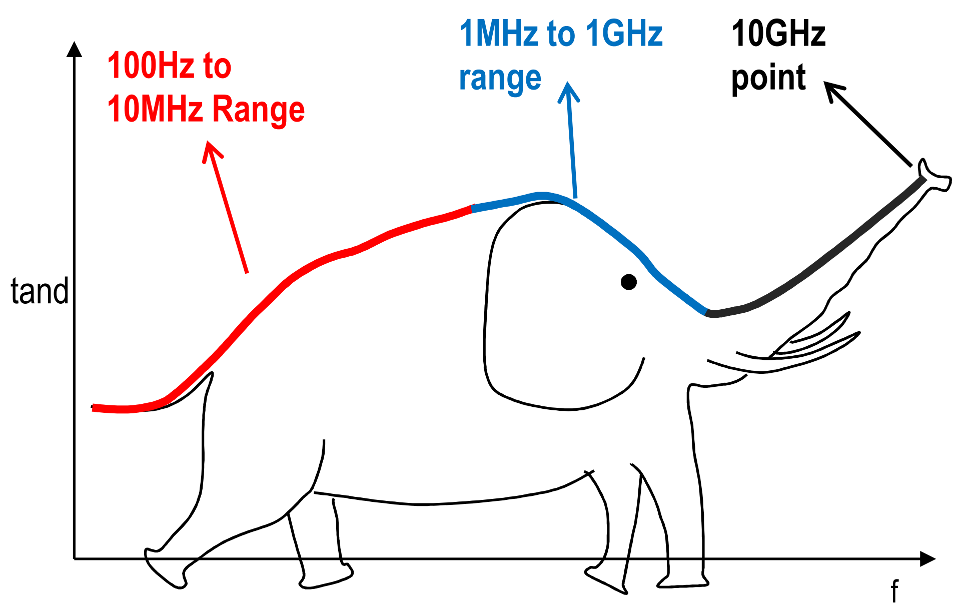
Inter-Dependence of Dielectric and Conductive Losses in Interconnects

Gustavo J. Blando

It all started in 2009.
We just wanted to measure the loss tangent!!!!

THE ELEPHANT



Industry Trend

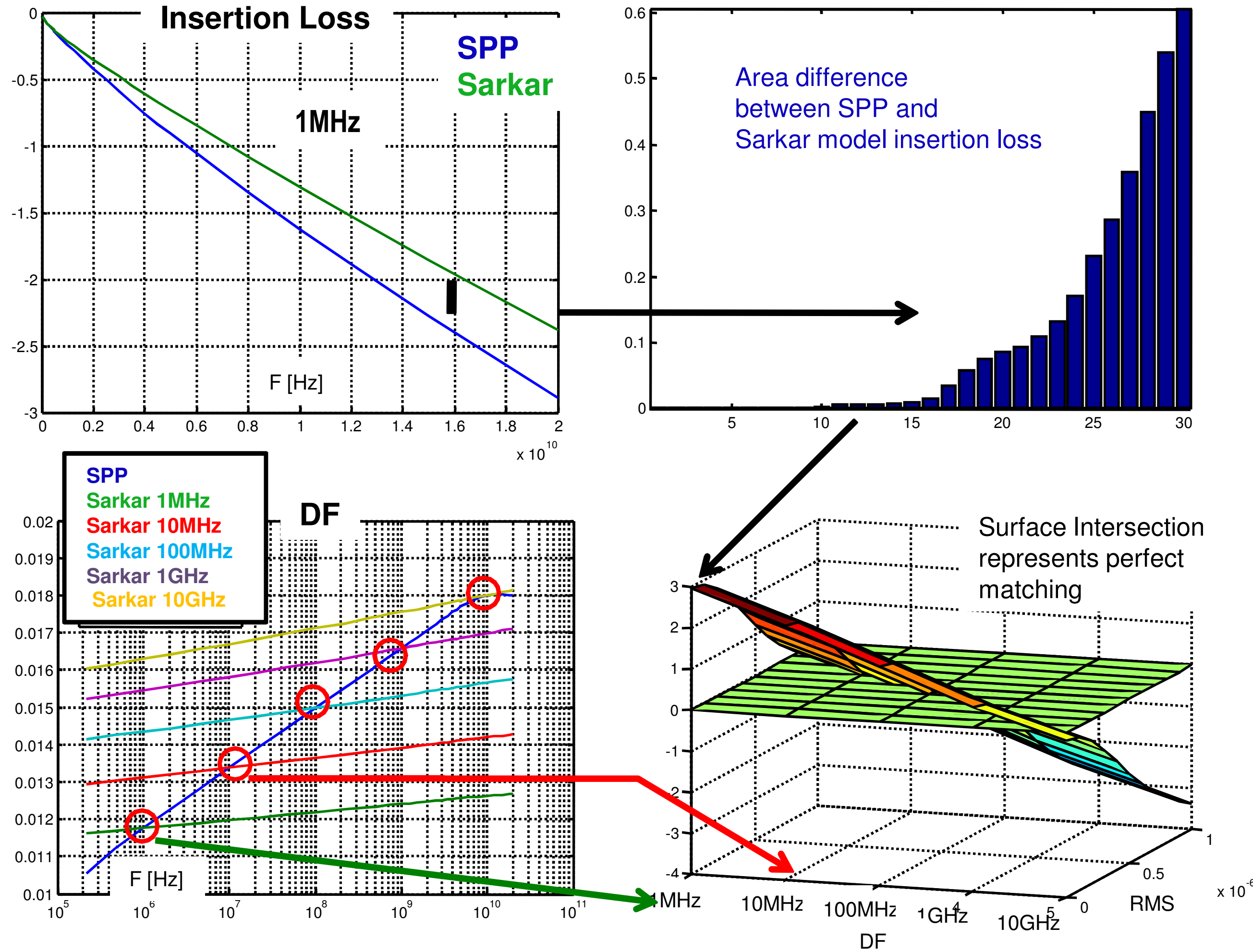
Pressed stack loss measurement methods:
Rely on a combination of models and measurements to extract losses. In particular when conductor/dielectric loss separation is required

Hinckley, et al., "Introduction and Comparison of an Alternate Methodology for Measuring Loss Tangent of PCB Laminates," DesignCon2010, Santa Clara, CA, February 1-4, 2010

A Simple Test Case

By adjusting one of the parameters a perfect match can be obtained, even for very different loss tangent profiles

As a minimum, this begs two questions:
1. How “correct” are these models?
2. Good correlation against what?



Is It possible to **DIRECTLY** measure copper and dielectric losses on a pressed stack?

(Without pre-assuming a model)

Theory

- Is it theoretically possible?
- If we were able to extract RLGC from measurement, separation of conductive and dielectric losses is automatic!!!!!!

Telegraphers Equation

$$\frac{d^2 I(z)}{dz^2} = \gamma^2 I(z) \qquad \frac{d^2 V(z)}{dz^2} = \gamma^2 V(z)$$

$$\gamma = \sqrt{z \cdot y} = \sqrt{(r + j\omega l) \cdot (g + j\omega c)}$$

$$= \alpha + j\beta$$

$$Zc = \sqrt{\frac{z}{y}} = \sqrt{\frac{(r + j\omega l)}{(g + j\omega c)}}$$

We are still assuming the t-line works in a TEM or Quasi-TEM mode.

Lossy Transmission Line ABCD

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A = \cosh(\gamma l) & B = -Zc \cdot \sinh(\gamma l) \\ C = -\frac{\sinh(\gamma l)}{Zc} & D = \cosh(\gamma l) \end{bmatrix} \cdot \begin{bmatrix} V_0 \\ I_0 \end{bmatrix}$$

$$\boxed{\gamma = \frac{a\cosh(A)}{l} \qquad Zc = \sqrt{\frac{B}{C}}}$$

The fundamental parameters we need to determine RLGC are: Propagation Constant and Characteristic Impedance

$$z = r + j\omega l = Zc \cdot \gamma$$

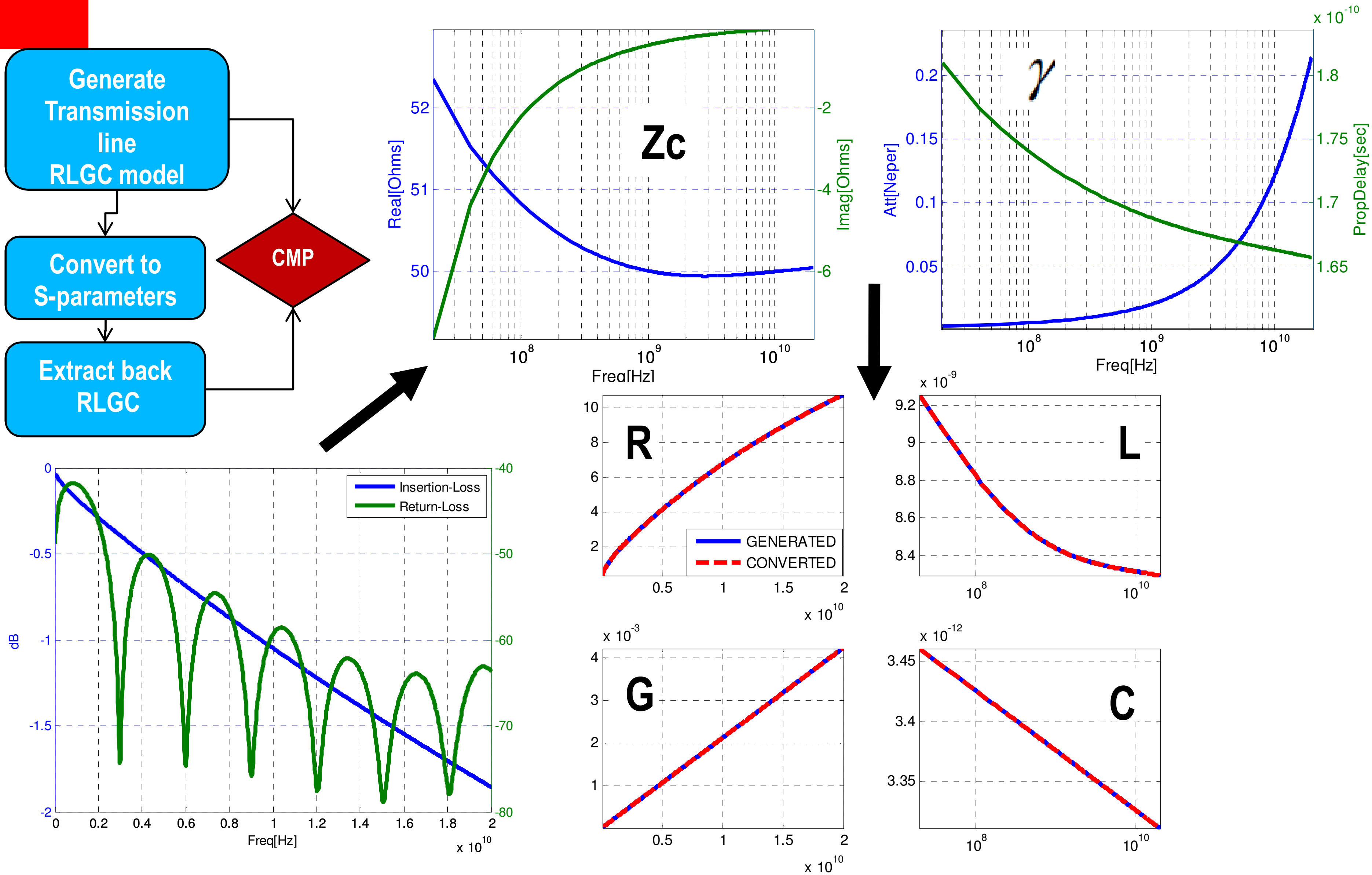
$$r = \mathrm{Re}(z), l = \frac{\mathrm{Im}(z)}{\omega}$$

$$\underbrace{df = g/(2 * \pi * \omega * c)}_{\text{Loss tangent}}$$

$$y = g + j\omega c = \frac{\gamma}{Zc}$$

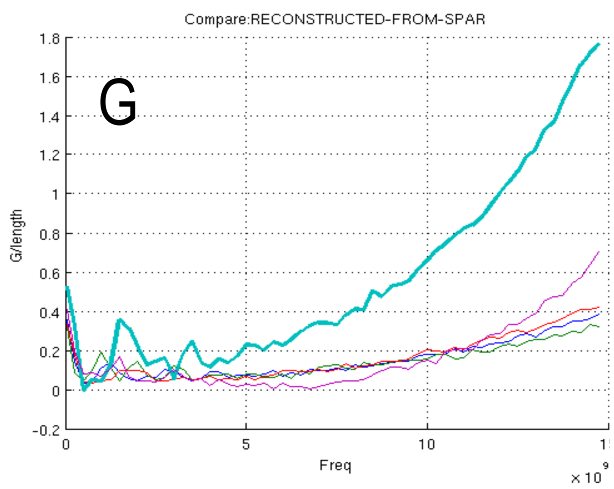
$$g = \mathrm{Re}(y), c = \frac{\mathrm{Im}(y)}{\omega}$$

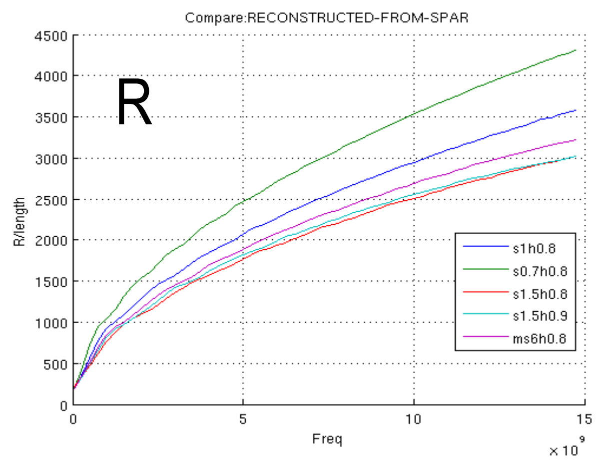
Proof of Concept (Simulated Test-Case-1)

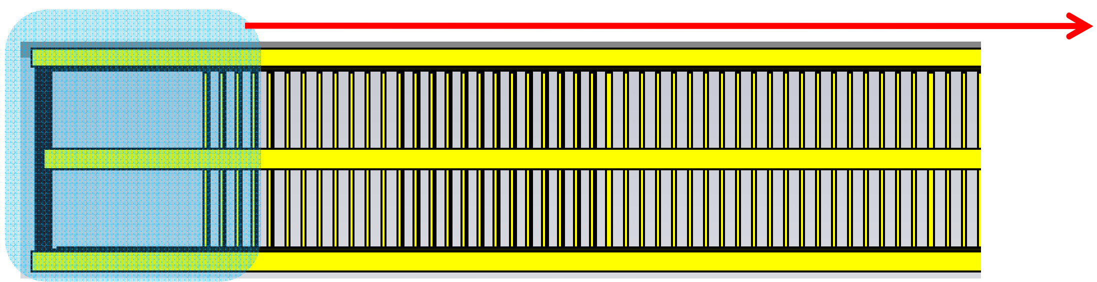


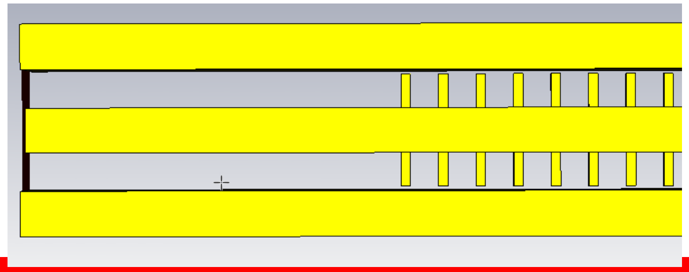
Interesting Applications on Simulated Data

- Explore the equivalent "uniform" RLGC parameters from a non-uniform 3-D structure.
- Lossless material with copper traces and perpendicular blades
- Does G and R change for different blade heights ?
- This methodology can help us explore the inner working of structures



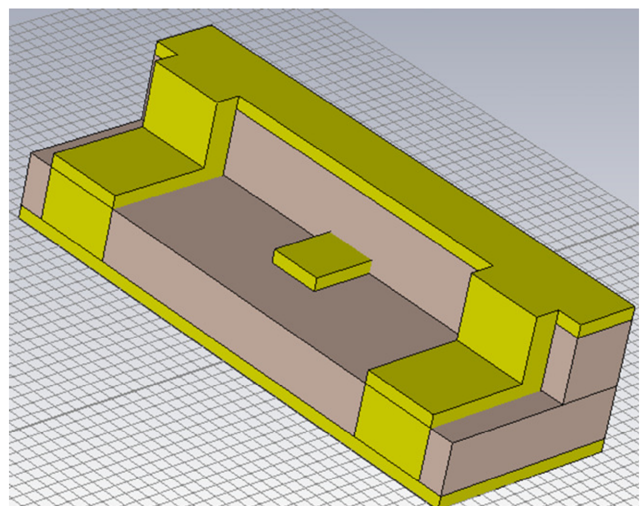






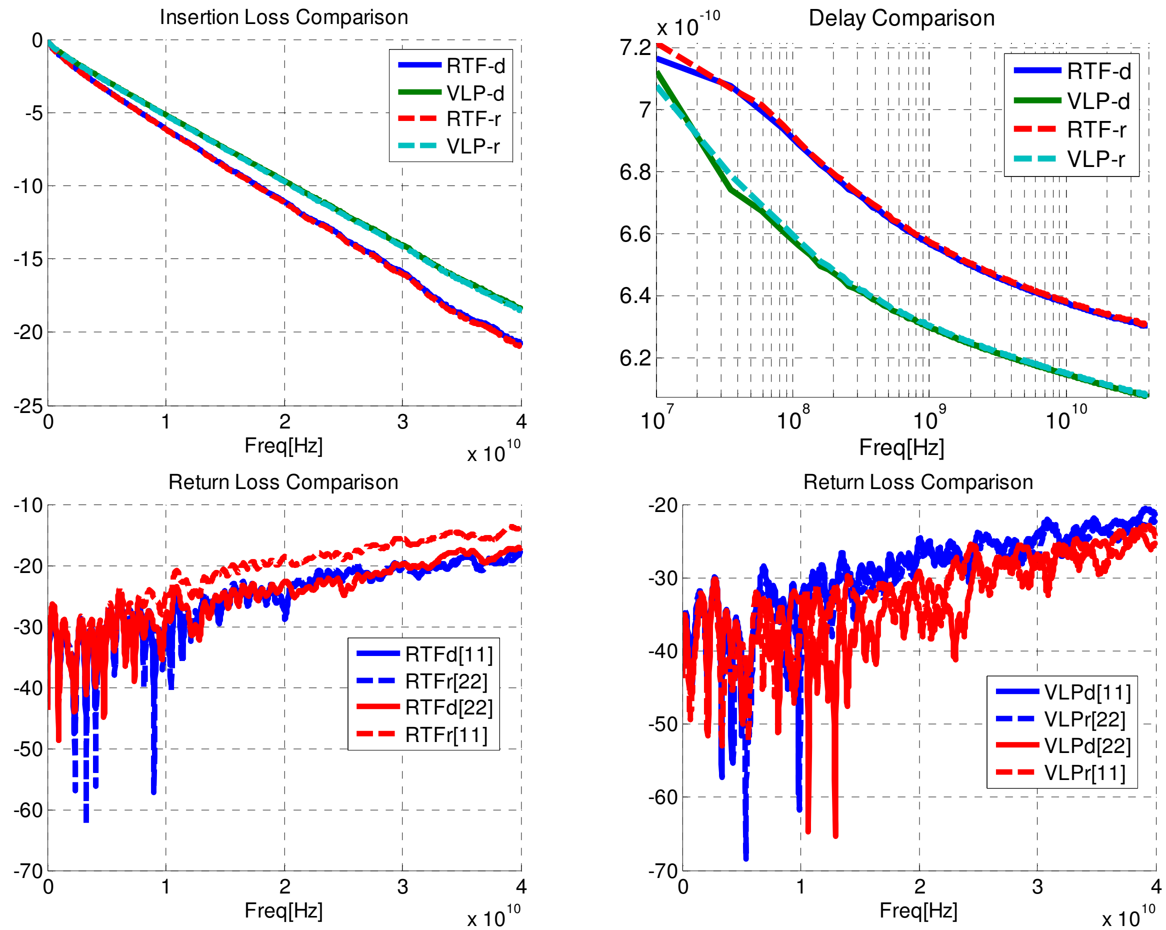
Let’s try the Process on Measurements

- Any type of discontinuities have to be minimized
- Wafer probes: GSG-225um
- SOLT calibration (to the TIPS of the wafer probes)
- Very small lead-in trace before the “uniform” piece of transmission line
- Bottom and top GND plane connected to minimize current path redistribution
- Four measurements per set were done, all on the SAME transmission line (long, long-reverse, and after cutting the same line we measured short and short-reverse)

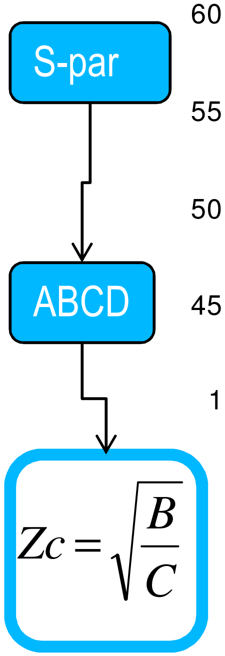


S-Parameter Measurements

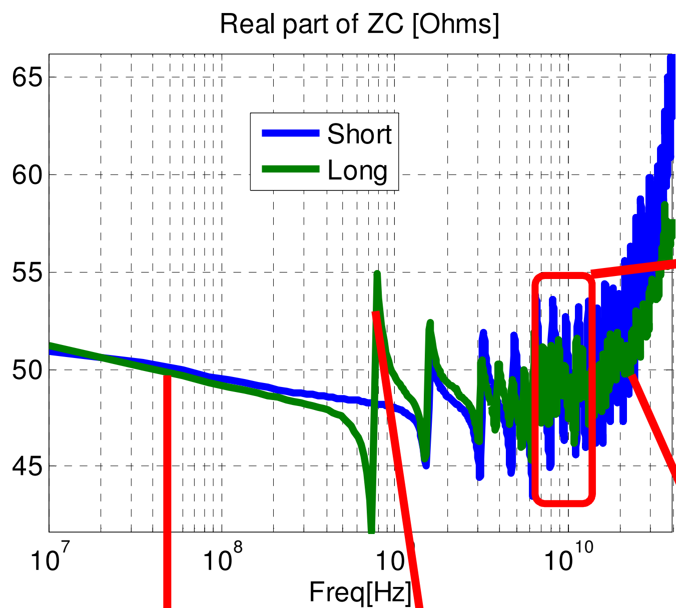
- Two samples shown (RTF and VLP), at two lengths (short, long)
- Very good insertion loss profile
- Reasonable return loss <-20dB up to 20GHz

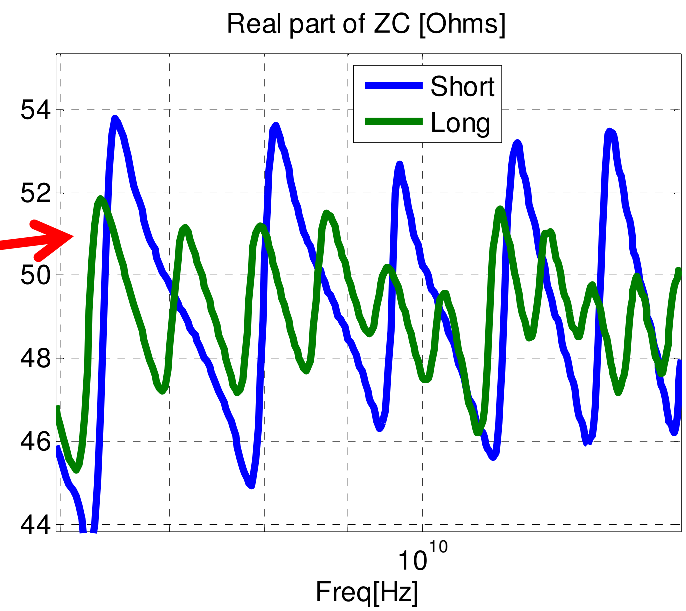


SO HOW DOES Zc LOOK!!!



$$Zc = \sqrt{\frac{B}{C}}$$





Upslope trend, maybe inductive discontinuity

½ wave resonance (end discontinuities)

In general pretty good overall baseline value, and correct trend

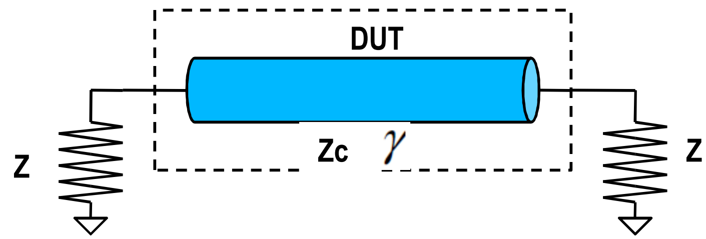
- Clearly, in contrast with simulation data, even very clean measurements have other issues. Other effects, such as error-terms, need to be considered if we ever hope to extract Zc cleanly.

Characteristic Impedance Extraction Methods

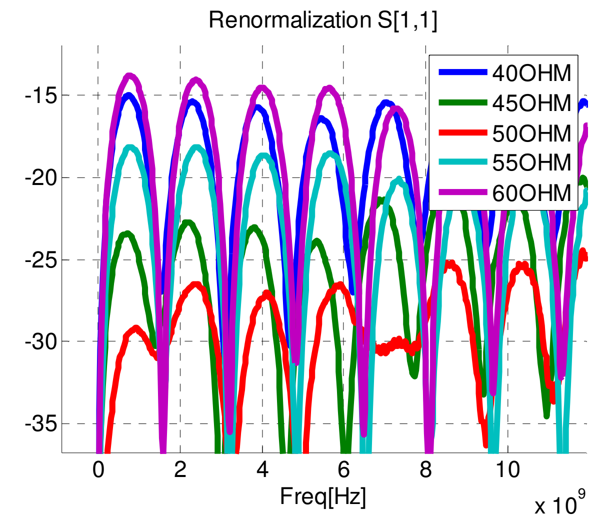
- Direct Inversion Method (shown previously)
- Impedance Renormalization
- Error Model Calculation
- Maximum Identification
- Frequency Adjustment

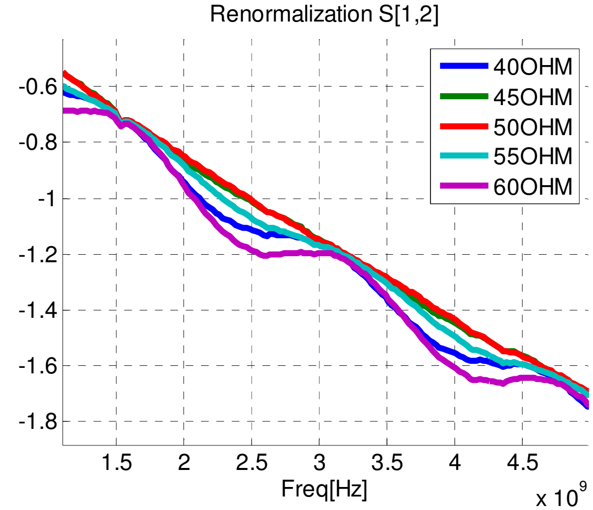
- Extraction of propagation constant has been shown in previous publications. In this work we'll focus primarily on Characteristic Impedance (Zc).

Characteristic Impedance by Renormalization Theory



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \left.\vphantom{\begin{bmatrix} a \\ a \end{bmatrix}}\right\} \text{With respect to Z}$$

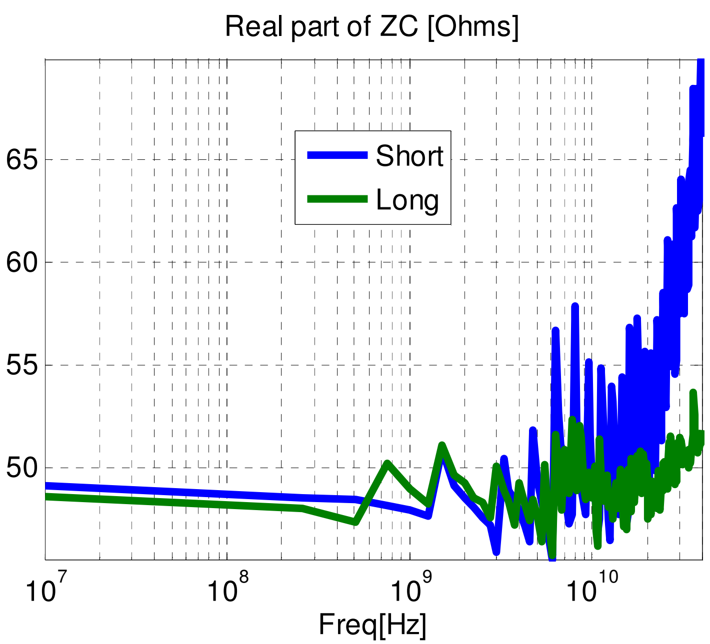


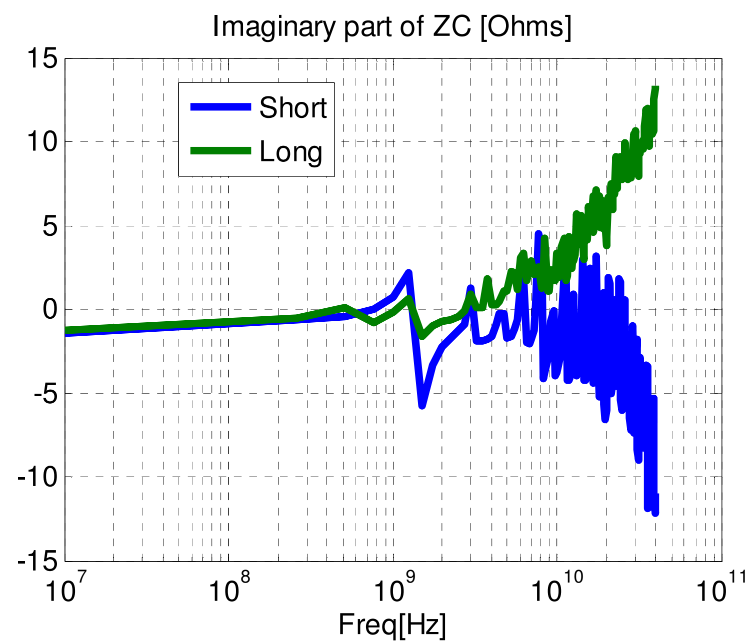


- Reflections (at the load) can be modified by mathematically changing “Z”. This is called impedance renormalization
- If Zc were known and used as the reference impedance, the reflection would be zero
- The method consist of doing a frequency dependent complex impedance renormalization to minimize the reflection on the curve

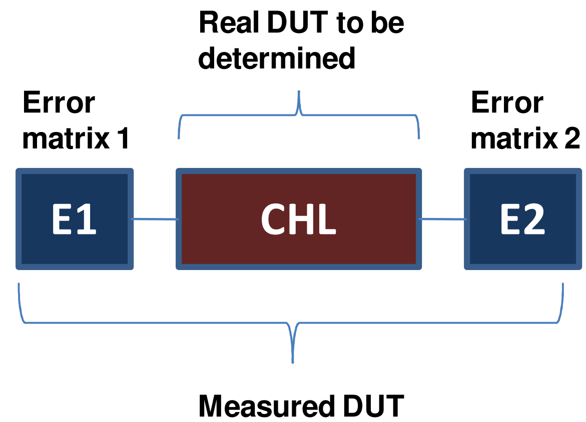
Characteristic Impedance by Renormalization Results

- We see that the improvement is minimal and likely due to the averaging of the algorithm.
- Two independent methods, similar results.
- **Are we only measuring the transmission line?**



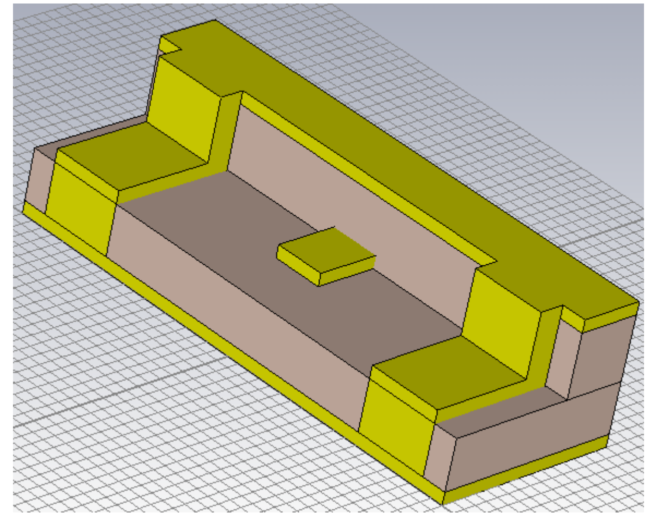


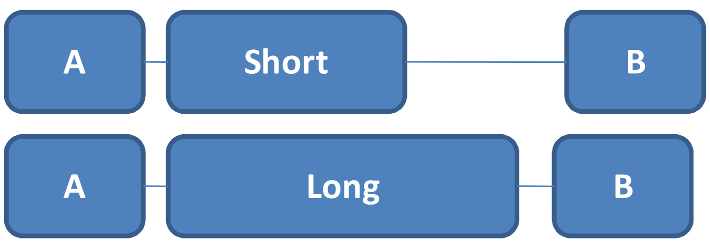
Characteristic Impedance by Error Model



Error terms could be:

- End physical discontinuities
- Measurement repeatability
- Instrument / Calibration errors
- Instrument noise floor
- Others ?





$$E = \begin{bmatrix} A_{e1} & B_{e1} \\ C_{e1} & D_{e1} \end{bmatrix} = \begin{bmatrix} 1 + z_e y_e & z_e \\ y_e & 1 \end{bmatrix}$$

- By measuring two lines (long and short), the complex propagation constant can be easily extracted
- This is not sufficient to get Zc, something else is needed?

$$N = (ABCD_{long}) \cdot (ABCD_{short})^{-1}$$

$$ye = error\_matrix$$

$$Zc^2 = \frac{\left[(N_{11} - 1)^2 + N_{12} \cdot N_{21}\right] \cdot \left[(N_{11} + 1)^2 + N_{12} \cdot N_{21}\right]}{\left[-2 \cdot N_{21} \cdot N_{11} + ye \cdot \left(N_{11}{}^2 - N_{12} \cdot N_{21} - 1\right)\right]^2}$$

Shlepnev, et al., "Practical Identification of Dispersive Dielectric Models with Generalized Modal S-parameters for Analysis of Interconnects in 6-100Gb/s Applications," DesignCon2010, Santa Clara, CA, February 1-4, 2010

Error Model Validation By Simulations and Measurements Results

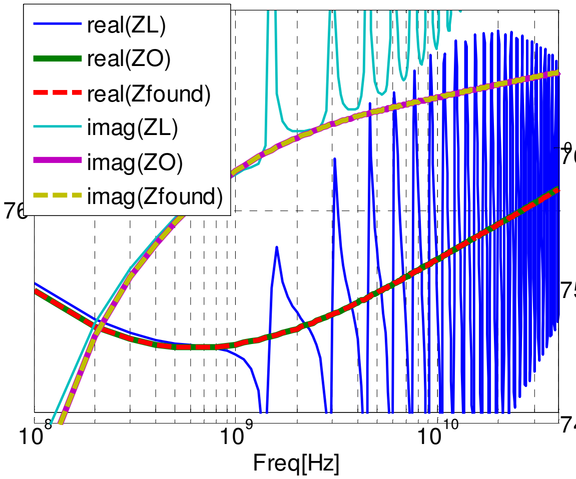
Left: Smaller discontinuity:

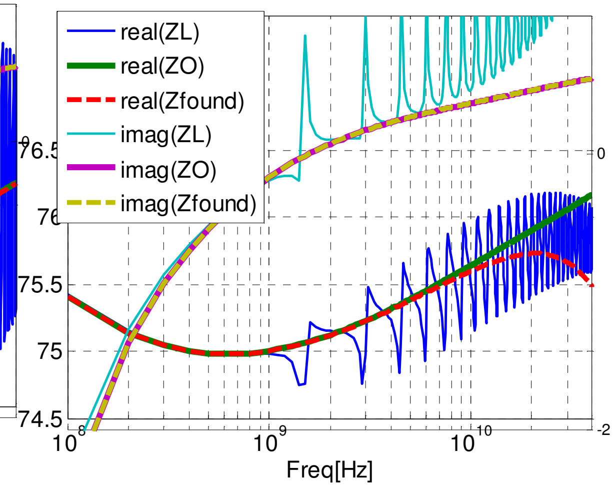
RLGCa=0.001, 0.03nH,0.5fF,1e-5
RLGCb=0.002,0.01nH,0.5fF,1e-5

Right: Bigger discontinuity

RLGCa=0.001, 0.03nH,50fF,1e-3
RLGCb=0.002,0.01nH,50fF,1e-3

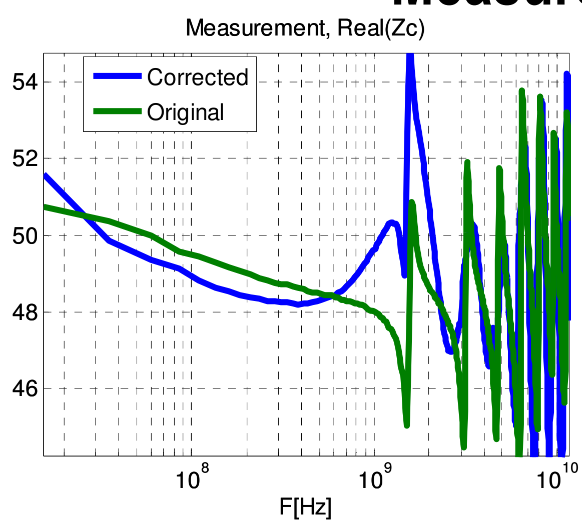
Simulated Data

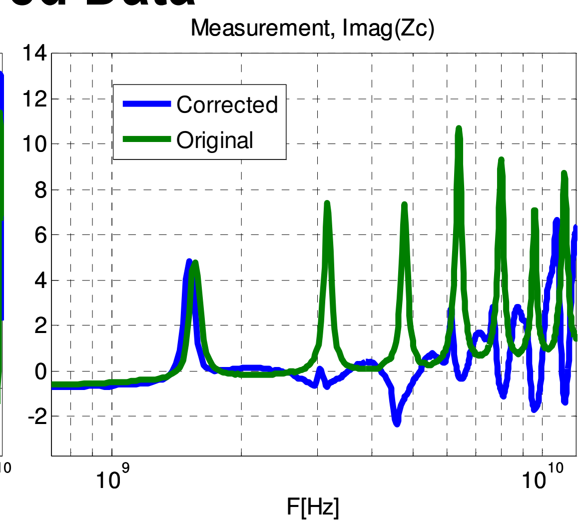


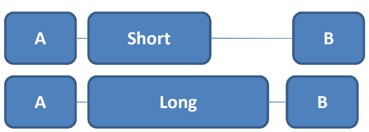


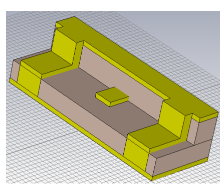
- The extraction is trying to correct the behavior but is unable to remove all the peaks and valleys

Measured Data









More repetitive connection (SMA) would work better but it would have to be done on different physical lines

Characteristic Impedance by Maximum Identification (1)

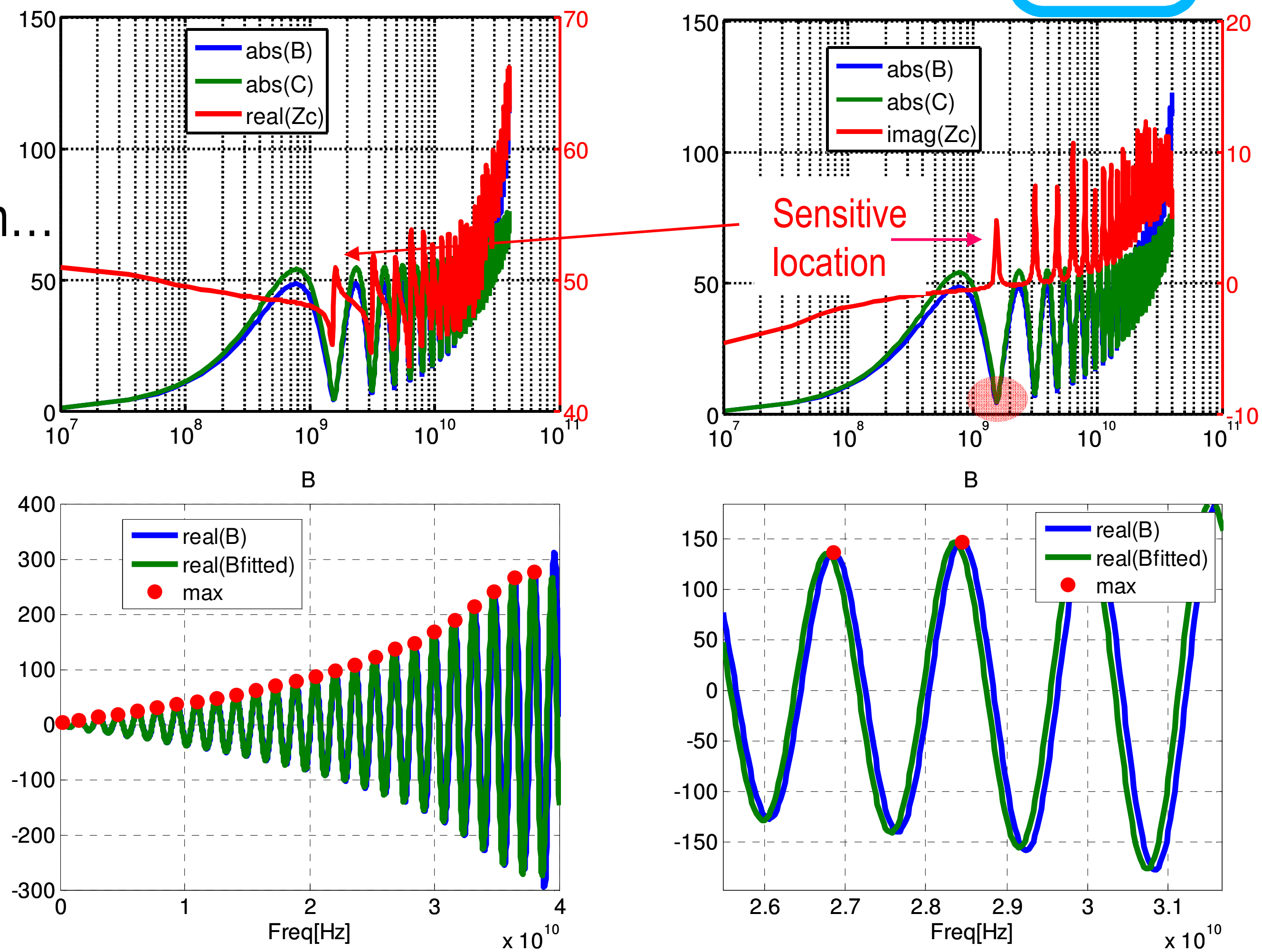
$$Zc = \sqrt{\frac{B}{C}}$$

- Let's try to understand where the dips are coming from…
- The maximums can be identified (away from sensitive areas)
- Less # of points but enough to understand frequency dependency

$$V(z) = V^{+}e^{-\gamma z} + V^{-}e^{\gamma z}$$

$$I(z) = I^{+}e^{-\gamma z} + I^{-}e^{\gamma z}$$

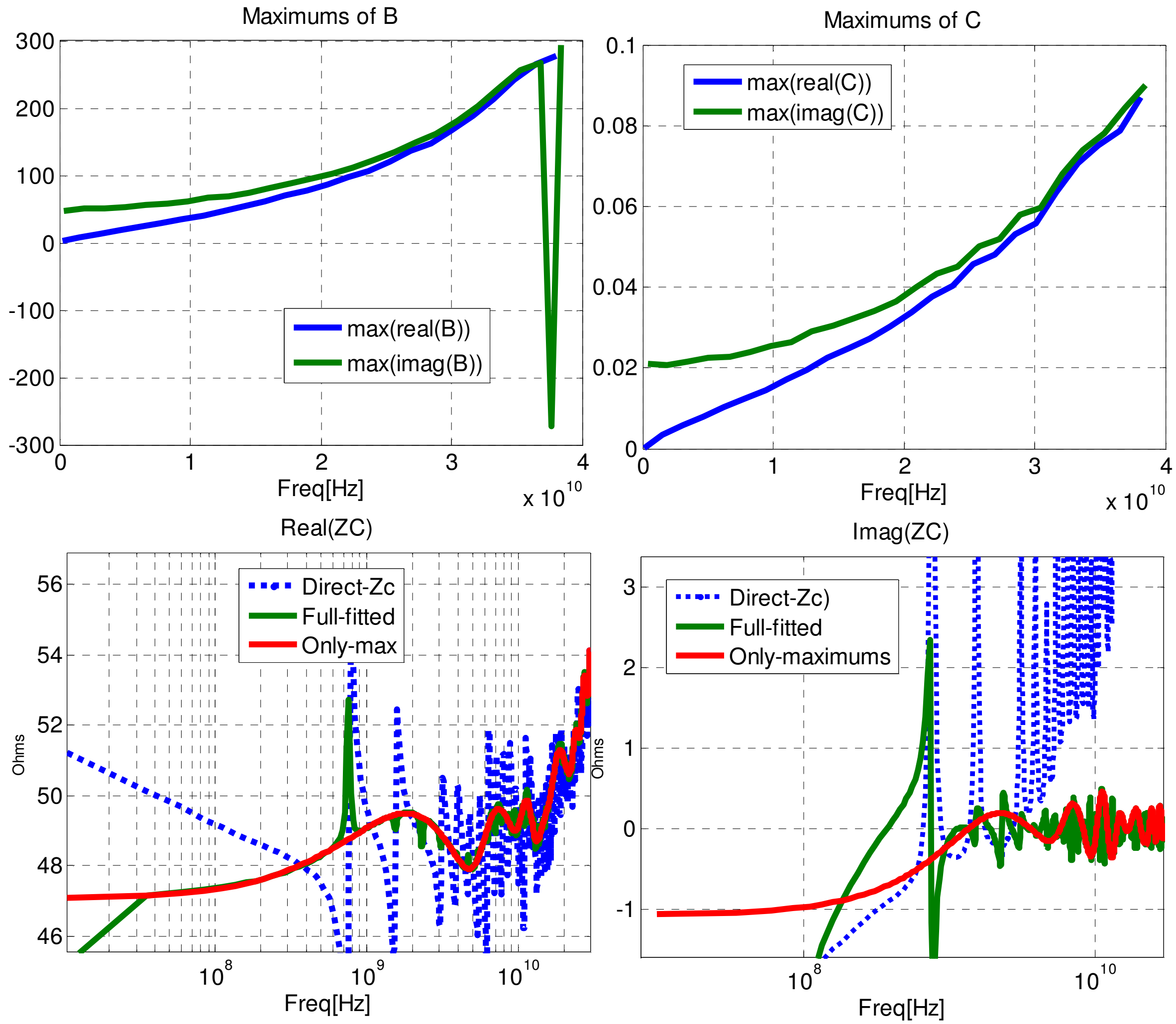
$$I(z) = \frac{V^{+}}{Zc}e^{-\gamma z} - \frac{V^{-}}{Zc}e^{\gamma z}$$



Characteristic Impedance by Maximum Identification (2)

- The Characteristic Impedance information is solely contained in the Bmax, Cmax curves

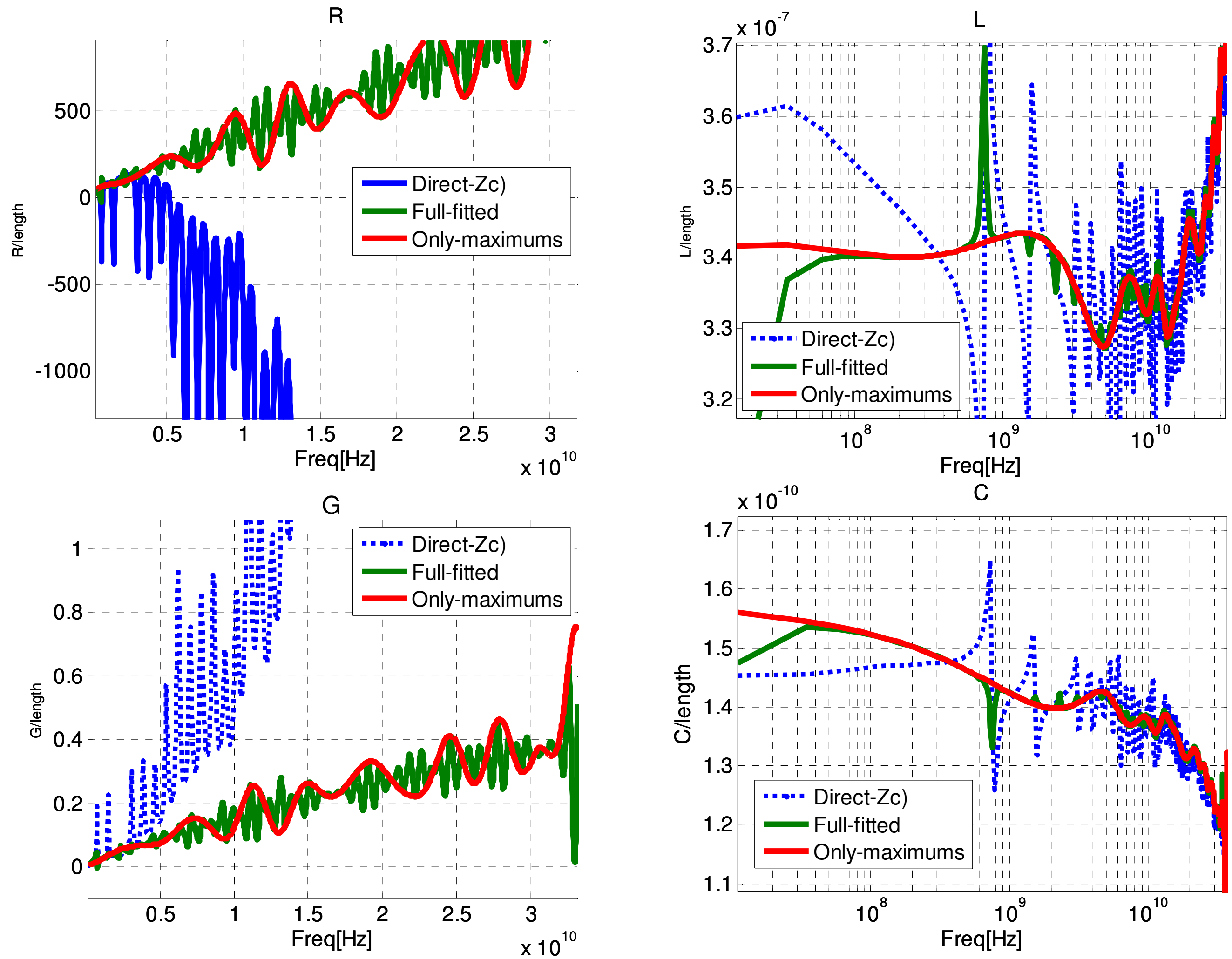
- We can see how it “almost” averages the results. The maximum-only curve doesn’t have peaks, but the shape is still very questionable



RLGC Results

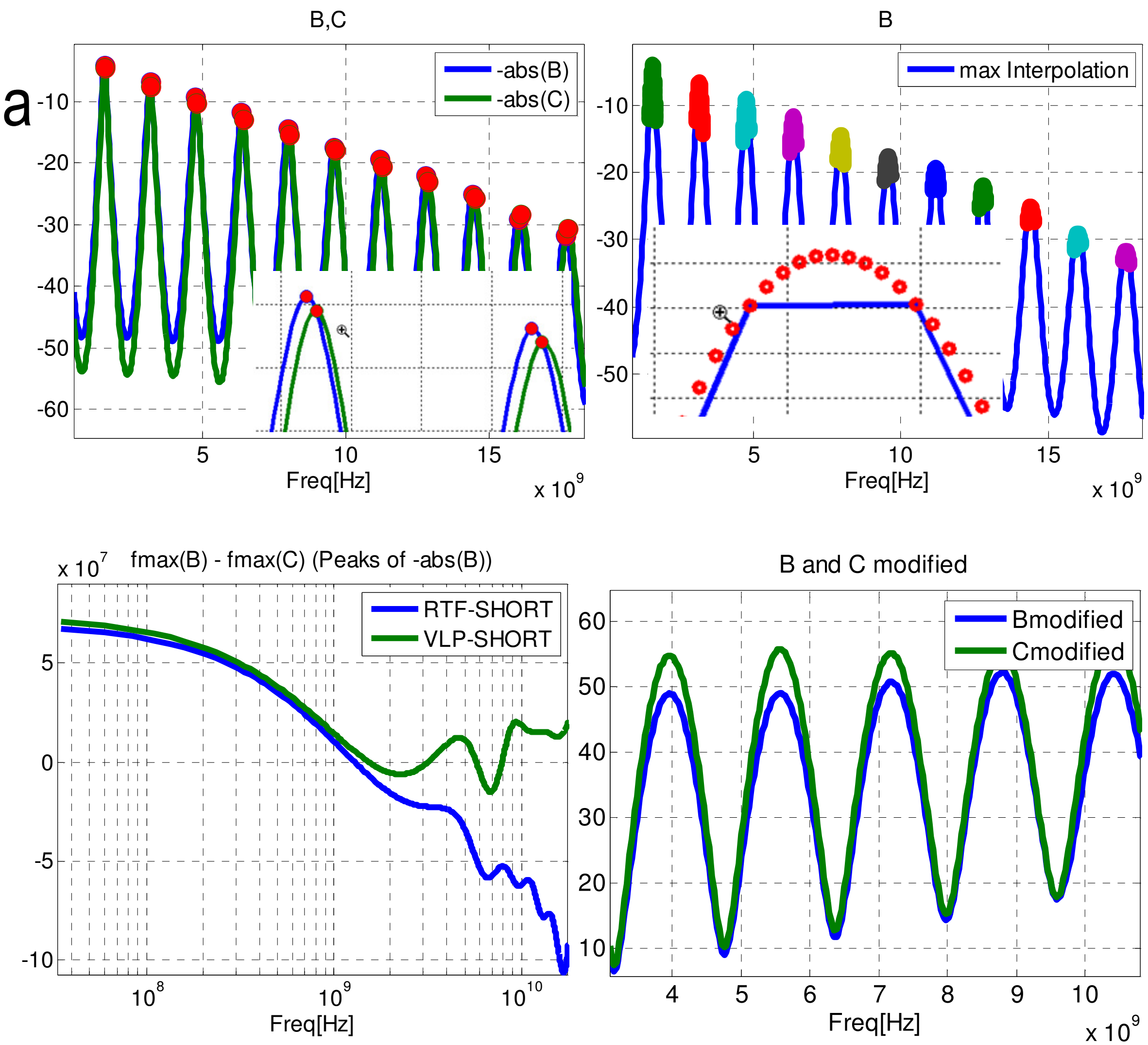
Characteristic Impedance by Maximum Identification

- RLGC seems to be modified in a drastic way, simply by picking the maximum values



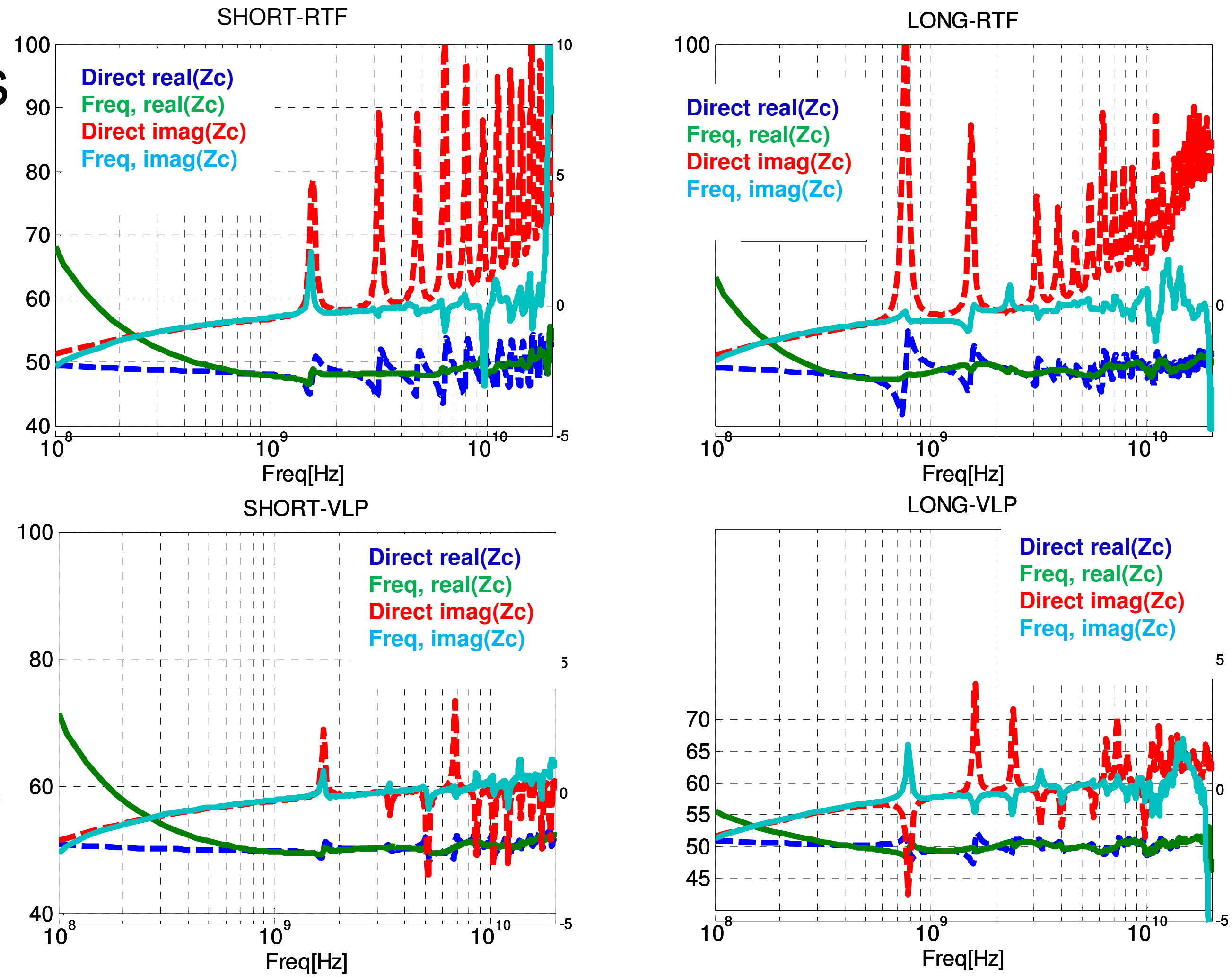
Characteristic Impedance By Frequency Adjustment (1)

- Identify the maxima
- Interpolate to get the most likely maximum
- Adjust each curve by half the difference



Characteristic Impedance By Frequency Adjustment (2)

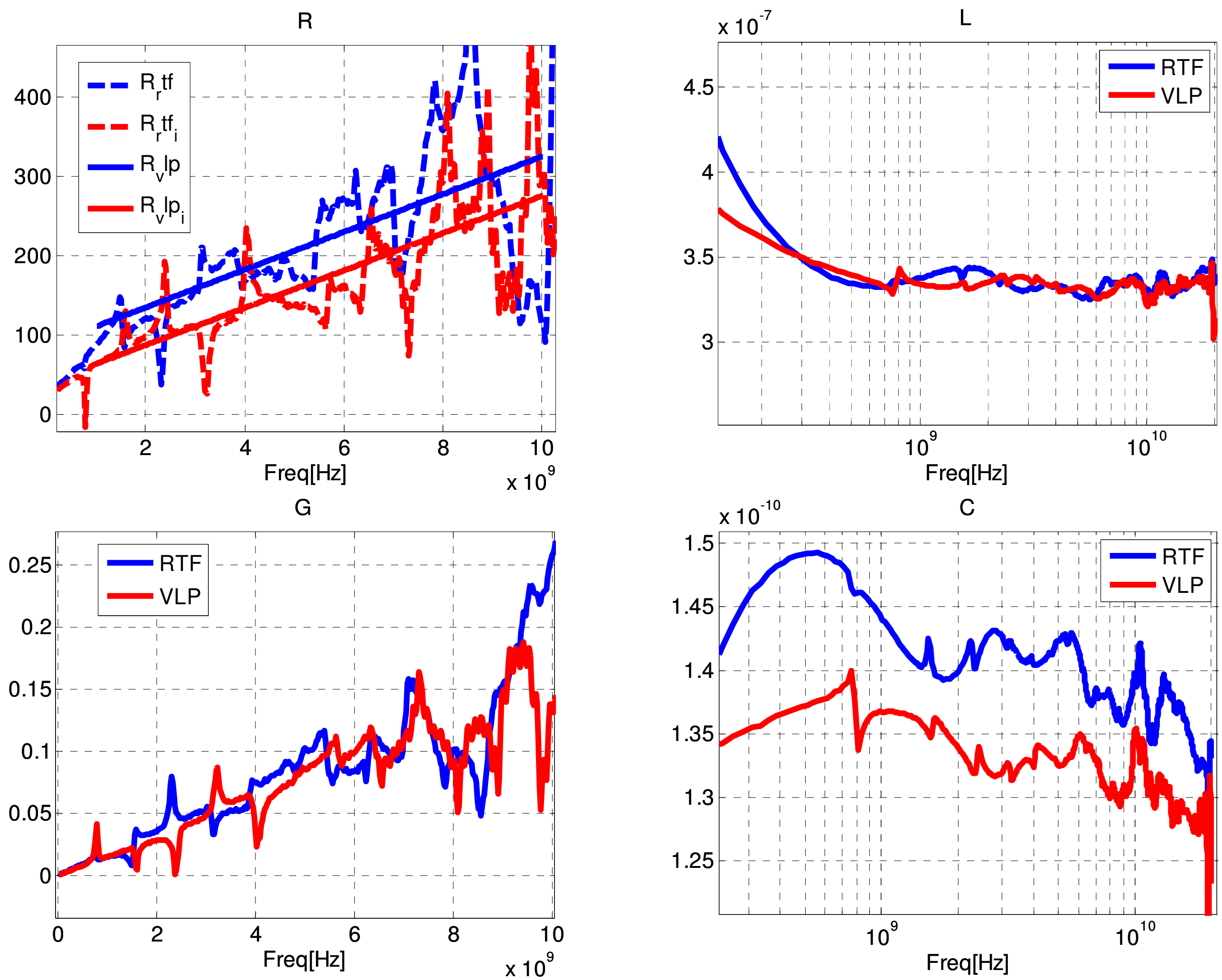
- This method cleans the curves very well
- Both, trends and the peaks are corrected
- **BUT, is this good enough for our ultimate goal??? (RLGC extraction)**



RLGC Results

Characteristic Impedance by Frequency Adjustments

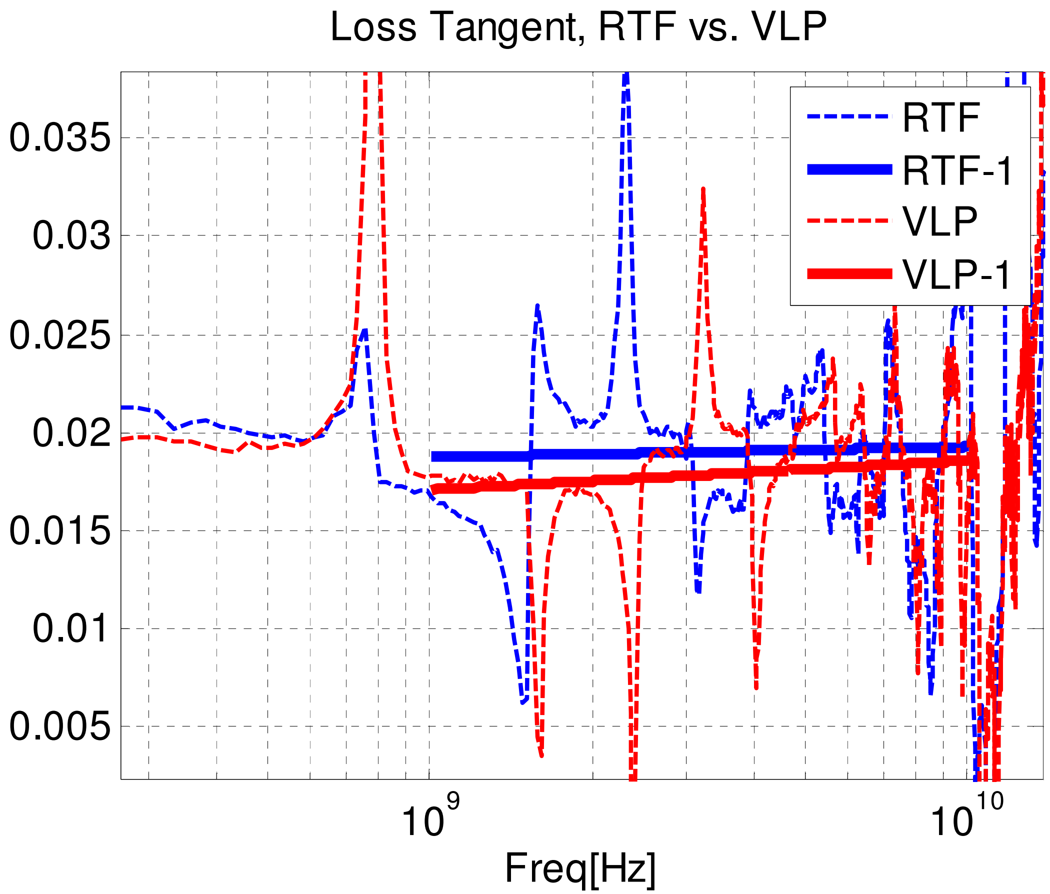
- The curves looks reasonable but still very noisy
- Let's push it further and extract the loss tangent from here



Loss Tangent Extraction

Characteristic Impedance by Frequency Adjustments

- Even though we get a correct overall averaged trend, the results are noisy enough to mask any necessary details



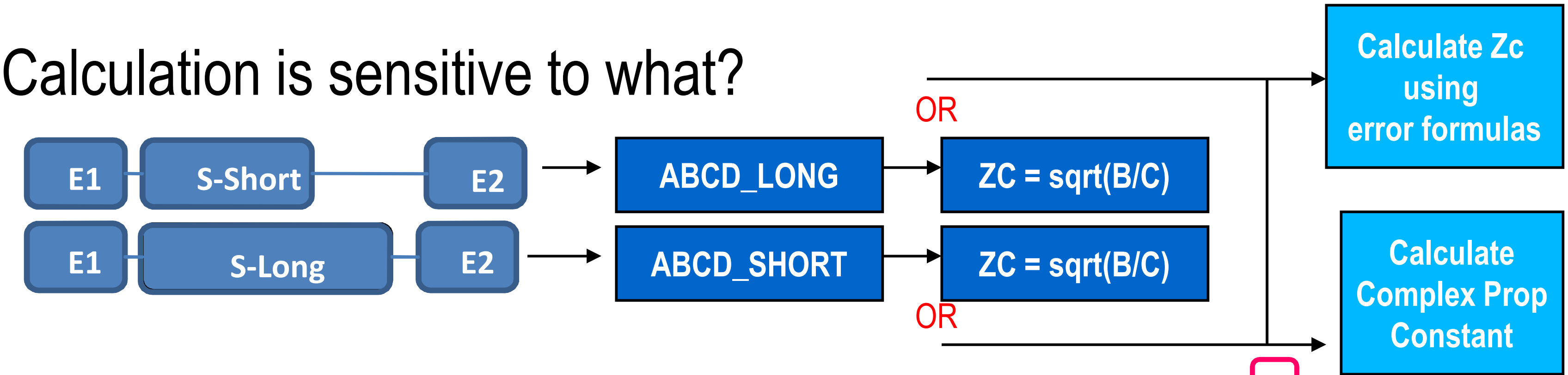
So Where are we?

- Shown accurate S-parameter measurements
- Shown how to extract the Characteristic Impedance using several methods (Direct-Inversion, Impedance Renormalization, Maximum Identification, Frequency Adjustment)
- Developed math to account for small end-discontinuities.
- Method works in simulations environment and it could be very useful to enhance our understanding of 3-D structures.
- Methods were found to be lacking when it came to working with actual lab measurements

AND IT WAS THE TIME TO SUBMIT THE PAPER!!!

Let's take a step back

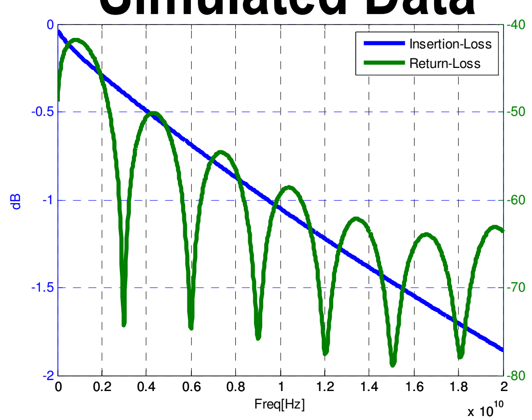
- Zc Calculation is sensitive to what?



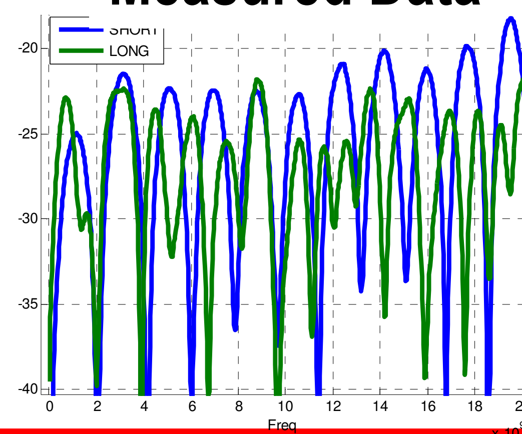
- How does Zc looks in terms of S-parameters directly

$$Zc(f) \equiv \frac{K + 2S_{11}}{K - 2S_{11}}$$

Simulated Data



Measured Data

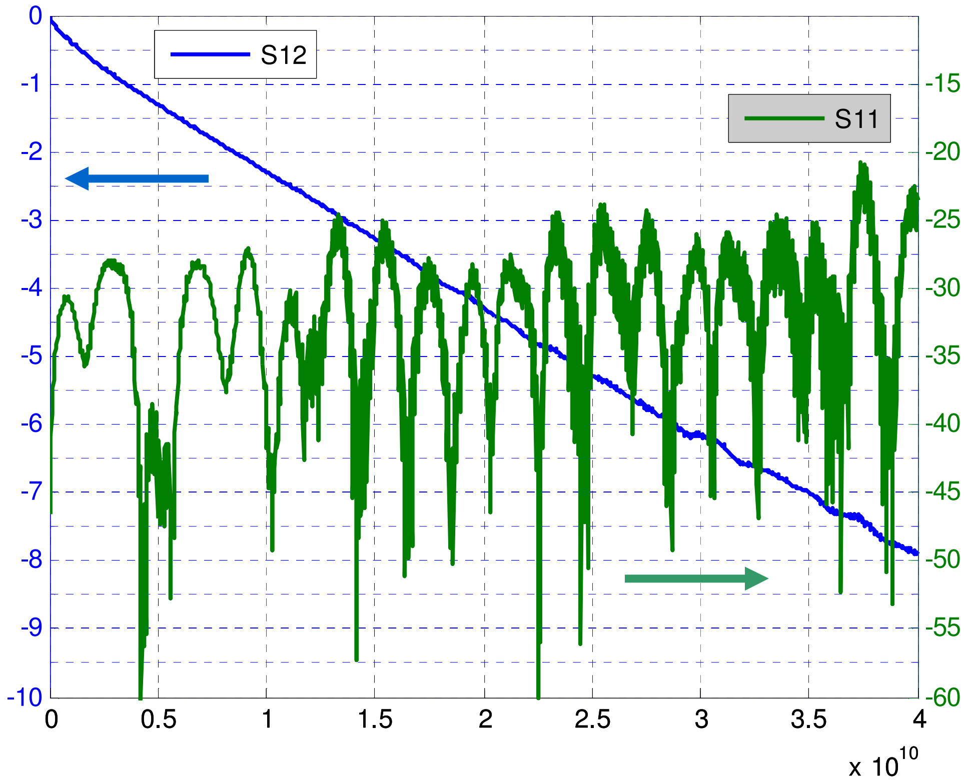


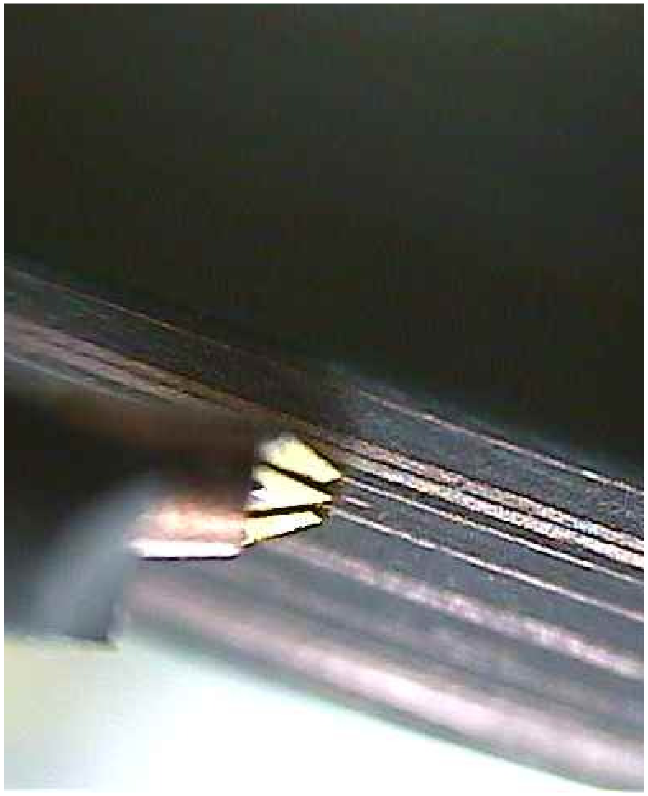
Going Back To Measurements

- Ways to further improve measurements
  - Remove lead-in and lead-out traces
  - Get data from other experts in the industry, with different methodologies, calibration techniques, to see if we can get better data
  - Somehow improve S11 noise margin against the “unknown” (VNA + Calibration noise floor)
  - Could it be that “real structural” effects on the transmission line are creating this behavior?, What about weave-effects? Get a measurements of a non-glass reinforced material

Removing Lead-in Lead-Out

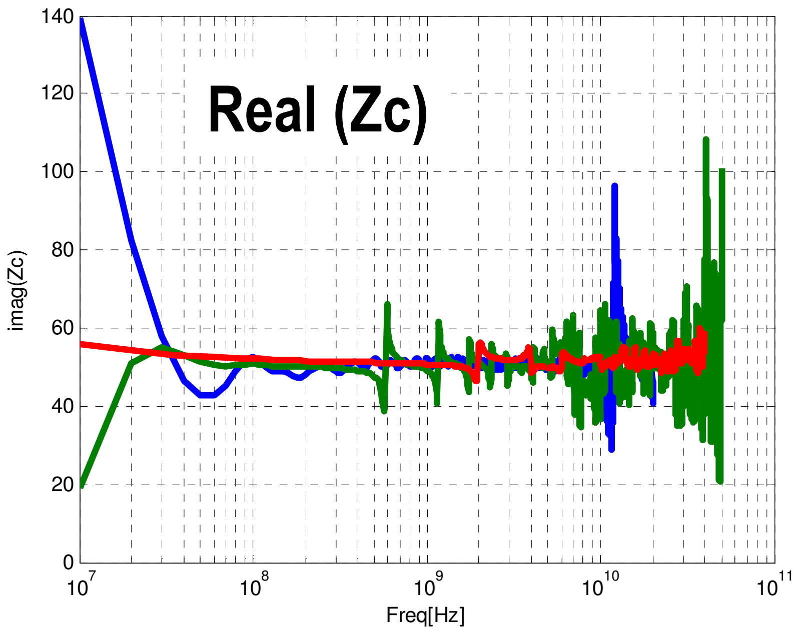
- Measurements from the side can be performed, hence completely eliminating lead-in and lead-out traces
- Mechanically complex calibration to do in our set-up

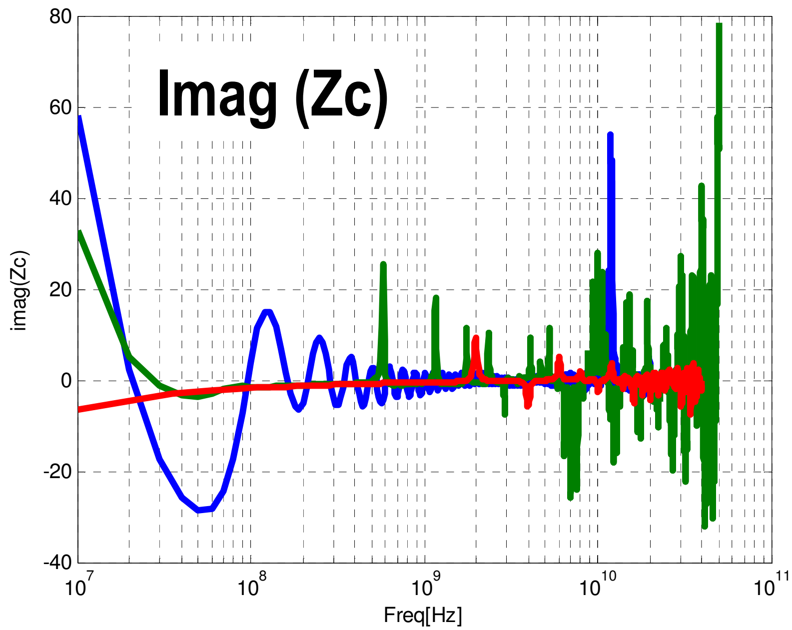




Getting Data from Other Experts

- Just to make sure we are not missing anything in our measurement methodology we wanted to compare the quality of our data to that of other industry experts





- Different Calibration techniques, different VNAs, different labs, different users, **SAME PROBLEM**

Conclusion

- It is starting to look like the fundamental RLGC telegrapher equations may not be directly applied to measurements for the purpose of separating Dielectric vs. Conductive Losses

BUT

- We are not yet convinced that this is not possible…..

Moving Forward

- Understand in further depth the error expected from the VNA
  - VNA return loss noise floor
  - VNA different calibration techniques
- Make sure the measurement artifact is not coming from real transmission line structural elements
  - Measure non-glass-materials in different ways
  - Measure simple coax semi-rigid cables with wafer-probes
- Improve measurement techniques by engaging with other industry experts
  - Compare S-parameter measurements on equivalent samples

Acknowledgements

- Thanks to Scott McMorrow, Al Neves and Mike Resso for their support and S-parameter samples.

Q & A

Thank You

Gustavo Blando