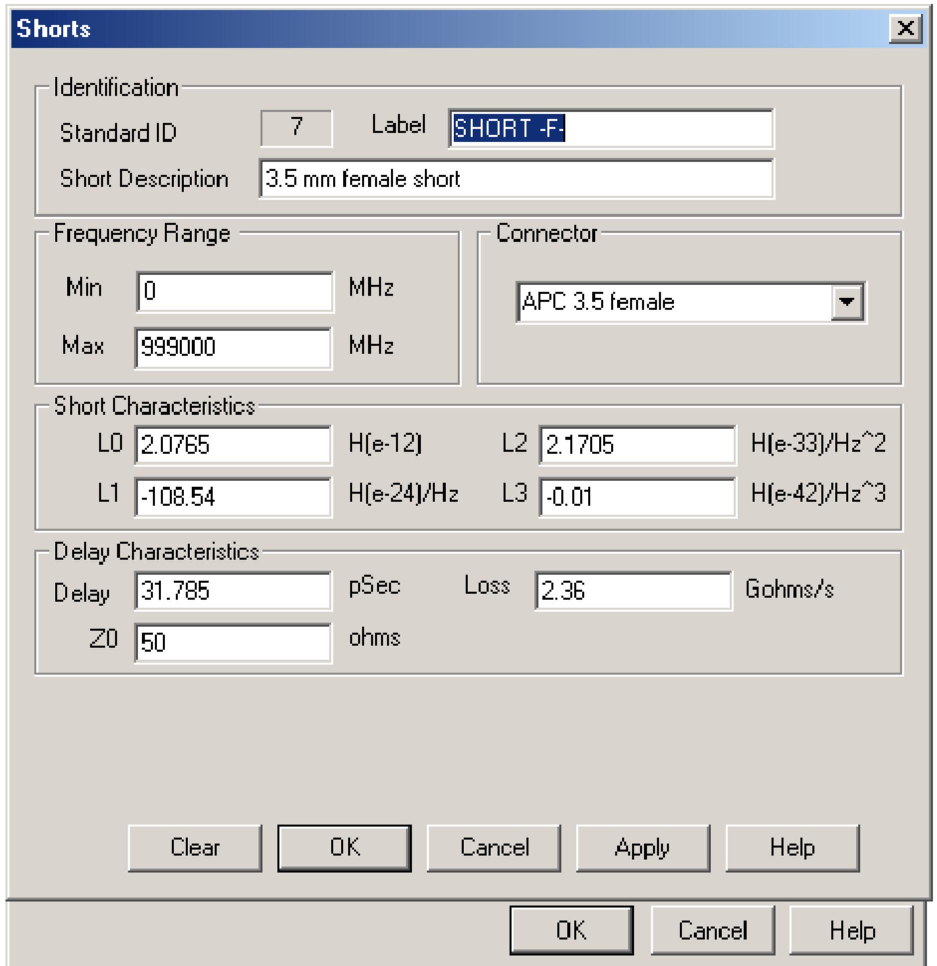
SOLT Short (similar for Open, Load, Thru)



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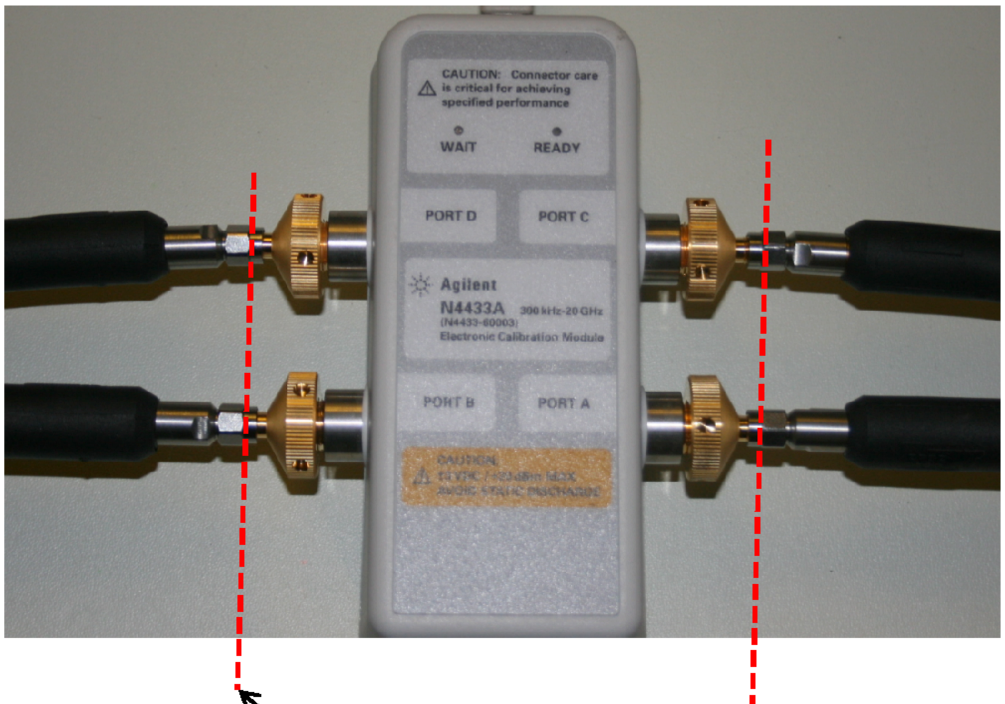
SOLT – Most often used to calibrate out to VNA cable ends, we LOVE the ECAL, it has saved our fingers

SOLT is an excellent method for coaxial calibration where the cal kit is pre-defined so that the models are already available



Calibration Plans

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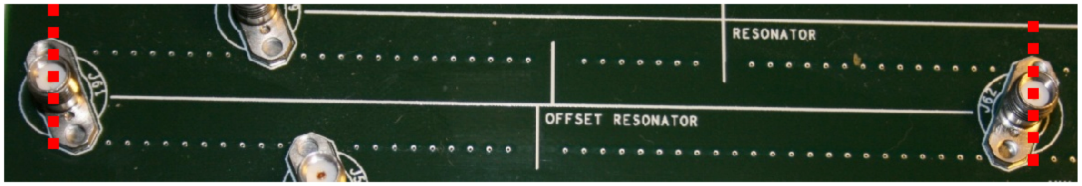
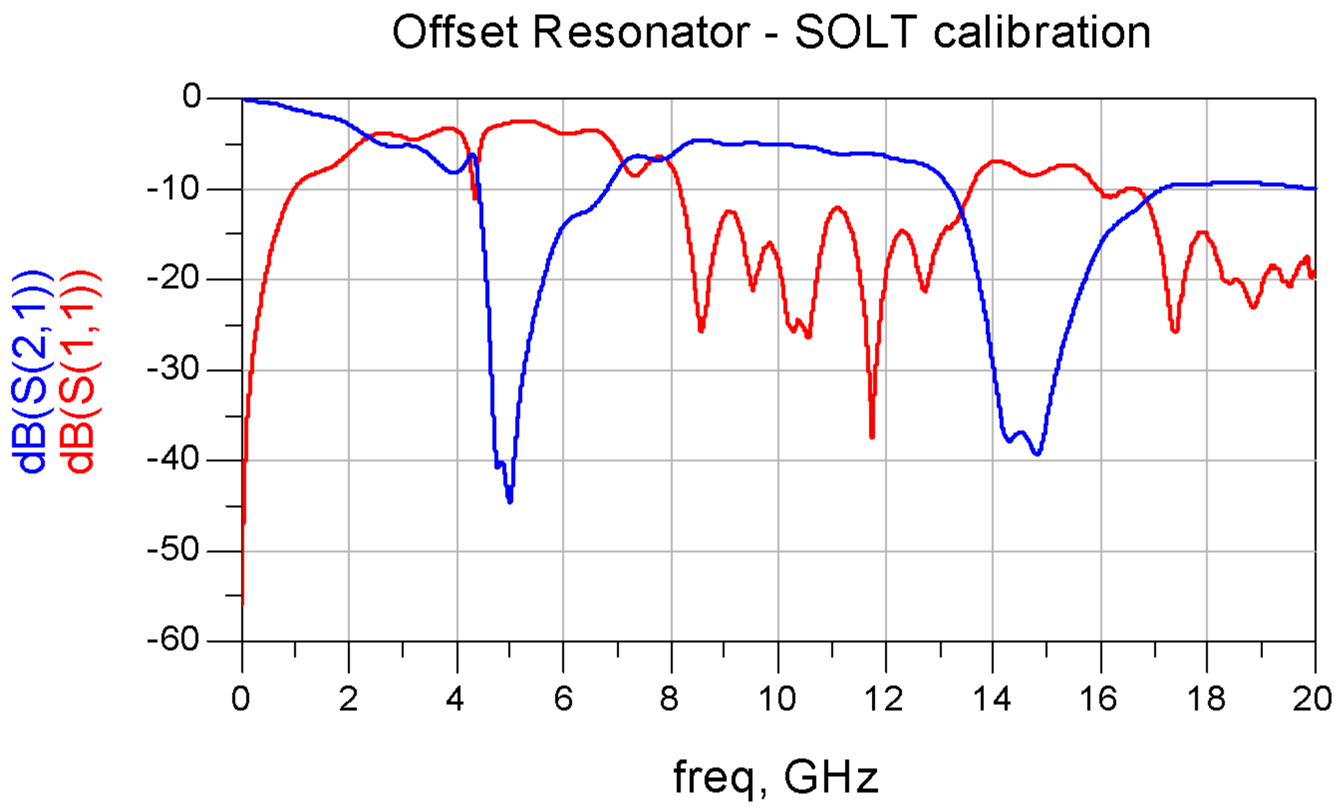
Example: SOLT Calibrated, Offset Resonator





Recall that this measurement reference planes are at SMA's

S21 includes loss of SMA, 1.75inch trace on each side of non-insertable DUT

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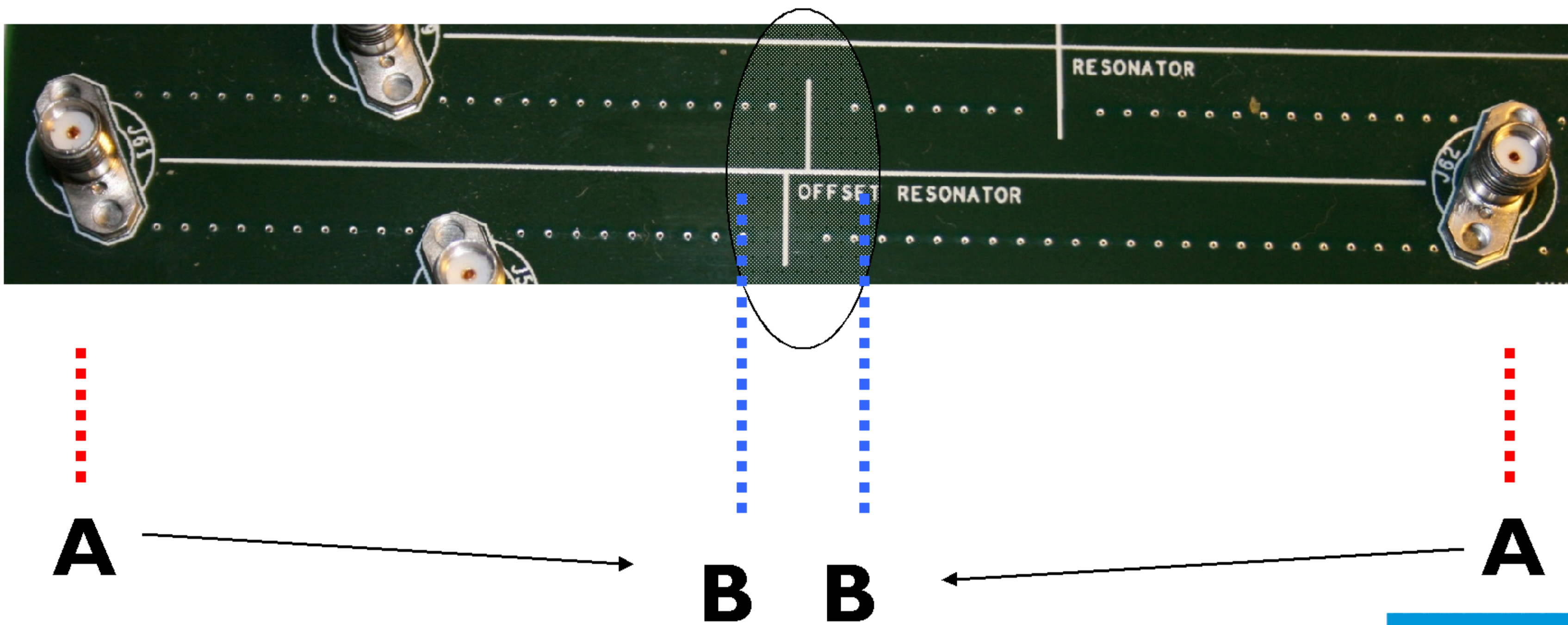
Moving the Measurement Reference Plane – Assuming a SOLT calibration to the end of Coaxial VNA cables



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Normalization (all measurements are SOLT calibrated, ref plane at SMA's)

PROCEDURE:

- Measure DUT, including test fixture
- Measure THRU (no DUT)
- In dB scale, subtract THRU from DUT

Normalization:

- corrects for loss and phase delay of test fixture
- will not correct for resonances
- should only be used when test fixture and DUT have low return loss

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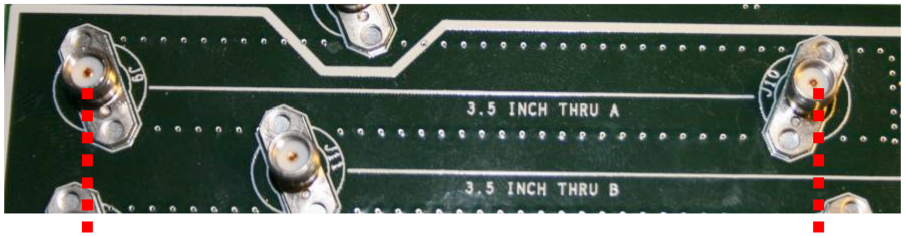
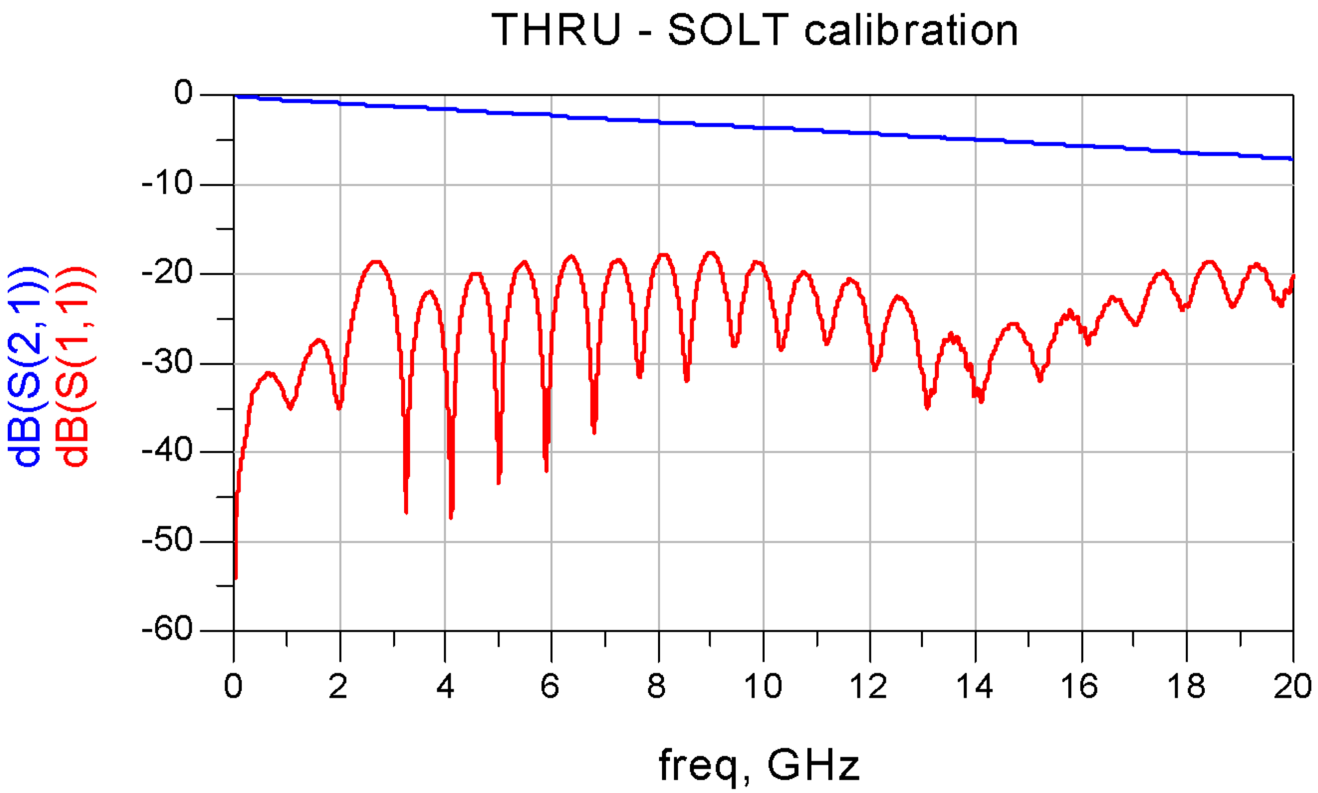
THRU SOLT calibrated measurement





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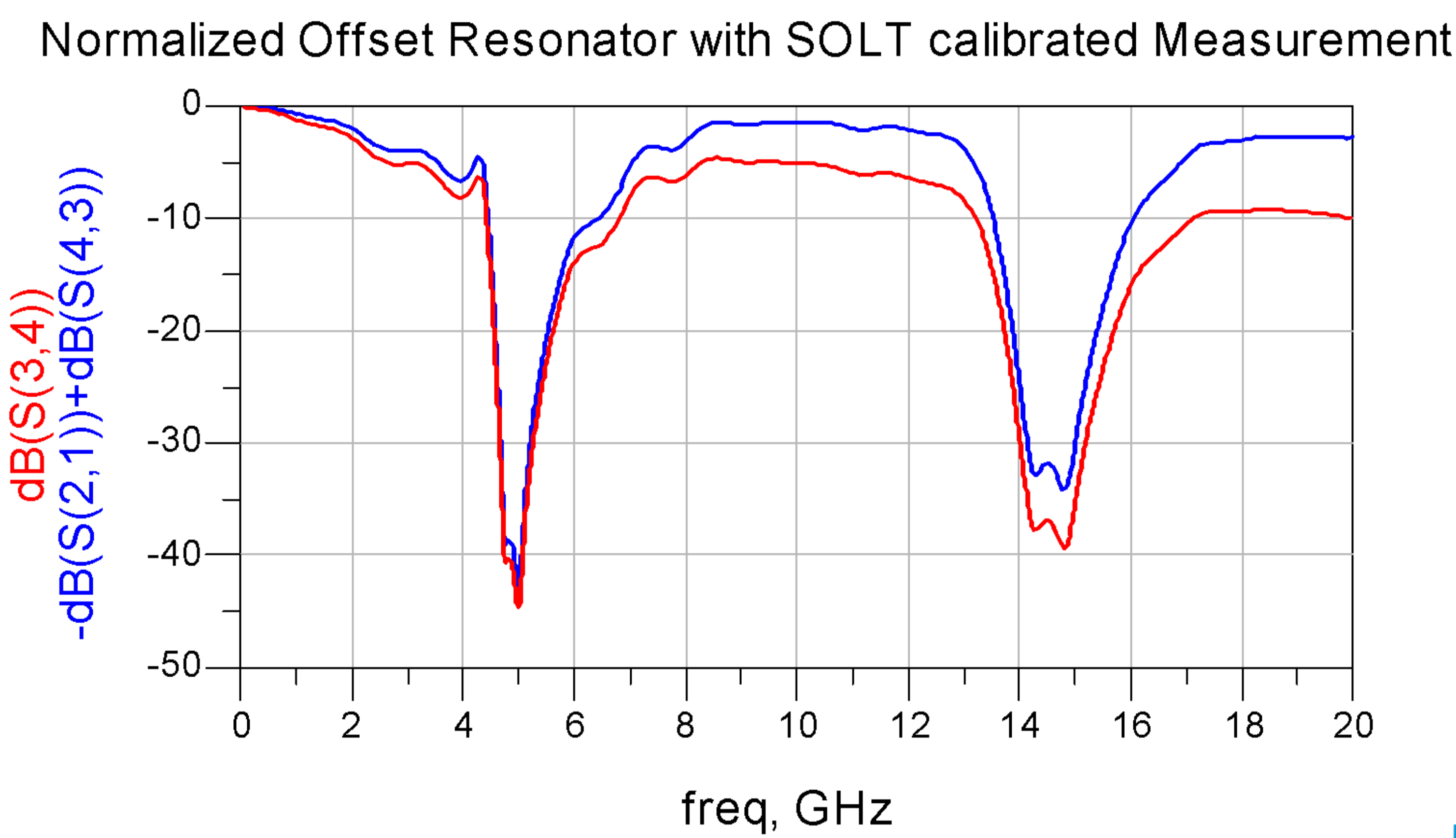
Comparing Normalized Result of Offset Resonator with SOLT measurement



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TRL Calibration

- TRL does not have significant demand for modeling each structure
- Makes it much better for on-board calibration, moving reference plane to DUT
- Requirements:
  - Launch must be good (low S11, no resonance) – good launch design
  - Connector repeatability from SMA to SMA – TDR confirm
  - Line lengths accurate – layout, etch
  - Impedance variation across board low – etch, fibre weave, etc.,

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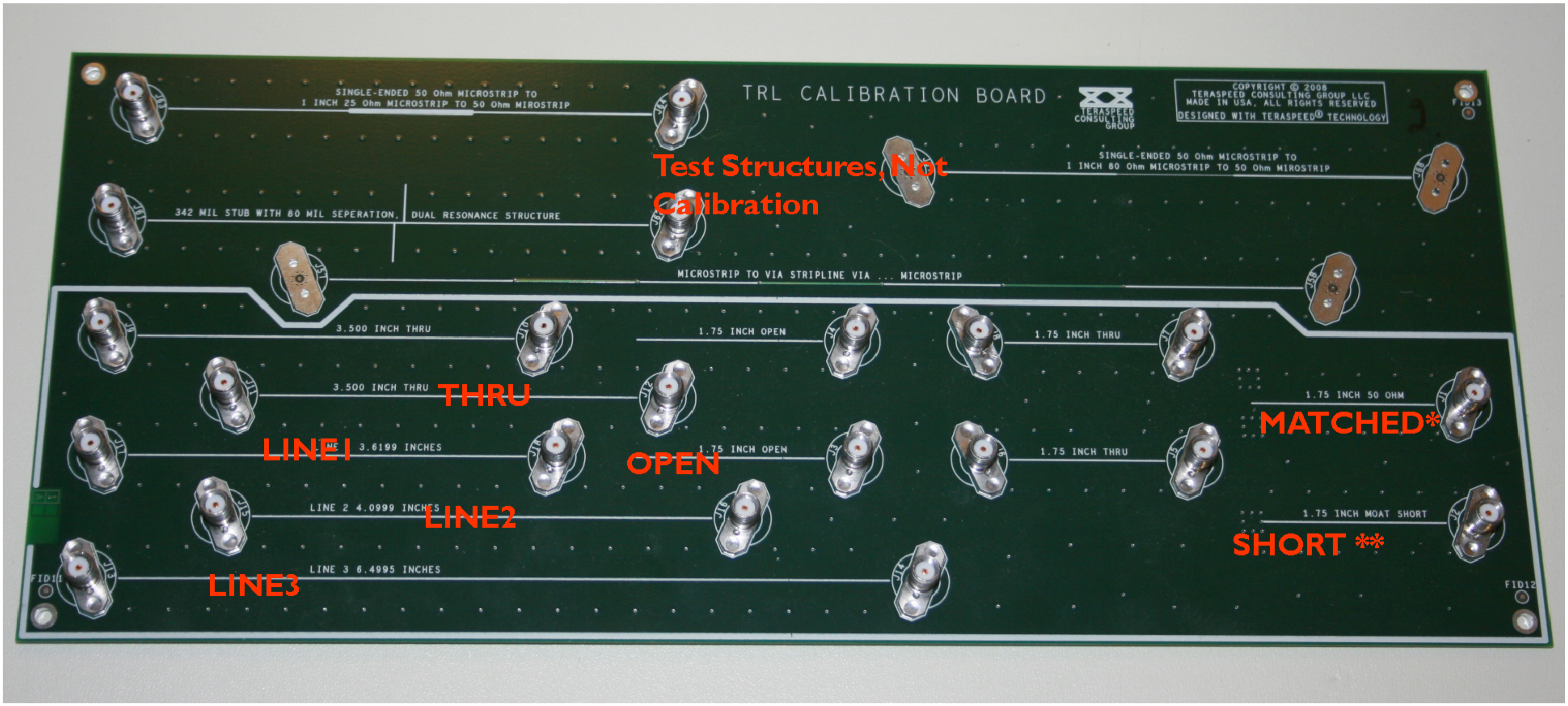
TRL Calibration Kit (hand out TRL board to audience)



MATCHED* - corresponds to LRM, Line-Reflect-Matched, similar to TRL, but has Matched Line

SHORT ** TRL only requires short OR open, not both

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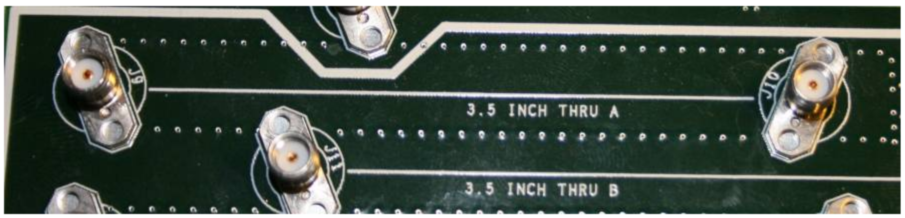
Basic Concept for TRL: THRU+DUT

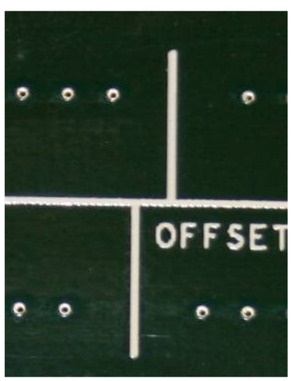
- Structure to calibrate out is THRU, leaving the DUT



THRU

+

DEVICE



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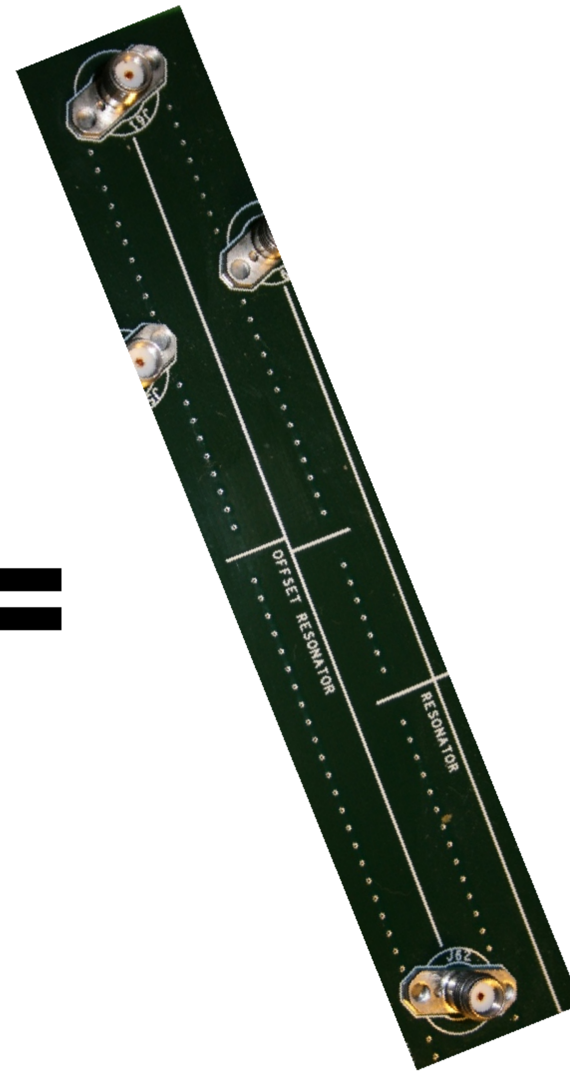

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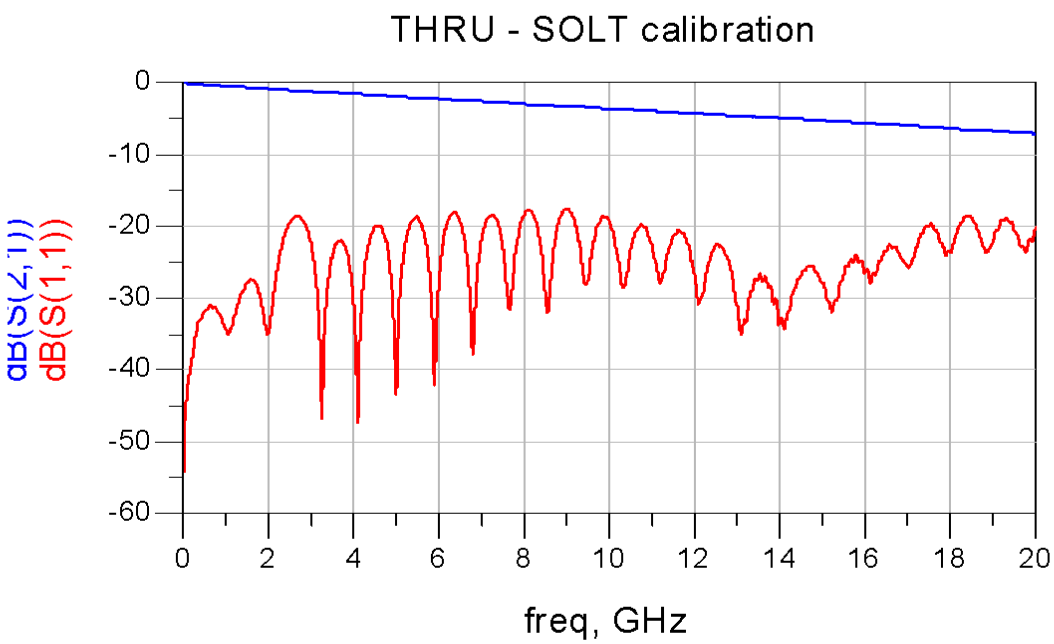
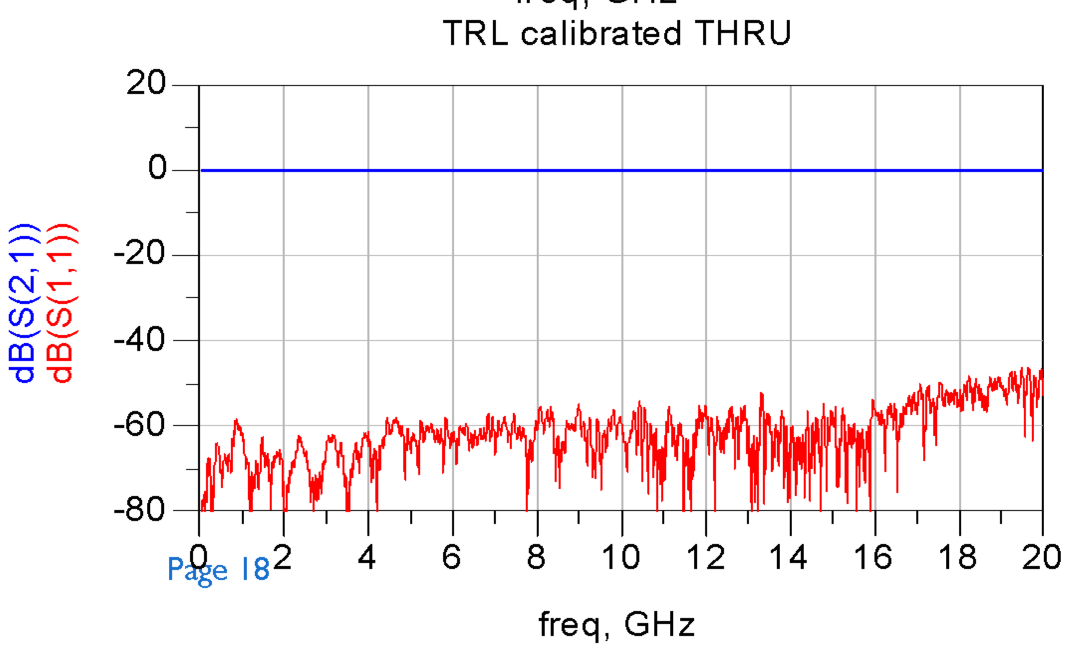
Compare SOLT Calibration with TRL Calibration measure of THRU





Notice the difference between SOLT versus TRL calibration.

For Solt calibration it will be necessary to mathematically subtract the insertion loss – called Normalization. This de-embedding method doesn't work in a general case since it does not deal with all the error terms

The TRL measured THRU, as expected, shows 0dB S21, or insertion loss and very good S11, or return loss. Adding a DUT to this exact structure will provide only the DUT response, and not fixturing

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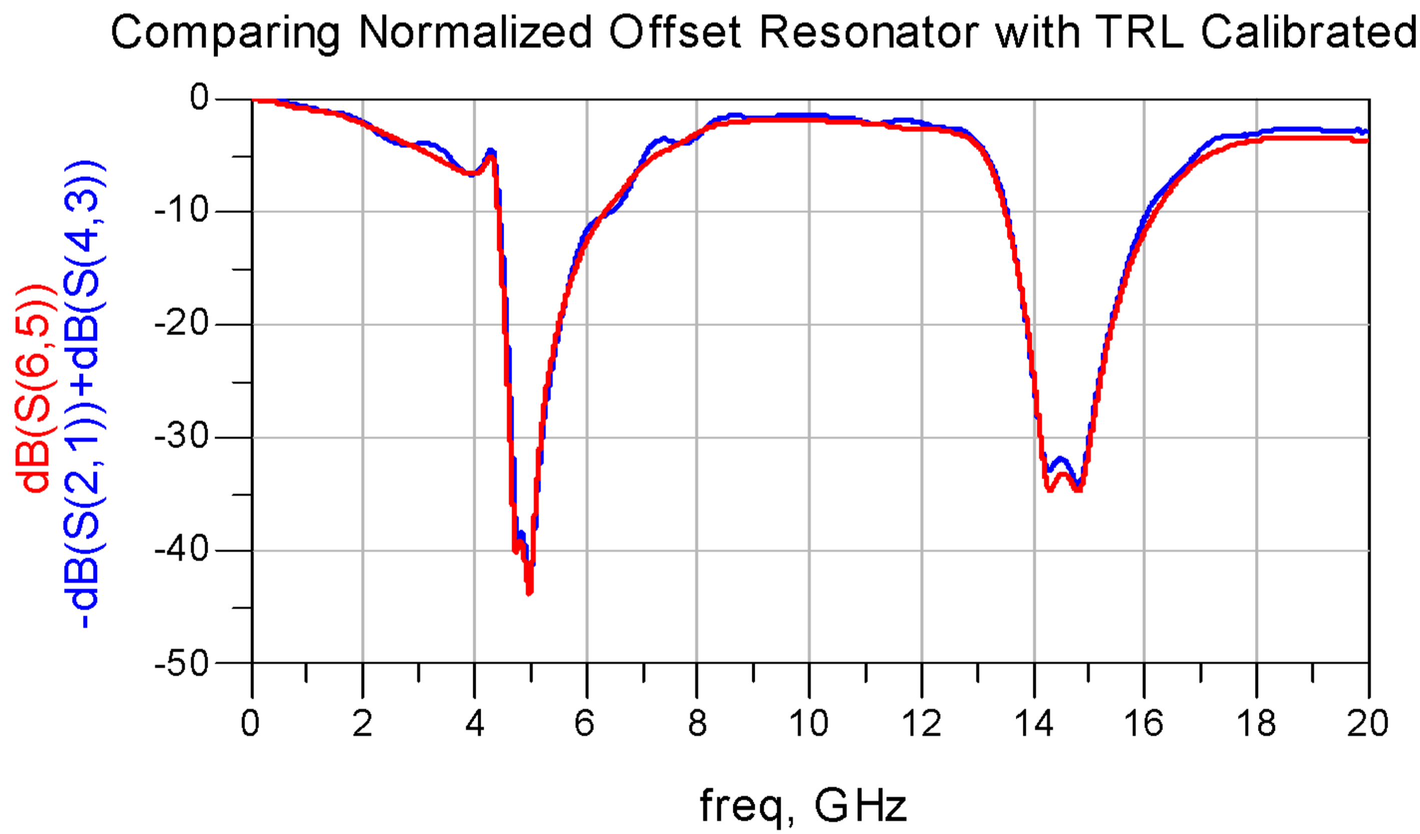
Offset Resonator comparison between Normalized and TRL calibrated- close but not exact!



Red trace is TRL calibrated Offset resonator, blue is Normalized

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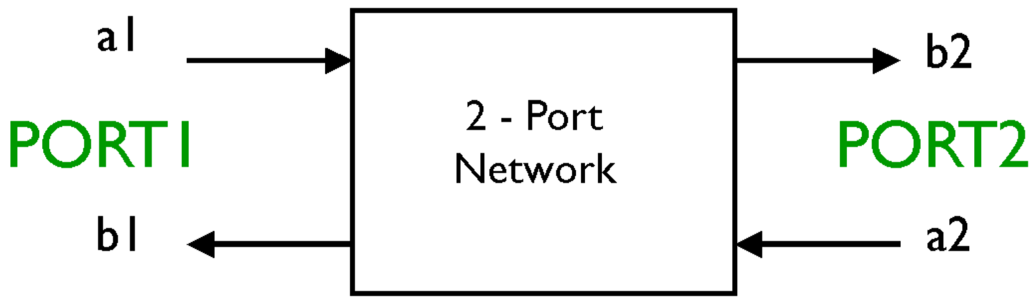
Basic Primer on Error Models

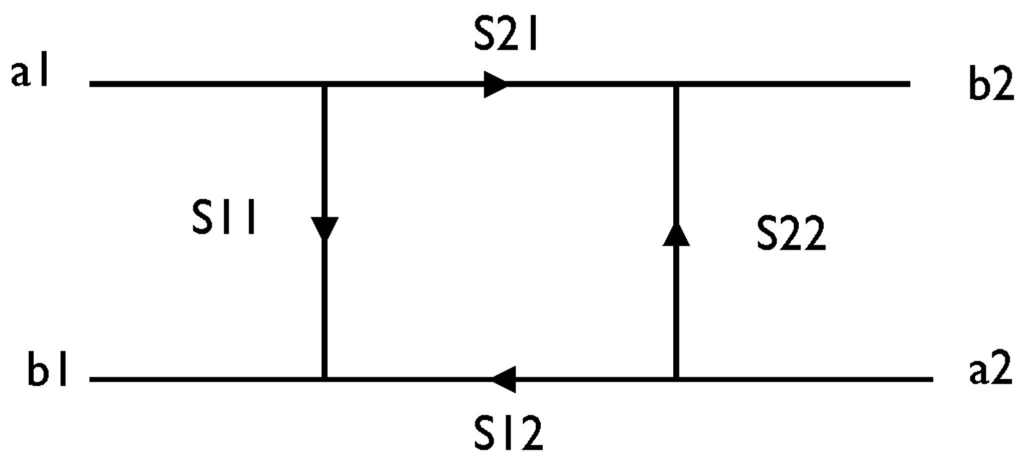
Network



$$b1 = S11a1 + S12a2$$

$$b2 = S21a1 + S22a2$$

Signal Flow

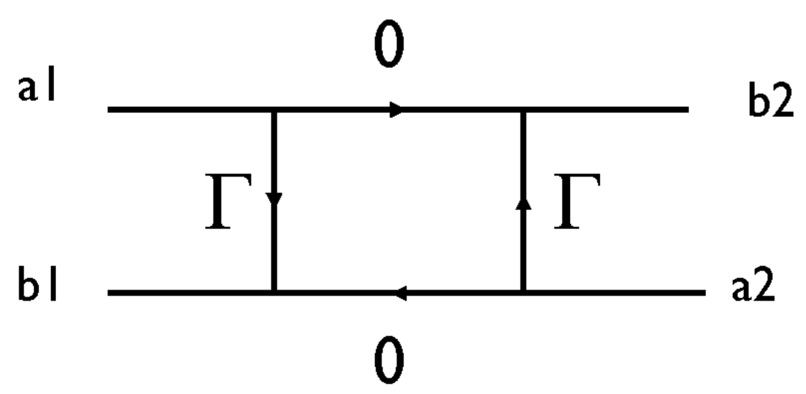


$$\begin{vmatrix} b1 \\ b2 \end{vmatrix} = \begin{vmatrix} S11 & S12 \\ S21 & S22 \end{vmatrix} \times \begin{vmatrix} a1 \\ a2 \end{vmatrix}$$

Normalization Method of De-Embedding Test Fixture

- Provides calibration when THRU is available
- Does not correct for some errors such as source mismatch (E_{SF}) and directivity (E_{DF})

Will first consider flow diagrams of Short and Thru



For a reflect signal flow graph, Gamma is either +1 (an open), or -1 (a short)

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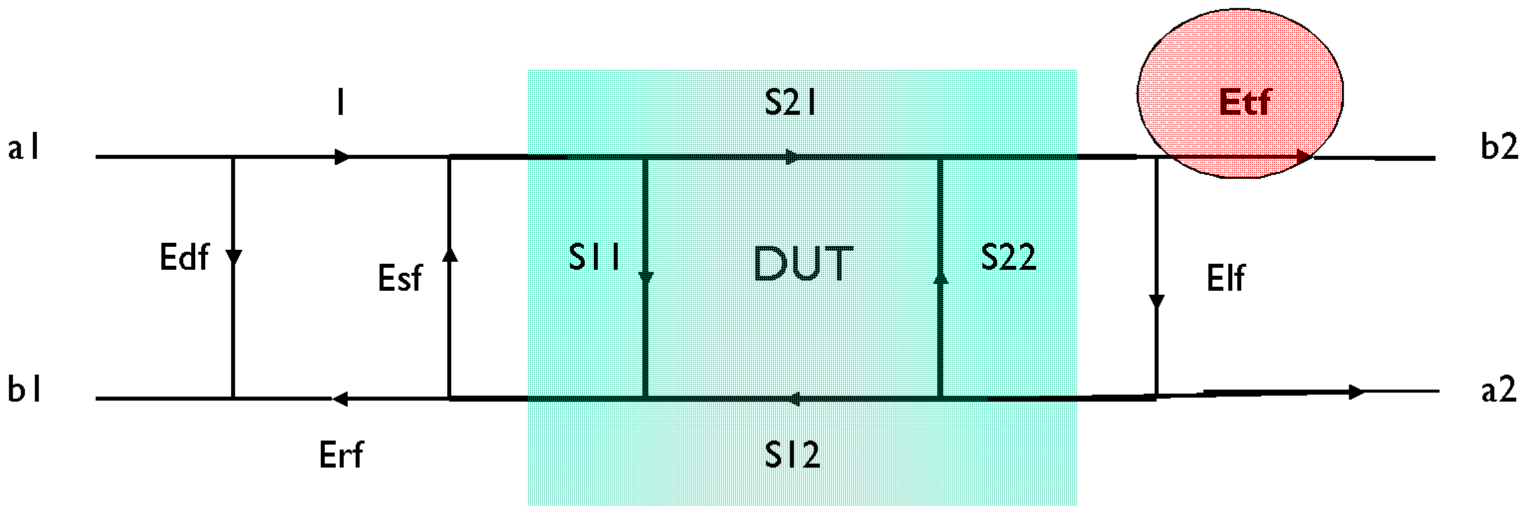
Signal Flow Diagram of THRU



General Signal Flow Diagram

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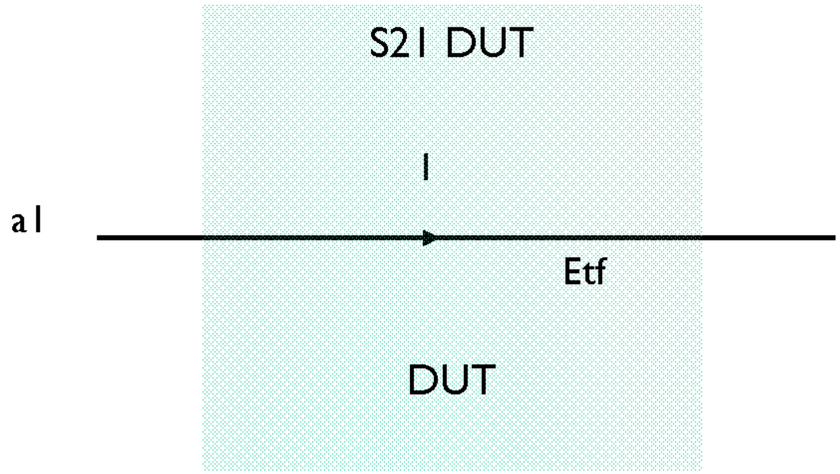
Normalization of THRU



$$S21, DUT = \frac{S21Measured}{E_{TF}}$$

$$S21Thru \approx E_{TF}$$

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TRL Calibration – Problem Definition

1. Highest Frequency: determine highest frequency of interest (example is using 24GHz for 20GHz VNA)
2. Establish THRU length. This relates to size of test board, and structure. Keep as short as possible.
3. Material properties, propagation velocity, cal board stack up, define traces (will you be using microstrip, stripline?)
4. Determine TRL calibration cal kit structures –lines, open, thru with equations or equivalent Excel tool

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TRL Calibration - Details

1. Establish Cal kit Definitions in VNA or Agilent PLTS Structures
   1. Open
   2. Thru
   3. Lines - Load
2. Perform User Global Delta Match
3. Create TRL calibration with measurements of TRL structures, save and apply cal file
4. Final Step: Confirm TRL calibration with THRU

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Concepts related to THRU and LINES 1,2, and 3 for TRL calibration

- Recall that the THRU in TRL represents zero-length structure:
  - 0dB insertion loss
  - 0° of phase
- All LINES are related to the THRU
  - LINES increase in length, and this delta length relates to the calibration frequency span of the line
  - LINES cannot span multiples of 180°

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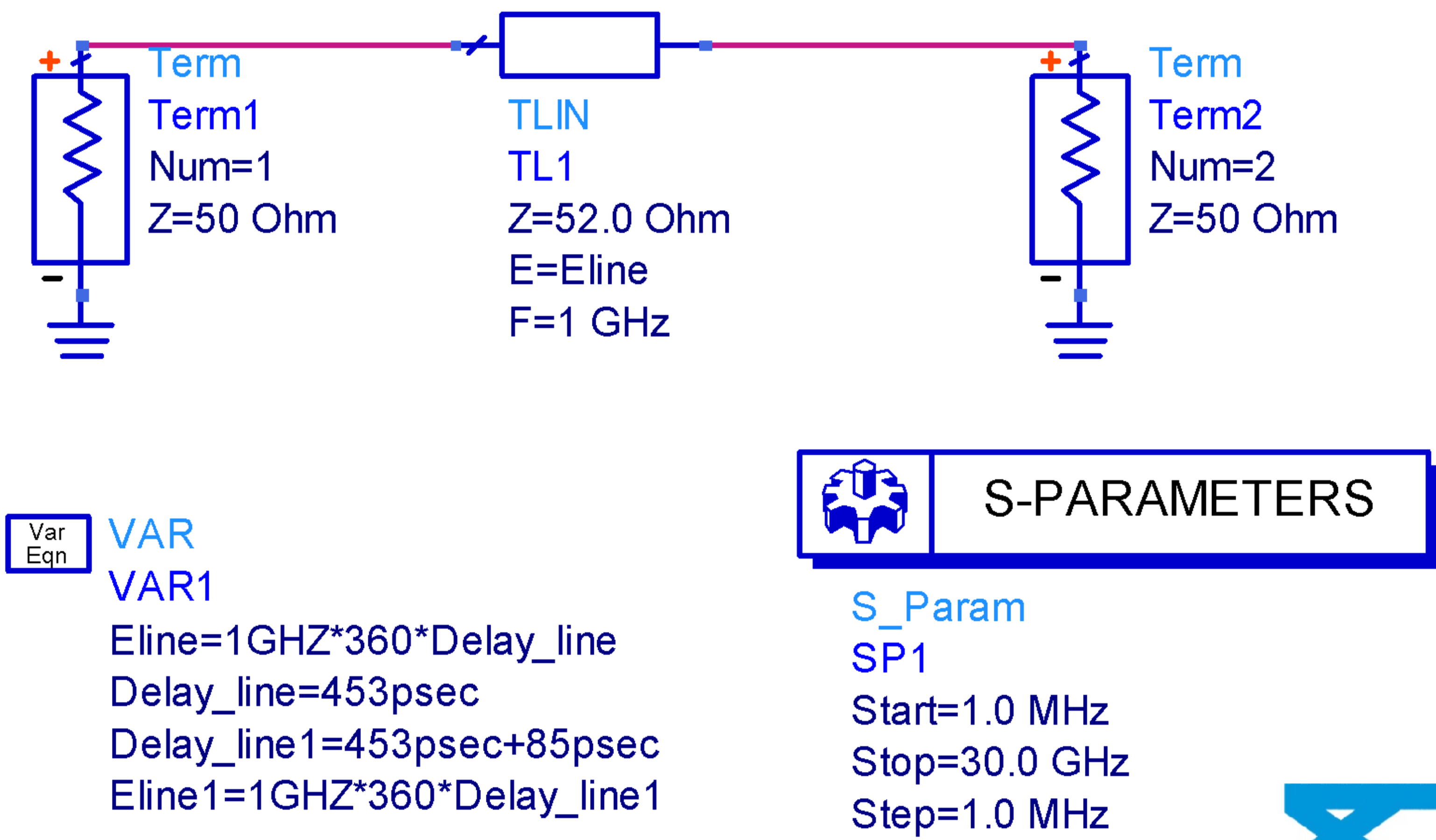
Building a Simple model of a THRU, lets say it is 52ohms



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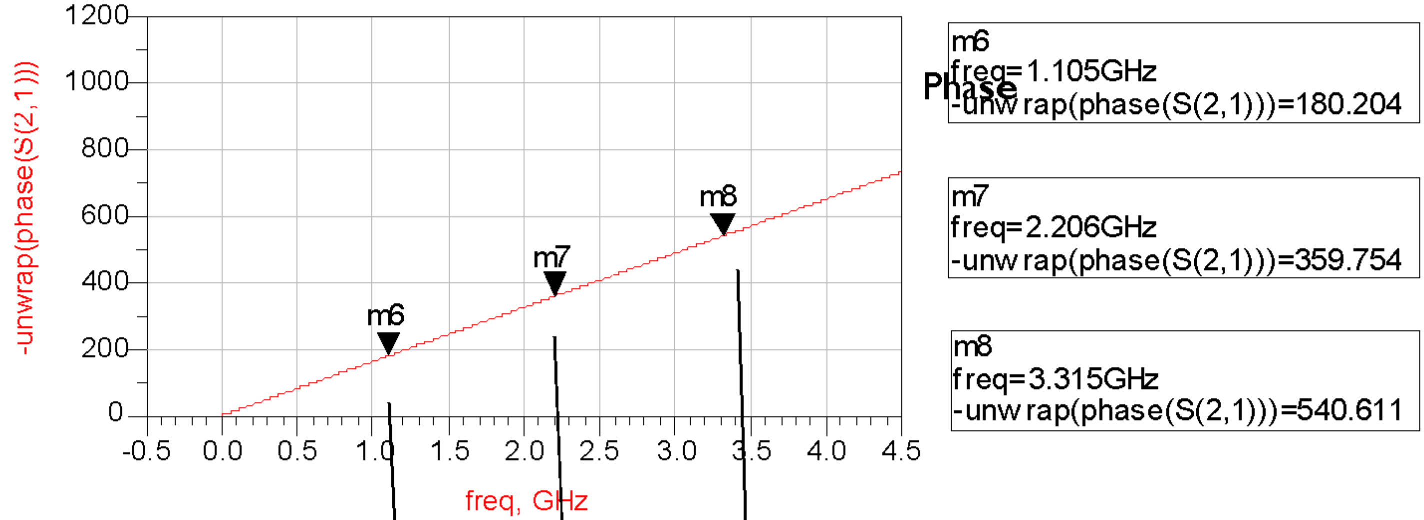
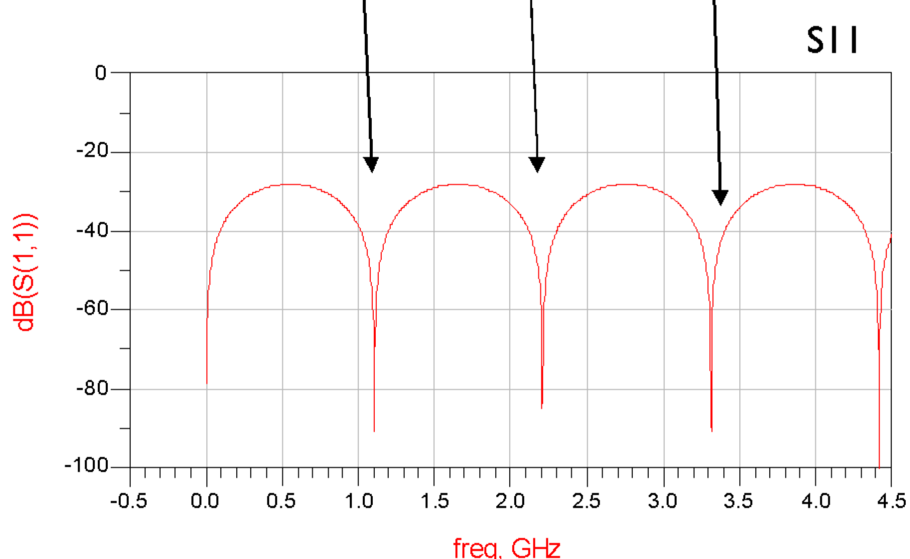
Phase, S11, and S22 of THRU with Length of 453psec





An actual THRU has resonances at every 180degrees. Lines 1,2, and 3 cannot overlap on at these frequencies. Typically 30 to 150 degrees are good offset frequencies.

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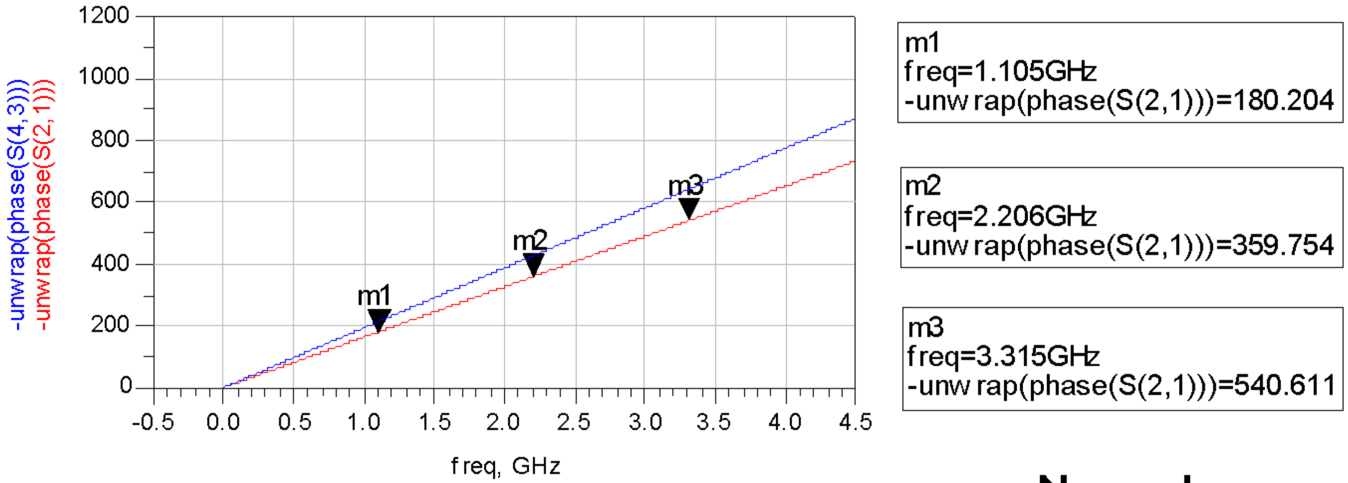
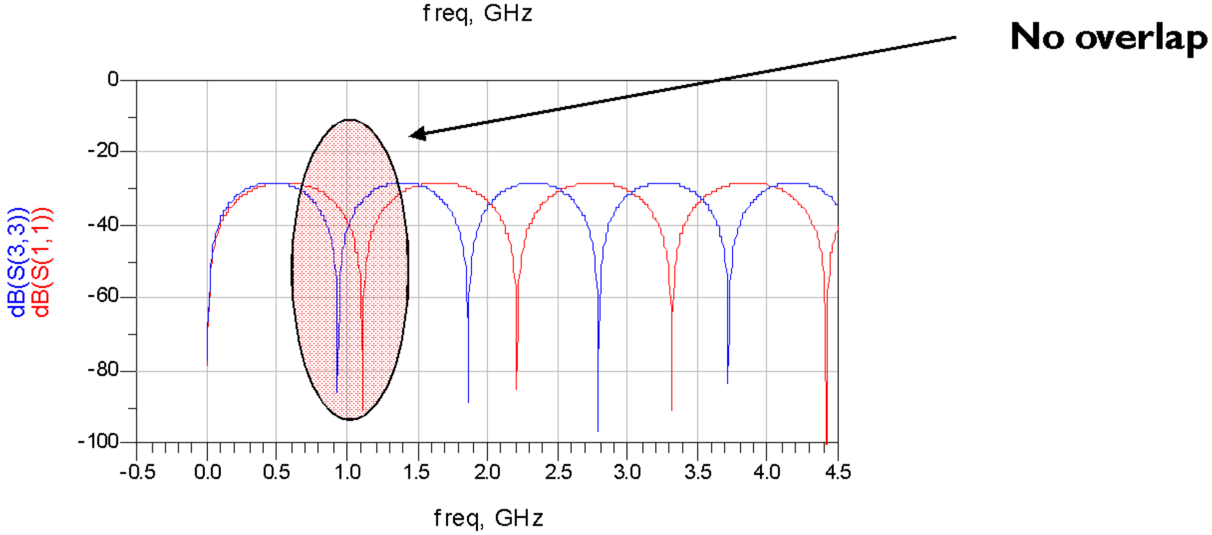
LINE1 (blue trace), 18psec longer than THRU (red trace)





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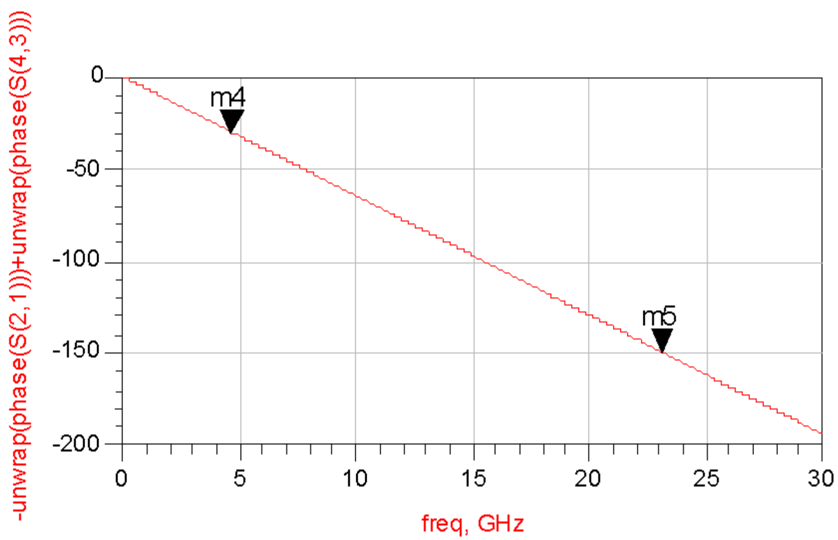
LINE 1 30 to 150degrees corresponds to 4.66GHz to 23.08GHz calibration span for this line

Note: LINE1 phase is subtracted from THRU



m4
freq= 4.662GHz
-unwrap(phase(S(2,1)))+unwrap(phase(S(4,3)))=-30.202

m5
freq= 23.08GHz
-unwrap(phase(S(2,1)))+unwrap(phase(S(4,3)))=-149.574

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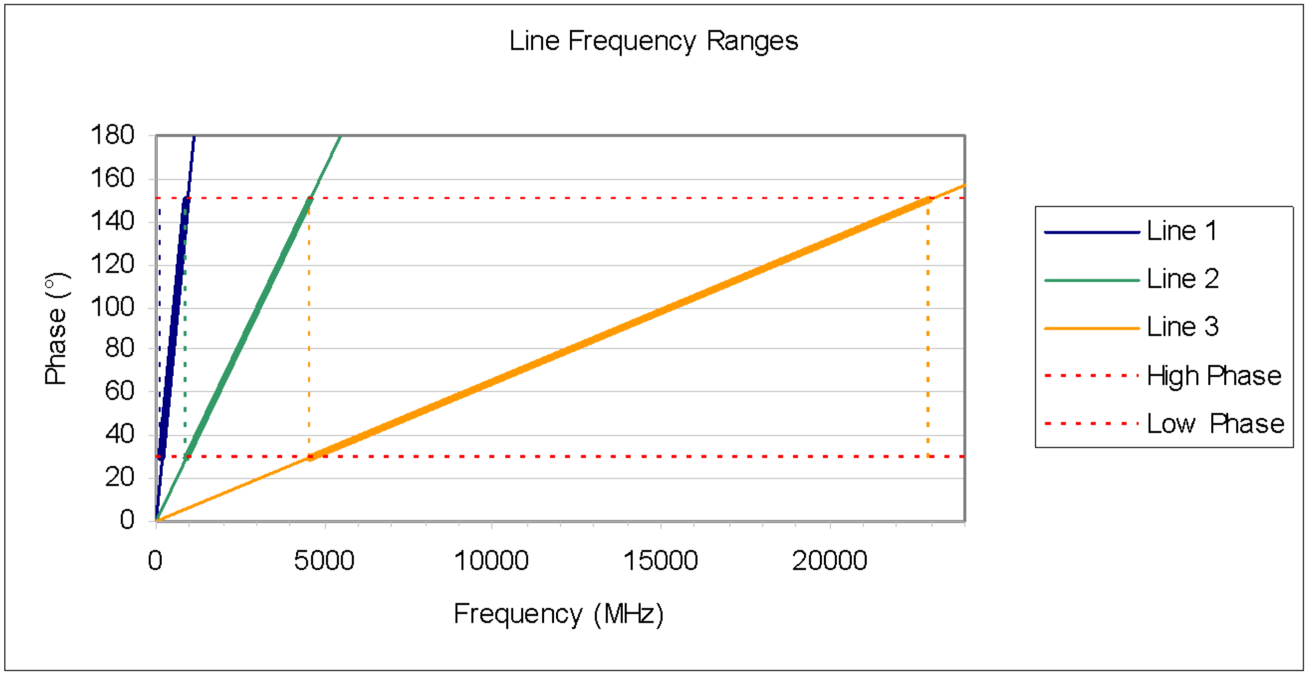
Line Definition

- We chose 30° and150° and computed:
  - Line1 = 18 psec
  - Line2 = 91 psec
  - Line3 = 454 psec



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Optionally use Molex Excel spreadsheet (used with permission)

TRL Calibration Calculator for Microstrip

Inputs:	Effective Dk	Reference Length(mm)	Reference Length(in)	Frequency Ratio	Low Phase	High Phase
	3.2	44.45	1.75	5	30°	150°

Outputs	Start Frequency (Ghz)	Stop Frequency (Ghz)	Time Delay (ps)	Line Length (mm)	Line Length (in)
Short/Open			0	44.45	1.75
Load	0	183.31	0	44.45	1.75
Line 3	183.31	916.55	454.61	165.0873	6.4995
Line 2	917.92	4589.6	90.79	104.1146	4.099
Line 1	4585.76	22928.8	18.17	91.94546	3.6199
Thru			0	88.9	3.5

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Design of Cal Kit TRL Structures

- Lines are T_{Thru} plus T_{Delta}
- Delta Line length are defined so that the time delay of the line fits between 30 and 150 degrees of the band of frequencies
- If T_{Delta} was 18psec
  - Low frequency
    - $30/360 * 1/F_{low} = 18$psec
  - High frequency
    - $150/360 * 1/F_{hi} = 18$psec

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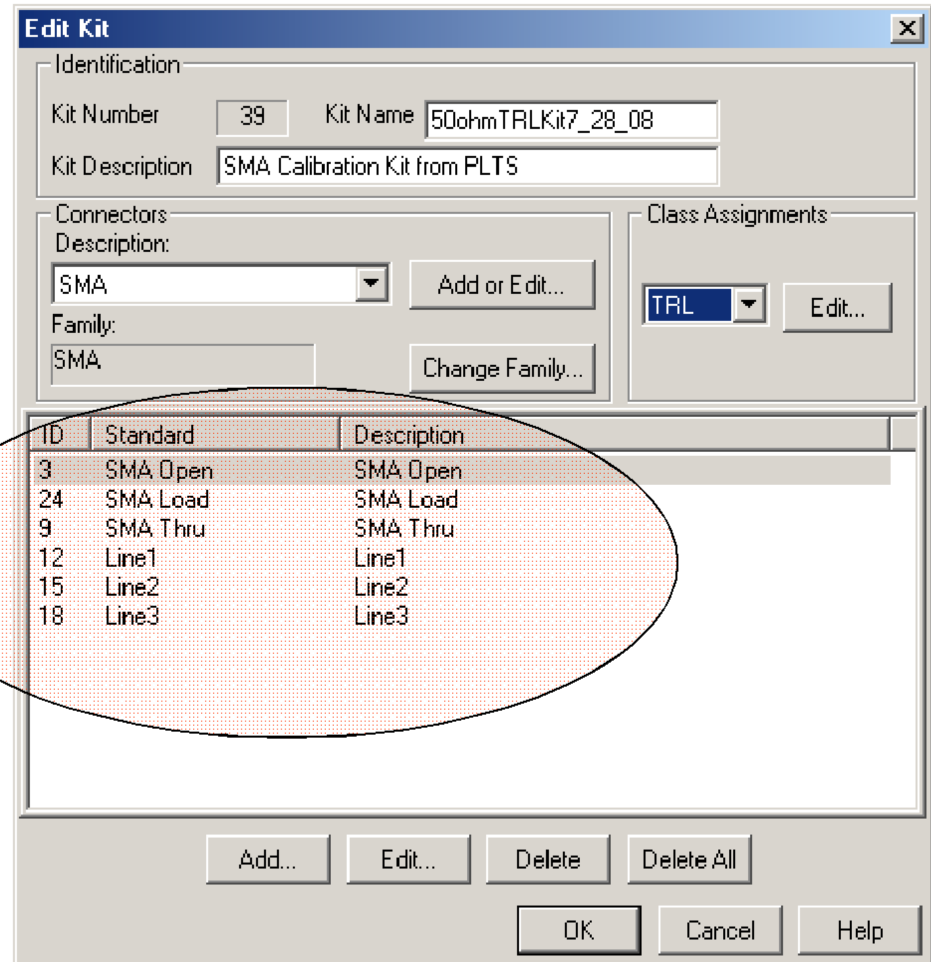
TRL Calibration Kit Definition

- Define Cal Kit Standards
- Save it
- Use it



Note that Load (or Match) refers to a LRM calibration (not TRL), which is Load-Reflect-Match

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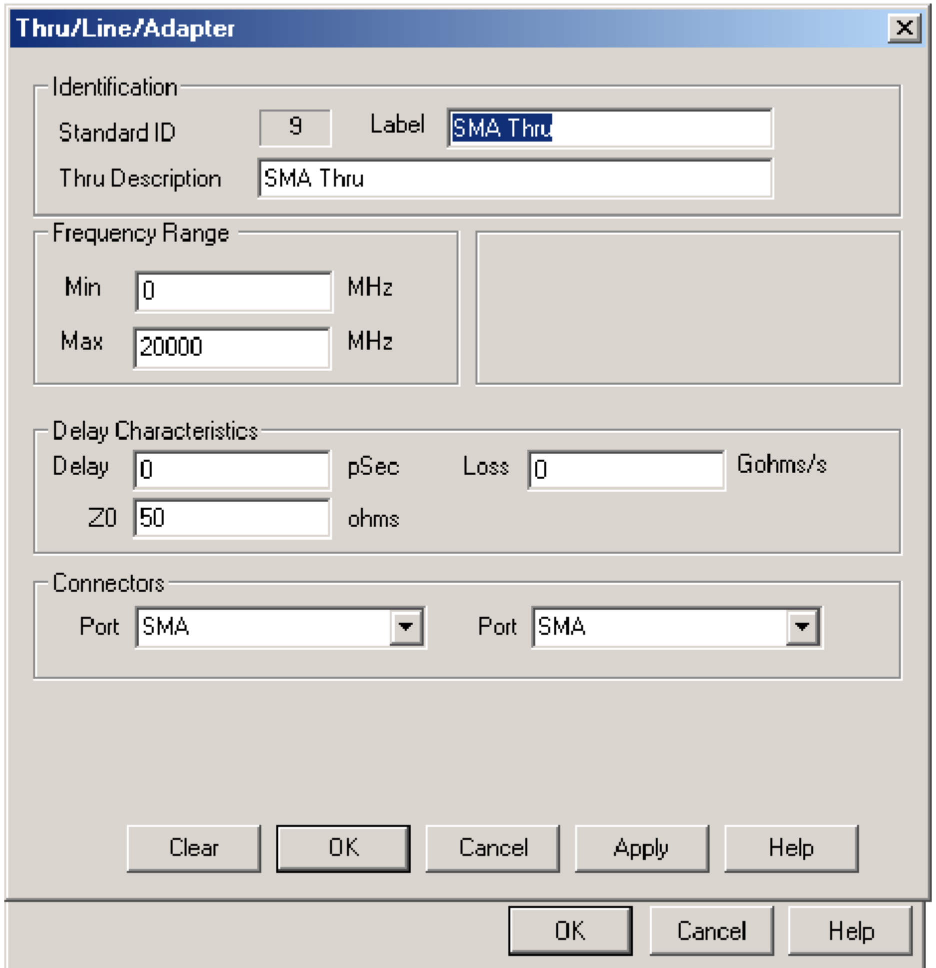
Thru Definition



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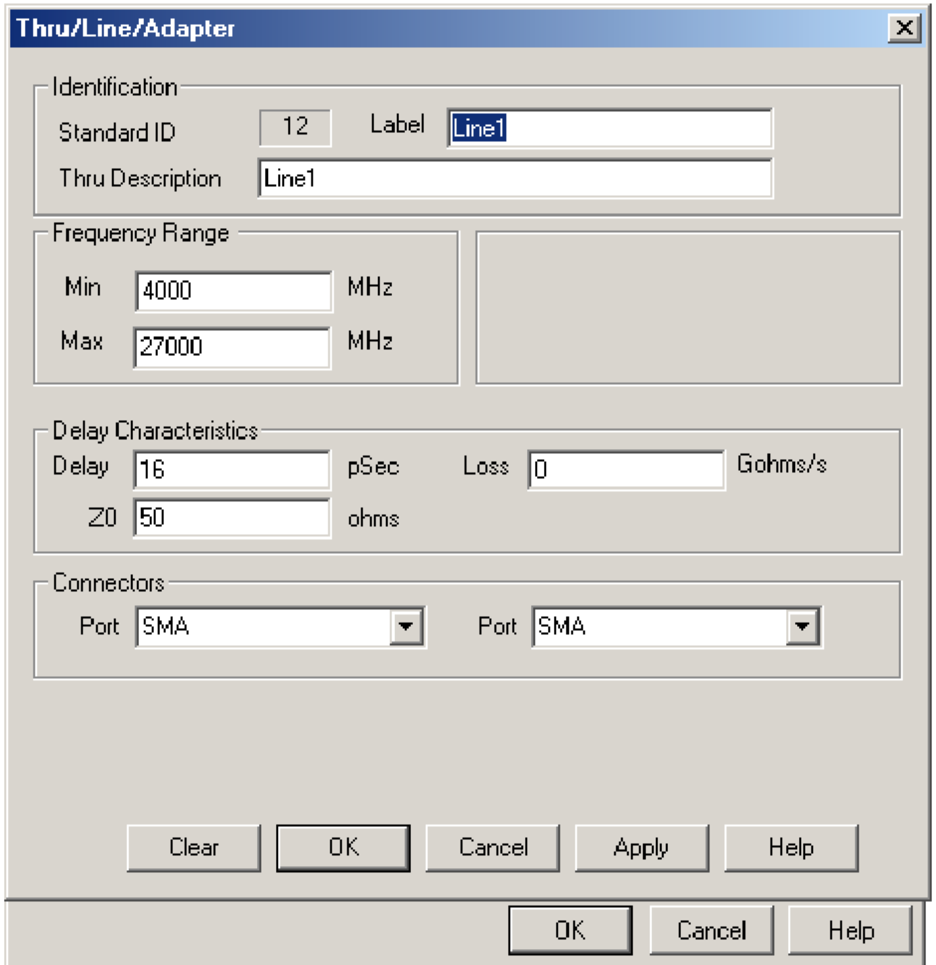
Line1 Definition



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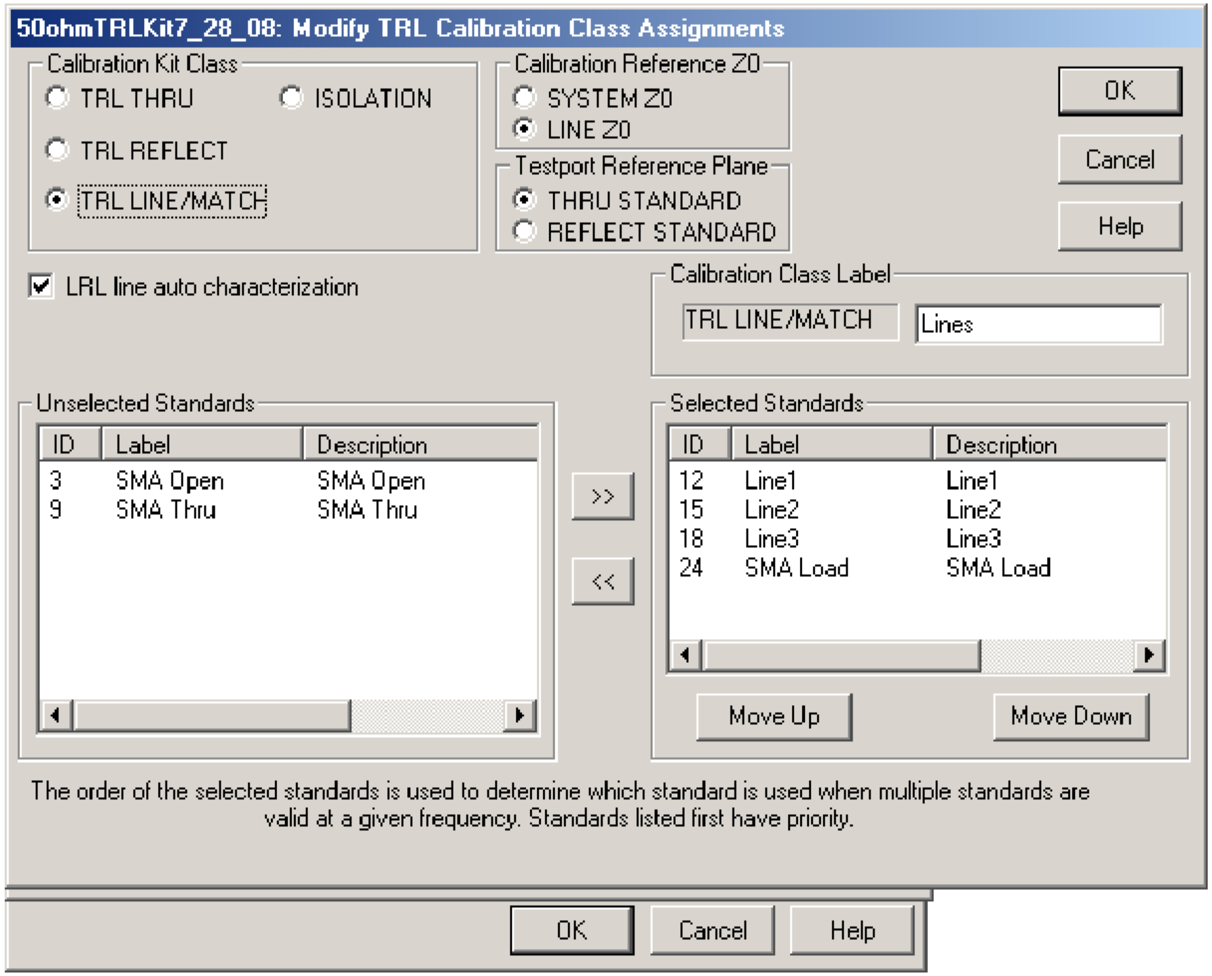
Line/Match Class



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What makes a good TRL calibration kit design?

- Consistent RF Launches
- Consistent Line impedance

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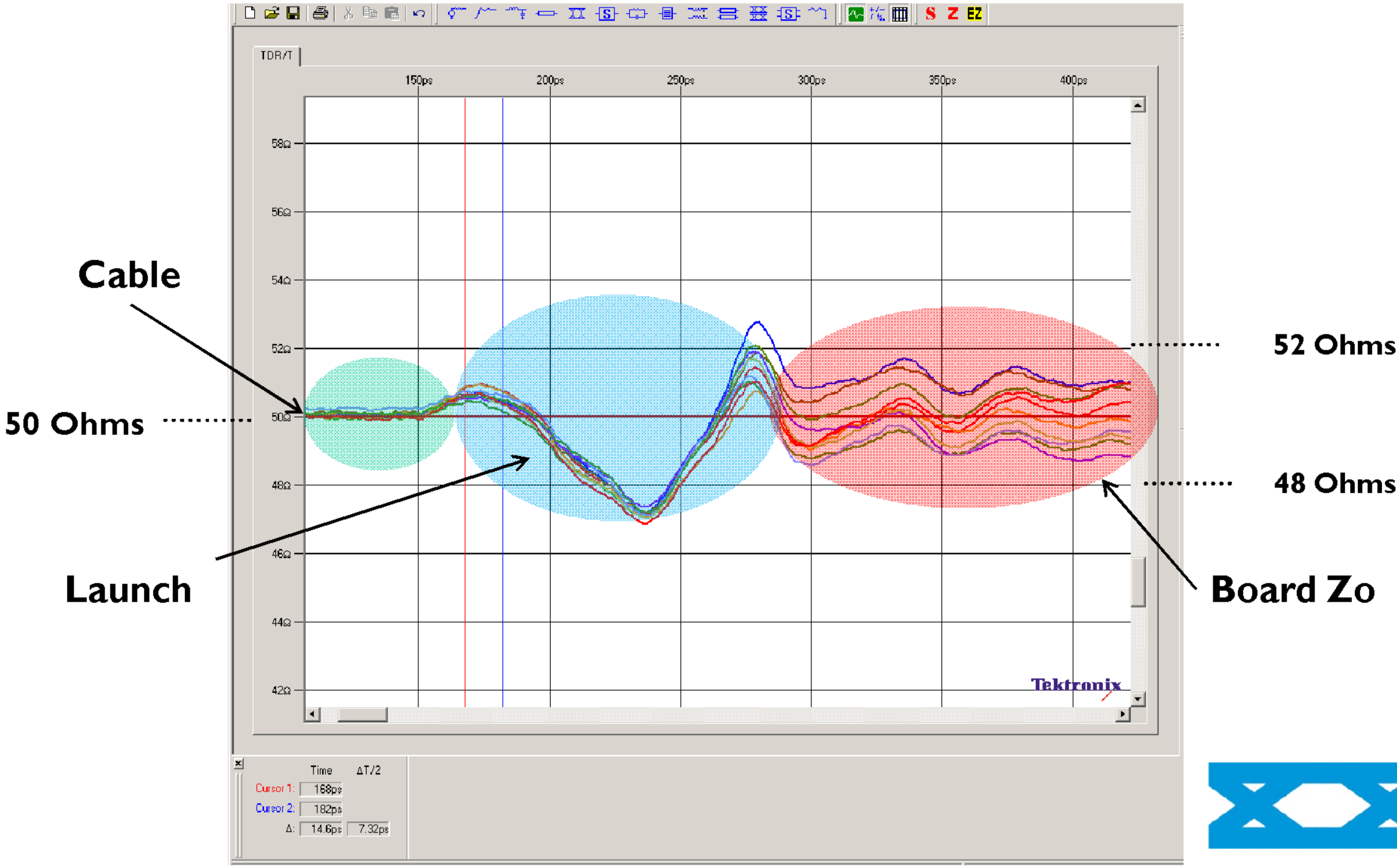
Goal is Consistent Zo through system



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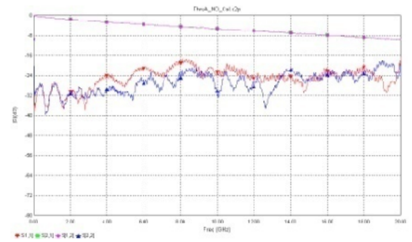
Performing the actual TRL/LRM Calibration

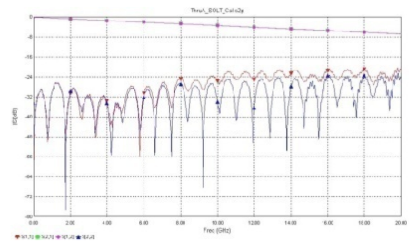
- Follow the prompts from the VNA
  - Measure Reflect
  - Measure Thru
  - Measure Lines and Load
- We have generated 2 and 4 port TRL calibrations

Calibration Comparison

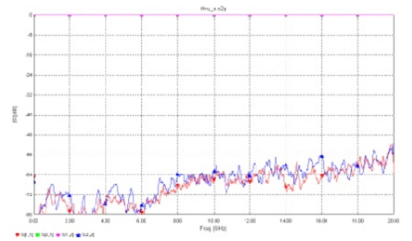
THRU A with No Calibration



THRU A with SOLT Calibration



THRU A with TRL Calibration



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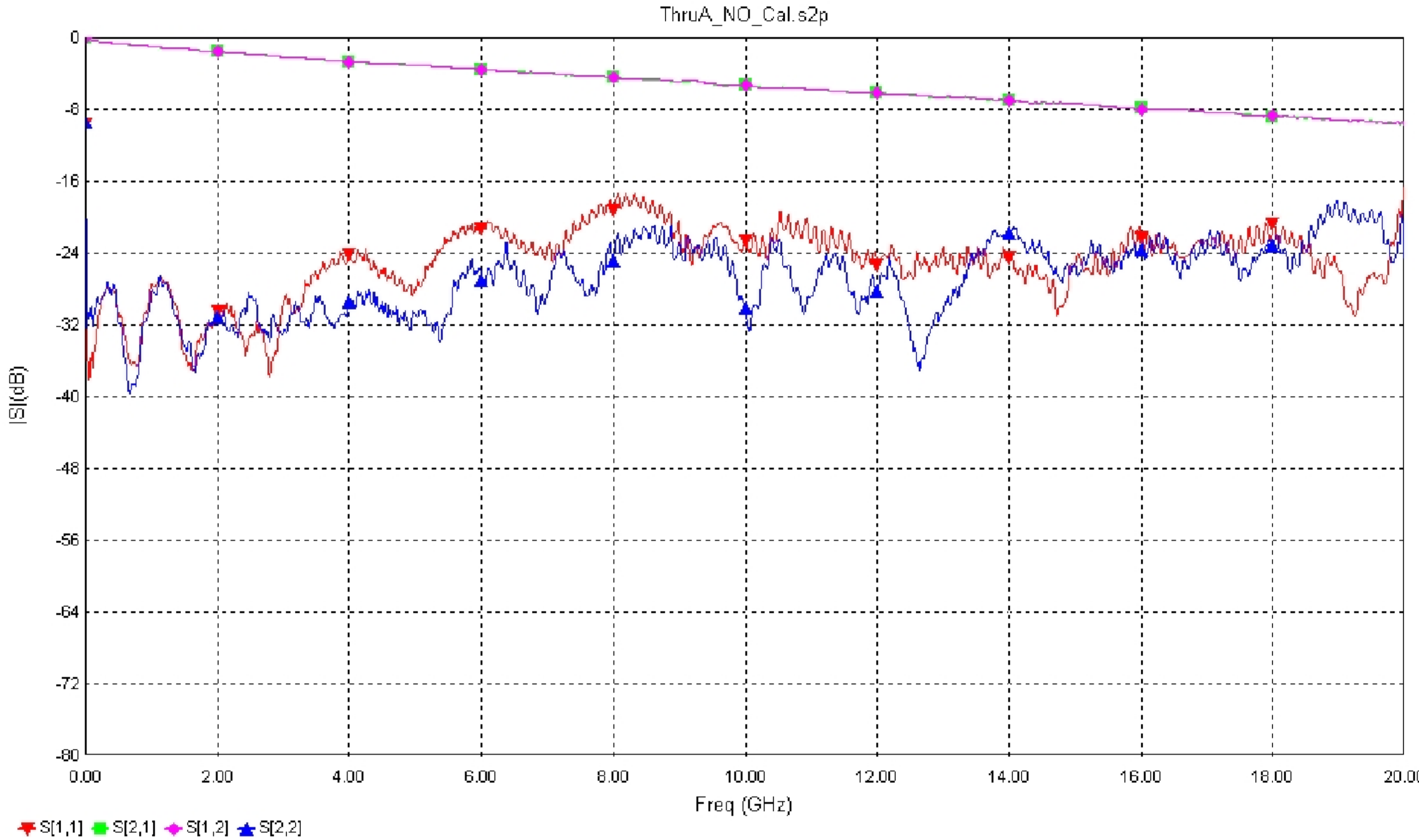
Thru A with no Calibration



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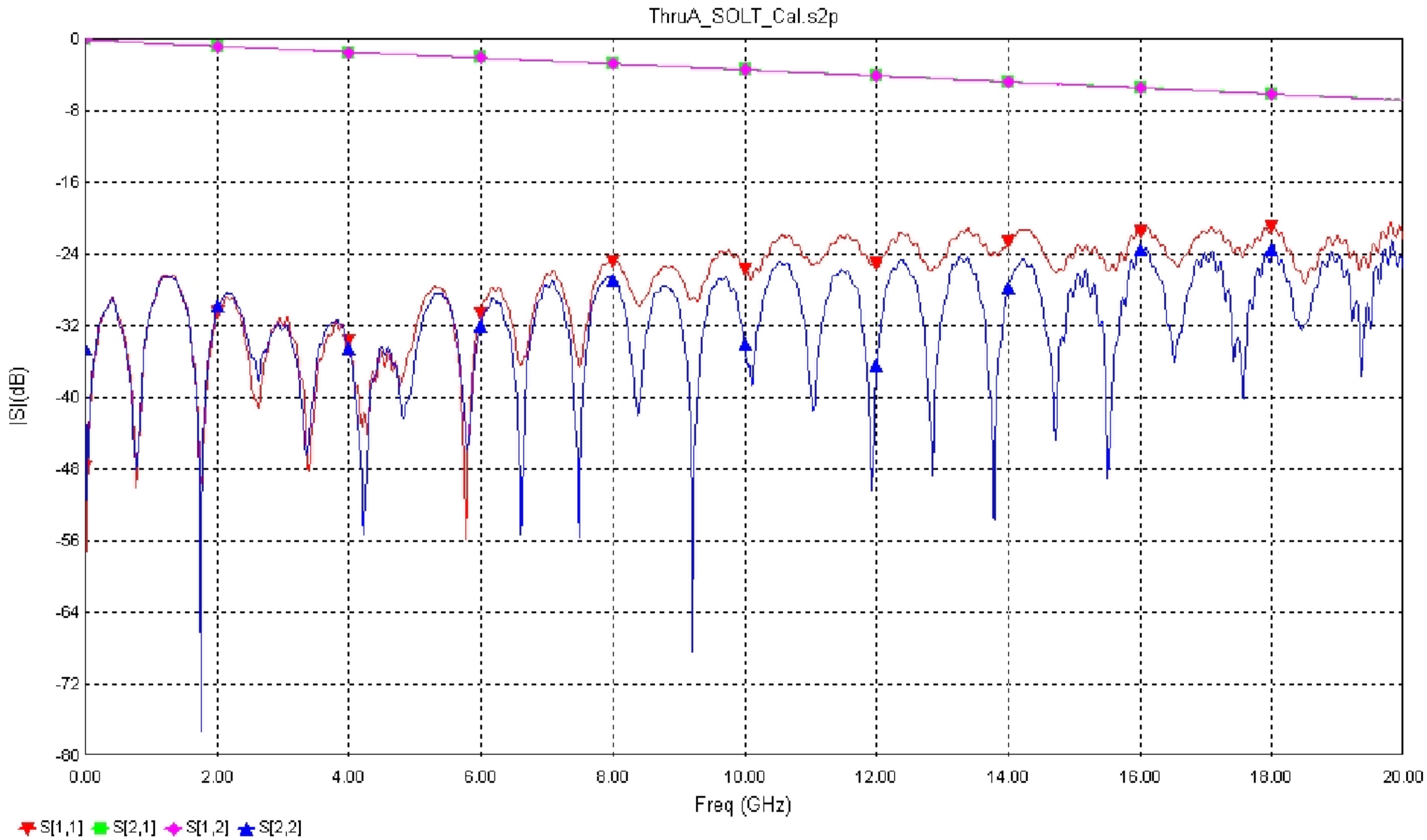
Thru A with SOLT Calibration



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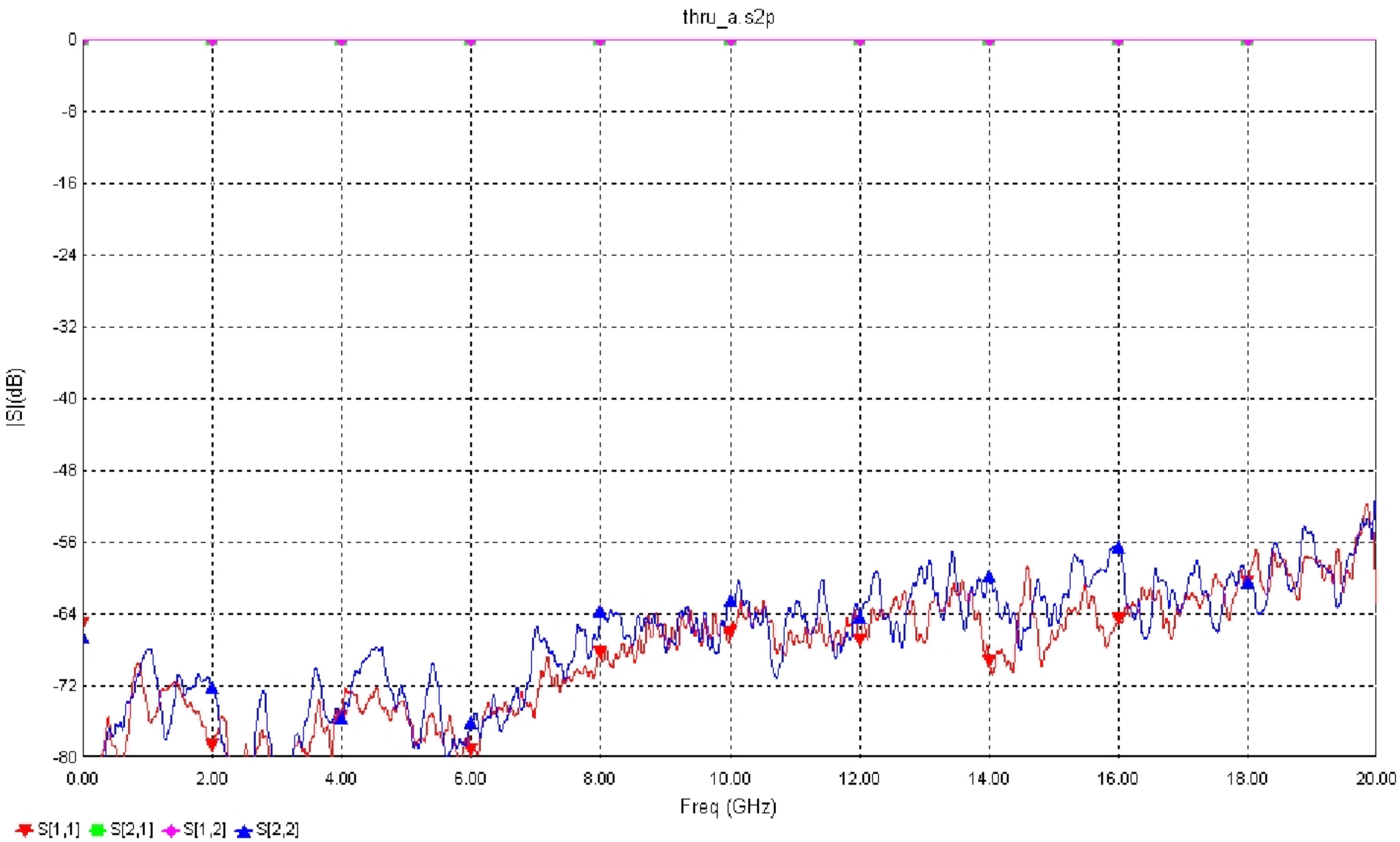
Thru A TRL Calibration



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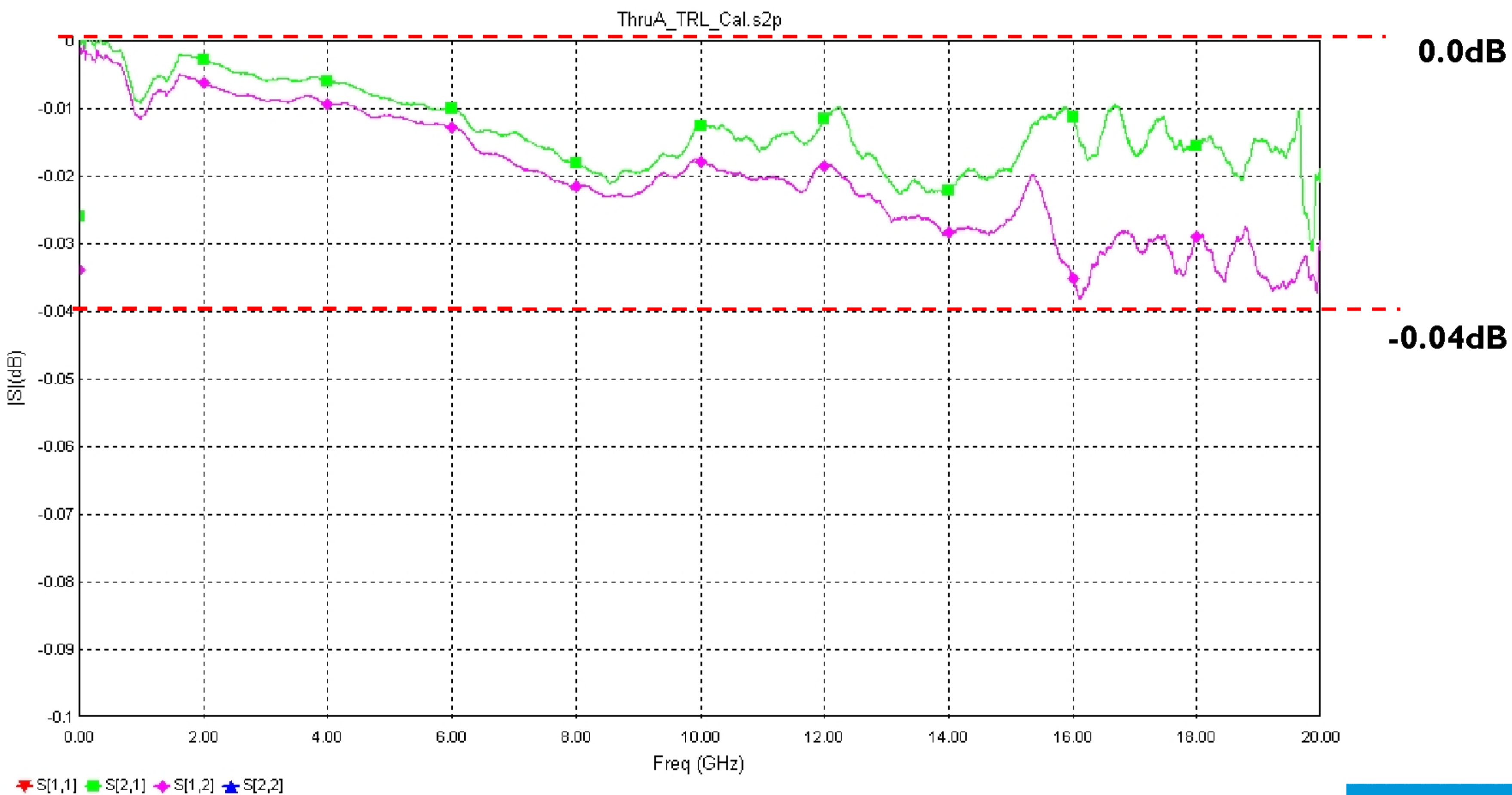
Thru A TRL S21 detail,

0.04dB error to 20GHz



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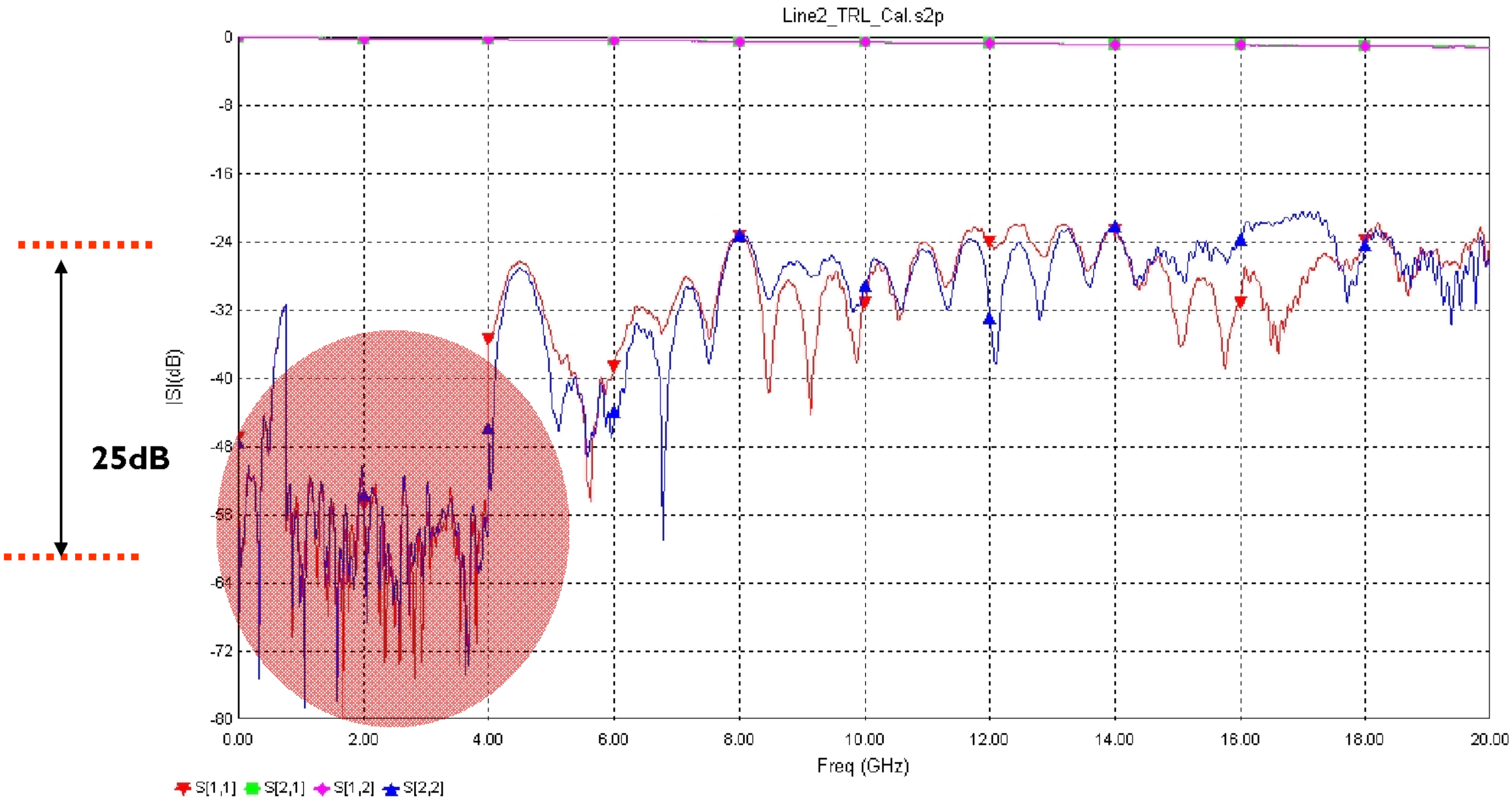
Line 2 S11 anomaly – low reflective structures similar to line standards



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Relate system Zo to s11 variation for TRL

Impedance, ohms	|s11| in %	|s11| dB
38	13.6	-17.3
40.0	11.1	-19.1
42.0	8.7	-21.2
44.0	6.4	-23.9
46.0	4.2	-27.6
48.0	2.0	-33.8
50.01	**0.0**	**-80.0**
52.0	2.0	-34.2
54.0	3.8	-28.3
56.0	5.7	-24.9
58.0	7.4	-22.6
60.0	9.1	-20.8
62.0	10.7	-19.4
64.0	12.3	-18.2

Impedance Match Goals

- Well matched is -20dB
- Good match is -30dB
- Difficult to achieve is -40dB

Recall:

- S11=(Zdut-Zo)/(Zdut+Zo)
- dB representation of S11 is 20*log(s11)

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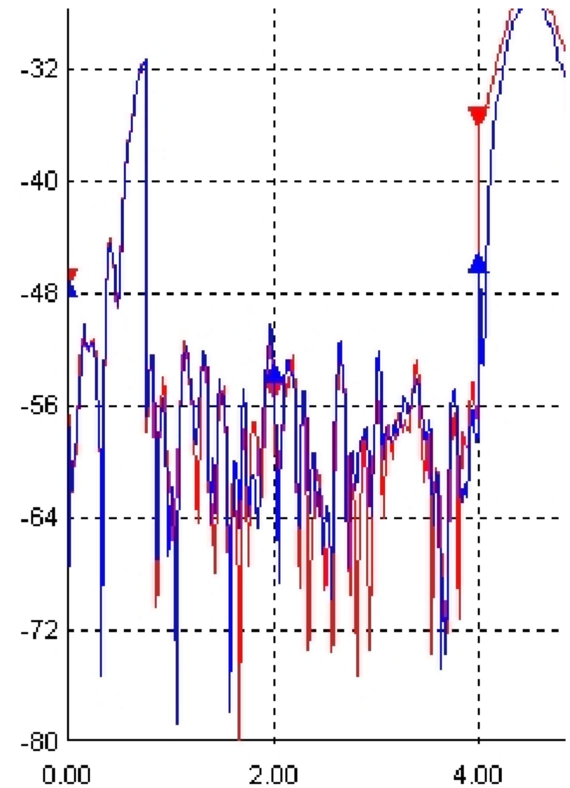
Explanation for low-reflective structure S11 anomaly

- Line 2 was used to calibrate in the 760 to 4600 MHz band
- Zo not calibrated outside of cal kit defined frequency range
- Variation of Line1,2,3 impedance in relation to TRL algorithm



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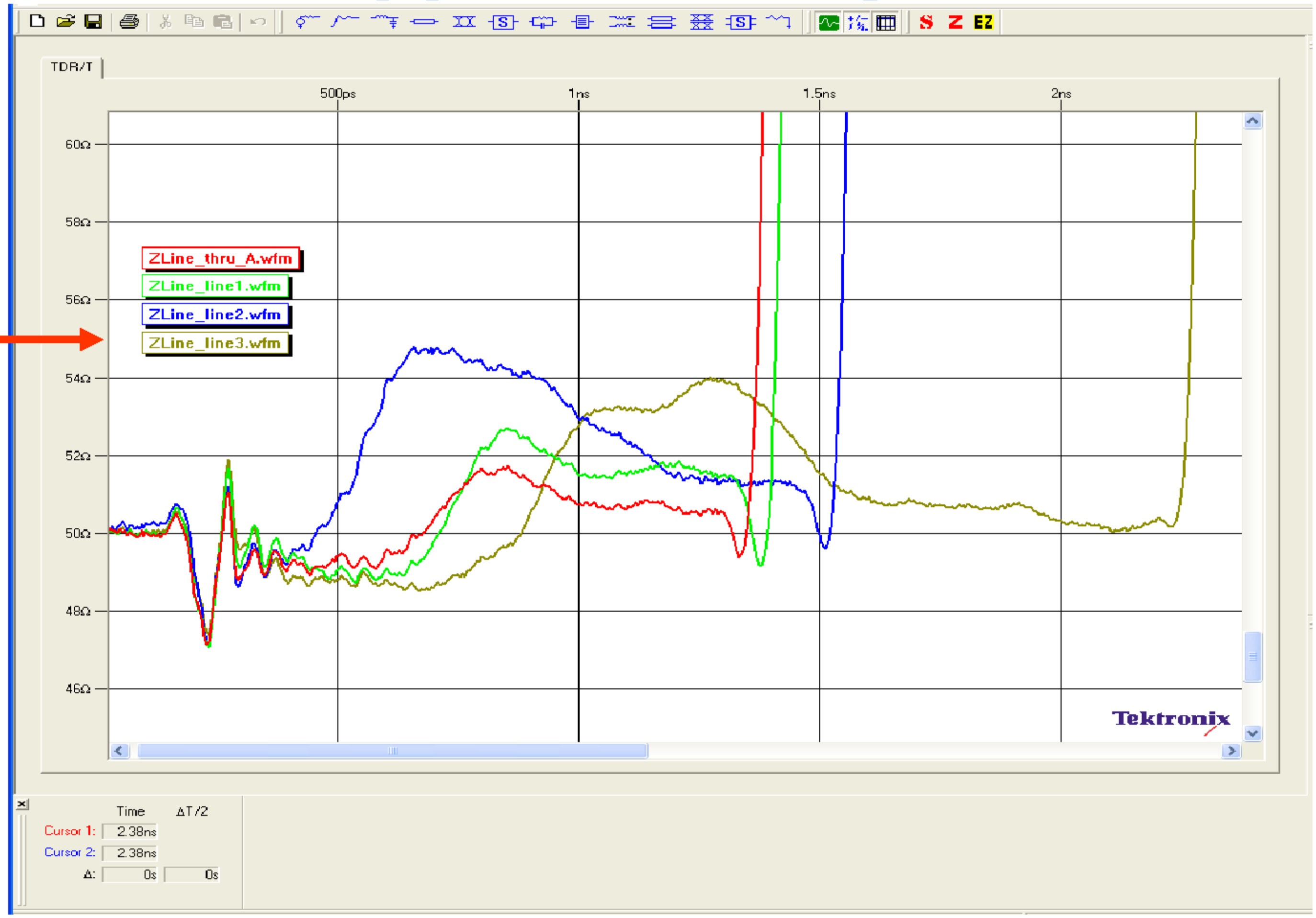
Impedance Profiles THRU, LINE1,2,3 variation approximately 10%

55ohms, or 10% impedance variation

Which agrees with S11 of -25dB



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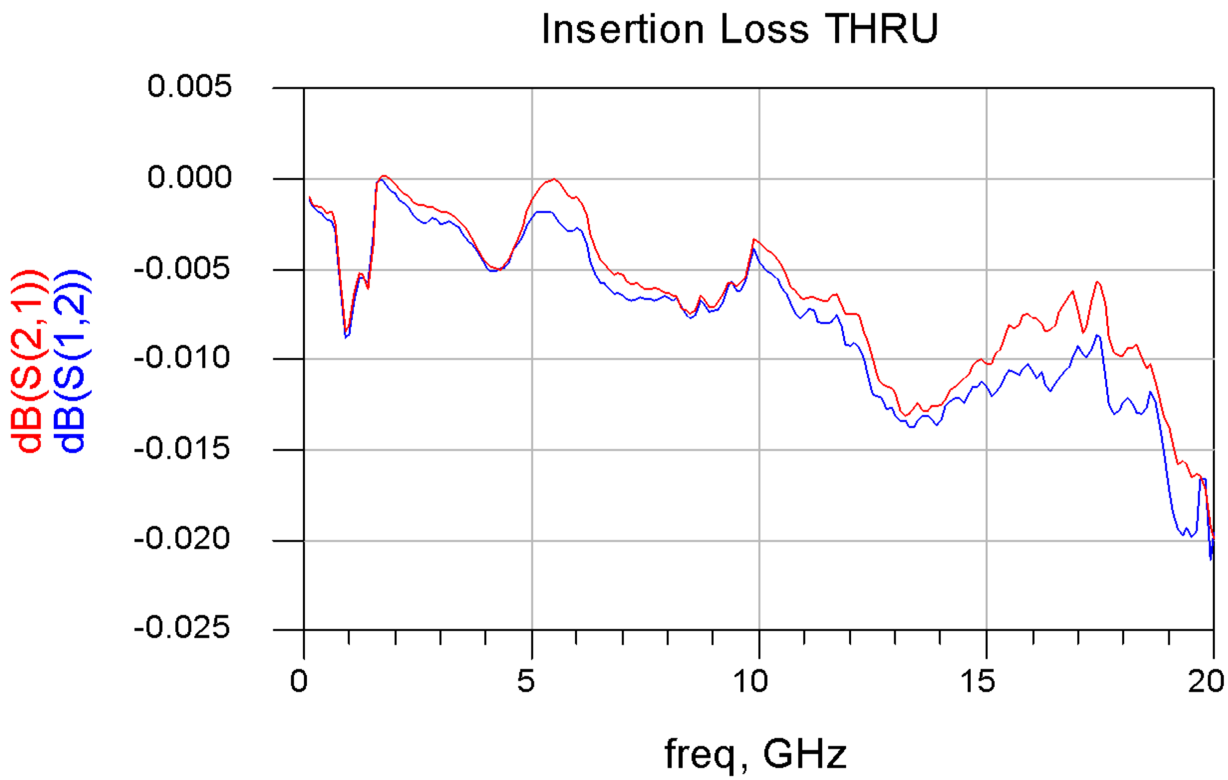
TRL Performance Measures:
Start with THRU measurement



THRU should have 0dB of magnitude loss, 0dB of phase, 0psec of Group Delay

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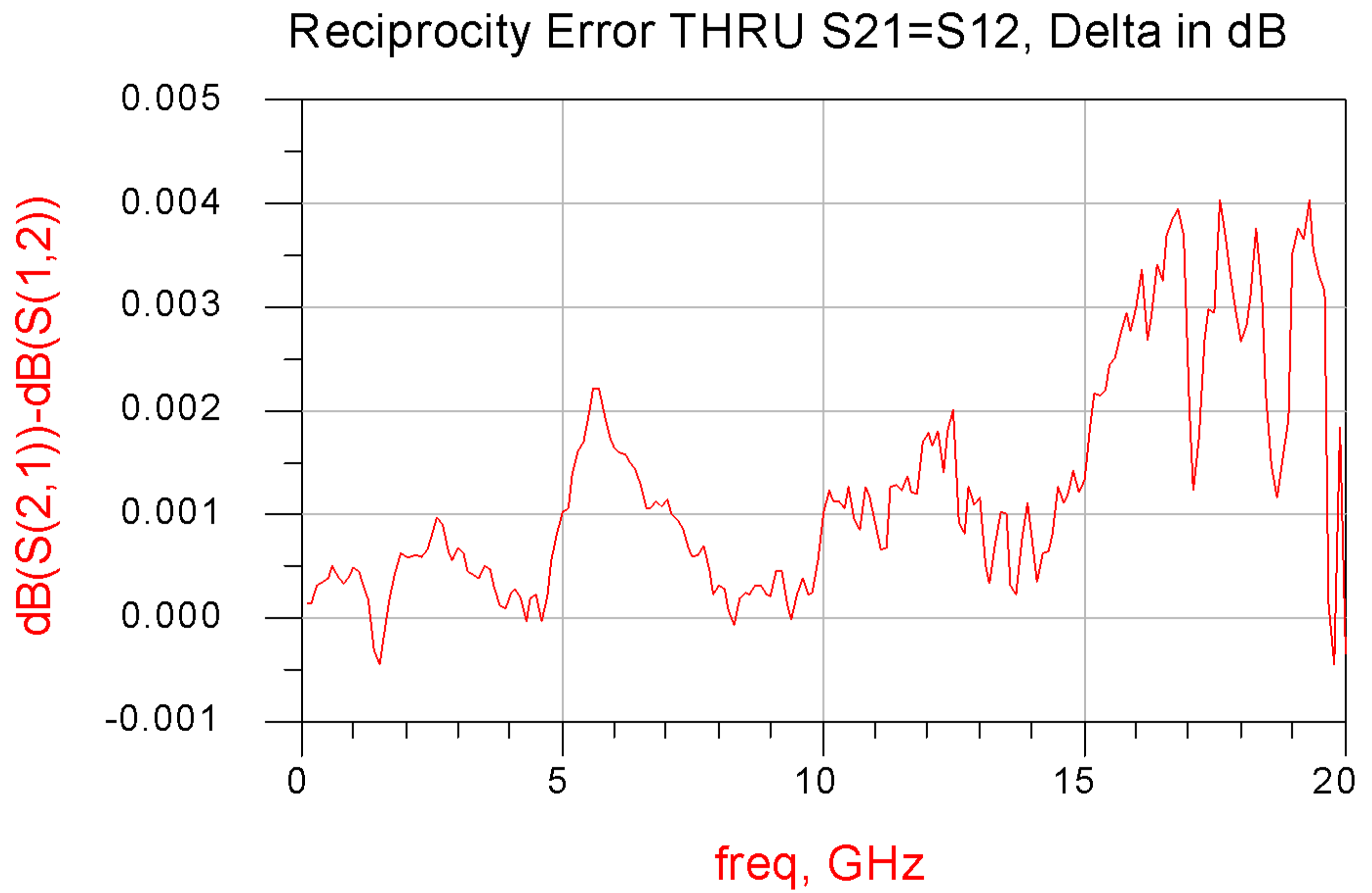
Very Low Reciprocity MAG Error, less than 0.005dB



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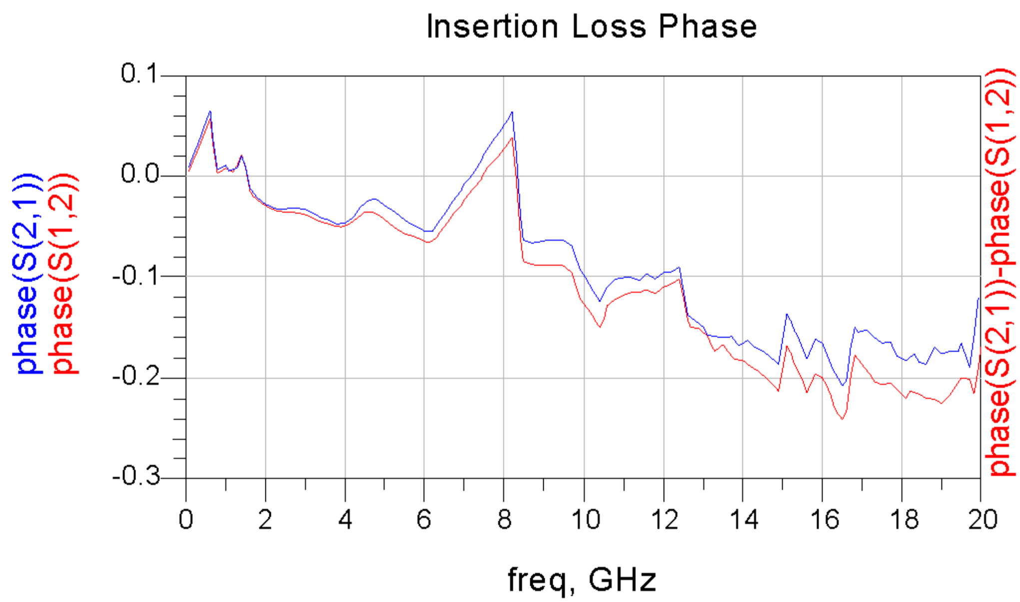
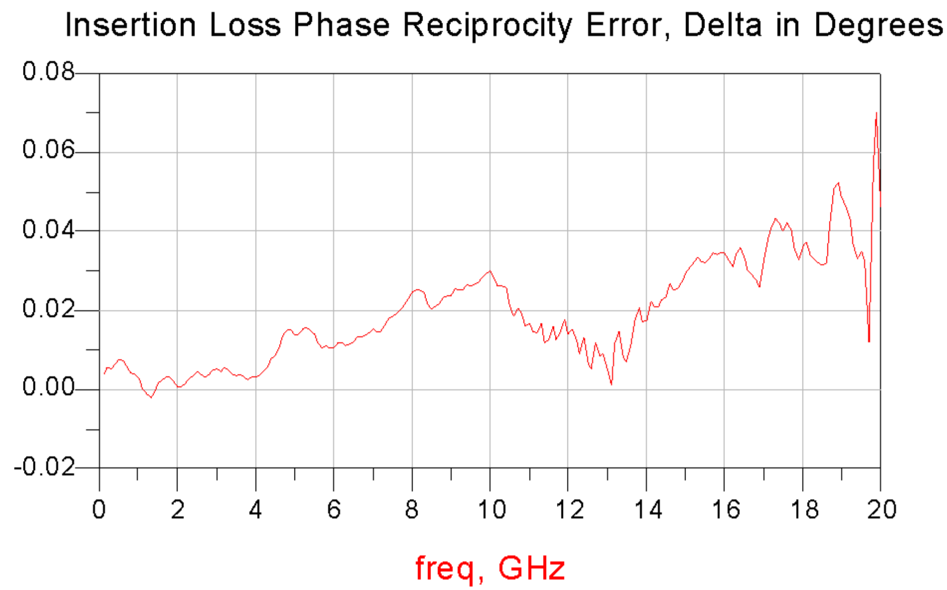
Reciprocity PHASE Error and Reciprocity for THRU Insertion, less than 0.4 degrees





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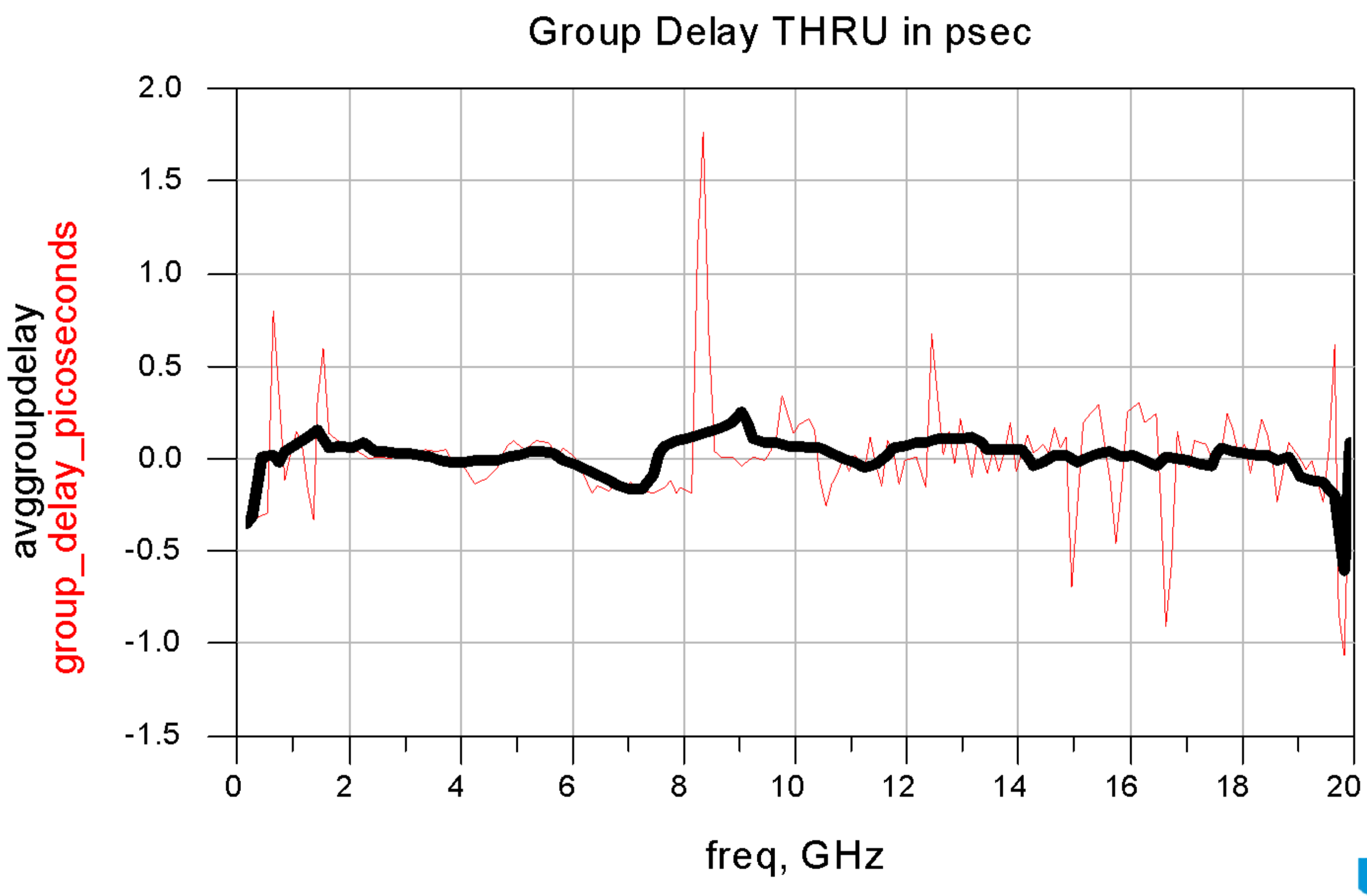
Group Delay and Box Car Average of THRU



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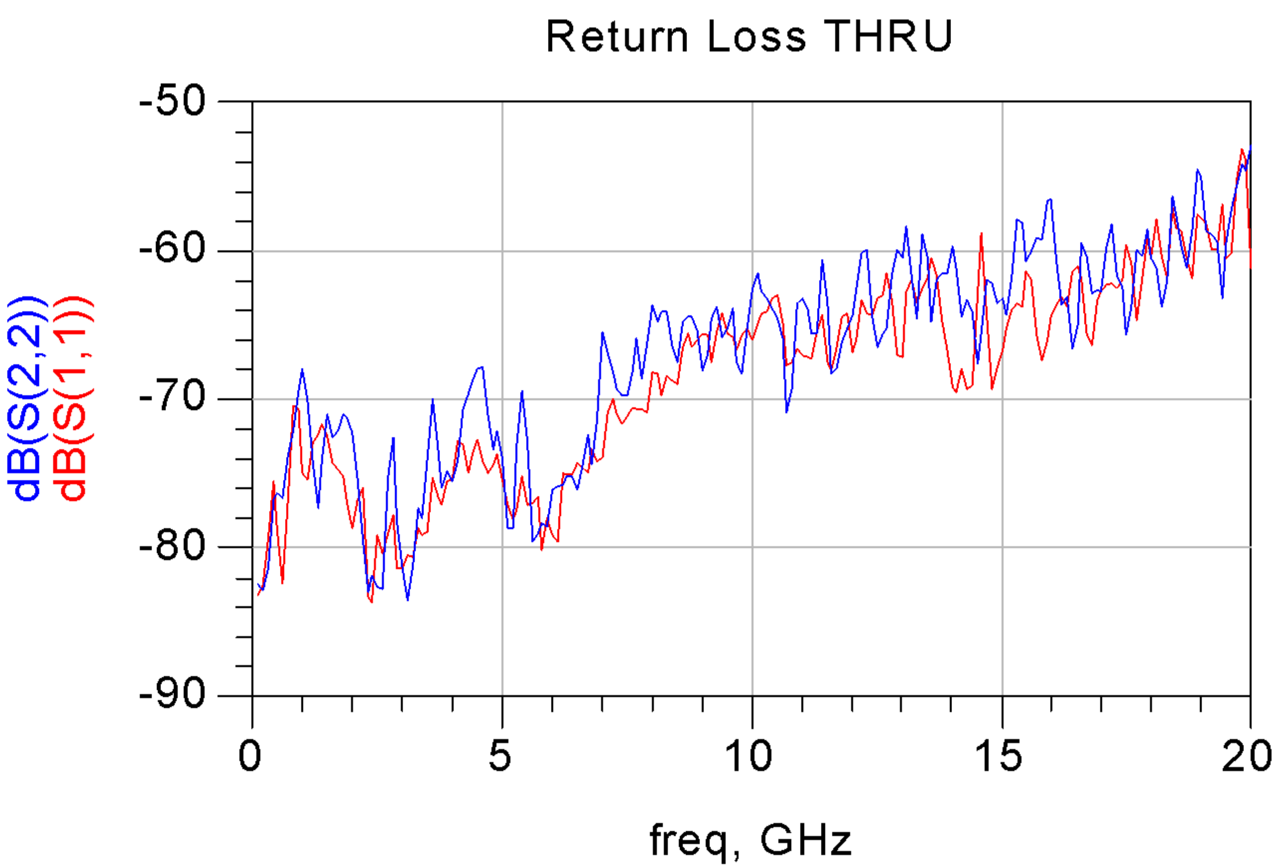
Return Loss THRU



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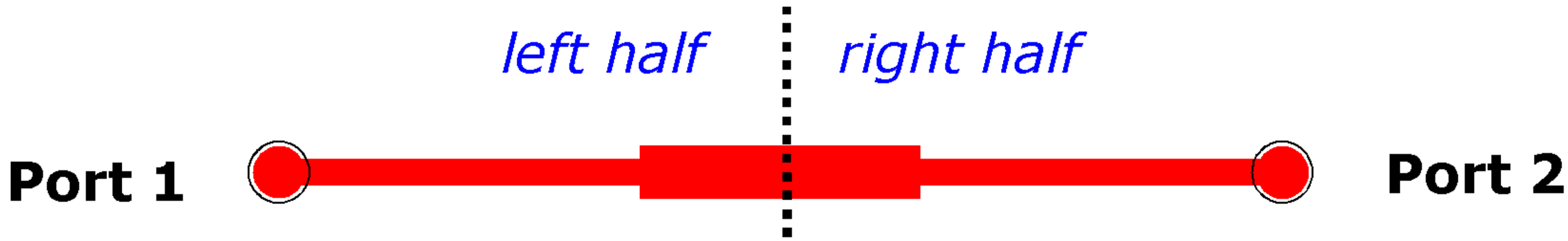
Improving TRL De-Embedded Data

Given a simple structure such as Beatty standard:



- Structure has 1st order geometric **symmetry** if (left half)=(right half), or reflection coefficients are equal: **S11=S22**
- Structure is reciprocal if no anisotropic materials used or **S21=S12**
- Structure is passive if no energy generated of *eigenvals***(S)<=1.0**

$$[\,\mathbf{S}\,] = \begin{vmatrix} S11 & S12 \\ S21 & S22 \end{vmatrix}$$

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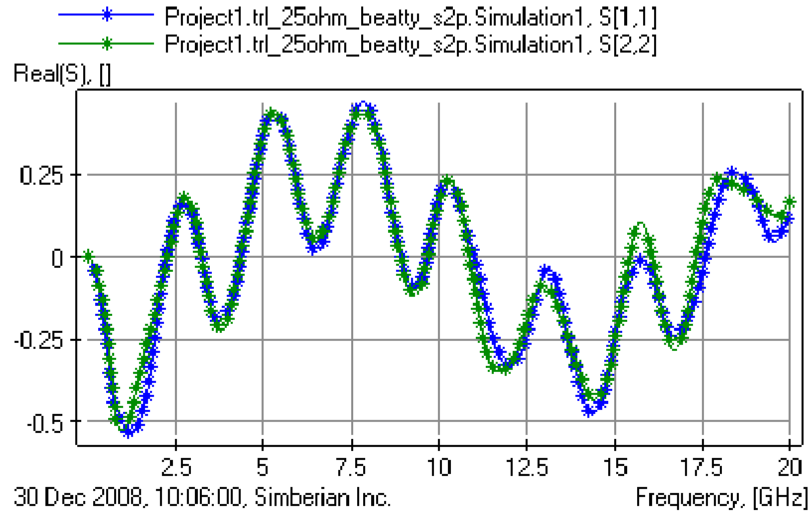
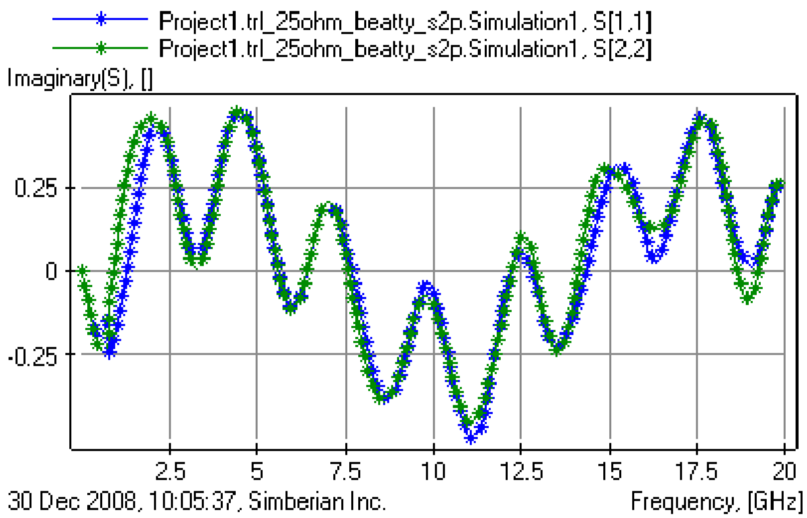
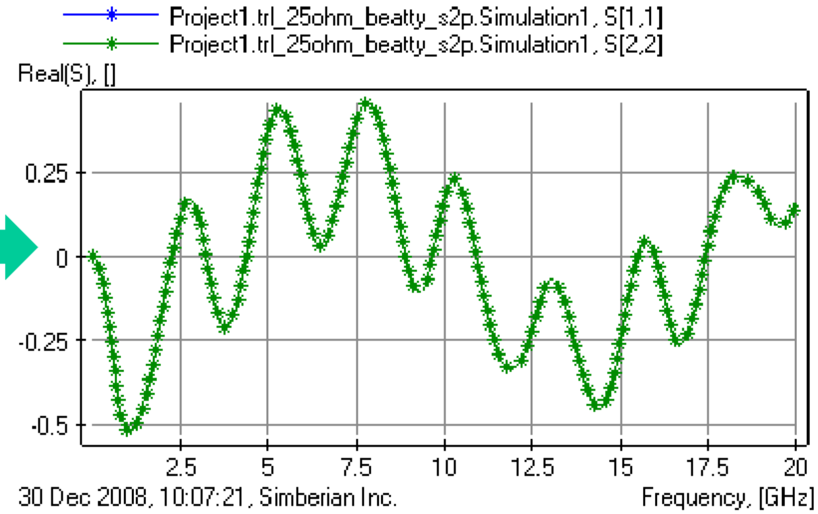
Example of Symmetry Enforcement for 25-Ohm Beatty

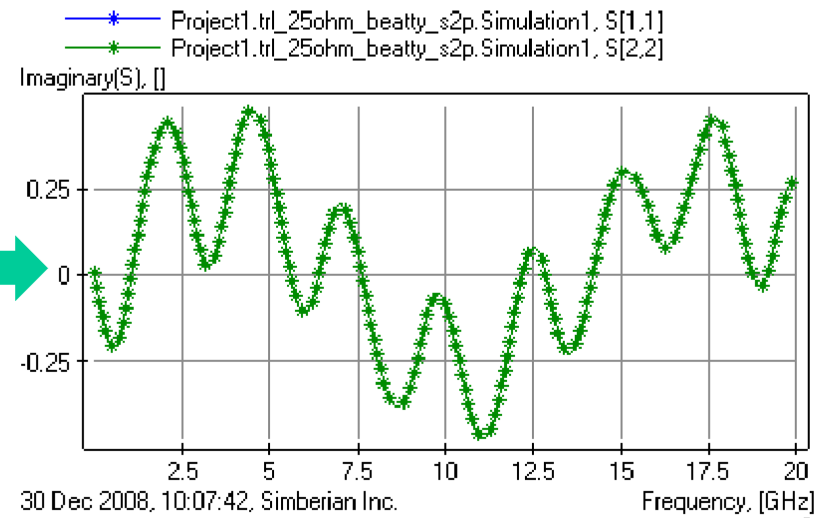
Initial non-symmetric data (S[1,1]!=S[2,2])





After enforcement of symmetry (S[1,1]=S[2,2])





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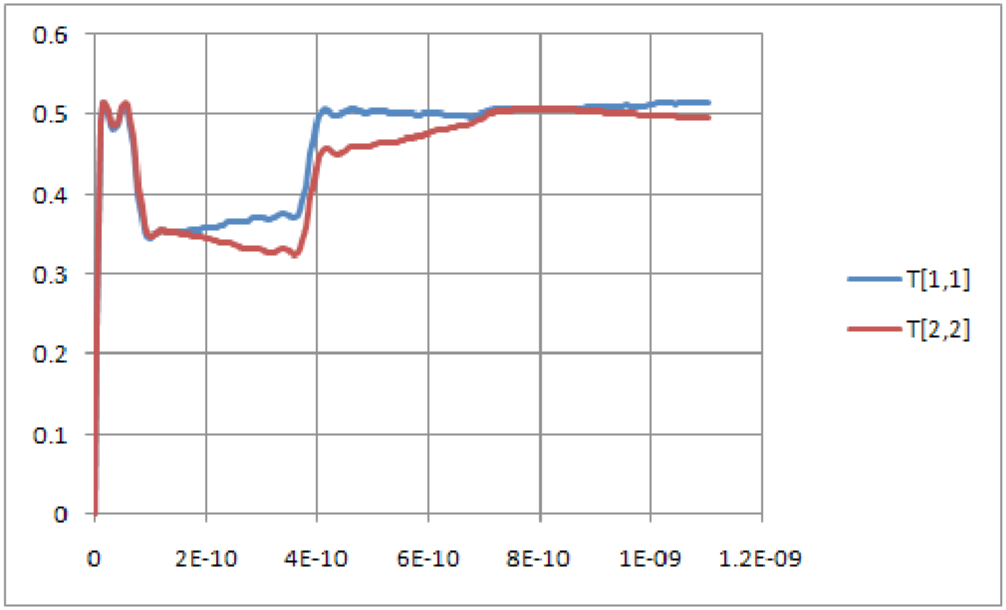
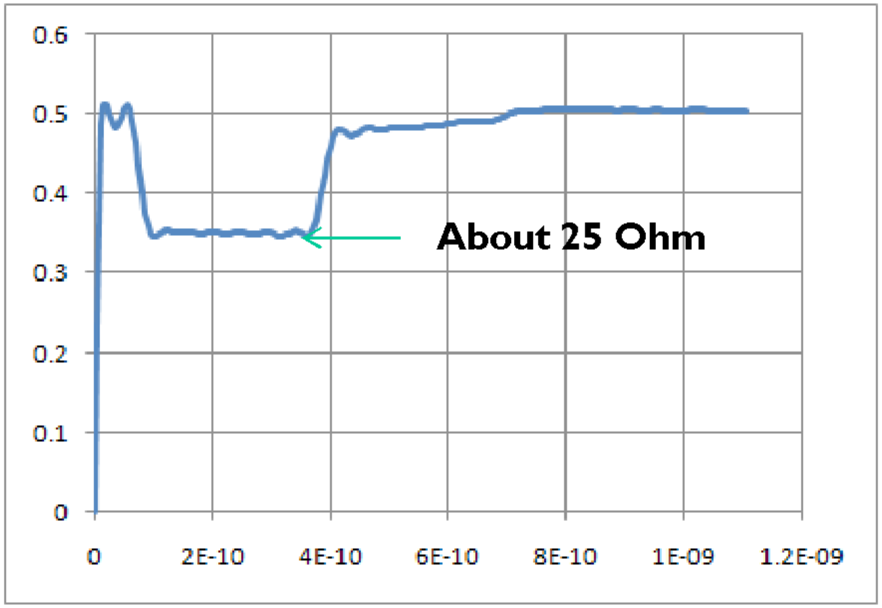
25-Ohm Beatty TDR After Data Quality Restoration

1-volt TDR calculated from the original measured S-parameters 0.5 – 50 Ohm, 0.35 – 25 Ohm



1volt TDR calculated from the measured S-parameters with restored symmetry



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Examples of measurement-based electromagnetic analysis

- Identify frequency-dependent dielectric properties
  - Fit electromagnetic analysis results with dispersive dielectric model and measured de-embedded S-parameters for line segments and resonant structures
  - More on that at Track 12-WA1
- Use identified dielectric model to build full-wave models of the other structures on the board
- Over 30 different typical PCB structures have been investigated

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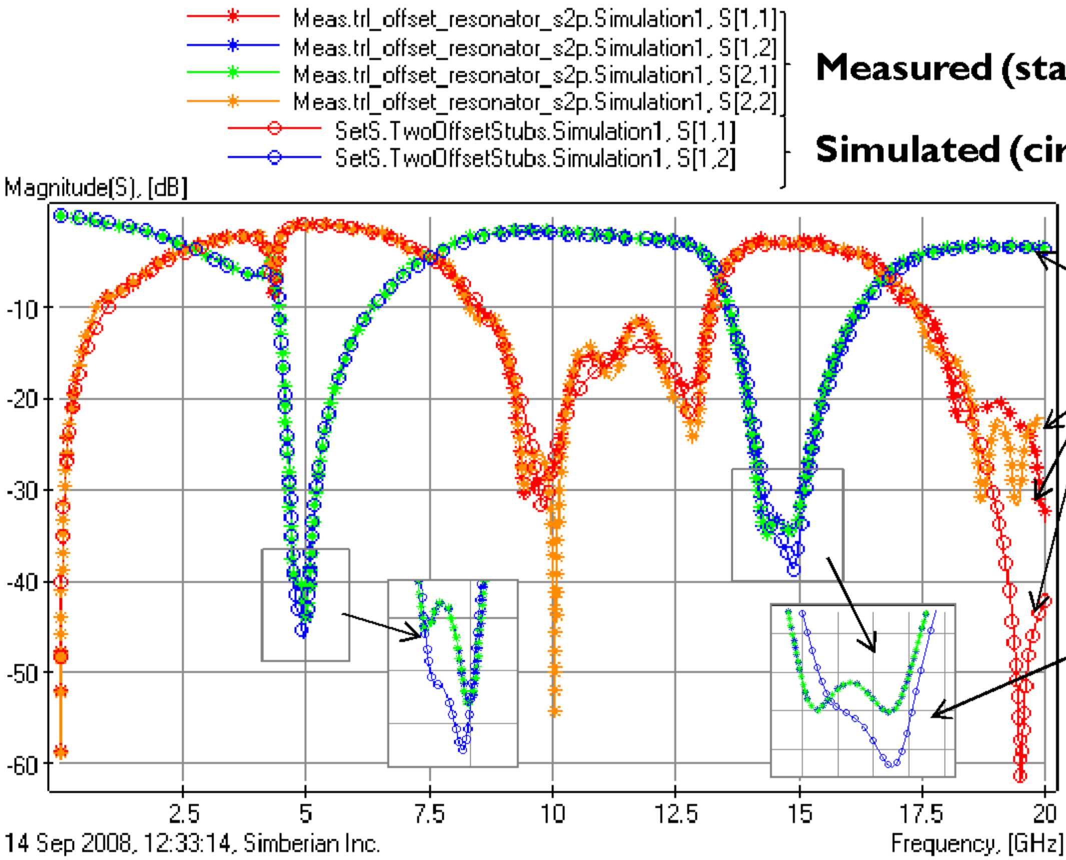
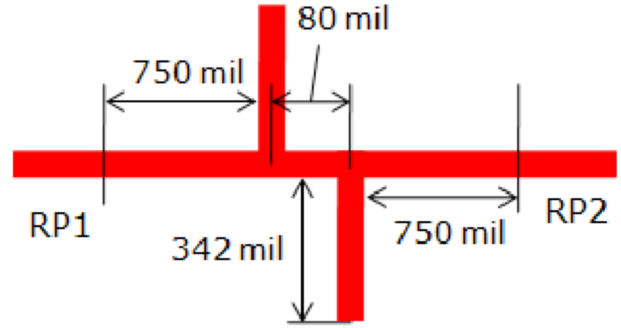
Offset Stub Resonator

- Magnitude of S-parameters



Measured (stars)

Simulated (circles)



DK=4.0, LT=0.02 @ 1 GHz

transmission

reflection

Double resonances is the effect of high-order modes between two tees (can be captured only with the full-wave analysis)

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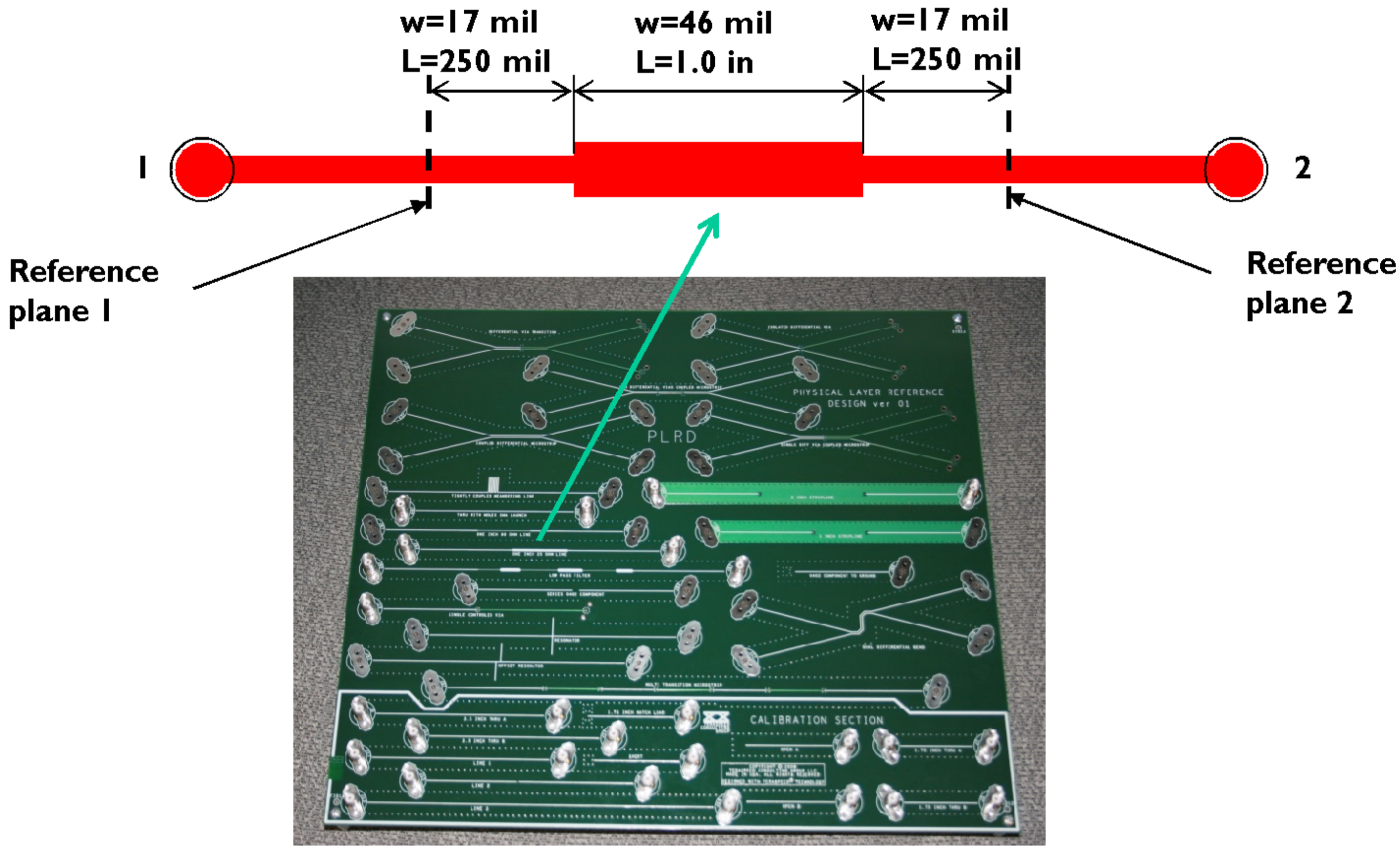
25-Ohm Beatty Standard

- 1-inch segment of micro-strip line with lower impedance connected with two segments of 50-Ohm micro-strip line



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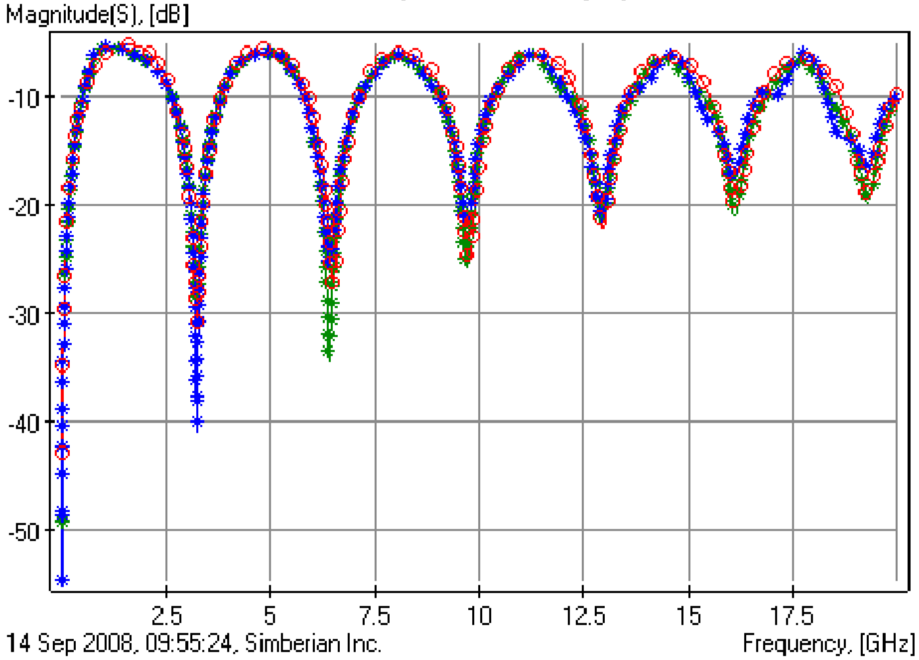
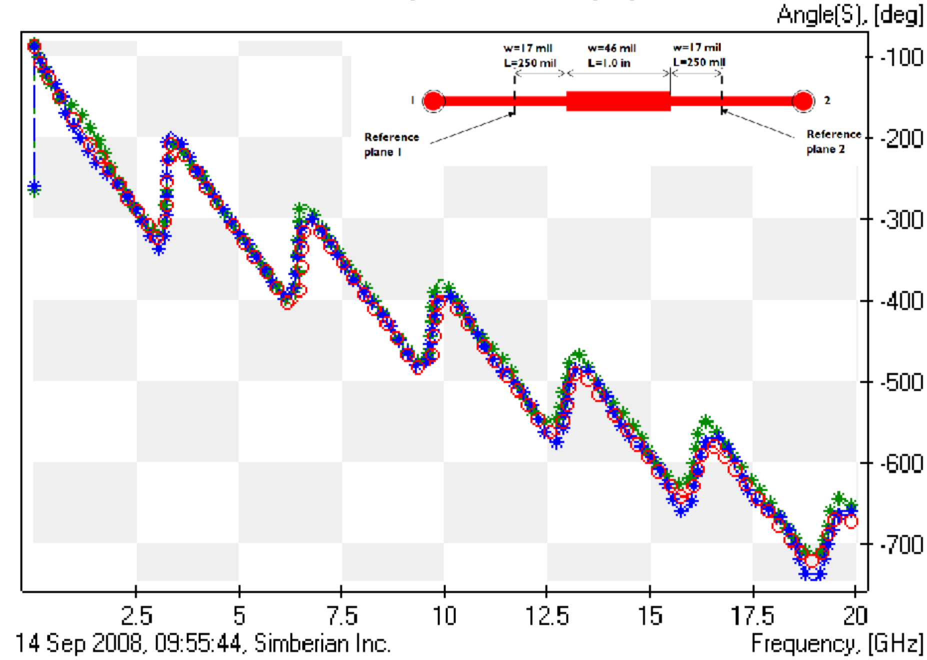
25-Ohm Beatty Standard

Good correspondence!

Reflection coefficients magnitude | **Reflection coefficients phase**

Measured – stars, simulated - circles





- Wideband Debye model: DK adjusted to 3.9 @ 1 GHz to have 1% error in phase of transmission coefficient and in position of the resonances in reflection coefficient

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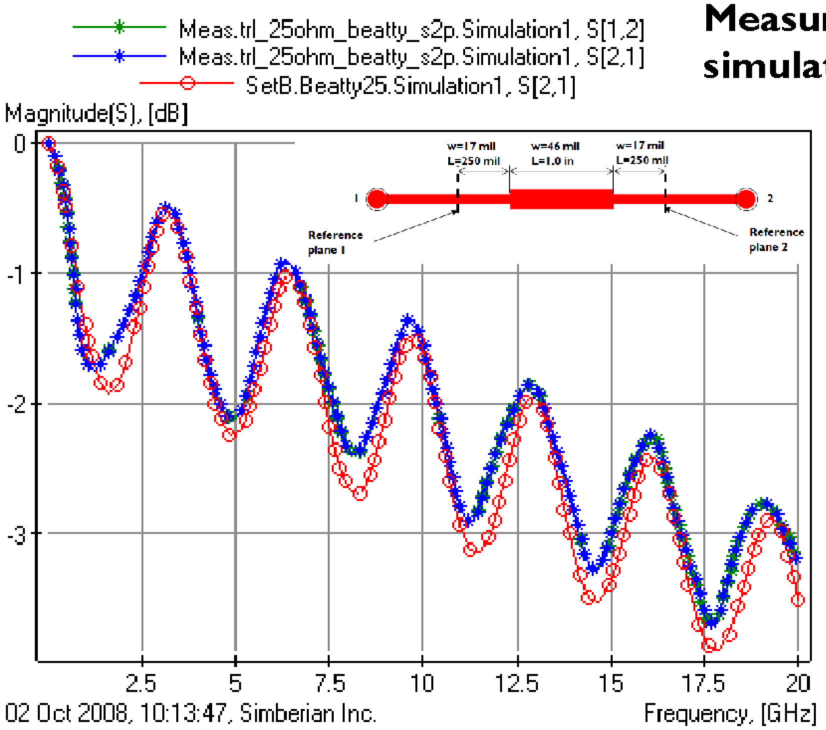
25-Ohm Beatty Standard

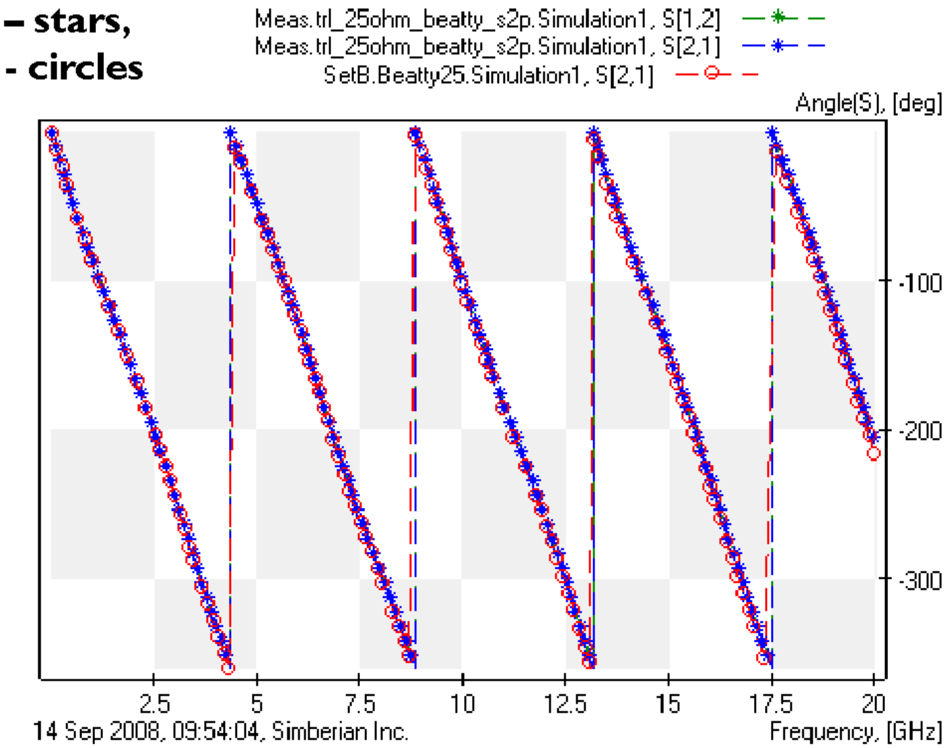
Good correspondence!

Transmission coefficients magnitude



Measured – stars, simulated - circles

Transmission coefficients phase



- Wideband Debye model: LT adjusted to 0.018 @ 1 GHz to minimize the difference in measured and calculated transmission coefficient

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Thank You

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  - 503-718-7172

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