

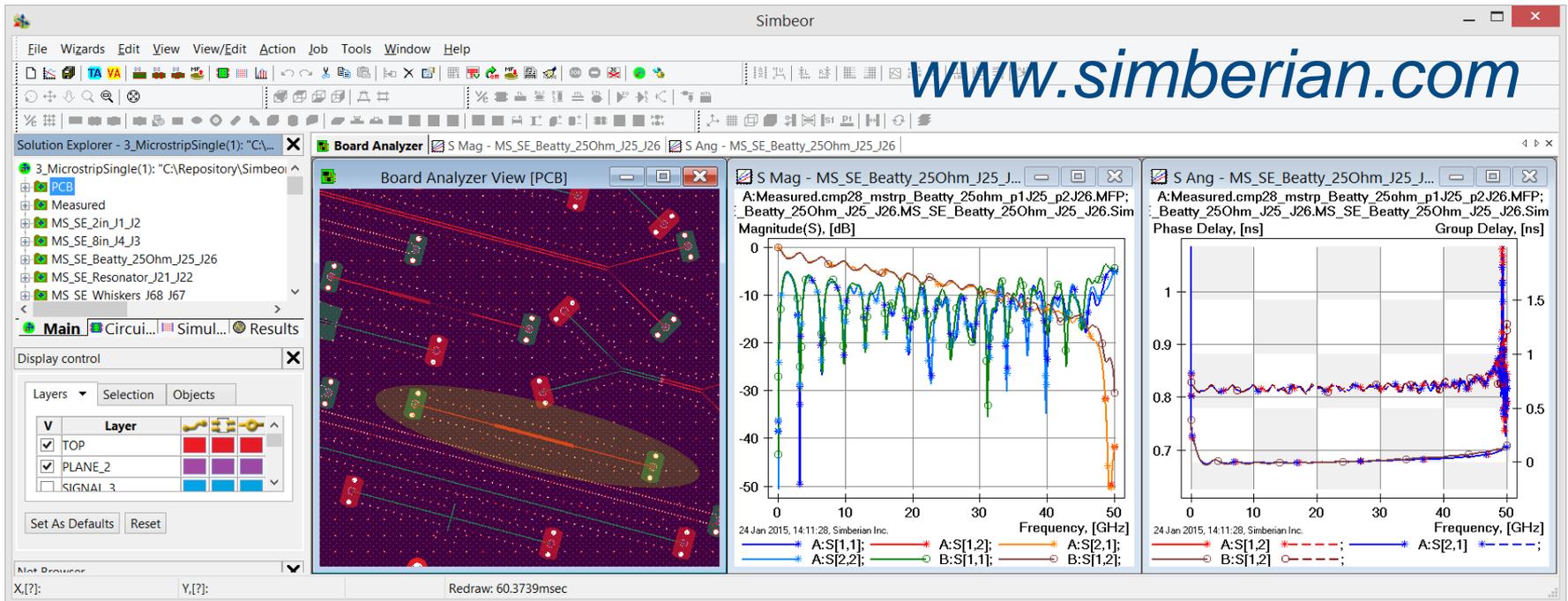


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Simbeor Application Note #2017\_03, August 2017  
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# Identification of dielectric and conductor roughness models with differential lines



Simbeor®: Accurate, Productive, Cost-Effective Electromagnetic Signal Integrity Software...

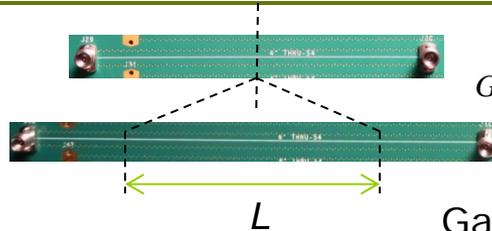
# Outline

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- Model identification with GMS-parameters
  - Step 1: Measure S-parameters for 2 line segment and ensure quality and consistency
  - Step2: Extract GMS-parameters
  - Step 3: Create model of line segment and compute GMS-parameters
  - Step 4: Identify dielectric and conductor roughness parameters
- Create model with two dielectrics (FEXT)
- Appendix: Results with causal Huray-Bracken roughness model

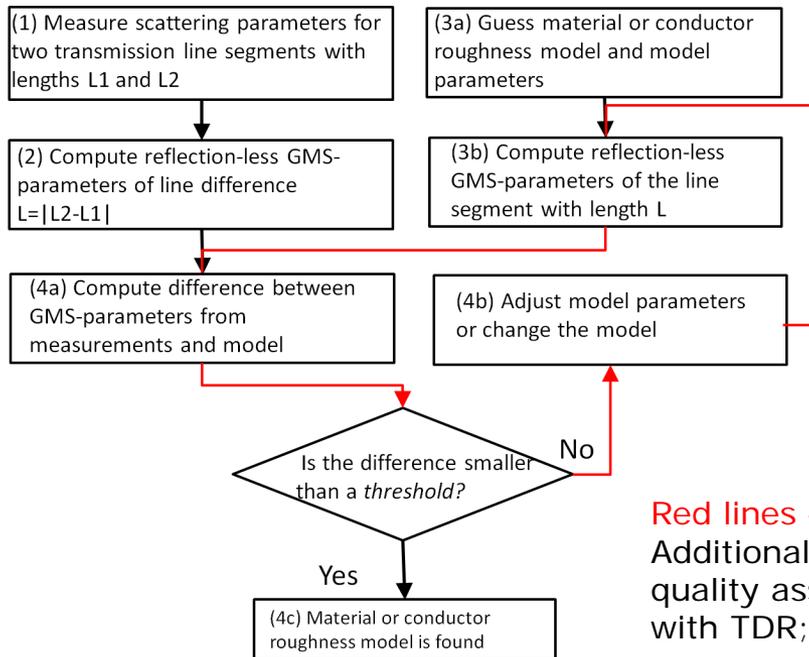
# Identification with GMS or SPP techniques

$$GMS = \begin{pmatrix} 0 & \exp(-\Gamma \cdot L) \\ \exp(-\Gamma \cdot L) & 0 \end{pmatrix}$$

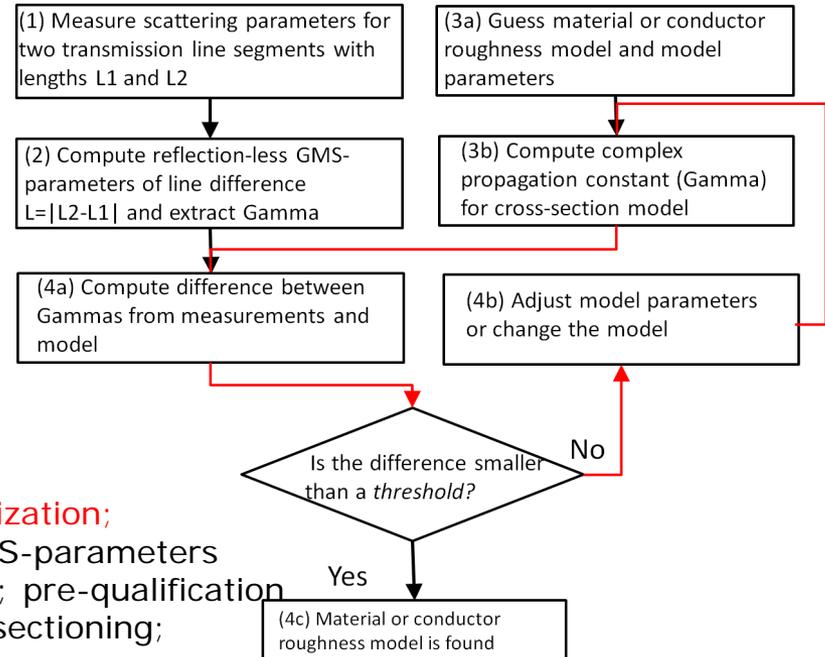


$$GMT = \text{eigenvals}(T2 \cdot T1^{-1}) = \begin{pmatrix} \exp(-\Gamma \cdot L) & 0 \\ 0 & \exp(\Gamma \cdot L) \end{pmatrix}$$

## Use of raw GMS-parameters



## Gamma extraction – “SPP Light”



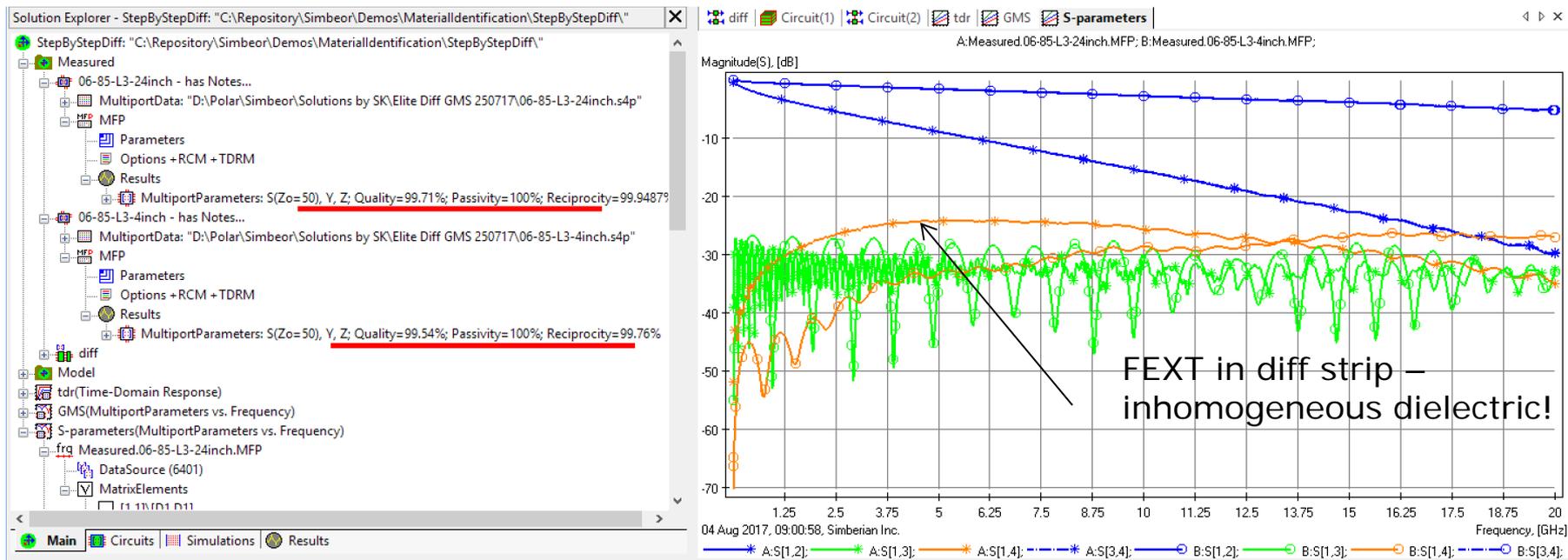
Red lines – optimization;  
 Additional steps: S-parameters quality assurance; pre-qualification with TDR; Cross-sectioning;

Y. Shlepnev, Broadband material model identification with GMS-parameters, EPEPS 2015.

Y. Shlepnev, Y. Choi, C. Cheng, Y. Damgaci, Drawbacks and Possible Improvements of Short Pulse Propagation Technique, EPEPS 2016.

# Step 1a: Measure S-parameters of 2 line segments, import into Simbeor and ensure quality

Quality of S-parameters of 24 inch in and 4 inch segment is good



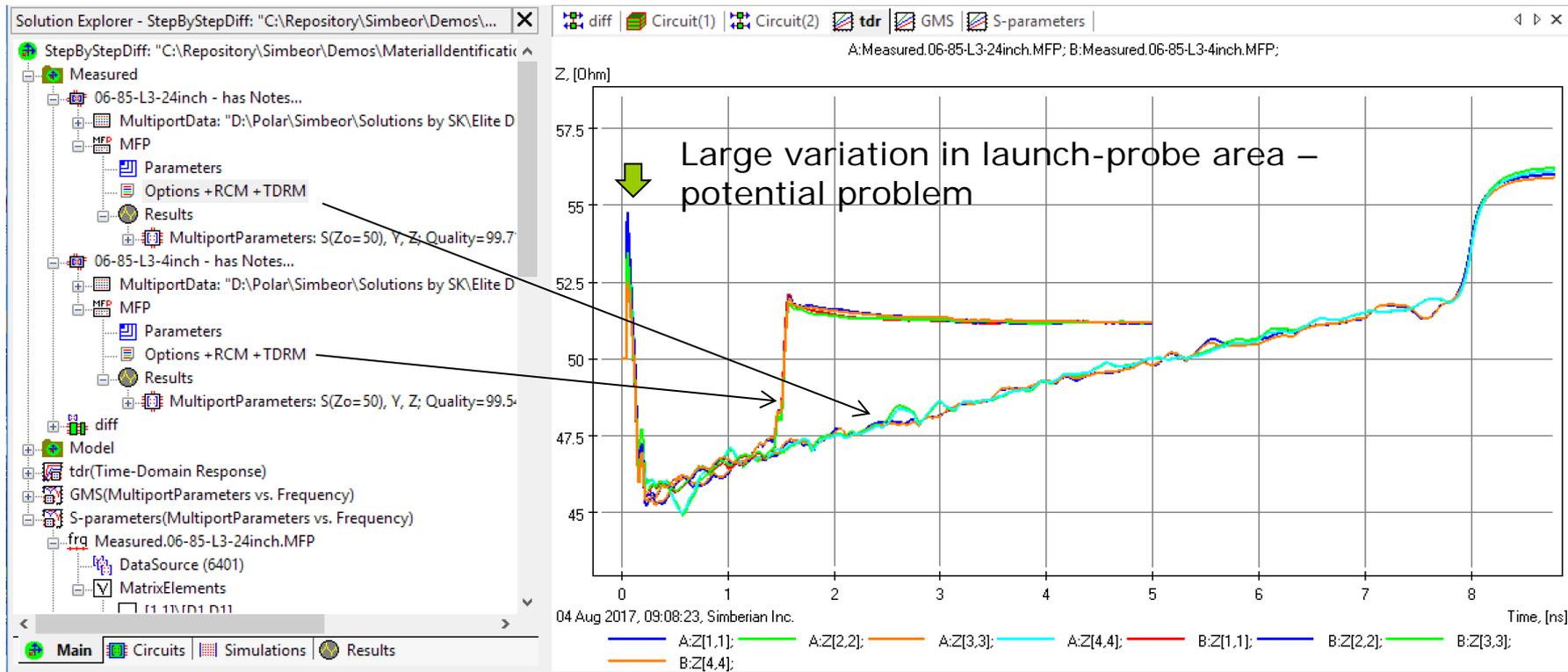
See more on the import of S-parameters and quality assurance at

[http://kb.simberian.com/browse\\_item.php?id=775](http://kb.simberian.com/browse_item.php?id=775)

[http://kb.simberian.com/browse\\_item.php?id=240](http://kb.simberian.com/browse_item.php?id=240)

# Step 1b: Ensure quality of test fixtures with TDR computed from S-parameters

TDRs of short and long segments are consistent, except the launch area  
Traces are about 46 Ohm



See more on TDR computation at

[http://kb.simberian.com/browse\\_item.php?id=202](http://kb.simberian.com/browse_item.php?id=202)

# Step 2: Extract GSM-parameters

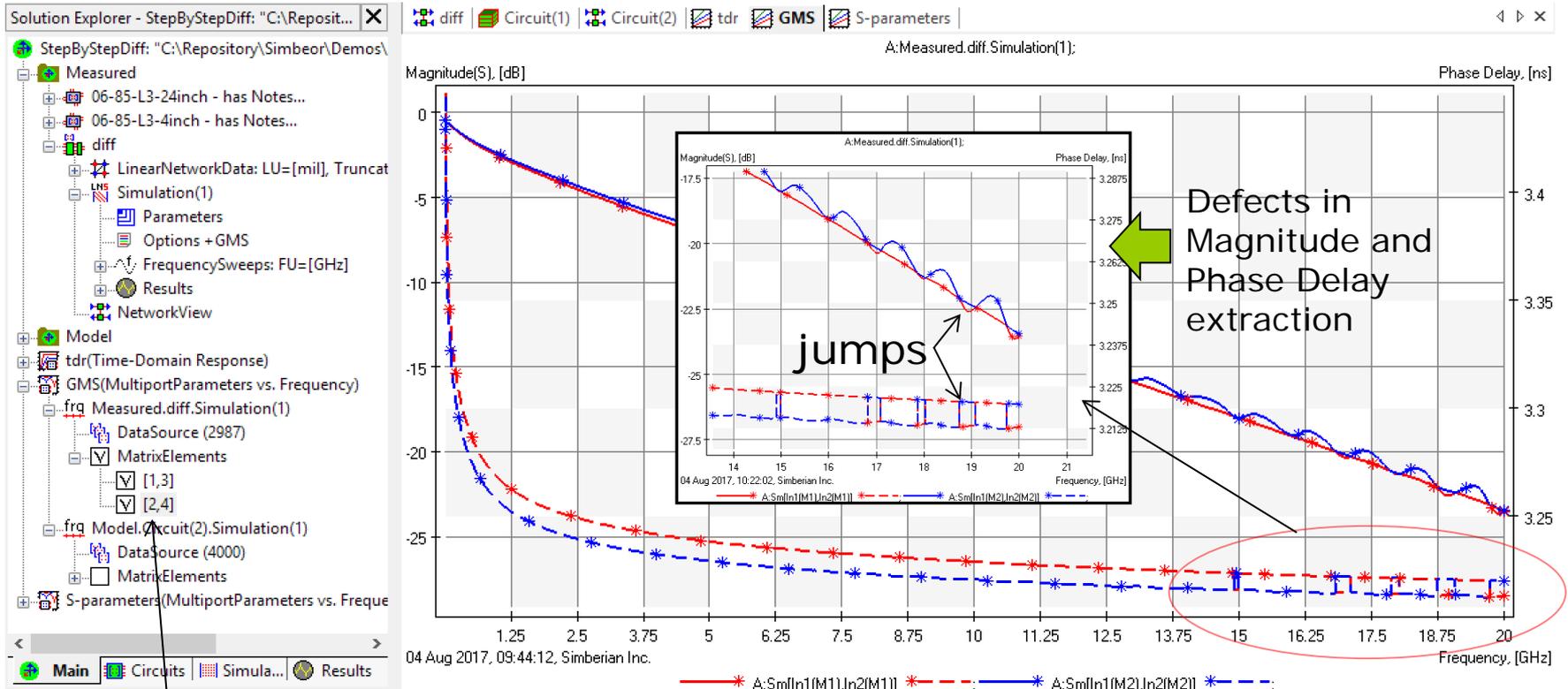
The screenshot displays the Simberian software interface. On the left, the Solution Explorer shows a project structure with a 'LinearNetworkData' component. The main workspace shows a circuit diagram with two multiports, MPT1 and MPT2, connected in series. A dialog box titled 'LinearNetworkSolver Options' is open, showing the 'Extract Generalized Modal S-Parameters (GMS-Parameters) From 2 Multiports' option selected. The 'Sort Modes by Phase' option is also checked. The circuit diagram includes two multiports, MPT1 and MPT2, each with two ports (IO1 and IO2). The multiports are connected in series, with MPT2 on the left and MPT1 on the right. The multiports are labeled with their respective material models: 'Measured.06-85-L3-24inch.MFP' for MPT1 and 'Measured.06-85-L3-4inch.MFP' for MPT2. The dialog box is titled 'LinearNetworkSolver Options' and has a 'Debug' tab. It contains several options: 'Connect Multiports (Concatenate/Subtract)', 'Build Rational Compact Model', 'Compute TD Response Matrix', 'Extract Generalized Modal S-Parameters (GMS-Parameters) From 2 Multiports' (selected), 'Extract Test Fixture S-Parameters From 2 Multiports for De-Embedding', 'Compute S-Parameters Difference of 2 Multiports: dS=S1-S2', 'Sort Modes by Phase (use if default ordering fails)' (checked), 'Filter Magnitude Noise By Fitting', and 'Filter Phase Noise by Fitting'. The 'Linear Network Solver Type' is set to 'Y\_FullGaussian'. A tip at the bottom of the dialog box states: 'Tip: Network must contain two multiports describing two line segments with different length and identical cross-section and possible transitions. The result is S-matrix of line difference in is modal space normalized to characteristic impedances of the modes. Can be used for the material parameters extraction.'

a) Create Linear Network with 2 multiports (long and short lines)

b) Check "Extract GSM" without any other options for preliminary analysis

See details and recommendations at [http://kb.simberian.com/browse\\_item.php?id=846](http://kb.simberian.com/browse_item.php?id=846)

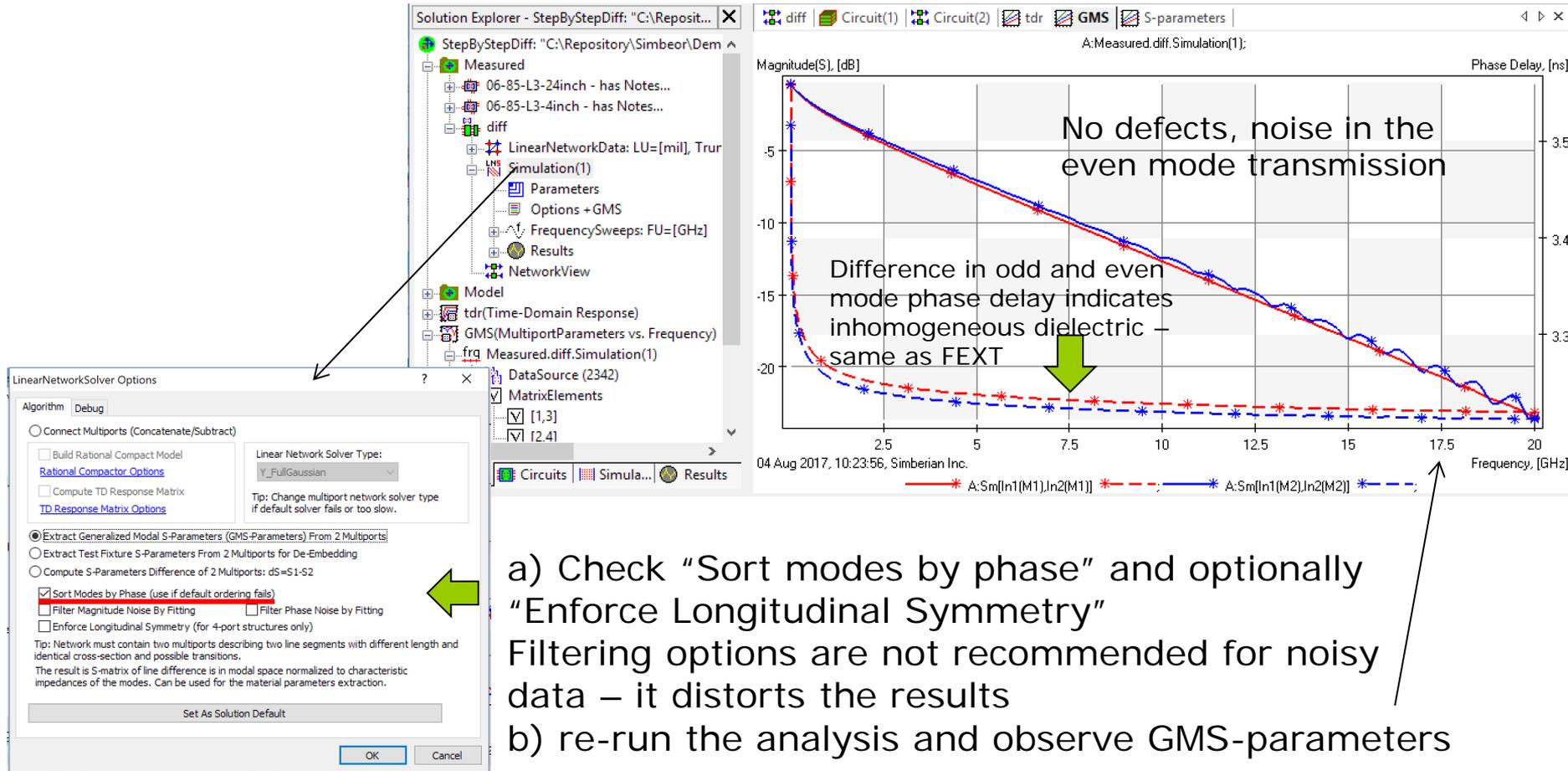
# Step 2: Extract GMS-parameters – plot Magnitude and Phase Delay



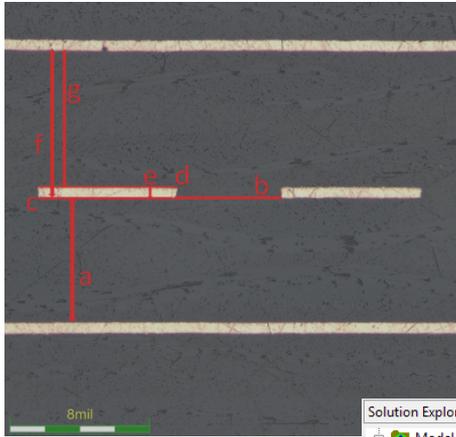
Elements GMS[1,3] – odd or differential mode transmission, GMS[2,4] – even or common mode transmission

Mode M1 is odd, mode M2 is even

# Step2: Extract GMS-parameters – use options to fix problems



# Step 3a: Compute GMS-parameters of line segment – cross section



Parameter	85-L3-4inch	85-L3-24inch
	Avg.	Avg.
a	5.66	5.67
b	7.41	7.35
c	6.51	6.58
d	6.67	6.74
e	0.65	0.65
f	5.80	5.82
g	5.15	5.16

Create model of differential strip cross-section – Wizards  
-> Create TLine Model...



Preliminary material models



Simbeor SFS solver is used for strips



The screenshot shows the Simberian software interface. On the right, a 3D view displays a cross-section of a differential strip on a PCB, with a vertical Z-axis (0 to 20 mil) and a horizontal Y-axis (-15 to 15 mil). The strip is shown in orange, with surrounding layers in green and red. On the left, the Solution Explorer tree view shows the simulation setup, including material models (Copper, FR4, Air), a stack-up, and a TLine model for the strips. The TLine model parameters are: Start "IO1" ExP=0, RP=0; End "IO2" RP=0, ExP=0. The strip is defined as: Strip: Active +1, "Signal1", "Copper", YC=-6.965, \###/ Wt=6.74, Wb=6.58, SEt=-10.335. The simulation is set to use the SFS solver for the strips.

Trapezoidal strips

# Step 3b: Compute GMS-parameters of line segment – model 20 inch diff strip segment

Solution Explorer - StepByStepDiff: "C:\Repository\Simbeor\Demos\MaterialIdentification\StepByStepDiff\"

Model

- Materials: T=20[C],...
- "Copper", RR=1
- "FR4", Dk=4.2, LT=0.02, PLM=WD, Dk(0)=5.06, Dk(inf)=3.83
- "Air"
- StackUp: LU=[mil], NL=3, T=13.02[mil]
  - 1| Plane: "Plane1", Cond="Copper", T=0.77, Ins="FR4"
  - 2| Medium: T=5.16, Ins="FR4"
  - 3| Signal: "Signal1", T=0.65, Ins="FR4", Cond="Copper"
  - 4| Medium: T=5.67, Ins="FR4"
  - 5| Plane: "Plane2", Cond="Copper", T=0.77, Ins="FR4"
- strip
- segment\_20in
  - LinearNetworkData: LU=[mil], Truncation=1.0[mil], IU=[nH], CU=[pF]
  - MultiportTopology: 2 inputs, 4 ports
  - Network: 1 multiport
  - Simulation(1)
    - Parameters
    - Options
    - FrequencySweeps: FU=[GHz]
    - Results
      - MultiportParameters: S(Zo=[Mod. Zm; Term. Zi]), Y, Z
      - Primary: YMatrix 4x4
      - Derived: SMatrix 4x4
      - Rational Compact Model: Not Available
      - TD Response Matrix: EMPTY
      - Descriptors: 2413 from 1e+007 to 2e+010 Hz

Linear Network segment\_20in

20 inch segment of diff strip

Multiport Parameters

Multiport Parameters Profile: Multiport Parameters To Output

Input Space: Modal

S-Matrix Normalization Type: Generalized

S-Matrix Normalization Impedance: 50 [Ohm]

List of S-Matrix Normalization Zo

Hints

To have different normalization impedances (Zo) for different inputs, define list of impedances and set normalization type to Generalized and Input space to Terminal or Mixed Mode.

If Input Space is defined as Modal and normalization as Generalized, t-line inputs are normalized to the characteristic impedance of t-line modes. The other ports are normalized either to Zo from the list or to Common Zo.

Set As Solution Default

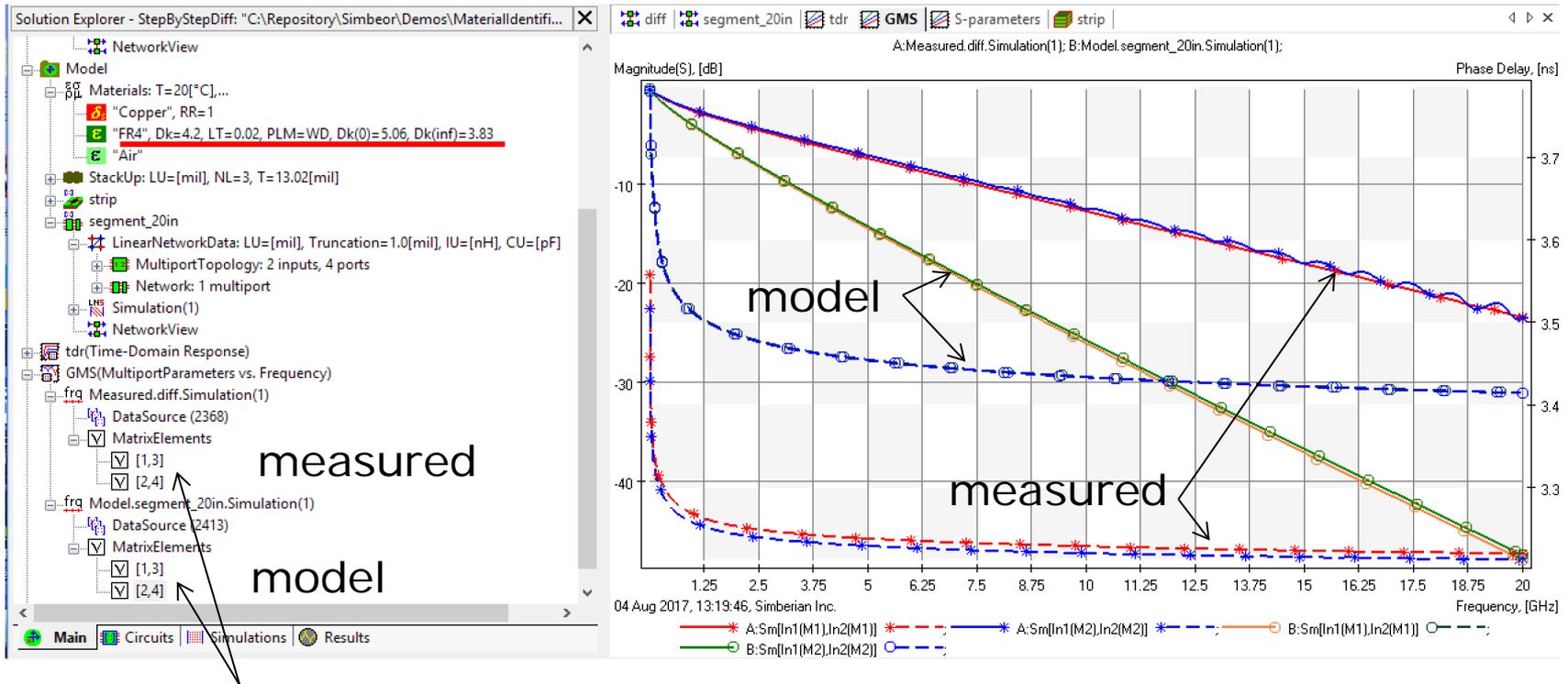
OK Cancel

Inc. Editor Mode (press <E> for Net

See more at

[http://kb.simberian.com/browse\\_item.php?id=847](http://kb.simberian.com/browse_item.php?id=847)

# Step 3c: Plot GMS-parameters of the model



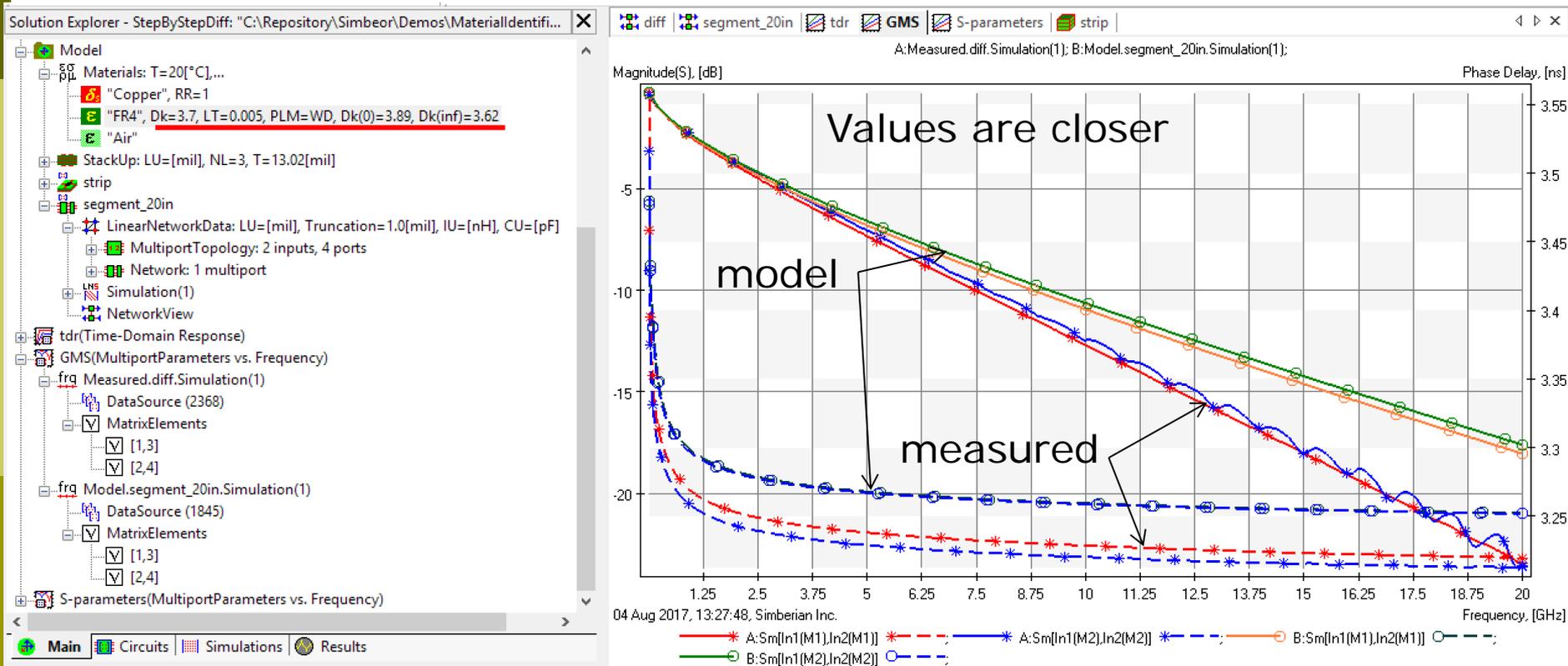
Elements GMS[1,3] – odd or differential mode transmission, GMS[2,4] – even or common mode transmission

Mode M1 is odd, mode M2 is even

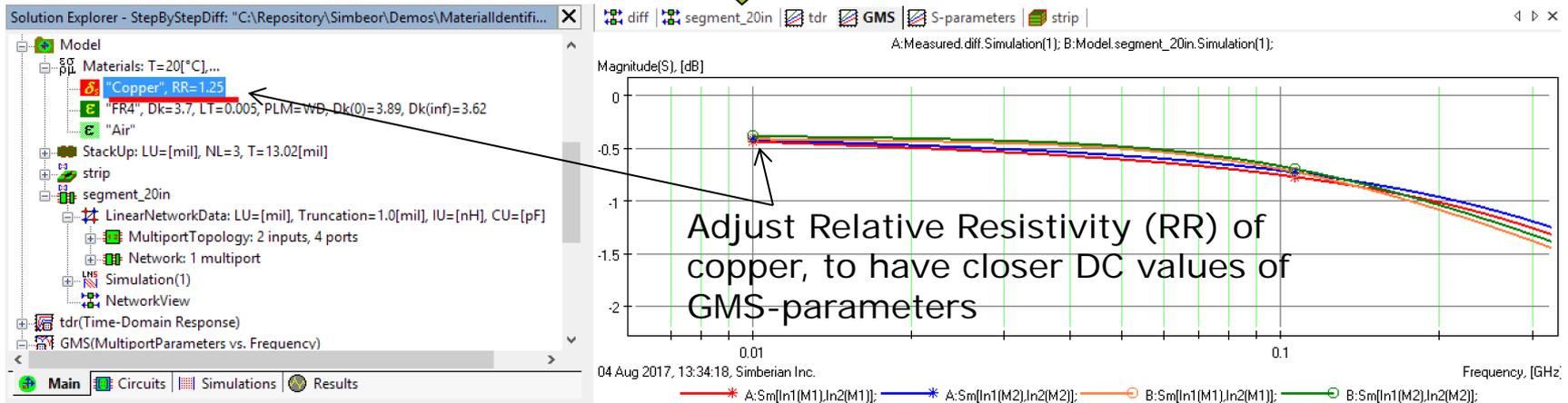
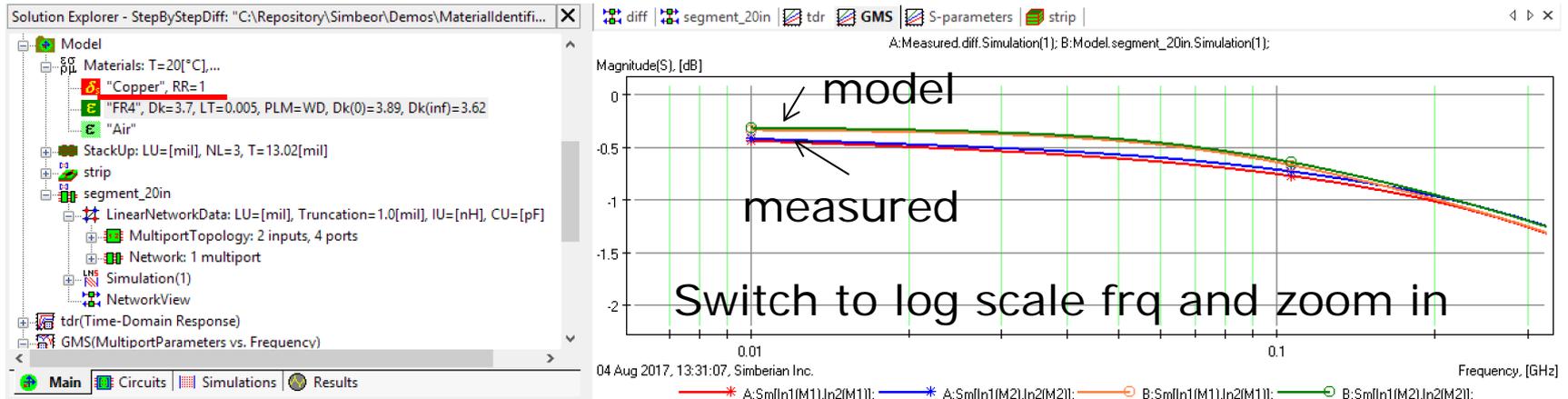
The first adjustment can be done without SiTune – from the Phase Delay we can see that the Dk and LT should be much lower (4.2 and 0.02@ 1 GHz are specified as the starting point)

# Step 4a: Manually adjust Dk and LT to have model GMS-parameters closer to measured

For instance, adjust Dk to 3.7 and LT to 0.005 and re-run the analysis



# Step 4b: Manual adjustment of resistivity

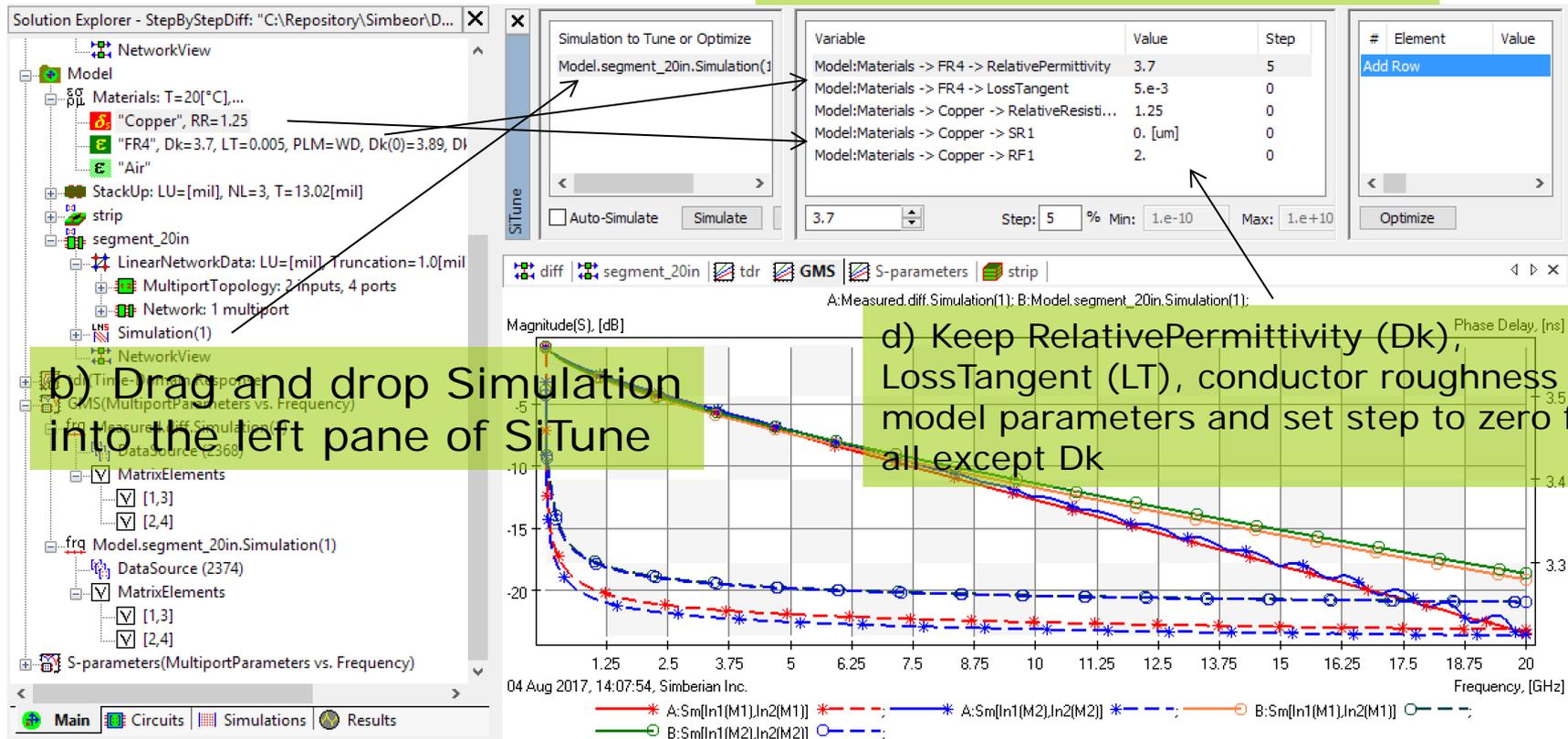


RR=1.25 gives better DC match, but this is questionable adjustment!

# Step 4c: Bring model parameters into SiTune for the optimization

a) Open SiTune from Tools menu

c) Drag and drop Copper and FR4 into variable pane



b) Drag and drop Simulation into the left pane of SiTune

d) Keep RelativePermittivity (Dk), LossTangent (LT), conductor roughness model parameters and set step to zero for all except Dk

# Step 4c: Set up goal for Dk

a) For GMS odd mode transmission parameter

b) Match Phase Delay to Measured GMS-par.

c) From 1 to max frequency (20 GHz in this case)

The screenshot shows the SI Tune software interface. On the left, a table lists variables for optimization:

Variable	Value	Step
Model:Materials -> FR4 -> RelativePermittivity	3.7	5
Model:Materials -> FR4 -> LossTangent	5.e-3	0
Model:Materials -> Copper -> RelativeResisti...	1.25	0
Model:Materials -> Copper -> SR1	0. [um]	0
Model:Materials -> Copper -> RF1	2.	0

Below this table, the 'Step' is set to 5, and the '% Min' is 1.e-10. An 'Optimize' button is visible at the bottom left of the main window.

The main window displays a table of optimization goals:

#	Element	Value	Operator	GoalType	Simulation/Polyline	A	B	C	Fmin, GHz	Fmax, GHz	We
1	S[1,3]	PhaseDelay	==	Simulation	Measured.diff.Simulation(1)	none	none	none	1.	20.	1.

An arrow points to the 'Optimize' button, which is labeled 'd) Click "Optimize" button'.

Optionally, check "Same Thread Simulation" in Solution -> Configuration -> Optimizer, to run all simulations during the optimization in one thread (each simulation will be parallelized if necessary)

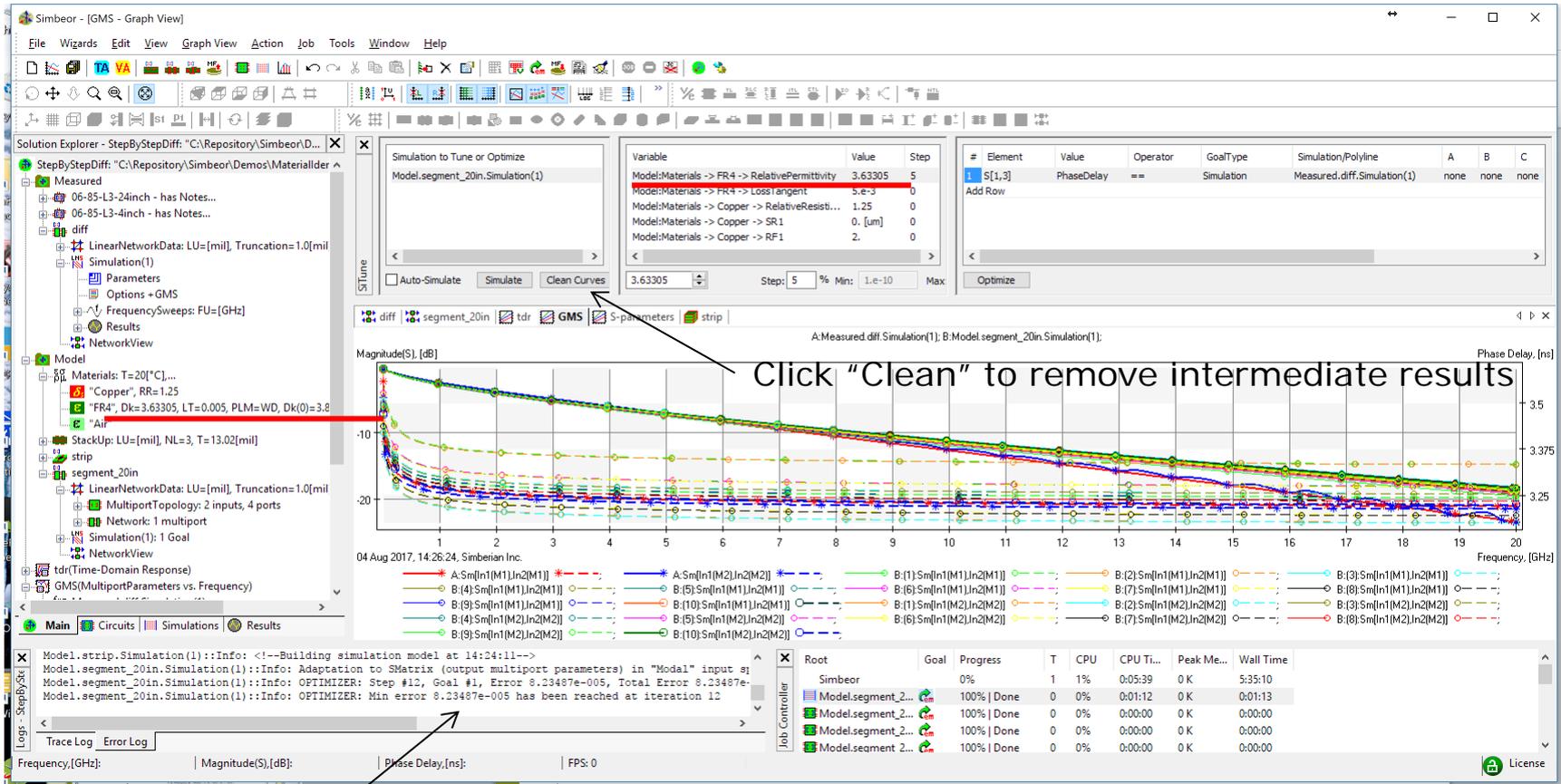
The screenshot shows the 'Solution Configuration' dialog box, specifically the 'Optimizer' tab. The following settings are visible:

- Step Change Limit: 1.002 [1., 1.5]
- Maximal Number of Steps: 5000 [1, 100000]
- Minimal Error: 0.0001 [0., 1000.]
- Cost Function: 1 [-4, 4]
- Step Change Algorithm: 2 [1, 2]
- Normalized Group Delay Scale: 10 [1., 10000000000.]
- Magnitude Scale: 10 [1., 100000000000.]
- Number of Curves To Keep: 20 [0, 1000]
- Auto Freeze Lattice Box Before Optimization
- Same Thread Simulations and Optimization (as before version 2017)

A red underline is drawn under the 'Same Thread Simulations and Optimization' checkbox. A tip at the bottom reads: 'Tip: Change configuration only if optimizer hangs or recommended by support.'

# Step 4c: Dk optimization result

## Dk value matching measured and simulated GMS Phase delay



# Step 4d: Set up goal for LT

a) For GMS odd mode transmission parameter

b) Match DBMagnitude to Measured GMS-par.

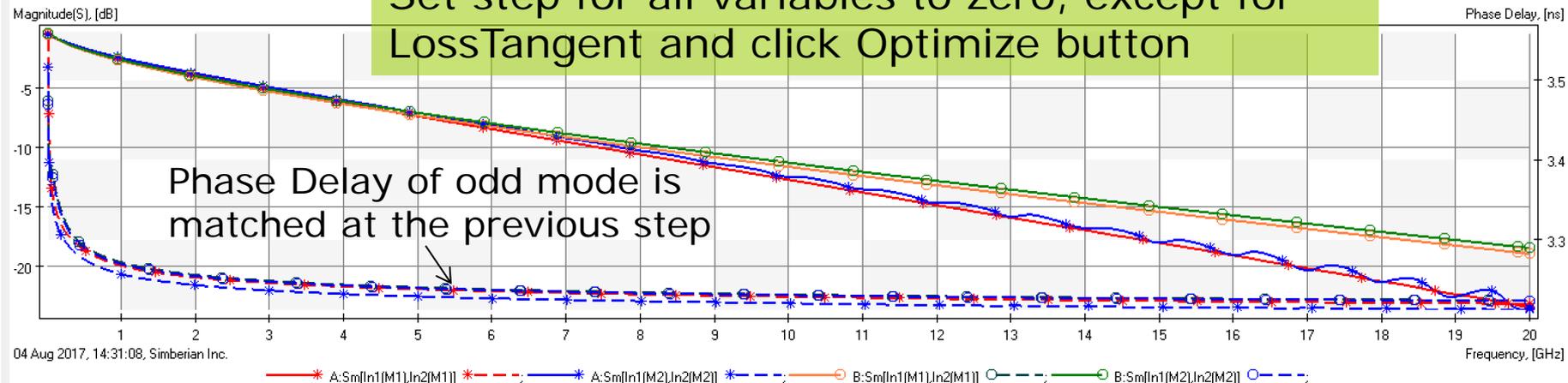
c) From 0.1 to 1-2 GHz

The screenshot shows the optimization software interface. On the left, a list of variables to be tuned is shown, including RelativePermittivity, LossTangent, and RelativeResistivity for FR4, and SR1 and RF1 for Copper. The 'Step' column indicates the optimization step for each variable. In the center, a table defines the optimization goal:

Element	Value	Operator	GoalType	Simulation/Polyline	A	B	C	Fmin, GHz	Fmax, GHz	Weight
1 S[1,3]	DBMagnitude	==	Simulation	Measured.diff.Simulation(1)	none	none	none	0.1	1.	1.

The 'Optimize' button is visible at the bottom of the goal configuration window.

Set step for all variables to zero, except for LossTangent and click Optimize button



d) Run Optimization, Clean Curves

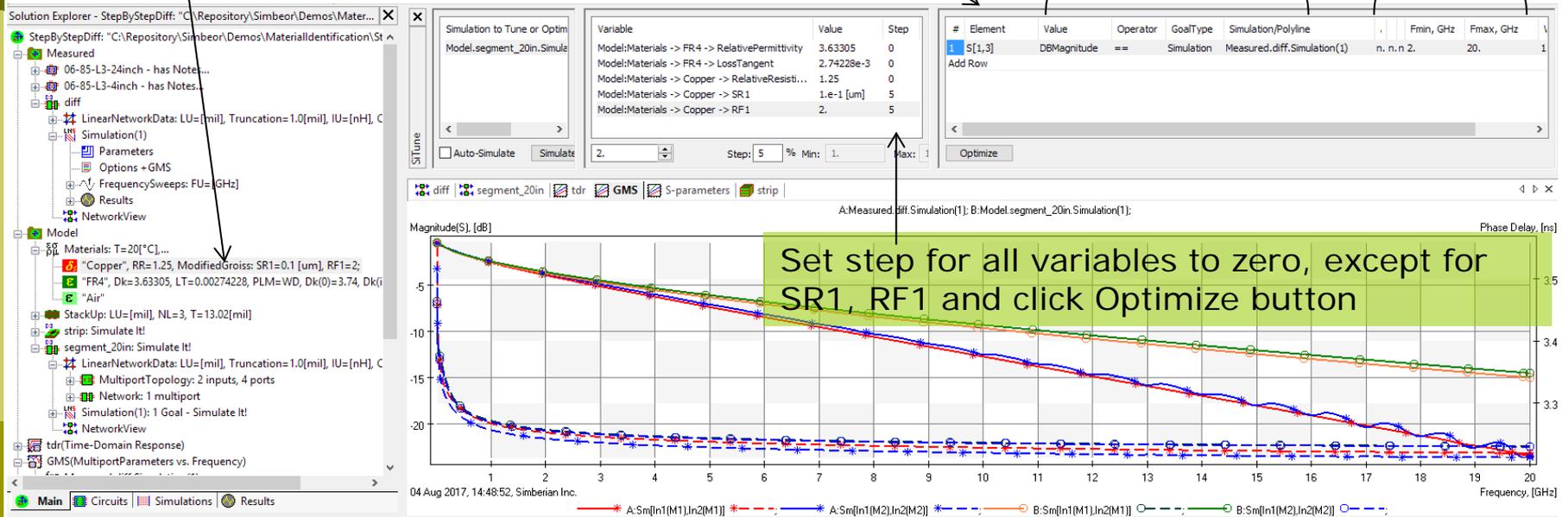
# Step 4e: Identify conductor roughness model

First set Copper Roughness model type (Groiss in this case) and non-zero initial value for SR1

b) Match DBMagnitude to Measured GMS-par.

a) For GMS odd mode transmission parameter

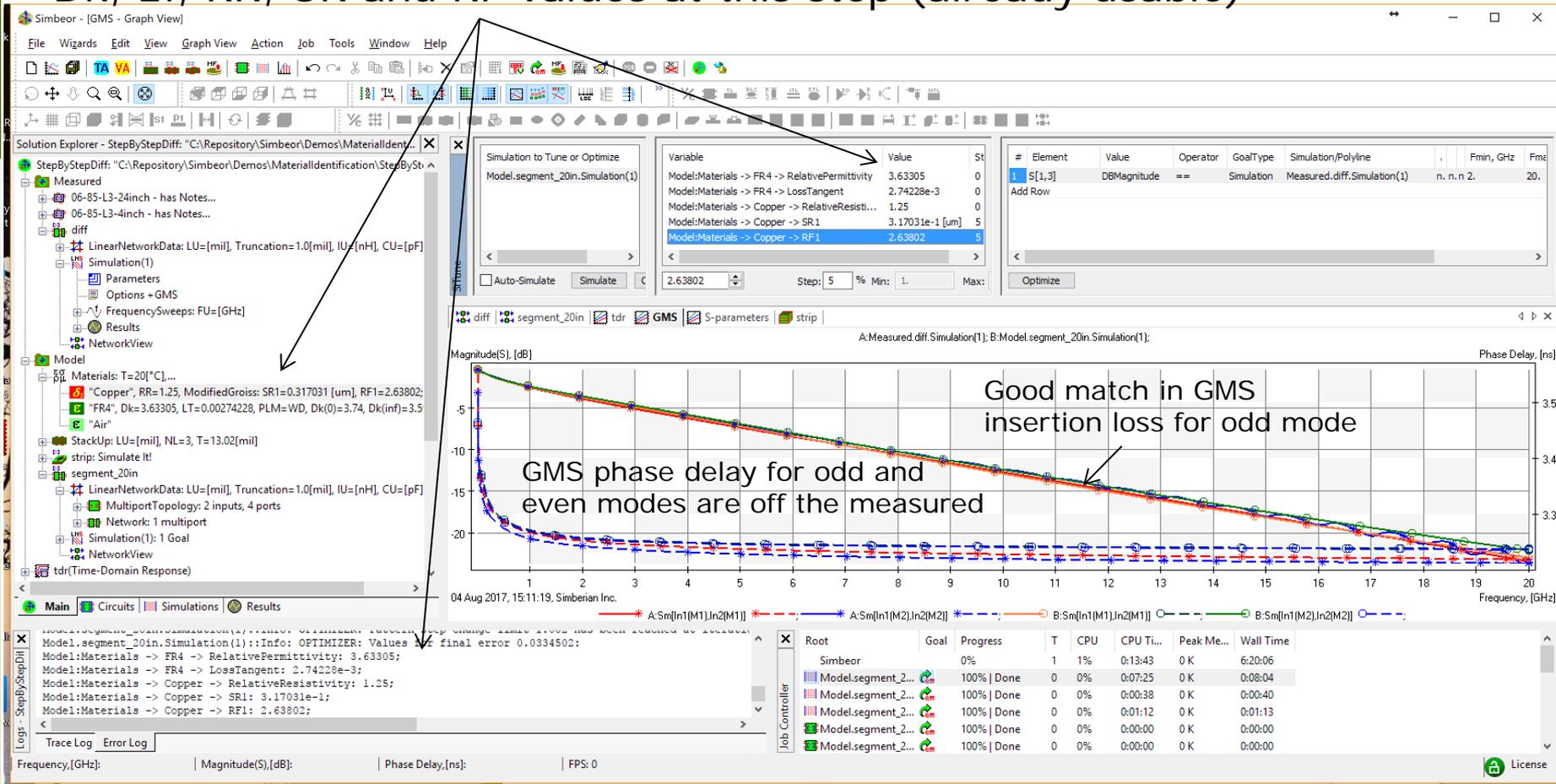
c) From 2 to max frq. (20 GHz here)



d) Run Optimization, Clean Curves

# Step 4e: Analysis of preliminary results

Dk, LT, RR, SR and RF values at this step (already usable)



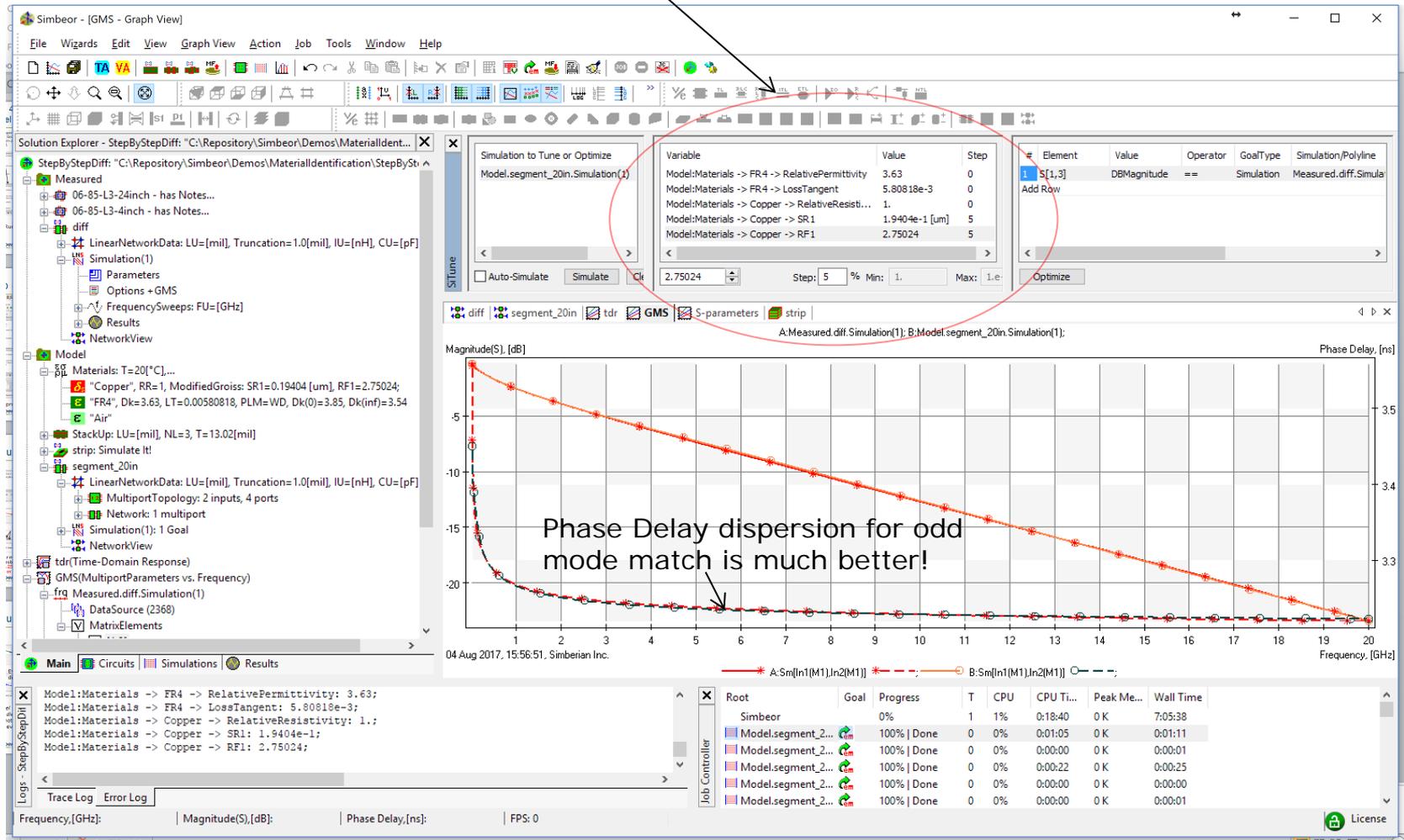
To improve accuracy, repeat step 4c

# Results are acceptable, but not perfect

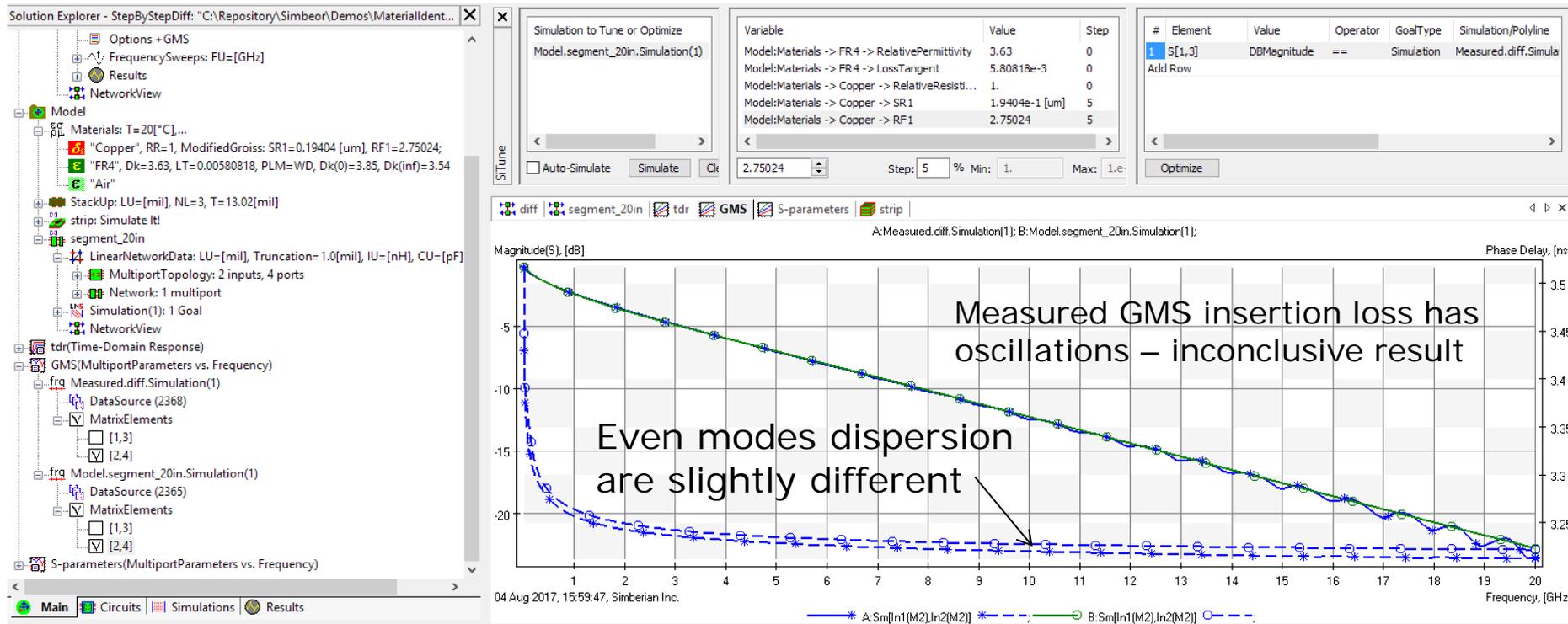


Higher measured dispersion in Phase Delay indicates that LT should be larger (dispersion)  
The problem is with the matching RR at DC that resulted in larger value of resistance  
RR=1.25 – this is questionable result (resistance 25% of annealed copper)!  
Solution – set RR back to 1 (annealed copper) and redo the matching...

# New results with RR=1

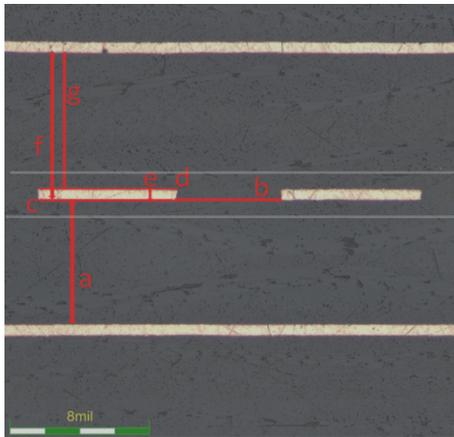


# What about the even mode?



*Problem: Model contains only one dielectric – cannot match simultaneously odd and even mode – though, it may be acceptable if FEXT is not large*  
**Solution: Create model with the additional layer of dielectric around the strips – see next slides...**

# Model with inhomogeneous dielectric



← Predominantly resin

	85-L3-4inch	85-L3-24inch
Parameter	Avg.	Avg.
a	5.66	5.67
b	7.41	7.35
c	6.51	6.58
d	6.67	6.74
e	0.65	0.65
f	5.80	5.82
g	5.15	5.16

Use parameters identified for homogeneous dielectric as the starting point for both models

→ resin + fiber

→ resin

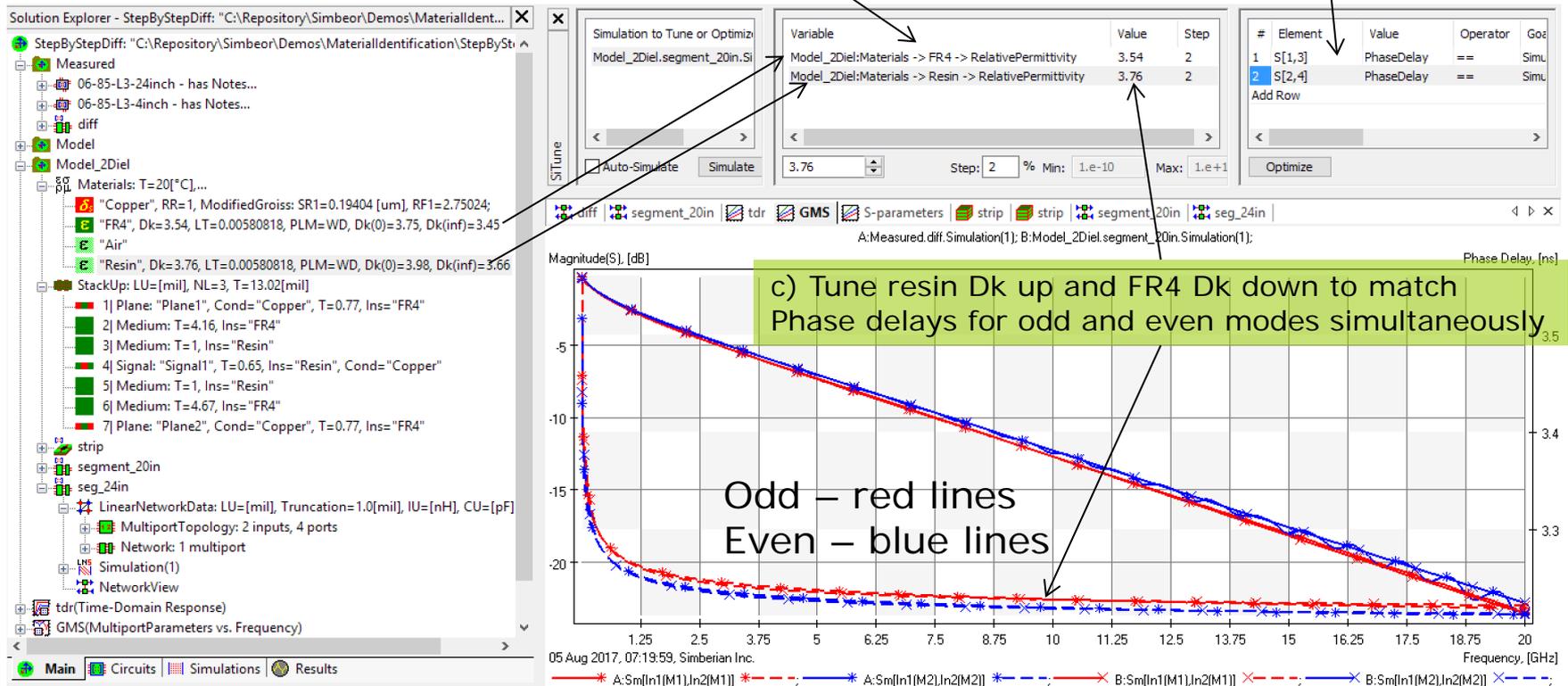
05 Aug 2017, 07:14:09, Simberian Inc. 3D View Mode (press <E> to Edit)

# Simultaneously match odd and even mode GMS-parameters

a) Use parameters identified for homogeneous dielectric as the starting point

b) Bring relative permittivities of the base material (FR4) and fill material (resin) to Variable pane to optimize or tune

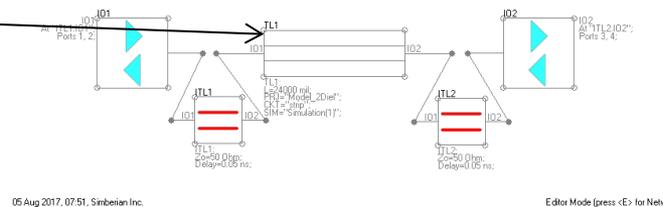
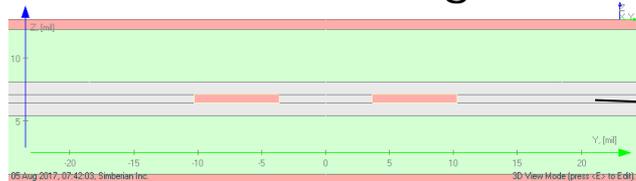
c) Alternatively set goals for Phase delays for 2 modes and optimize



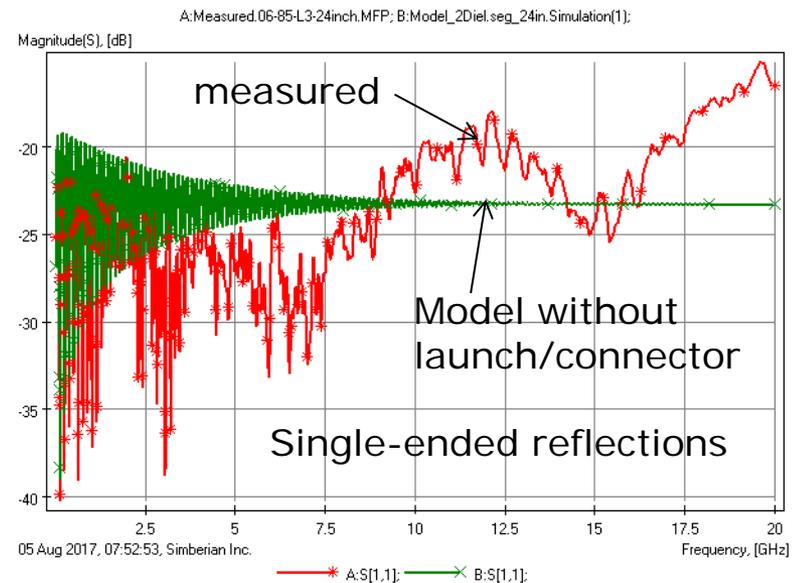
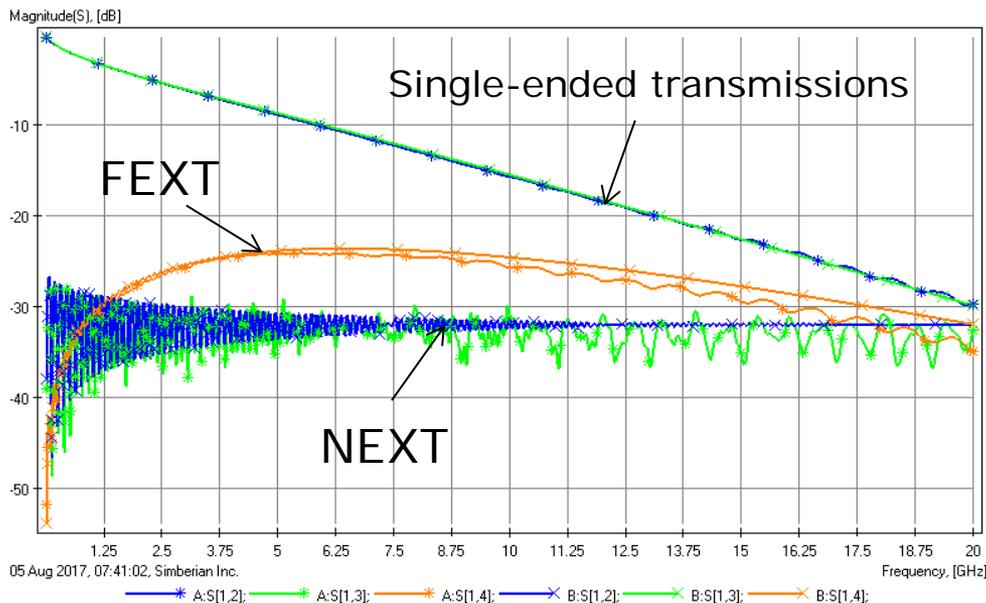
Final dielectric models: Wideband Debye FR4 Dk=3.54, LT=0.0058 @ 1 GHz; Resin Dk=3.76, LT=0.0058 @ 1 GHz; Copper roughness model: Groiss SR=0.19 um, RF=2.75

# Compare raw single-ended S-parameters for 24 inch segment

24-inch segment model with ideal 100 Ohm connector model

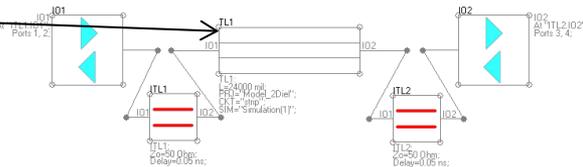
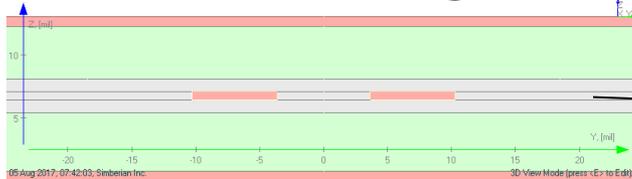


A: Measured.06-85-L3-24inch.MFP; B: Model\_2Diel\_seg\_24in.Simulation(1);



# Compare raw differential S-parameters for 24 inch segment

24-inch segment model with ideal 100 Ohm connector model

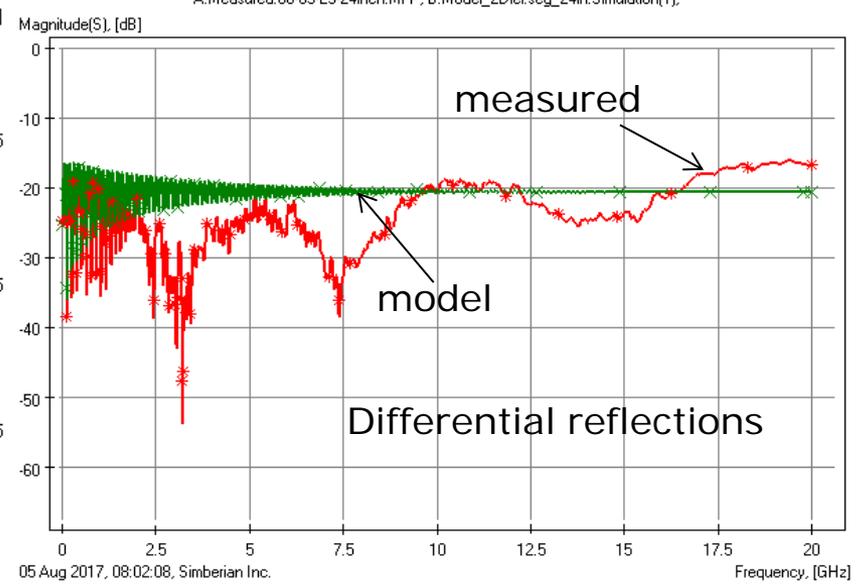
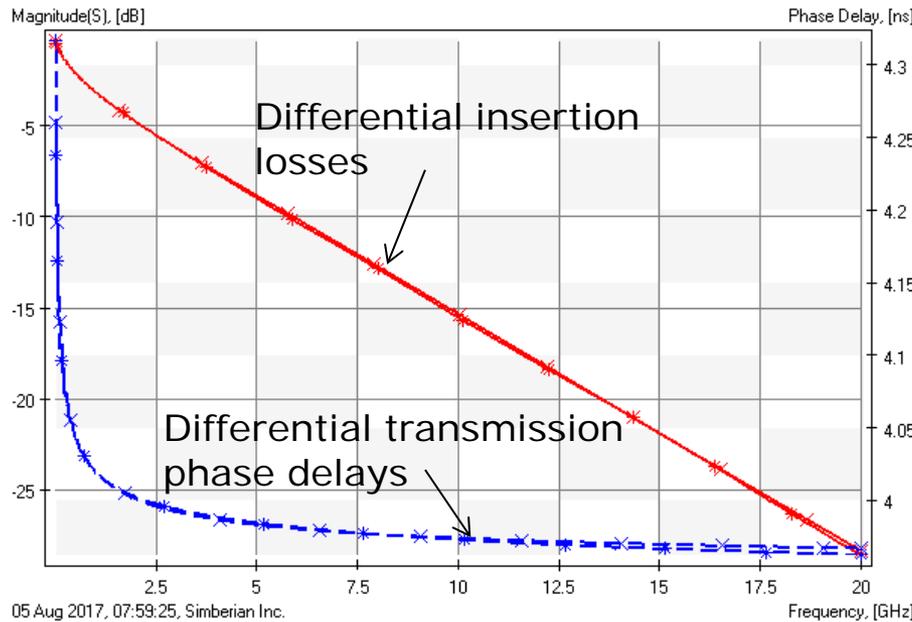


05 Aug 2017, 07:51, Simberian Inc.

Editor Mode (press <E> for Net)

A: Measured.06-85-L3-24inch.MFP; B: Model\_2Diel\_seg\_24in.Simulation(1);

A: Measured.06-85-L3-24inch.MFP; B: Model\_2Diel\_seg\_24in.Simulation(1);

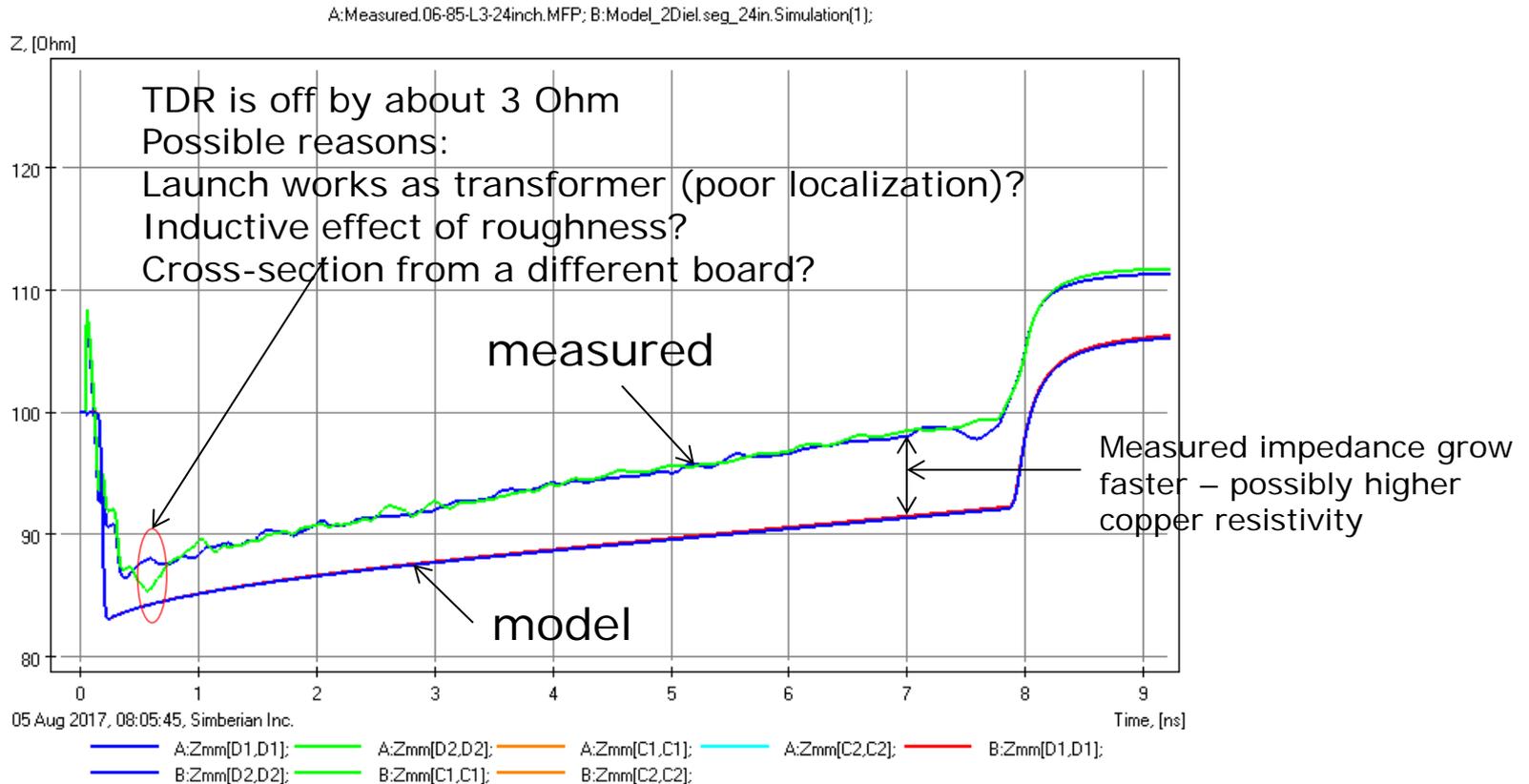


05 Aug 2017, 08:02:08, Simberian Inc.

—\* A:Smm[D1,D1]; —\* B:Smm[D1,D1];

—\* A:Smm[D1,D2] \* - - - ; —\* B:Smm[D1,D2] \* - - - ;

# Compare TDR for 24 inch segment



Requires further investigation – see appendix...

# Conclusion

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- ❑ Always identify or validate dielectric, conductor and conductor roughness models
- ❑ Use of GMS-parameters is simplest and most accurate technique for the material model identification
- ❑ Differential strip is useful to identify dielectric inhomogeneity and fit 2 dielectric models simultaneously
- ❑ Use homogeneous dielectric if no FEXT observed or FEXT is not a part of design
- ❑ Use two dielectric models to match phase delay of two modes – it leads to match in the FEXT

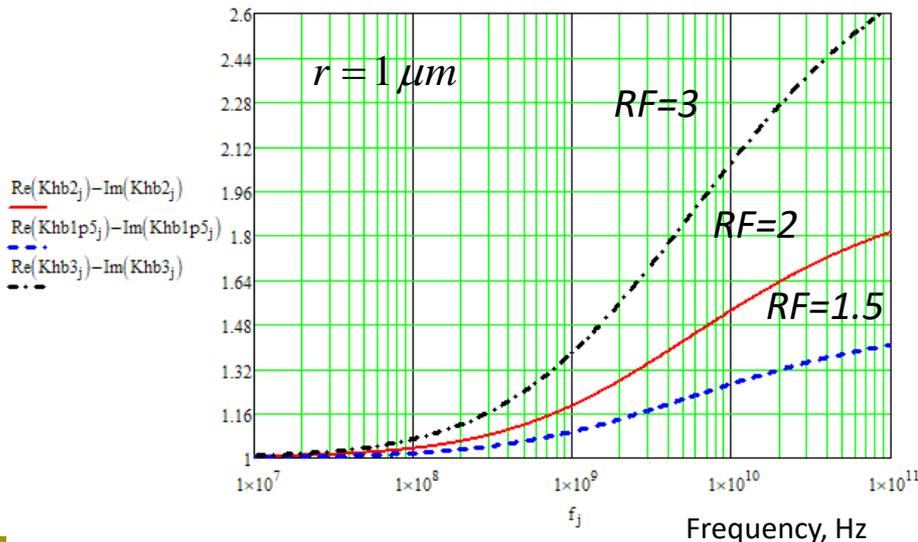
# Appendix: Causal Huray-Bracken roughness model

$$K_{sr} = 1 + \sum_k \left( (RF_k - 1) \cdot \left( 1 + (1-i) \frac{\delta_s}{2r_i} \right)^{-1} \right) \quad \delta_s = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}} \quad Z_{rough} = K_{sr} \cdot (1+i) \cdot \delta_s$$

$RF_i$  - roughness factor, defines maximal growth of losses due to all balls with radius  $r_i$ ;  
 $r_i$  - ball radius (SRI parameter in Simbeor);

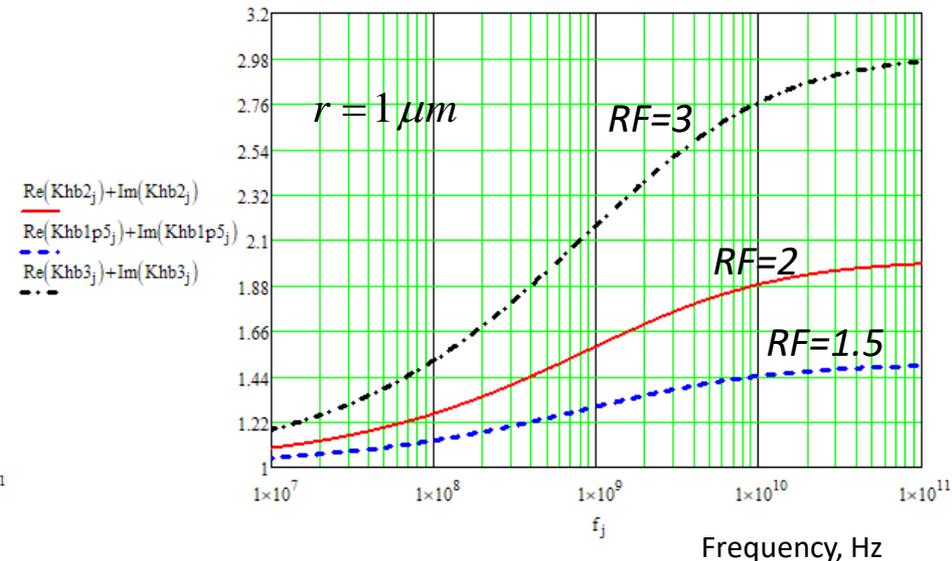
Conductor losses (same as in Huray model)

$$\text{Re}(Z_{rough}) = [\text{Re}(H_{sr}) - \text{Im}(H_{sr})] \cdot \delta_s$$



Additional conductor inductance

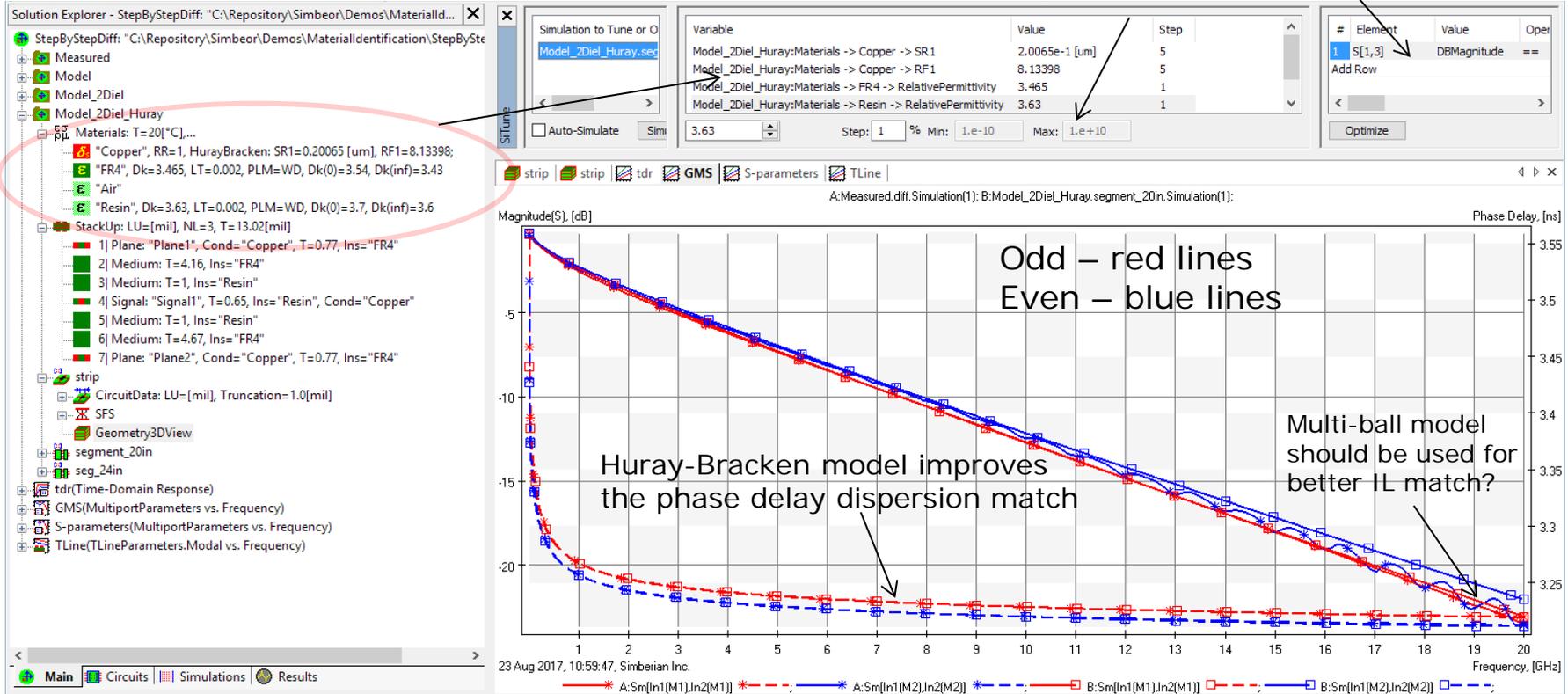
$$\text{Im}(Z_{rough}) = [\text{Re}(H_{sr}) + \text{Im}(H_{sr})] \cdot \delta_s$$



J. E. Bracken, A Causal Huray Model for Surface Roughness, DesignCon 2012

# Appendix: Results with causal Huray-Bracken model

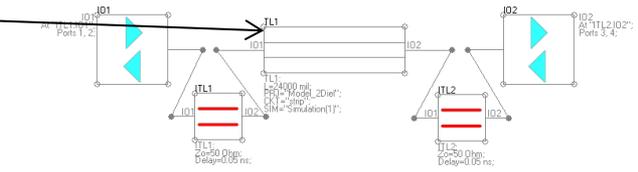
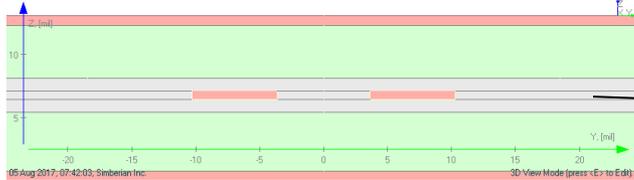
- Use parameters identified for inhomogeneous dielectric as the starting point, set LT to 0.002 (specs);
- Optimize roughness model parameters (SR1, RF1), to match GMS IL from 2 to 20 GHz
- Adjust Dk of FR4 and Resin, to match the even and odd mode Phase Delay



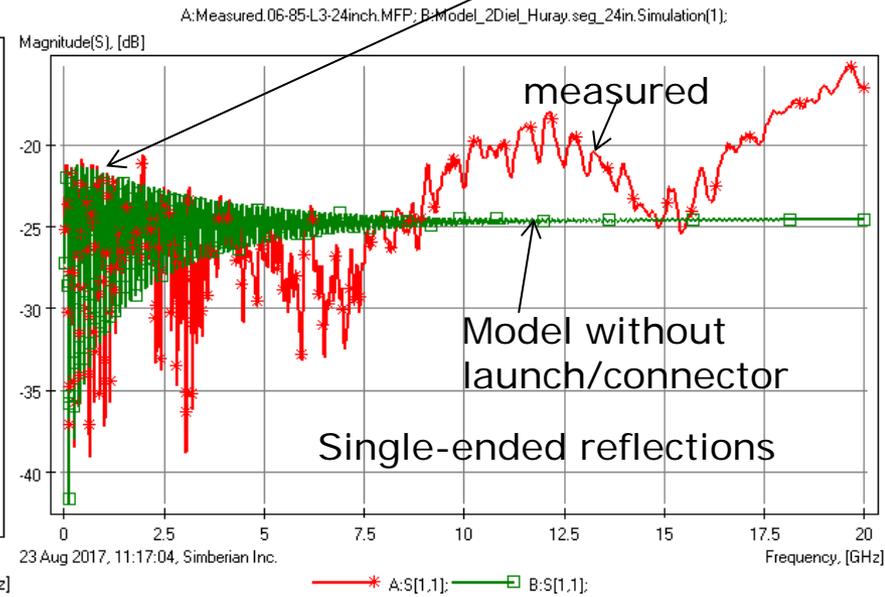
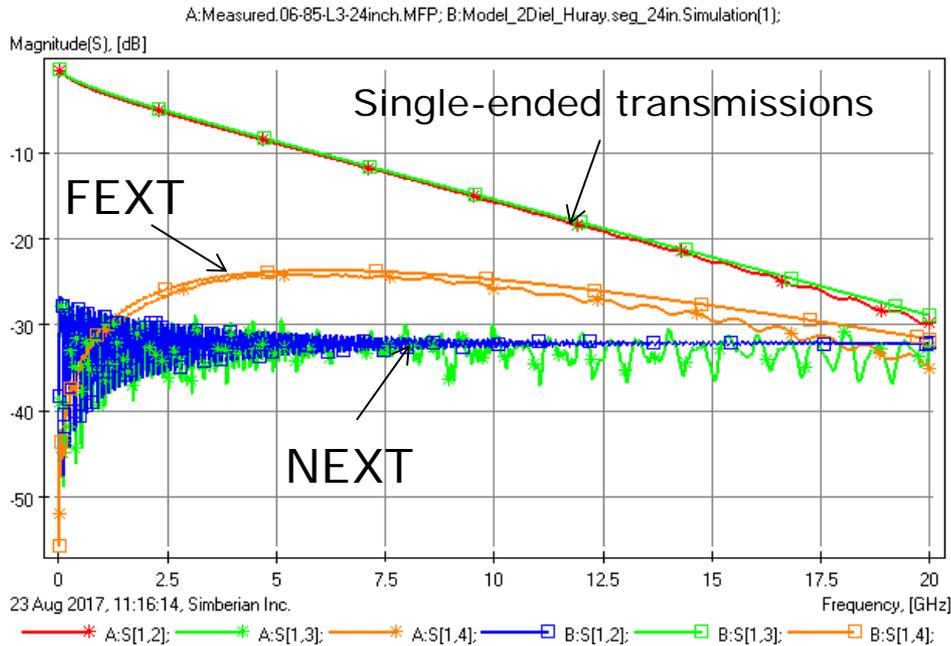
Final dielectric models: Wideband Debye FR4 Dk=3.465, LT=0.002 @ 1 GHz; Resin Dk=3.63, LT=0.002 @ 1 GHz; Copper roughness model (RR=1): Huray-Bracken SR=0.2 um, RF=8.134  
 If copper relative resistance is adjusted to RR=1.2, Huray-Bracken model is SR=0.2, RF=7.75

# Appendix: Validation with causal Huray-Bracken model

24-inch segment model with ideal 100 Ohm connector model

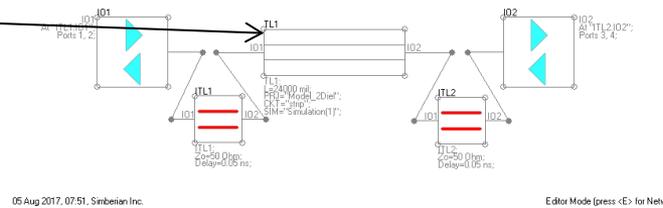
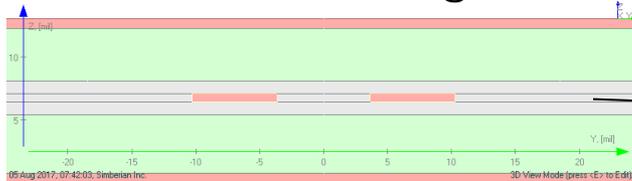


Much better correlation at lower frequencies

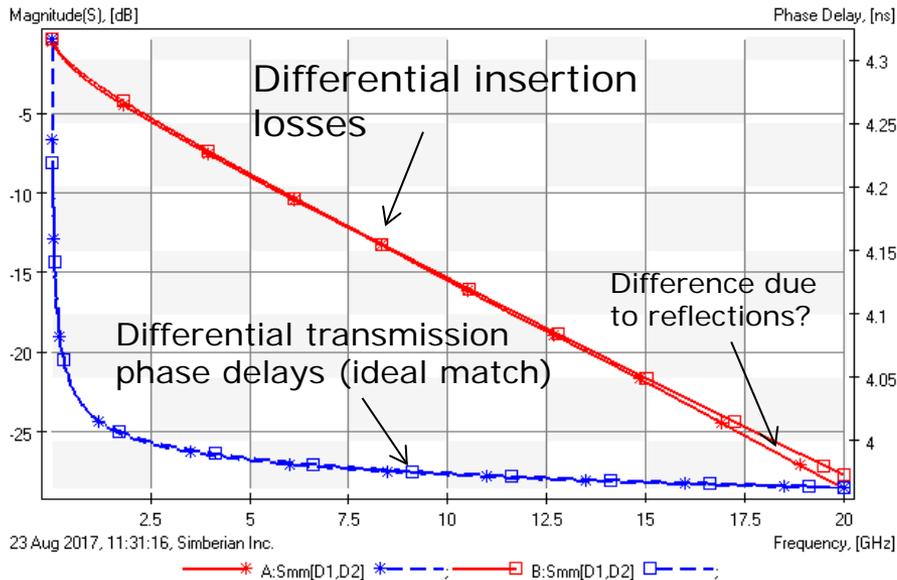


# Appendix: Validation with causal Huray-Bracken model

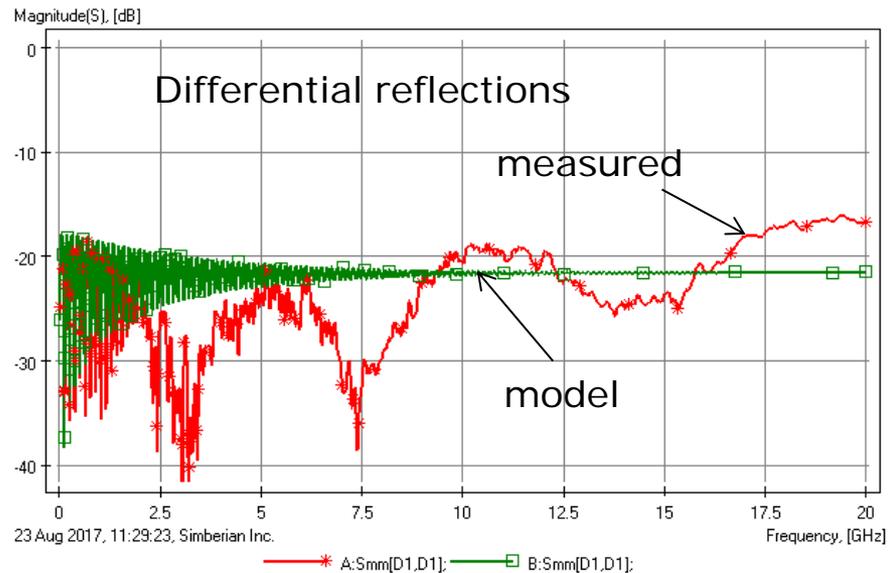
## 24-inch segment model with ideal 100 Ohm connector model



A: Measured\_06-85-L3-24inch.MFP; B: Model\_2DieI\_Huray\_seg\_24in.Simulation(1);

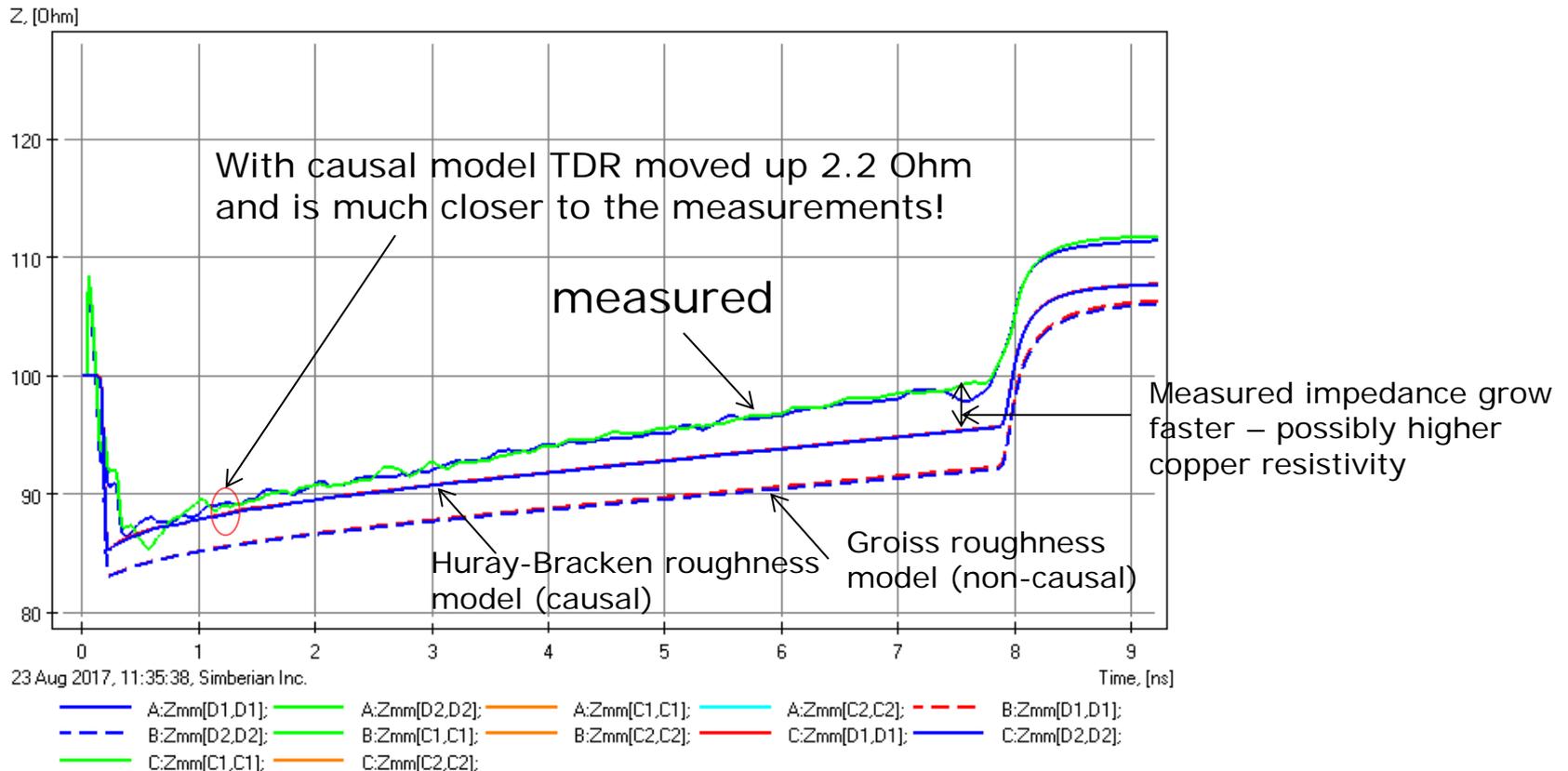


A: Measured\_06-85-L3-24inch.MFP; B: Model\_2DieI\_Huray\_seg\_24in.Simulation(1);



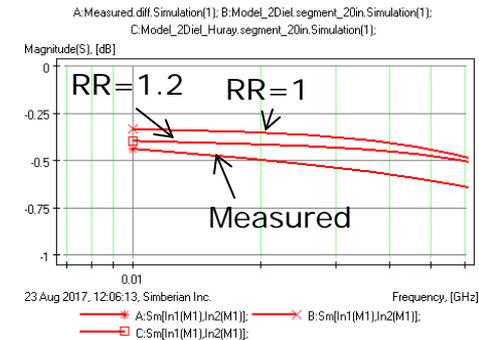
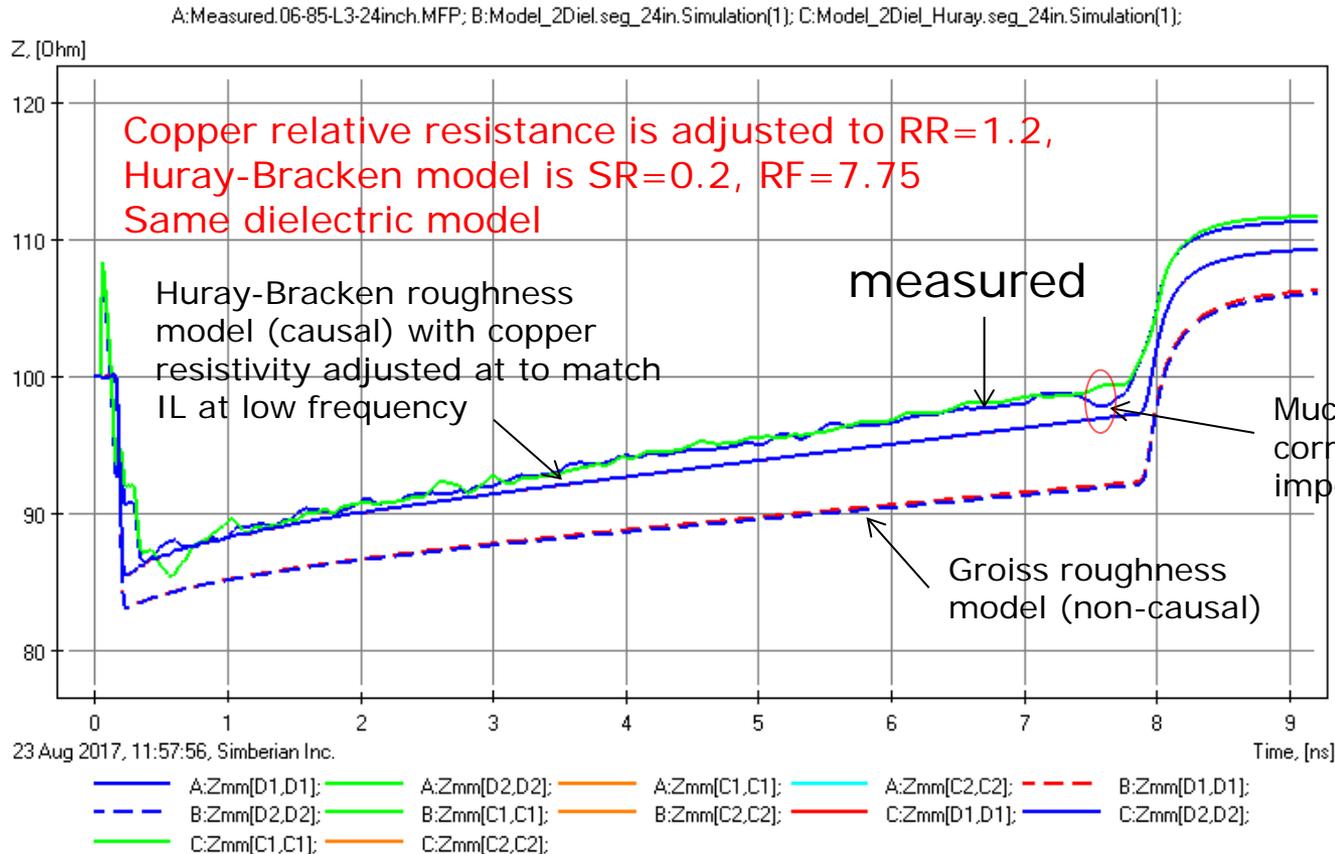
# Appendix: TDR for 24 inch segment with Huray-Bracken roughness model

A: Measured.06-85-L3-24inch.MFP; B: Model\_2Diel\_seg\_24in.Simulation(1); C: Model\_2Diel\_Huray\_seg\_24in.Simulation(1);



...the impedance mystery solved!

# Appendix: TDR for 24 inch segment with Huray-Bracken roughness model



*TDR can be used to validate the relative resistivity in addition to matching GMS IL at the lowest frequency...*

# Simberian Inc.

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## □ Mission

- Build accurate, easy-to-use, and cost-effective electromagnetic software for high-speed electronic design automation

## □ Incorporated in USA on February 28, 2006

- Founder and President Yuriy Shlepnev
  - PhD in computational electromagnetics
  - 25-years experience in building electromagnetic software

## □ Development in Westlake Village, USA, St. Petersburg and Voronezh Russia

## □ Location and contacts

- Corporate office: 2629 Townsgate Rd. Suite #235, Westlake Village, CA 91361 USA  
Tel/Fax +1-702-876-2882, skype *simberian*
- Web: [www.simberian.com](http://www.simberian.com)
- Support knowledge base [www.kb.simberian.com](http://www.kb.simberian.com)