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Methods of Improving 3D EM Model Development and Associated Time/Frequency Domain Measurements

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Anritsu Tektronix wildriver technology DesignCon 2013 UBM Tech

Agenda

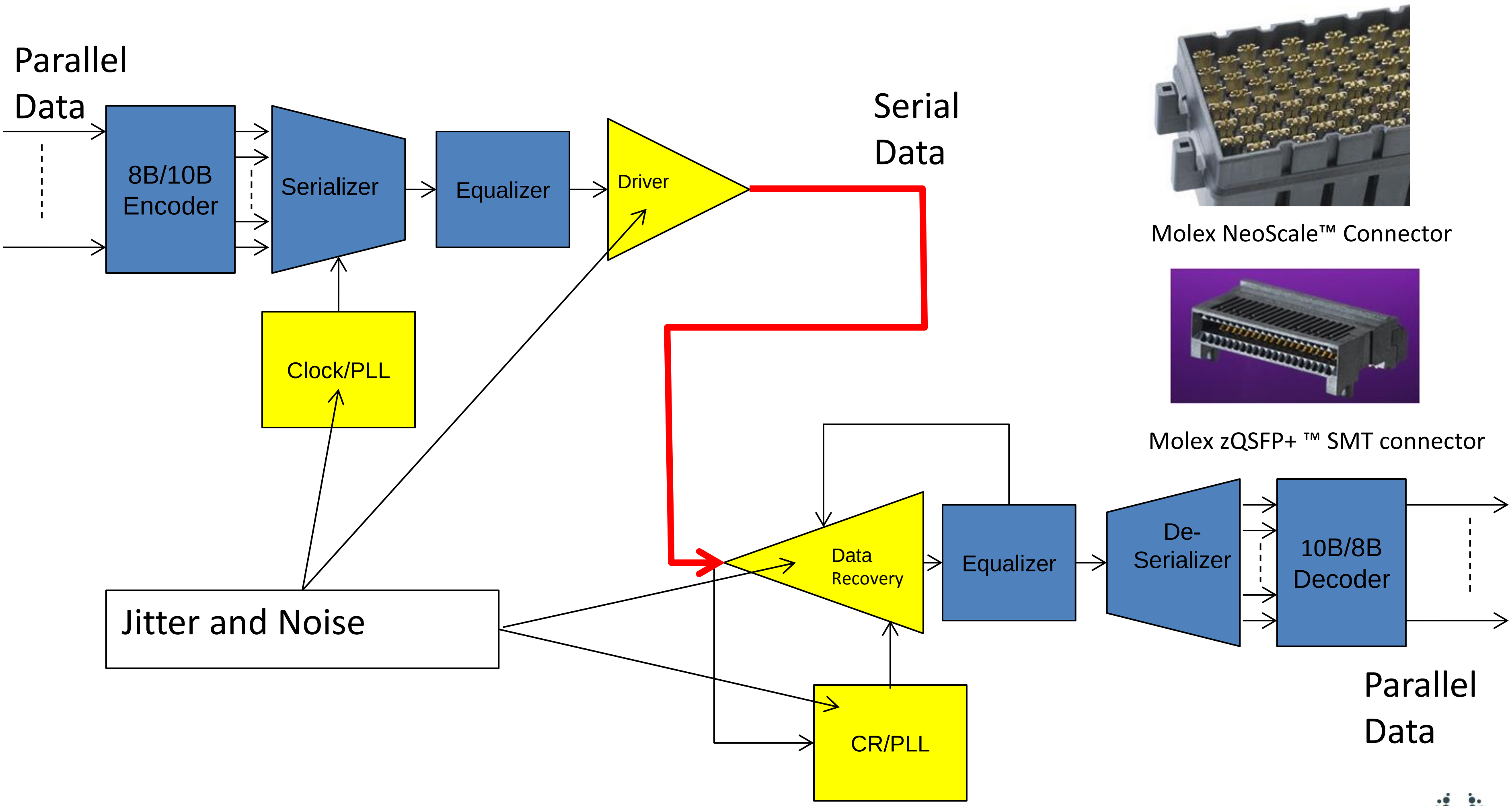
- **Introduction**
- The Metrologist's Tale
  - Practical calibration methods suited for 3D-EM
    - Jon Martens
- The Signal Integrity Practitioner's Tale
  - Verification and assurance
    - Jim Bell and Al Neves
- The 3D-EM Modeler's Tale
  - Time domain processing and 3D-EM model development
    - Josiah Bartlett
- **Questions**

Data-Driven World

- London 2012 Olympics*
  - NBC
    - 159 million video streams
    - 9.9 million PC/Mobiles registered with NBC
  - BBC
    - 106 million video streams
    - 9.5 million daily unique visitors to sport site
- 2.4 billion internet users**
- Proliferation of smartphones and tablets

* FierceOnlineVideo.com and ciena.com
** June 30th, 2012 data from www.internetworldstats.com

Challenges for Signal Integrity Engineers



Molex NeoScale™ Connector

Molex zQSFP+ ™ SMT connector

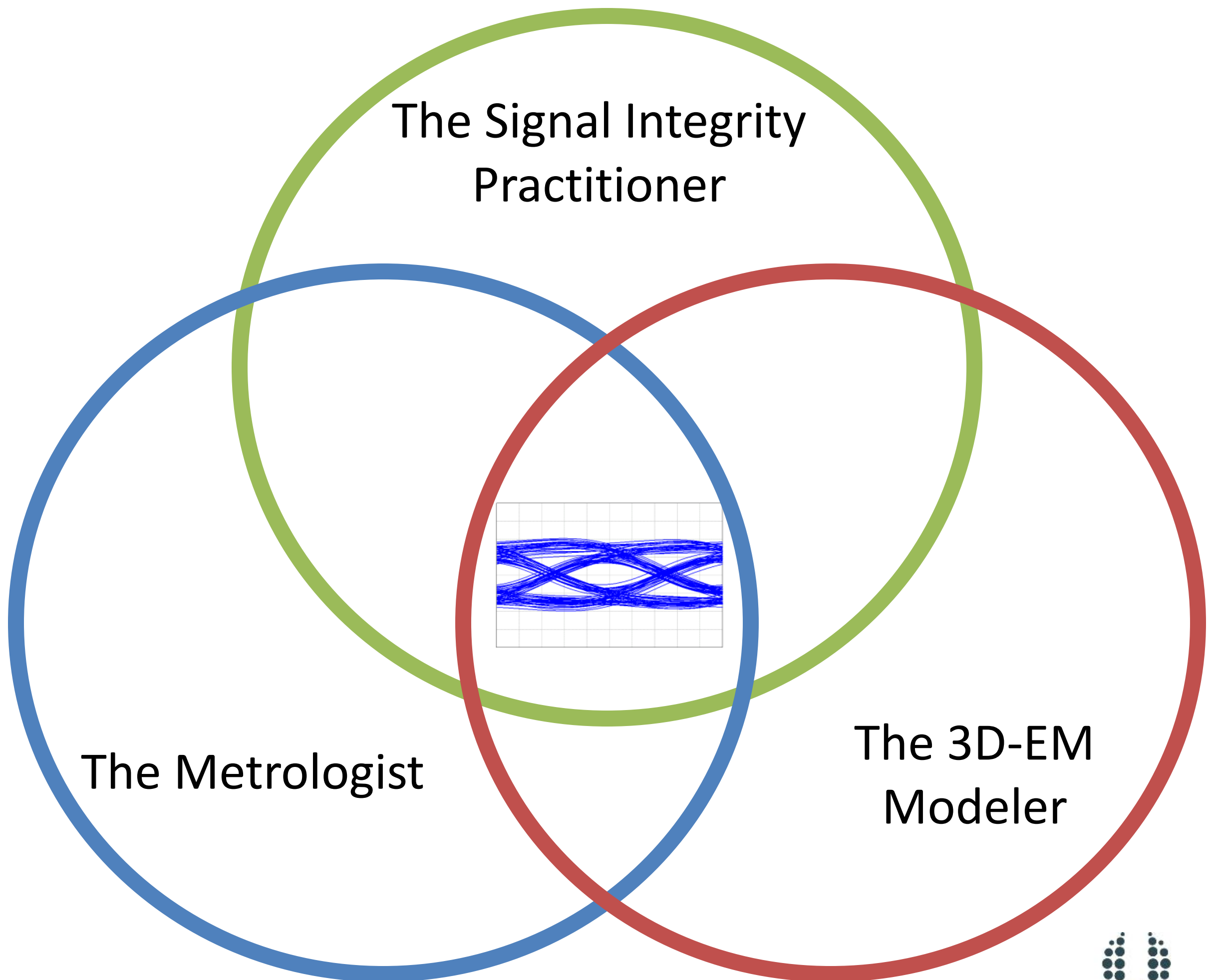
Canterbury Tales

- Geoffrey Chaucer – late 14th Century
- Goal: Pilgrimage to Canterbury Cathedral
- Stories told by the pilgrims along the way
  - Knight's tale, Miller's tale…
- Different perspectives – one common goal!

A woodcut from William Caxton's second edition of the Canterbury Tales printed in 1483

Signal Integrity Tales

- Three groups on a journey together
- Each with own expertize and perspective
- Understand interplay between the perspectives to achieve one common goal!



The Metrologist's Tale

- Importance of solid and reasonably accurate characterization of structures on the path to good signal integrity
- High integrity data needed
  - Confirm performance
  - Help generate models for system prediction and design
  - Satisfy conditions for causality and passivity
  - Good calibrations are required for good measurements

- How to choose the appropriate calibration method from the many available?
- What can I do to improve the quality of my measurement so it is suitable for 3D-EM modeling?

The Practitioner's Tale

- Needs to understand all aspects
  - Uses algorithms/methodologies from metrologist
  - Makes measurements
  - Performs some modeling

- How to validate and confirm integrity of the S-parameters?

The 3D-EM Modeler's Tale

- Desire to create accurate models that minimize schedule and NRE costs
- Challenges
  - Tools often originally designed for narrow band RF use
  - Lack of input data quality can create lack of credibility
  - Pure-looking models mask real-world variations
  - Disconnect between modelers and measurers

- How can you perform meaningful and practical 3D-EM modeling?

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Practical Calibration Methods Suited to 3D-EM

From one point-of-view, a critical problem is getting good measurement data and establishing a path to 'show' that the data is good…

Metrology - Measurement

3D Modeling

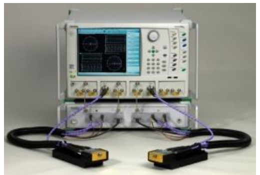
S.I. Practitioner

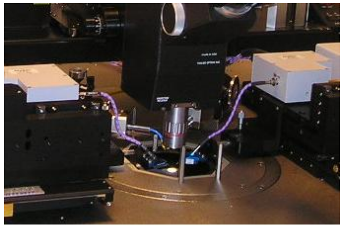
General SI Issues

Development - Business - Marketing

…from the viewpoint of metrology and measurement physics

Instrumentation assessment

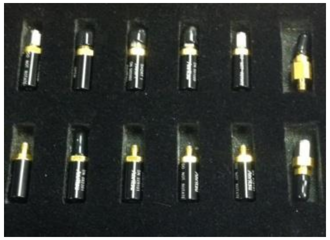




Calibration and verification tools

Matched thru

Mismatched thru



Fundamental metrology (dimensional and electrical)

3D CMM machines

Air gages

Electrical impedance/ voltage references

Practical Calibration Methods Suited to 3D-EM

- The proper choice of a method for the materials, geometry, and standards available can help produce data more amenable to model comparison and integrated simulations.

- Through sensitivity analysis and measurement examples, some choices will be explored.

In this section…

- Brief review of calibration concepts and error sources
  - Common SOLT and TRL families
  - Hybrid techniques
  - Partial information methods
  - Time domain-based methods
  - Imposed assumption enhancements

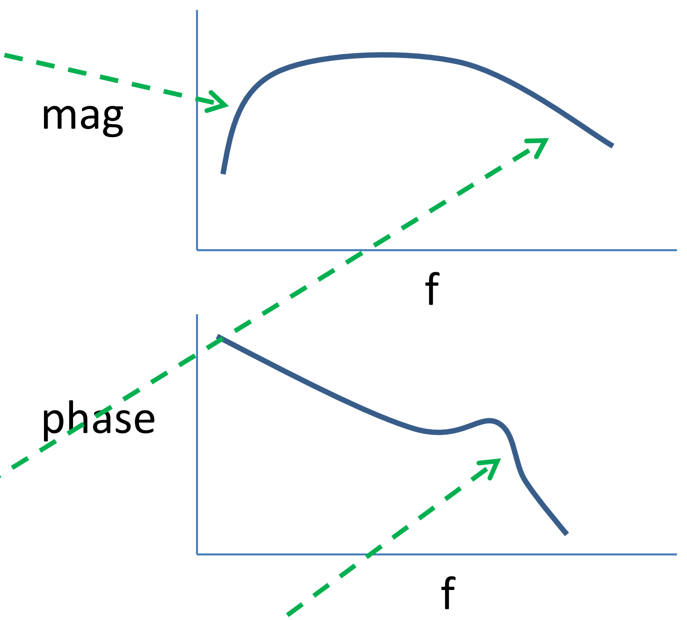
Calibrations: Intro 2

- *Sensitivity/uncertainty analysis of these techniques.*
  - What standards and measurement issues are challenges for the different methods?

- *What attributes are particularly problematic for co-analysis with 3D-EM?*
  - The dependence of errors on frequency
  - The importance of phase error and reference plane positioning…

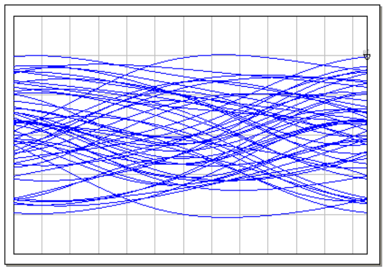
Potential Problem Areas

- Low freq. issues affect large-scale structure in time domain (eye diagrams, average impedance levels...)
  - Low end coupler roll off->stability and drift; calibration issues sometimes
  - Contact problems
- High freq. issues affect fine scale structure and resolution; mismatch effects can alter system simulation results.
  - Media and calibration problems

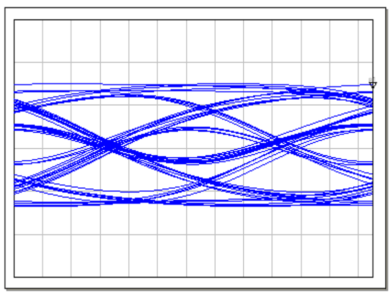


Phase errors affect time placement and reference plane positioning. Can be a system simulation issue
- Calibration problems

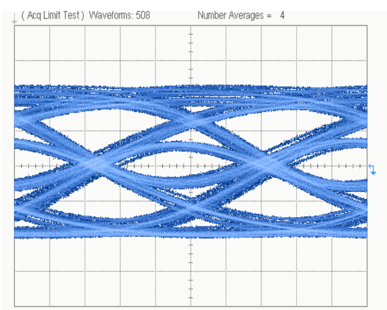
Potential Problem Areas: Low Frequency Example



Eye pattern simulated with S-parameter data with issues below 10 MHz (non-physical data roll)



Eye pattern simulated with S-parameter data with no issues down to 70 kHz



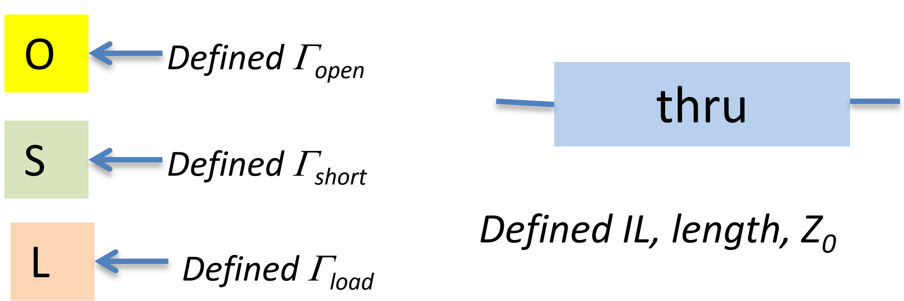
Eye pattern on same DUT measured directly

Calibrations: Technique Classes

- Next:
  - Most common techniques and attributes
  - Error sources
  - Other methods (de-embedding or calibration)
    - Hybrid
    - Partial information
    - Time domain-based
    - Imposed assumptions

Defined-standards Methods (e.g., SOLT)

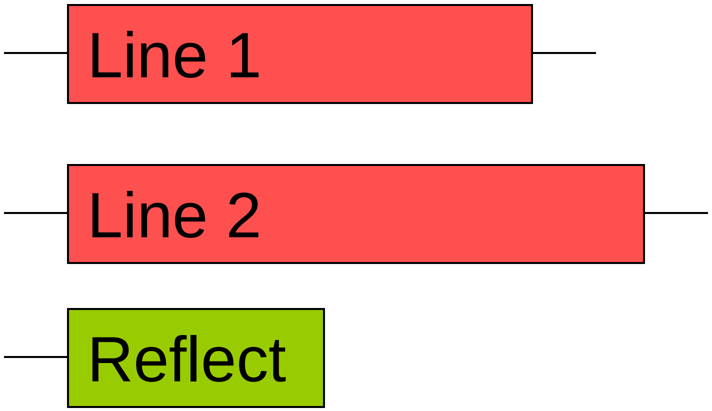
- Must precisely characterize all standards
- Relatively robust when that is done (often over-determined)
- Not the best in complex media (hard to make good standards)
- Moderate resistance to repeatability issues



OR: substitute a general reciprocal network for the thru (not too lossy or reflective). Less-overdetermined and low-insertion-loss measurements are harder but don't need the known thru. (SOLR)

TRL Family of Methods

- Relatively little standards-knowledge needed but must have consistency and ‘ideal’ transmission lines
- Can be over-determined or precisely determined
- Relatively sensitive to repeatability problems
- Key element is a transmission line; can be good in complex media if consistency can be guaranteed.

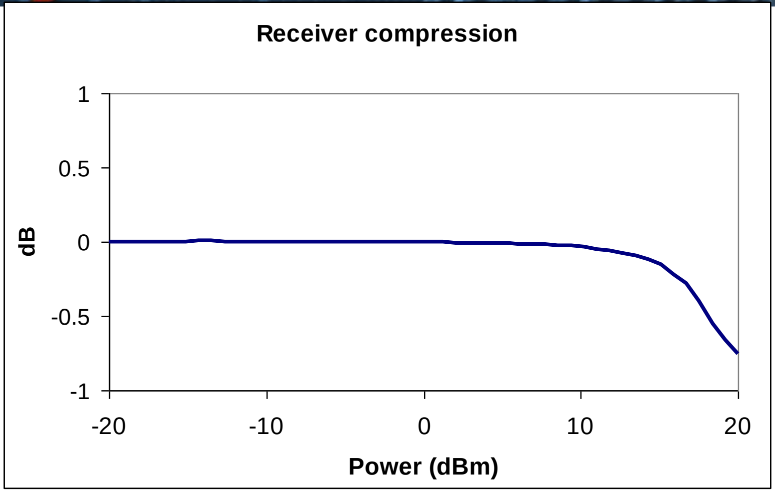


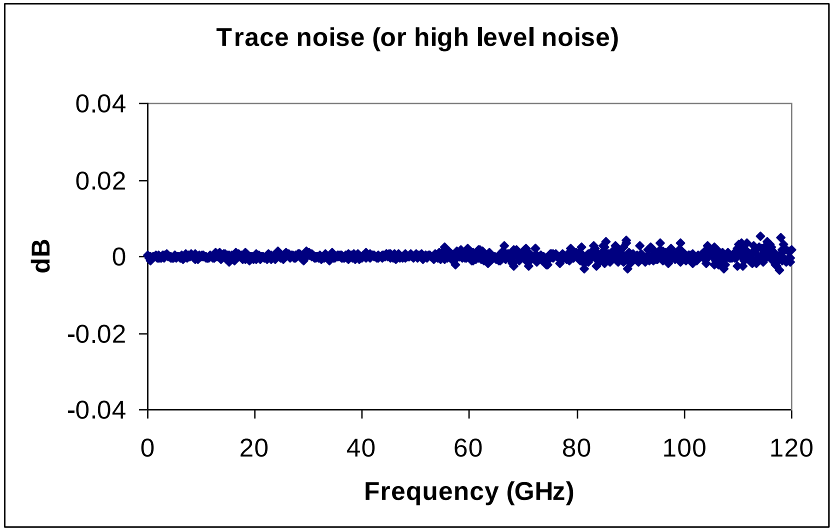
Error Sources

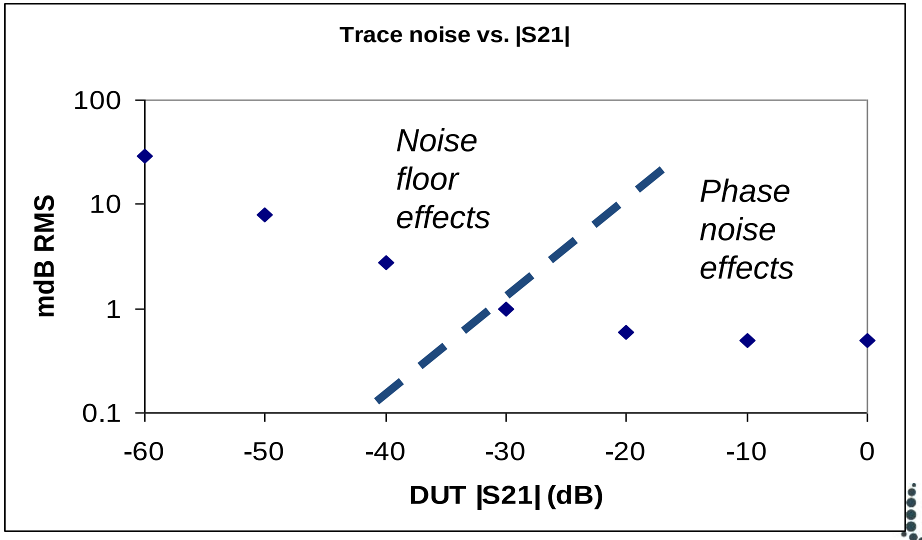
- Given these common calibration techniques, what are the main error sources?
- How does the calibration method choice affect the net error?

Calibrations: Error Sources 1

- Non-hardware terms: *the calibration*
- Hardware terms: *linearity, noise effects, repeatability*

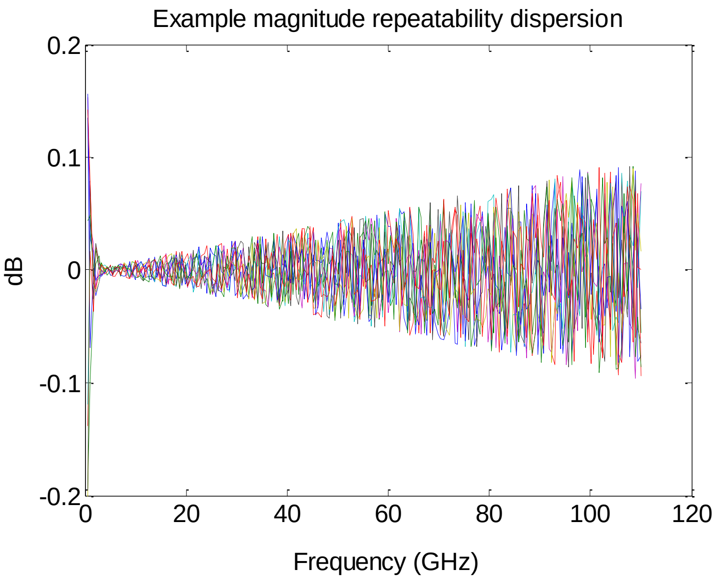


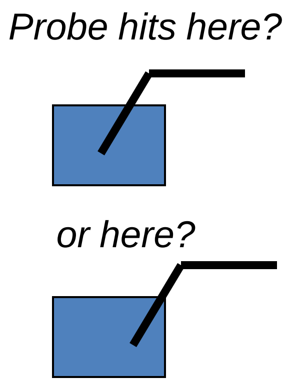


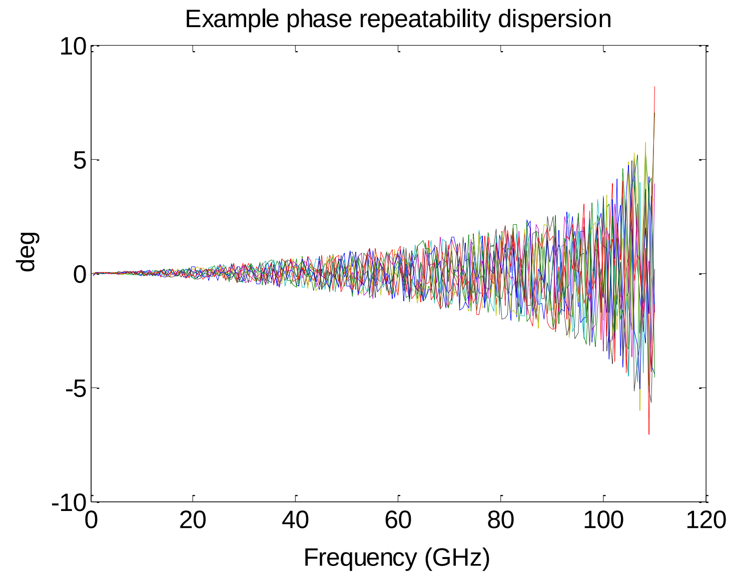


Calibrations: Repeatability

- Repeatability (between calibration and measurement or between standards)
  - Placement errors (higher frequency and particularly phase)
  - Contact errors (lower frequency)





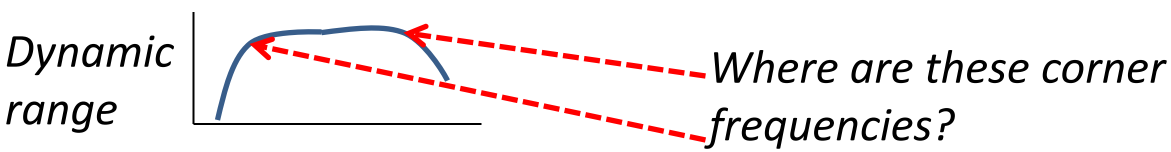


Repeatability and general sensitivities

- *SOLT effects*
  - Load measurement sensitivity (directivity)
  - Thru sensitivity (phase and load match)
- *SOLR effects*
  - Load sensitivity (directivity and load match)
  - Open/short sensitivity (ref plane)
- *TRL family effects*
  - Launch admittance variations->transmission line non-ideality

Drift

- Normally a hardware and setup limitation (how long are those cables and how good are they!)
- If just cable-limited, will tend to get worse linearly with frequency (magnitude AND phase).
- If related to hardware roll-off, drift may be more localized.
  - Example: couplers roll-off at high end and low end. Drift will often be worse in both places.



Phase Effects

- *Reference plane problems and global phase*
  - Different methods use different mechanisms to determine transmission phase reference
    - SOLT: relies on the thru definition
    - SOLR: relies on the open/short definition
    - TRL: Middle of line 1 ref plane is 'free'; otherwise relies on extracted propagation constant (dependent on line consistency and ideality)
- Match issues can distort transmission phase in more complicated ways (leading to eye diagram and waveform distortion).

Calibrations: Technique Classes Revisited

- Based on these error topics, the common methods can be ~compared:

A concern?	SOLT, etc.	SOLR, etc.	TRL, etc.
Standard def.	Yes	Yes/maybe	Usually no
Standards ideality	Maybe	Maybe	Yes
Repeatability	Maybe	Maybe	Yes
Ref. plane	Yes	Maybe	Can be (which one?)
Media issues	Yes	Maybe	Maybe
Standards count	Yes for high N	Yes for high N	Yes for high N

- Are other approaches able to optimize on some of these concerns?

Other Techniques

- Let us look at some variations on these calibration/de-embedding techniques that might be able to improve data quality:
  - *Hybrid methods* (optimize method choice based on paths within the fixture/DUT)
  - *Partial information techniques* (don't try to solve for everything)
  - *Time domain methods* (use spatial separation to help)
  - *Imposed assumptions* (use other knowledge about the fixture to simplify the process)

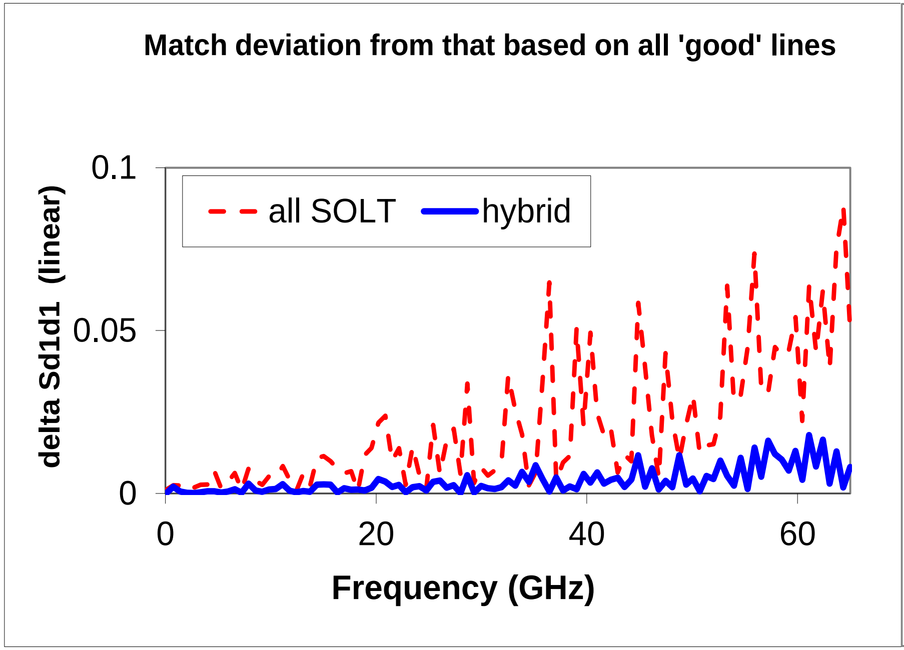
Calibrations: Hybrid Methods 1

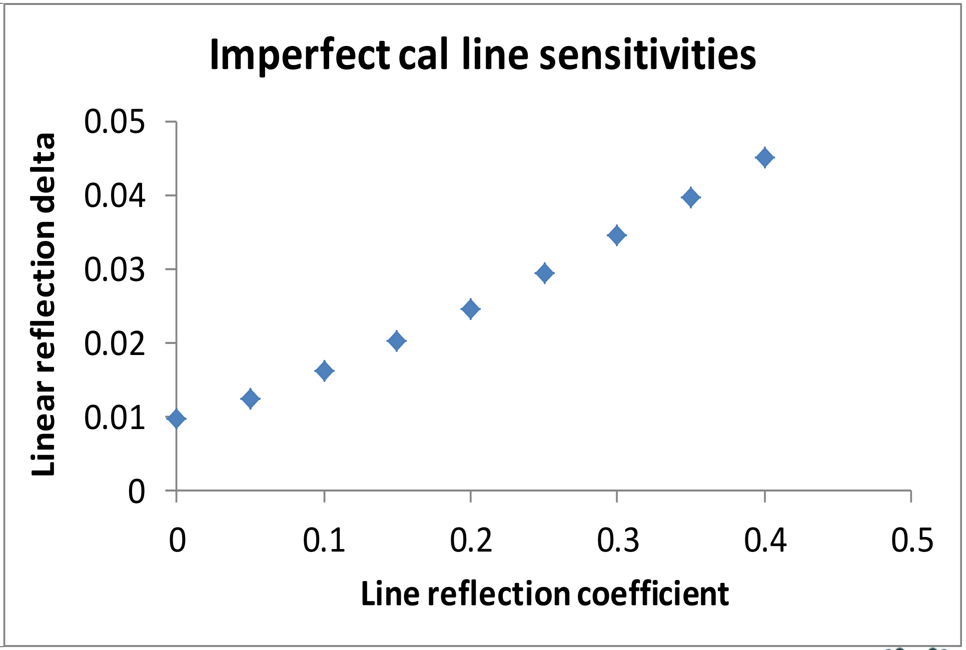
- Central concept: Different paths/ports in a problem may want different methods.
  - Mixed media: different standards are available
  - Certain paths allow for more ideal transmission lines than others.

Example: use TRL/LRL on 1-3 and 2-4 but use SOLR on others
1-2 is likely to be 'dirty' (i.e., with mismatch and radiation, hard to characterize)
Example: use paths with well-defined ports in calibration but use redundancy to solve for paths to less-well-defined ports

Calibrations: Hybrid Methods 2

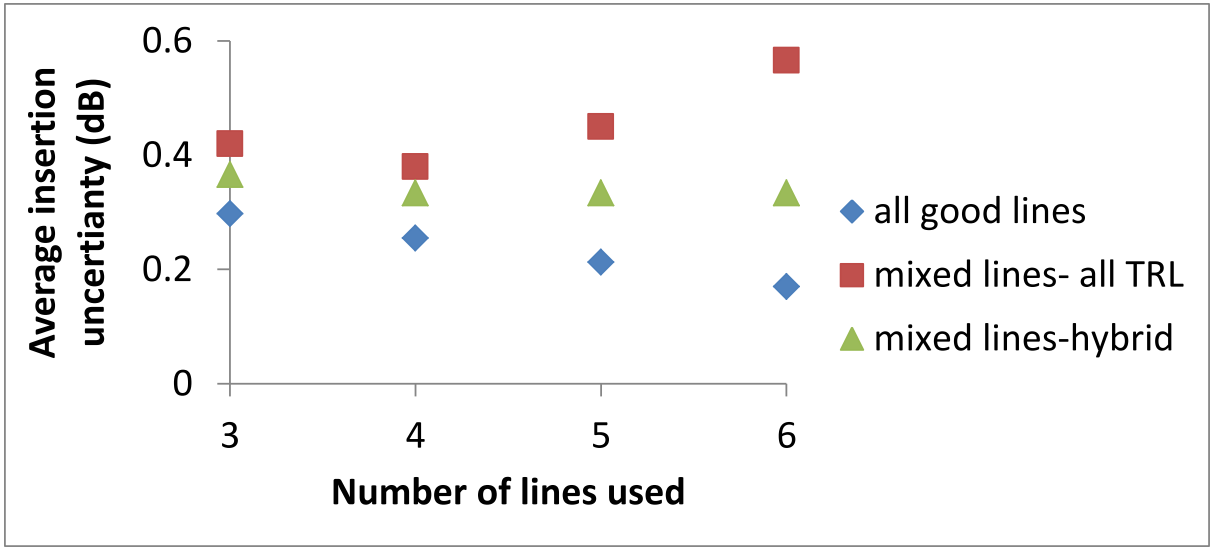
- Not only are the chances for basic error greater with a 'dirty' line (poor characterization), but the sensitivities to mistakes are also greater.





Calibrations: Hybrid Methods 3

- Choosing whether to use a path at all as well as choosing the method can be important.

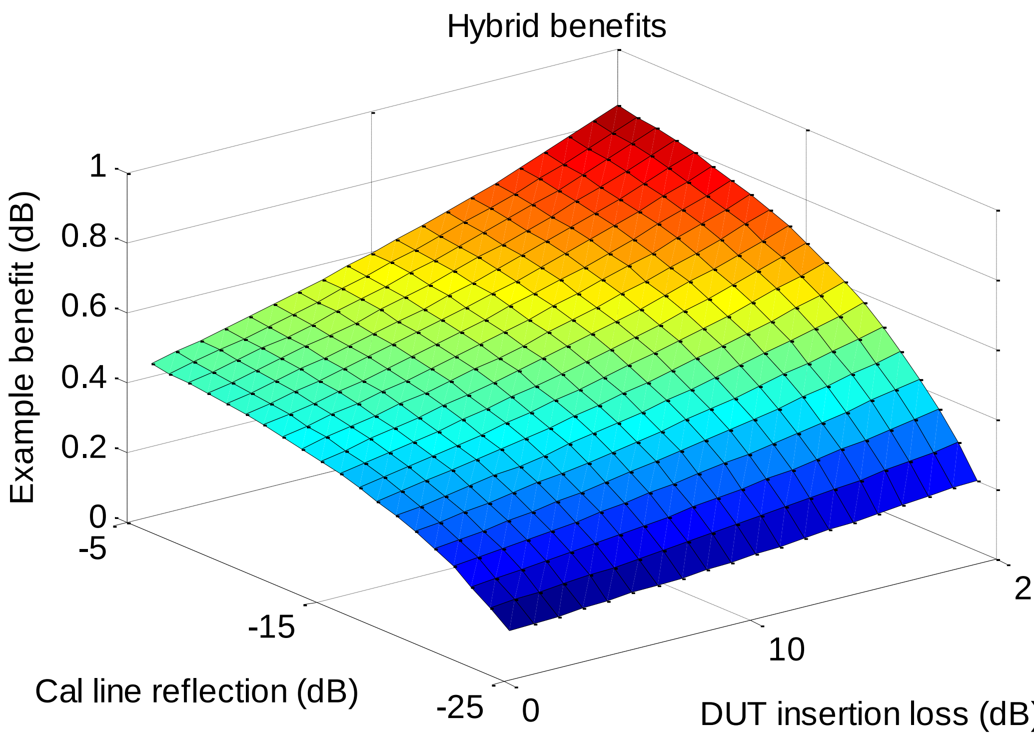


- Adding additional standards can sometimes help but only if 'good' and if they fit the method…

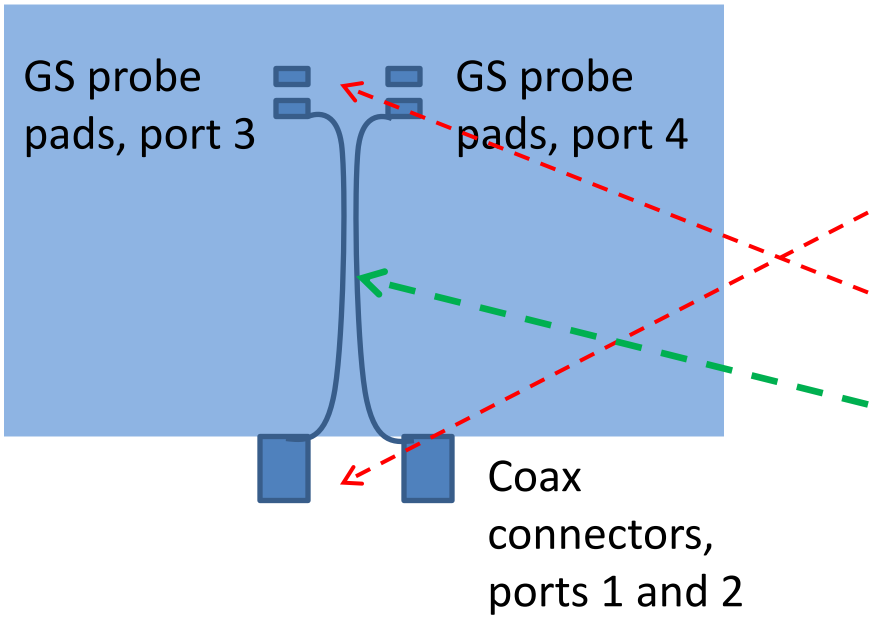
Calibrations: Hybrid Methods 4

- An added complication can be how DUT parameters align with available calibration line paths…

If low-loss DUT paths are aligned with ‘dirtier’ calibration paths, the choice of method becomes more critical.



Hybrid Example



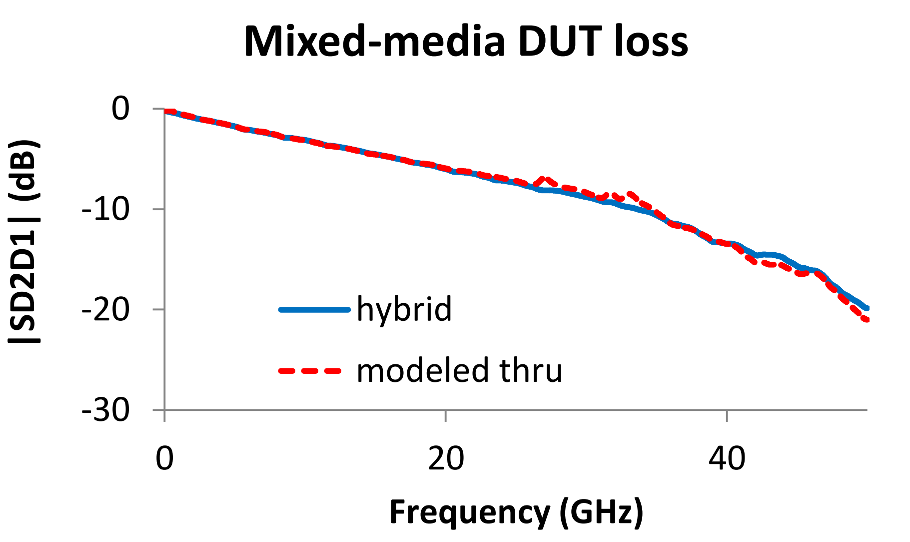
20 GHz measurement

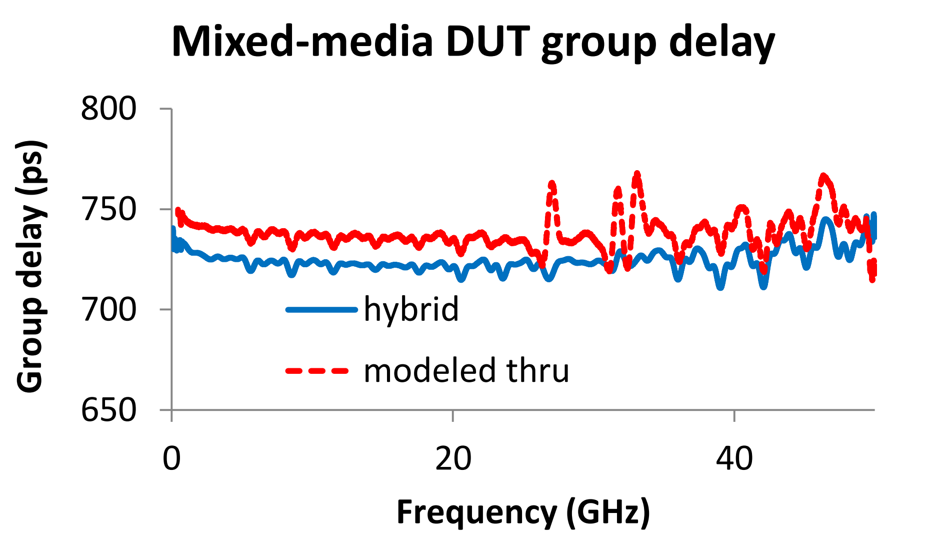
Well-defined coax SOLT (1-2)
Well-defined on-wafer LRM (3-4)
Reciprocal completion paths 1-3 and 2-4

The fixture in this case has two different well-defined interface and a 'dirty' interconnect between them. Hybridizing two 2-port methods and a reciprocal completion step is logical.

Hybrid Example 2

A modeled approach to the ‘dirty’ interconnect (treating it as a thru with loss and mismatch) can get average loss values correct but introduces false structure and can easily misplace the reference plane (group delay shift).

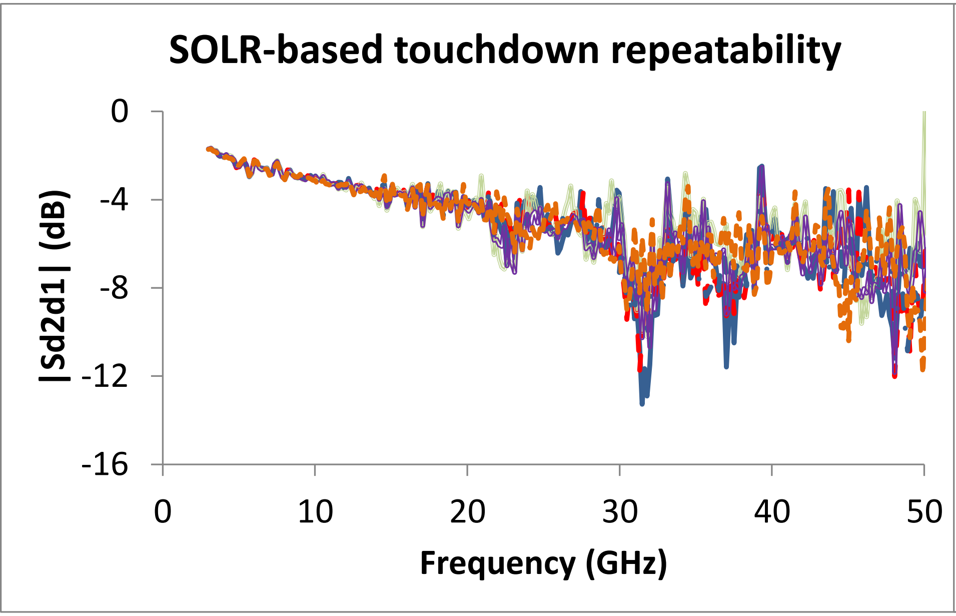


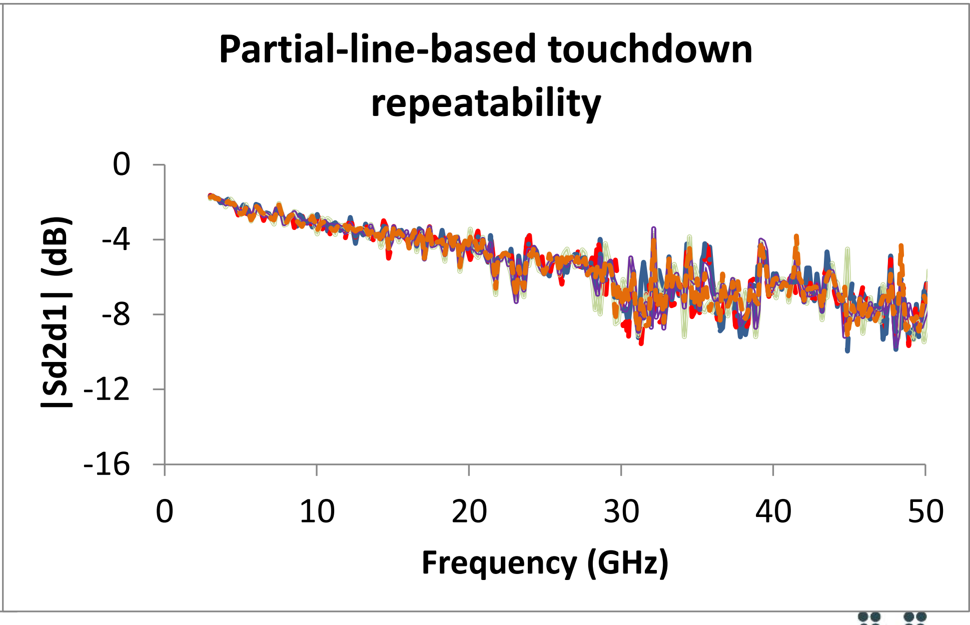


…could lead to more problematic modeling or system simulation

Calibrations: Is repeatability very poor?

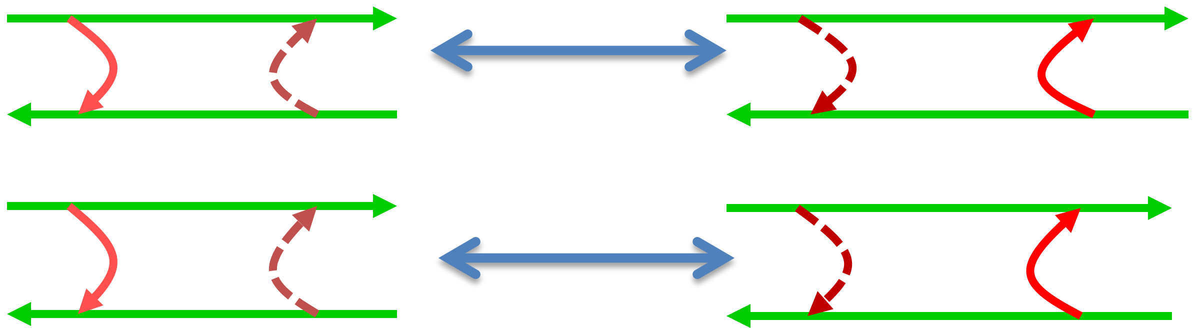
- If a setup is repeatability-challenged, trying to completely solve this system can be a problem. Hyper-sensitive match terms can cause disruptions:





Partial Information 2

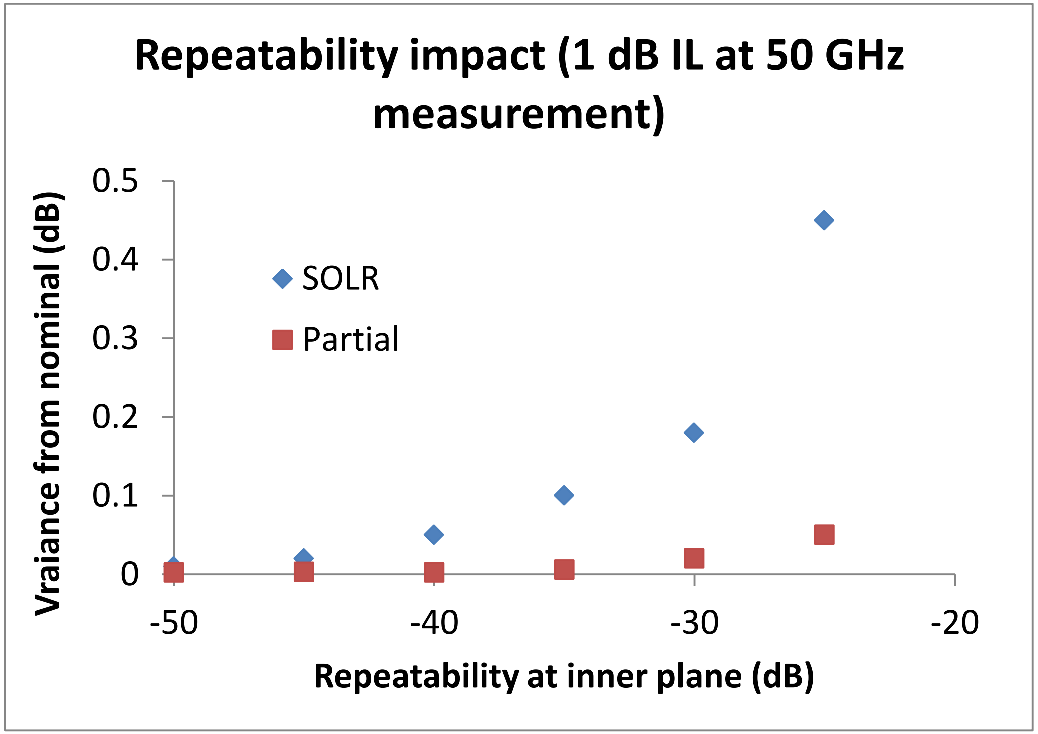
- By choosing not to directly solve for some terms (e.g., inner plane match), more robust insertion data may be possible.



- Generally a few line-connections only are used at the inner plane to minimize interfacial changes at that plane.
- The methods are based on solving the transmission path with minor match weightings.

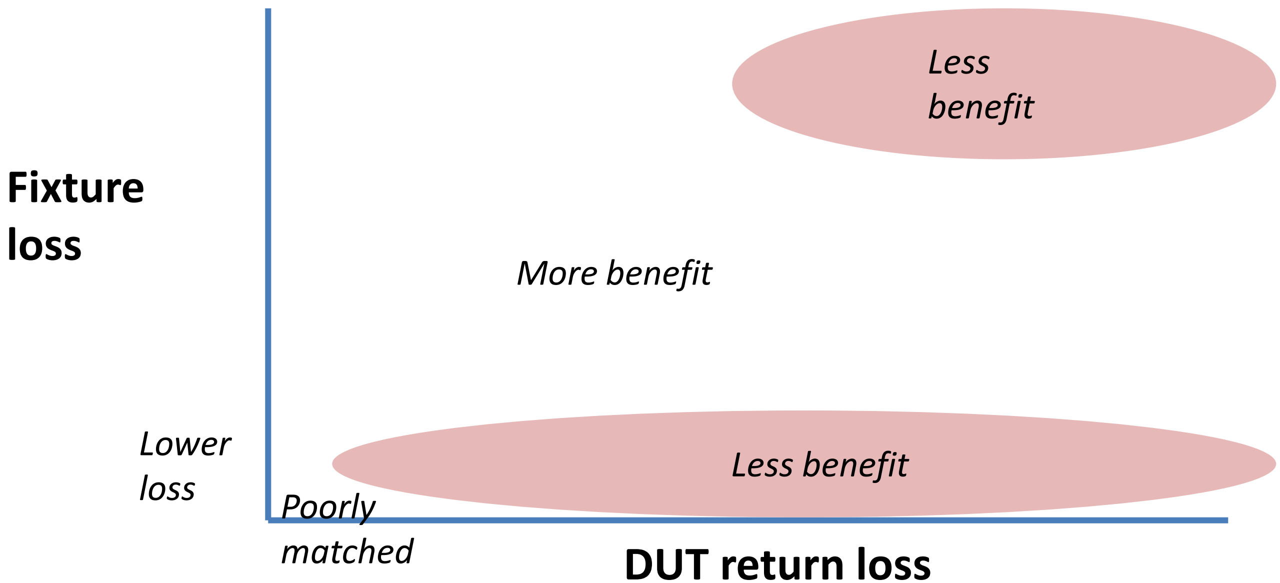
Calibrations: Partial Information 3

- If the match at the inner plane is poor enough (~>-10 dB), relatively minor repeatability problems can have significant effects.



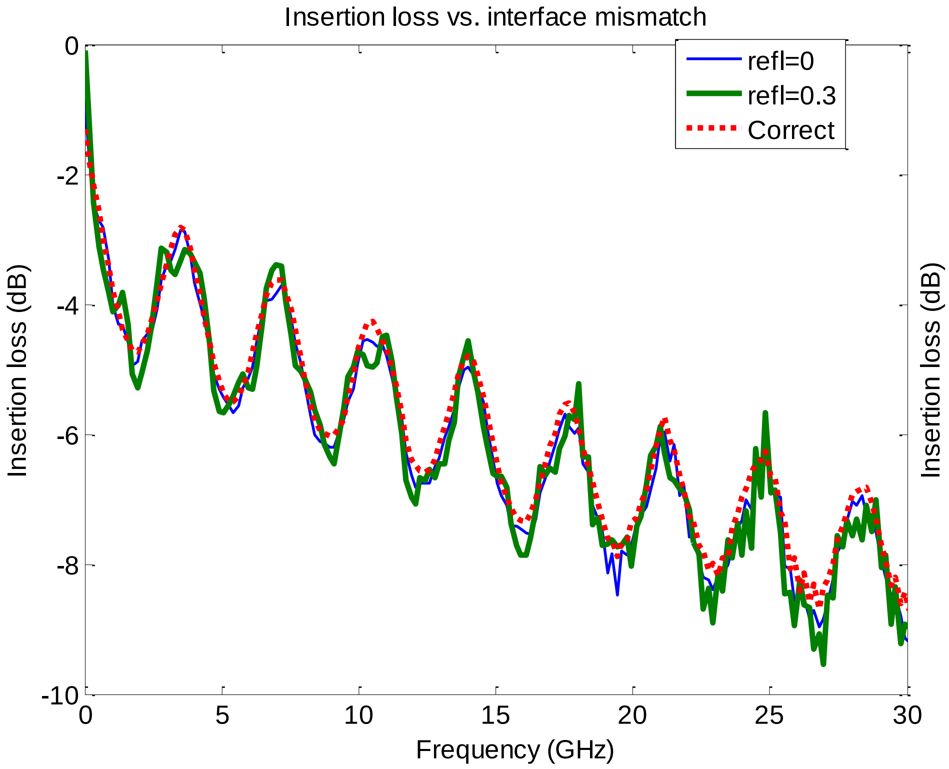
Calibrations: Partial Information 4

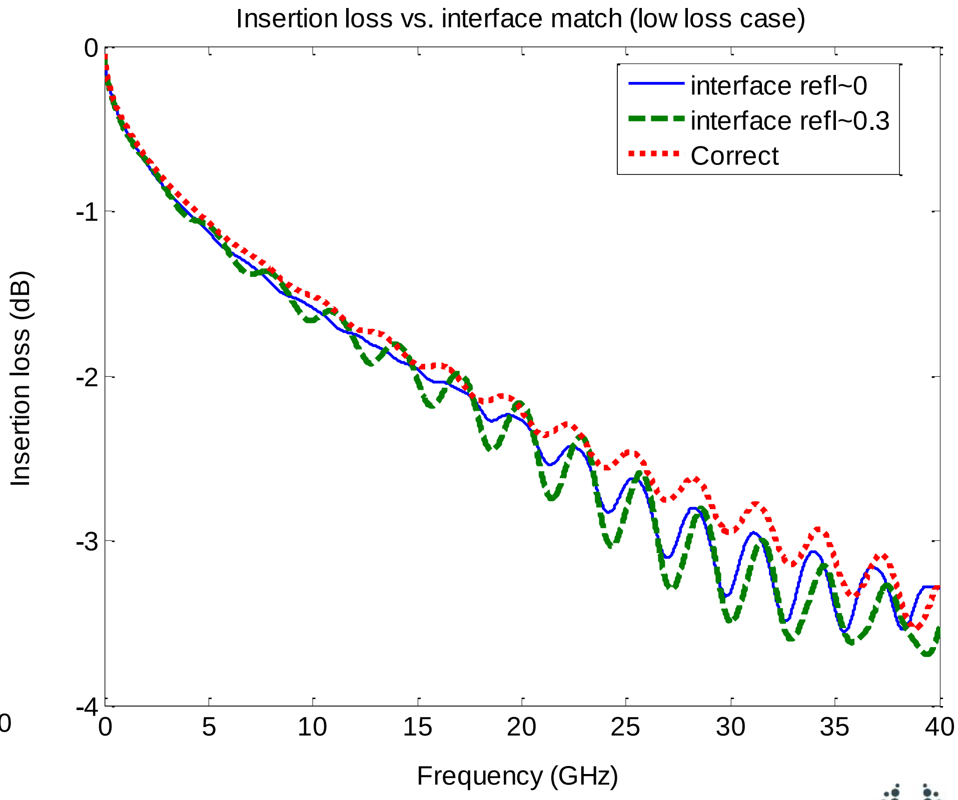
- If the fixture insertion loss is very high, the inner match matters less unless the DUT match is very poor.
- If the fixture insertion loss is very low, usually the inner plane match is decent. If not, its effects will be magnified.



Partial Info Sensitivities

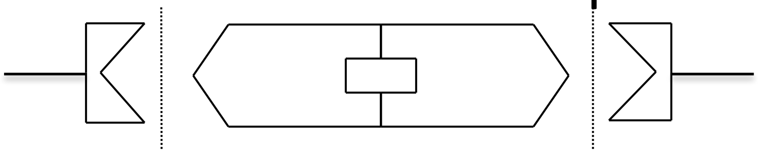
Sensitivities do tend to increase at lower insertion loss levels.

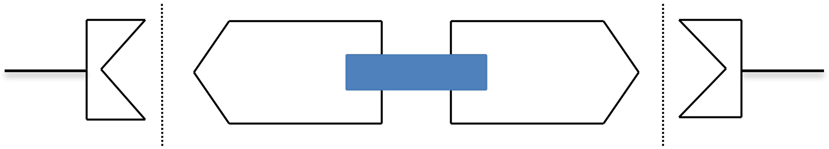


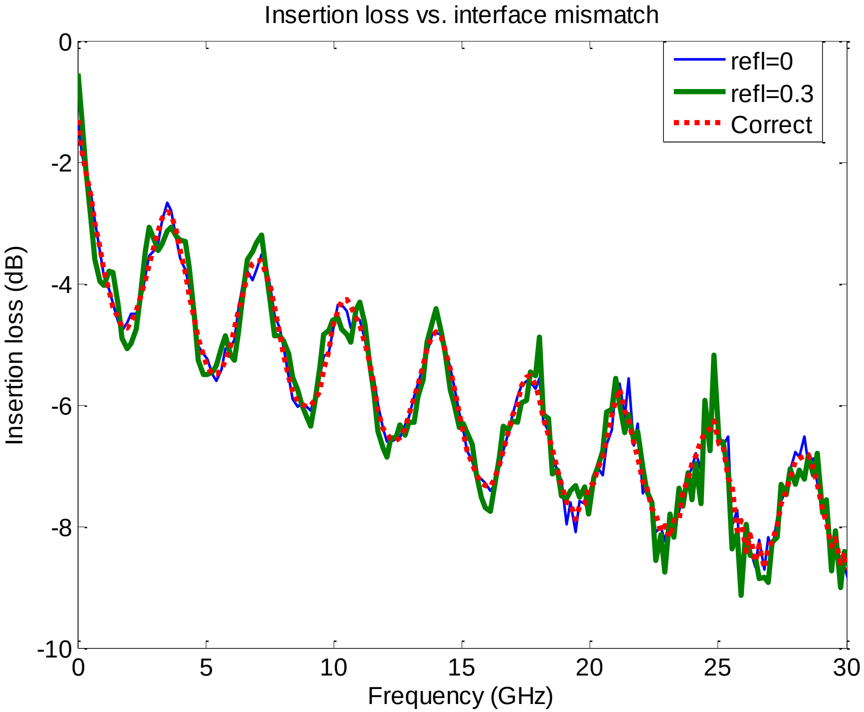


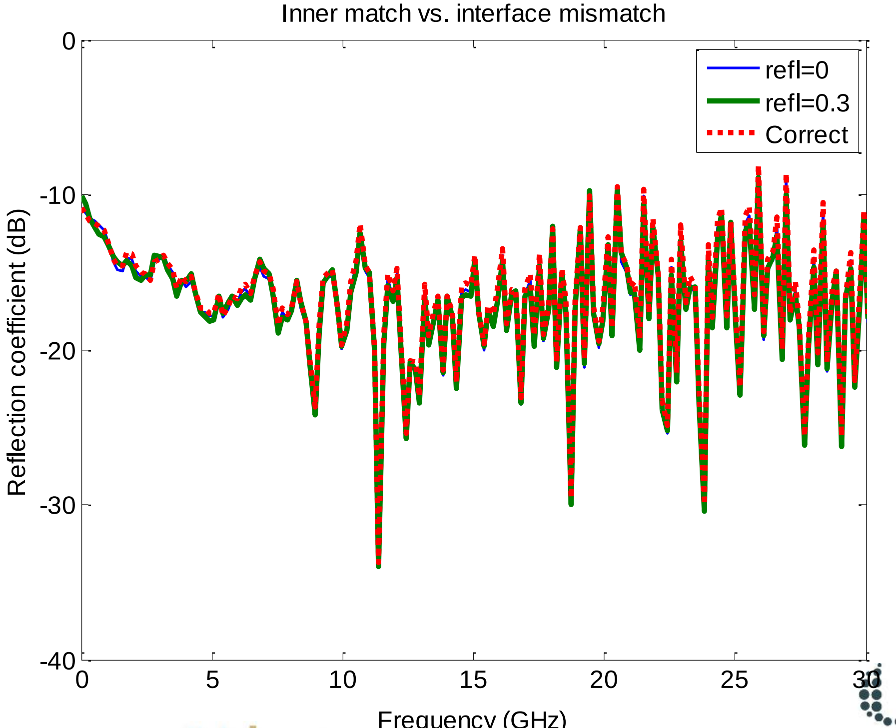
Partial Information Sensitivities 2

Use a two-line method exists (lengths assumed known) to resolve some of the inner match problems…



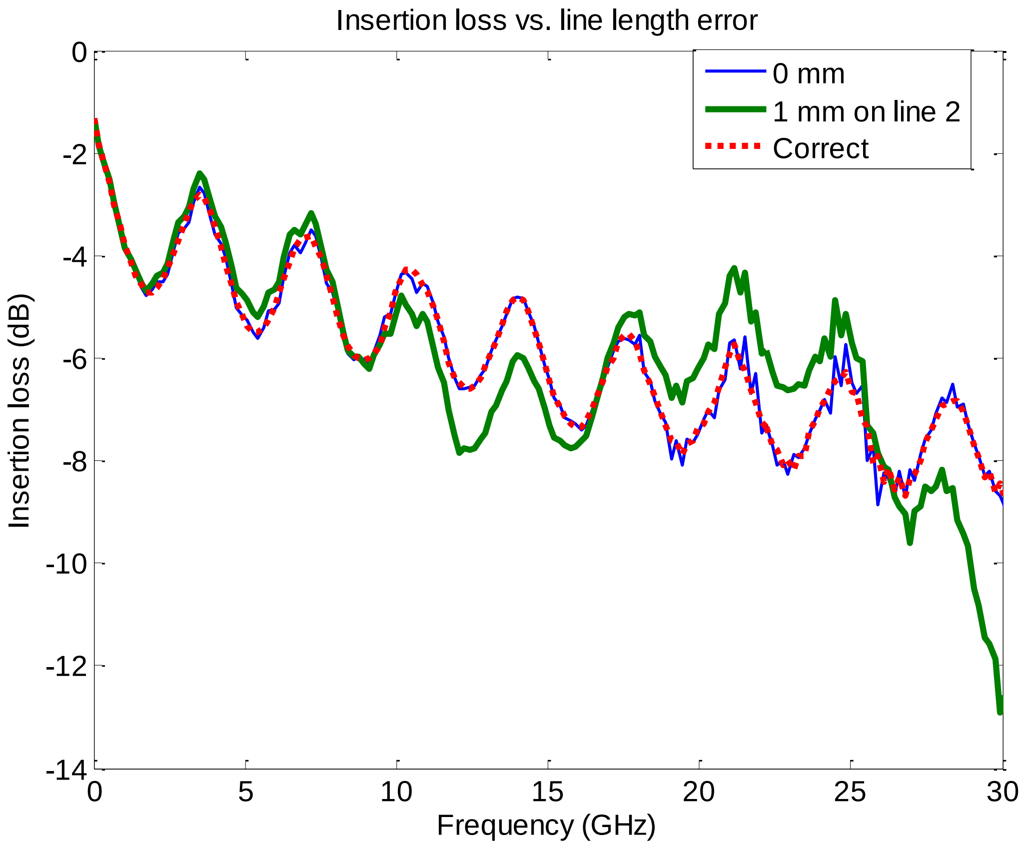






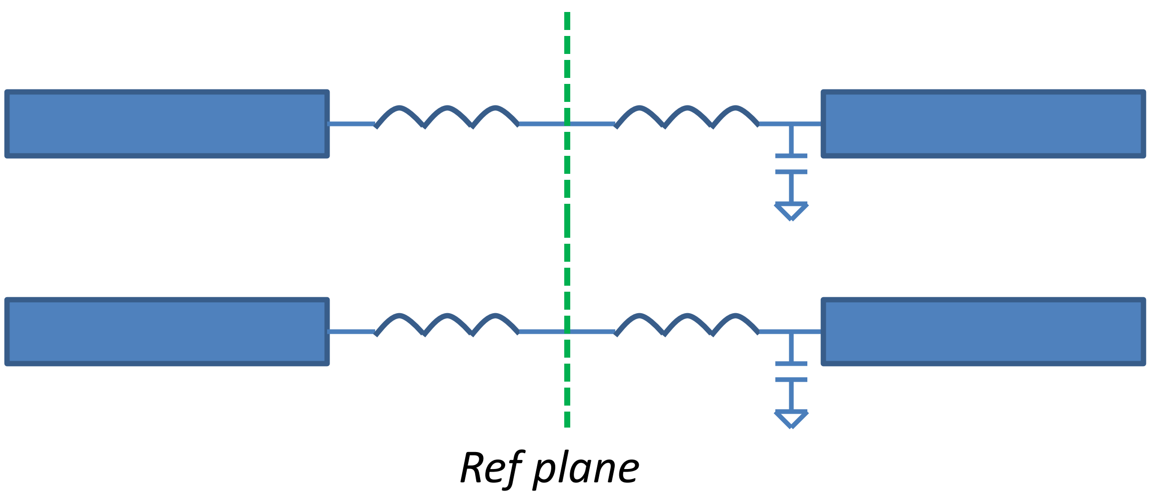
Partial Info Sensitivities 3

The trade-off is that one must know the lengths accurately….



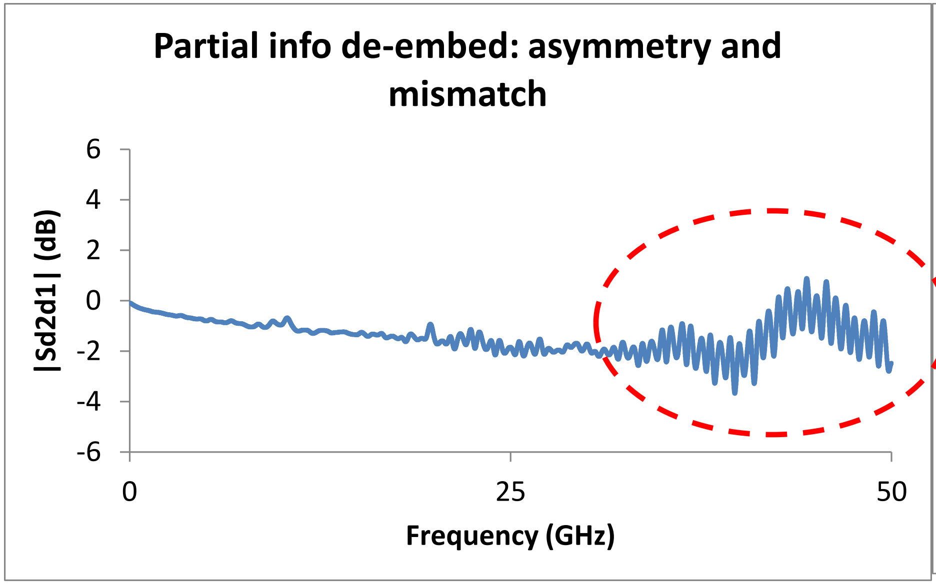
Calibrations: Partial Information Example

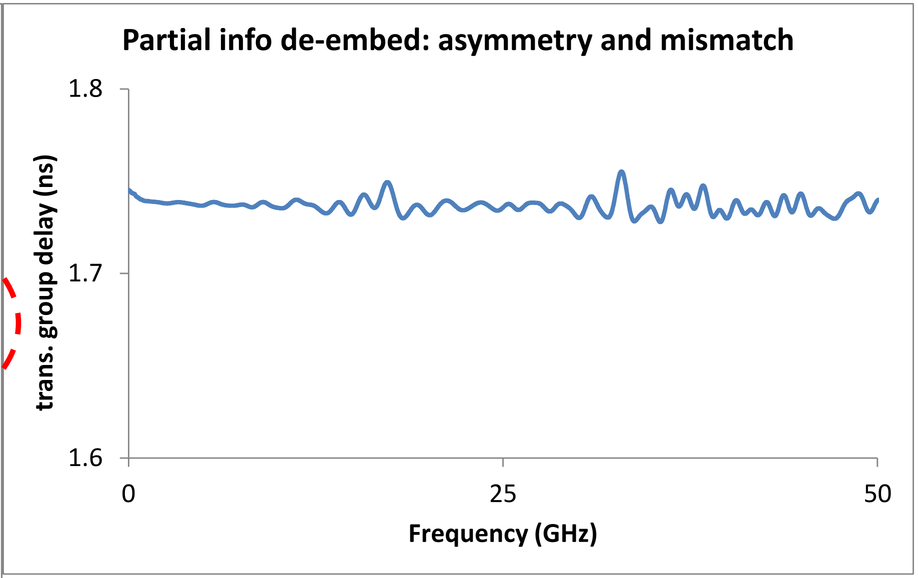
- Test case: pin interface board.
- Well-matched and symmetric at lower frequencies, less so >30 GHz. Total insertion loss ~5 dB at 30 GHz.
- Look at single-line and double-line methods (use an additional measurement to partially solve the inner interface)



Partial Information Example 2

Single line: asymmetry and larger interface mismatch lead to passivity and other problems at higher frequencies. Below ~30 GHz, the IL and reference plane behavior is better.

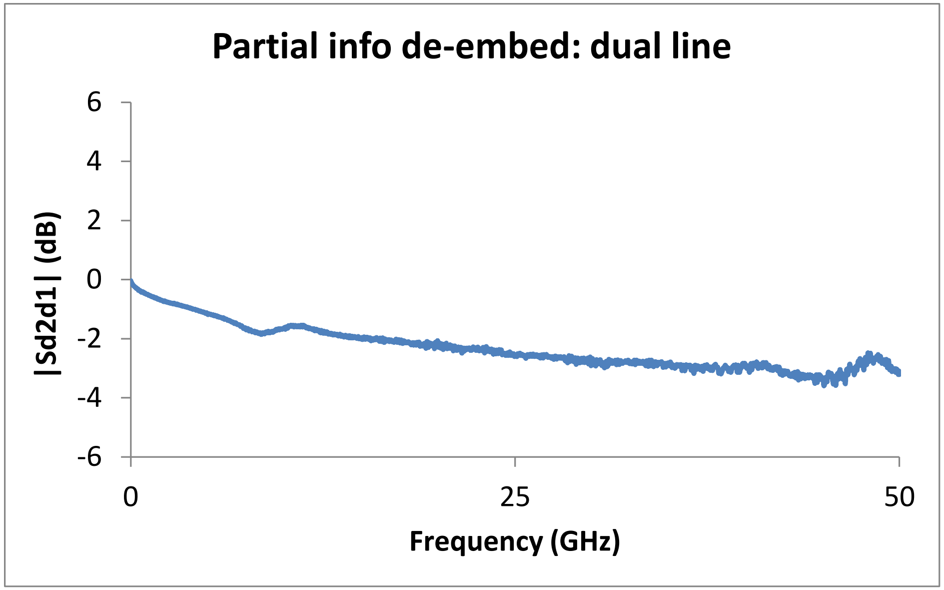




While potentially better than the alternatives, using this data for extraction/simulation outside of its 'bounds of reason' will cause issues…

Partial Information Example 3

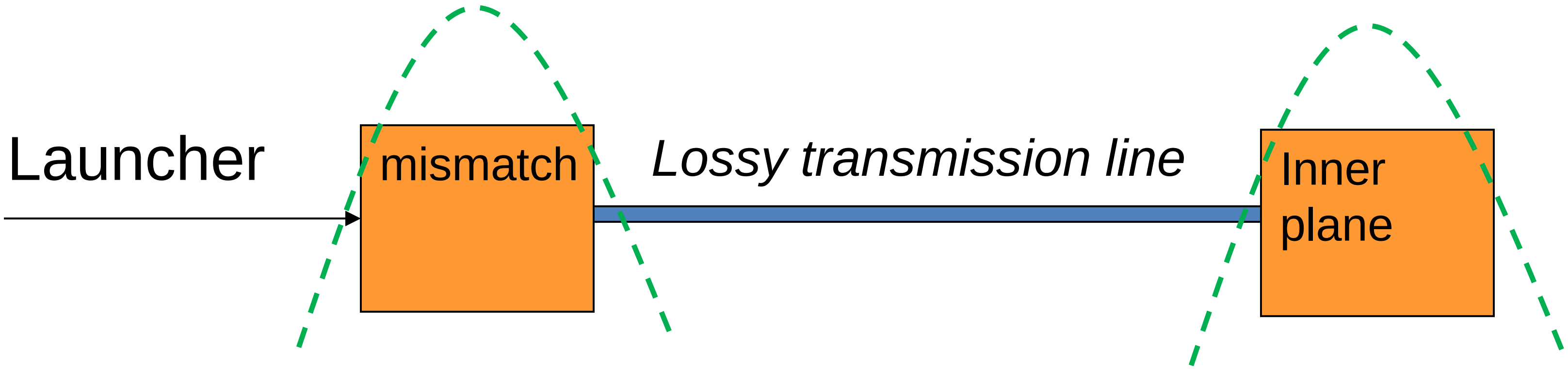
- Double line method with precision length deltas (*Important!*)
- Slightly different DUT
- Mismatch handled better. Asymmetry still leads to some issues above 40 GHz.



As long as the line length data is accurate, this data can likely be used over a broader frequency range for further simulation…

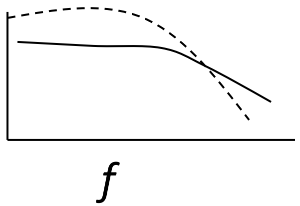
Calibrations: TD Methods 1

- Time domain separation of structures in a fixture can be an effective tool that requires fewer and less complex standards.
- Given sufficiently separated structures, the parameters of individual elements can be de-embedded.

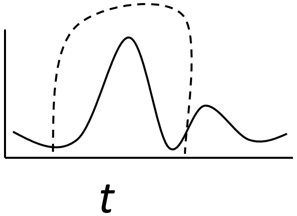


Calibrations: TD Methods 2

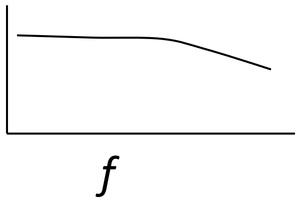
- A number of processing steps are involved, each with their own potential for data degradation. Some information gets thrown away at each stage!



Freq. domain data is windowed to reduce sidelobes in time domain



Time domain data is created and a gate selected. The gate has its own extent.



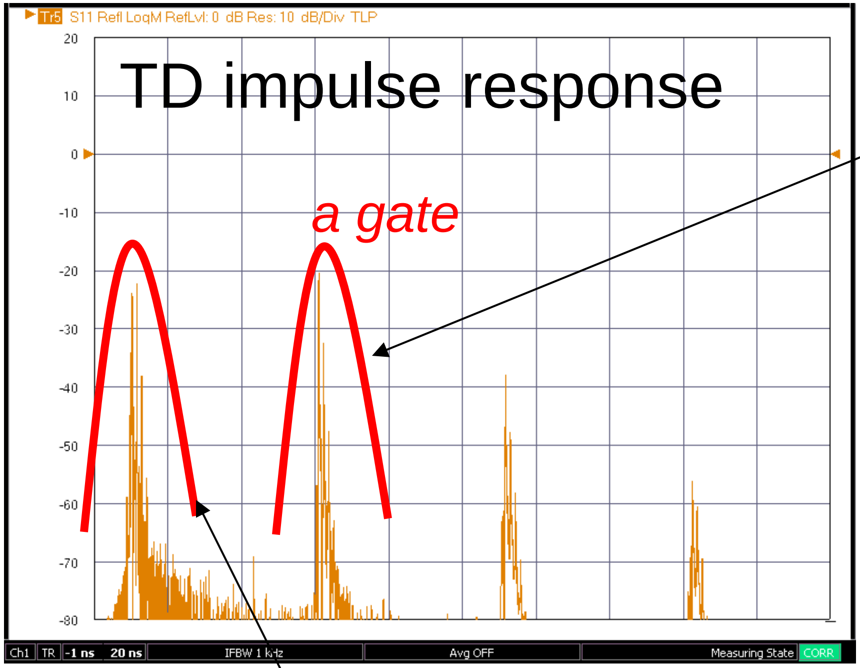
The data is transformed back to the frequency domain and re-windowed/re-scaled if necessary.

Calibrations: TD Methods 3

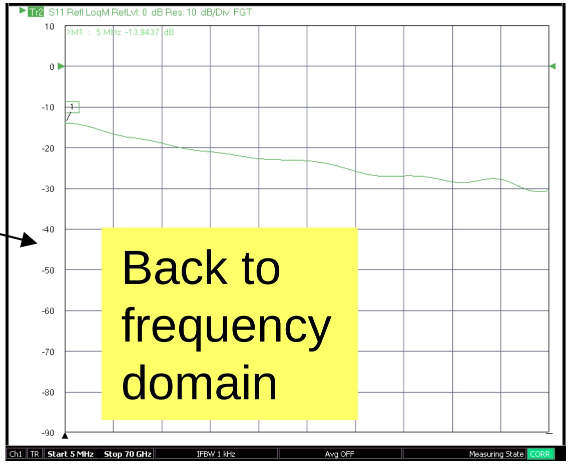
- Different extraction methods
  - ‘Onion-peel’ fitting
    - Separate out dominant structures in a fixture and model each one (a launch, a transmission line run with vias,…)
  - Reflection separation
    - Use a known reflection to generate loss/phase model of the main fixture
  - Other options
    - Combine gated results with other methods (SOLR,…)

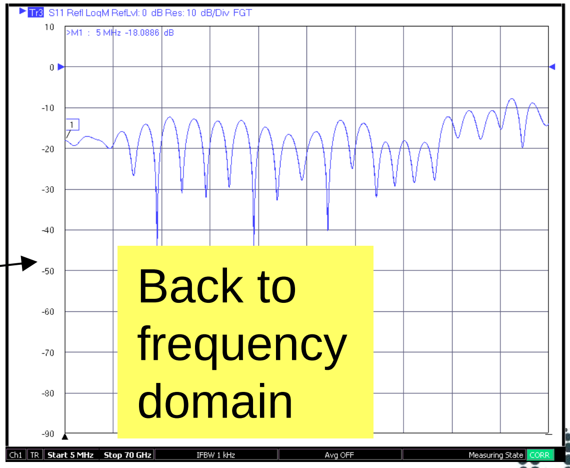
Calibrations: TD Methods 4

- Separated section responses can be more easily modeled (assuming adequate resolution)



Loss of line+reflect at end





Mismatch at launch

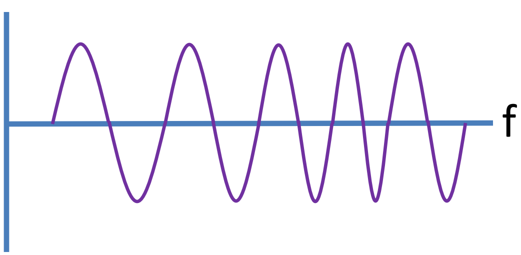
Launcher → mismatch

Lossy transmission line

Time Domain Method Sensitivities

- Less susceptible to traditional standards issues. The transform itself removes some of those oscillatory behaviors. Here G(t) is the transform of a set of transitions and h(ω) is an uncertainty function.

$$G(t)=\frac{1}{2\pi}\sum_k a_k\int\left(e^{-\alpha_k\omega}e^{-j\omega\cdot t_k}+h(\omega)\right)\cdot e^{j\omega\cdot t}\,d\omega$$

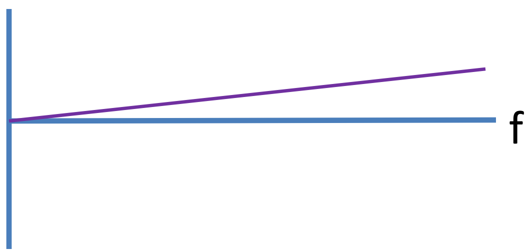


Integration over all frequency

Not much error
(dispersed, low-level)

Time Domain Sensitivities 2

- More susceptible to data slope (drift or ref plane issues), low frequency behavior, and window/gate distortions.

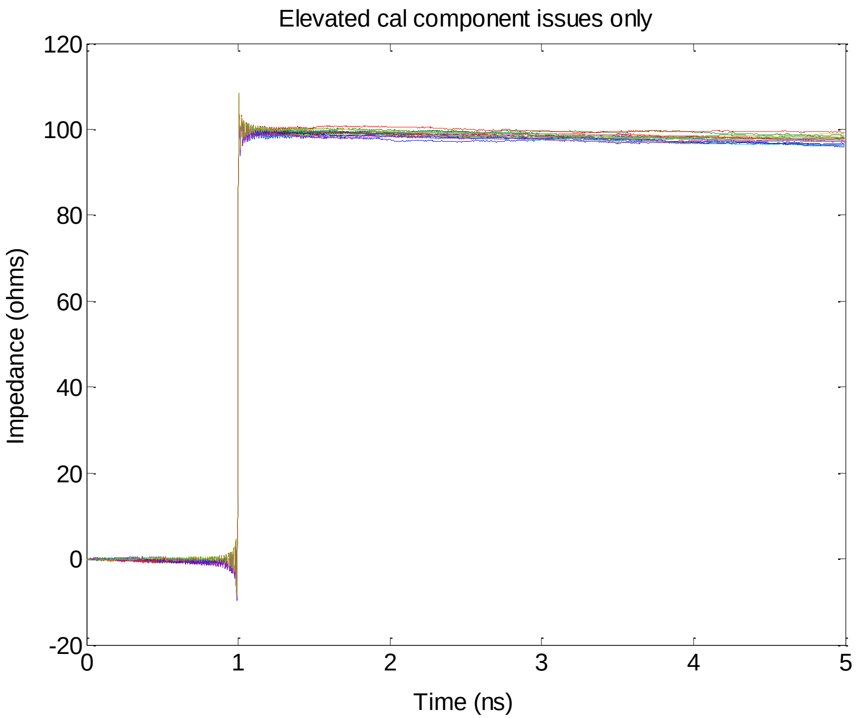


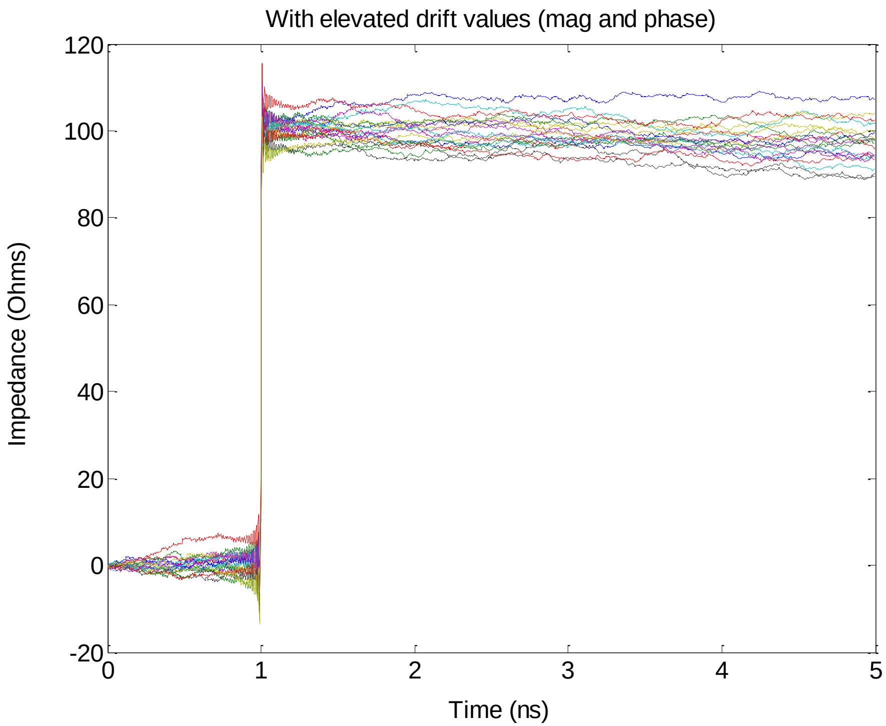
Integration over all frequency

Potentially a large error contribution

Time Domain Sensitivities 3

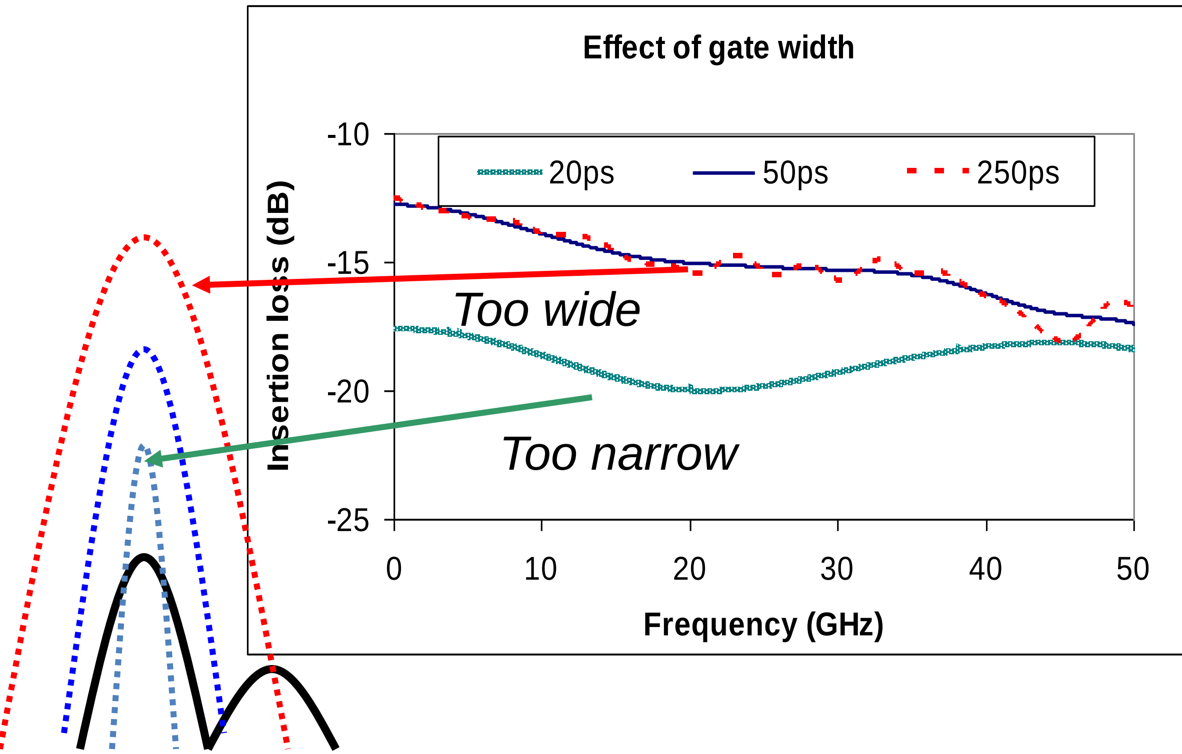
- A Monte Carlo analysis with just calibration kit issues and one with drift issues show the relative impacts.



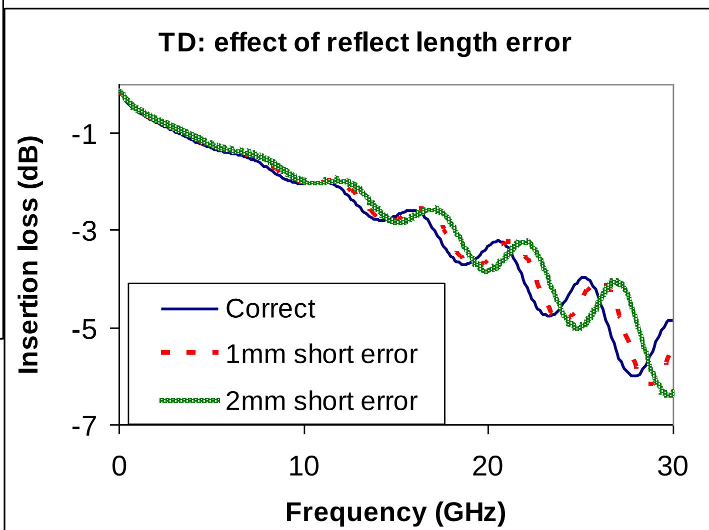


TD Sensitivities: Gate/Window Choice and Reflect Standards

Improper gate choice can lead to loss of energy or inclusion of unintended structure.

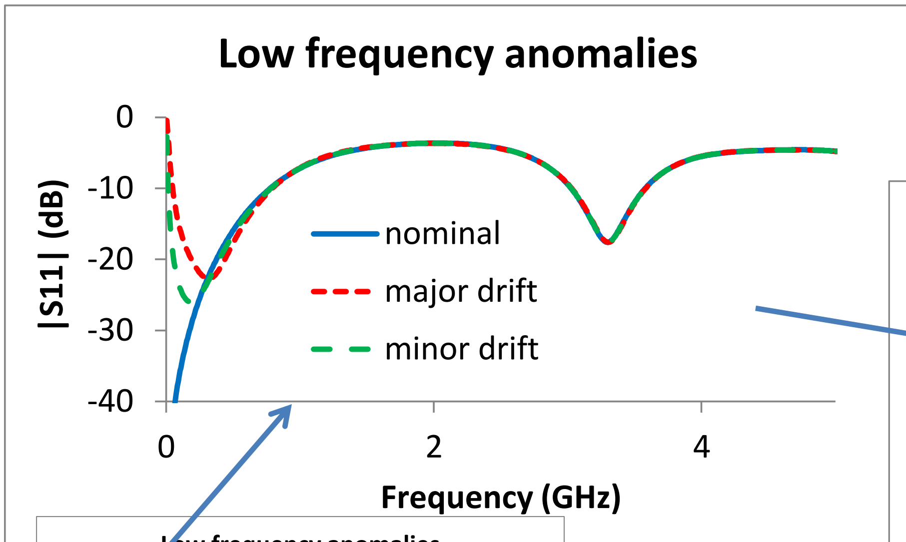


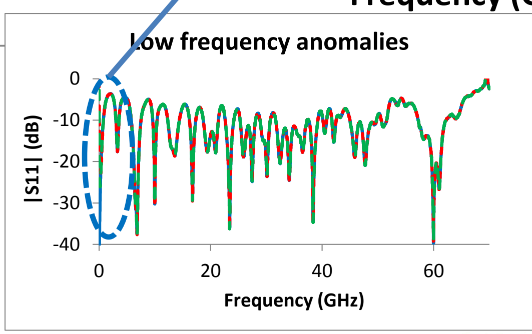
Improper reflect definition leads to reference plane problems.

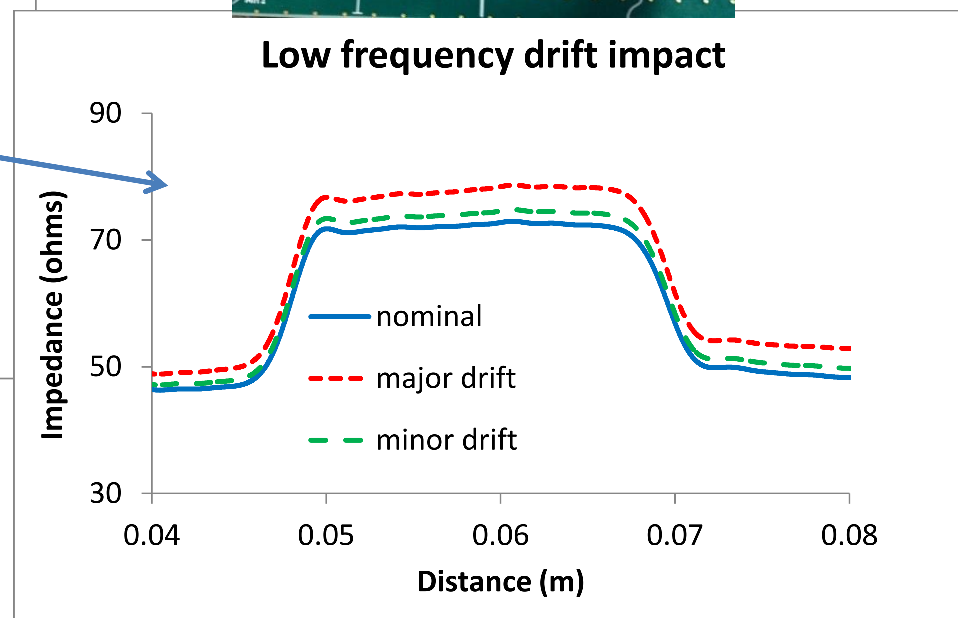


Low Frequency Effects

Low frequency data issues (drift/instability…) can have an out-sized effect on transformed data because of its criticality to large-distance-scale structure.

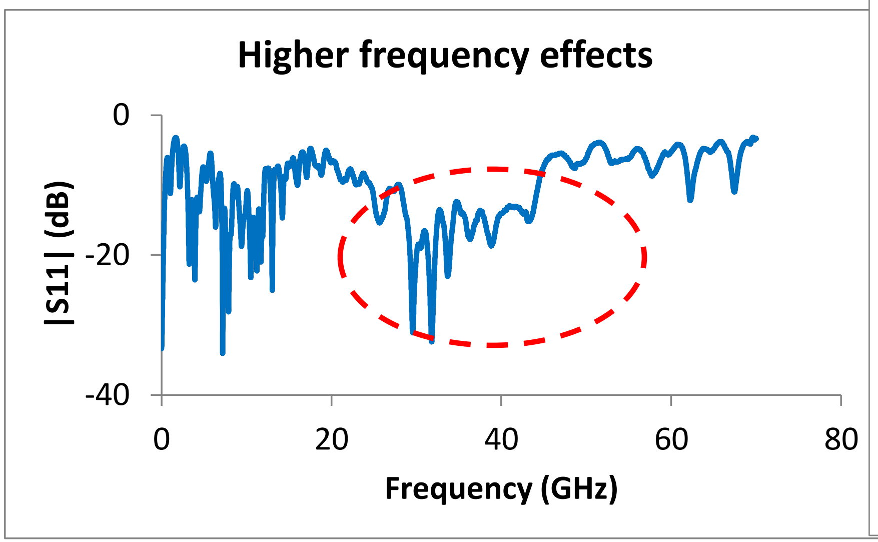


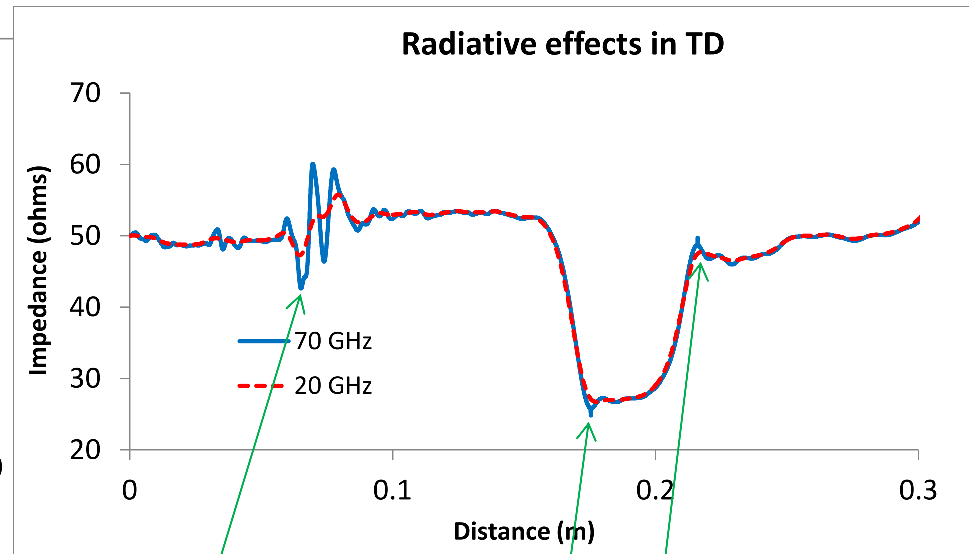




Bandwidth and Resolution

While greater bandwidth leads to more resolution, if the DUT/fixture starts to radiate, the data may be unstable and the results less usable for further analysis.



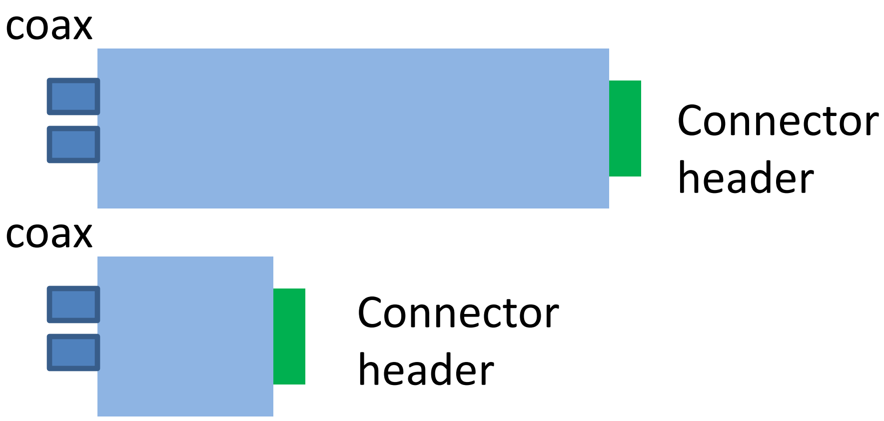


DUT is radiating here making it environmentally sensitive….

Some of the structure change is better resolution, some is radiative artifacts…

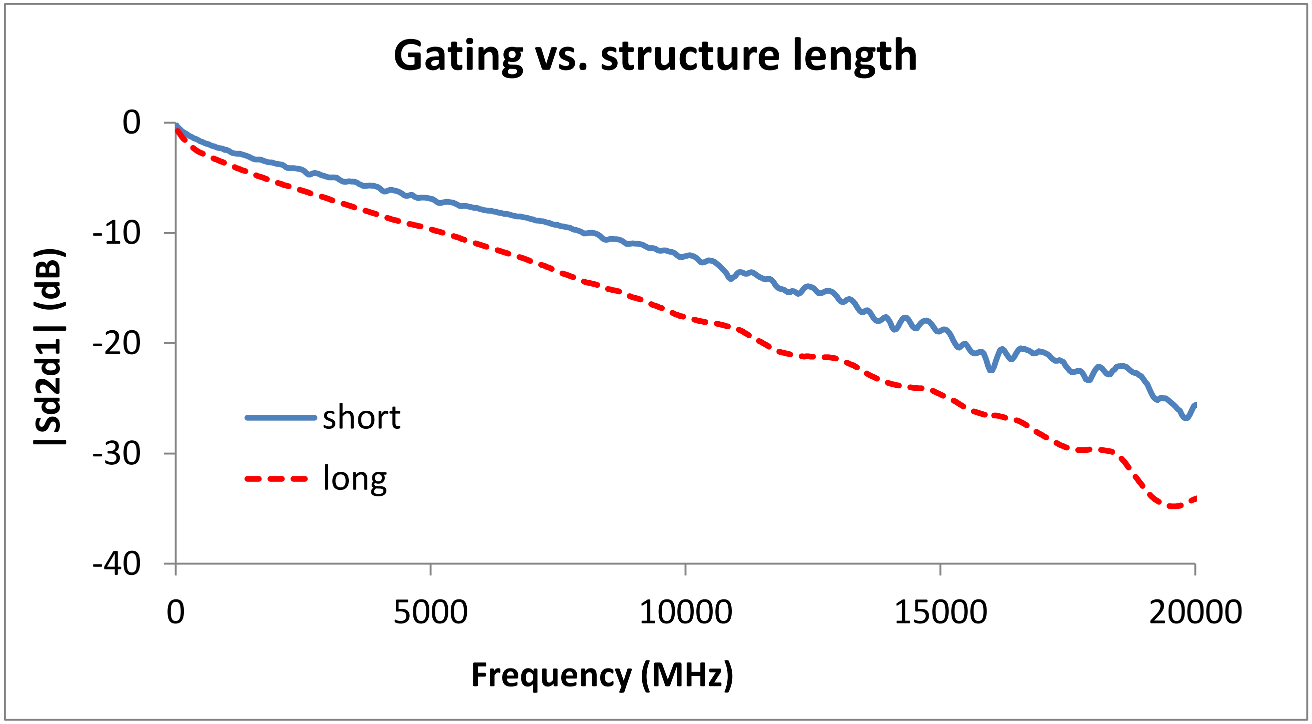
Calibrations: TD Methods 4

- Test case: via board or long interface fixture
- Use a known reflect (short) at the inner plane and gate to solve for the fixture path
- Compare results for different fixture lengths



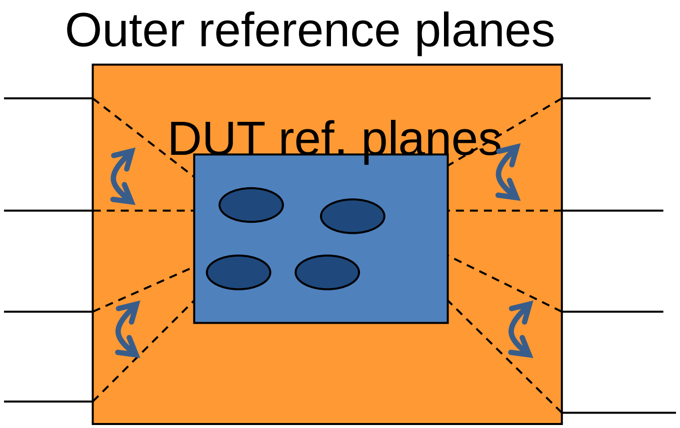
TD Example: Resolution

Because the short DUT is closer to resolution limit, the launch-induced ripples are harder to separate. That added structure can propagate through the measurements (particularly in phase).



Calibrations: Imposed Assumptions 1

- In high-port-count crosstalk measurements with leaky fixtures, the number of standards required can be large
- Enforcing passivity, reciprocity, and (maybe) symmetry, can reduce the standards count and repeatability issues. (12 in some 4 port fully leaky fixtures…down to 5 or 6)

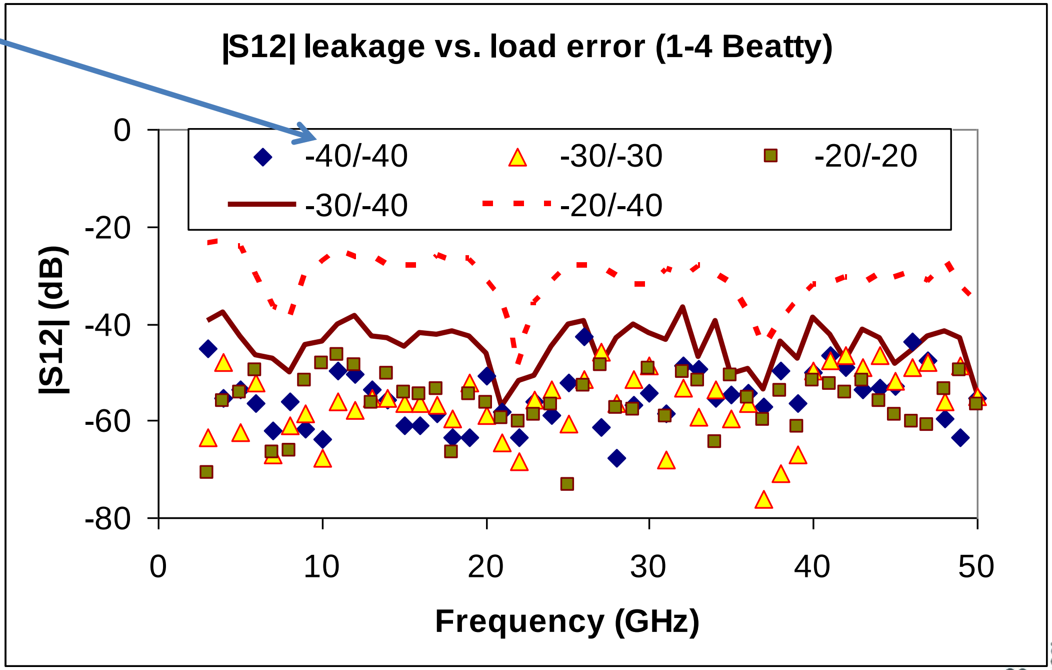


By keeping standards count low, the likelihood of a data-destroying repeatability problem is reduced…

Calibrations: Imposed Assumptions 2

- Standards symmetry can be more important than the absolute levels. Sensitivity to load defects is below:

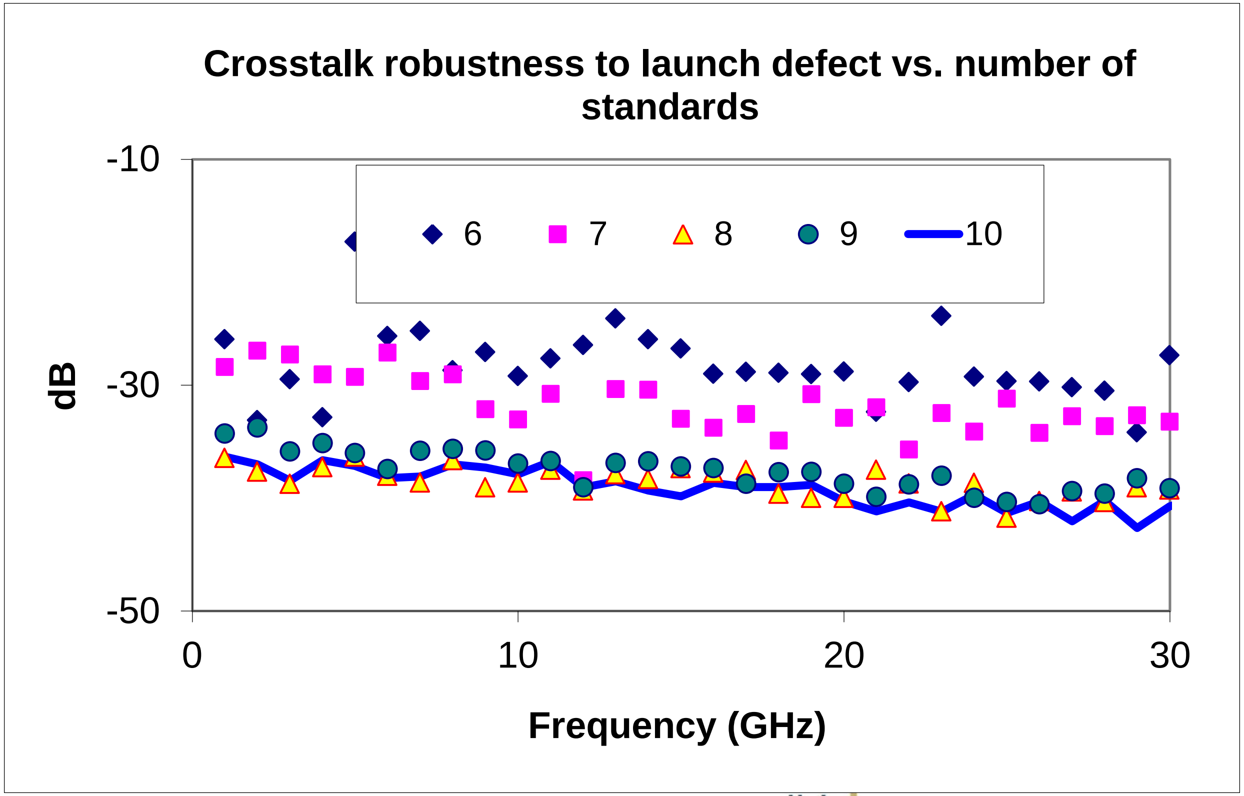
Reflection coefficients of two different loads used. Symmetry matters when solving for isolation.



Measuring FEXT when the dominant path is somewhat reflective. Note sensitivity to the main path reflection.

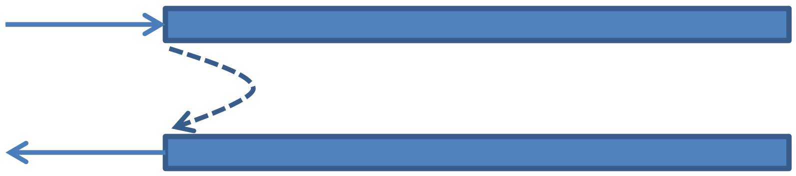
Imposed Assumptions: Adding Standards

When trying to de-embed highly leaky fixtures for NEXT/FEXT, additional standards can help to a point. Beyond that, one just adds risk of reducing data quality from repeatability issues.



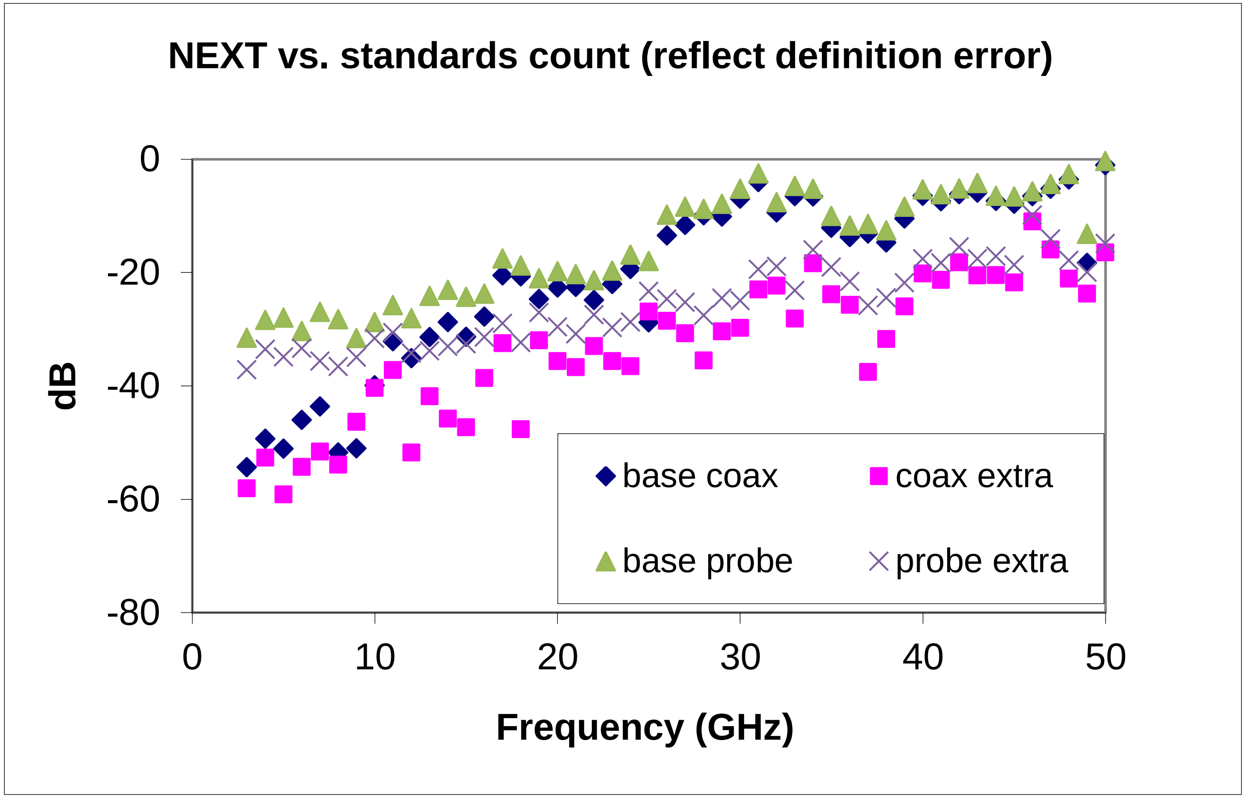
Calibrations: Imposed Assumptions 3

- Test case: crosstalk measurement with a leaky fixture; use reciprocity and fixture symmetry.
- Consider both connectorized and probe measurements (difference mainly in repeatability)
- Consider effect of adding an extra standard (split termination)



Imposed Assumptions Example

Base probe results are worse due to repeatability. An extra standard helps in both cases, somewhat more in the higher-repeatability connectorized case.



Calibrations: Summary 1

- A number of methods have been presented with an eye on maximizing data integrity for later processing. Low-end data, phase behavior, and repeatability effects can be central.

- Knowing the standards behavior, the repeatability spectrum and the paths involved on the fixture and DUT can help one choose a method.

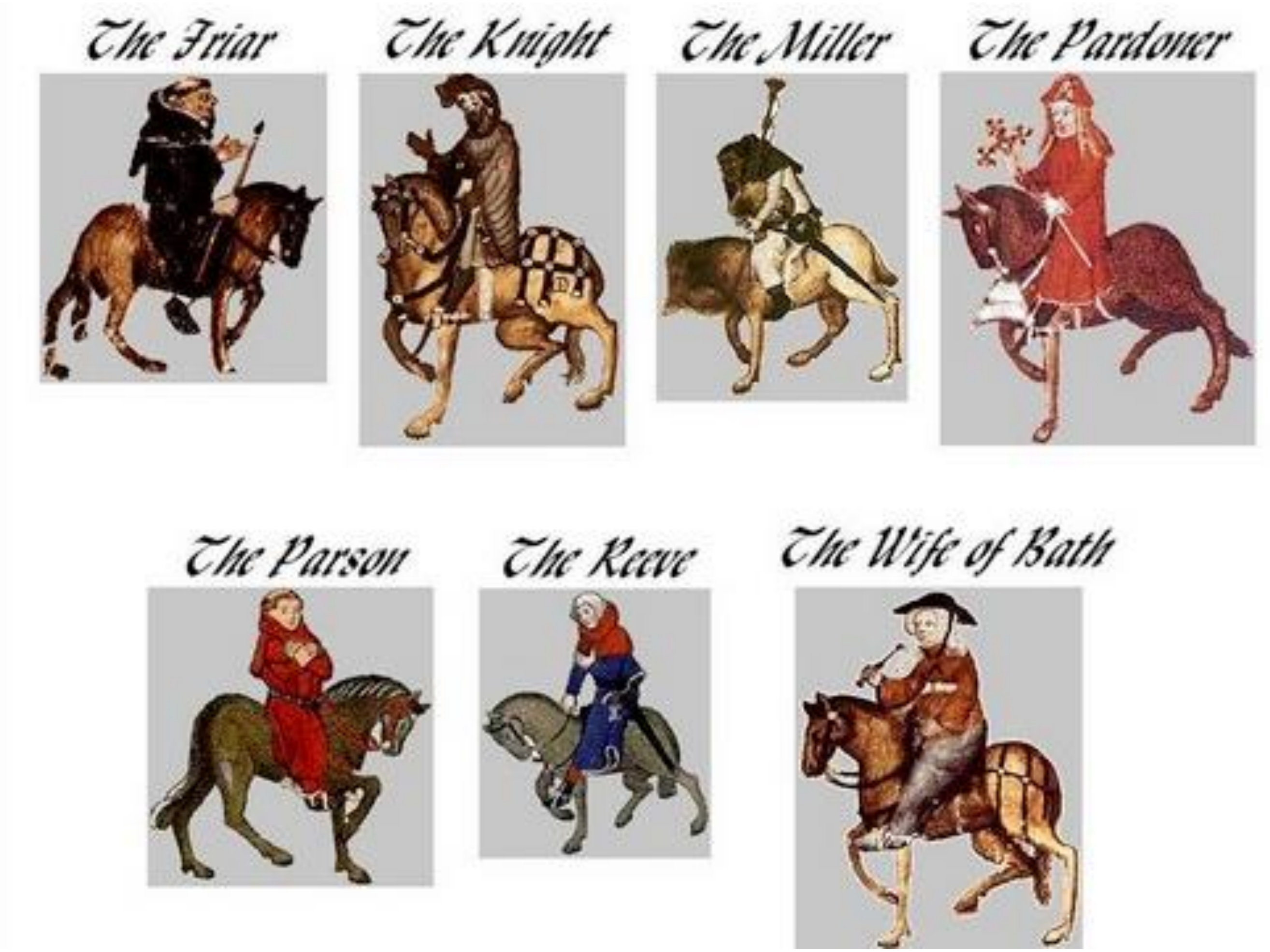
Calibrations: Summary 2

A concern?	SOLT, etc.	SOLR, etc.	TRL, etc.	Hybrid	Partial	TD-based	Imposed
Standard def.	Yes	Yes/maybe	Usually no	Less so	No	Less so	Yes
Standards ideality	Maybe	Maybe	Yes	Less so	Maybe	Maybe	Maybe
Repeatability	Maybe	Maybe	Yes	Less so	No	Less so	Maybe
Ref. plane	Yes	Maybe	Can be (which one?)	Maybe	Maybe	Maybe	Maybe
Media issues	Yes	Maybe	Maybe	Less so	No	Less so	Less so
Standards count	Yes for high N	Yes for high N	Yes for high N	Yes for high N	No	Usually No	Usually No

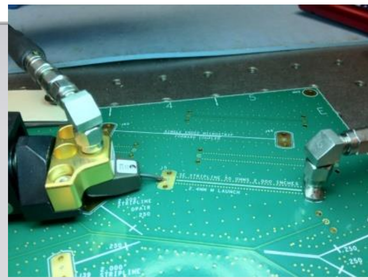
Agenda

- Introduction
- The Metrologist's Tale
  - Practical calibration methods suited for 3D-EM
    - Jon Martens
- The Signal Integrity Practitioner's Tale
  - Verification and assurance
    - Jim Bell and Al Neves
- The 3D-EM Modeler's tale
  - Time domain processing and 3D-EM model development
    - Josiah Bartlett
- Questions

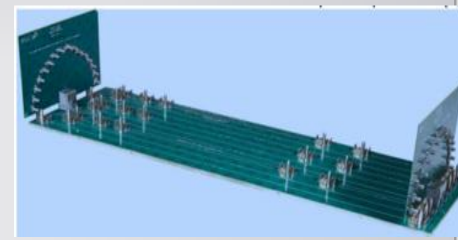
First:
What Role Does the S.I. Practitioner Play?



The Signal Integrity Practitioner
- Nexus of many Disciplines



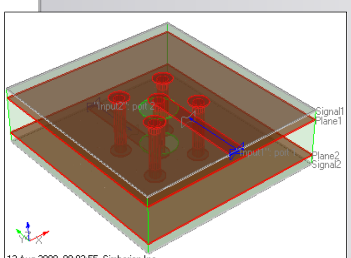
Metrology - Measurement



3D Modeling

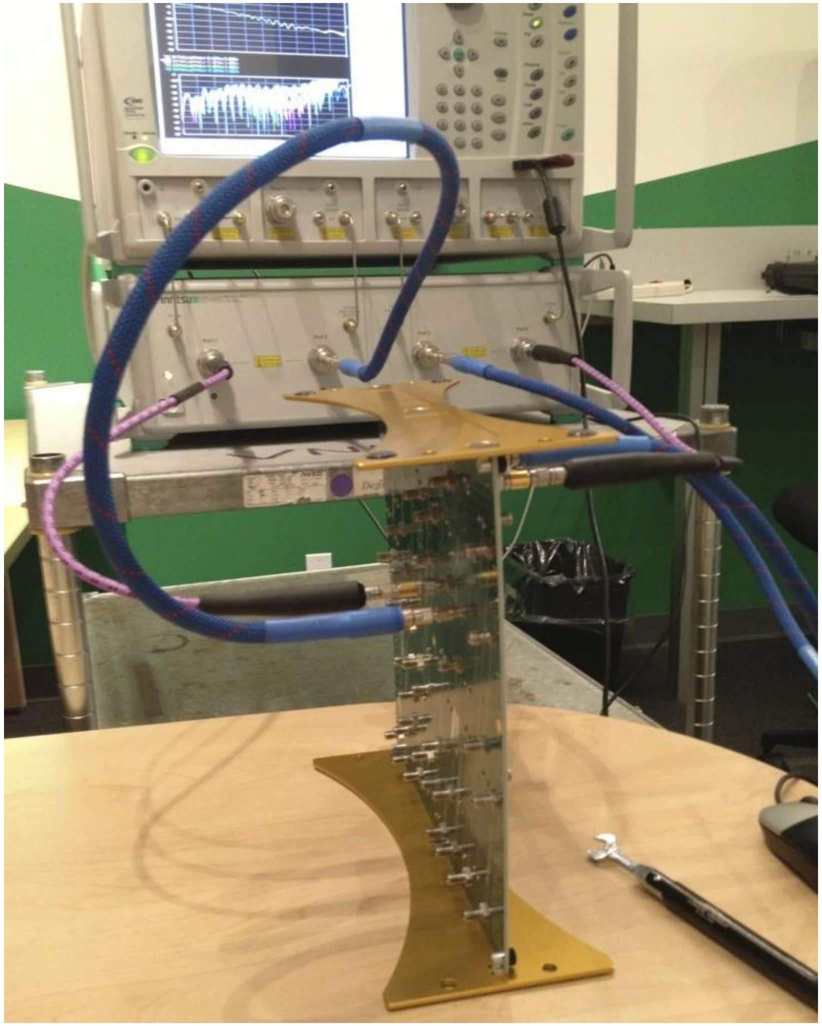
S.I. Practitioner

General SI Issues

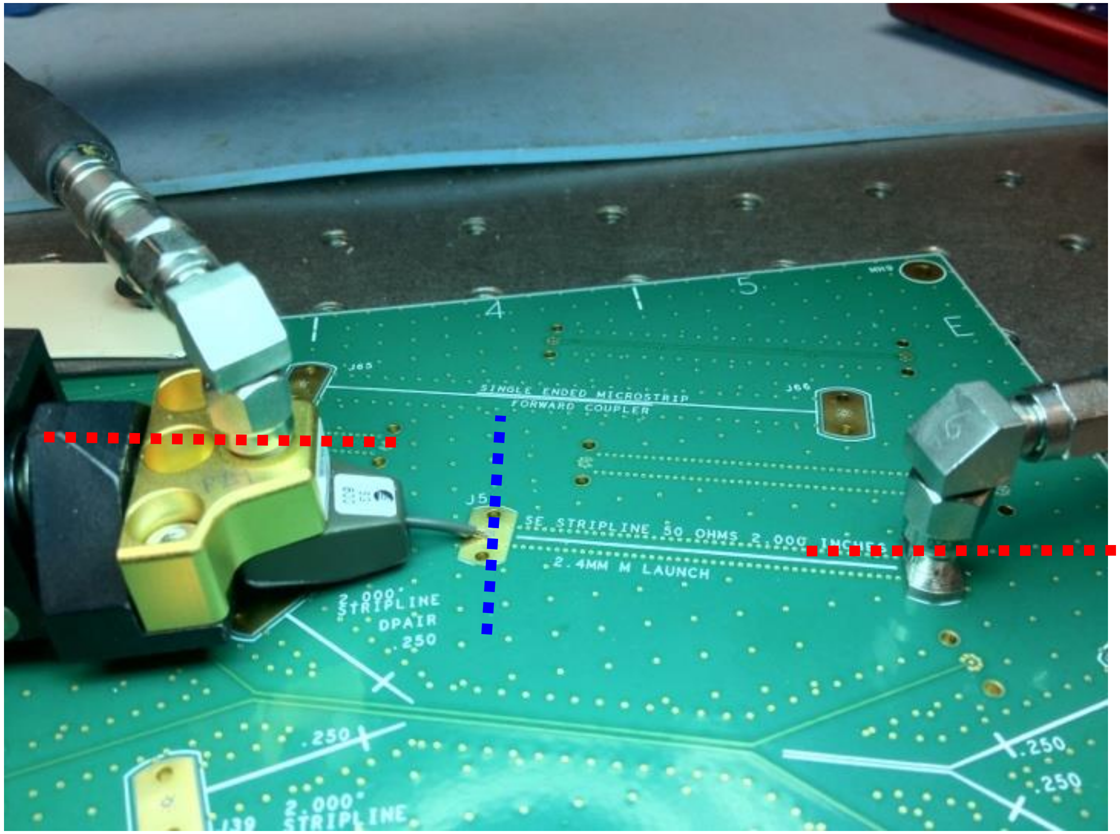


Development - Business - Marketing

3D-EM to Measurement

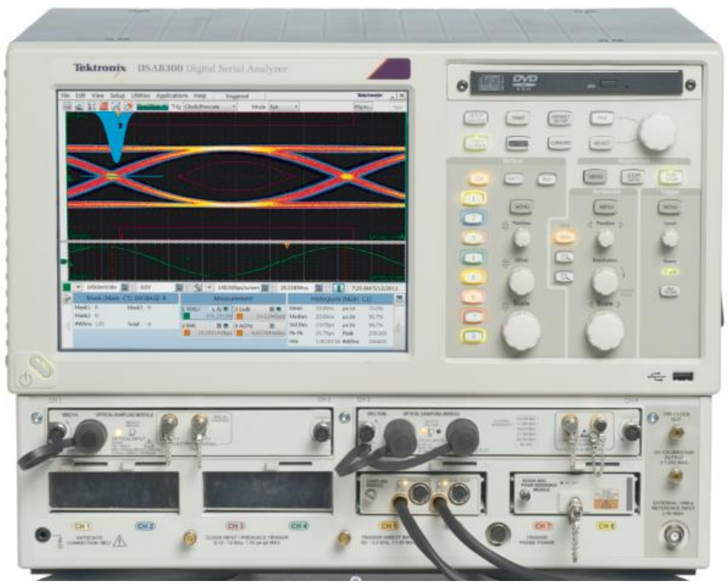


Practical Calibrations - Hybrid, Multi-Tier, Validation



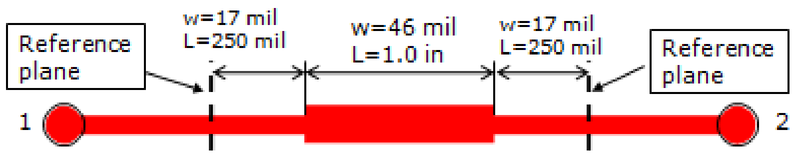
Key Tools for the S.I. Practitioner

Frequency

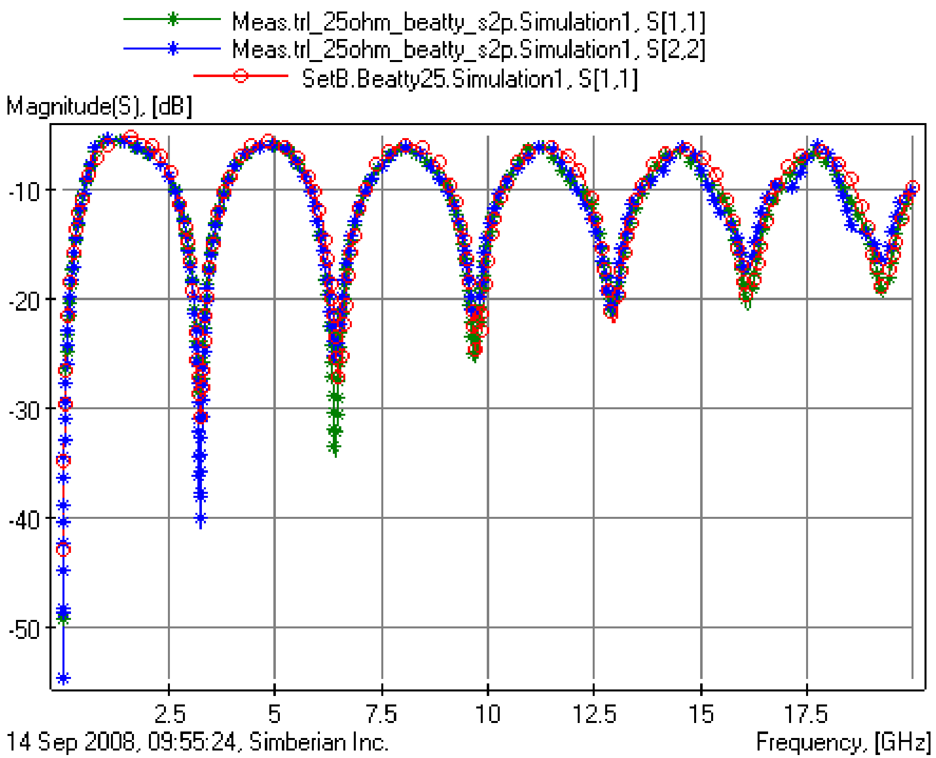


Time

3D-EM Correspondence to Measurement



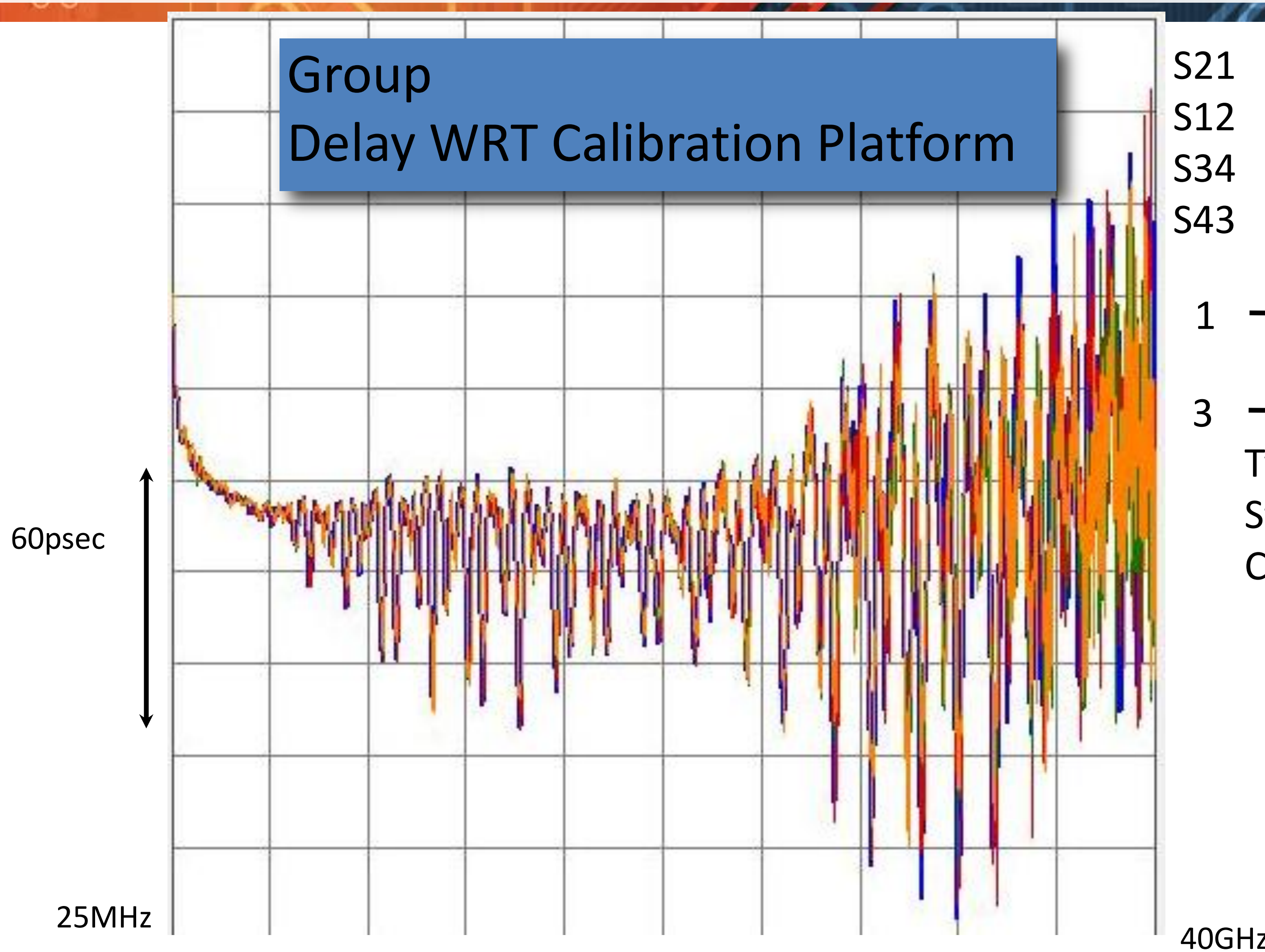
Reflection coefficients magnitude



S-Parameters as Measured with VNA - The Real World

- Limited in BW
  - Fstop is exactly that!
- Systematic and Non-systematic noise issues- IF BW
- Difficult to calibrate at times, especially hybrid, mixed, partial methods
- S-Parameter validation issues
- Transform issues for time domain
- Low Frequency Directivity issues for Coupler, Calibration problems at low frequencies
- Need for SI Folks to Embrace Standards!

It is Not Always Noise - Sometimes it is Symmetric and Reciprocal Even for Two Lines!



1 ———— 2

3 ———— 4

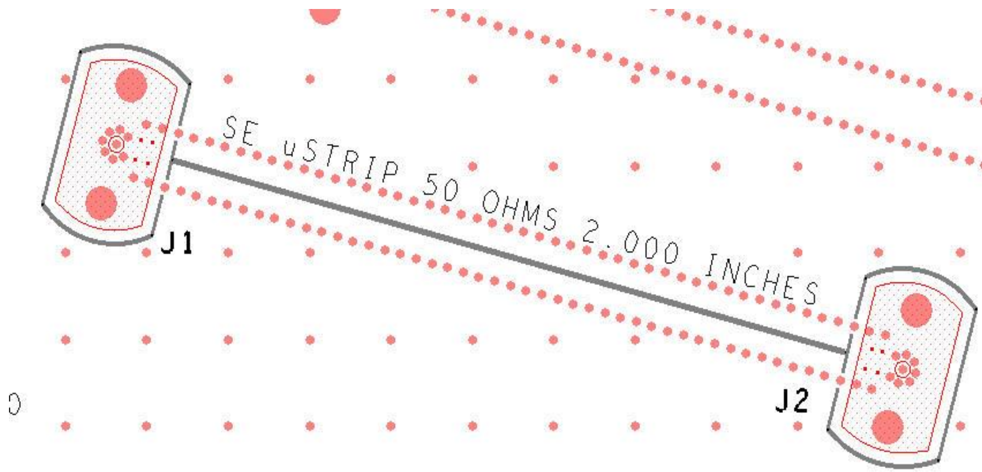
Two Uncoupled Striplines on CMP platform

Issues Relevant to SI Practitioner

- How many companies market VNA capital equipment AND EDA tools?
- There is (often) a schism between EDA companies and practical measurement methodology
- Need for Comprehensive Benchmarking of tools using Standards
- Tool is Marketed outside of intended applications scope without careful benchmarking

Let us go on a S-Parameter Testing Pilgrimage

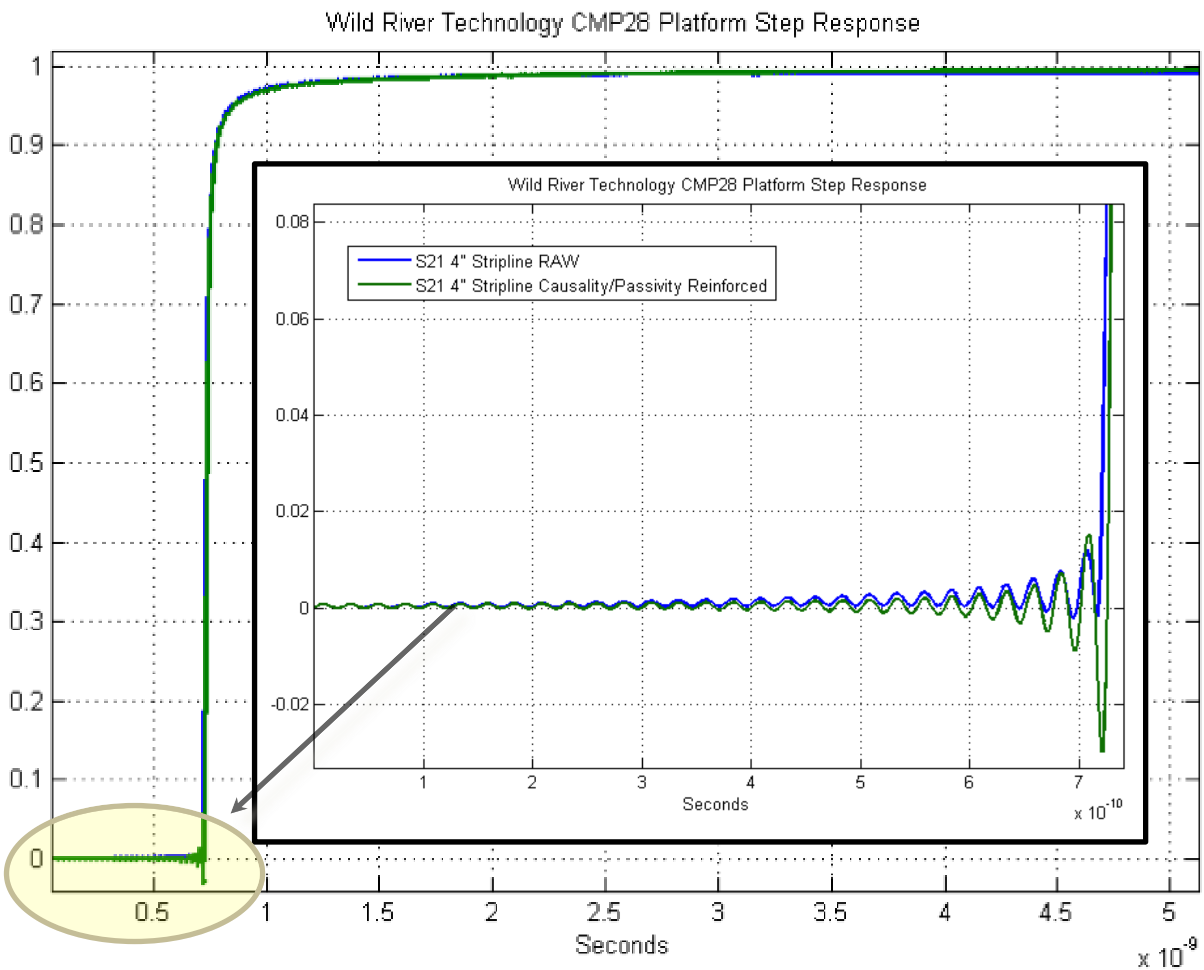
Let’s Start our Journey with a very simple structure:



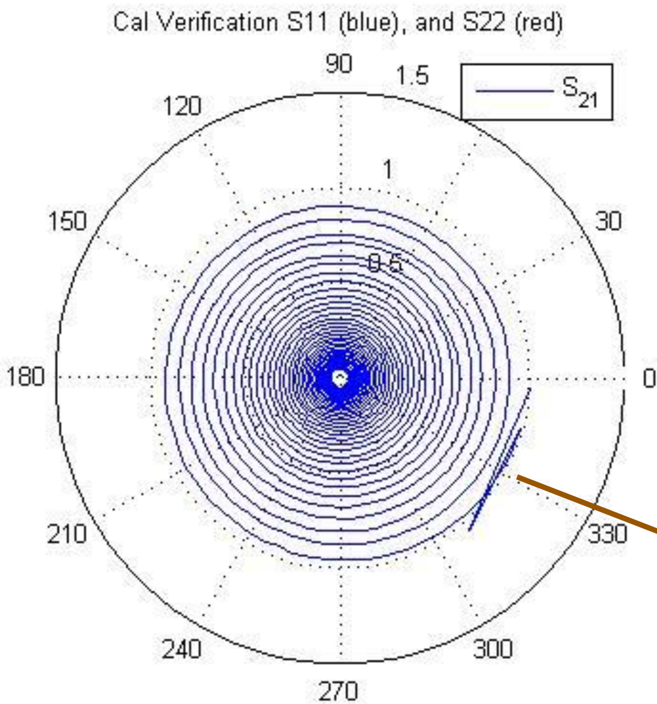
Tool A and B Reported…

- Tool A:
  - passive, reciprocal (s21=s12), symmetric, non-causal approx. 100percent
- Tool B:
  - passive, reciprocal, symmetric, slightly non-causal 0.2783 on S22 (does anyone know what this means?)
- Tool C: Rational Polynomial Expansion

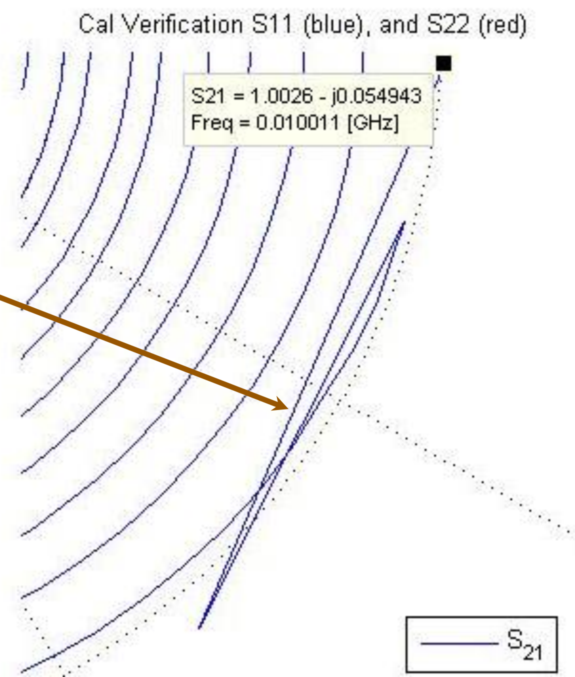
Pulse Response from S-parameter - This S-parameter looks fine!



Polar Plot Simple Causality Testing

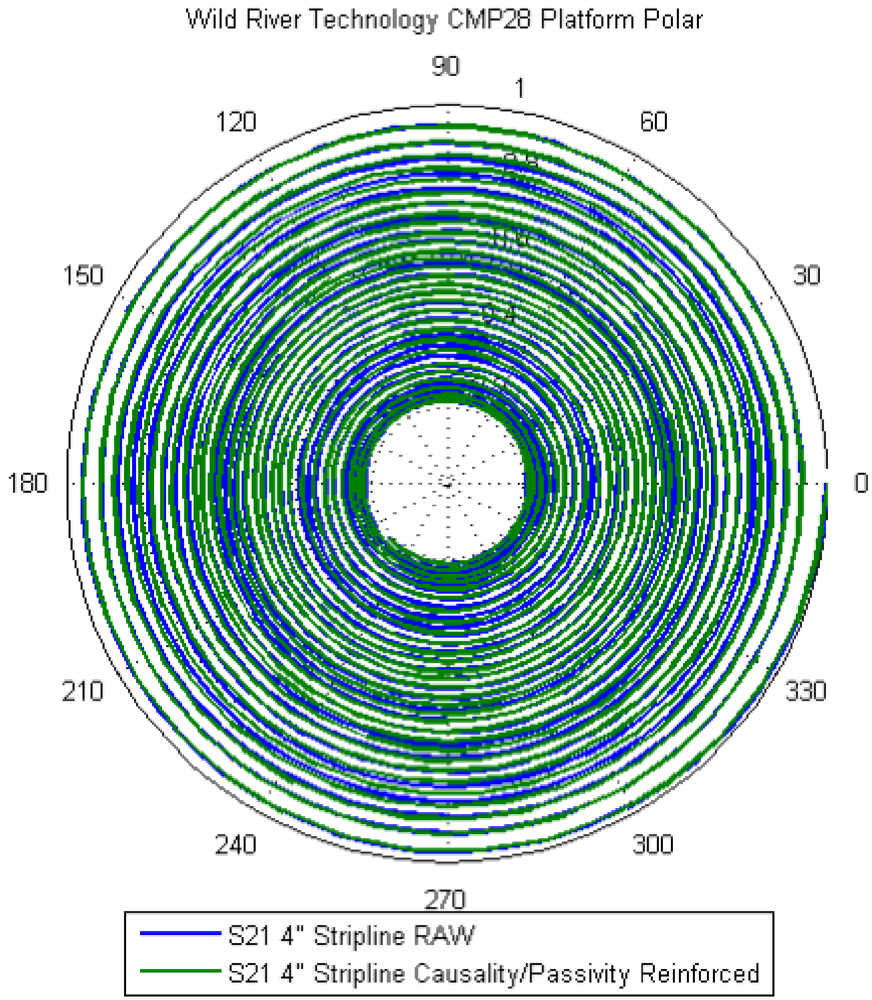


Analysis of Calibration Causality Using Polar Plot, Causal S-parameters should only rotate clockwise



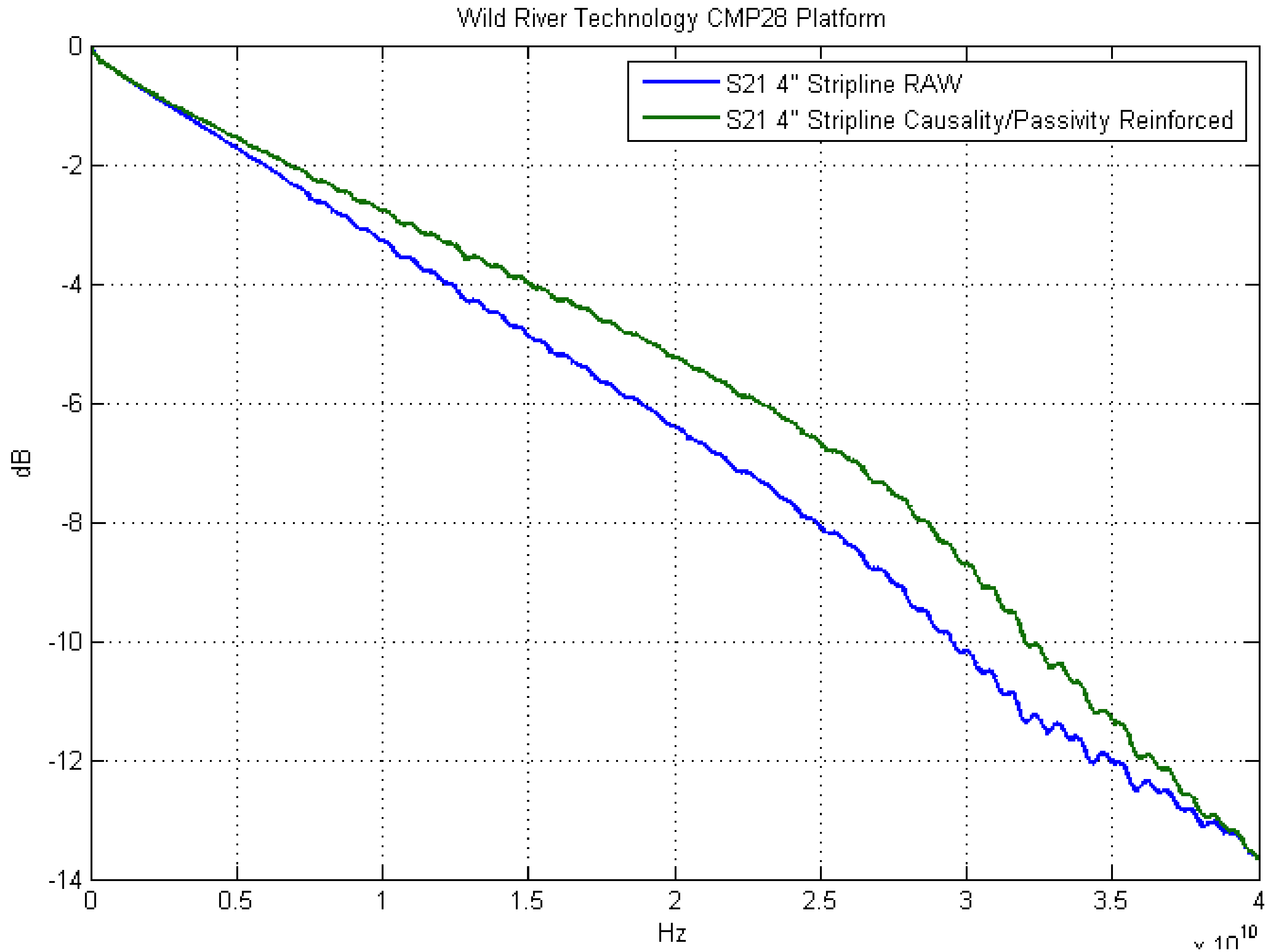
Quick Polar view of Insertion locates non-causal behavior

Before-After Polar Tool A Corrected for Passivity/Causality



There were no apparent issues before we made correction.

Magnitude Impacted by Fix with Tool B



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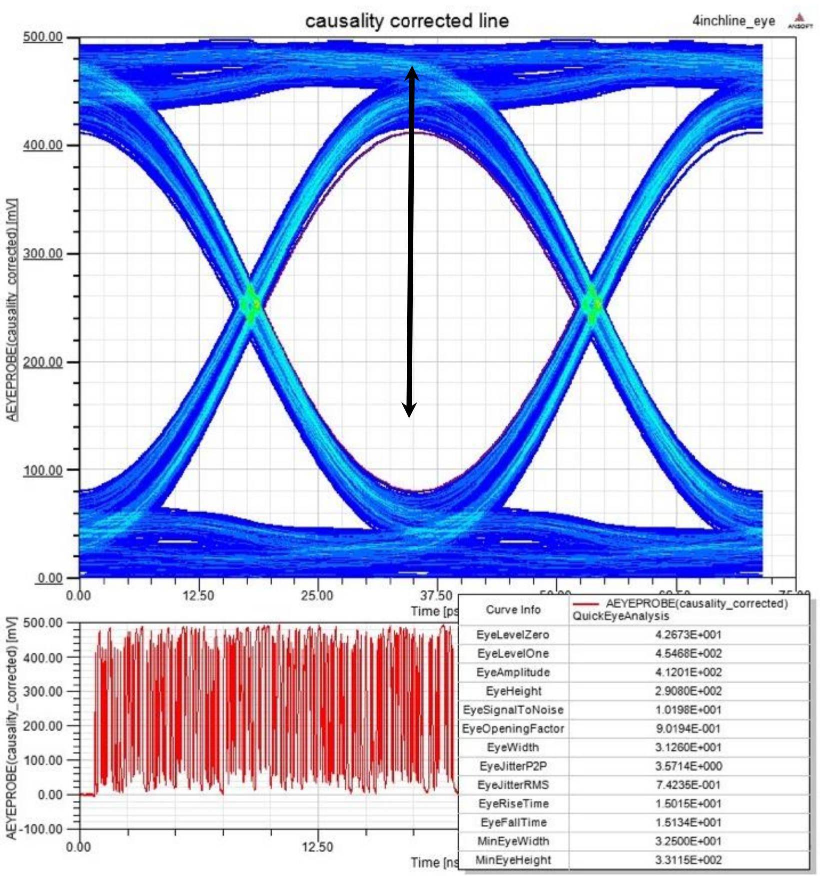
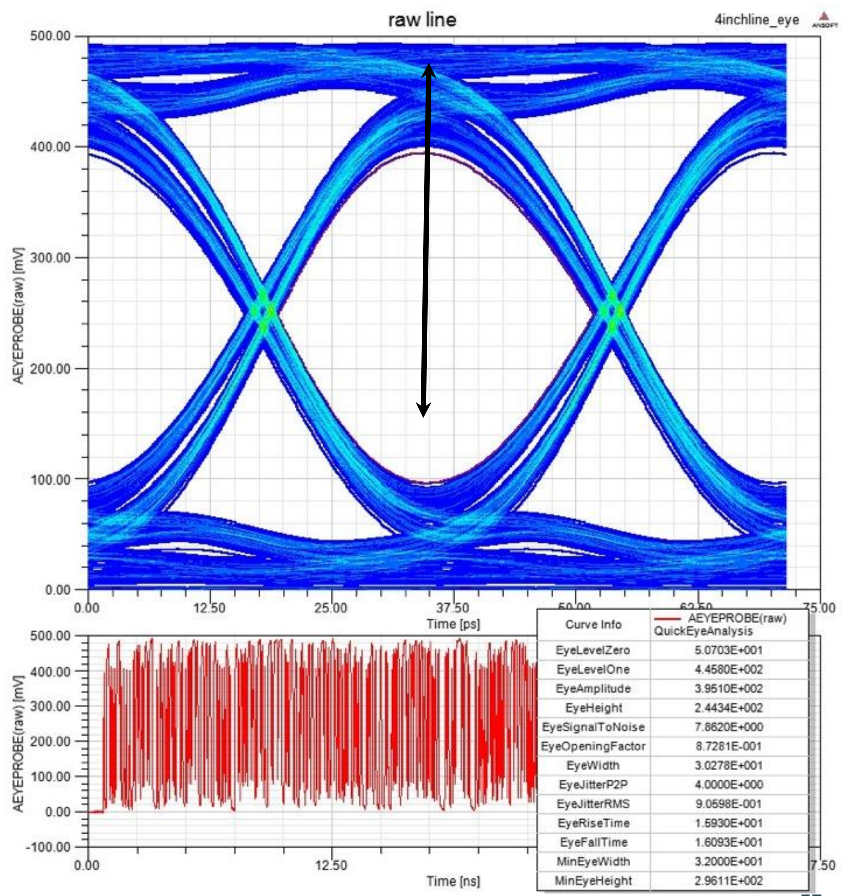
28 Gbpsec Eye Opening Impact from Causality Fix Tool B

44mV Eye Height, 0.5psec Jitter Delta!

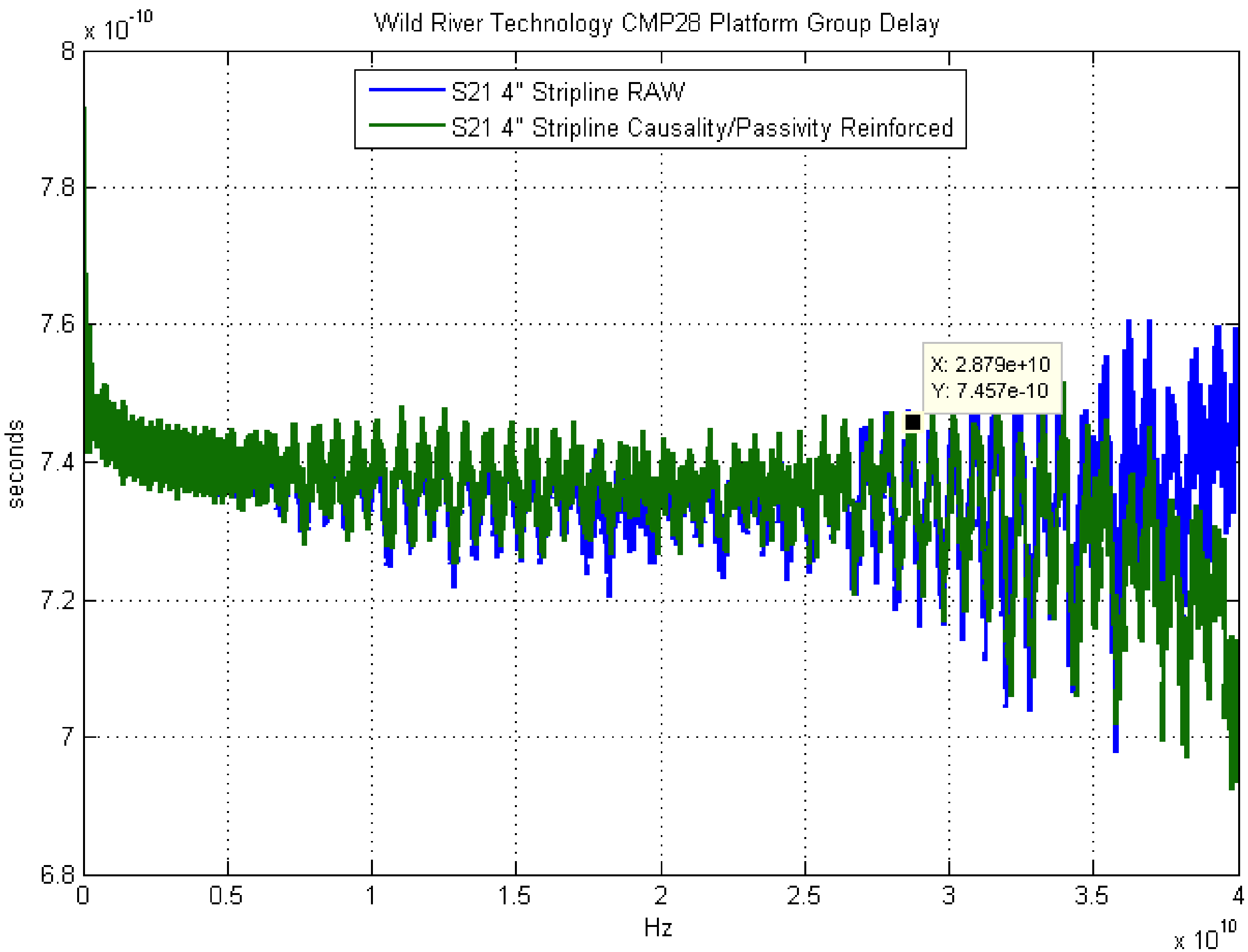


Curve Info	AEYEPROBE(causality_corrected) QuickEyeAnalysis
EyeLevelZero	4.2673E+001
EyeLevelOne	4.5468E+002
EyeAmplitude	4.1201E+002
EyeHeight	2.9080E+002
EyeSignalToNoise	1.0198E+001
EyeOpeningFactor	9.0194E-001
EyeWidth	3.1260E+001
EyeJitterP2P	3.5714E+000
EyeJitterRMS	7.4235E-001
EyeRiseTime	1.5015E+001
EyeFallTime	1.5134E+001
MinEyeWidth	3.2500E+001
MinEyeHeight	3.3115E+002

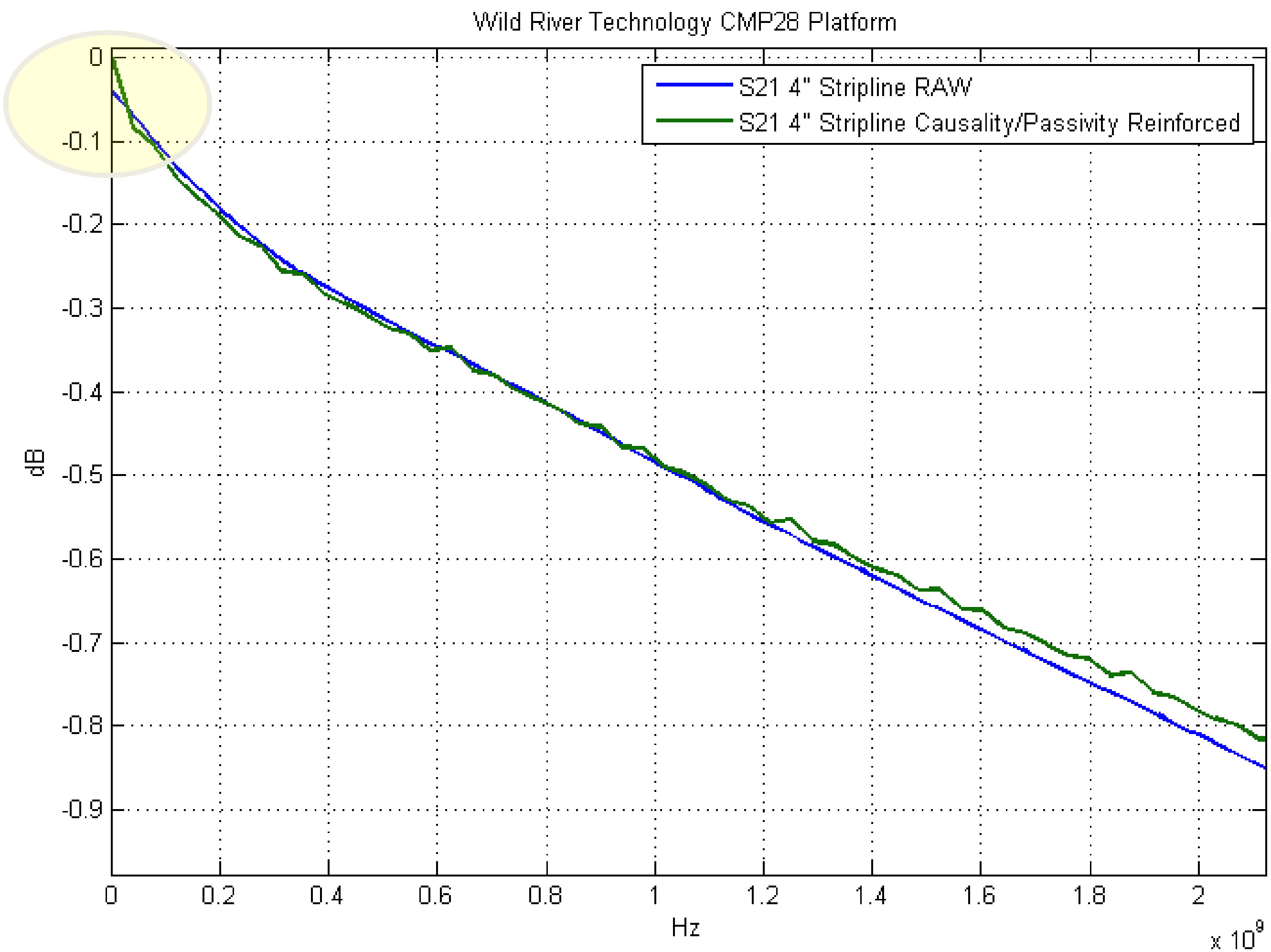


Curve Info	AEYEPROBE(raw) QuickEyeAnalysis
EyeLevelZero	5.0703E+001
EyeLevelOne	4.4580E+002
EyeAmplitude	3.9510E+002
EyeHeight	2.4434E+002
EyeSignalToNoise	7.8620E+000
EyeOpeningFactor	8.7281E-001
EyeWidth	3.0278E+001
EyeJitterP2P	4.0000E+000
EyeJitterRMS	9.0598E-001
EyeRiseTime	1.5930E+001
EyeFallTime	1.6093E+001
MinEyeWidth	3.2000E+001
MinEyeHeight	2.9611E+002

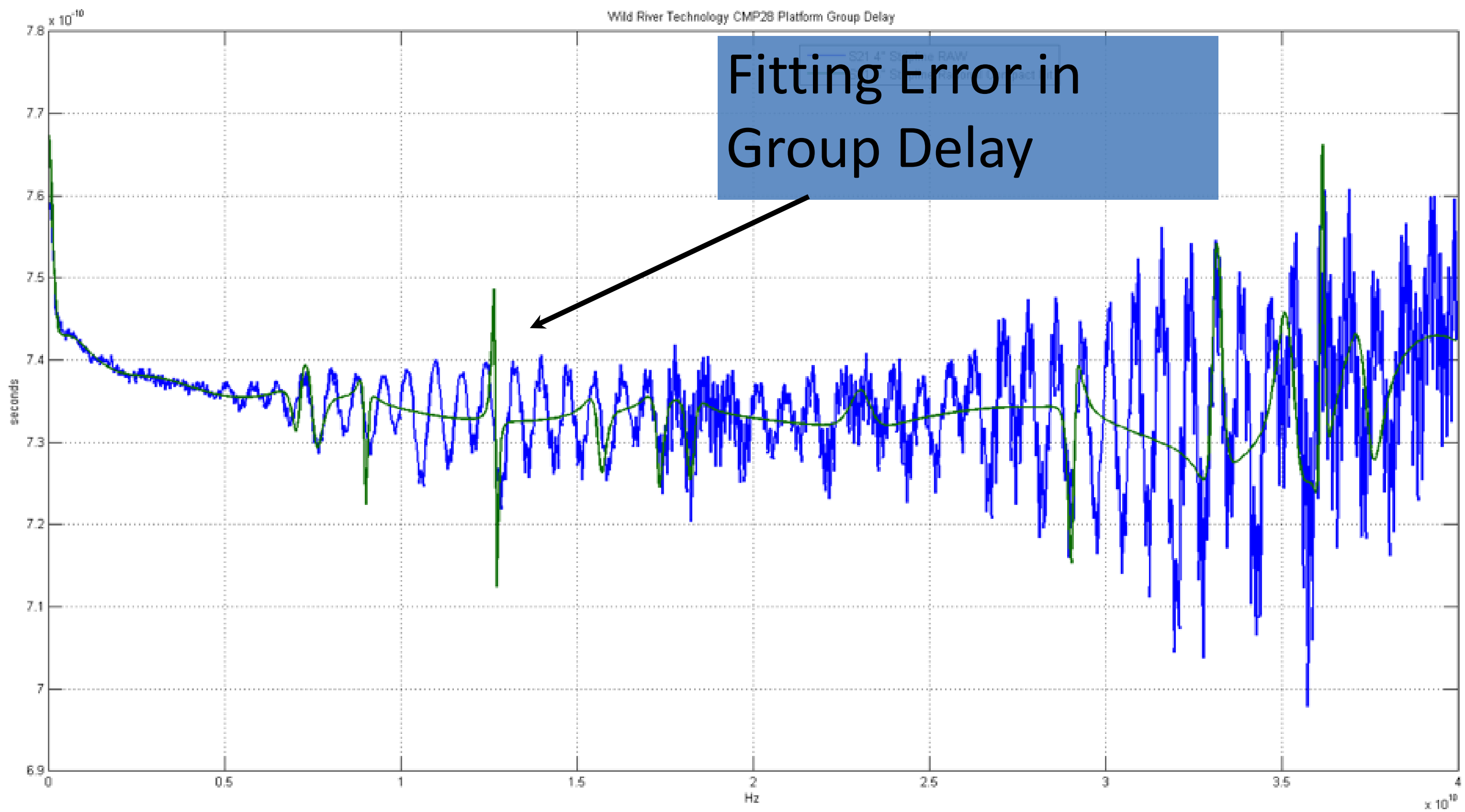
Compare Group Delay Raw versus Fix - Not Significant



Fixed Causality Impacted Sampled Points, Including D.C.



Polynomial Fit: S-parameters looked OK, Except for Group Delay



Conclusion

- Fixing is problematic
- Need for Good Calibration
- Benchmarking with Standards
- Exhaustive Testing at Data Rate

"SI Folks don't Buy Airlines" Why Not?

18A50

18N50

19S50

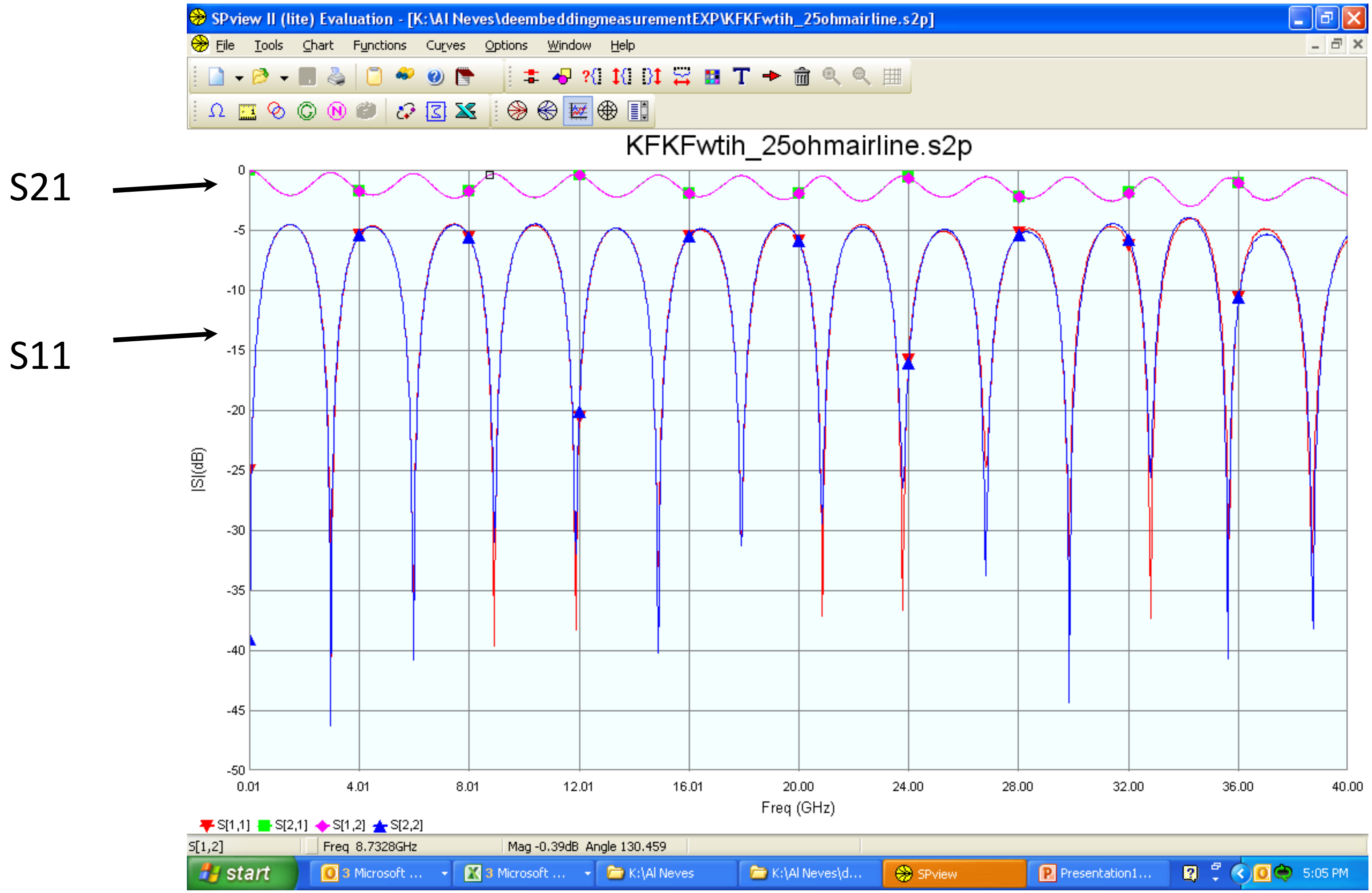
- NIST traceable Zo
- Delay accurate
- No modes to very high Freq, TE11
- low loss, superb launch (coaxial)

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{b}{a}\right) \approx 59.939045 \times \ln\left(\frac{b}{a}\right) \qquad (\Omega)$$

$$delay = \ell\sqrt{\mu\varepsilon} \approx 3.336723 \cdot \ell \qquad (\text{ps})$$

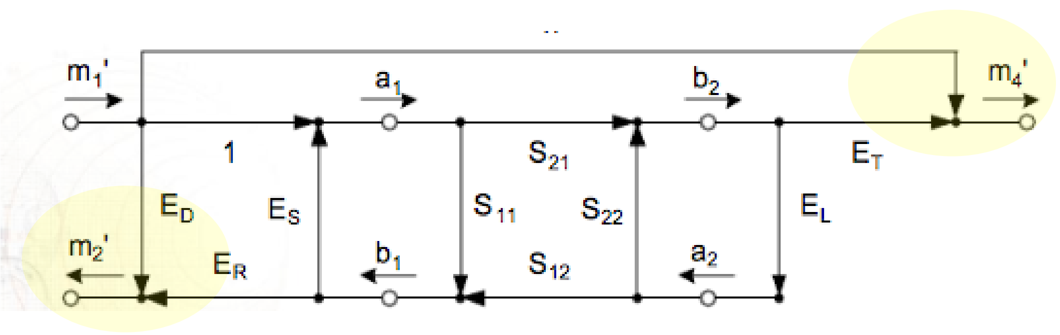
where:
- $b =$ diameter of outer conductor (mm)
- $a =$ diameter of center conductor (mm)
- $l =$ length of outer conductor (mm)
- $\varepsilon = \varepsilon_0\varepsilon_r$
- $\mu = \mu_0\mu_r$

Example of 25Ω 2.92mm Stepped Impedance Airline

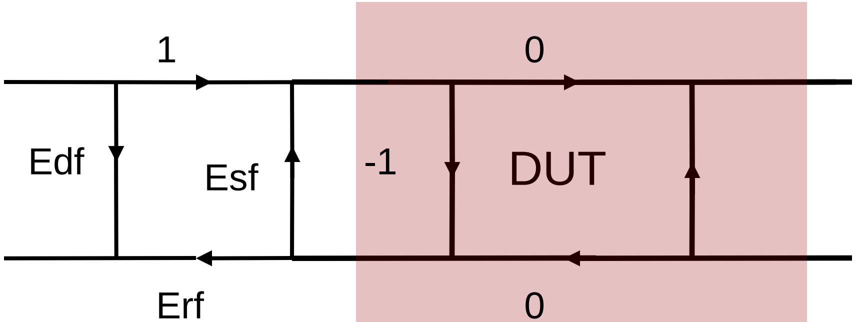


Stepped Impedance Line is Important for Measurement Validation

12 Term Error Box

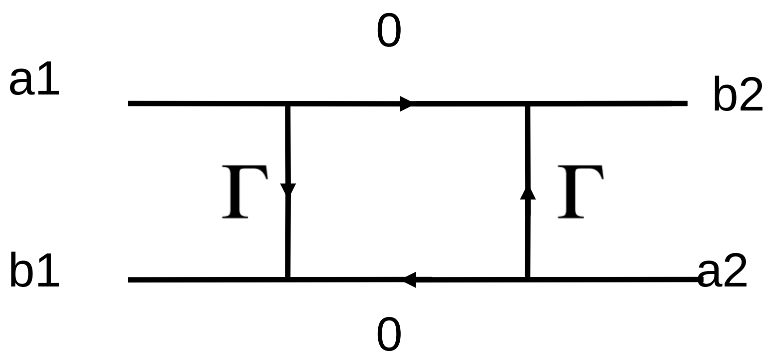


Relate Measurement To Error in Box



Signal Flow Diagram of Short

Signal Flow Example of a Perfect Short



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

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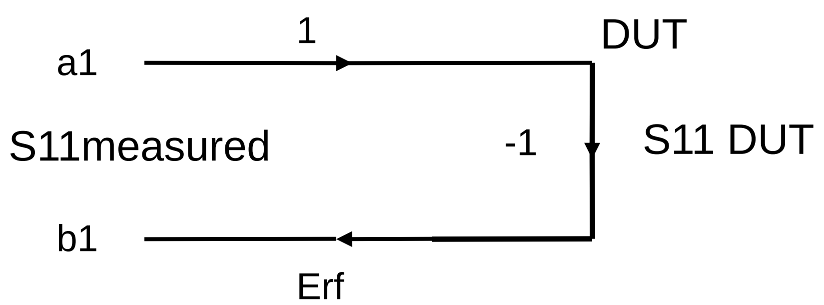
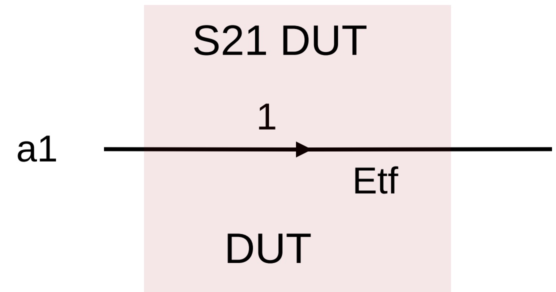
For Example…





$$S11, DUT = \frac{S11Measured}{E_{RF}}$$

ERF is the reflection tracking error, or

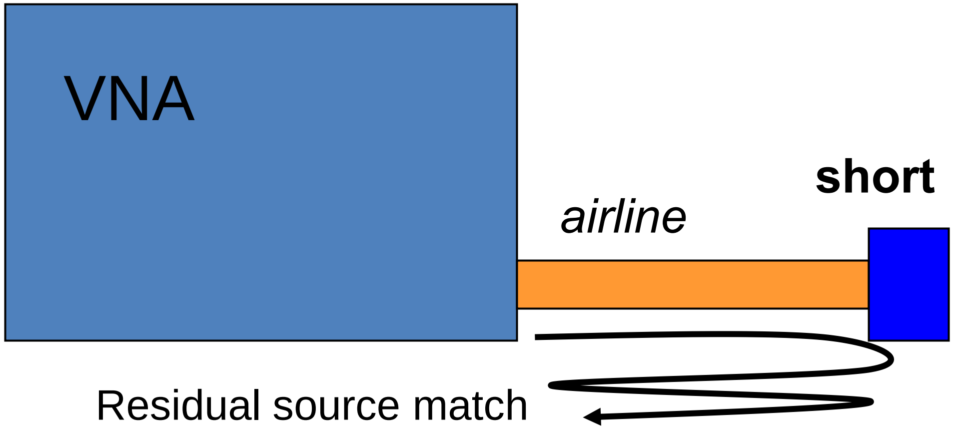
$$S11Short \approx -E_{RF}$$

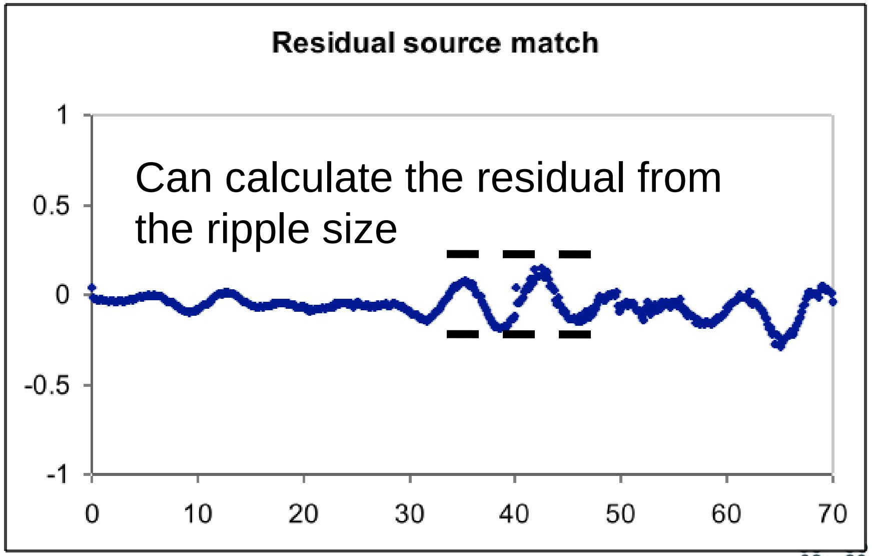
$$S21, DUT = \frac{S21Measured}{E_{TF}}$$

$$S21Thru \approx E_{TF}$$

Simple Calibration Validation

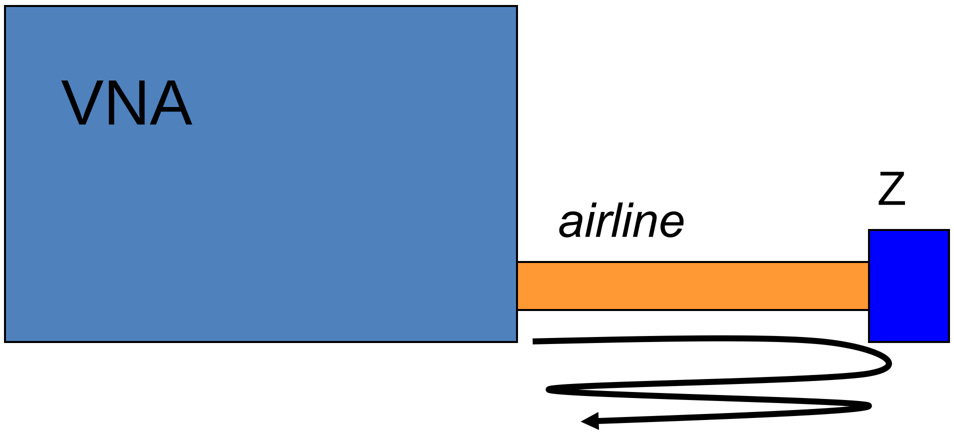
- Key concept: *Systematic non-idealities can be removed to a certain degree*.
- *Residuals:* The systematic error left over after calibration (due to imperfect calibration, linearity,….).
- Usually measured with some artifact. Example: residual source match using an airline.

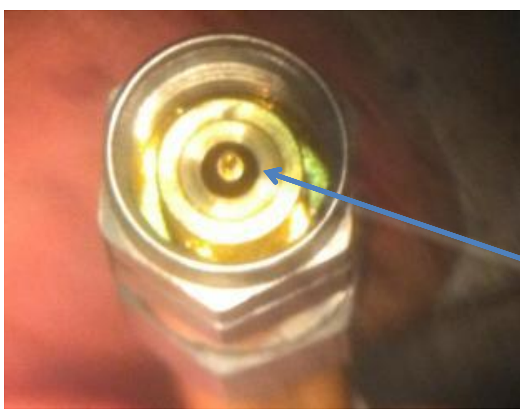




Calibration

- Residual directivity is measured in a similar way. The terminating impedance is closer to Z_0 to focus on directivity instead of source match.





Ripple relative to the mean reflection level gives the residual directivity.

Free-standing center conductor (at this end)

Airlines and residuals: Why?

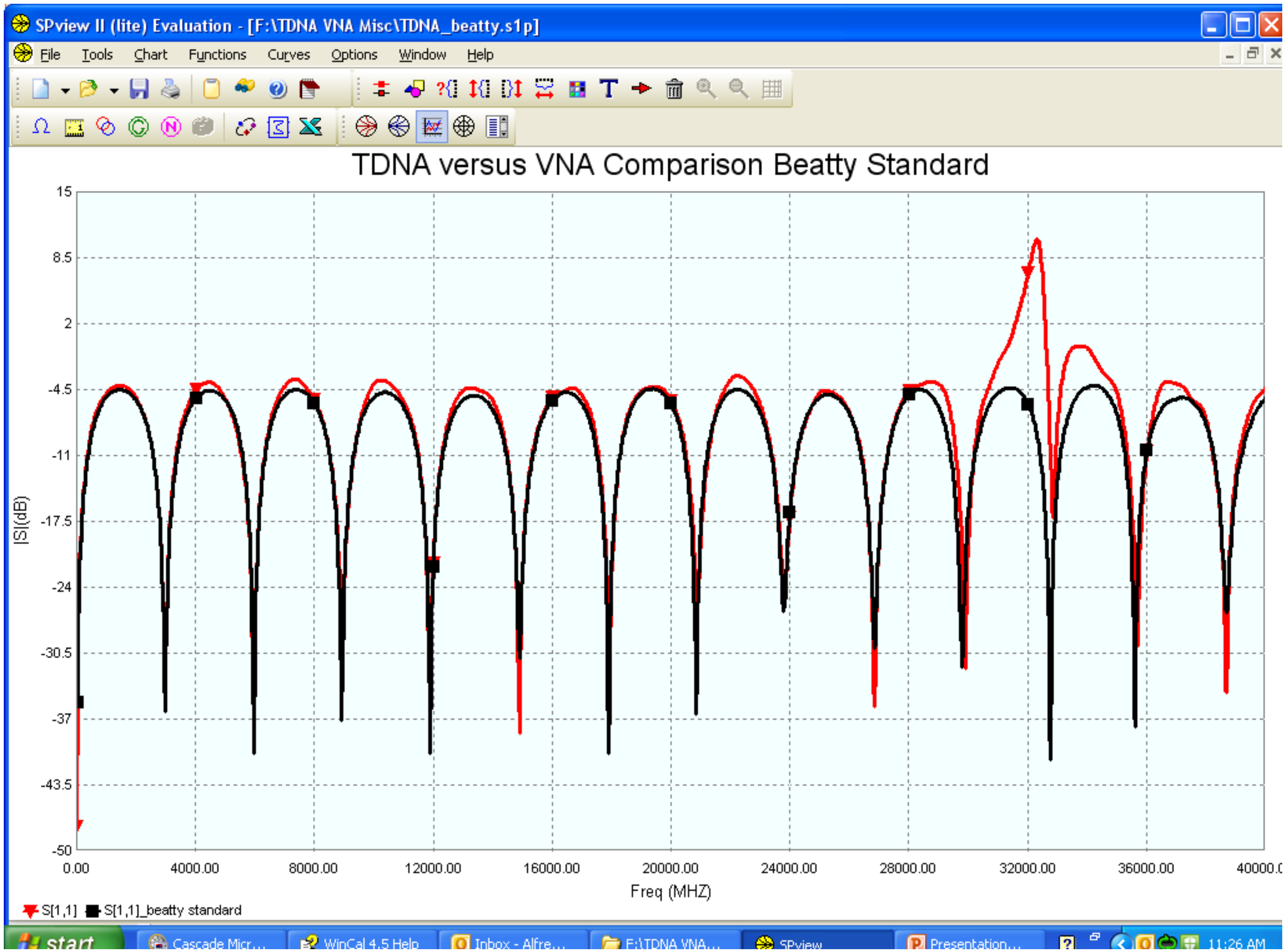
- One of the most traceable ways to validate a calibration. The airline dimensions (and hence its impedance) can be known with great precision and relatively low uncertainty.

- A precise way to evaluate a calibration. Most airline return losses are 50-60 dB…better than almost any calibration.

Airline S.I. Applications

- NIST traceable Impedance standard for TDR - used prior to DUT
- Comparing measurement domains - TDR derived S-parameters versus VNA
- Benchmarking capitol equipment
- Comparing VNA calibrations
- Examining non-systematic versus systematic noise in S-parameters
- Variability of measurement, Bounded Errors

Example of Benchmarking S-parameter Measurement Approaches Using Stepped Impedance Airline

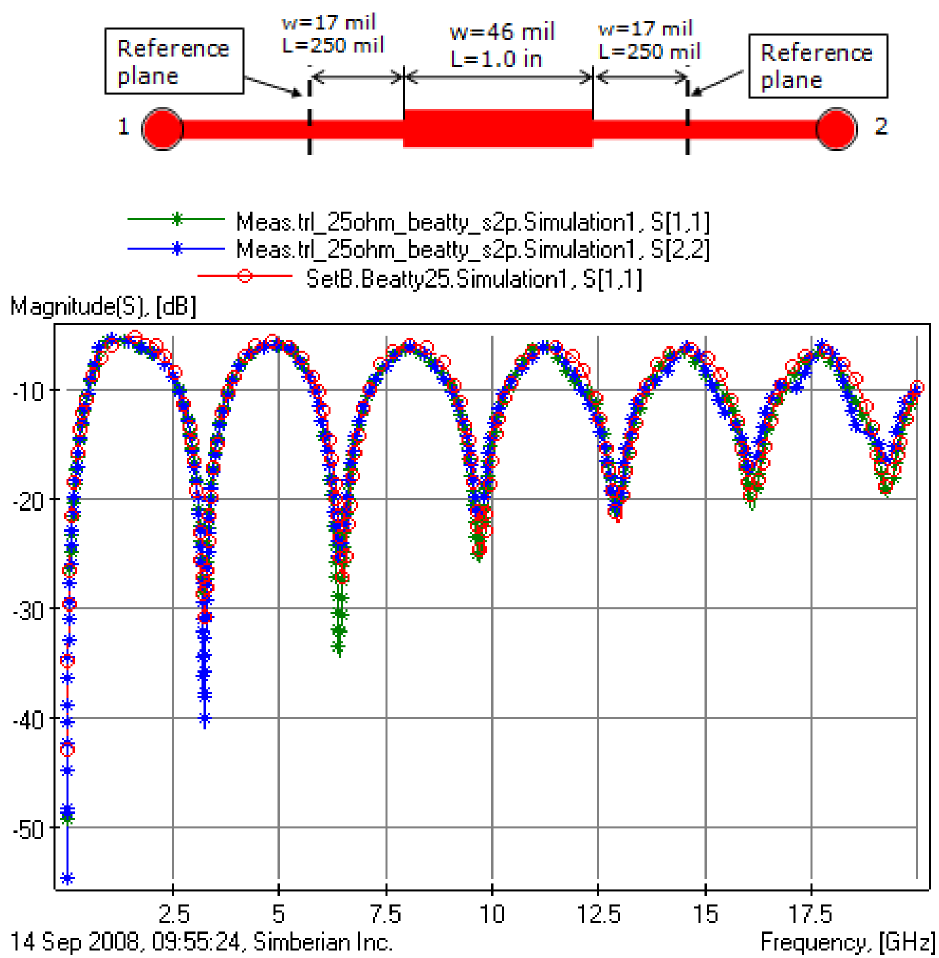


How "Pseudo Standards" Help with 3D EM Modeling

- Airlines are not interesting from a 3D EM - measurement perspective
- Introduce a few CMP28 standards - whisker, multi-impedance, VIA designs, offset resonator

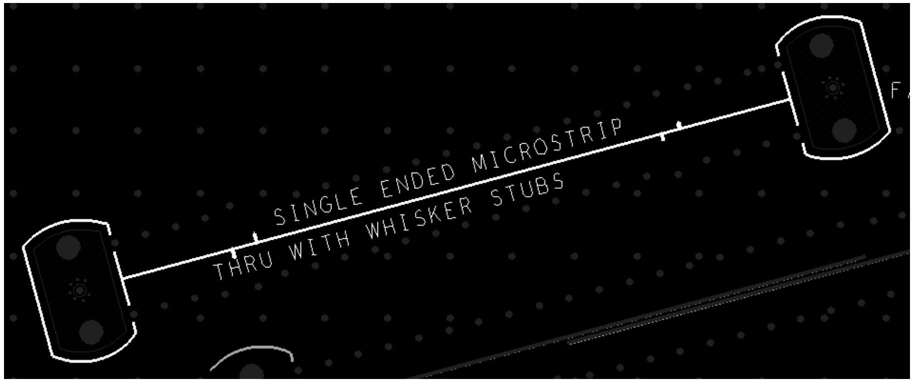
Example Correspondence - Frequency

Reflection coefficients magnitude



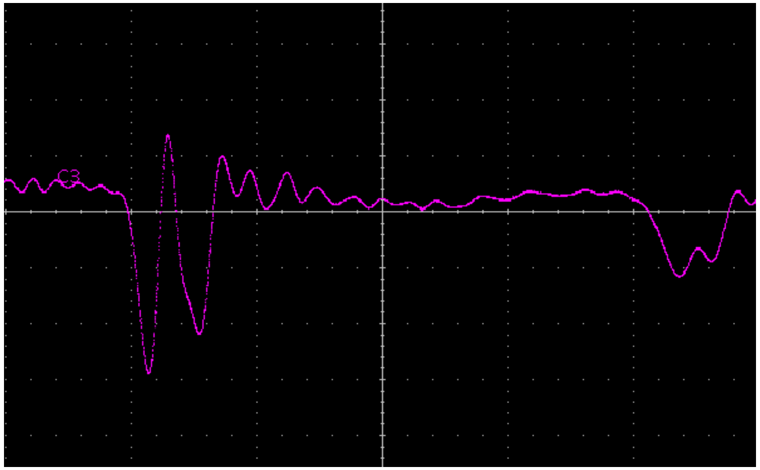
Example Correspondence - Time

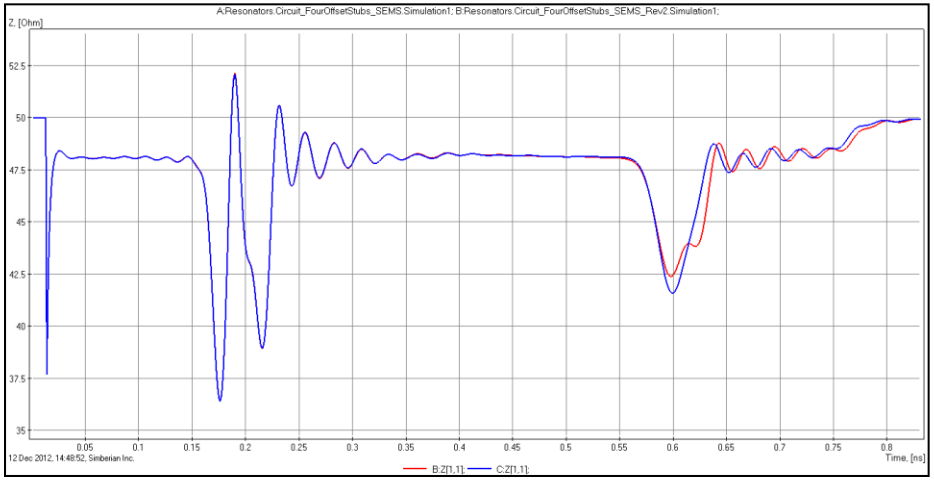
Time Domain Resolution
Standard, CMP-28 Platform



11psec Trise correspondence 3D EM to measurement, Tek 80E10

Simulation Results Simbeor 2012





Agenda

- Introduction
- The Metrologist's Tale
  - Practical calibration methods suited for 3D-EM
    - Jon Martens
- The Signal Integrity Practitioner's Tale
  - Verification and assurance
    - Jim Bell and Al Neves
- The 3D-EM Modeler's Tale
  - Time domain processing and 3D-EM model development
    - Josiah Bartlett
- Questions

Time Domain Processing and 3D EM Model Development

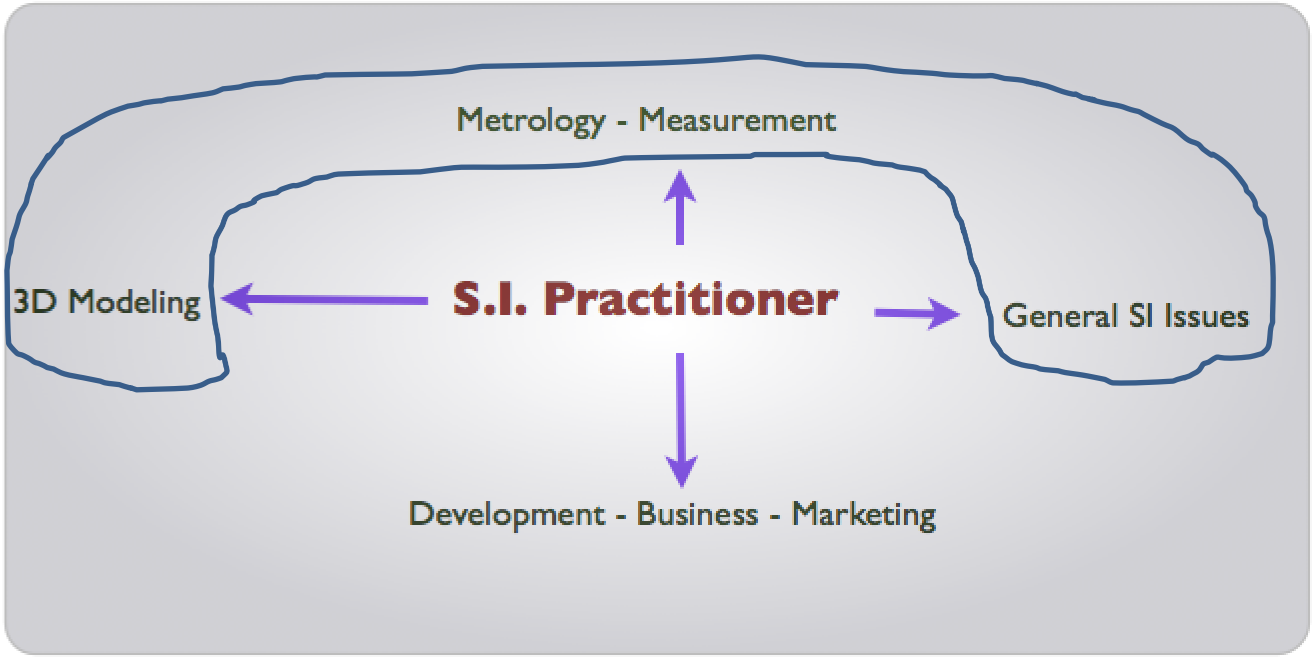
- Introduction
- How to trust a model
- 5 pitfalls of EM modeling
- Low Frequency S parameter Discussion
- Cleaning up Models with Simulation and Rational Compact Models
- The Economics of Modeling

Josiah’s Background

- Sr. Design Engineer in Tektronix Performance Probes
- Designing circuits and DSP systems with >30 GHz BW
- Extensive 3DEM modeling background
- Characterization and Calibration
- Passive and Active Devices
- Signal and Power Integrity

The 3D Modeler

The Signal Integrity Practitioner
– Nexus of many Disciplines



VNA versus 3DEM Simulator

VNA

- "Real Life" DUT:
  - Hardware is hardware
  - Connectors are limited
  - Can be verified with other instruments
  - Complexity doesn't affect measurement
- "Non-ideal" Instrument :
  - Noise
  - Inaccuracy
  - Drift
  - Limited Bandwidth
  - Must be calibrated

3DEM Simulator

- Virtual DUT
  - A model of the hardware
  - Material properties must be adequate to describe the real DUT
  - Has difficulty with complexity
- Ideal instrument
  - No noise
  - No drift
  - "Infinite" bandwidth

Section VI: Time Domain Processing and 3D EM model Development

- Introduction
- How to trust a model
- 5 pitfalls of EM modeling
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How to Trust a Model

Matching Simulation Parameters to Physical System

Frequency spacing interval for total electrical length:

- $f_s = \frac{1}{T_{max}}$, where f_s is the frequency spacing in Hz
- therefore a non-repetitive, un-aliased 40ns time record length requires 25MHz even frequency point spacing

Minimum Sampling (time) Interval to avoid aliasing:

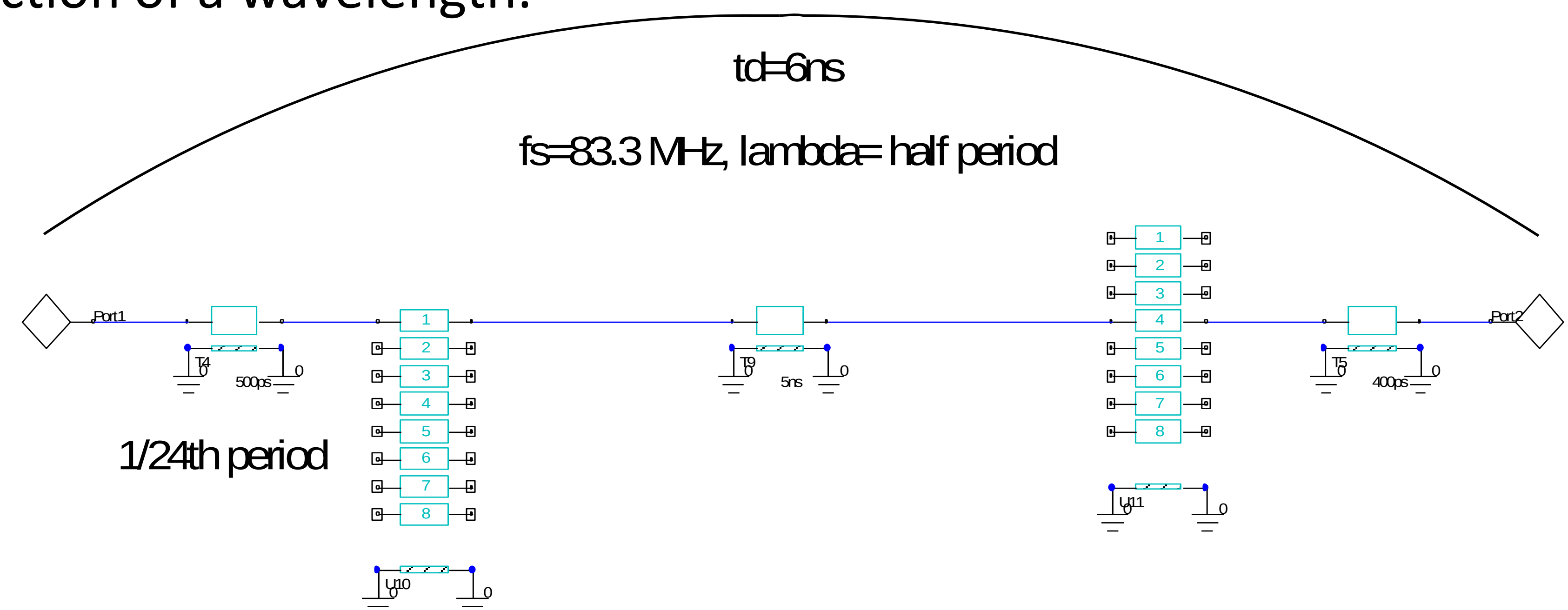
- $t_s = \frac{1}{2 * F_{max}}$, where F_{max} is Nyquist frequency
- Therefore a 10ps time resolution requires at least 50GHz of bandwidth (100 GS/s sample rate)

This is the bare minimum from Fourier Transform math!

Effect of Time Domain on Frequency Domain Sample Interval

When cascading individual models, we must have a low enough frequency point for each model to represent the round-trip electrical length of the entire system (Reflections have to return from far end).

This can mean that individual models only represent a very small fraction of a wavelength.

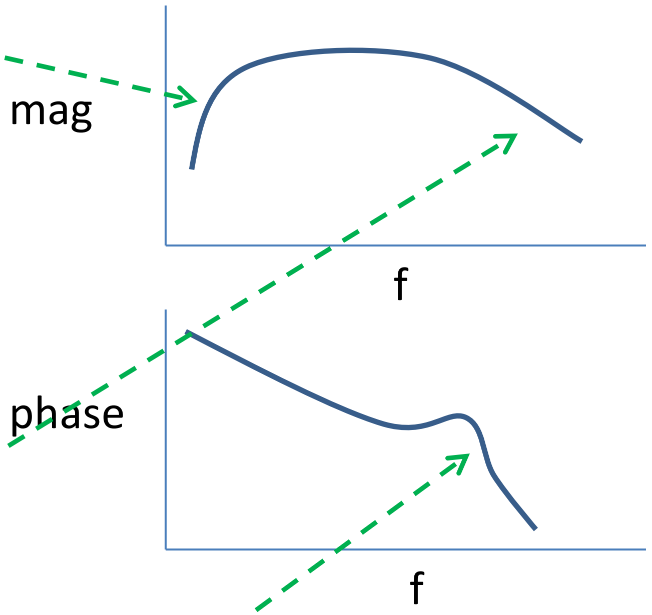


Matching Simulation Points to Entire system

- Often system models are built up out of several combined simulations
- It may be easier to pick the frequency span and resolution to cover the entire model than to interpolate and extrapolate afterward
- However, this may put extra constraints on material model requirements.
- This is a major issue when mixing models from different sources.
- An error budget is an important tool to gain confidence in models

Potential Problem Areas

- Low freq. issues affect large-scale structure in time domain (eye diagrams, average impedance levels…)
  - Small structures don't have enough electrical length at low frequency to be accurate
  - Extrapolation problems
- High freq. issues affect fine scale structure and resolution; mismatch effects can alter system simulation results.
  - Material characterization issues

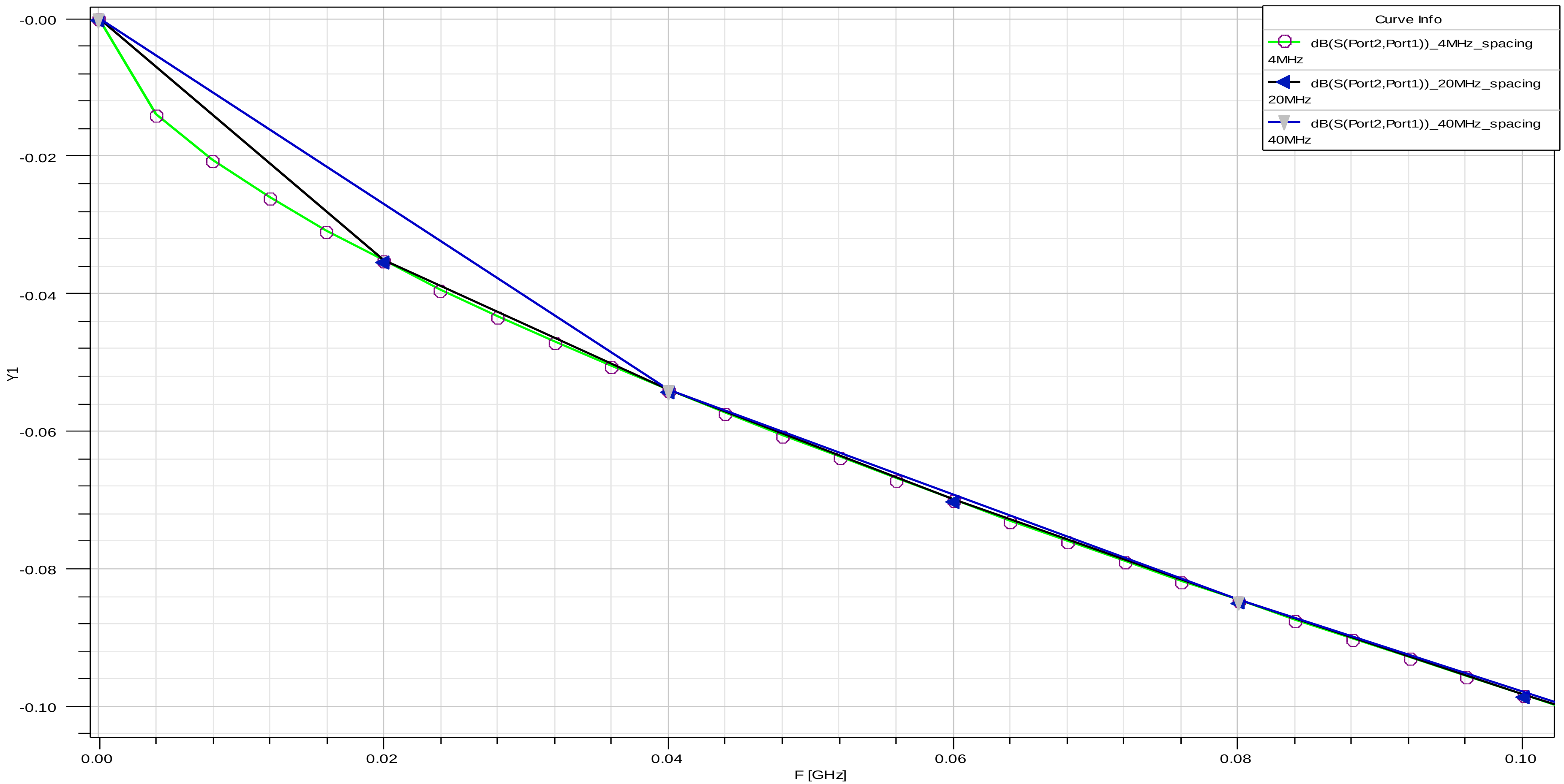


Phase errors affect time placement and reference plane positioning. Can be a system simulation issue

- Causality Problems

1m T-line Behavior at Low Frequency

- Minimum measured frequency point can result in DC extrapolation error



Simulation Uncertainty: Sensitivity Analysis

3DEM Hidden Problems

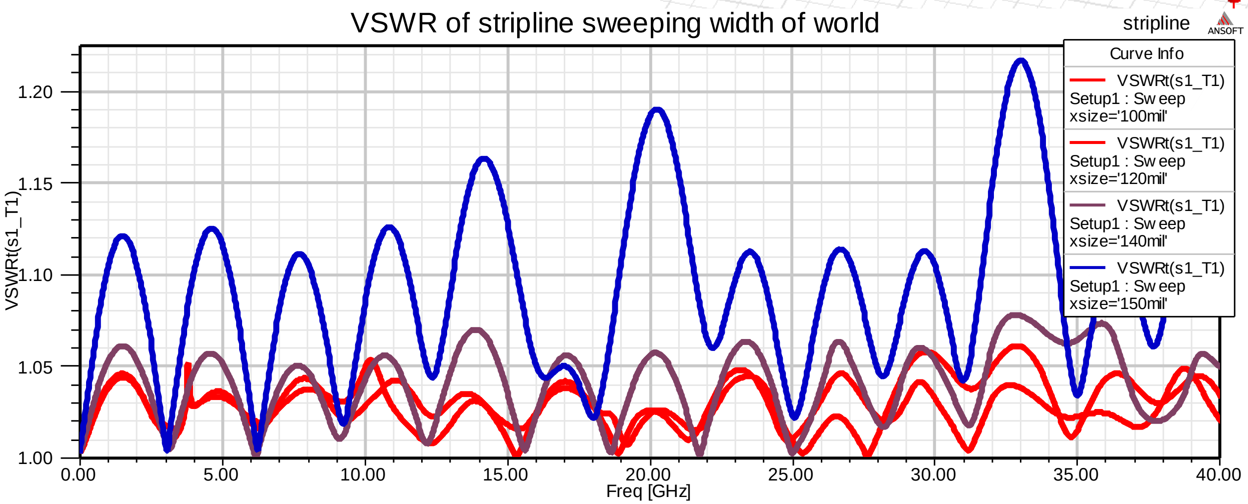
- Improper meshing errors
- Evanescent or non-TEM propagation modes
- Cavity and Plane Resonance
- Manufacturability concerns
- Over- or Under- specification of geometry
- Port Field sensitivity

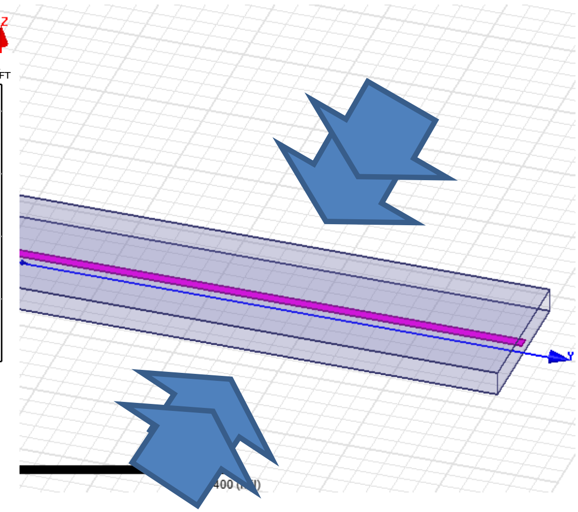
Numerical Cascading hidden Problems

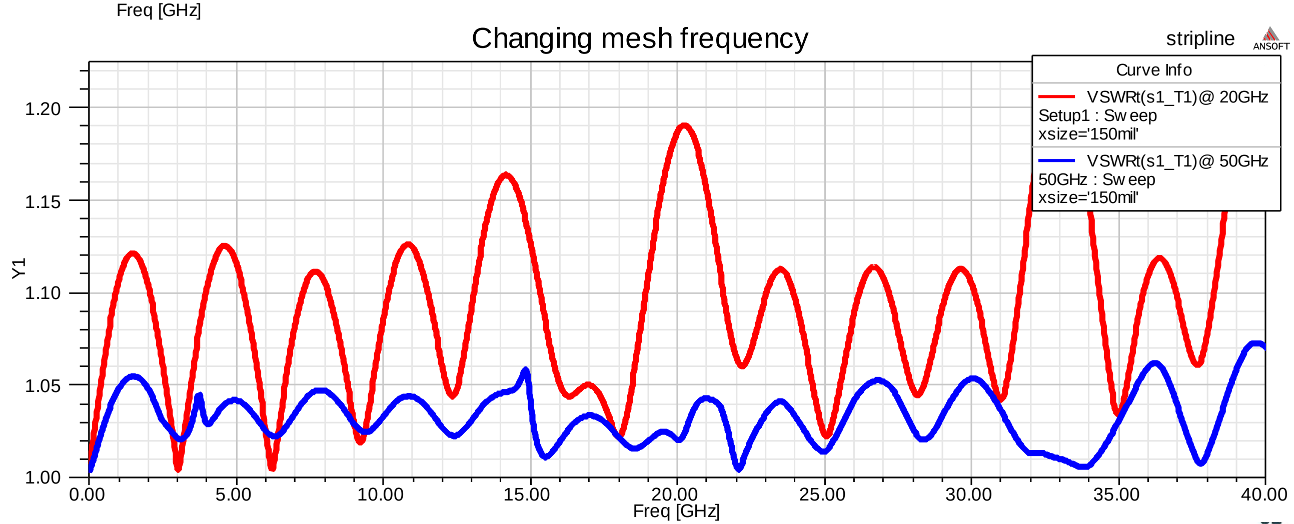
- Calibration Issues
- Causality, Noise, and Passivity
- Improper resolution and span
- Reference Plane Sensitivity
- DC extrapolation problems

Note that a lot of these points apply to measurements too!

Simulation Uncertainty: Sensitivity Analysis

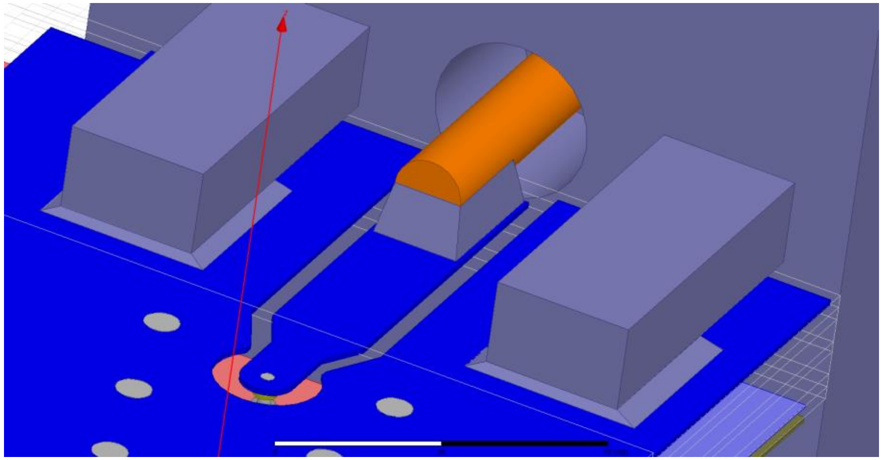


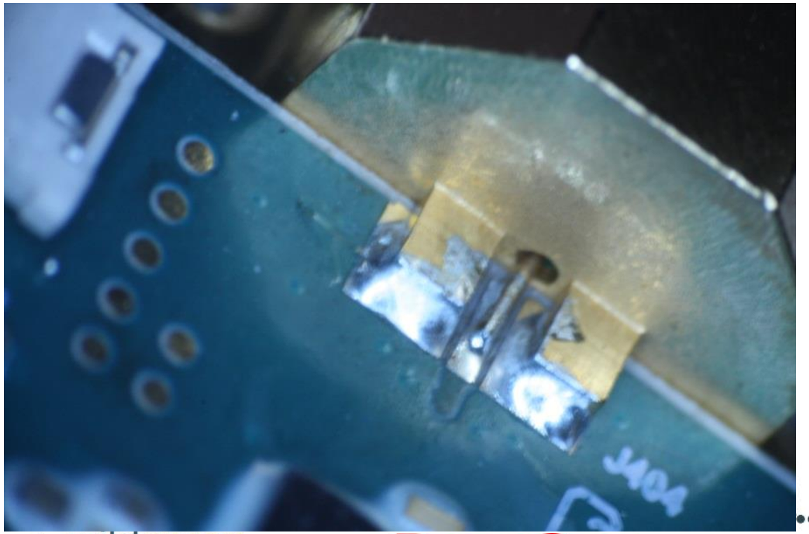




Simulation Uncertainty: Tolerance Control

- We simulate using nominal dimensions but manufactured parts have physical tolerances
- Usually we extract simulation geometry from film layers
- We must understand how film is used to create hardware to accurately represent reality in simulators





Benchmarking

- Create physical standards that can directly infer material properties
  - For Example, dielectric models should not compensate for conductor skin effect
- Account for physical variations
- Model both the desired and the broken behavior
- Compare to desired and broken measured prototypes
- Close the loop- measure what you've modeled

Time Domain Processing and 3D EM Model Development

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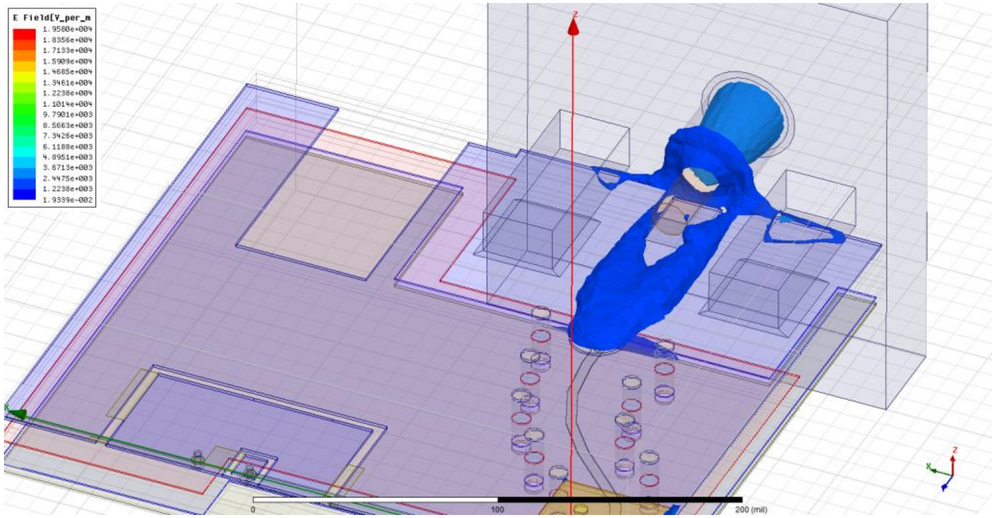
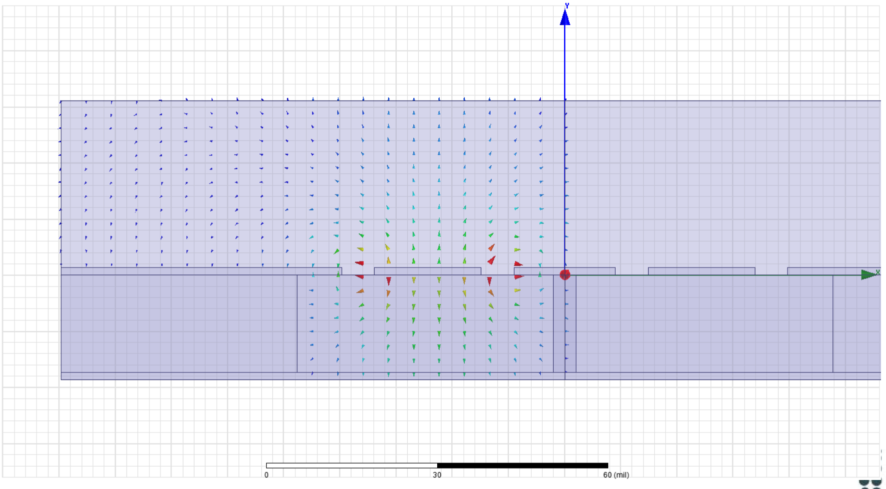
5 Pitfalls of EM Modeling

- Reference Planes and Boundary Conditions
- Material Modeling
- Artifacts of Ideality
- Incomplete Verification
- Over and Under Modeling

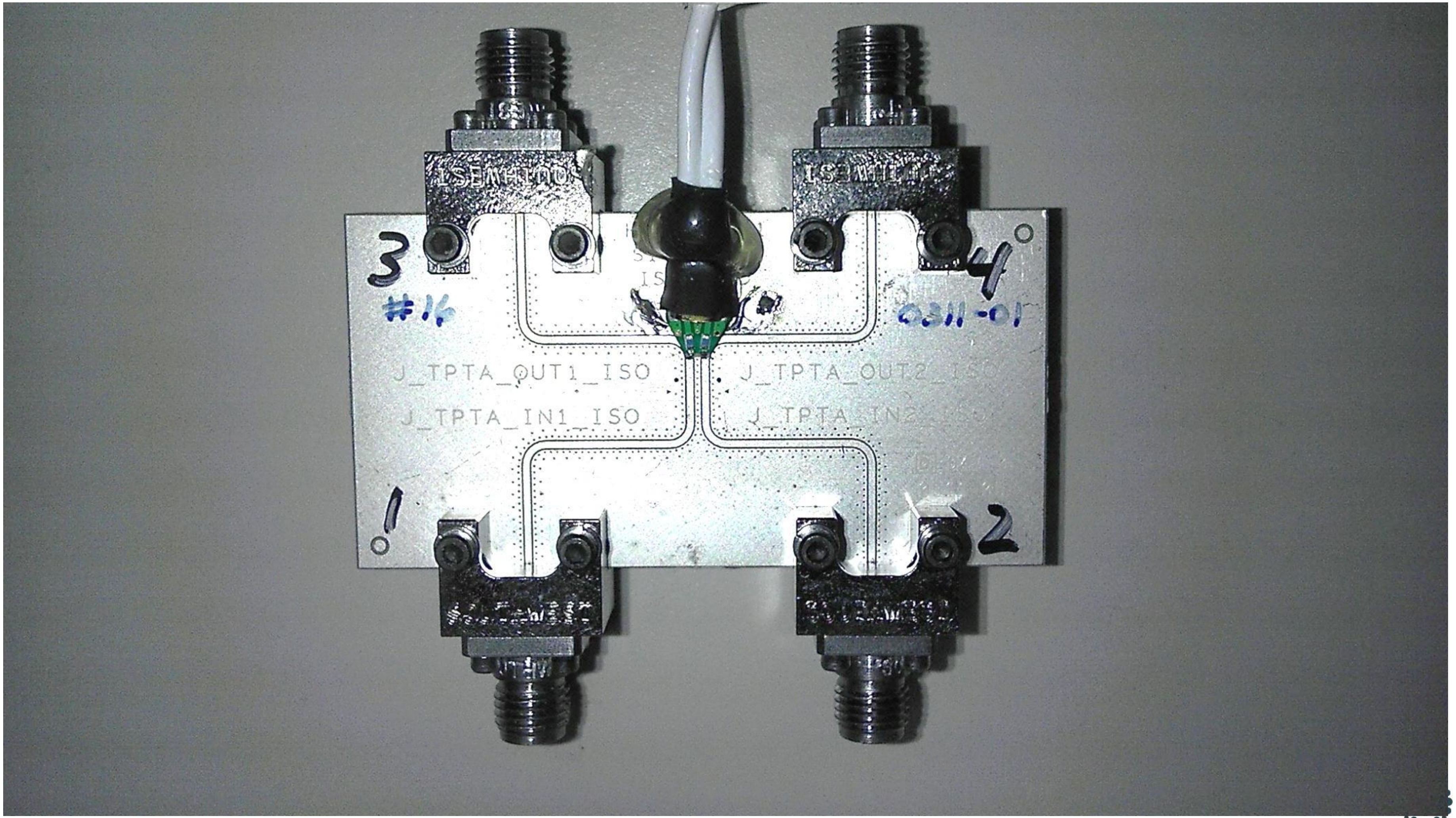
5 Pitfalls of EM Modeling:
Reference Plane Issues

- Much as in the real world, the measurement ports ('probes') force boundary conditions on the 3dEM model.
- Models must be constructed in such a way that the electromagnetic propagation modes at the ports match the modes in the models that are cascaded with it.
- Ensure that the fields at the all ports, both measured and simulated, are planar and the field that is outside the "black box" does not affect the field inside it.
- Never allow something "interesting" to happen at a port. Leave room between the port and the DUT to allow the impulse response caused by the feature to settle out before reaching the port.



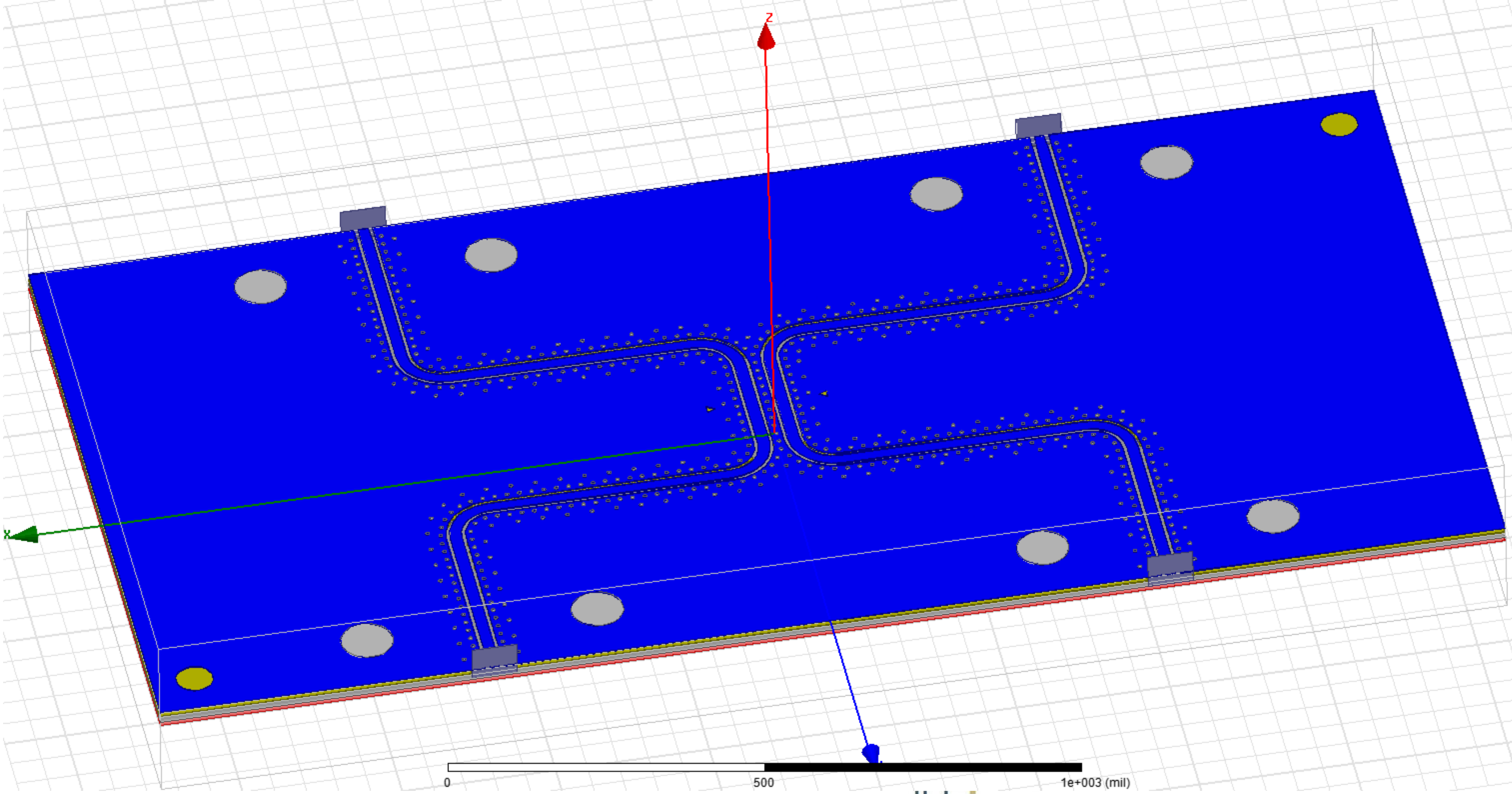


Example: De-embed Fixture from Probe S parameters

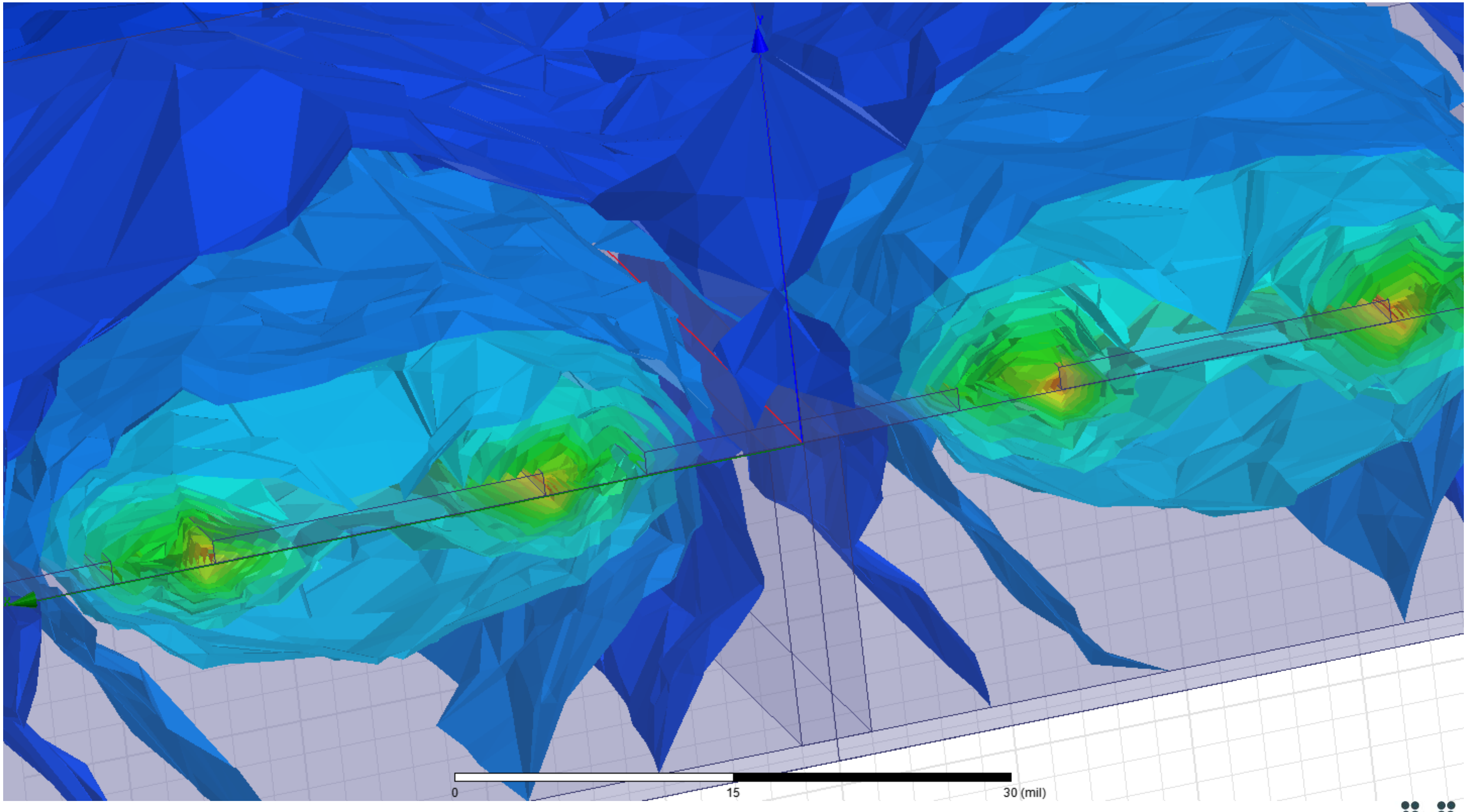


Reference Plane Example

- Split model at axes origin

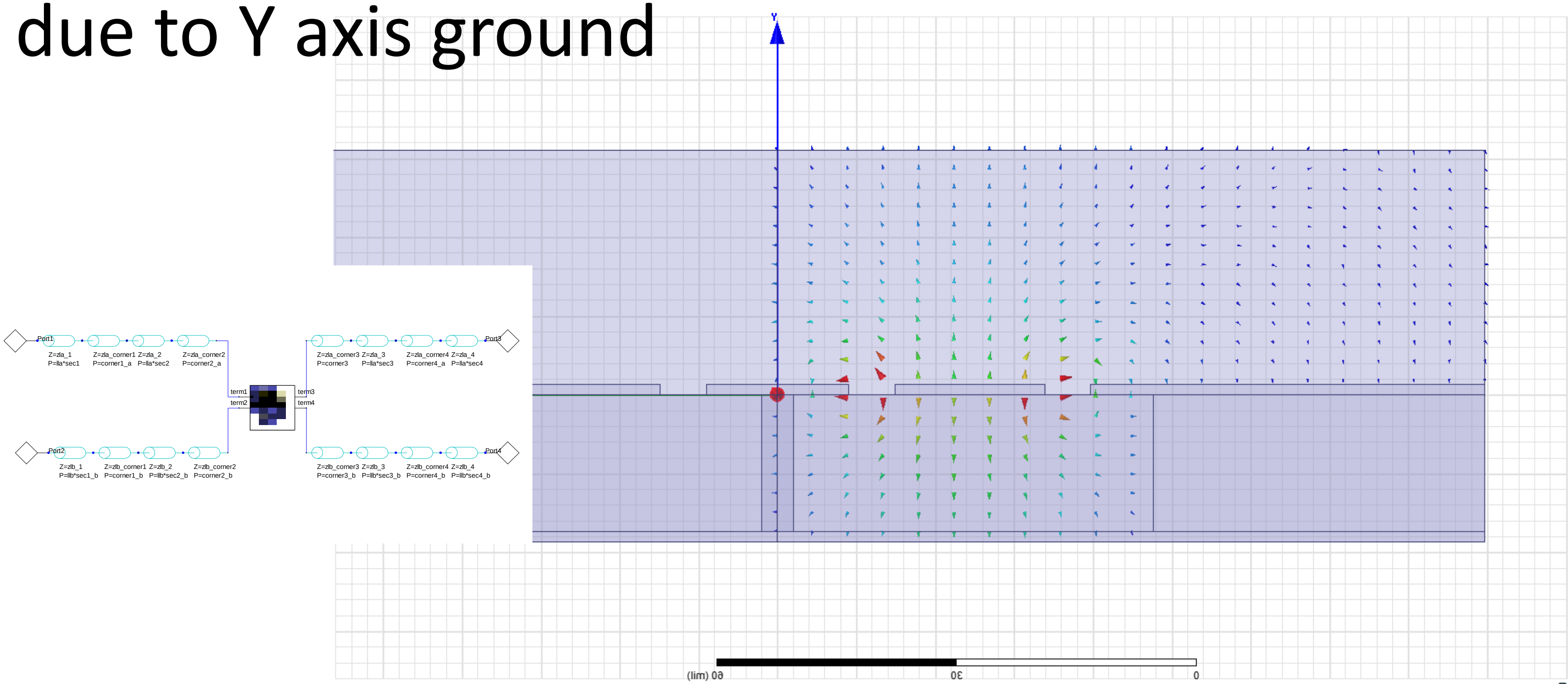


Reference Plane Example



Reference Plane Example

- Model was split to simplify simulation
- Single ended port field solution is asymmetrical due to Y axis ground

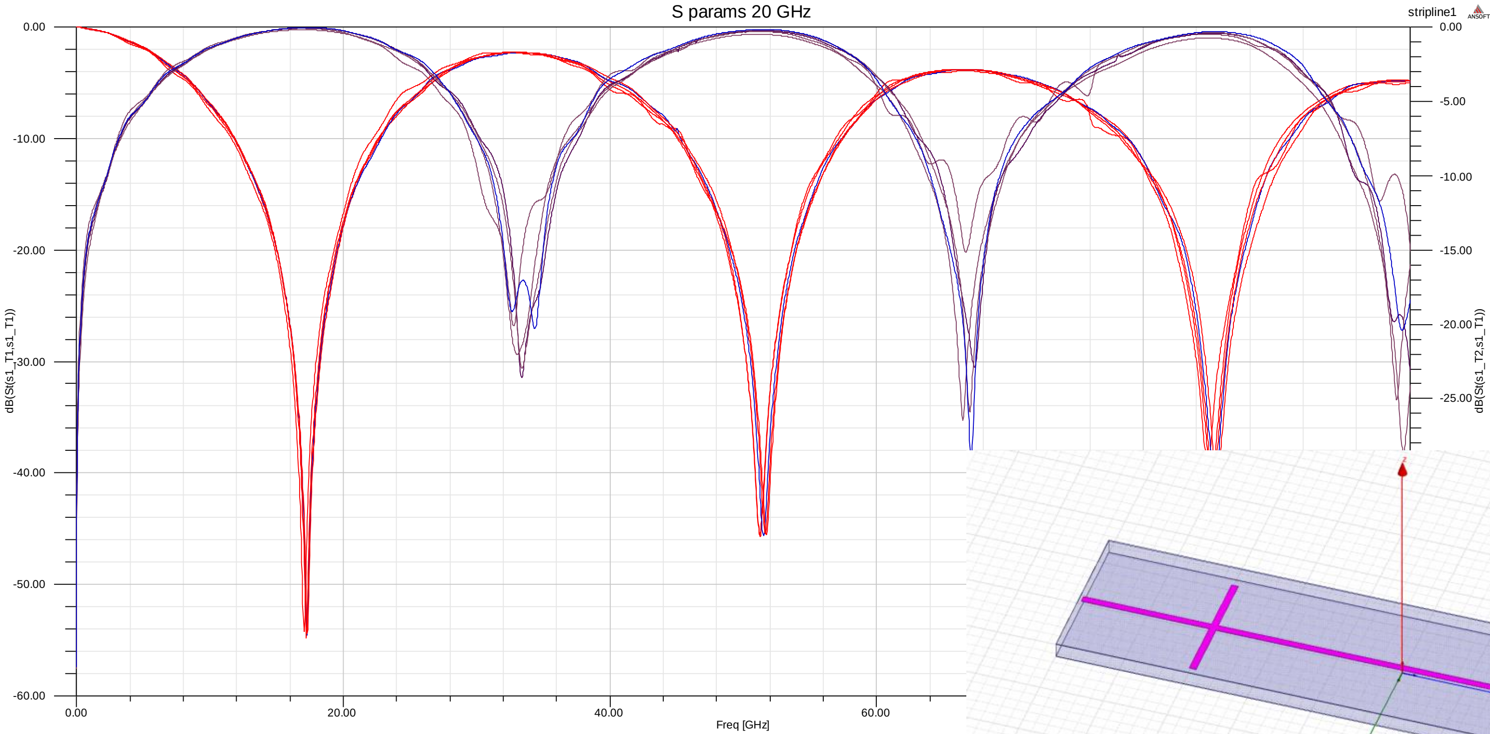


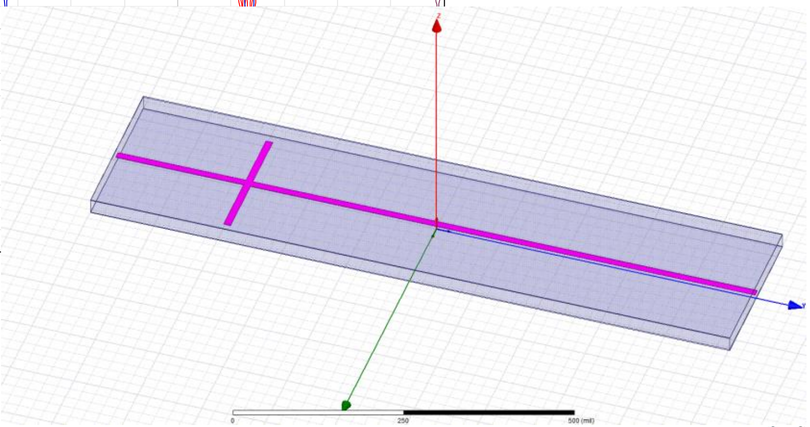
Reference Plane Example

- Solver Ports impose planar boundary conditions
- GCPW port also imposed symmetry
- Real life E field may not be planar at point where ports were drawn due to corners in traces
- Port symmetry caused poor CMRR when traces driving center section were unequal electrical length
- Result was that minor changes in modeled length of trace caused jumps in odd-mode Z0 of system

Reference Planes Are Boundary Conditions

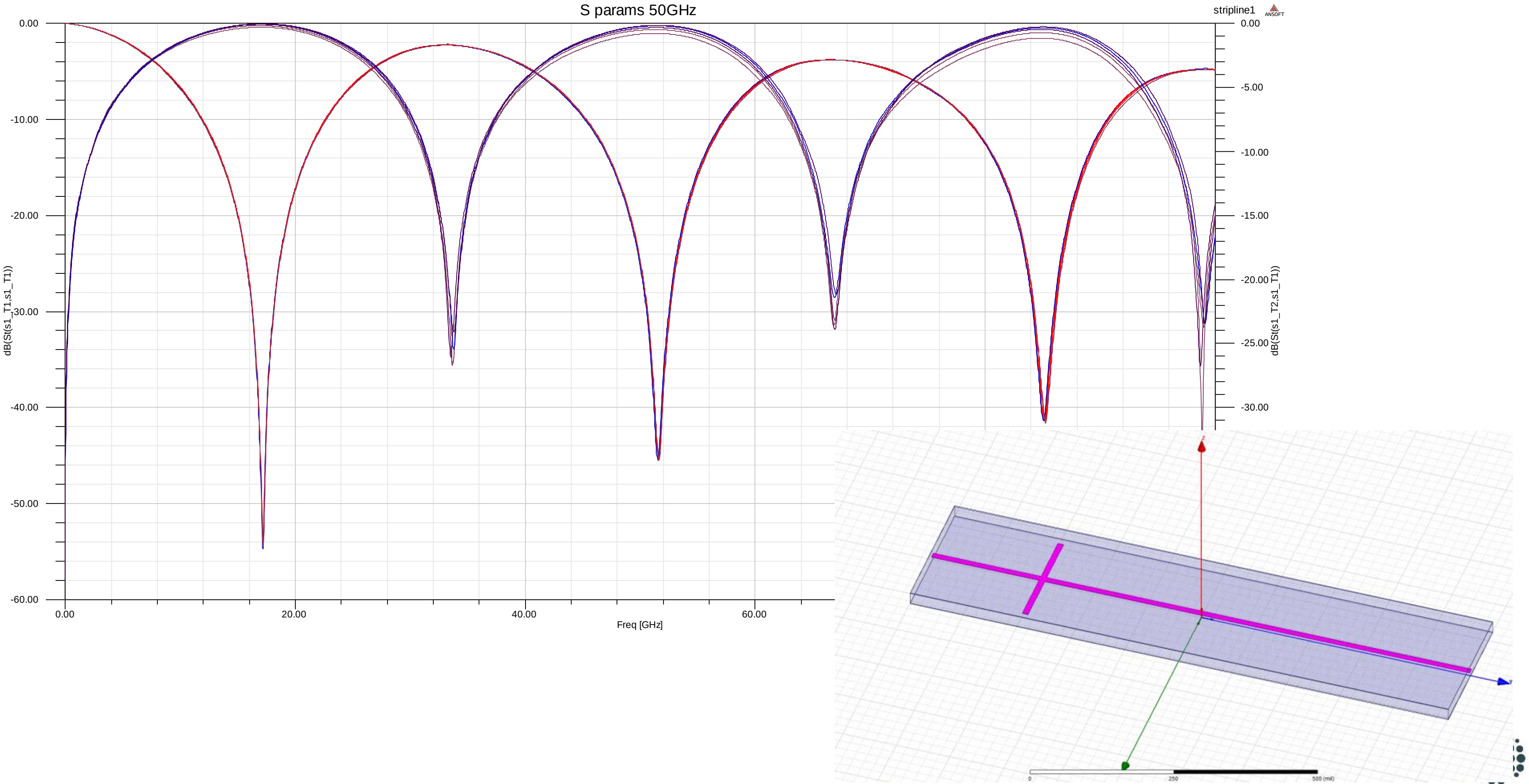
- Moving reference plane (port) close to resonator





Internal Simulator Settings Affect Sensitivity

- Using a higher mesh frequency



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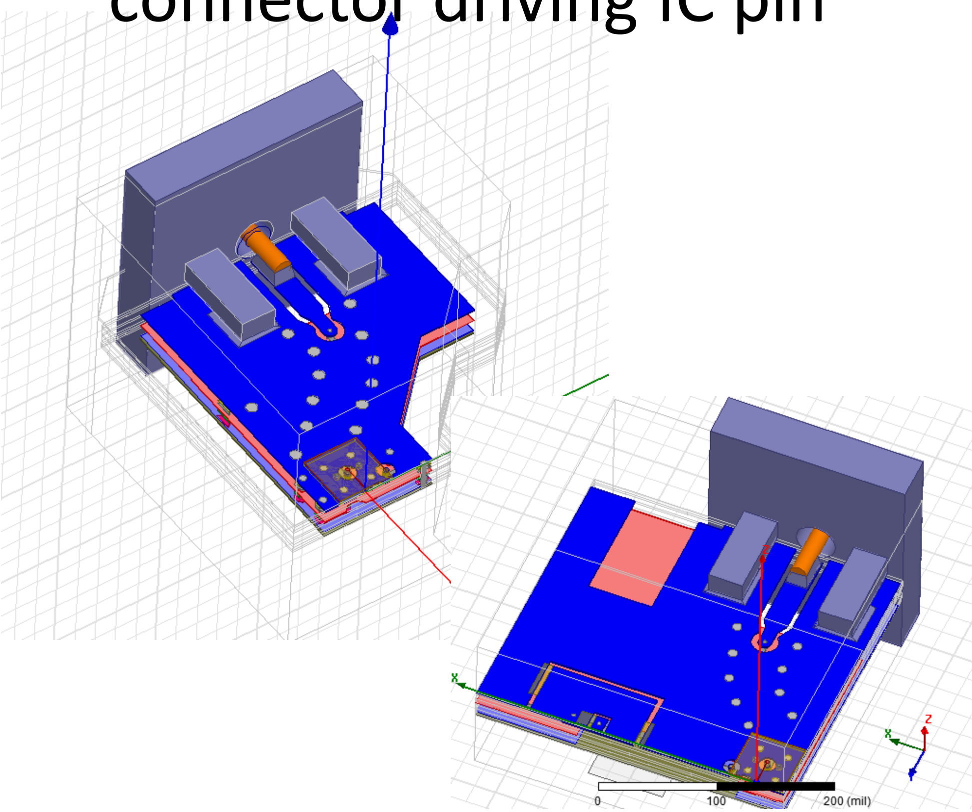
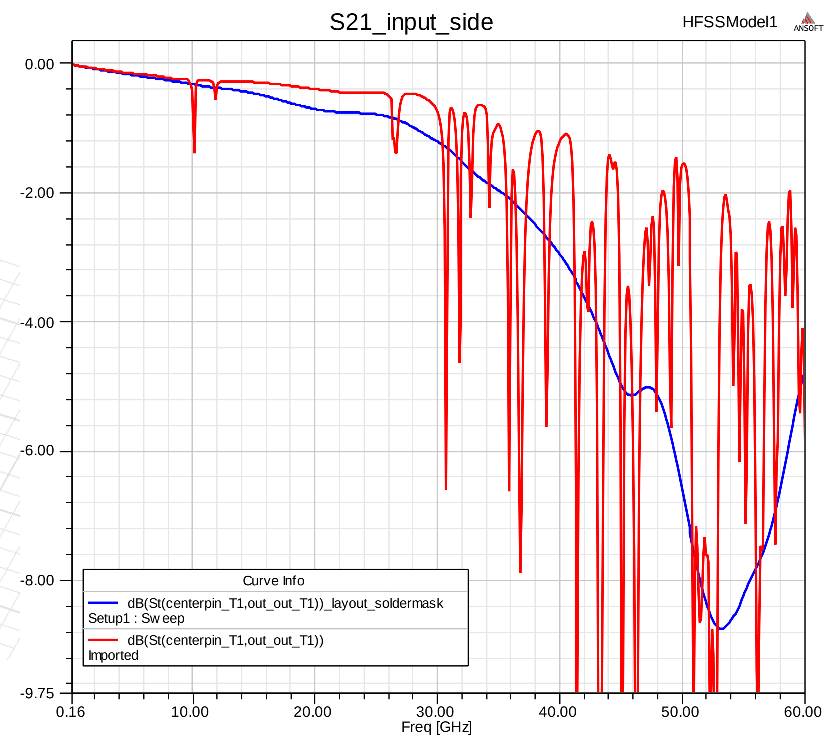
Boundary Conditions: It's a Small World

- Edge Launch coax connector driving IC pin



- Cavity Resonances appear from improperly defined "world boundary"



* Soldermask added between simulations

5 Pitfalls of EM Modeling:
Artifacts of Ideality

- Cavity resonance of “universe boundary”
- Non-physical propagation modes
- Non-ideal port behavior
- Noise, or lack thereof
- Low Frequency Extrapolation issues
- Missing manufacturing tolerances
- Over-simplification of materials
  – Homogeneity
  – Plane conductivity

5 Pitfalls of EM Modeling:

Material Modeling

- "Behavioral Bandwidth"
  - Go beyond your DUT's bandwidth
- Material causality
- Homogeneity of Materials
  - Real dielectrics are usually made up of several compounds and then set using pressure/temperature
  - Most materials can be considered homogenous up until the point where the heterogeneity can be resolved in the time domain
- Surface Roughness/Skin Effect
- DC behavior
  - Often a 3DEM model doesn't have a lot of electrical length at low frequency. Cascading several models like this results in gross error

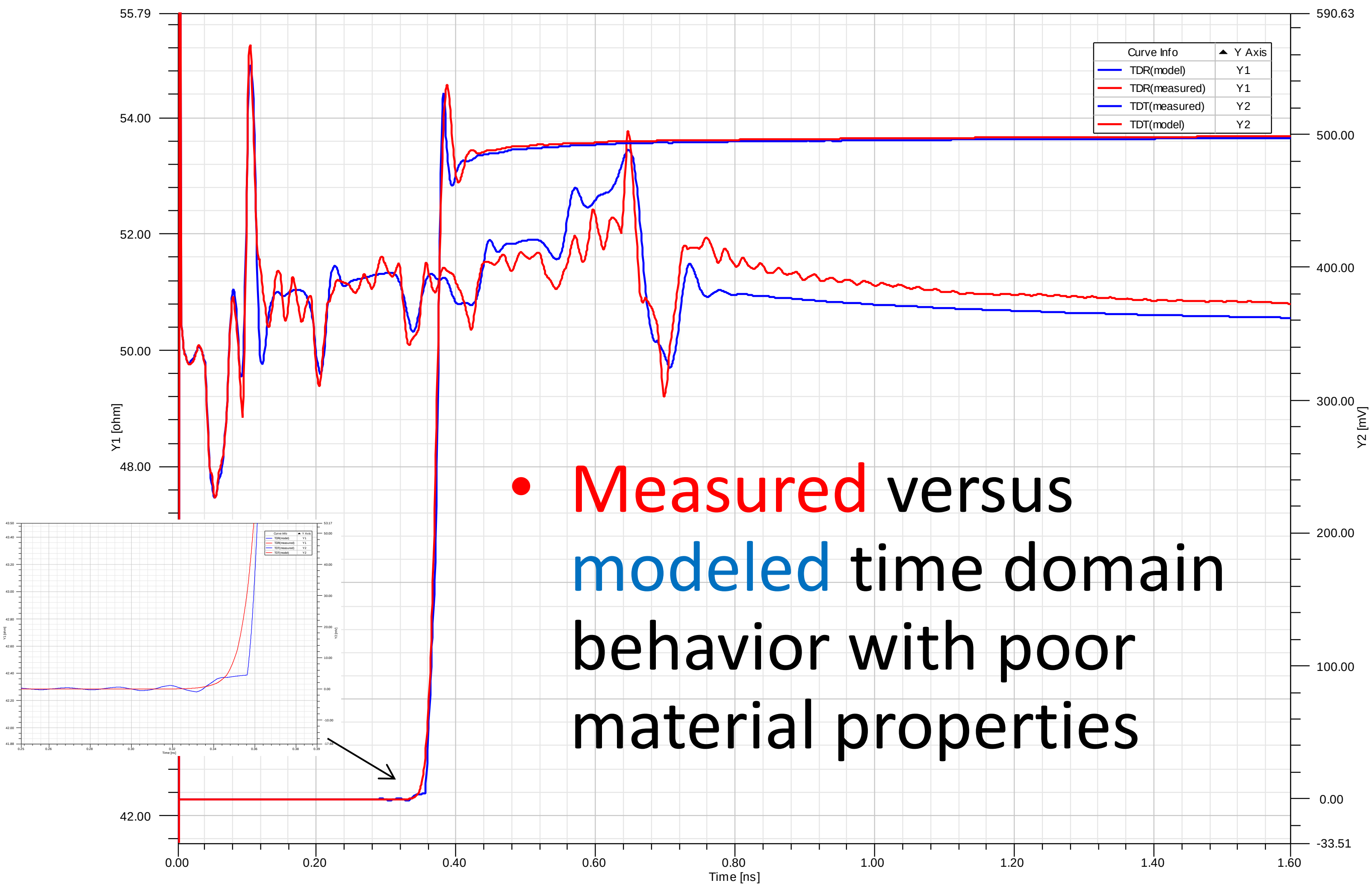
A Quick Note on Causality

- Causality is very important in the calibration of measurement devices and in material models
- Causality issues can be difficult to differentiate from bandwidth limiting effects
  - Sin(x)/x filtering in the time domain resulting from truncating a DFT record
- When defining test structures to extract material properties, we must be careful to design structures that are known to measure out causally
- For example: Crosstalk structures…
  - A 90 degree coupler typically has a lot of energy coupled before what is considered the main edge in the transient response of the coupled port. This confuses a lot of S parameter causality checkers. The device itself is causal because no energy exits the device before it entered.

Material Modeling Example

- Group Delay of causal measurement versus non-causal simulation (poor material properties)

Material Model Example



- Measured versus modeled time domain behavior with poor material properties

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5 pitfalls of EM modeling

Incomplete Verification

Physical Measurement Calibration

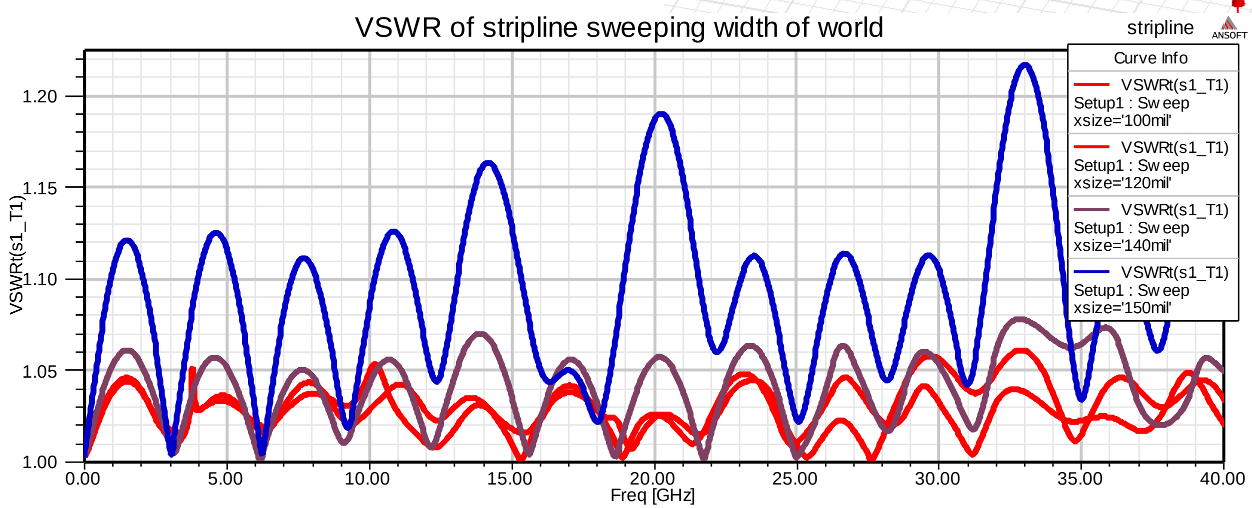
- VNA error sources
- TDR/TDT error sources
- Low frequency errors
- High frequency errors
- Directionality/Recipricosity
- Linearity
- Drift
- Timebase

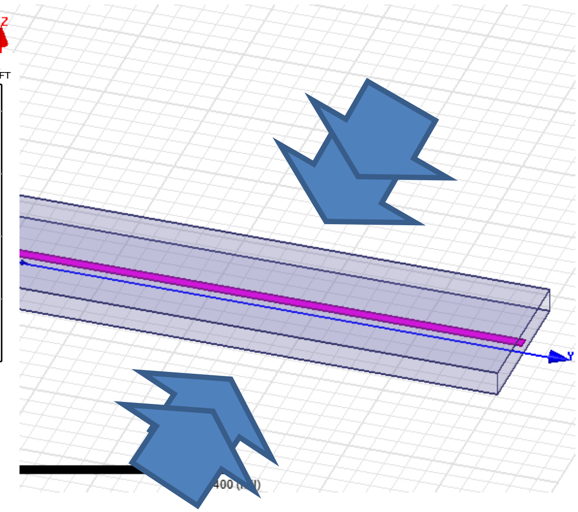
3DEM Simulation Calibration

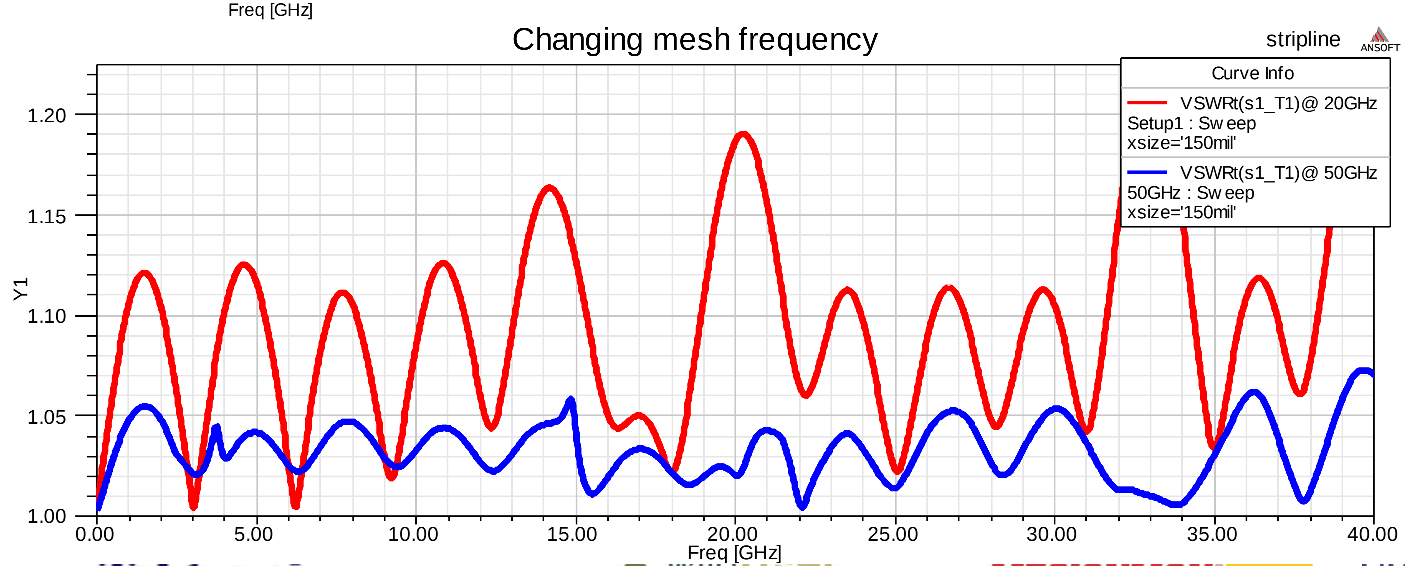
- Individual Material Characterization
- Physical geometry matching
- DC/low frequency behavior
- Skin effect modeling
- Material homogeneity
- Convergence
- Complexity

Incomplete Verification

Simulation Uncertainty: Sensitivity Analysis







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5 Pitfalls of EM Modeling

Under and Over Modeling

- Geometric Complexity
- Field concentration
- Material Characterization
- Passive and Causal enough?
- Are you going to get it done before it becomes moot?

Simplifying a model to the proper complexity resulted in simulation run times of hours versus days with no loss in accuracy

5 Pitfalls of EM Modeling

- Reference Planes and Boundary Conditions
  - Both measurements and modeling can have issues
- Material Modeling
  - Must be adequately modeled across region of interest
- Artifacts of Ideality
  - You get what you asked for, not what you want
- Incomplete Verification
  - Did you check what happens on the fringes?
- Over and Under Modeling
  - Make your boss and customers happy

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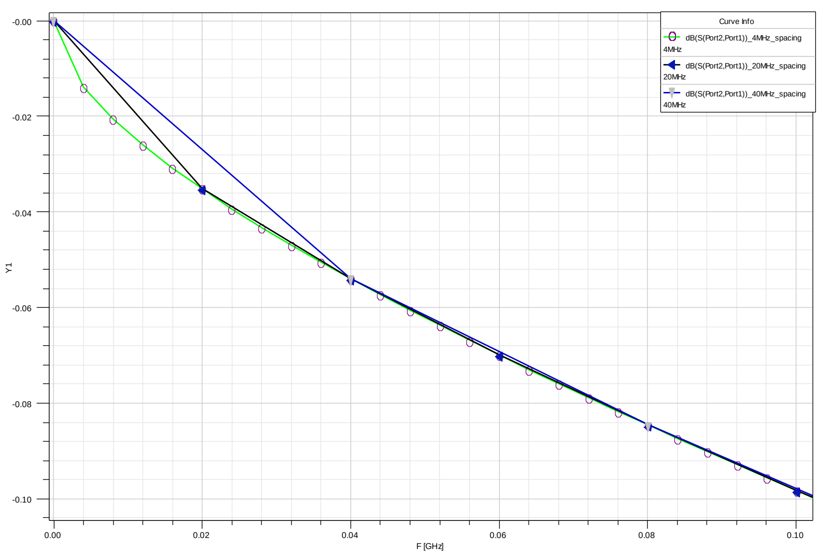
Low Frequency S params
Effects on Convolutional Calculations

- DC point error
- Frequency Spacing/Span errors
  - Settling time issues
  - Aliasing
- Causality errors
- Magnitude/Phase relationship in LF points
  - Likely Causes
    - Poor directivity in measured S params
    - Poor accuracy in 3Dem

Cascaded Extrapolation Errors



- The plot represents the low frequency behavior of an idealized transmission line.
- If I linearly extrapolate the DC behavior from the 40 MHz point, the DC value of S21 is approximately .025 db.

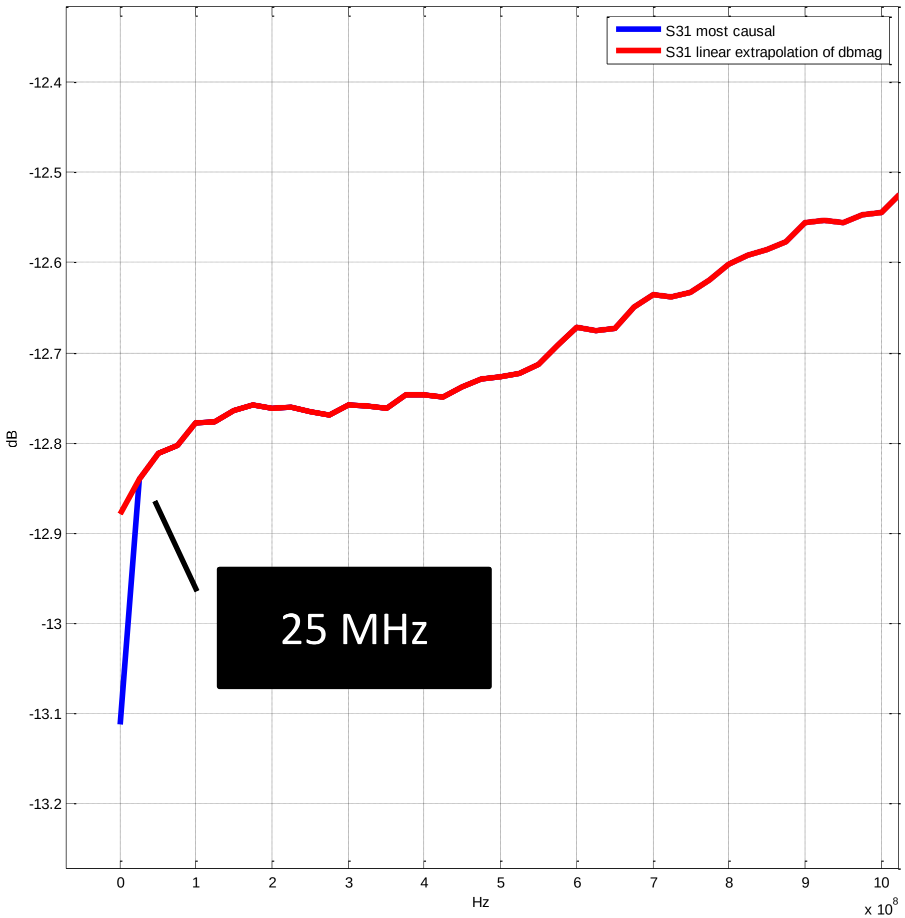
Cascading several sections together of the erroneously extrapolated model would leave an DC value of ~.1 db, which is a fairly gross error since the real DC value is closer to 0db.

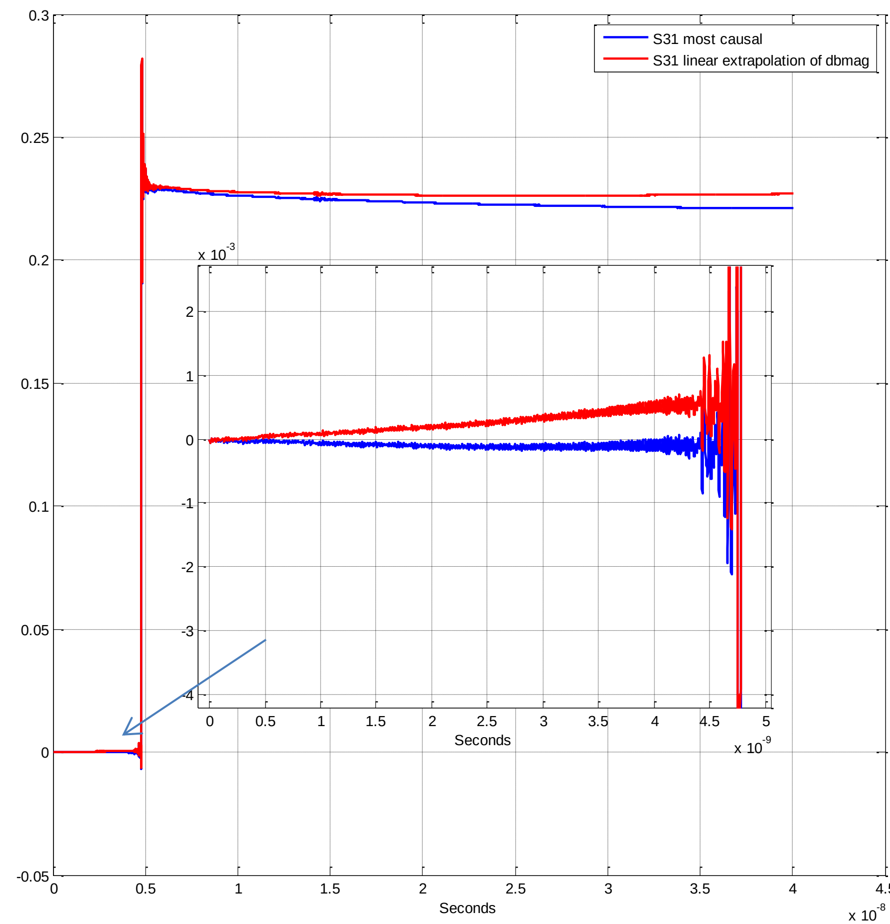
Next I will demonstrate how low frequency extrapolation errors affect the time domain

Extrapolating the DC point: Pitfalls

- Direct measurement of the DC point doesn't usually yield good results when stitched with VNA data
- Interpolation is also difficult
- Why:
  - Measurement system calibration causality error
  - Simulation errors or incomplete material extraction
- The following example is a 3 port measurement of a 50 ohm differential active probe's S parameters
- The S parameters were measured in 25 MHz steps

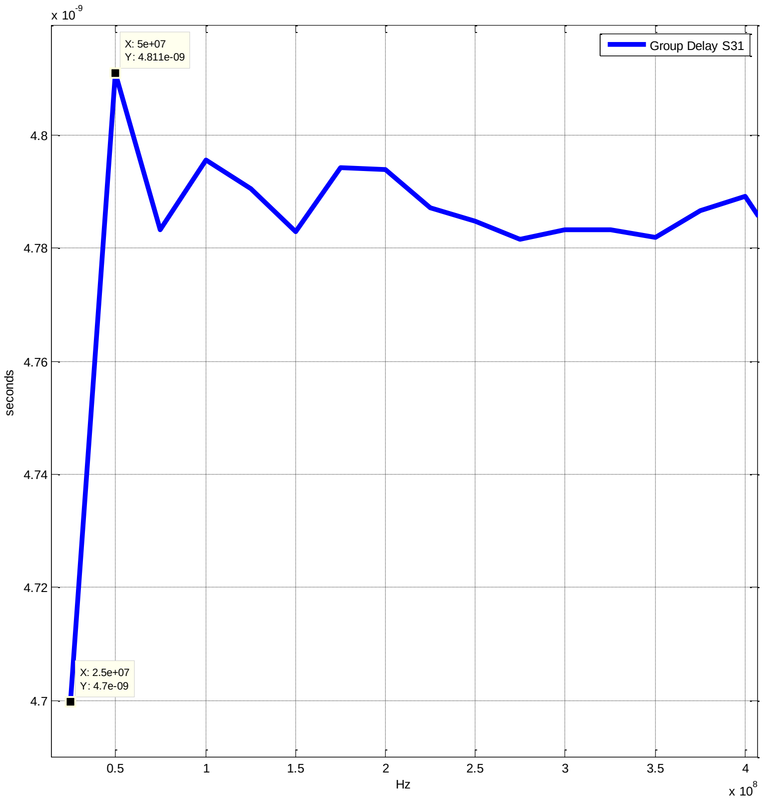
Extrapolation Example





Extrapolation Example

- Linear DC extrapolation of S31 resulted in causality issue
- Looking at long term shape of TDT, we also see a “bow” after the edge
- Examining the group delay, we see an unusual jump between 25MHz and 50 MHz
- We have a calibration issue!



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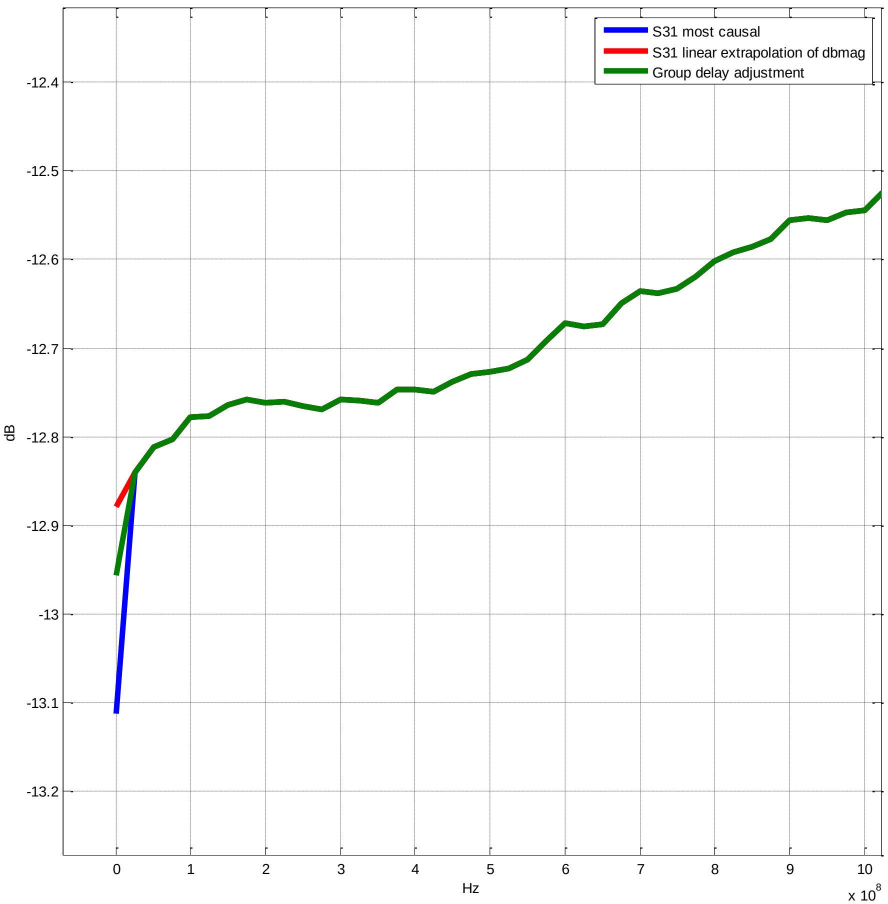
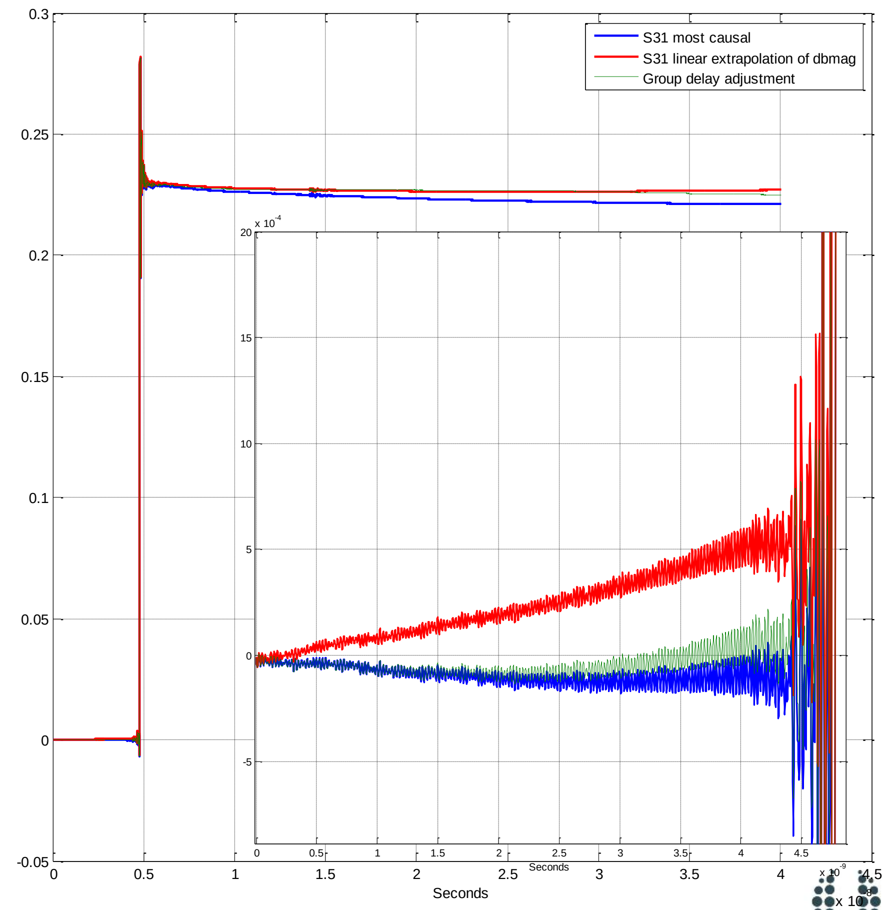
Extrapolation Example

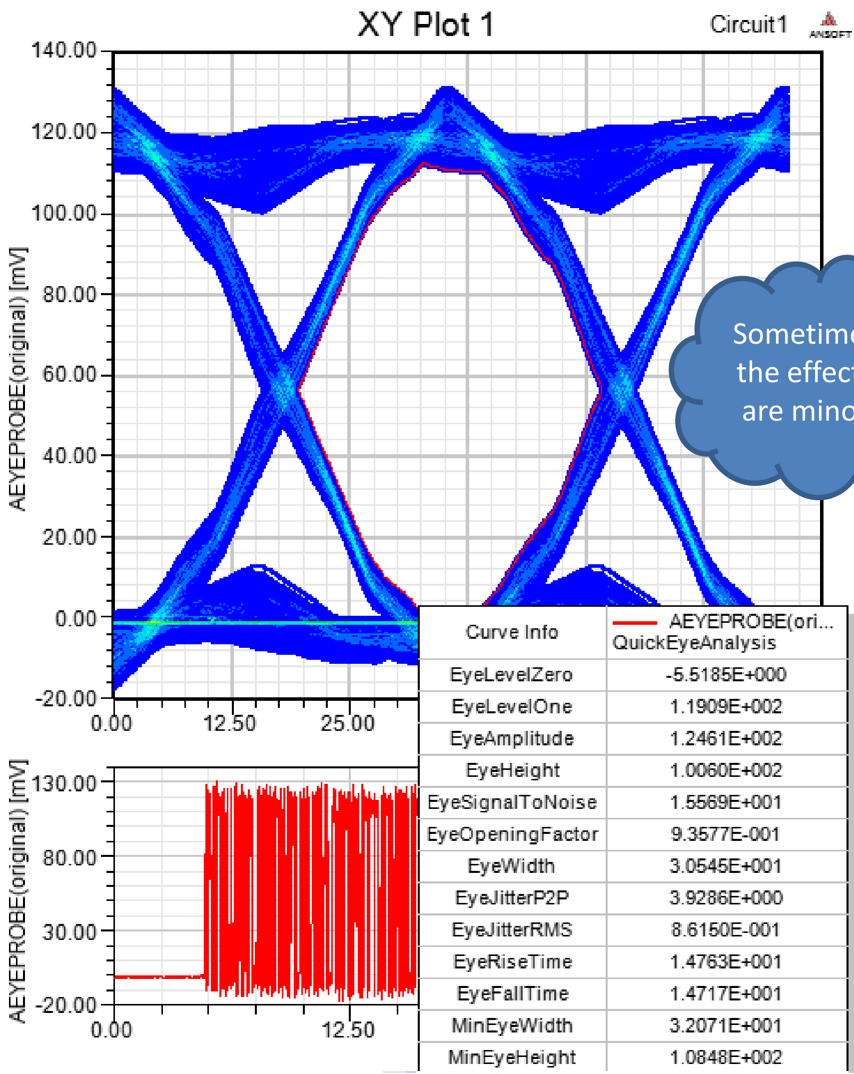
I edited the 25 MHz point phase by 1 radian. There is quite a difference in the step response!



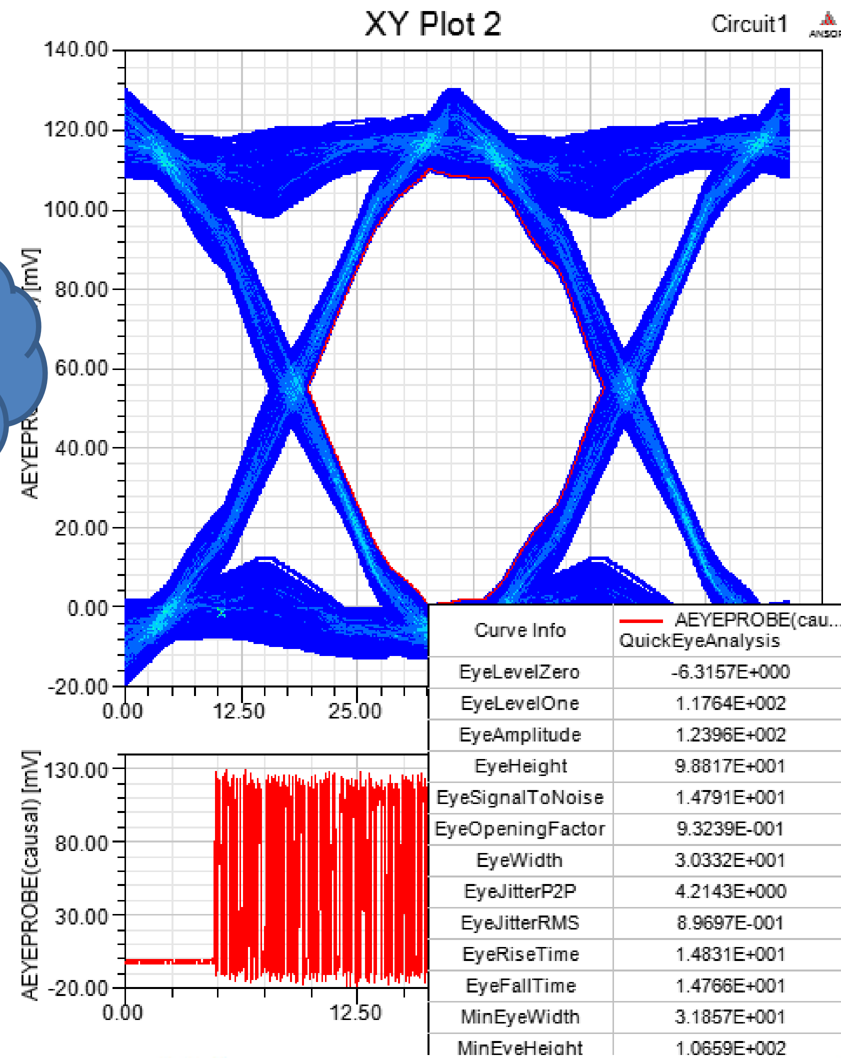


Low Frequency S parameters

DC and LF Point Error Effects on 28G Eye



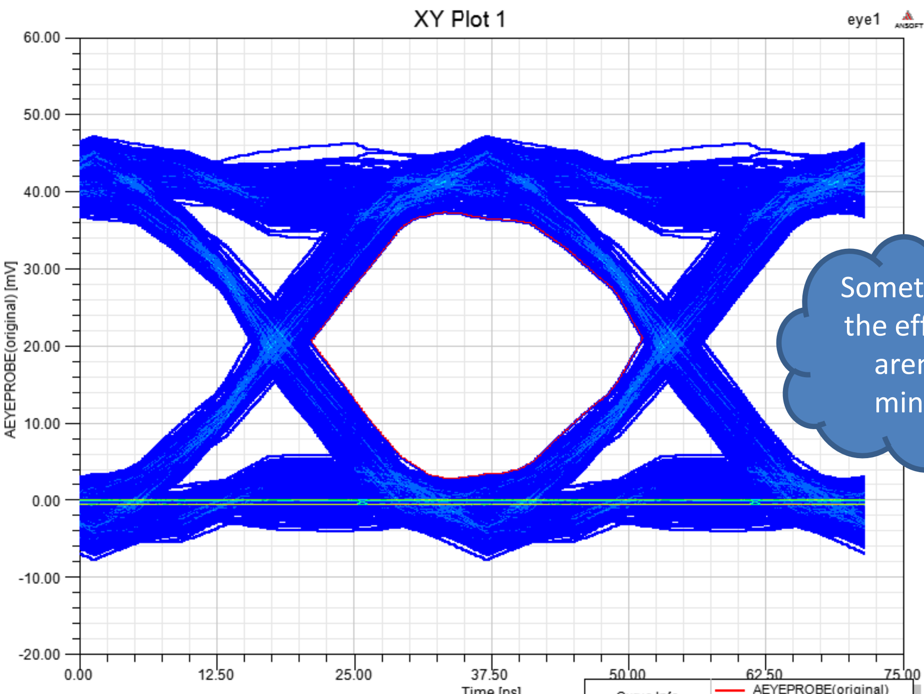
Curve Info	AEYEPROBE(ori... QuickEyeAnalysis
EyeLevelZero	-5.5185E+000
EyeLevelOne	1.1909E+002
EyeAmplitude	1.2461E+002
EyeHeight	1.0060E+002
EyeSignalToNoise	1.5569E+001
EyeOpeningFactor	9.3577E-001
EyeWidth	3.0545E+001
EyeJitterP2P	3.9286E+000
EyeJitterRMS	8.6150E-001
EyeRiseTime	1.4763E+001
EyeFallTime	1.4717E+001
MinEyeWidth	3.2071E+001
MinEyeHeight	1.0848E+002

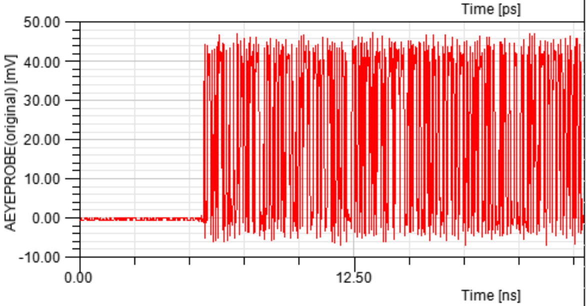


Curve Info	AEYEPROBE(cau... QuickEyeAnalysis
EyeLevelZero	-6.3157E+000
EyeLevelOne	1.1764E+002
EyeAmplitude	1.2396E+002
EyeHeight	9.8817E+001
EyeSignalToNoise	1.4791E+001
EyeOpeningFactor	9.3239E-001
EyeWidth	3.0332E+001
EyeJitterP2P	4.2143E+000
EyeJitterRMS	8.9697E-001
EyeRiseTime	1.4831E+001
EyeFallTime	1.4766E+001
MinEyeWidth	3.1857E+001
MinEyeHeight	1.0659E+002

Low Frequency S parameters

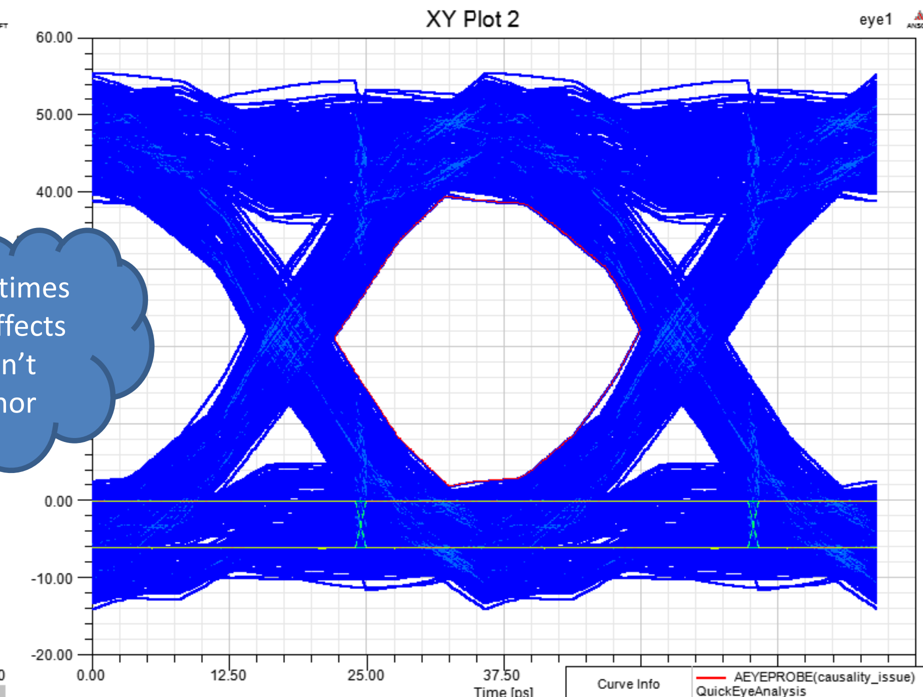
DC and LF Point Error Effects on 28G Eye

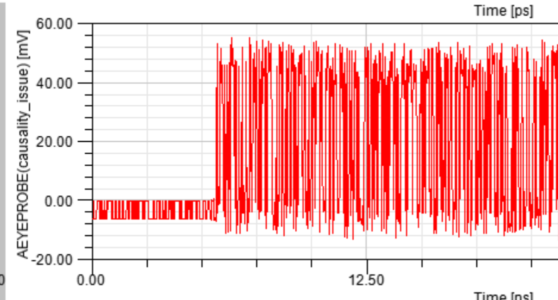




Curve Info	AEYEPROBE(original) QuickEyeAnalysis
EyeLevelZero	-1.0872E+000
EyeLevelOne	4.1887E+001
EyeAmplitude	4.2974E+001
EyeHeight	3.0397E+001
EyeSignalToNoise	1.0251E+001
EyeOpeningFactor	9.0245E-001
EyeWidth	2.9030E+001
EyeJitterP2P	6.2857E+000
EyeJitterRMS	1.1141E+000
EyeRiseTime	1.5018E+001
EyeFallTime	1.4944E+001
MinEyeWidth	2.9714E+001
MinEyeHeight	3.3726E+001

Sometimes the effects aren't minor

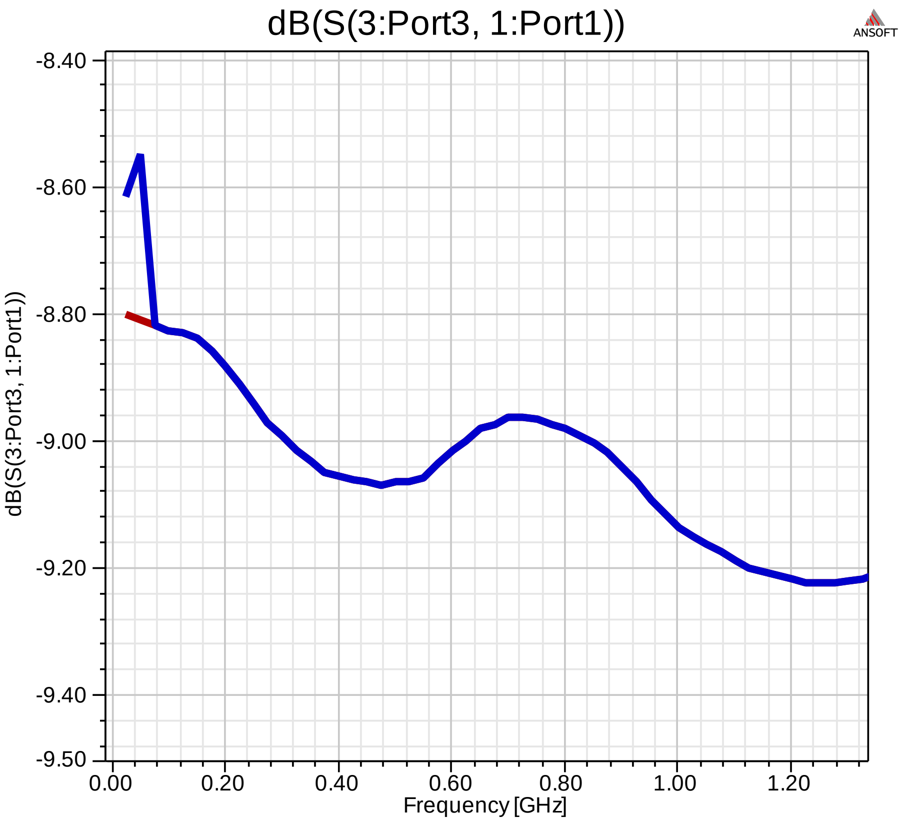


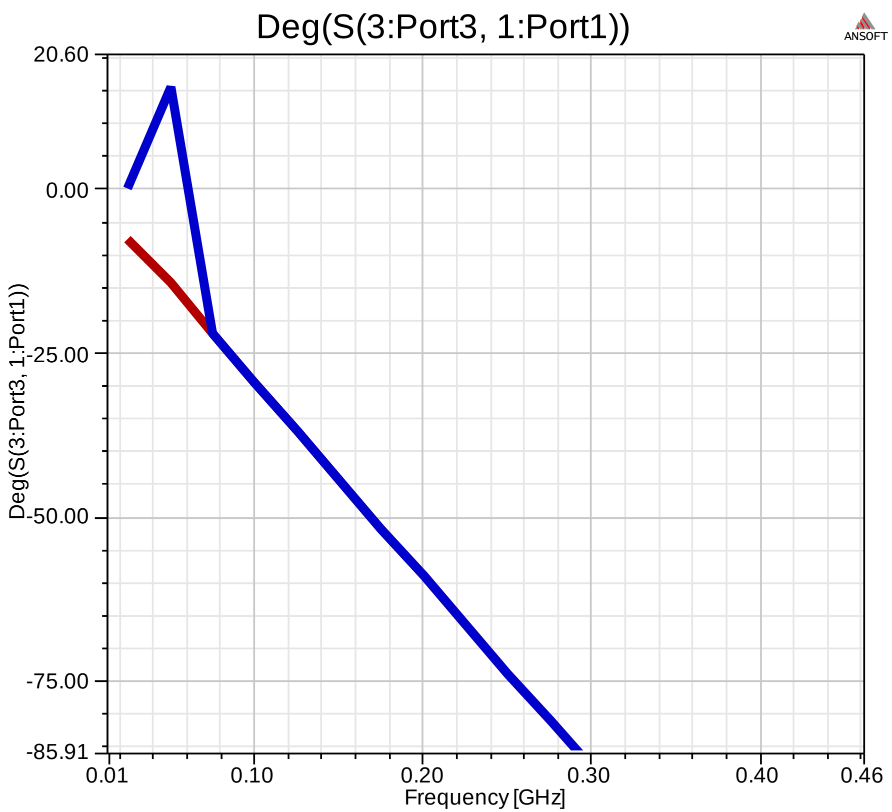


Curve Info	AEYEPROBE(causality_issue) QuickEyeAnalysis
EyeLevelZero	-4.6028E+000
EyeLevelOne	4.6804E+001
EyeAmplitude	5.1407E+001
EyeHeight	2.9512E+001
EyeSignalToNoise	7.0438E+000
EyeOpeningFactor	8.5803E-001
EyeWidth	2.4798E+001
EyeJitterP2P	8.5714E+000
EyeJitterRMS	1.8194E+000
EyeRiseTime	1.5459E+001
EyeFallTime	1.5239E+001
MinEyeWidth	2.7357E+001
MinEyeHeight	3.6240E+001

Low Frequency S parameters

DC and LF point error effects on 28G eye





- 25 and 50 MHz point errors for previous slide
- Phase error causes causality problems

Working with Low Frequency Points: Suggestions

- Compare direct measurement of DC point to extrapolated point to look for calibration or material model issues (and fix cal/materials)
- Use physical TDR/TDT to verify frequency domain measurements and models
- When scaling frequency domain magnitude, maintain causality and passivity
  - Don't arbitrarily adjust DC or other frequency points
  - Use causality and passivity editing tools with caution

Low Frequency S params

6 Common Traps

- Phase Zeroing/adjustment at DC
- Guessing at material conductivity and other material properties in simulation
- Ignoring link between real/imaginary (or mag/phase) when averaging or extrapolating
- 1/F and other noise in measurements
- Ignoring conservation of power between ports when averaging or extrapolating
- Ignoring red flag warnings
  - Why aren't you paying attention to phase and group delay?
  - Dismissing resonances as being non-physical

Time Domain Processing and 3D EM Model Development

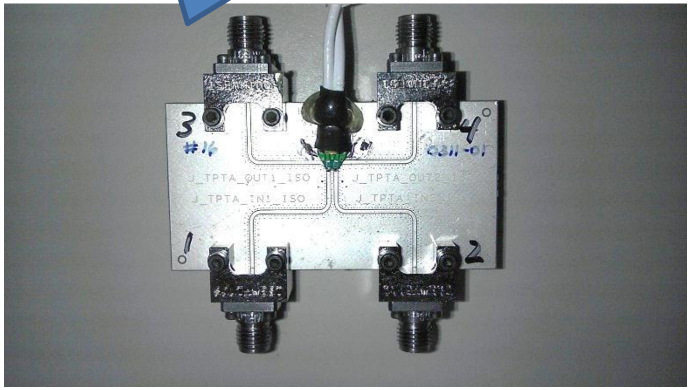
- Introduction
- How to trust a model
- 5 pitfalls of EM modeling
- Low Frequency S parameter Discussion
- Cleaning up Models with Simulation and Rational Compact Models
- The Economics of Modeling

Cleaning Up Models

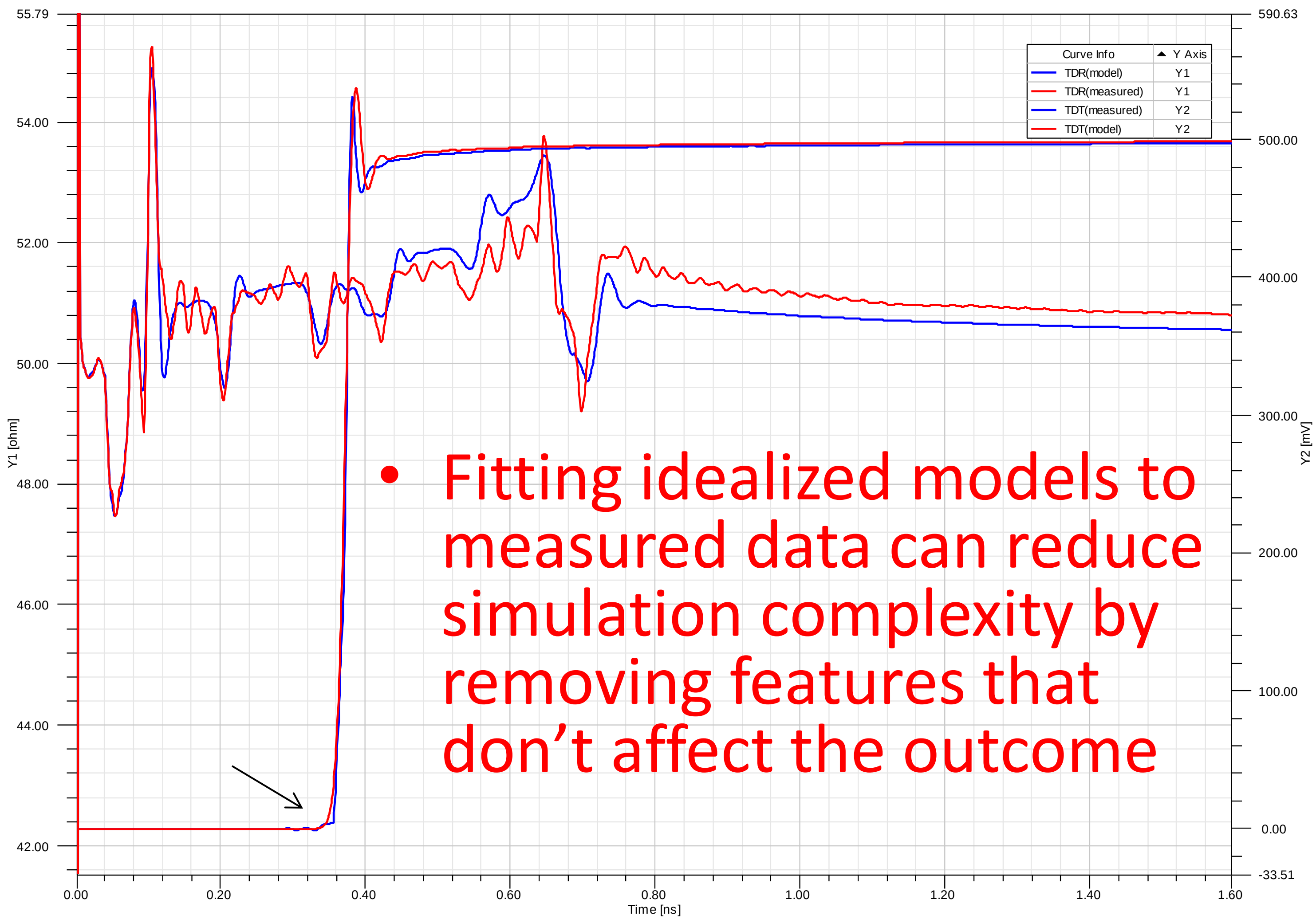
With Simulation and Rational Compact Models

- Cleaning up measured models
  - Removing noise and calibration errors
- Using Simulation to perform difficult de-embedding or cascading
  - Arbitrary model splitting
  - Many-port S parameter models
  - Development of "Typical" model from many measured models

Tip: Always check models for proper behavior. Even good fit rational compact or 3DEM models can have hard-to-spot defects that cause difficulty in Signal Integrity use.



Cleaning Up Models



- Fitting idealized models to measured data can reduce simulation complexity by removing features that don’t affect the outcome

Time Domain Processing and 3D EM Model Development

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Economics

Measuring versus Modeling

Measuring only

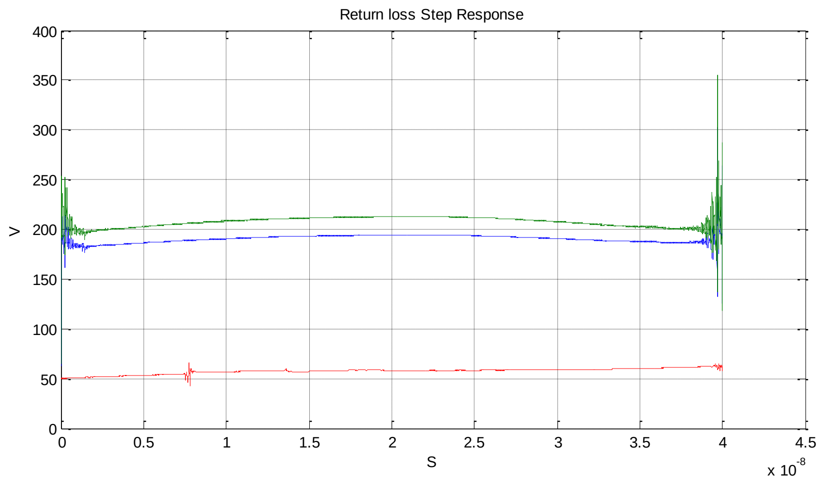
- Safe if technology isn't being stressed
- Scale modeling is still relevant
- Specific hardware may be difficult to represent in simulator
- Real world is always causal
- Real measurements have noise
- Experience required for consistent results

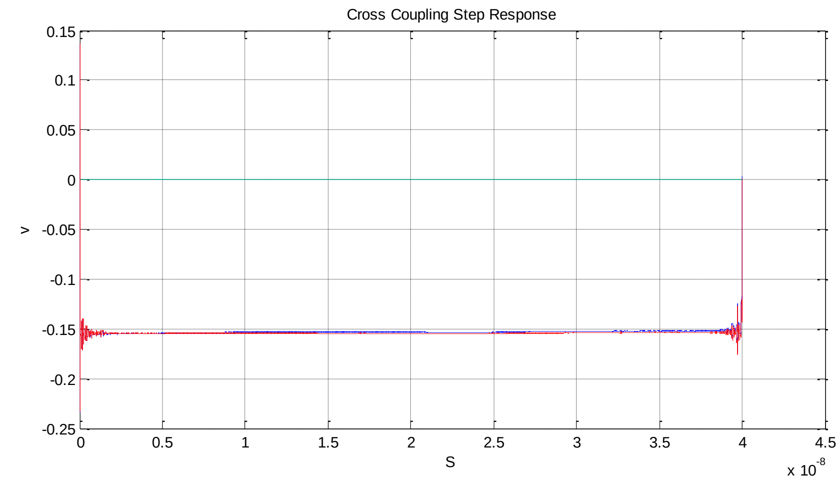
Modeling

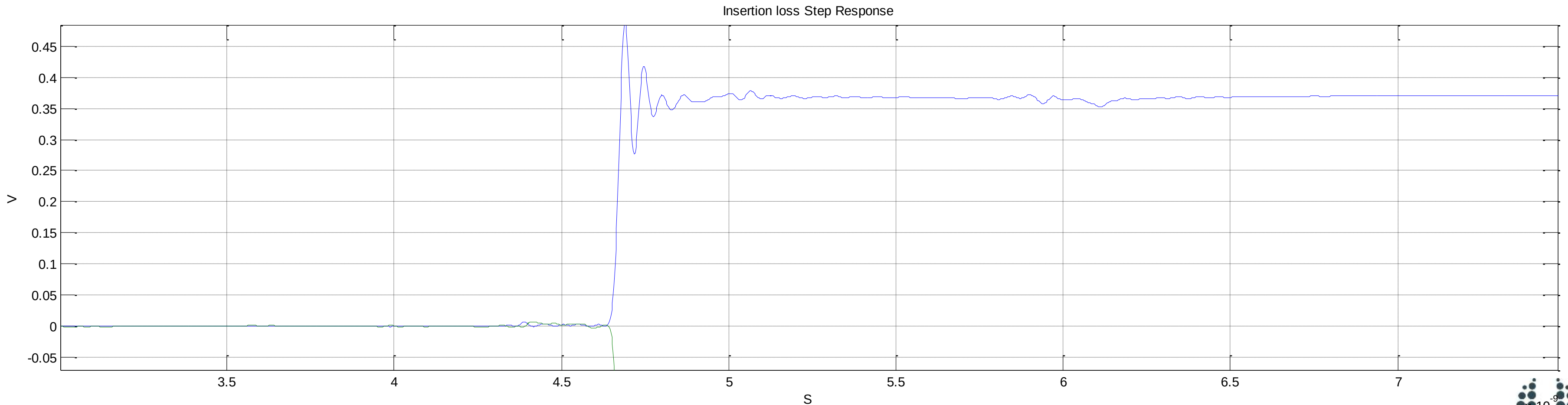
- Simulation usually reduces design turns
- Simulation offers insight into invisible attributes
- Material libraries can be built up
- Must always build to verify
- Simulations cost money too
- Experience required for consistent results

Economics

Managing Expectations

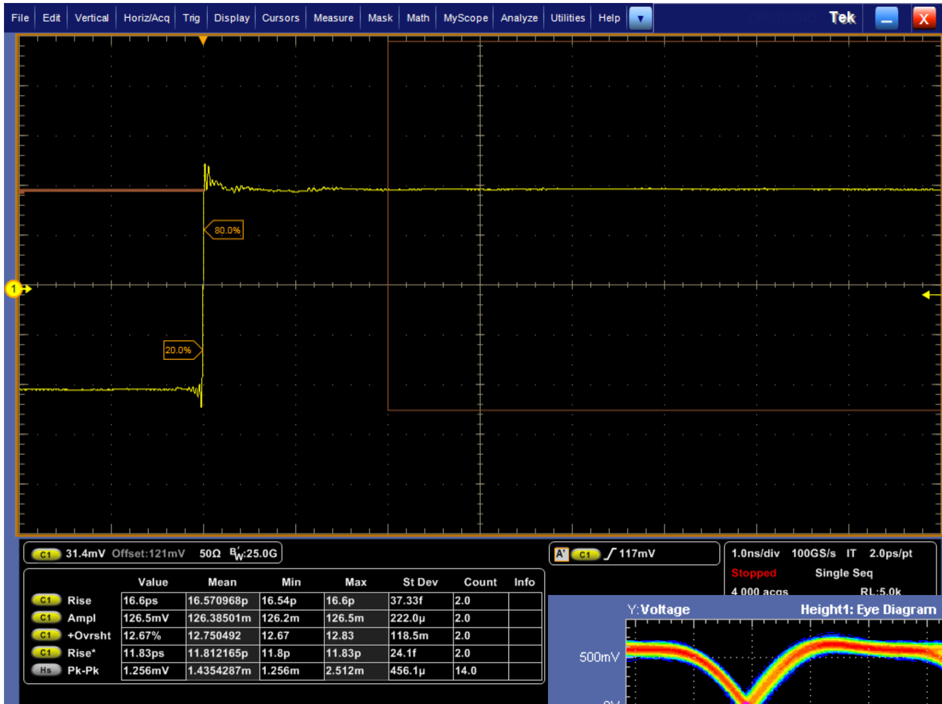






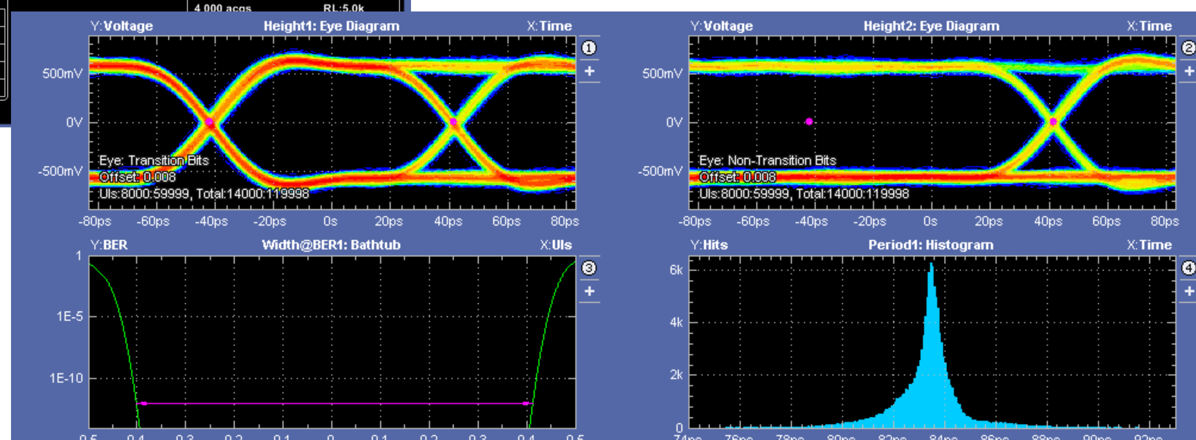
Economics

Managing Expectations



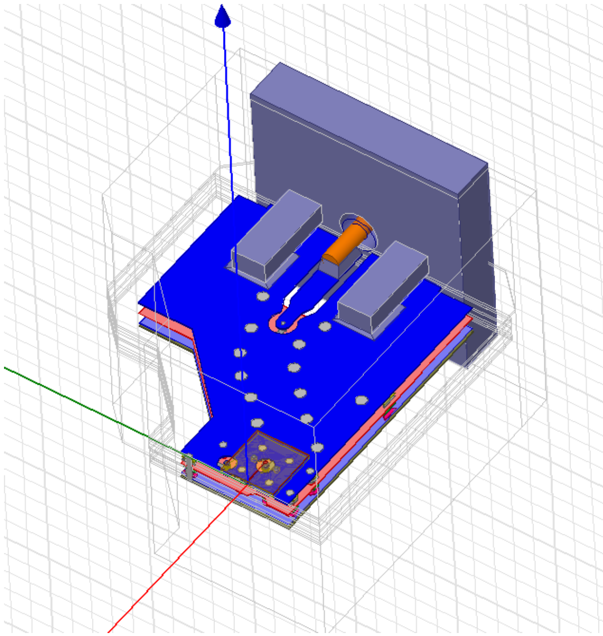
Is my error budget realistic to my application?

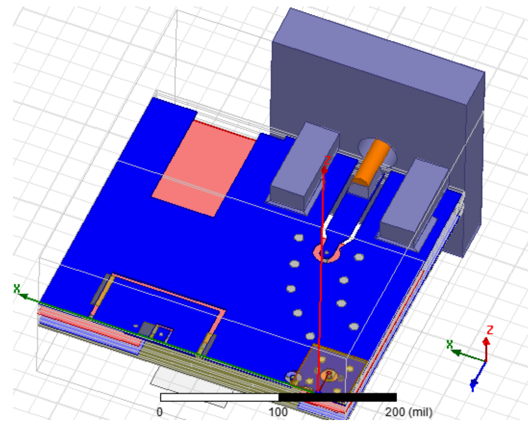
Did I nerd out over something that didn't matter?



Economics

Striving for Imperfection





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Solution Process			
Total	07:08:47	06:59:47	

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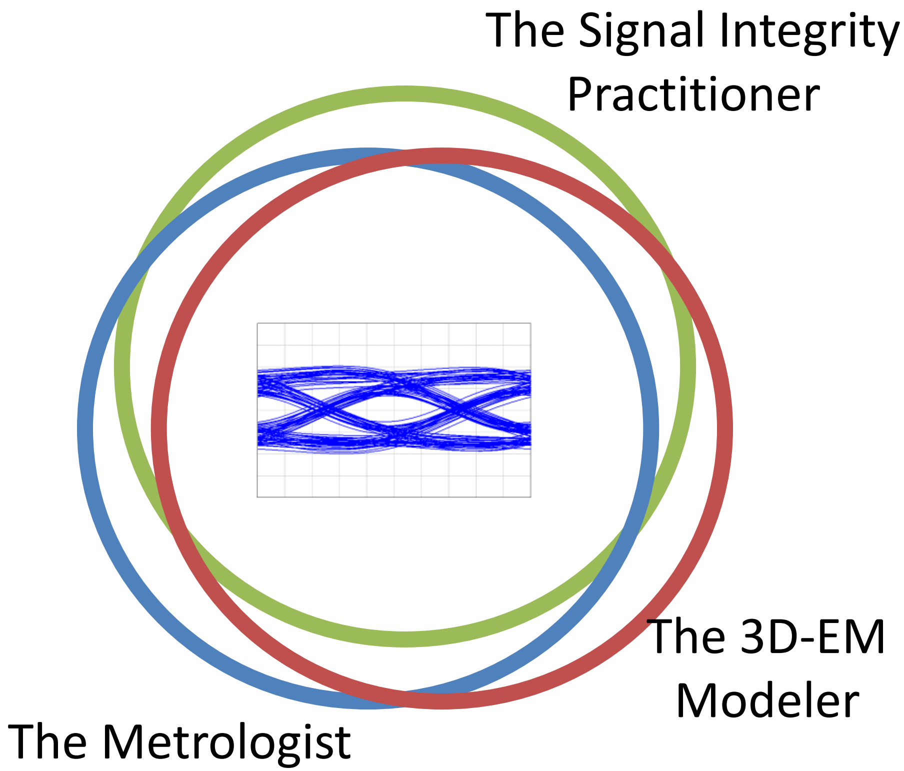
Time: 04/21/2011 22:27:40, Status: Normal Completion

3DEM Conclusion

- Create and understand the error budget
- Understand relationship between time and frequency domain, especially with respect to calibration and causality
- Measure and model materials with full property observe-ability whenever possible
- Perform sensitivity tests
- Break the models and observe the signs of broken-ness
- Close the loop, improve the process

Summary

- Low frequency data just as important as high frequency in both measurement and models
- Remember the basics - Start with the appropriate calibration and verify it
- Beware of the tools – understand what they are doing
- Simulate to reduce design-turns but measure to close the loop



Agenda

- Introduction
- The Metrologist's Tale
  - Practical calibration methods suited for 3D-EM
    - Jon Martens
- The Signal Integrity Practitioner's Tale
  - Verification and assurance
    - Jim Bell and Al Neves
- The 3D-EM Modeler's Tale
  - Time domain processing and 3D-EM model development
    - Josiah Bartlett
- **Questions**