DesignCon 2019
WHERE THE CHIP MEETS THE BOARD

Effect of PCB fabrication variations on interconnect loss, delay, impedance and identified material models for 56 Gbps interconnect designs

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Outline

- Introduction
- Material models and model identification
- Test coupon design and measurements
- Cross-sectioning and geometry variations
- Attempt of dielectric and conductor loss separation
- Material model identification results
- Conclusion

Introduction

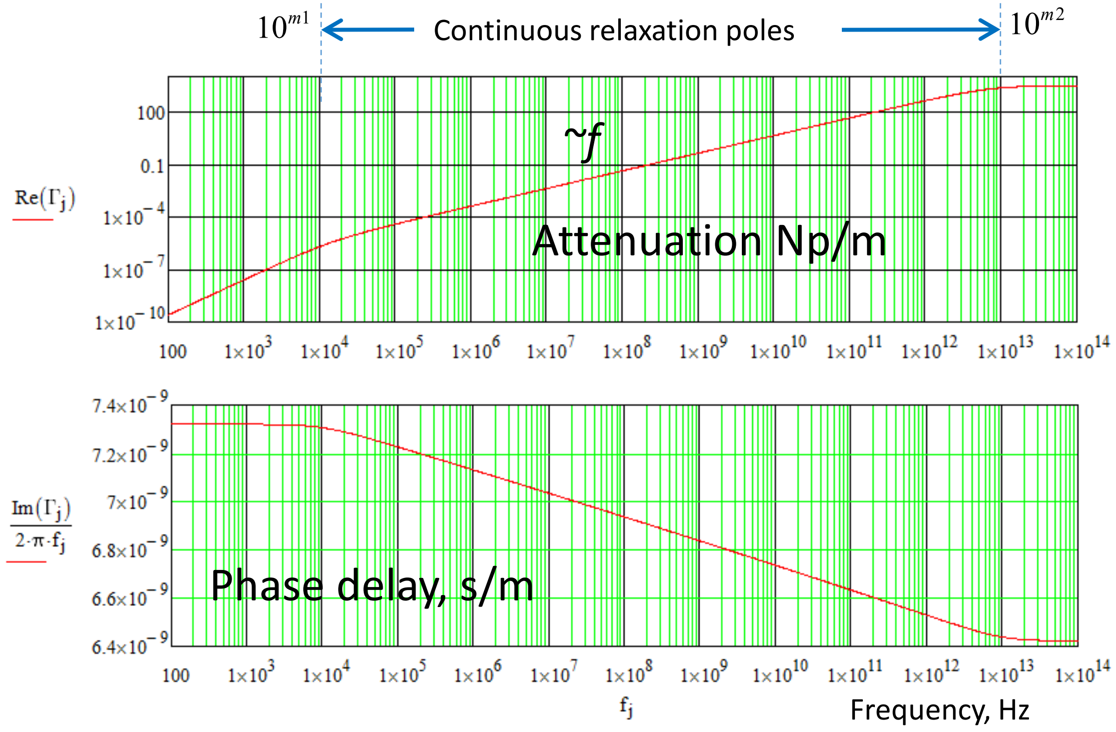
- Design of predictable PCB interconnects for 56 Gbps PAM-4 data links requires dielectric and conductor roughness models with bandwidth up to 50 GHz
- Such material models (especially for roughness) are not readily available
- Material models can be identified with either GMS-parameters or SPP method
- How PCB manufacturing variations affect the identified material models?
- This is the subject of this investigation
- We will try to separate the geometry and material parameters variations with the goal to build statistical models, to predict interconnect behavior for 56 Gbps links

Material models and model identification

Dielectric model to identify – Wideband Debye

Aka Djordjevic-Sarkar or Swensson-Dermer

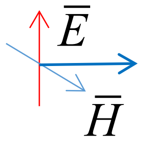
$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k}{1 + i\,f/f_{rk}} \;\Rightarrow\; \varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$



Example:

Plane wave propagation constant

$$\Gamma(f) = i2\pi f\sqrt{\varepsilon_r(f)\cdot\varepsilon_0\cdot\mu_0}$$

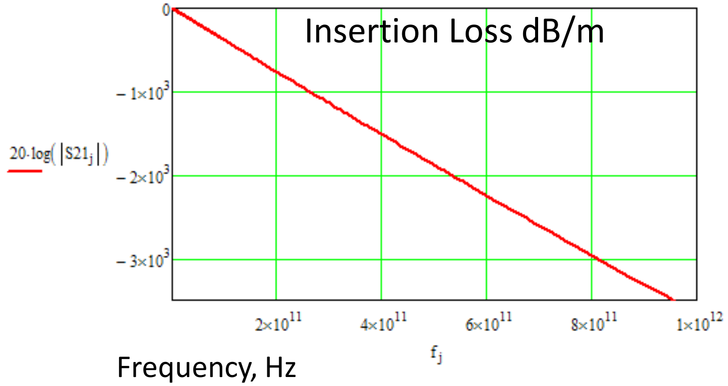


$\varepsilon_\infty = 3.707;\ \Delta\varepsilon = 1.108;\ m1 = 4;\ m2 = 13;$

$\mathrm{Re}\left(\varepsilon(10^9)\right) = 4.2;\ \tan\delta\left(10^9\right) = 0.02$

Generalized transmission parameter for distance *l*:

$$S21(\omega) = e^{-\Gamma\cdot l}$$



This model can be defined with Dk and LT measured at 1 frequency point!

Other wideband model options: Havriliak-Negami

Conductor roughness model to identify – Huray Braken

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

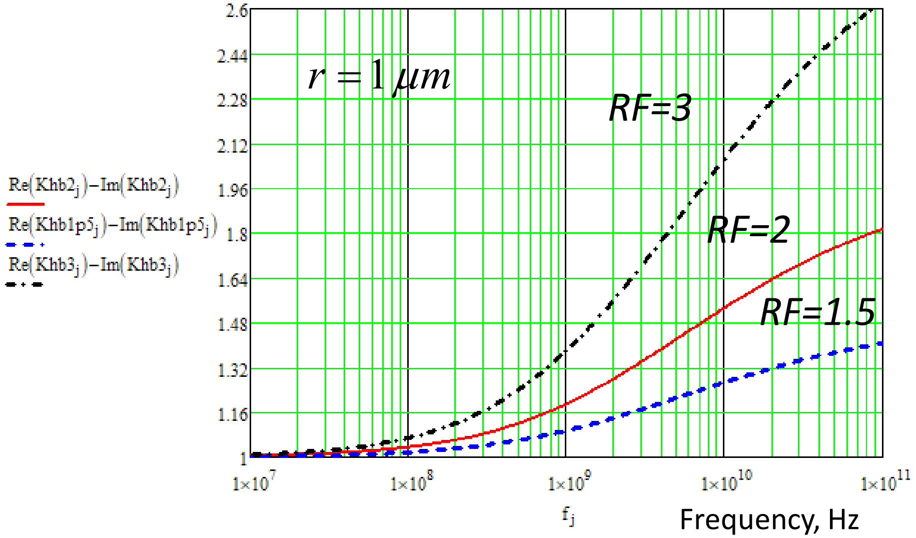
$$K_{sr} = 1 + \sum_k \left((RF_k - 1) \cdot \left(1 + (1-i)\frac{\delta_s}{2r_i} \right)^{-1} \right) \qquad \delta_s = (\pi \cdot f \cdot \mu \cdot \sigma)^{-1/2}$$

Makes SIBC causal! $$Z_{rough} = \frac{K_{sr}}{\sigma \cdot \delta_s} \cdot (1+i)$$

RFi - roughness factor, defines maximal growth of losses due to all balls with radius ri;
ri – ball radius (SRi parameter in Simbeor);

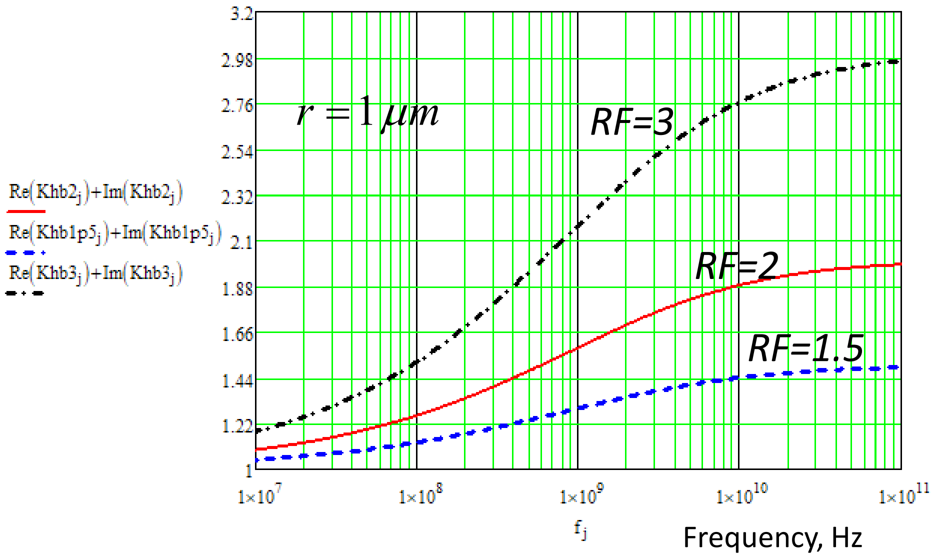
Conductor losses (same as in Huray model)

$$\mathrm{Re}(Z_{rough}) = \underbrace{\left[\mathrm{Re}(K_{sr}) - \mathrm{Im}(K_{sr}) \right]}\cdot \frac{1}{\sigma \cdot \delta_s}$$



Additional conductor inductance

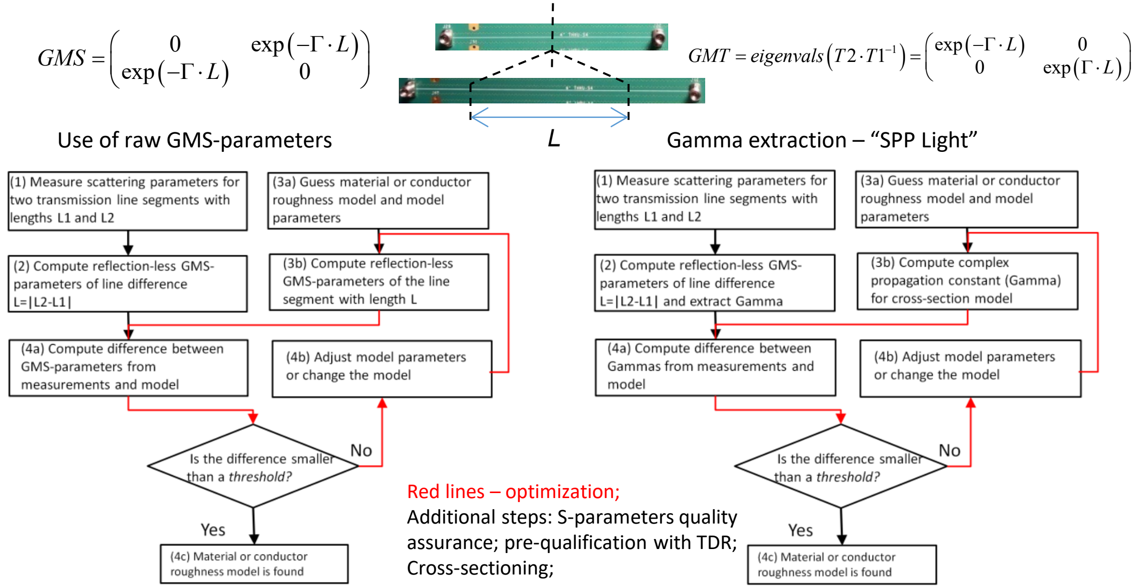
$$\mathrm{Im}(Z_{rough}) = \underbrace{\left[\mathrm{Re}(K_{sr}) + \mathrm{Im}(K_{sr}) \right]}\cdot \frac{1}{\sigma \cdot \delta_s}$$



One-level model with just 2 parameters (SR and RF) is used

Material model identification

1. Create strip line segment model with dimensions from cross-sections (or mean values) with dielectric and conductor roughness models with preliminary parameters;
2. Identify copper resistivity (RR) by matching measured and computed GMS insertion loss at the lowest frequency (from 10 to 20 MHz);
3. Identify dielectric constant (Dk @ 1 GHz) by matching measured and computed GMS phase delay (from 1 to 40 GHz);
4. Identify loss tangent (LT @ 1 GHz) by matching measured and computed GMS insertion loss at lower frequencies (from 0.05 to 1-2 GHz);
5. Identify conductor roughness model parameters (SR and RF in (2.2)-(2.3)) by matching GMS insertion loss at higher frequencies (from 2 to 25-35 GHz);
6. Adjust dielectric constant (Dk @ 1 GHz) by matching measured and computed GMS phase delay (from 1 to 40 GHz);



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.

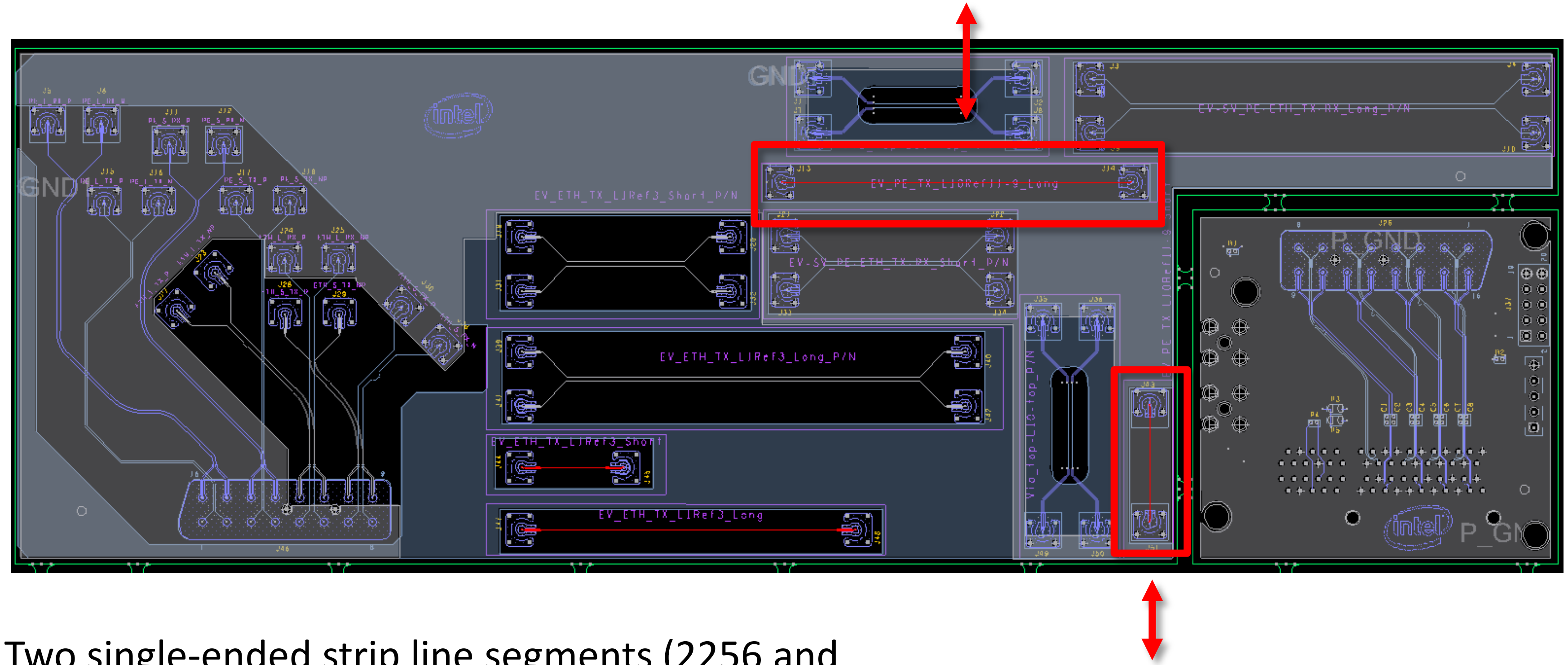
Implemented in Simbeor SDK (with API for scripting C/C++ or matlab)

Spoiler: did not work so well due to the extremely low losses in dielectric…

Test coupons design and measurements

Coupons design

L10_Long
EV_PE_TX_L10Ref11-9_Long_J13_J14

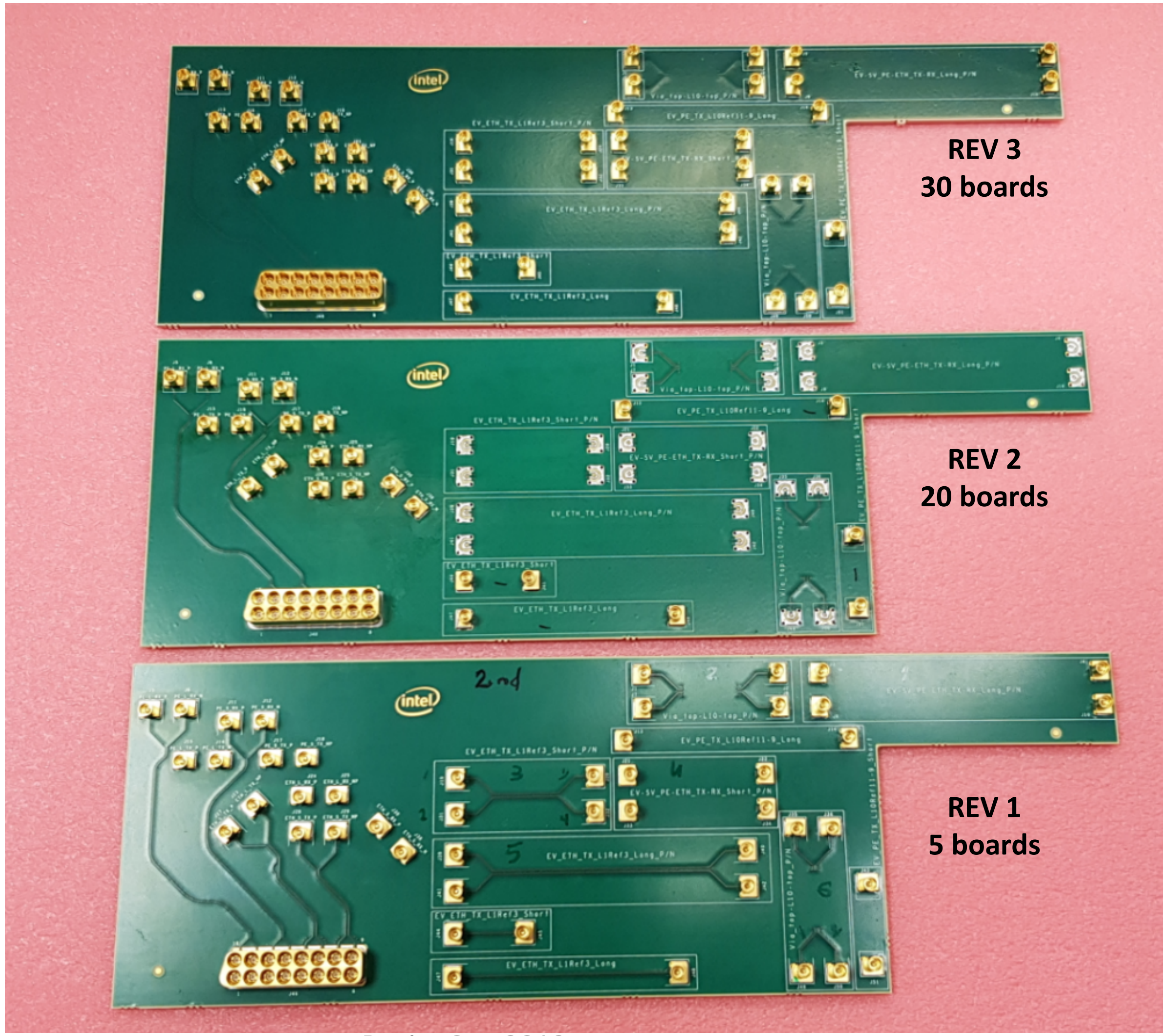


Two single-ended strip line segments (2256 and 756 mil, 1500 mil difference) with 1.85 mm coaxial connectors

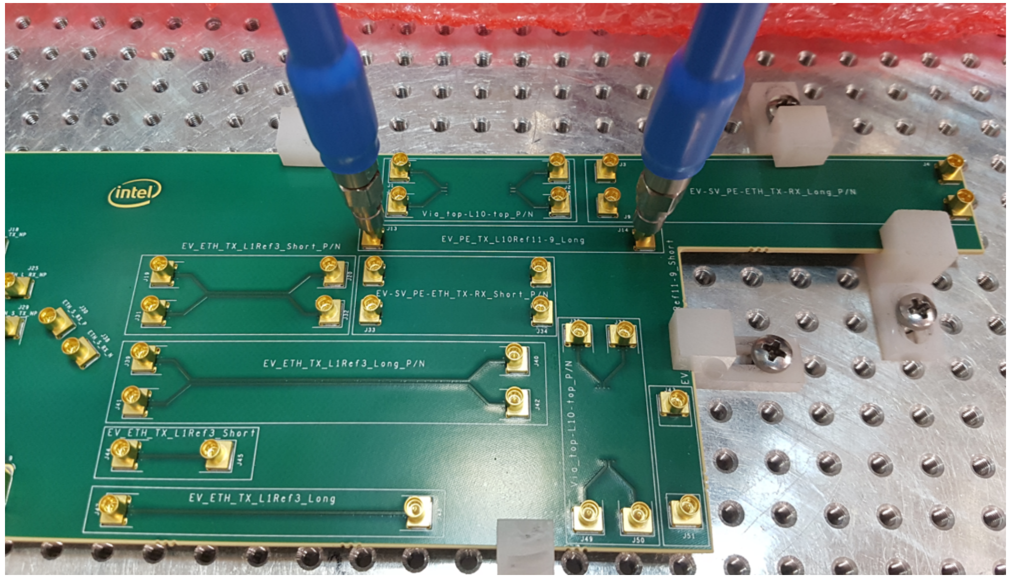
EV_PE_TX_L10Ref11-9_Short_J51_J43
L10_Short

Three revisions are fabricated in different batches

Same manufacturer – different design of the coupons
Rev1 has different types of launches
Rev2 has via stubs
Rev3 has stubs back-drilled



Measurement equipment and setup



Keysight PNA Network Analyzer model: N5227A 10MHz-67GHz
SN: US51270505
Calibration: 85058B – 1.85 mm
Setup: MMPX adaptors X2 and 1.85f to 2.92m adaptors X2
Verification: Keysight 1.85mm 85058B Standard Calibration Kit

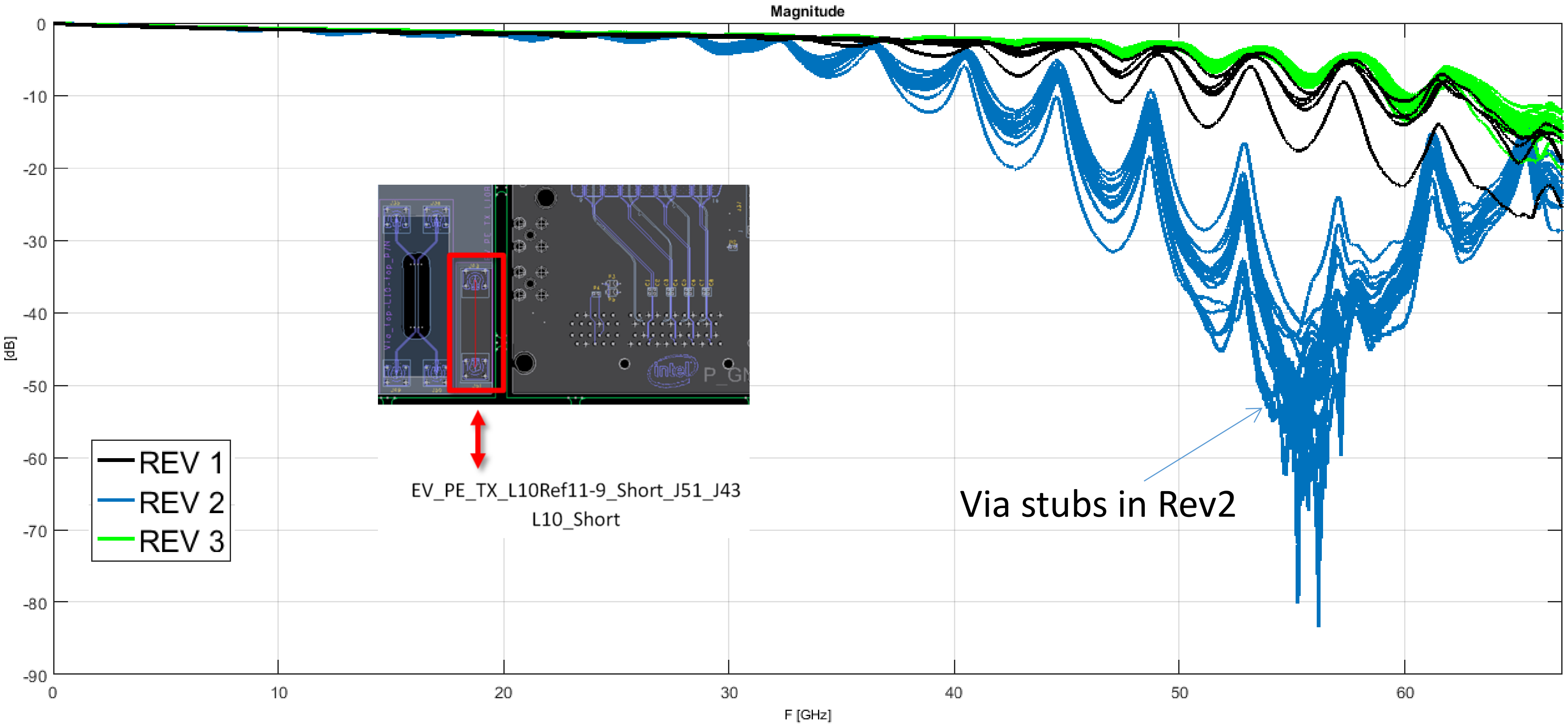
Setup:
Number of points: 6700
IF BW: 1k
Start frequency: 10MHz
Stop frequency: 67 GHz
Power: -2dbm
Averaging: 0

Short line insertion loss

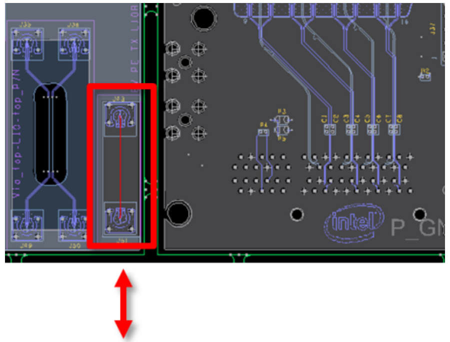
Rev3 looks like the best for the identification

Excellent quality metrics

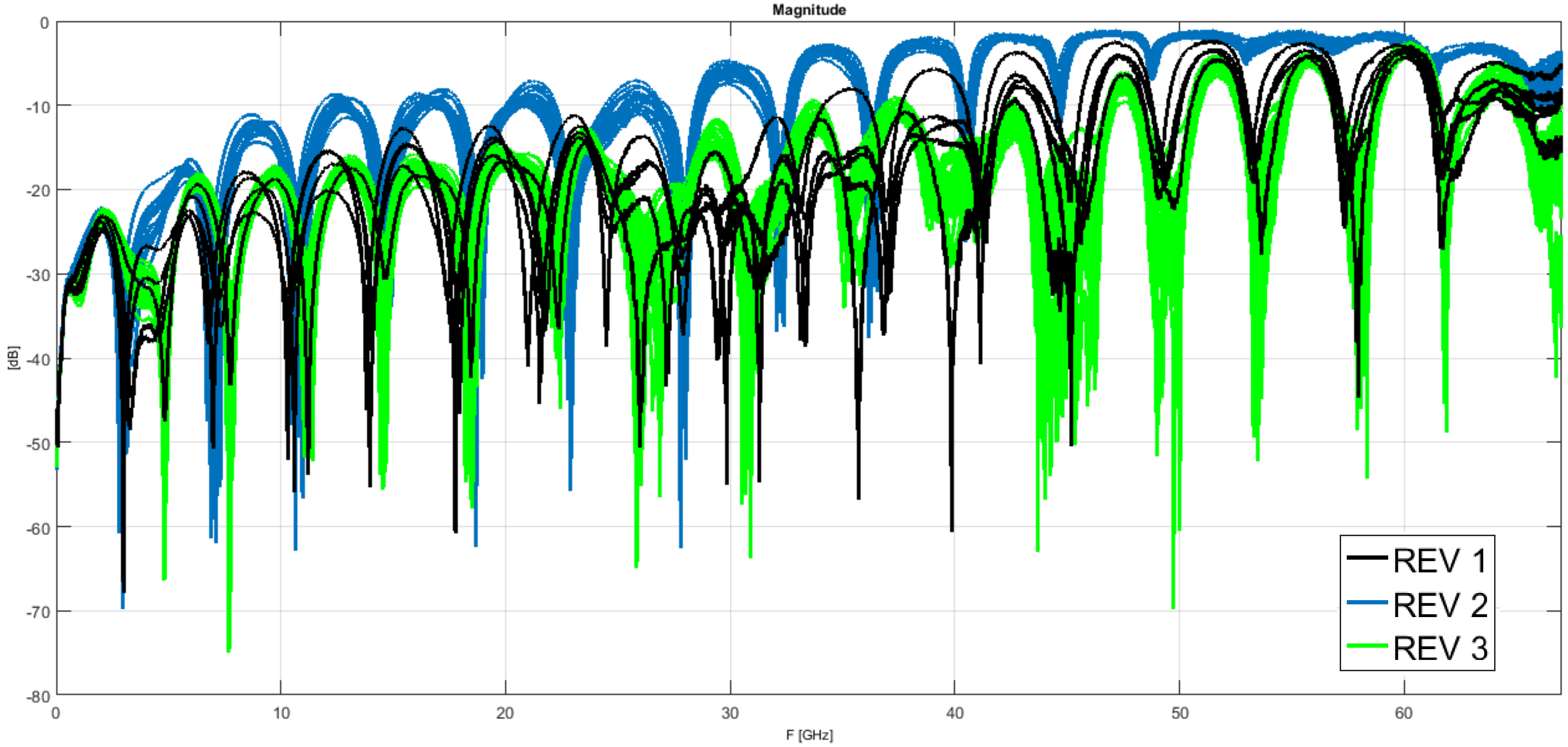
File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\Support\Intel\Oct2_2018_DesignCon2019\Measure...				
BC001_L10_Short_Rev2.s2p	99	99.9	99.6	-
BC002_L10_Short_Rev2.s2p	98.9	99.9	99.6	-
BC003_L10_Short_Rev2.s2p	94	99.9	99.5	-
BC004_L10_Short_Rev2.s2p	98.9	99.9	99.6	-
BC005_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC006_L10_Short_Rev2.s2p	98.8	99.9	99.5	-
BC007_L10_Short_Rev2.s2p	98.4	99.9	99.5	-
BC008_L10_Short_Rev2.s2p	99	99.9	99.6	-
BC009_L10_Short_Rev2.s2p	98.5	99.9	99.6	-
BC010_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC011_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC012_L10_Short_Rev2.s2p	99.1	99.9	99.6	-
BC013_L10_Short_Rev2.s2p	98.7	99.9	99.5	-
BC014_L10_Short_Rev2.s2p	98.6	99.9	99.5	-
BC015_L10_Short_Rev2.s2p	98.3	99.9	98.6	-
BC016_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC017_L10_Short_Rev2.s2p	99	99.9	99.5	-
BC018_L10_Short_Rev2.s2p	99.1	99.9	99.4	-
BC019_L10_Short_Rev2.s2p	99	99.9	99.4	-
BC020_L10_Short_Rev2.s2p	98.6	99.9	99.3	-
BC021_L10_Short_Rev3.s2p	99.1	99.9	98.6	-
BC022_L10_Short_Rev3.s2p	99.1	99.9	99.2	-
BC023_L10_Short_Rev3.s2p	99.2	99.9	99	-
BC024_L10_Short_Rev3.s2p	99	99.9	98.9	-
BC025_L10_Short_Rev3.s2p	98.9	99.9	99.1	-
BC026_L10_Short_Rev3.s2p	98.9	99.9	98.9	-



Short segment return loss



EV_PE_TX_L10Ref11-9_Short_J51_J43
L10_Short

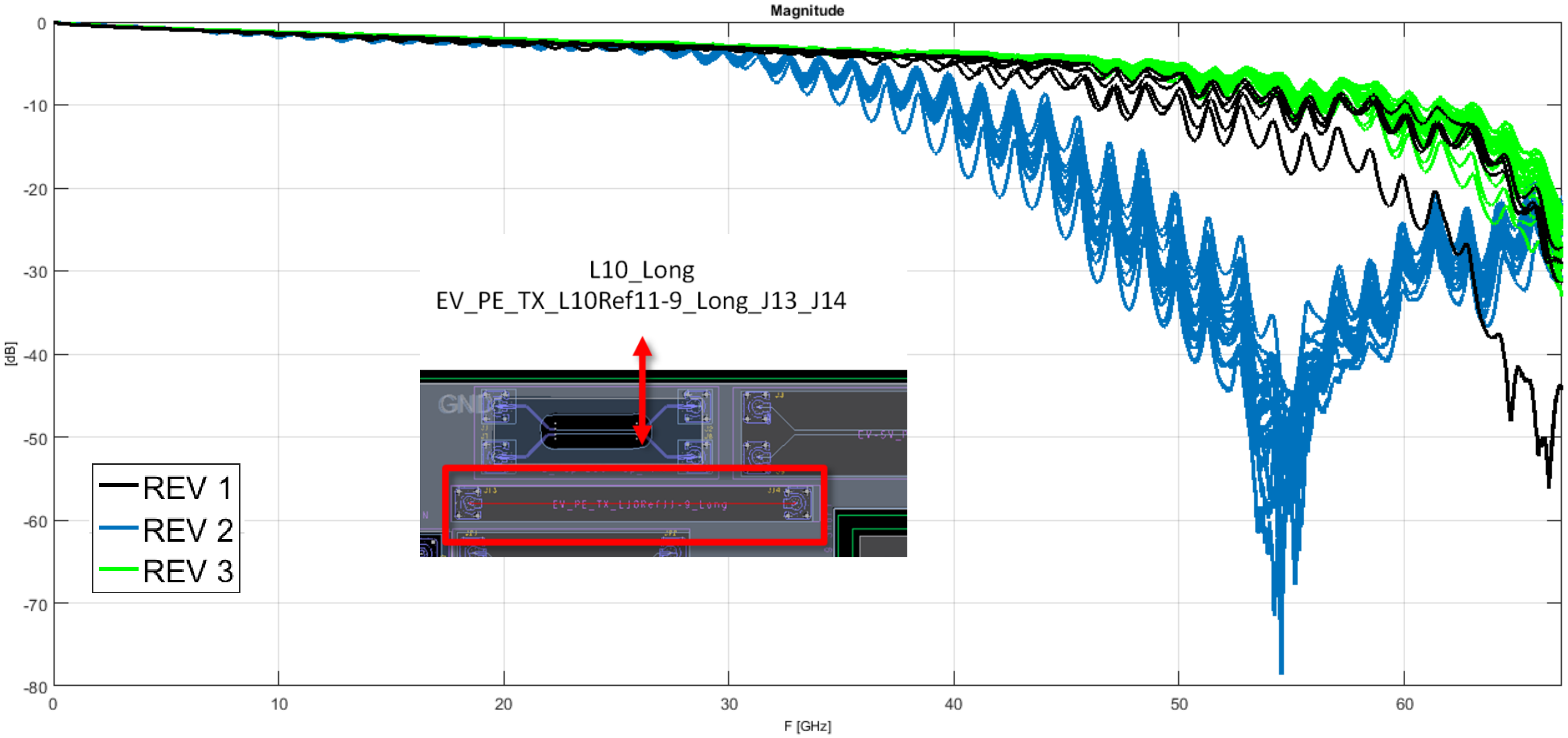


Long segment insertion loss

Excellent quality metrics

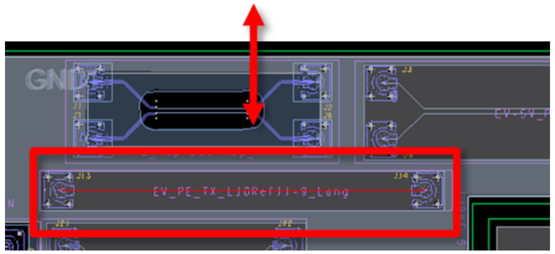
File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\Support\Intel\Oct2_2018_DesignCon2019\Measure...				
BC001_L10_Long_Rev2.s2p	98.4	100	99.6	-
BC002_L10_Long_Rev2.s2p	97.7	100	99.5	-
BC003_L10_Long_Rev2.s2p	98.6	100	99.6	-
BC004_L10_Long_Rev2.s2p	97.9	100	99.6	-
BC005_L10_Long_Rev2.s2p	98.1	100	99.6	-
BC006_L10_Long_Rev2.s2p	98.3	100	99.6	-
BC007_L10_Long_Rev2.s2p	98.7	100	99.2	-
BC008_L10_Long_Rev2.s2p	98.5	100	99.6	-
BC009_L10_Long_Rev2.s2p	98.6	100	99.6	-
BC010_L10_Long_Rev2.s2p	97.9	100	99.5	-
BC011_L10_Long_Rev2.s2p	98.3	100	99.6	-
BC012_L10_Long_Rev2.s2p	98.1	100	99.6	-
BC013_L10_Long_Rev2.s2p	98	100	99.5	-
BC014_L10_Long_Rev2.s2p	98.4	100	99.6	-
BC015_L10_Long_Rev2.s2p	98	100	99.5	-
BC016_L10_Long_Rev2.s2p	98.2	100	99.5	-
BC017_L10_Long_Rev2.s2p	98.4	100	99.5	-
BC018_L10_Long_Rev2.s2p	98.1	100	99.6	-
BC019_L10_Long_Rev2.s2p	98	100	99.5	-
BC020_L10_Long_Rev2.s2p	98.5	100	99.4	-
BC021_L10_Long_Rev3.s2p	98.7	100	98.9	-
BC022_L10_Long_Rev3.s2p	98.3	100	99.2	-
BC023_L10_Long_Rev3.s2p	97.1	100	99	-
BC024_L10_Long_Rev3.s2p	98.6	100	99	-
BC025_L10_Long_Rev3.s2p	98.3	100	99.2	-
BC026_L10_Long_Rev3.s2p	98.3	100	99.3	-

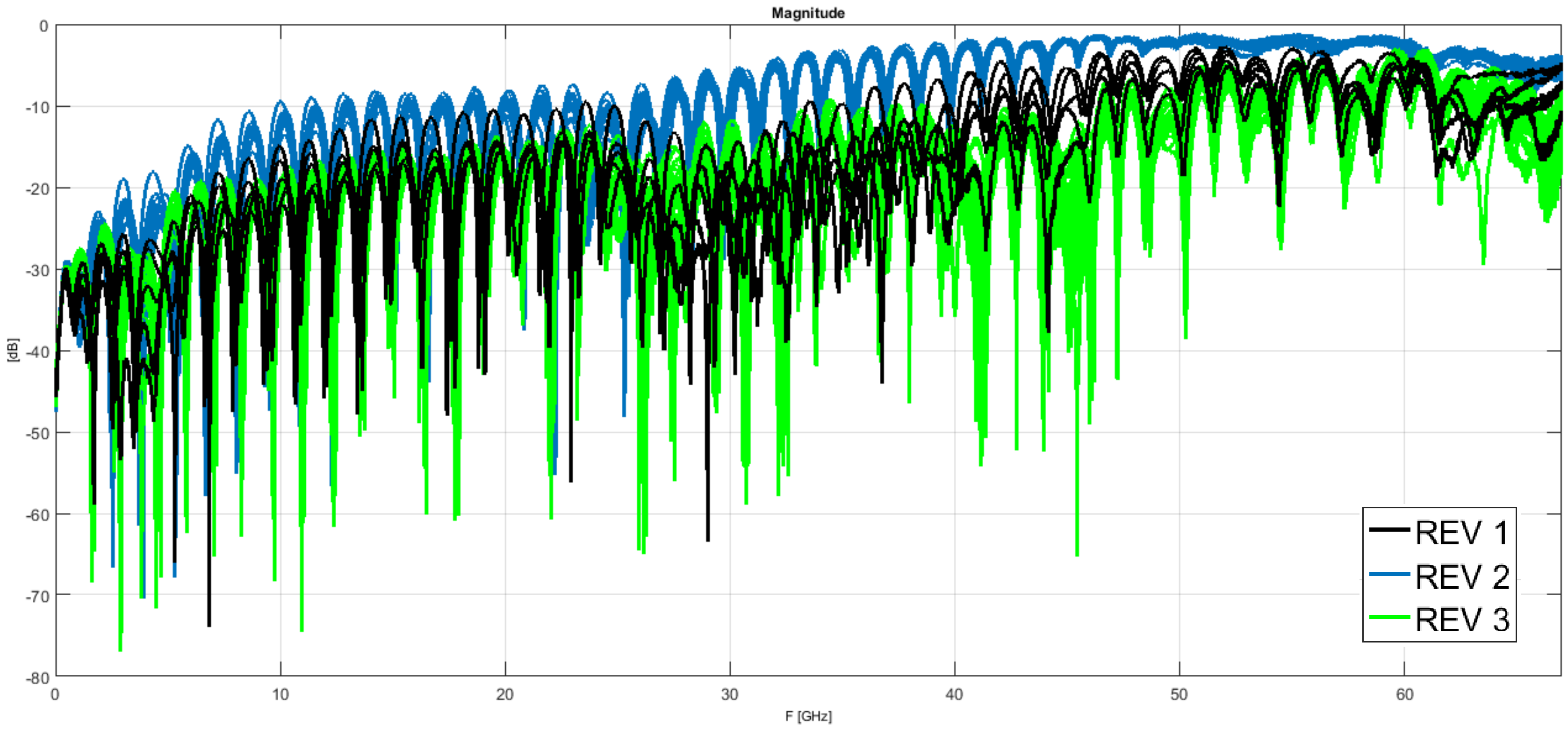
Rev3 looks like the best for the identification



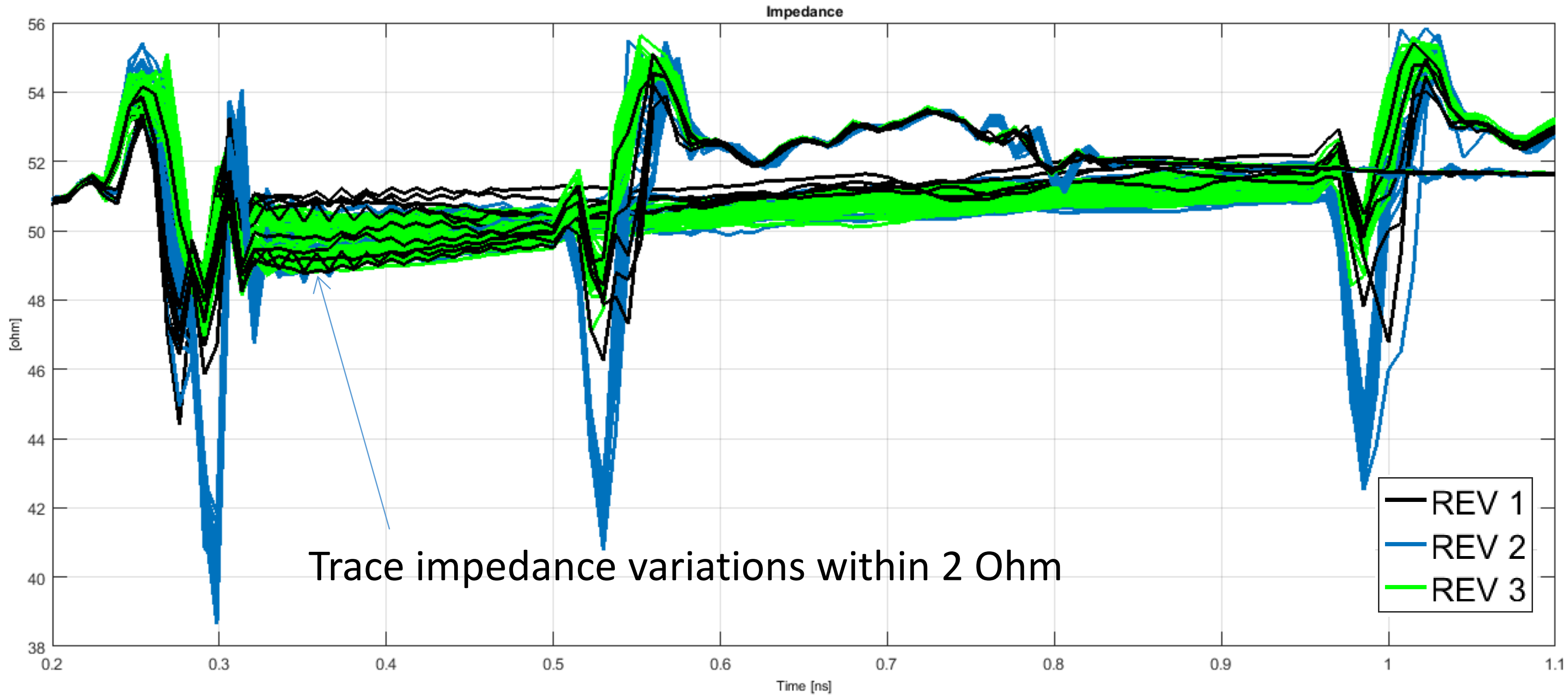
Long segment reflection loss

L10_Long
EV_PE_TX_L10Ref11-9_Long_J13_J14

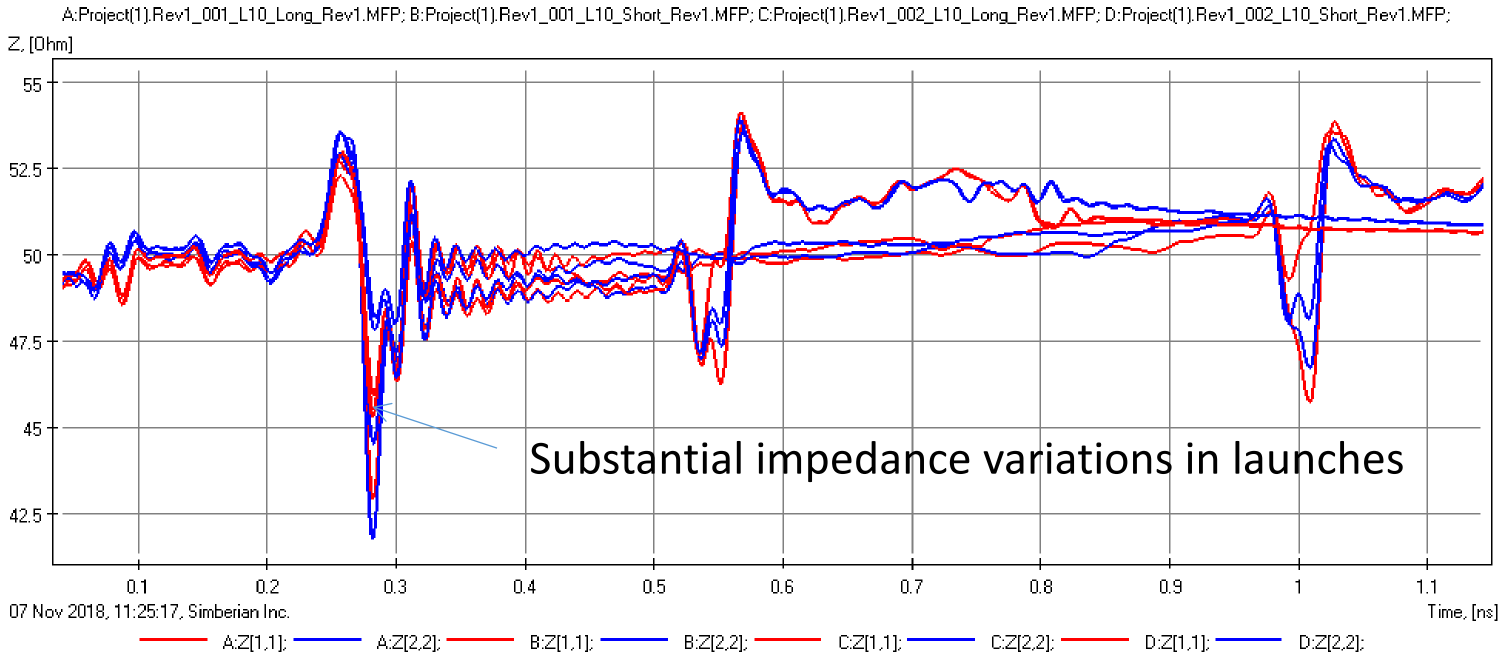




TDR for short and long segments



TDR for Rev1 – detailed response computed with rational approximation

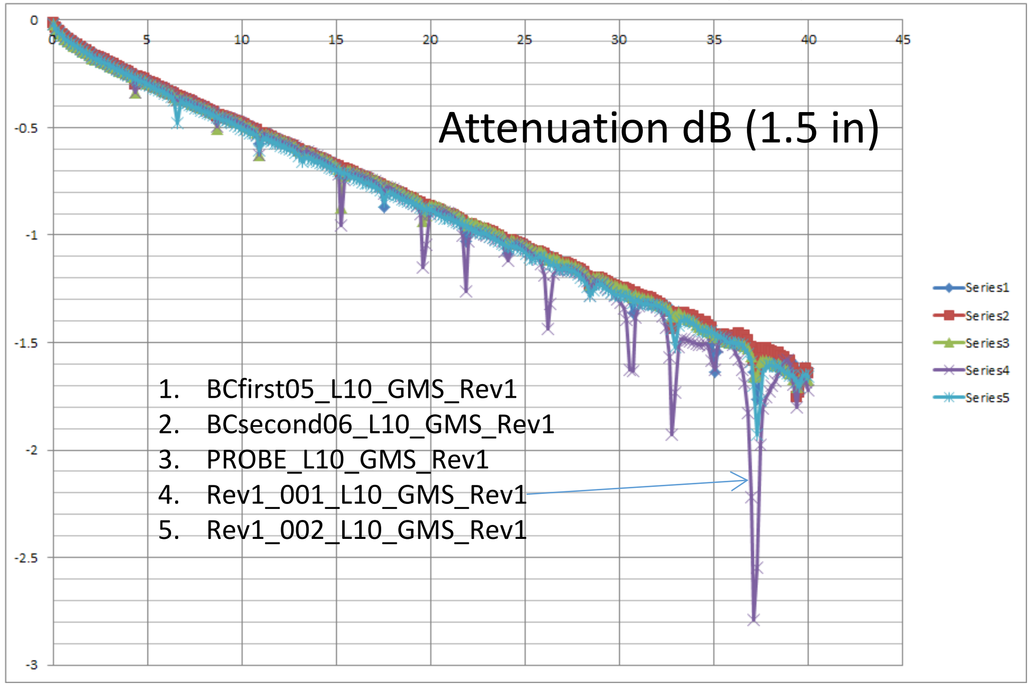


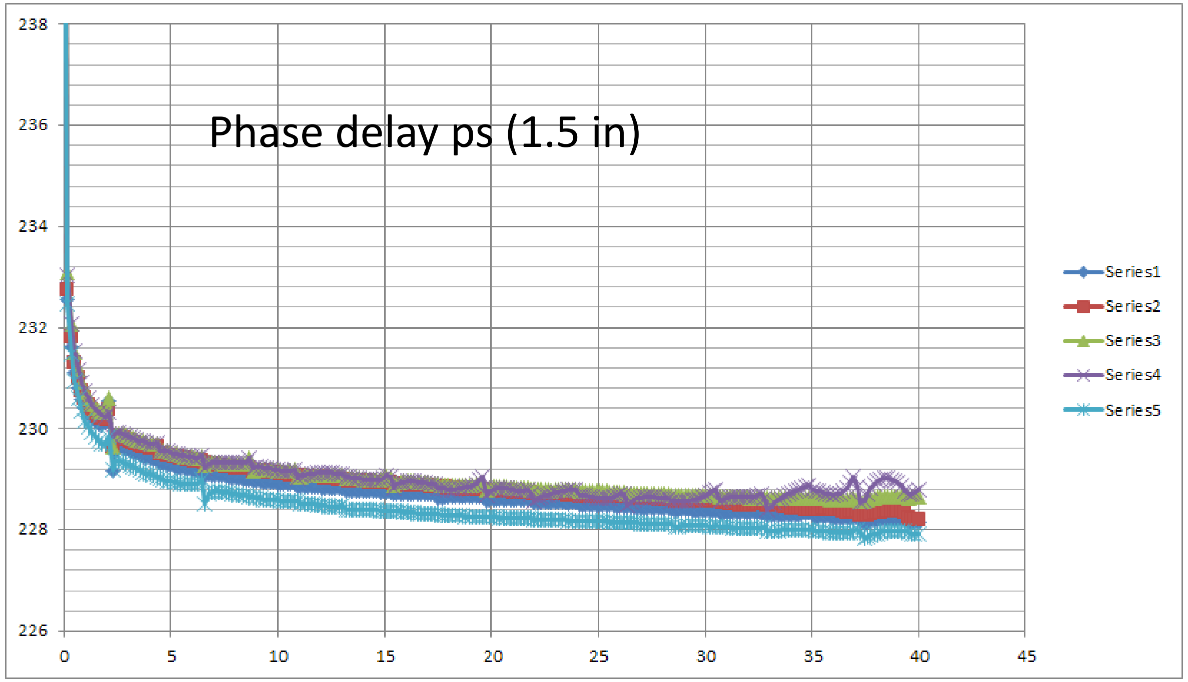
Some systematic impedance difference observed between short and long – due to the orthogonal orientation?

GMS-parameters extraction: Rev1

Extracted from measurements for 5 pairs of segments

Frequency, GHz



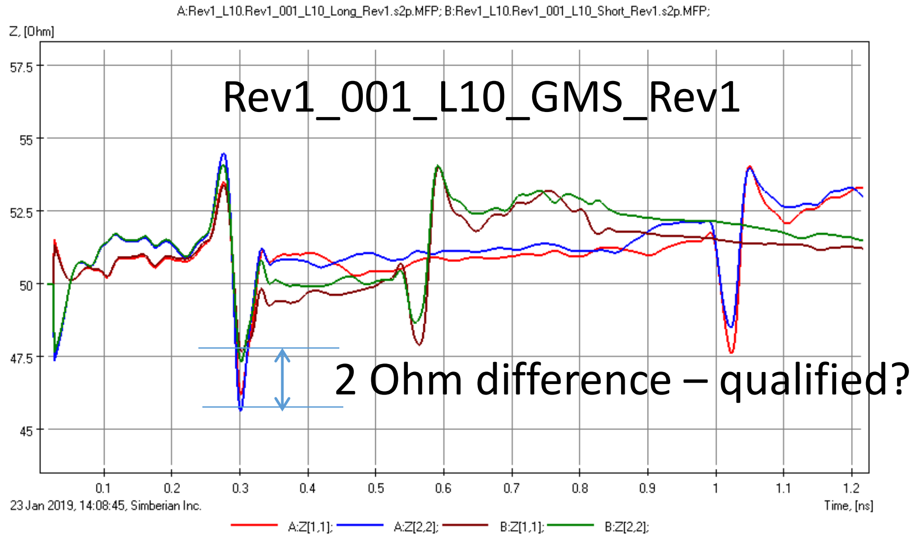


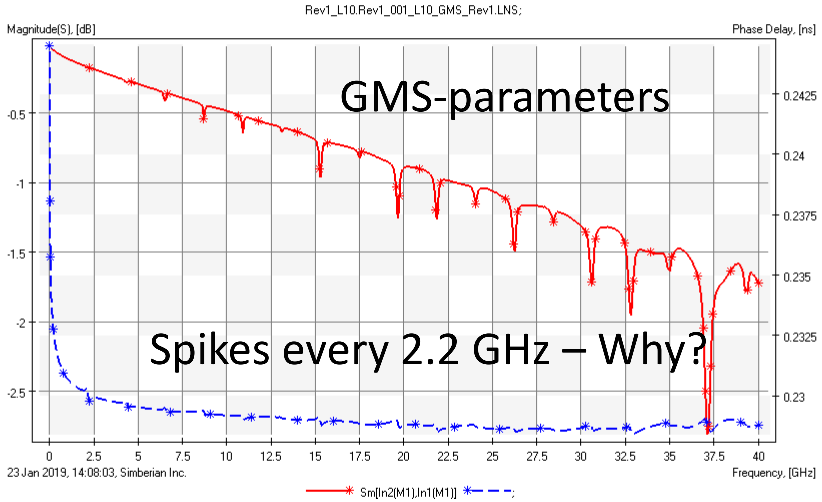
Frequency, GHz

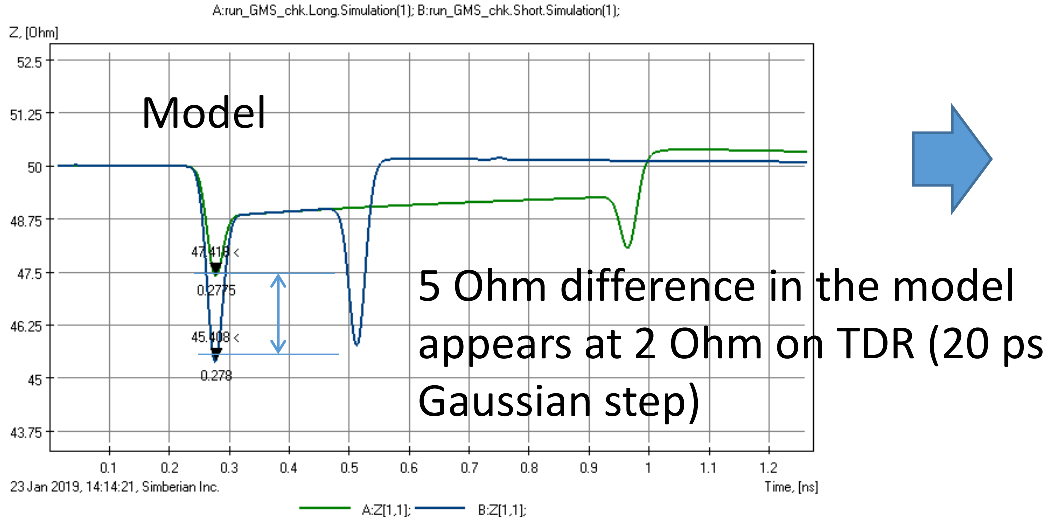
Extracted up to 40 GHz – too noisy above
Periodic spikes due to connector/launch geometry difference (see next slide)
Run identification up to 35 GHz

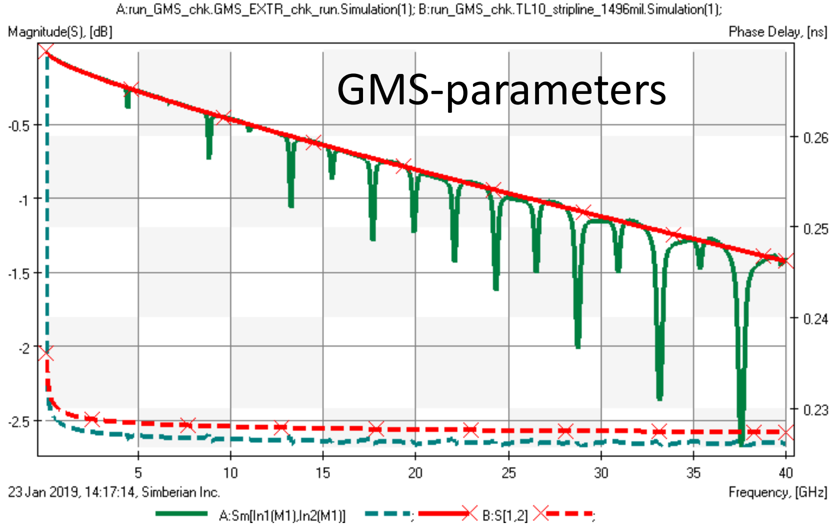
Extracted with Simbeor SDK

Explanation of periodic spikes



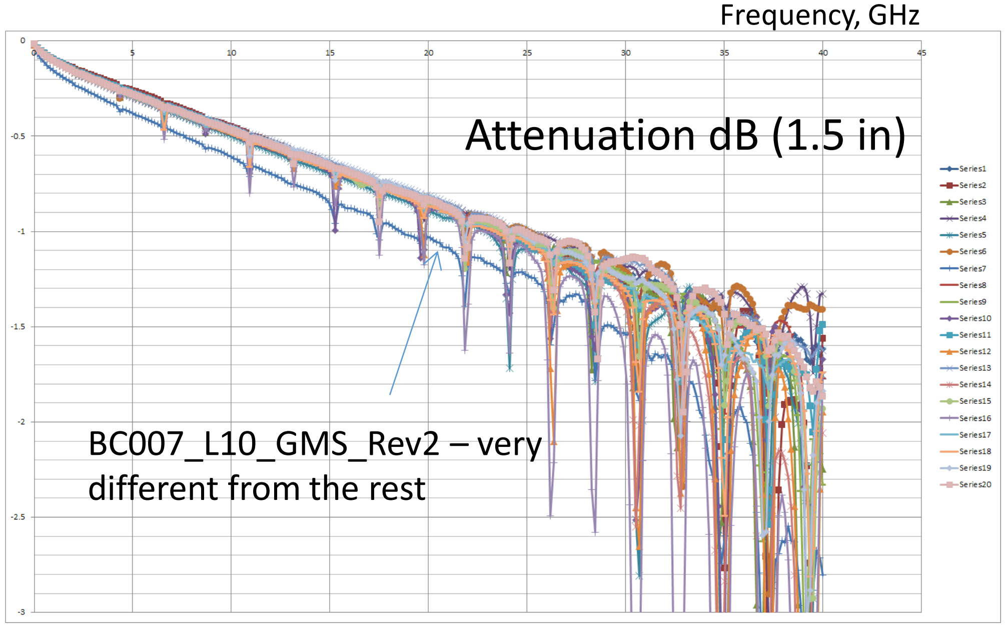


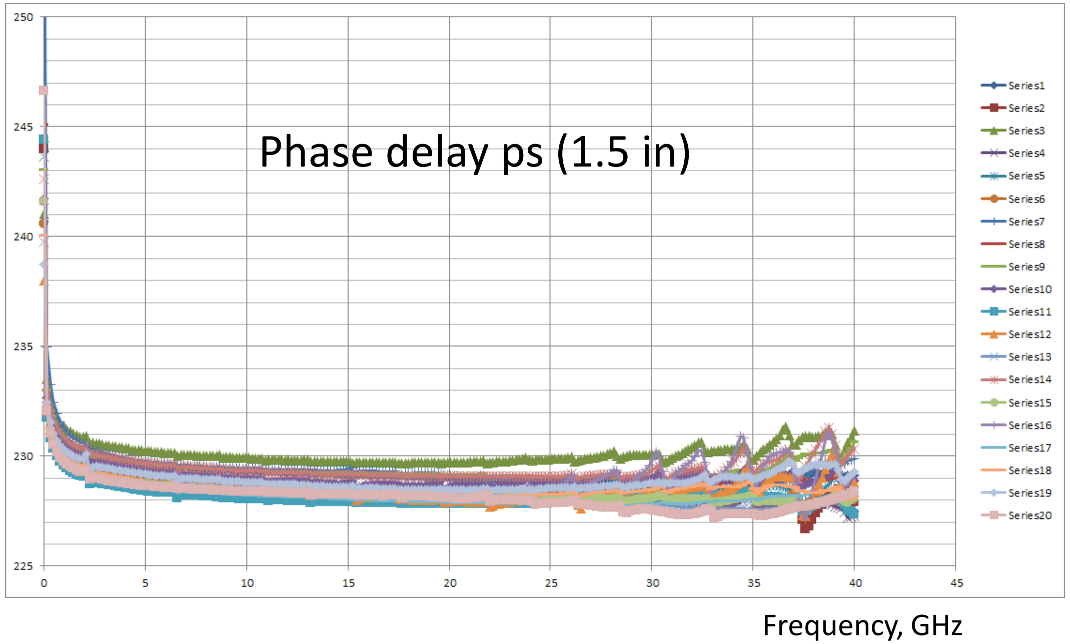




GMS-parameters extraction: Rev2

Extracted from measurements for 20 pairs of segments





1. BC001_L10_GMS_Rev2
2. BC002_L10_GMS_Rev2
3. BC003_L10_GMS_Rev2
4. BC004_L10_GMS_Rev2
5. BC005_L10_GMS_Rev2
6. BC006_L10_GMS_Rev2
7. BC007_L10_GMS_Rev2
8. BC008_L10_GMS_Rev2
9. BC009_L10_GMS_Rev2
10. BC010_L10_GMS_Rev2
11. BC011_L10_GMS_Rev2
12. BC012_L10_GMS_Rev2
13. BC013_L10_GMS_Rev2
14. BC014_L10_GMS_Rev2
15. BC015_L10_GMS_Rev2
16. BC016_L10_GMS_Rev2
17. BC017_L10_GMS_Rev2
18. BC018_L10_GMS_Rev2
19. BC019_L10_GMS_Rev2
20. BC020_L10_GMS_Rev2

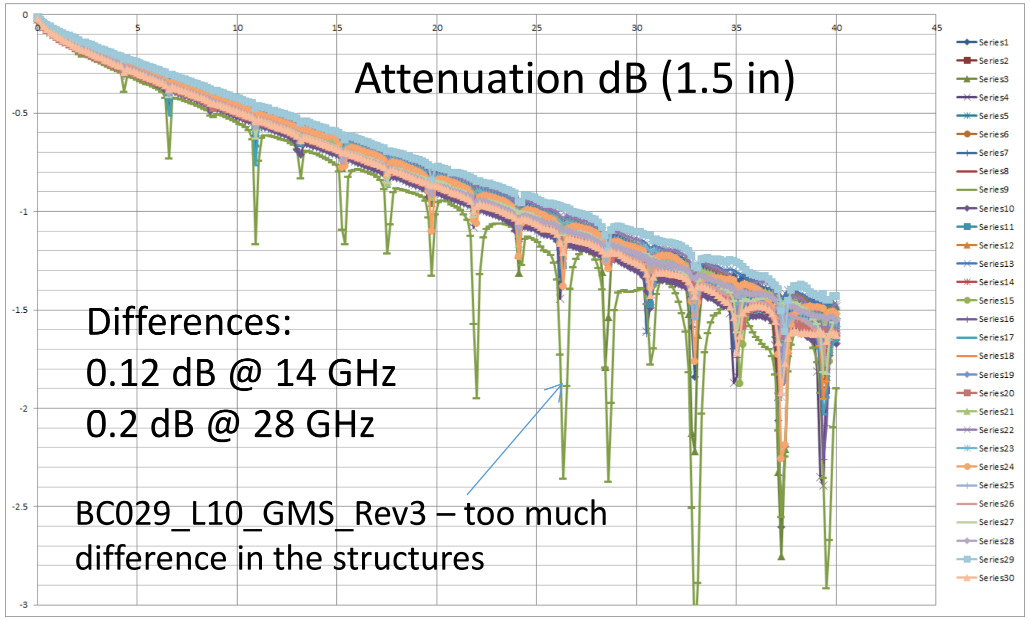
Extracted with Simbeor SDK

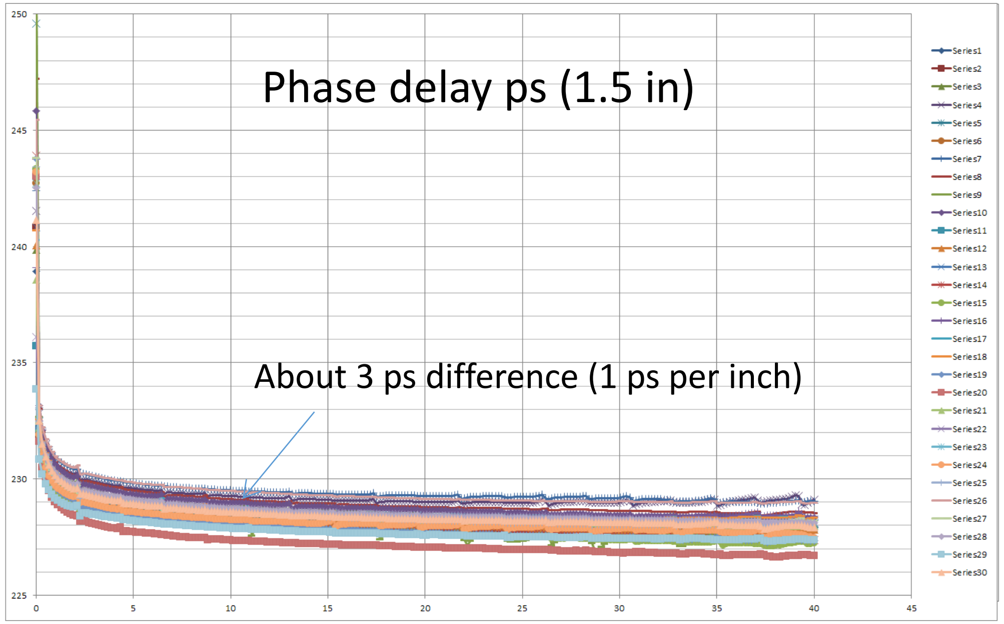
Extracted up to 40 GHz – too noisy above and more noise in attenuation for the structures with stubs
Periodic spikes are due to geometry difference in connectors/launches
Run identification up to 25 GHz

GMS-parameters extraction: Rev3

Extracted from measurements for 30 pairs of segments

Frequency, GHz





Frequency, GHz

Extracted with Simbeor SDK

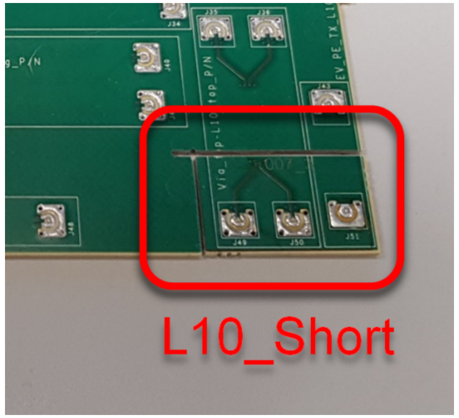
1. BC021_L10_GMS_Rev3
2. BC022_L10_GMS_Rev3
3. BC023_L10_GMS_Rev3
4. BC024_L10_GMS_Rev3
5. BC025_L10_GMS_Rev3
6. BC026_L10_GMS_Rev3
7. BC027_L10_GMS_Rev3
8. BC028_L10_GMS_Rev3
9. BC029_L10_GMS_Rev3
10. BC030_L10_GMS_Rev3
11. BC031_L10_GMS_Rev3
12. BC032_L10_GMS_Rev3
13. BC033_L10_GMS_Rev3
14. BC034_L10_GMS_Rev3
15. BC035_L10_GMS_Rev3
16. BC036_L10_GMS_Rev3
17. BC037_L10_GMS_Rev3
18. BC038_L10_GMS_Rev3
19. BC039_L10_GMS_Rev3
20. BC040_L10_GMS_Rev3
21. BC041_L10_GMS_Rev3
22. BC042_L10_GMS_Rev3
23. BC043_L10_GMS_Rev3
24. BC044_L10_GMS_Rev3
25. BC045_L10_GMS_Rev3
26. BC046_L10_GMS_Rev3
27. BC047_L10_GMS_Rev3
28. BC048_L10_GMS_Rev3
29. BC049_L10_GMS_Rev3
30. BC050_L10_GMS_Rev3

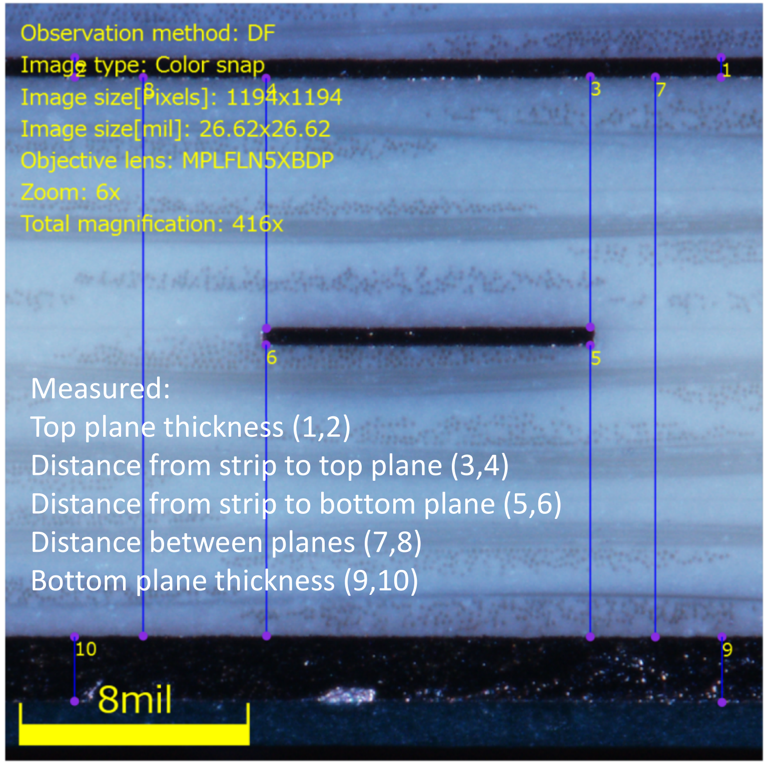
Extracted up to 40 GHz – too noisy above
Periodic spikes are due to geometry difference in connectors/launches
Run identification up to 35 GHz

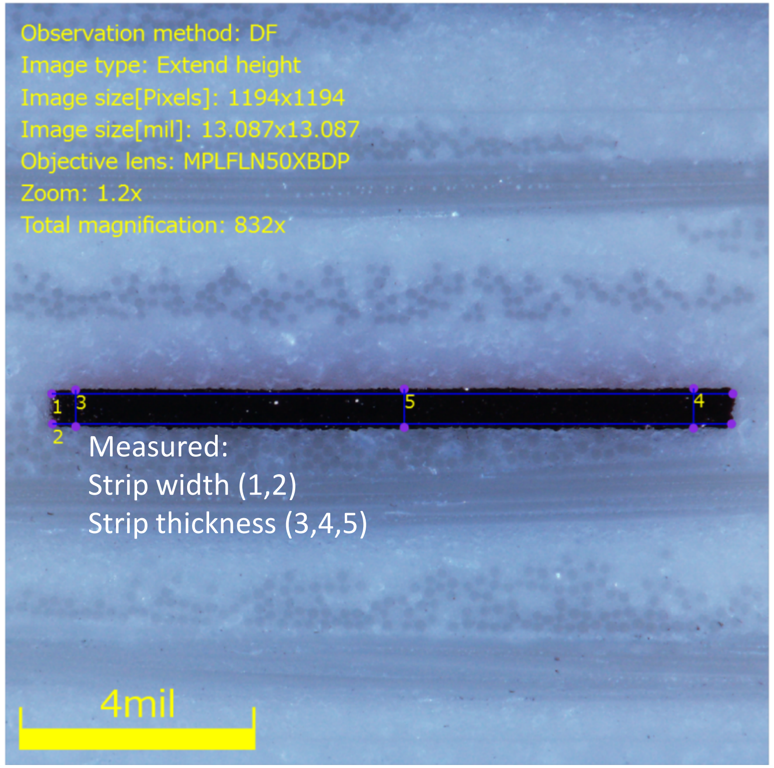
Cross-sectioning and geometry variations

Cross-sectioning – L10 short

Every board is cut at the same location
All parameters are measured at 2-3 locations and averaged



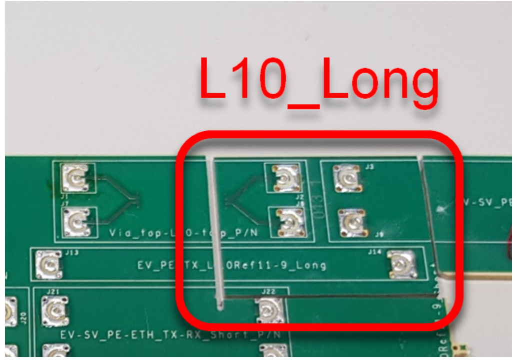


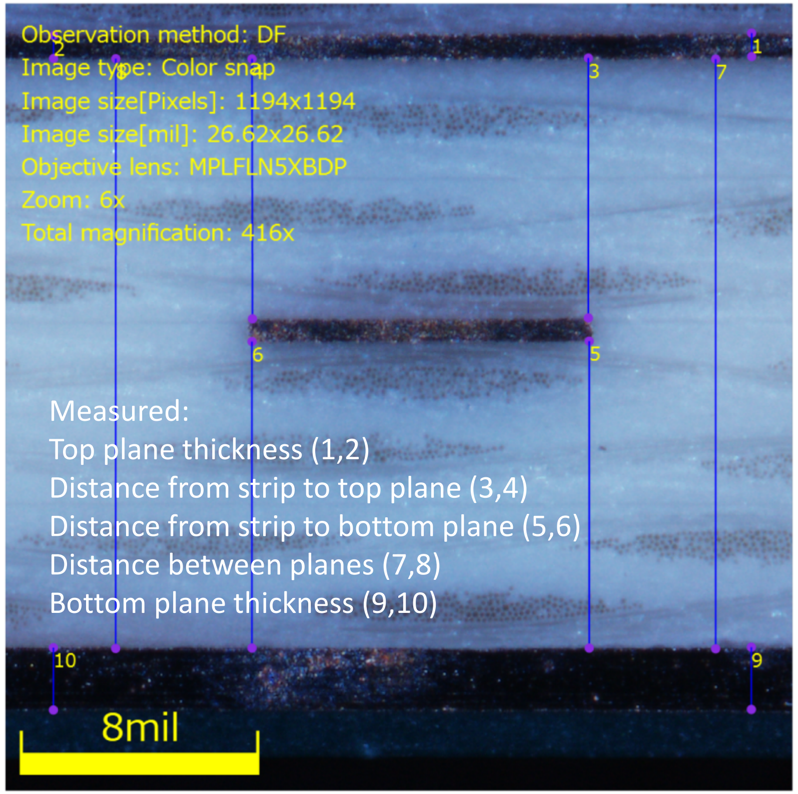


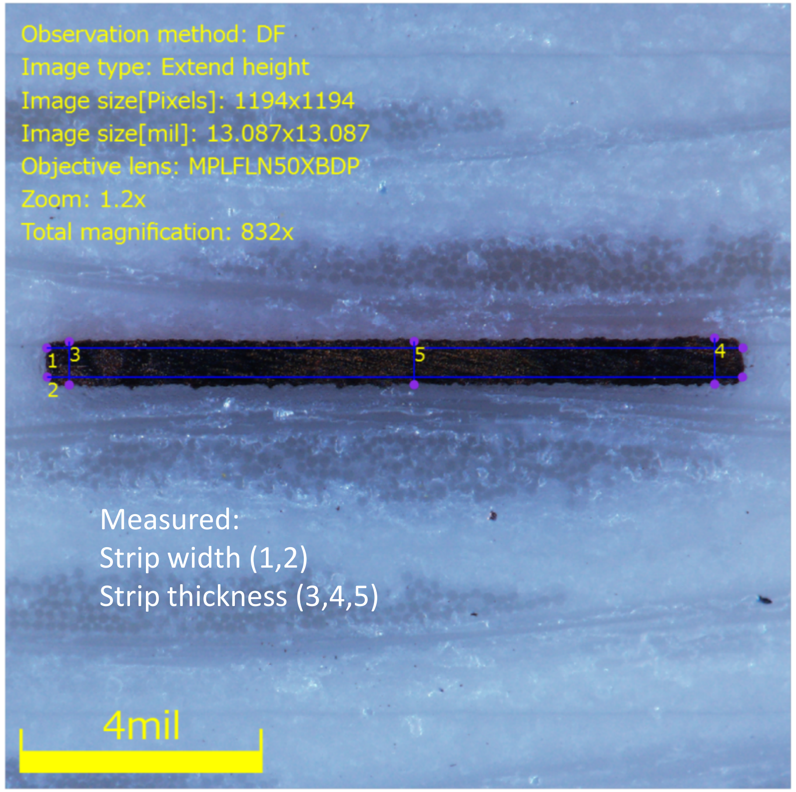
Let's take a look at strip size and laminate thickness (distance from strip to planes) – the main contributors to losses and impedance …

Cross-sectioning – L10 long

Every board is cut at the same location
All parameters are measured at 2-3 locations and averaged



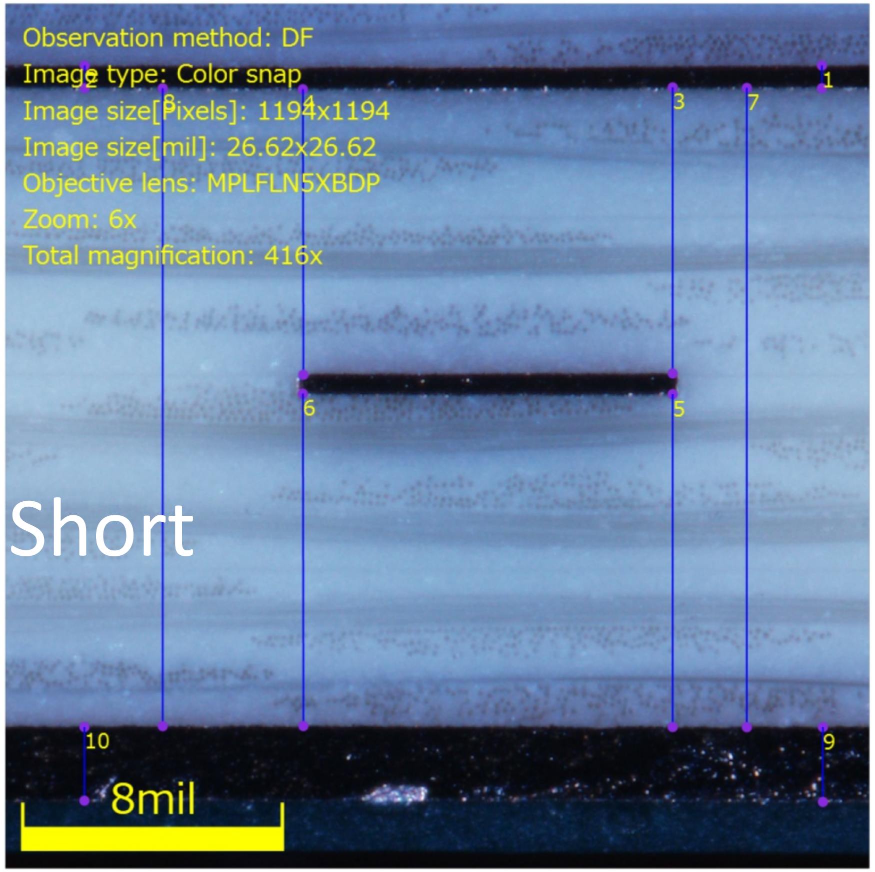


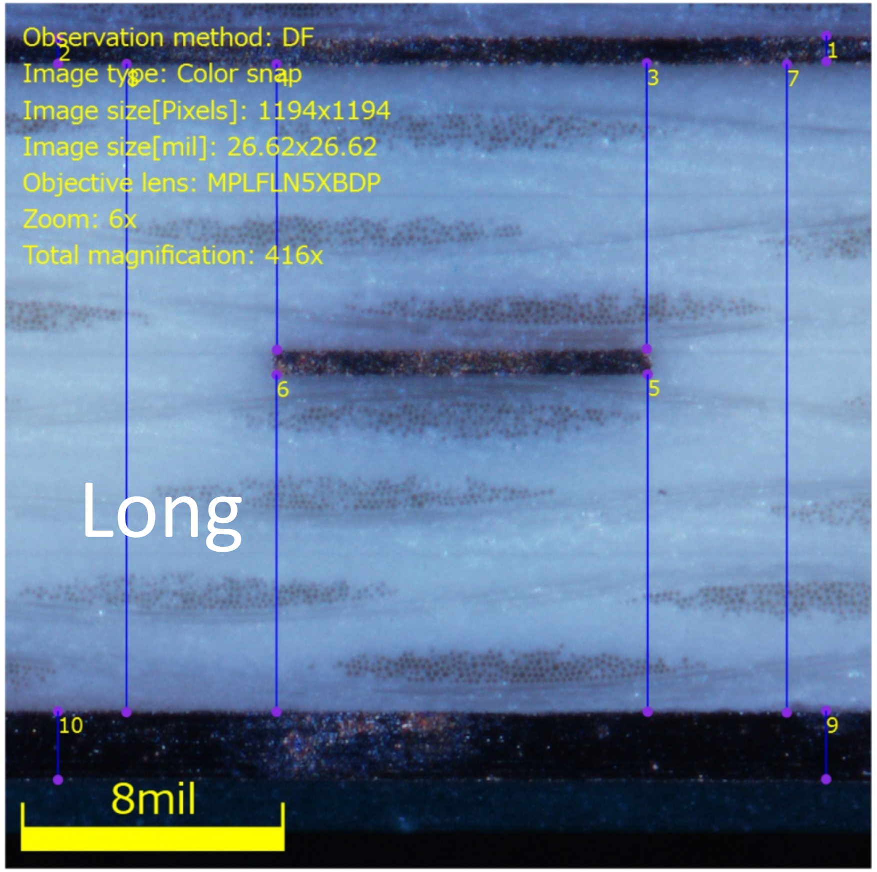


Let's take a look at strip size and laminate thickness (distance from strip to planes) – the main contributors to losses and impedance …

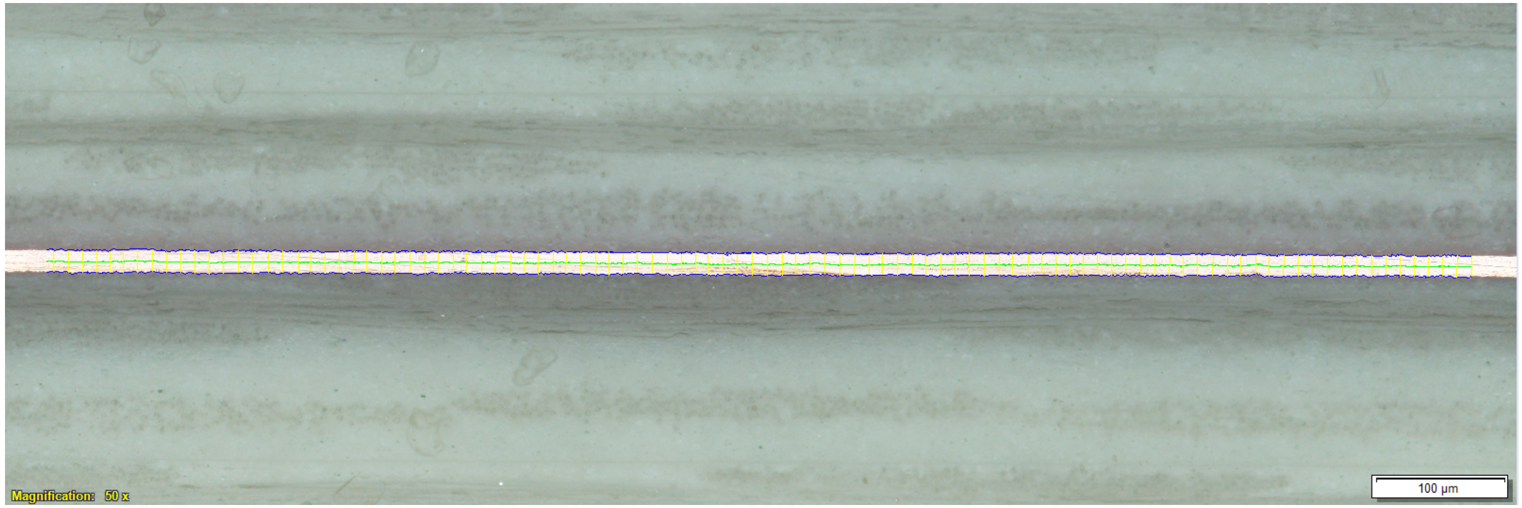
Comparison of long and short - FWE

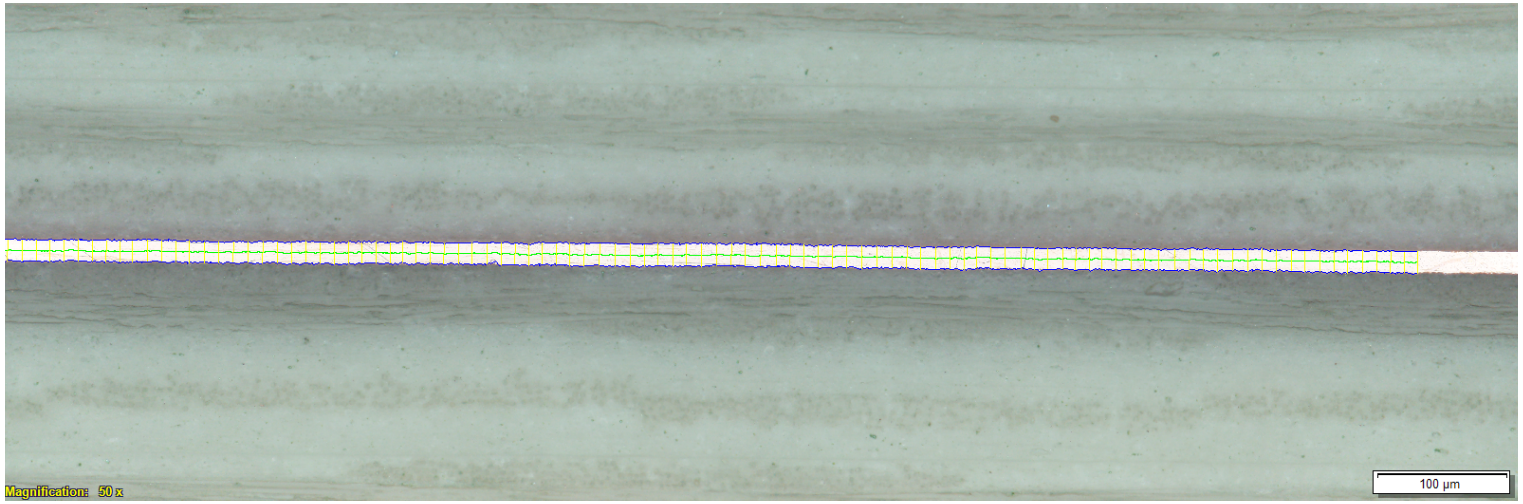
Looks like the fiber is spread along one direction only – may explain systematic difference in impedance and variations of Dk



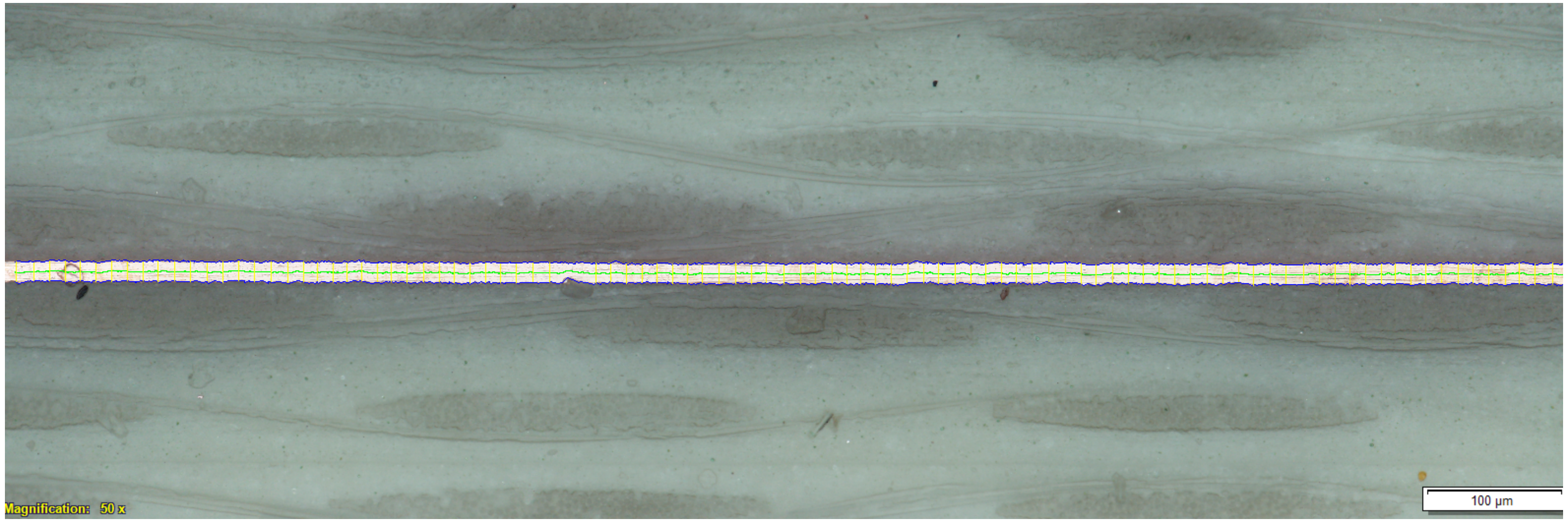


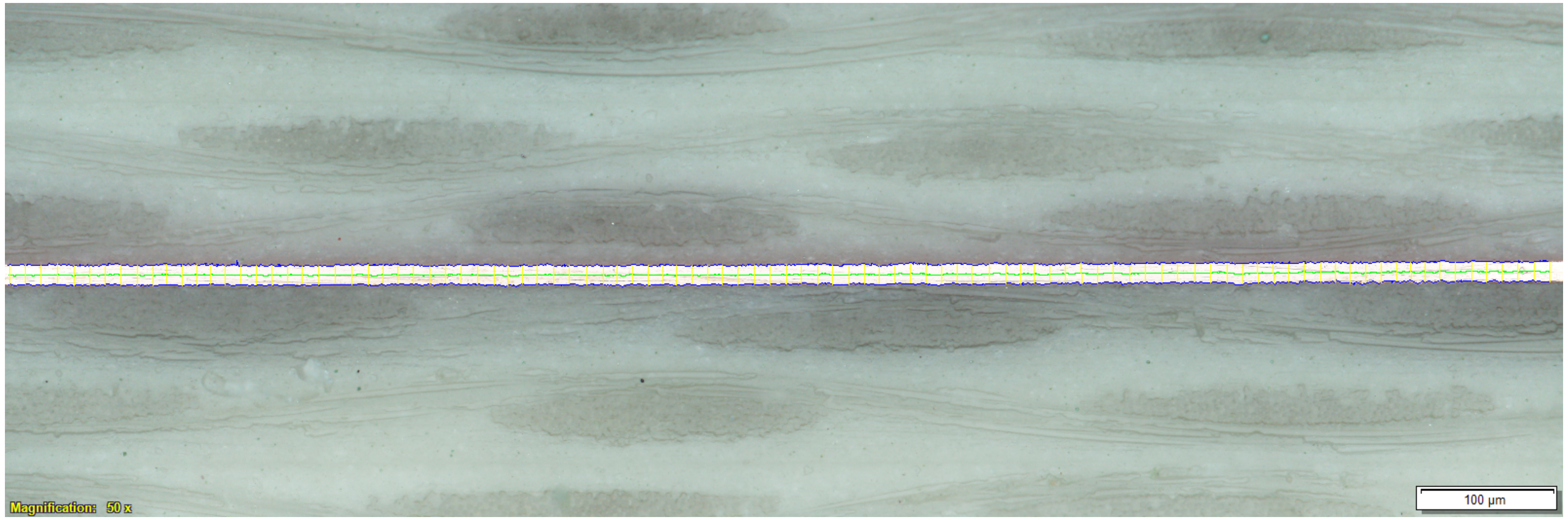
Fibers along the long line



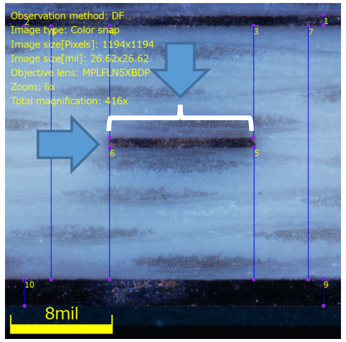


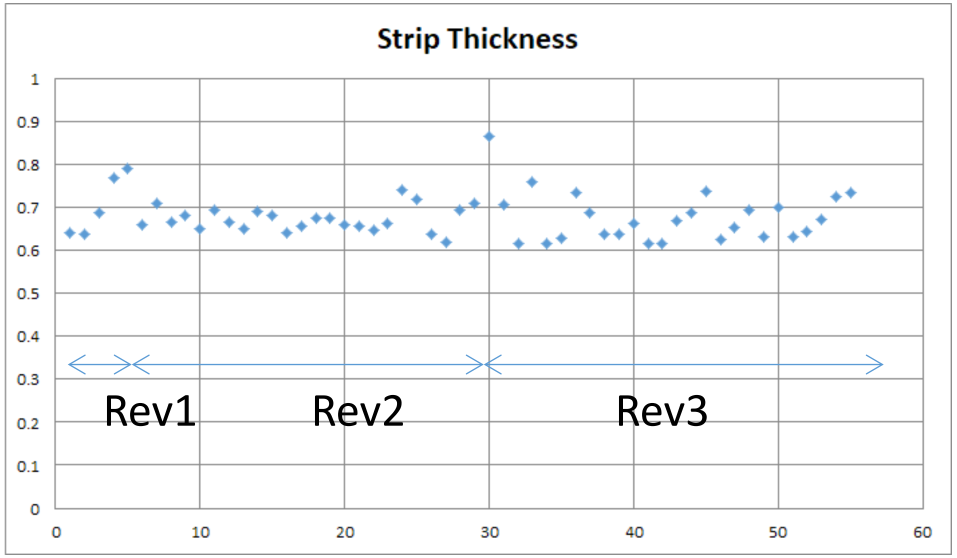
Fibers along short line

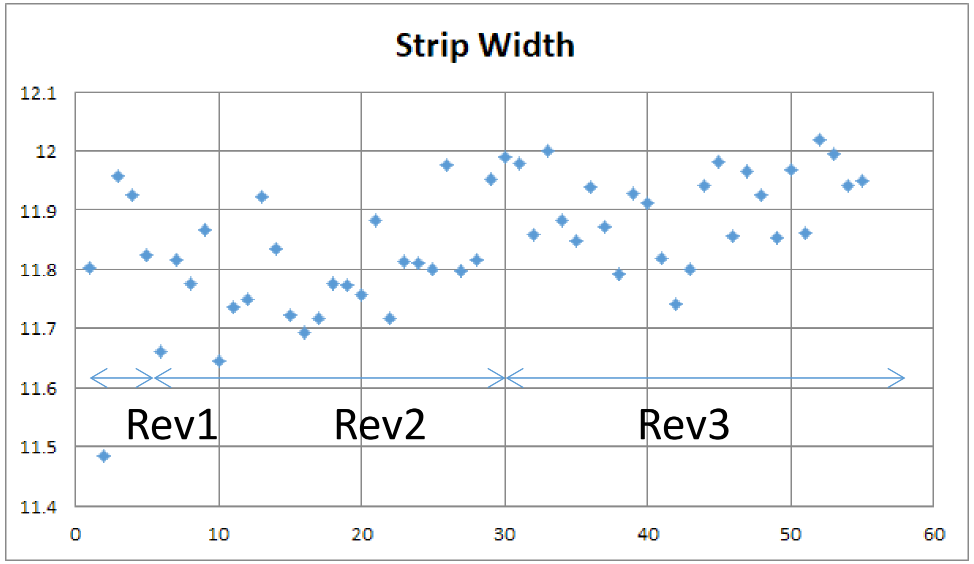




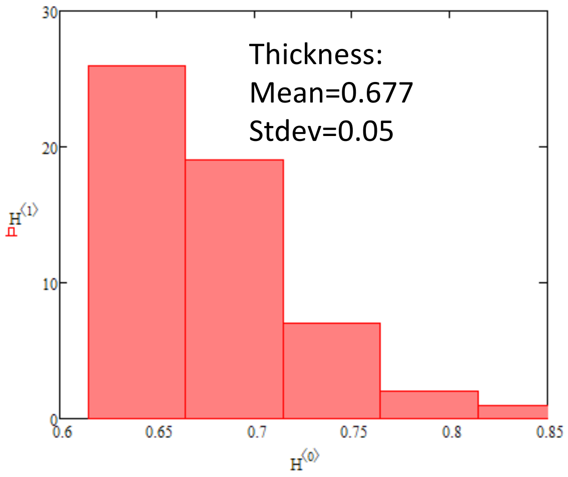
Cross-sectioning – strip geometry

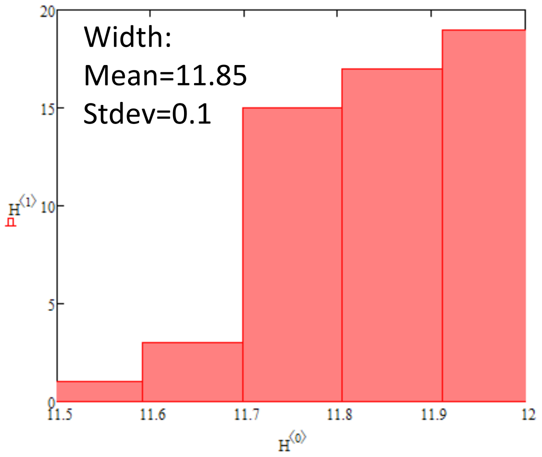




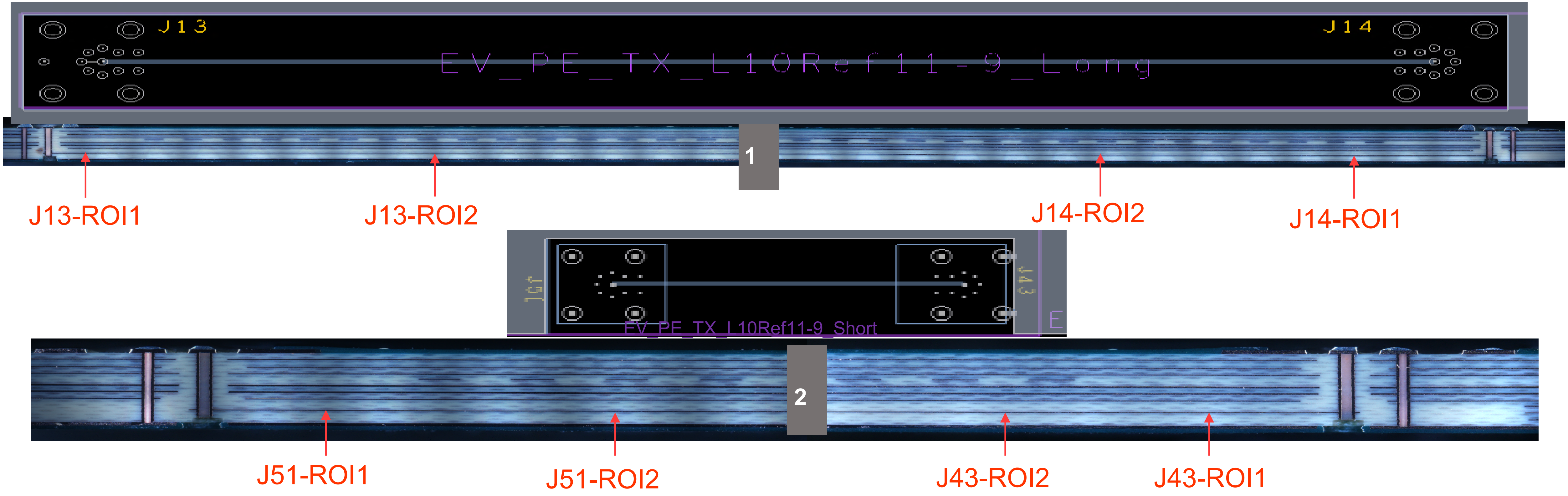


Over 30% variation in the cross-section! It should produce substantial effect on impedance and losses, if we assume that the trace thickness and width are changing along each segment





Transmission Lines Thickness Statistical Measurements

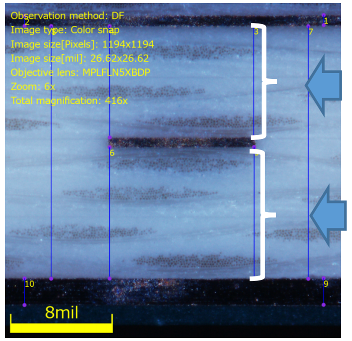


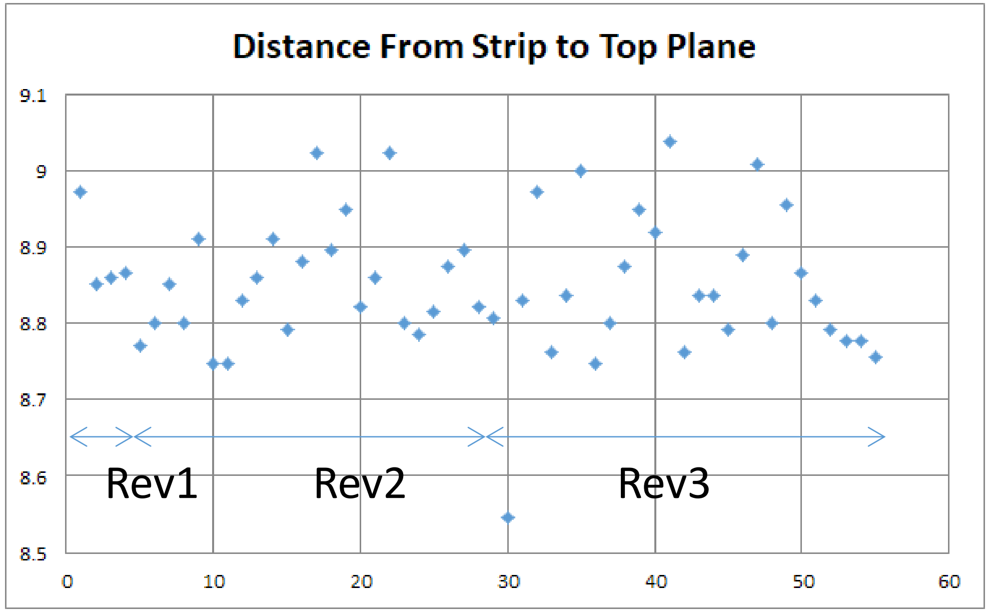
Measurement description: ROI- little rectangular area (10milx50mil).
in each ROI 100 height measurements

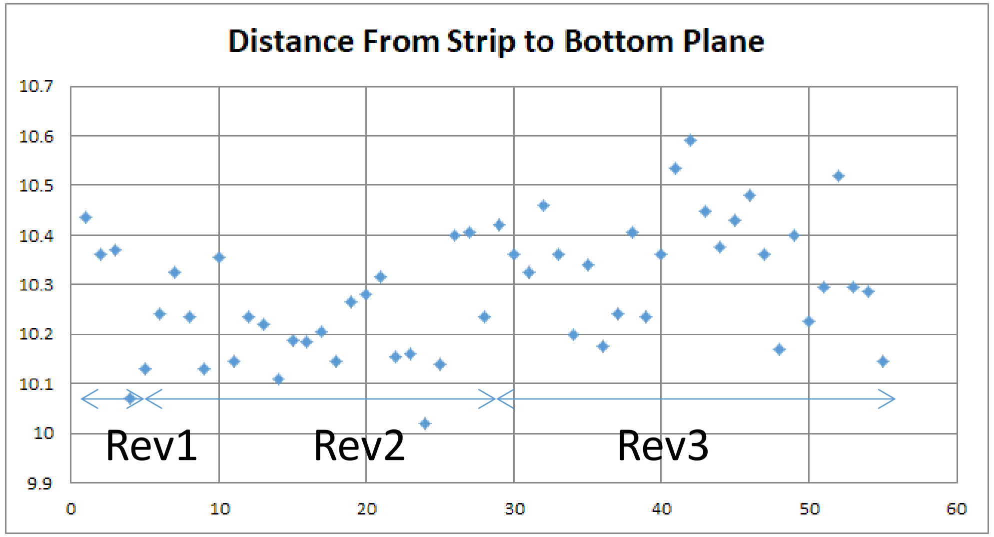
See examples below

	ROI1			ROI2		
	Min [mil]	*Average [mil]*	*Max [mil]*	*Min [mil]*	*Average [mil]*	*Max [mil]*
J13	0.615	0.665	0.733	0.580	0.661	0.714
J14	0.589	0.669	0.736	0.618	0.665	0.733
J43	0.565	0.615	0.657	0.558	0.607	0.654
J51	0.549	0.596	0.641	0.544	0.589	0.657
	Min [mil]	*Average [mil]*	*Max [mil]*			
Short TL sum	**0.600**	**0.665**	**0.729**			
Long TL sum	**0.569**	**0.616**	**0.672**			

Cross-sectioning- laminate thickness

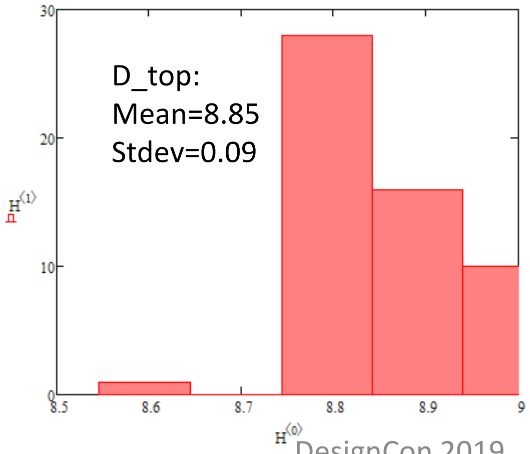


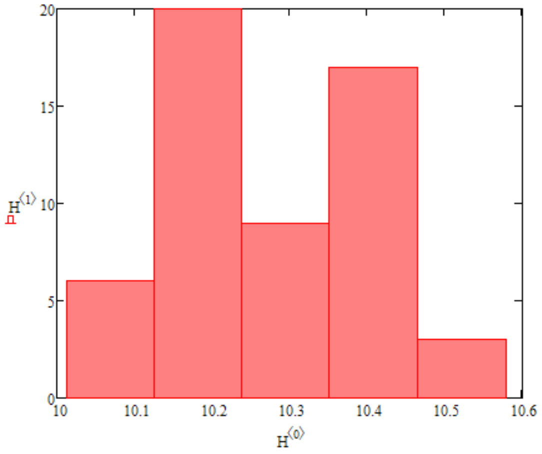




Insignificant variations in the laminate thickness – should not affect the impedance significantly, but still contribute

Should not have effect on losses



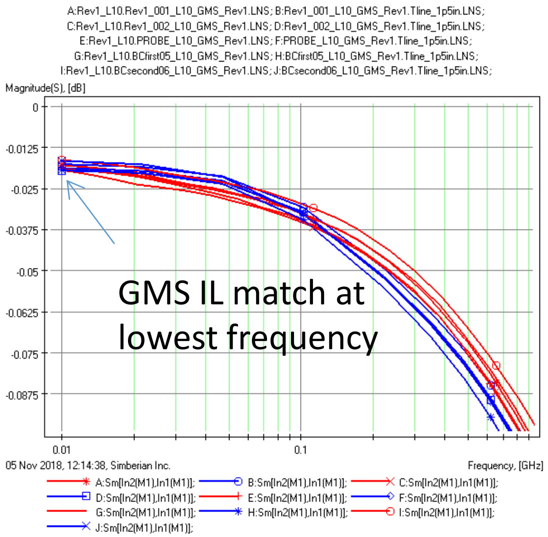


D_bottom:
Mean=10.28
Stdev=0.13

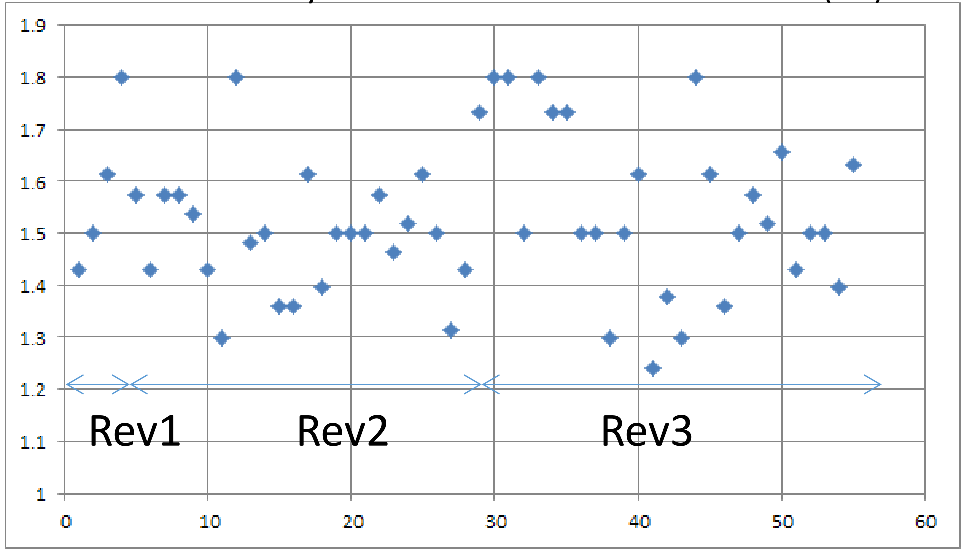
Attempt of dielectric and conductor loss separation

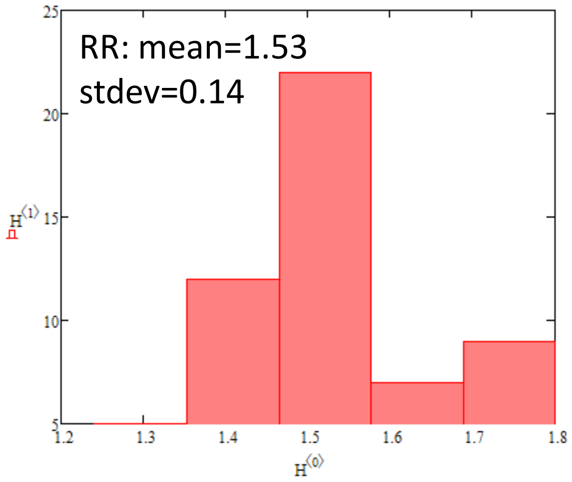
Copper resistivity identification uncertainty

Large variation of the identified relative resistivity – “effective resistivity”
Correlate with the distribution of geometry – 30% variation in strip cross-section cause about 30% variation in the “effective resistivity”



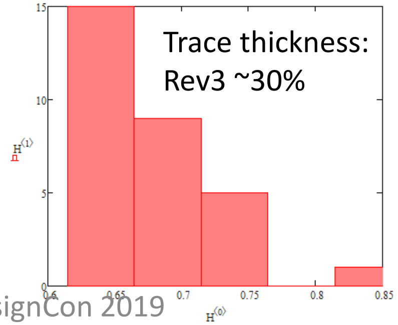
Resistivity normalized to 1.724e-8 Ohm*m (RR)

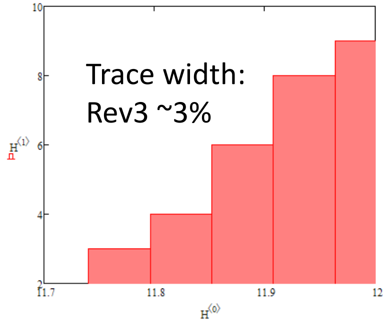




Extracted with Simbeor SDK

Use minimal value RR=1.2 or average RR=1.5?
Changes in RR can cause variations of losses at lower frequencies that affect the identification of the loss tangent





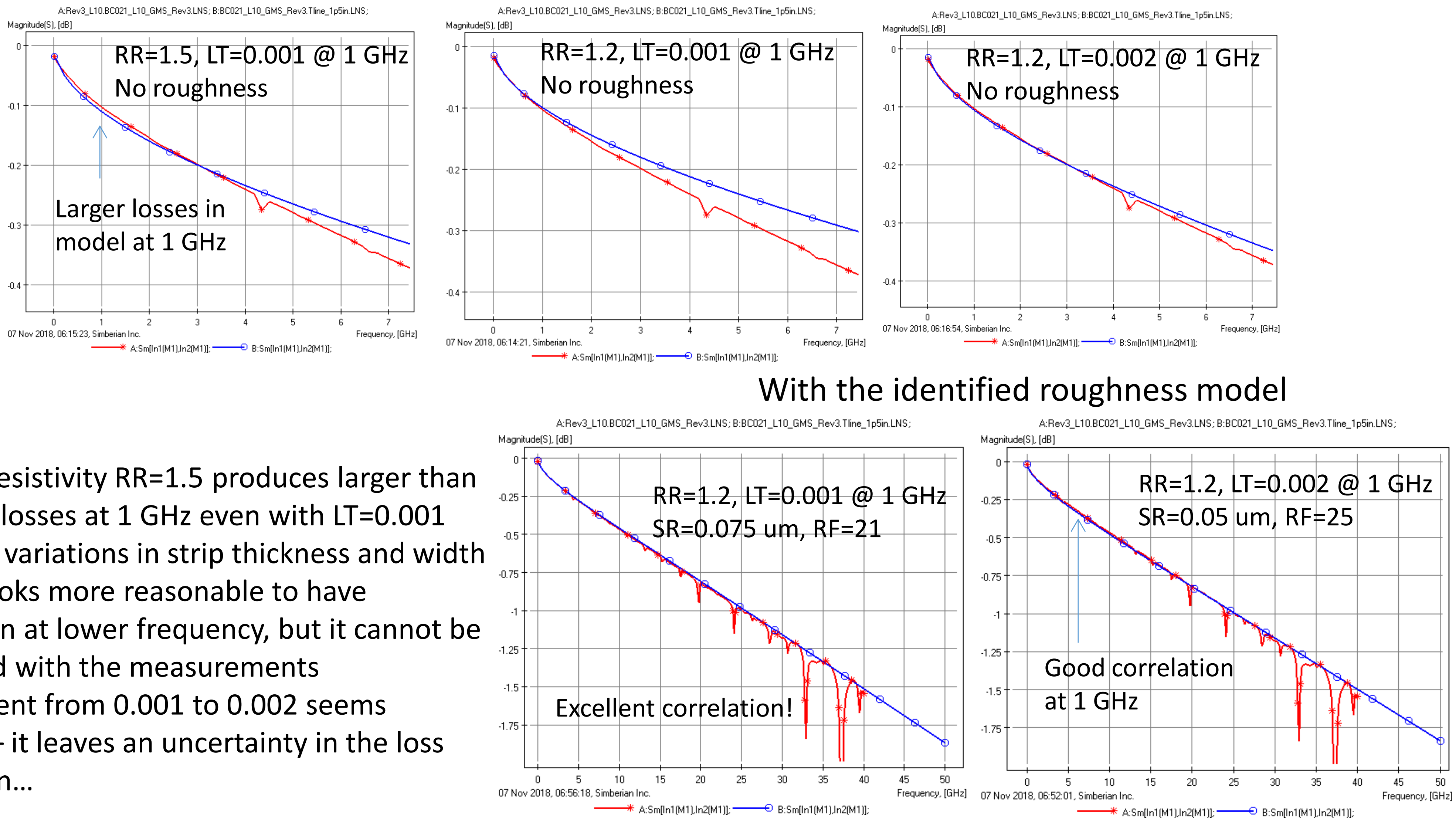
Loss tangent identification uncertainty

- Dielectric is extremely low loss in this case

Dielectric Constant (Dk)	@1GHz	-	IPC TM-650 2.5.5.9	C-24/23/50	3.63	3.37
	@ 12GHz	-	*Note 1	C-24/23/50	3.61	3.35
Dissipation Factor (Df)	@1GHz	-	IPC TM-650 2.5.5.9	C-24/23/50	0.002	0.001
	@ 12GHz	-	*Note 1	C-24/23/50	0.003	0.002

- Considering the observed variation of the strip cross-section, the conductor and dielectric loss separation at lower frequencies is not possible (explanation is on the next slides)
- We can try to use LT=0.001 (minimal value from specs) and LT=0.002 (maximal value from specs)

Dielectric and conductor loss separation



Relative resistivity RR=1.5 produces larger than expected losses at 1 GHz even with LT=0.001

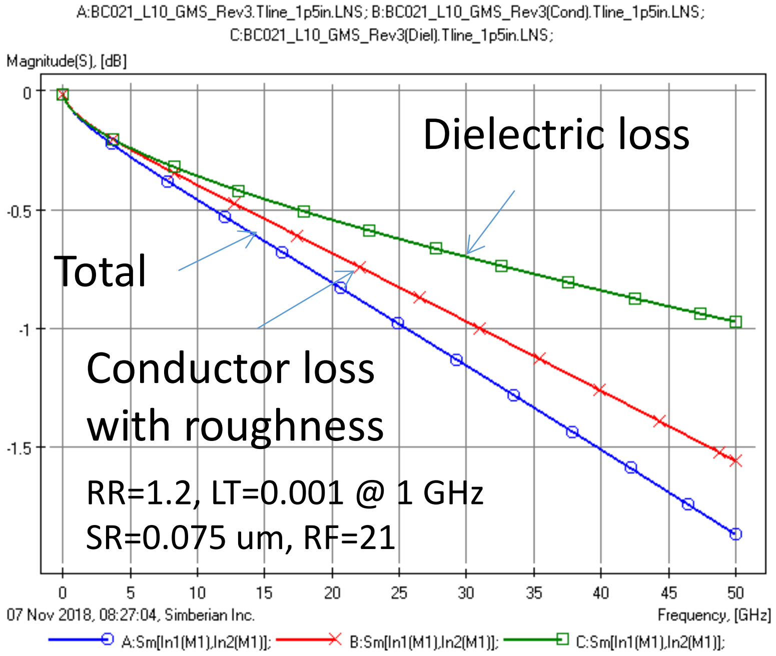
It reflects variations in strip thickness and width

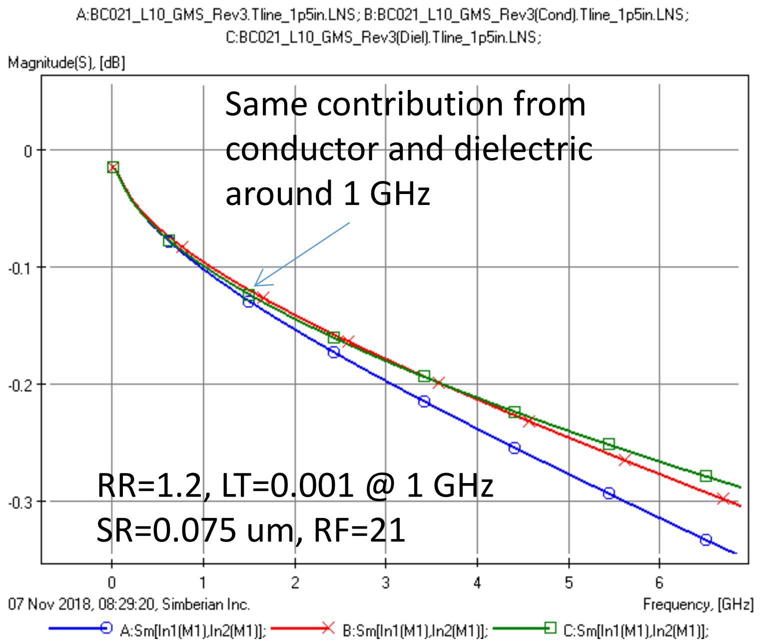
RR=1.2 looks more reasonable to have correlation at lower frequency, but it cannot be confirmed with the measurements

Loss tangent from 0.001 to 0.002 seems possible – it leaves an uncertainty in the loss separation…

Dielectric and conductor loss separation

Lowest possible dielectric loss (optimistic)

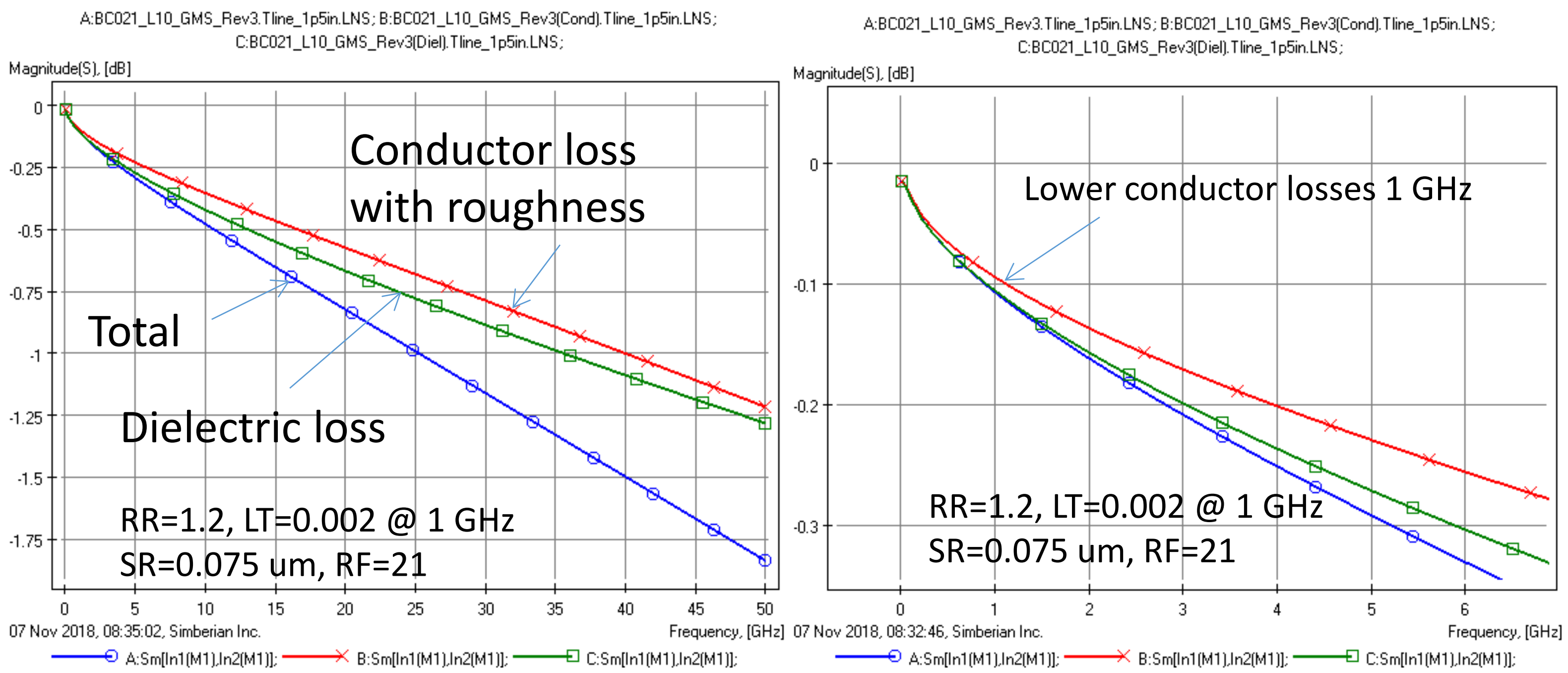




The loss tangent identification in this case will be very sensitive to the conductor cross-section, resistivity and even conductor roughness!

Dielectric and conductor loss separation

Highest possible dielectric loss (pessimistic)



The conductor and dielectric losses are still comparable and identified LT would be sensitive to the strip cross-section, resistivity and roughness model

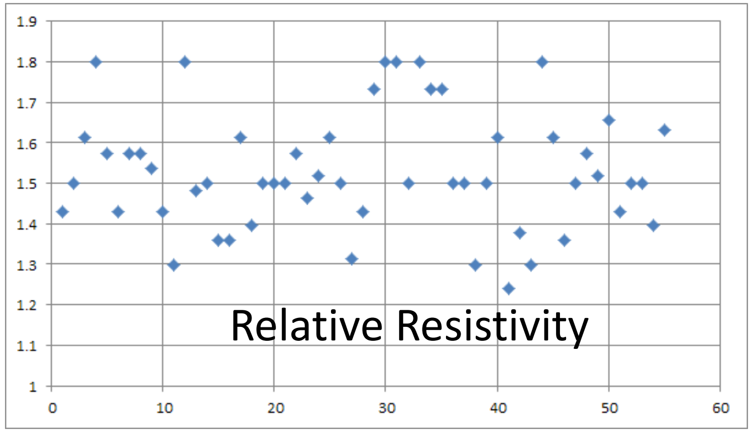
Which one is correct – with more conductor/roughness losses or more dielectric losses?
It is not possible to decide… - variations of resistivity, trace thickness and roughness has considerable effect on the losses at lower frequencies and alter the identified loss tangent

Material models identification results

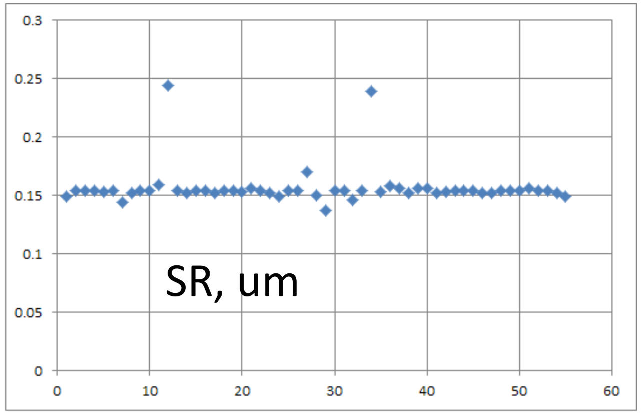
The first attempt to identify material model parameters

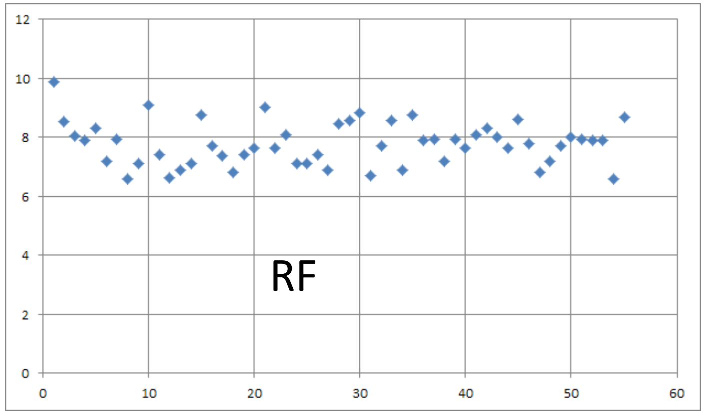
- Cross-section geometry parameters as measured for the short line in each pair are used in the identification
- Allow relative resistivity (RR) range from 1 to 1.8 and identify it first by matching attenuation at 0.01 GHz
- Follow the original algorithm without the LT adjustment – just fix LT=0.001 @ 1 GHz
- Identify Dk @ 1 GHz, then roughness model SR and RF parameters and correct Dk after this

Identified material model parameters



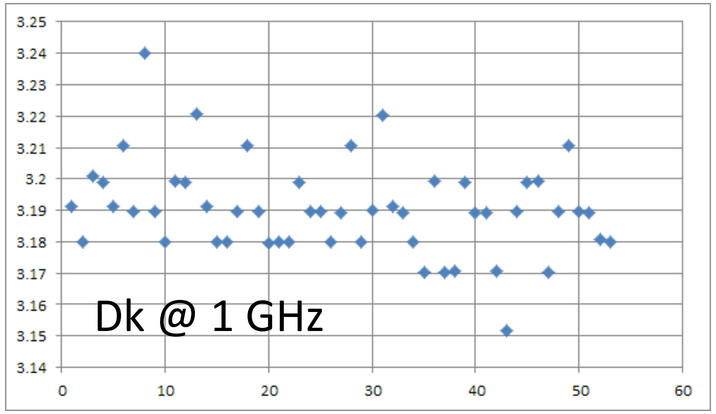
Huray-Bracken roughness model





Cross-section dimensions are adjusted as measured on short segment
Geometry, conductor and dielectric models produce about 1 Ohm variations in the characteristic impedance (about 2 Ohm in reality)

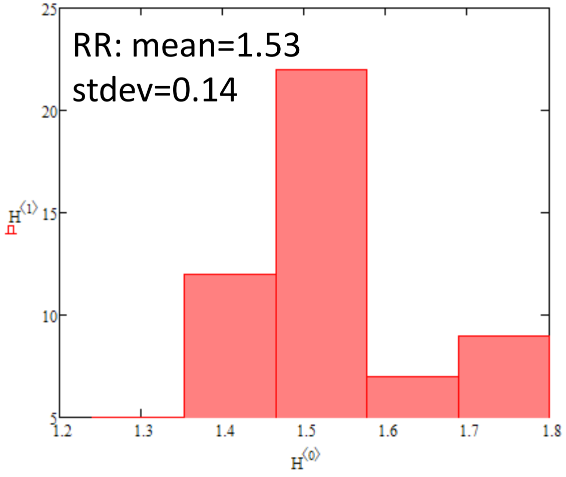
Wideband Debye dielectric model – LT=0.001 @ 1 GHz



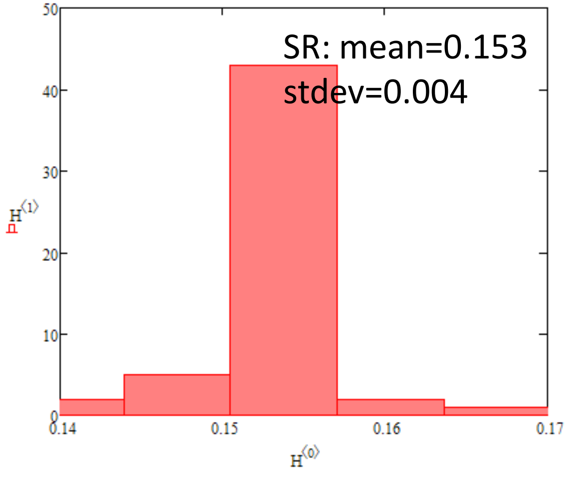
Identified material model parameters

Huray-Bracken roughness model

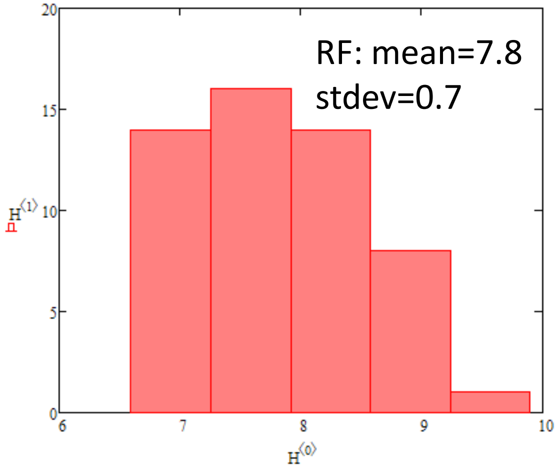
Relative resistivity



Surface roughness (SR, um)

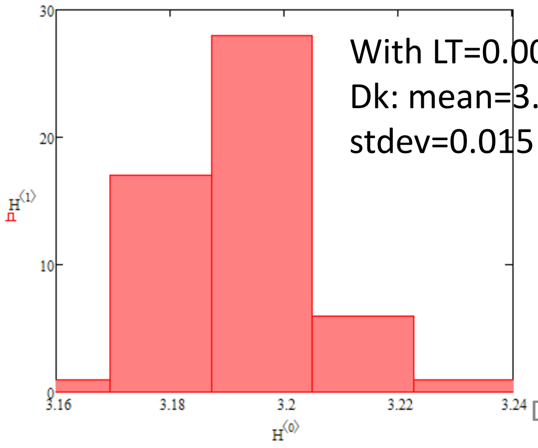


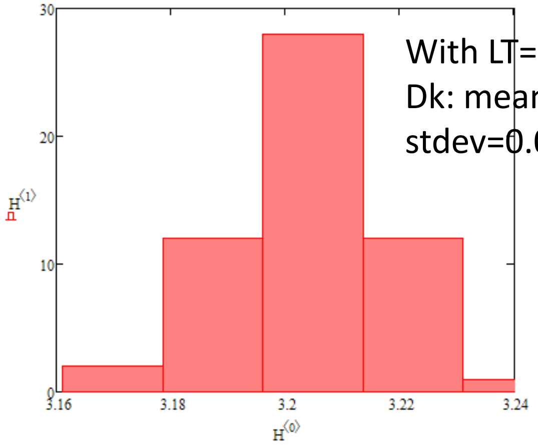
Roughness factor (RF)



Wideband Debye dielectric model – Dielectric constant (Dk @ 1 GHz)

Too many models to build –
too complicated!
Let's try to simplify

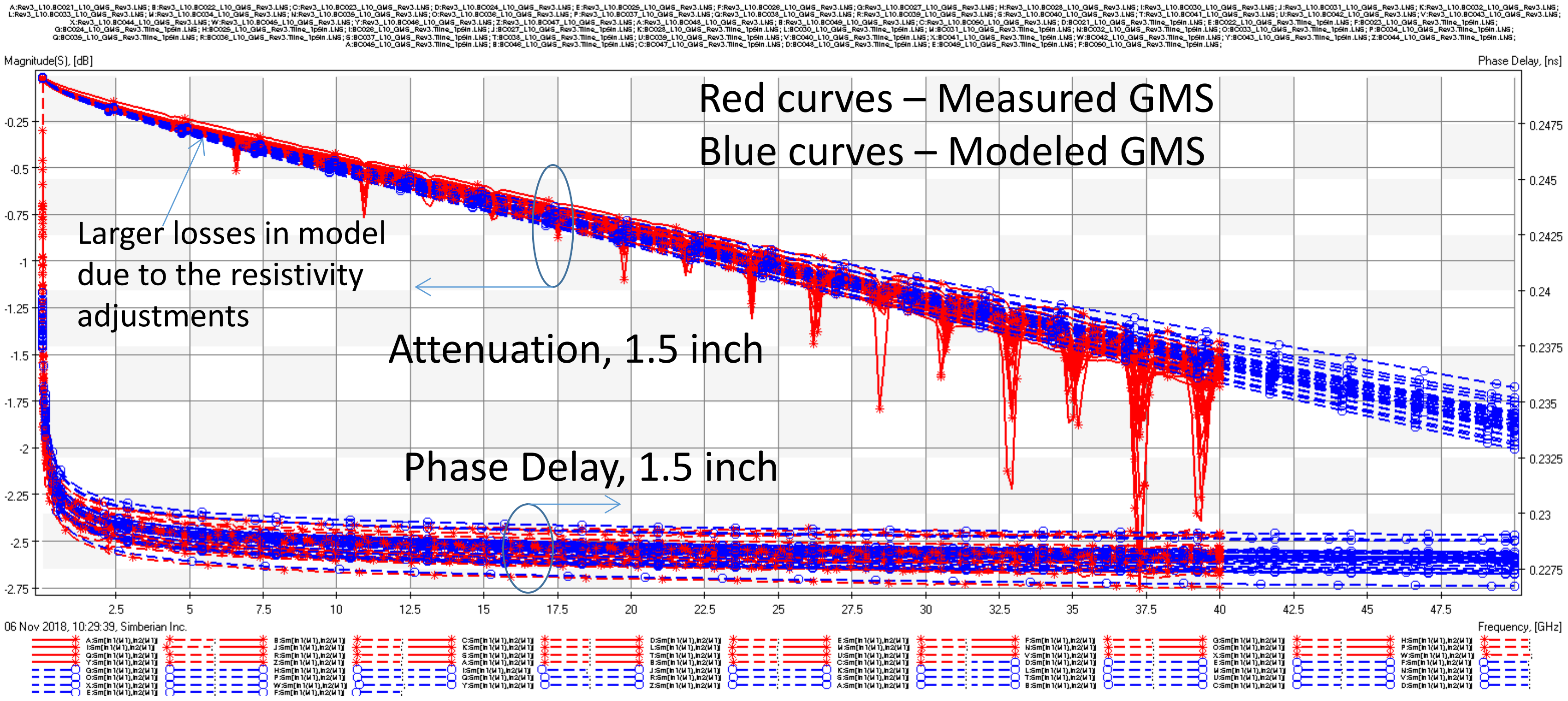




Rev3: GMS parameters correlation

LT=0.001 @ 1 GHz, Dk, RR, SR and RF are adjusted

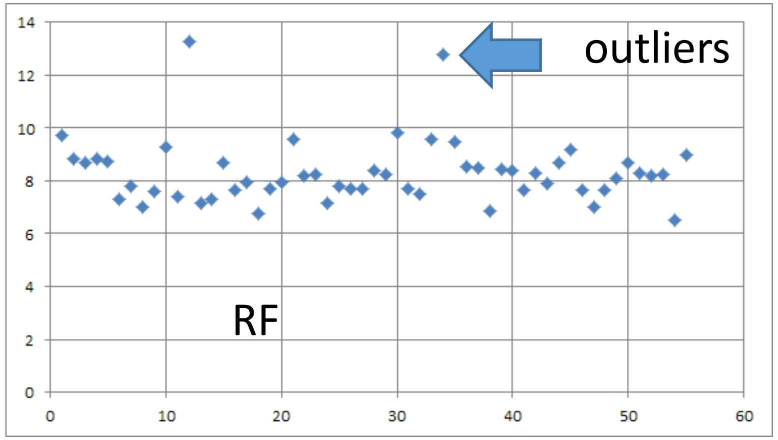
Rev3, 28 cases

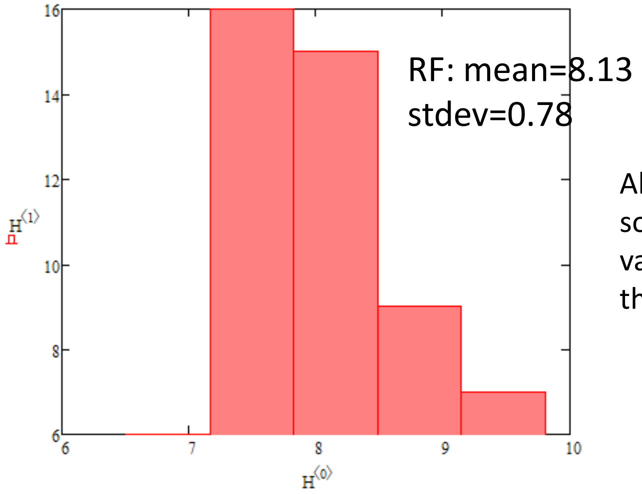


Simplified model: LT=0.001, RR=1.5, SR=0.15 um

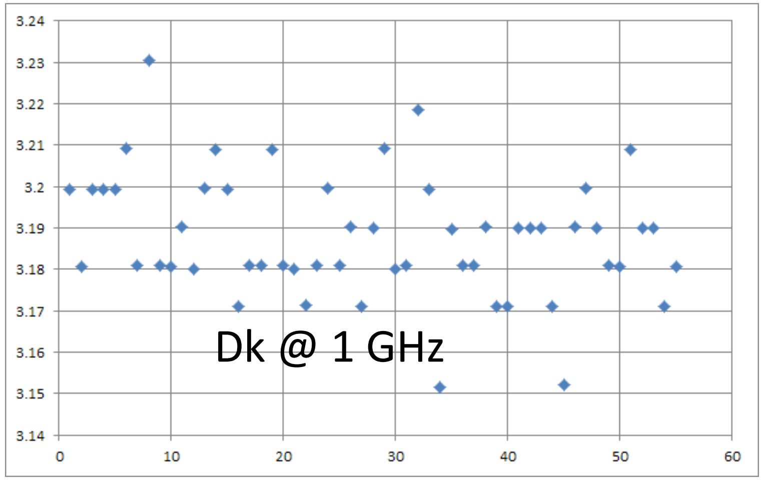
Relative Resistivity – RR=1.5, Roughness – SR=0.15 um, RF is adjusted
Wideband Debye model for dielectric – LT=0.001 @ 1 GHz, Dk is adjusted
Huray-Bracken model for roughness

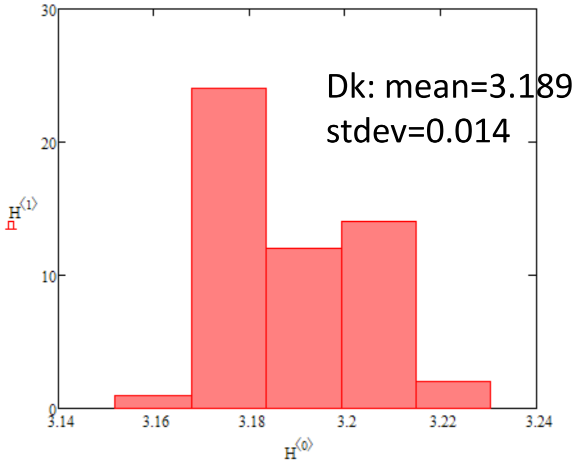
Mean values are used for relative resistivity (RR) and surface roughness (SR) parameters
Cross-section dimensions are adjusted as measured on short segment – that can be further simplified by use of the mean values
Characteristic impedance variations are defined by the cross-section variations in addition to the roughness and dielectric parameters – too many contributing parameters…





All conductor losses and some impedance variations are included in this parameter



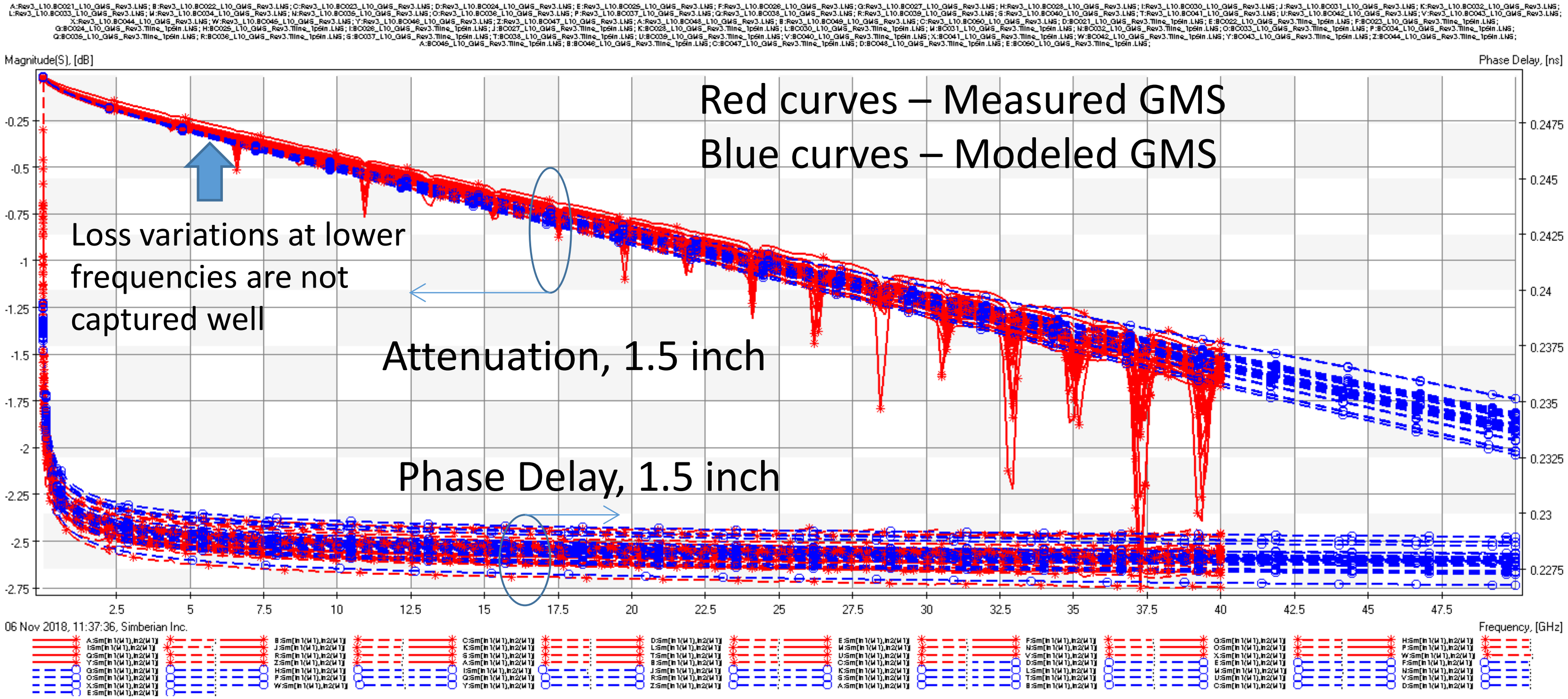


All phase delay variations and some impedance variations are included in this parameter

Rev3: GMS parameters correlation with simplified model

LT=0.001 @ 1 GHz, RR=1.5, SR=0.15 um, Dk, and RF are adjusted

Rev3, 28 cases



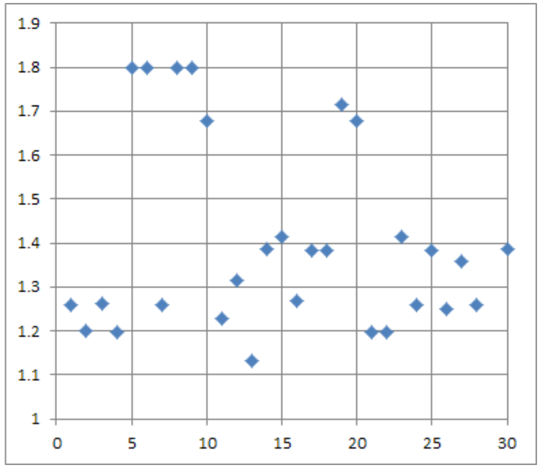
Simplified model works as well as the complete one – not much difference

Another option with fixed cross-section

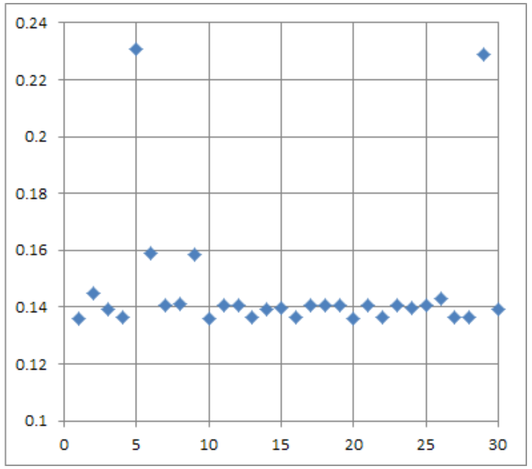
- Fix all cross-section parameters to mean values
- Identify Dk @ 1 GHz first by matching GMS phase delay from 2 to 40 GHz
- Identify relative resistivity (RR) with loss tangent LT @ 1 GHz simultaneously by matching GMS attenuation from 0.01 to 2 GHz (restrict RR range)
- Identify roughness model SR and RF parameters by matching GMS attenuation from 2 to 25-35 GHz
- Correct Dk @ 1 GHz by matching GMS phase delay from 2 to 40 GHz

Results with the fixed cross-section and simultaneous identification of RR and LT

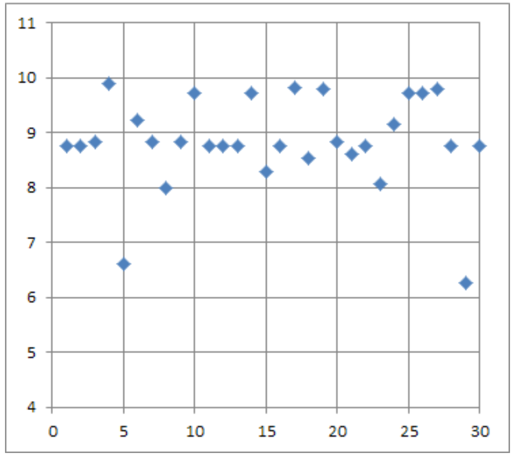
Relative resistivity



Surface roughness (SR, um)

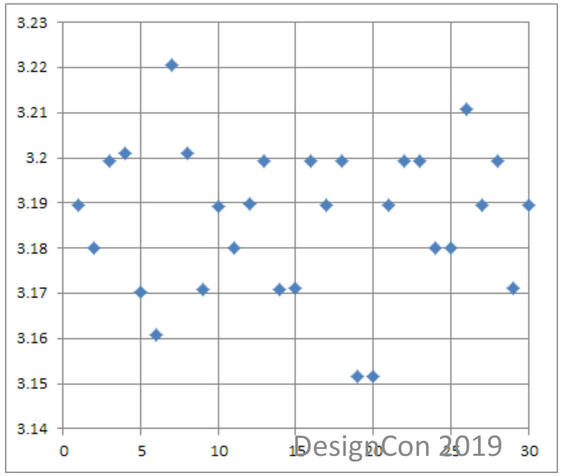


Roughness factor (RF)

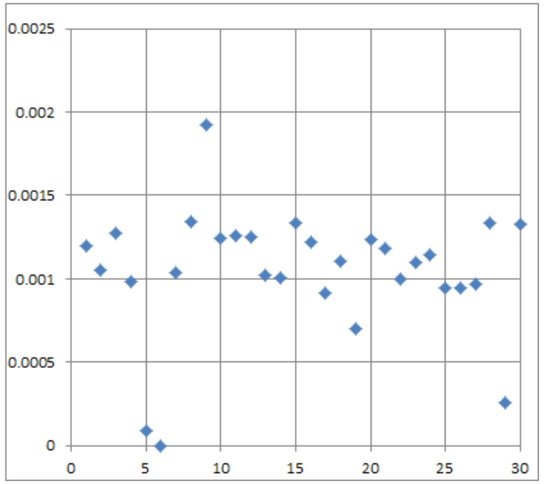


Data for Rev3 case

Dielectric constant DK @ 1 GHz

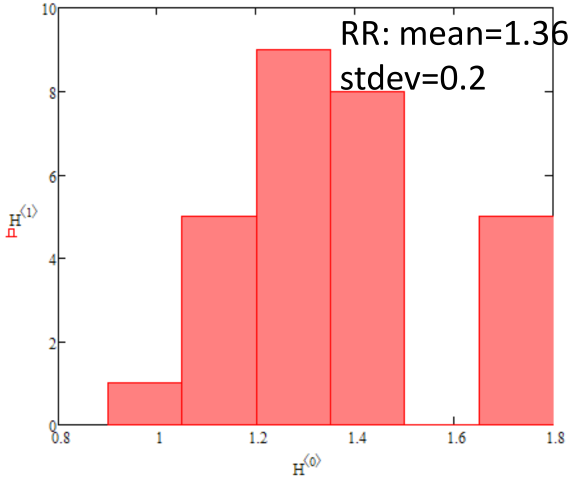


Loss tangent LT @ 1 GHz

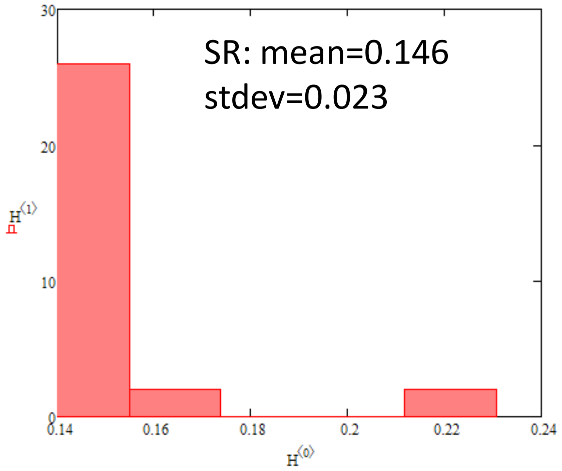


Results with the fixed cross-section and simultaneous identification of RR and LT

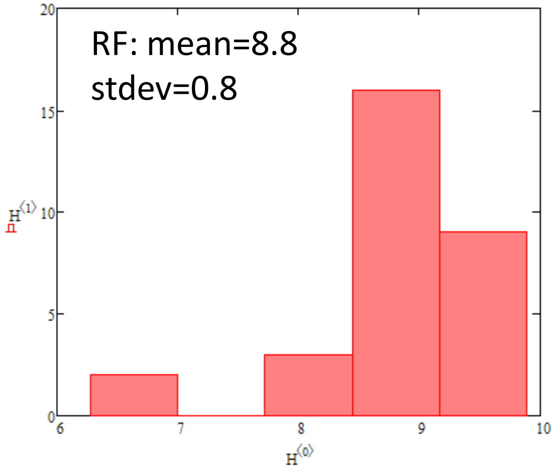
Relative resistivity



Surface roughness (SR, um)

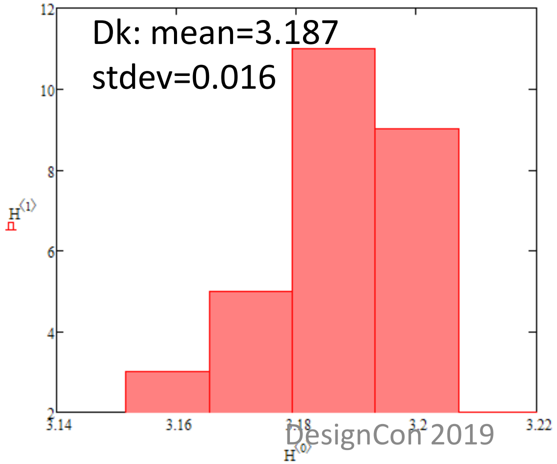


Roughness factor (RF)

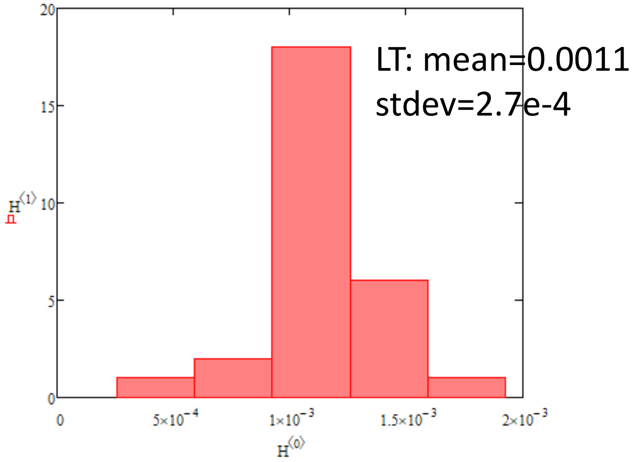


Data for Rev3 case

Dielectric constant DK @ 1 GHz

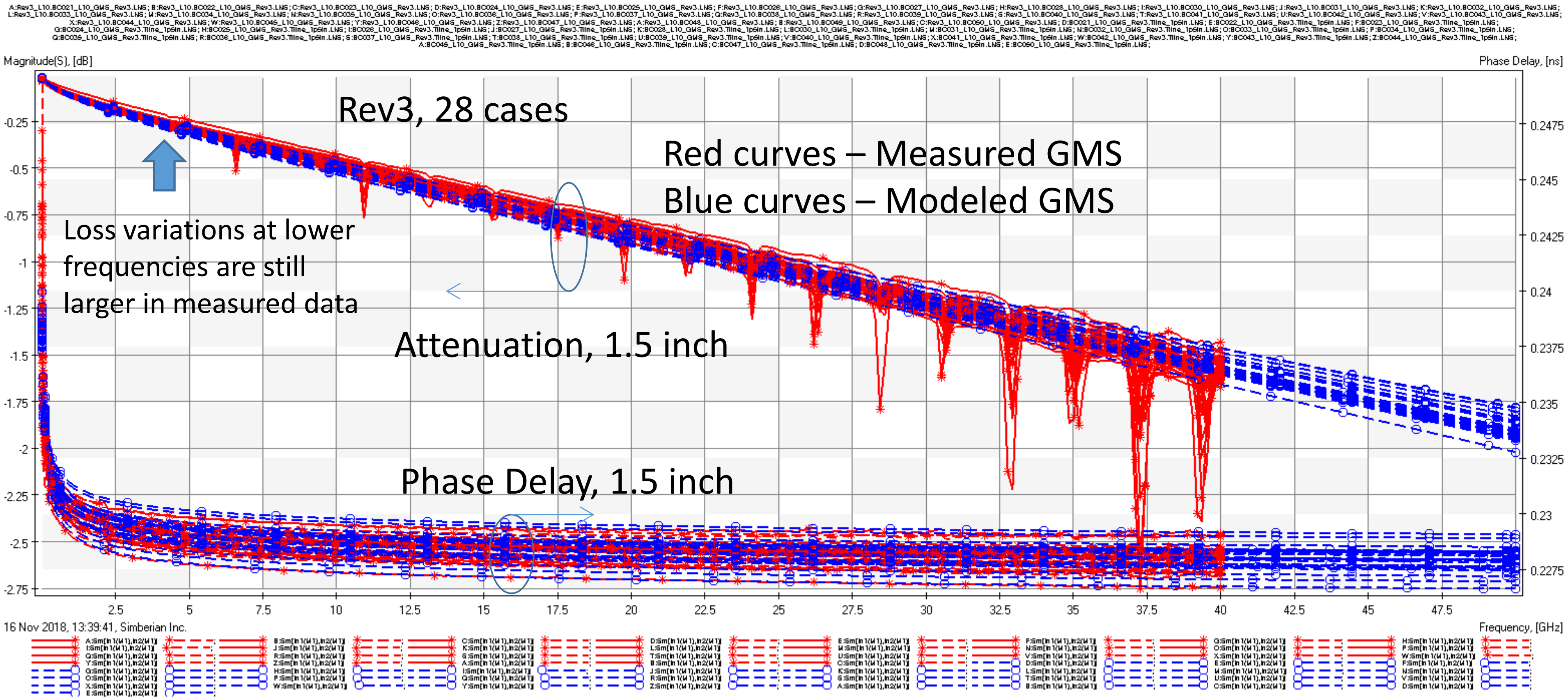


Loss tangent LT @ 1 GHz



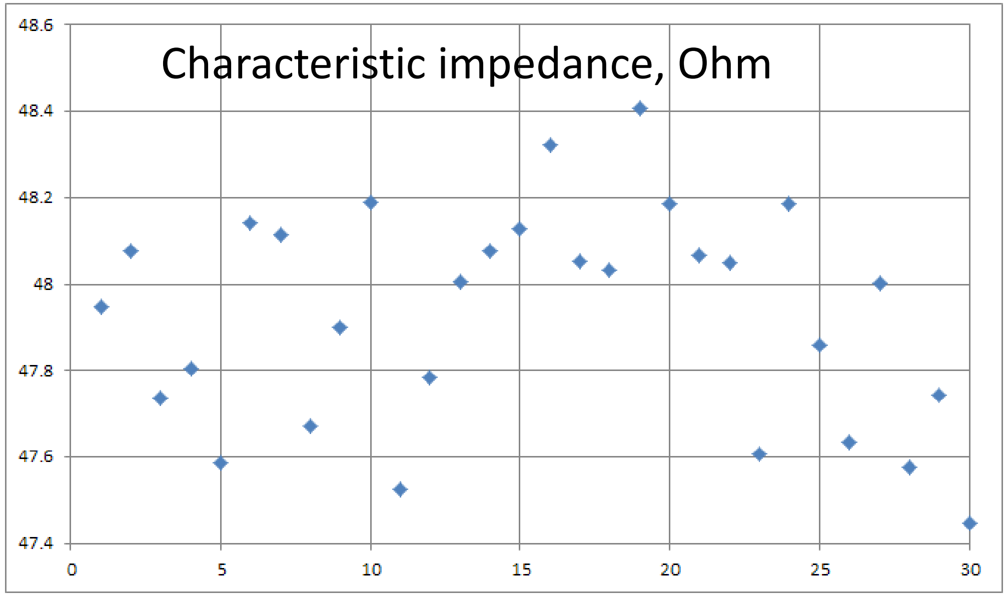
Rev3: GMS parameters correlation with fixed cross-section and simultaneous identification of RR and LT

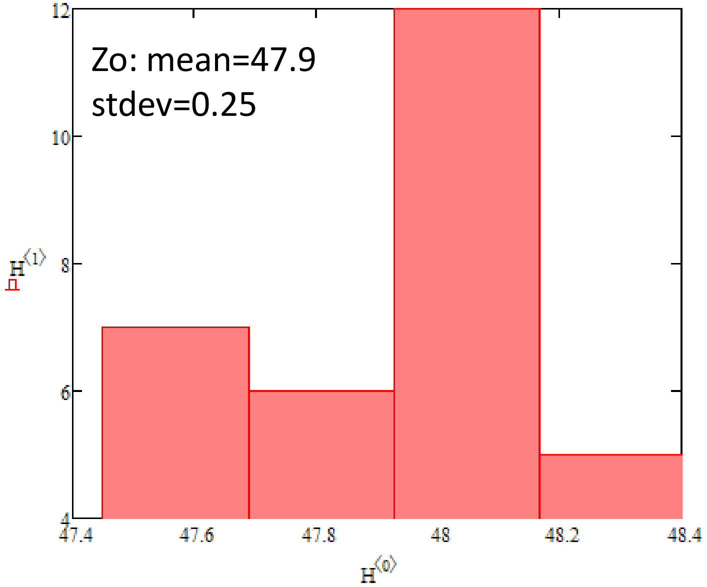
LT and RR are adjusted simultaneously, Dk, SR and RF are adjusted



This model is better, but still too complicated for practical use

Modeled characteristic impedance variations





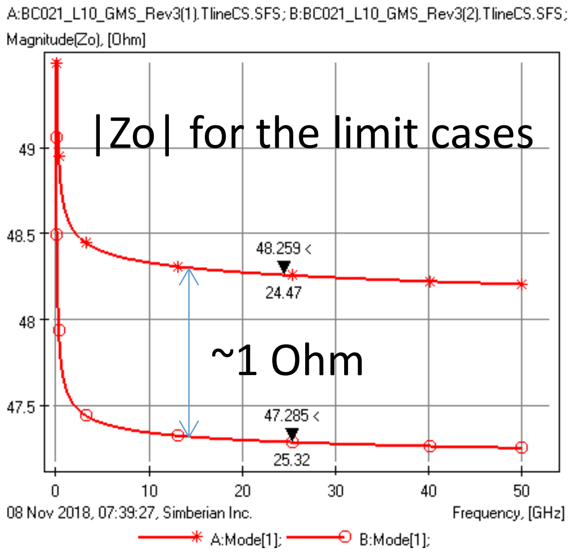
About 1 Ohm variation

Attempt to build the simplest models

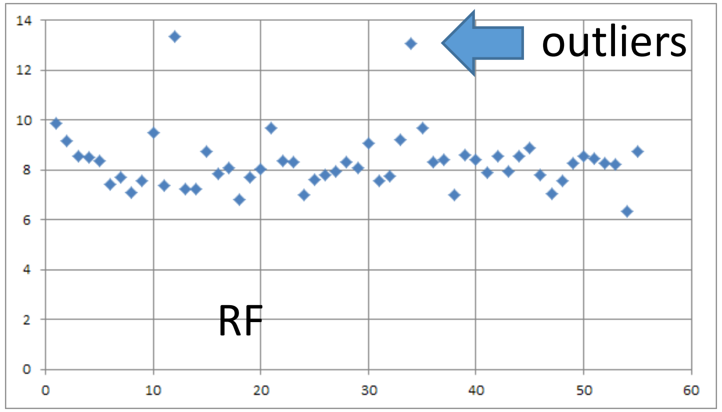
- Fix all cross-section parameters to mean values
- Fix loss tangent LT @ 1 GHz to 0.001 or mean value 0.0011 identified earlier
- Fix relative resistivity to a “reasonable” value RR=1.2 or to mean value RR=1.5 identified earlier
- Fix conductor roughness model parameter SR to some value or mean value identified earlier SR=0.15 um
- Identify roughness model RF parameter by matching GMS attenuation from 2 to 25-35 GHz
- Correct Dk @ 1 GHz by matching GMS phase delay from 2 to 40 GHz

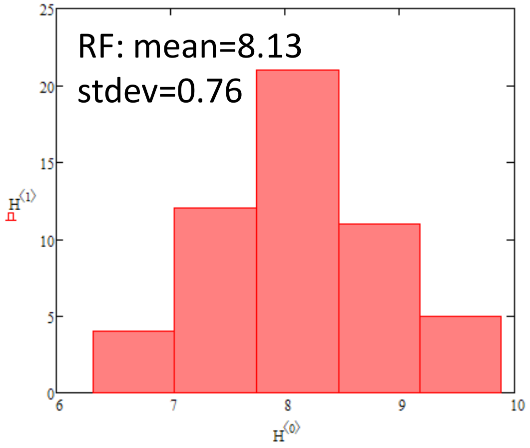
Simple statistical model (Tst=0.677, Wst=11.85): LT=0.001, RR=1.5, SR=0.15 um

Mean values are used for relative resistivity (RR), surface roughness (SR), strip thickness (Tst) and width (Wst) parameters
Characteristic impedance variations: Maximal roughness and minimal Dk give 48.26 Ohm and minimal roughness and maximal Dk give 47.29 Ohm

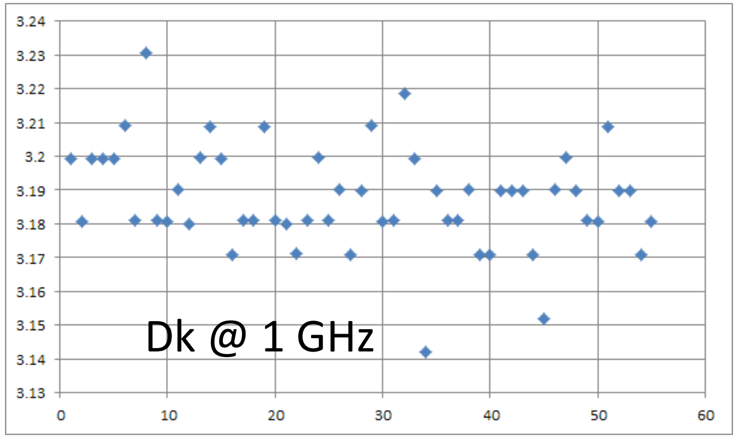


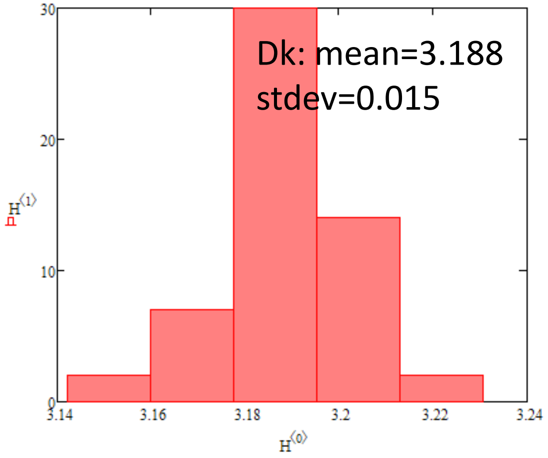
Relative Resistivity – RR=1.5, Roughness – SR=0.15 um, RF is adjusted
Wideband Debye model for dielectric – LT=0.001 @ 1 GHz, Dk is adjusted
Huray-Bracken model for roughness





All conductor losses and some impedance variations are included in this parameter



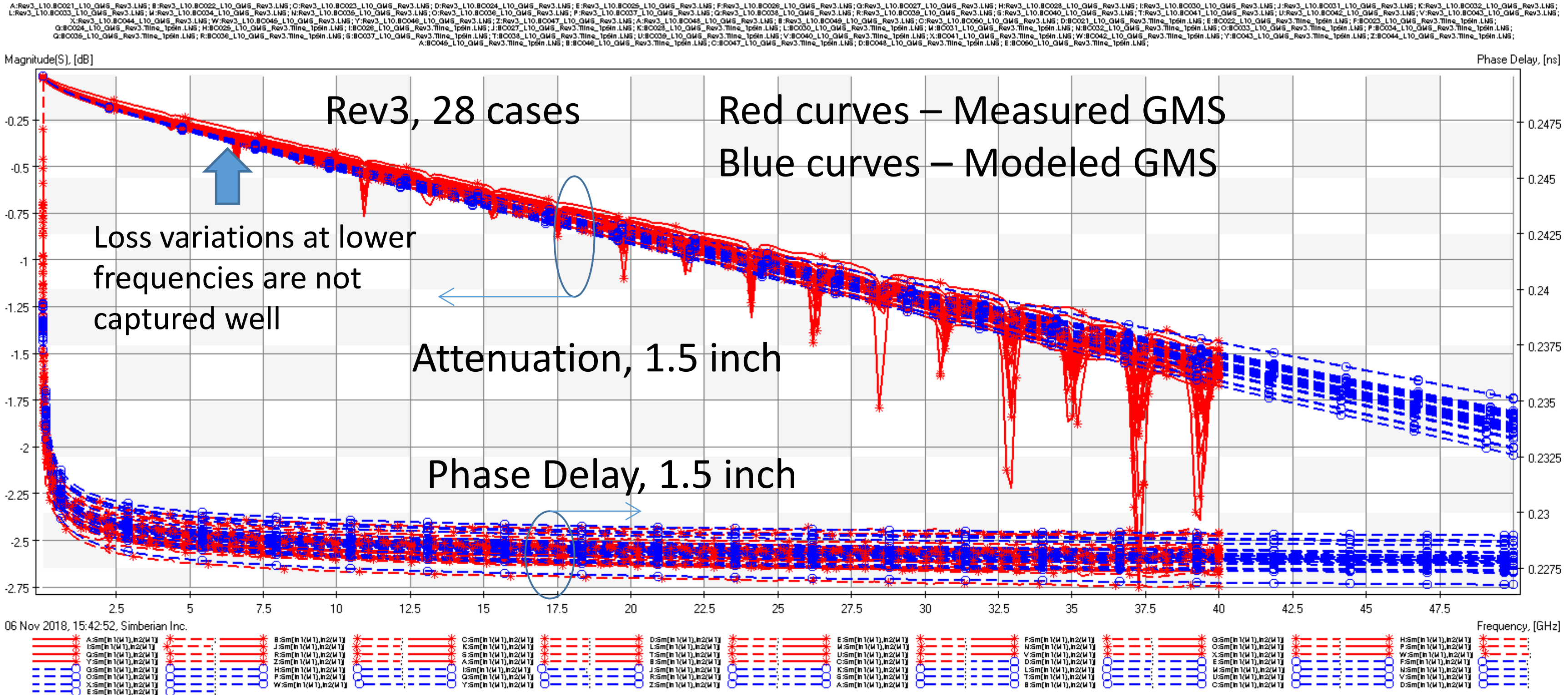


All phase delay variations and some impedance variations are included in this parameter

Rev3: GMS parameters correlation with simplified model and fixed trace thickness and width

LT=0.001 @ 1 GHz, RR=1.5, SR=0.15 um, Dk, and RF are adjusted

The model quality at lower frequencies can be further improved by taking into account the actual strip geometry variations

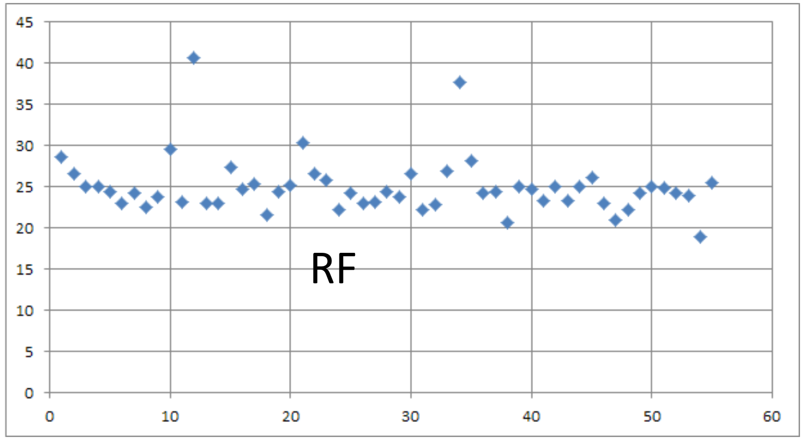


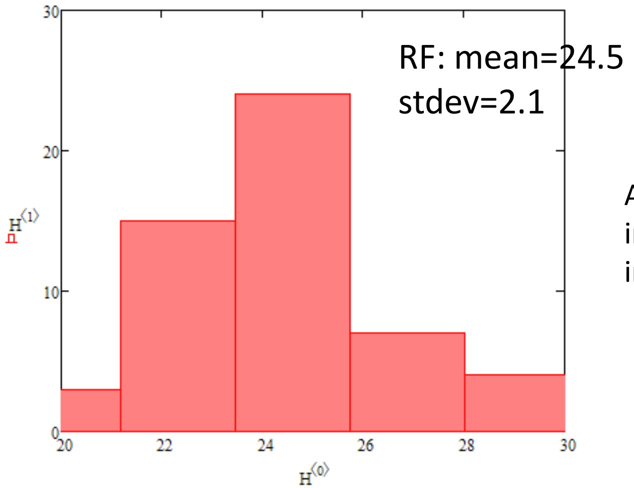
Simplified model with fixed cross-section works reasonably good

Another option with lower relative resistivity (LT=0.001 @ 1 GHz, RR=1.2 case)

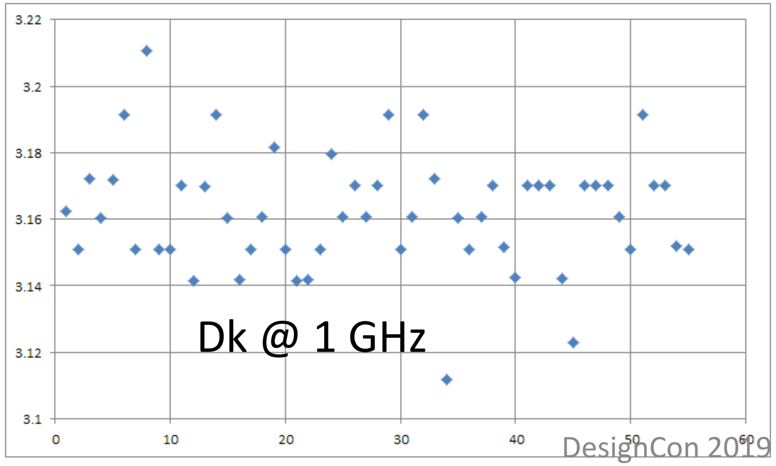
Relative Resistivity – RR=1.2, Roughness – SR=0.075 um, RF is adjusted
Wideband Debye model for dielectric – LT=0.001 @ 1 GHz, Dk is adjusted
Huray-Bracken model for roughness

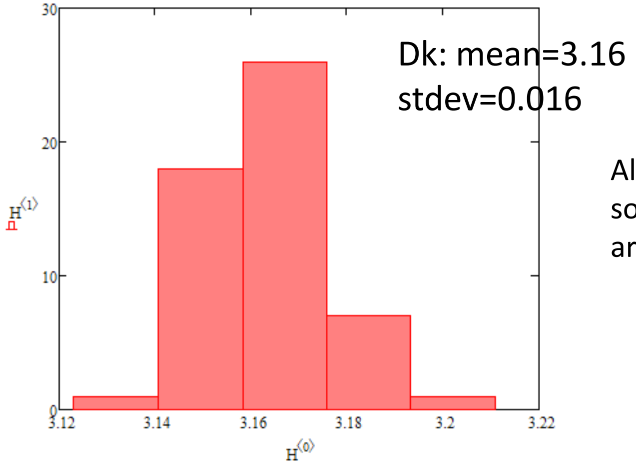
Simple statistical model with mean values for strip thickness and width (Tst=0.677, Wst=11.85), and fixed values for loss tangent, relative resistivity and surface roughness SR parameters





All conductor losses and some impedance variations are included in this parameter





All phase delay variations and some impedance variations are included in this parameter

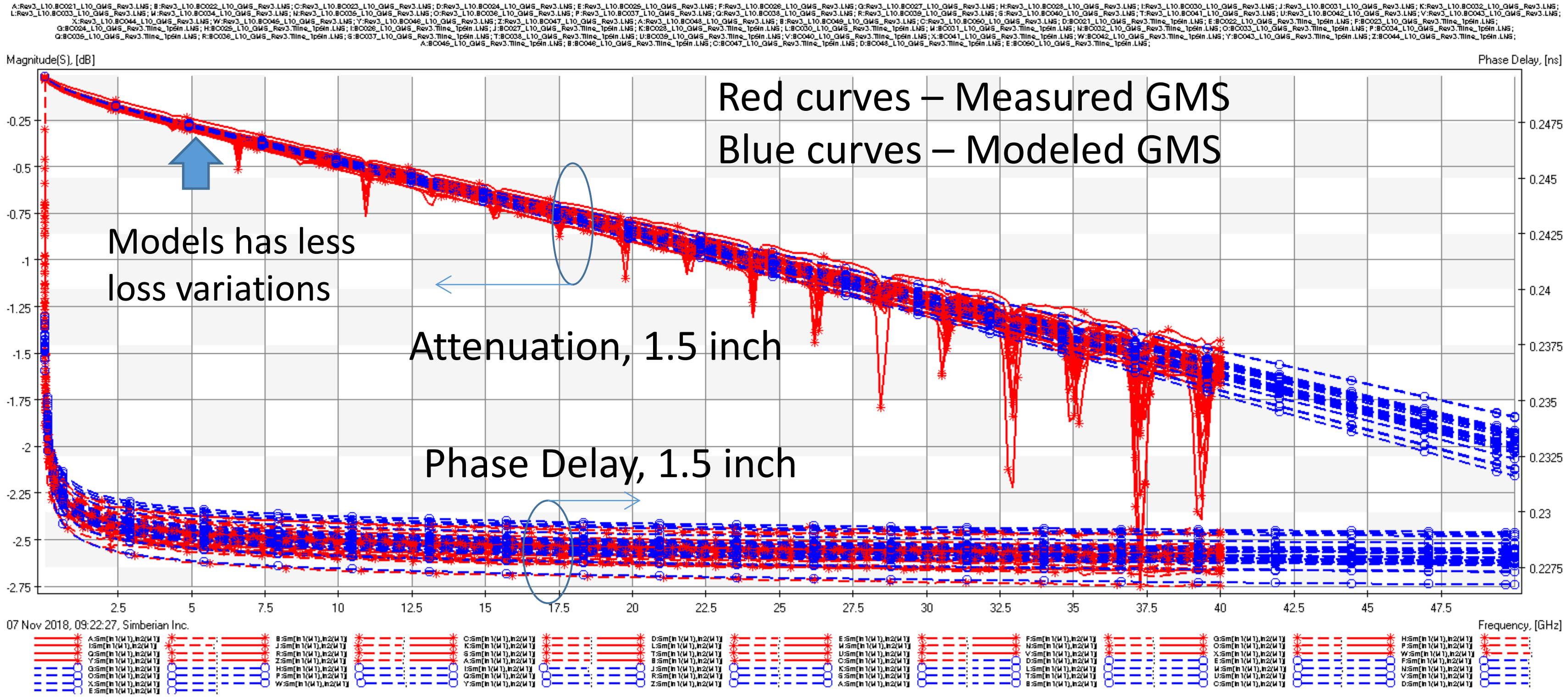
Rev3: GMS parameters correlation with simplified model with lower relative resistivity

Tst=0.677, Wst=11.85, LT=0.001 @ 1 GHz, RR=1.2, SR=0.075 um, Dk, and RF are adjusted

Technically, it is impossible to model such wide variations of the losses at lower frequencies without realistic model for strip geometry variations

Loss tangent LT=0.002 produces very similar results with smaller loss variations comparing to the measured

Rev3, 28 cases



Conclusion

- Variations in interconnect losses and dispersion are reduced to two model variables with acceptable accuracy
- Identified material model are usable up to 50 GHz – that is suitable for 56 Gbps PAM4 signal analysis
- Trace geometry and roughness causes most of the loss variations in this extremely low loss dielectric case
- Relatively small variations in identified dielectric constant
- About half of the observed impedance variations can be from change in dielectric constant (0.5 Ohm) and half from the conductor roughness (0.5 Ohm) – the rest is probably due to the geometry variations and fiber weave effect
- Further development
  - Measure bulk resistivity of copper – it will add more certainty into the identification process
  - Get rid of the peaks in the GMS insertion loss (use better connectors, trace orientation)
  - Use Kolmogorov-Smirnov test to identify distributions for the conductor and dielectric model parameters and may be for trace thickness (major contributor to loss and impedance)