Analysis to Measurement Validation with S-Parameters Similarity Metric

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Outline

- Introduction
- New look at S-parameters in 3D space
- Measuring S-parameters similarity with modified Housdorff distance in 3D space
- Examples
- Conclusion

Why do we care?

Because the signal bandwidth is increasing…

Data Rate, Gbps Code Type	Bit or Symbol Time ps	Rise Time ps	Nyquist Frq. GHz	Analysis or Meas. Bandwidth, GHz
10, NRZ	100	50	5	20
16,NRZ	62.5	30	8	32
28, NRZ	35.7	18	14	54
32, NRZ	31.25	16	16	61
56, PAM4	35.7	18	14	54
64, PAM4	31.25	16	16	61
128, PAM4	15.625	15	32	89
128, PAM4	15.625	10	32	108

Microwave

Millimeter Wave

and we need to validate our analysis with measurements over such bandwidths – **this is necessary element for design success!**

Analysis to Measurement Validation

- Formal “Sink or Swim” systematic design process was introduced at
  - Y. Shlepnev, Sink or swim at 28 Gbps, The PCB Design Magazine, October 2014, p. 12-23.
  - M. Marin, Y. Shlepnev, Systematic approach to PCB interconnects analysis to measurement validation, Proc. of 2018 IEEE Int. Symp. on EMC and SIPI, July 30- August 3, 2018, Long Beach, CA.
- Though, the last validation step was “visual” assessment like that

Structure	IL [GHz] SE & MM	RL [GHz] SE & MM	FEXT & NEXT [GHz]	TDR (Ω) ~ SE / MM	Eye (30 Gbps, diff.)	Notes
INNER1 5cm 10cm	 25 25	 15 15	 30	 1 / 2 1 / 2	 1% EH & EW	There is uncertainty in the epoxy filling after the backdrilling, the launches is more inductive then predicted. DM/CM phase delay correlate up to 25GHz.
INNER2 5cm 10cm	 30 30	 25 25	 30	 1 / 2 1 / 2	 1% EH & EW	Trace width seems to be 95um instead of 99um. Launch more inductive then predicted, PCB trace width variation. DM/CM phase delay correlate up 30 GHz.
INNER3 5cm 10cm	 30 30	 30 30	 30	 1 / 2 1 / 2	 3.6% EH, 1% EW	Core/prepreg dielectric models – layered anisotropy. Resonance frequency little lower than predicted. Launches have long stubs (not backdrilled).
INNER6 5cm 10cm	 30 30	 10-15 10-15	 30 30	 1 / 3 2 / 4	 2% EH, 1% EW	Differences in RL expected due to geometry differences Mode conversions in measurements up to -30dB DM/CM phase delay correlation ~ 30GHz Impedance variations, launch mismatch, loss of localization.

- Feature Selective Validation was the alternative – tried to use it…

Feature Selective Validation (FSV)

1. Apply Fourier Transforms to compared data sets (amplitudes of S-parameters)
2. Apply low-frequency (LF) and high-frequency (HF) filters and Inverse Fourier Transforms to get 2 sets of filtered data
3. Compute Amplitude Difference Measure (AMD) with data filtered with LF filter, to compare amplitudes and trends
4. Compute Feature Difference Measure (FMD) with data filtered with HF filter, to compare rapidly changing features
5. Combinations of AMD and FMD gives Global Difference Measure (GMD), that can be used to evaluate and rank the difference from excellent (y<=0.1) to very poor (y>1.6)

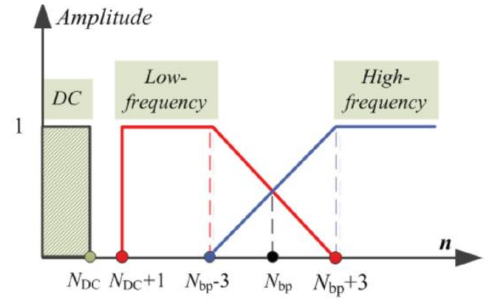


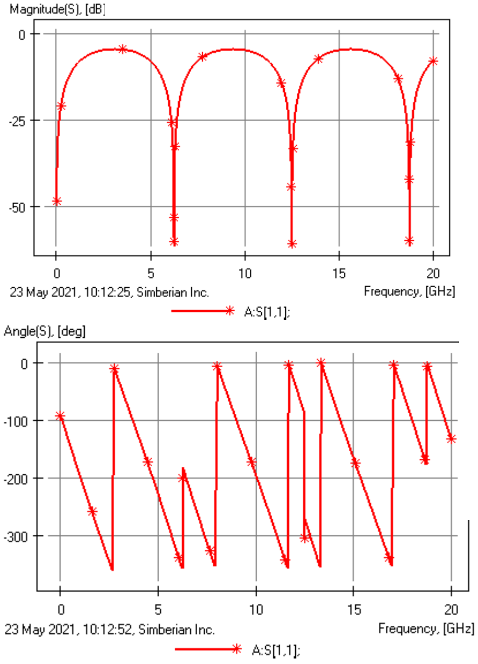
Fig. 2. Filter used in the original FSV method in [13].

Recommended by IEEE Standard 1597.1/2 for automated validation
Overview and details in A.P. Duffy, G. Zhang, FSV: State of the Art and Current Research Fronts, IEEE Electromagnetic Compatibility Magazine, Volume 9, #3, 2020, p. 55-62.

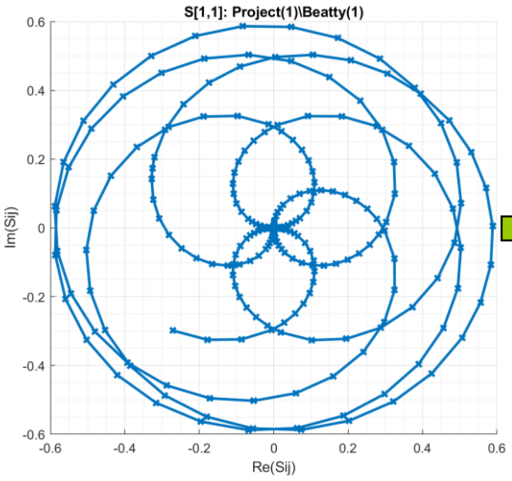
Relatively complicated - we needed something simpler and working both for amplitude and angle…

New Way to Look at S-parameters

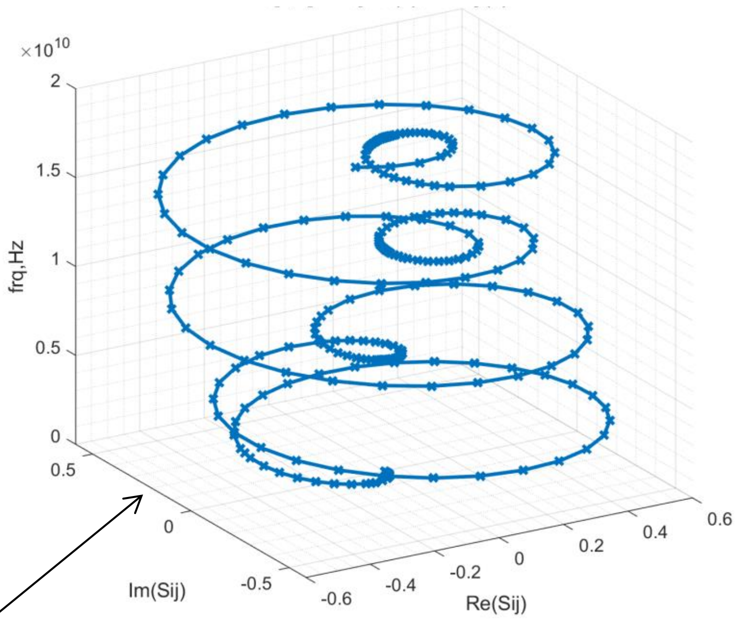
Bode Plots



Nyquist/Polar Plots



3D Spiral Plots



Real-Imaginary-Frequency or RIF Space –
NO INTERSECTIONS – can be used for comparisons

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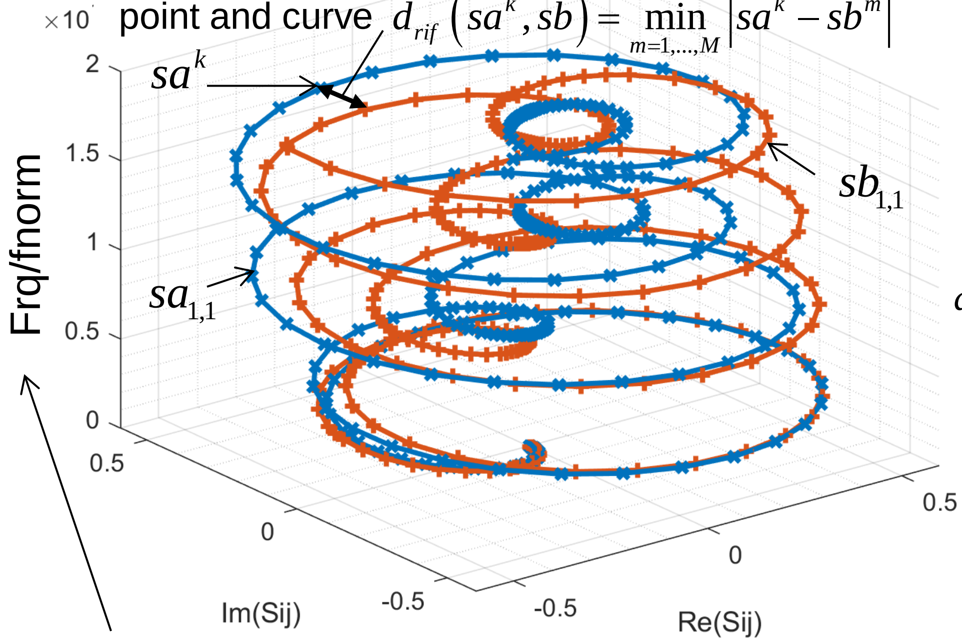
Distance Between 2 S-Parameters in RIF Space

Distance in RIF space between point and curve $d_{rif}\left(sa^k, sb\right) = \min\limits_{m=1,\dots,M}\left|sa^k - sb^m\right|$



Modified Housdorff Distance(MHD) for S-Matrix Element *i,j*

$$d_{MH}\left(sa, sb\right) = \frac{1}{K}\sum_{k=1}^{K} d_{rif}\left(sa^k, sb\right)$$

MHD for S-Matrix *NxN*:

$$d_{MH}\left(SA, SB\right) = \max\left[d_{MH}\left(sa_{i,j}, sb_{i,j}\right),\ i, j = 1,\dots,N\right]$$

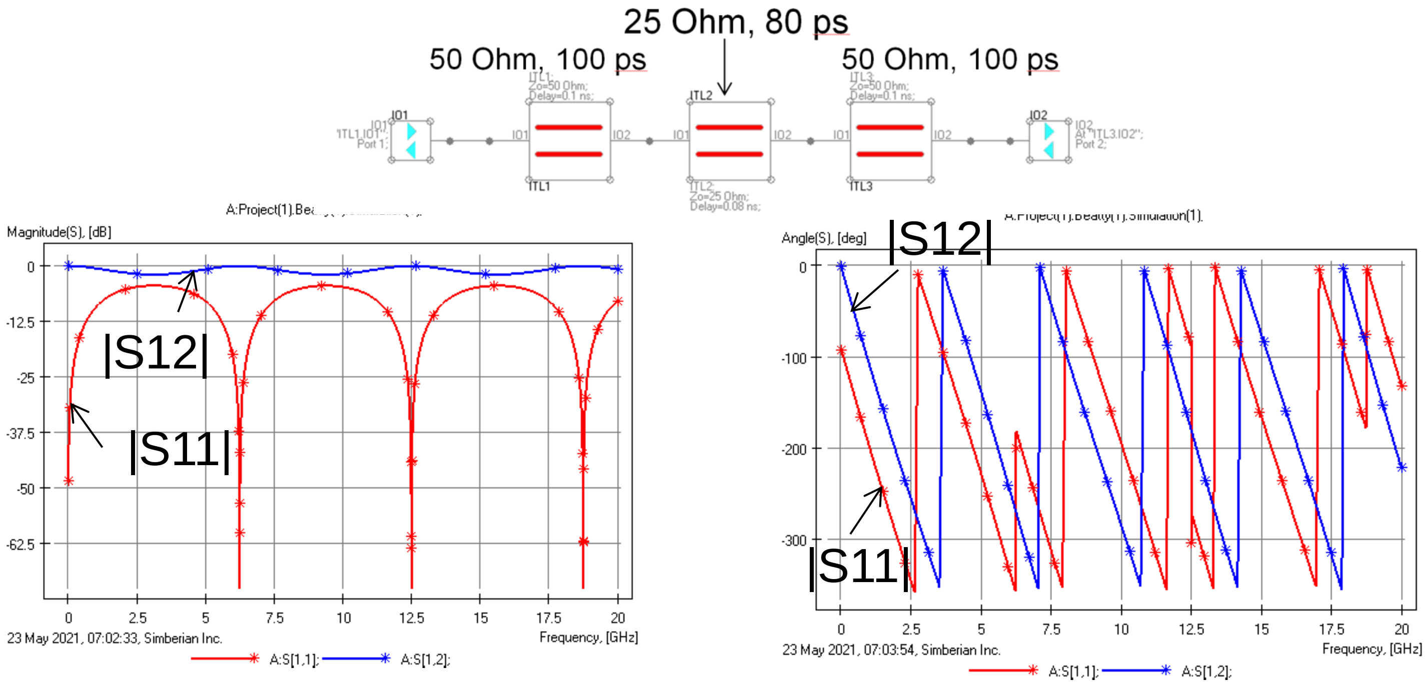
S-Parameters Similarity (SPS) Metrics:

$$SPS\left(sa_{i,j}, sb_{i,j}\right) = 100\cdot\max\left(1 - d_{MH}\left(sa_{i,j}, sb_{i,j}\right), 0\right)\%$$

$$SPS\left(SA, SB\right) = \min\left(SPS\left(sa_{i,j}, sb_{i,j}\right), i, j = 1,\dots,N\right)\%$$

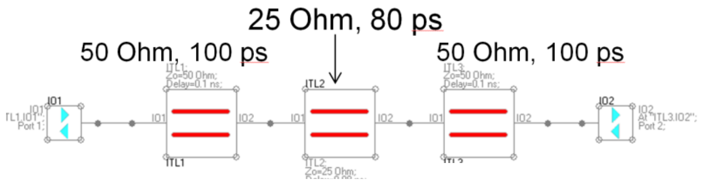
Frequencies are divided by fnorm – it defines unit along the frequency axis (compresses it) and allows comparison of non-identically sampled data sets

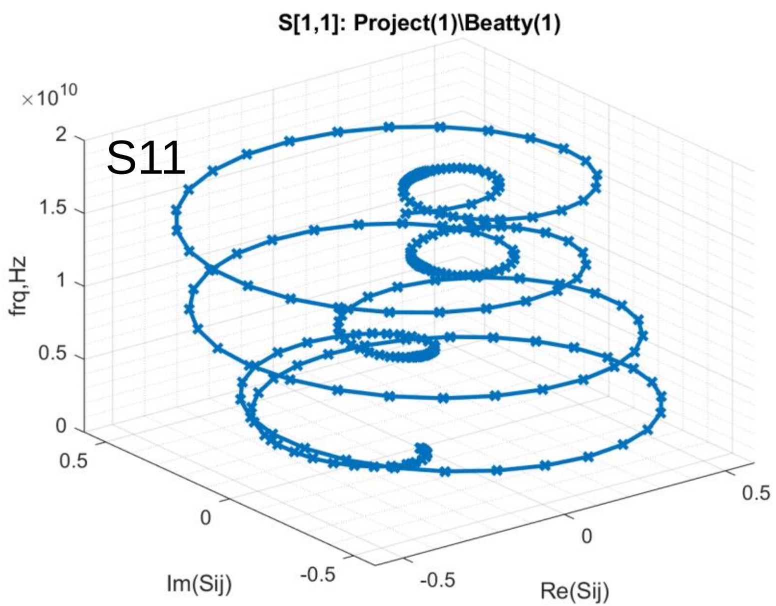
Simple Example: Beatty Resonator

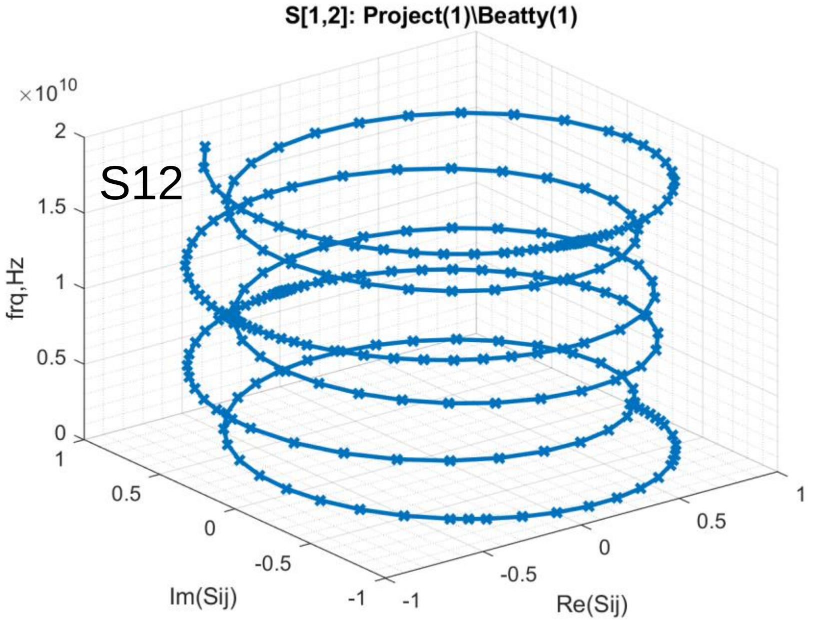


Adaptive frequency sampling is used – more frequency points at the resonances

Beatty Resonator: 3D Spiral Plots

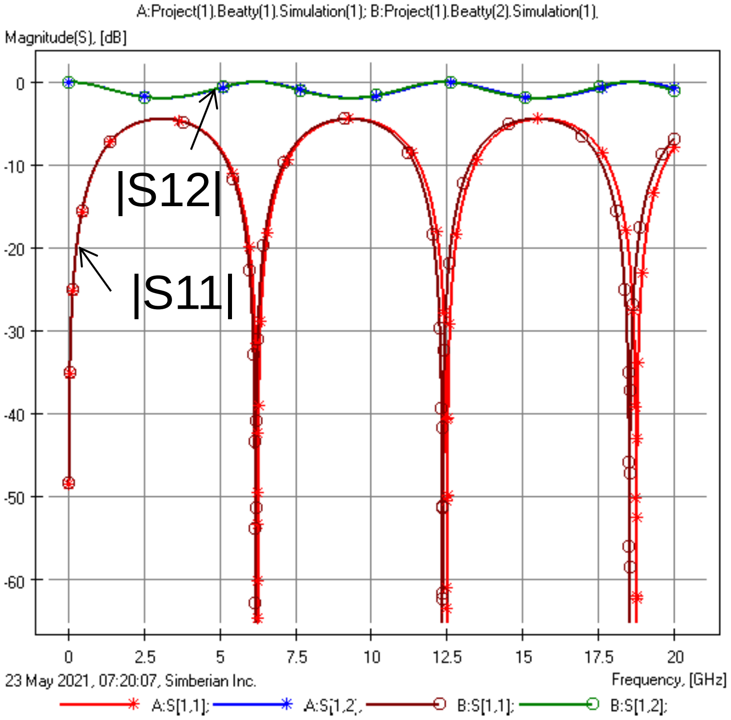


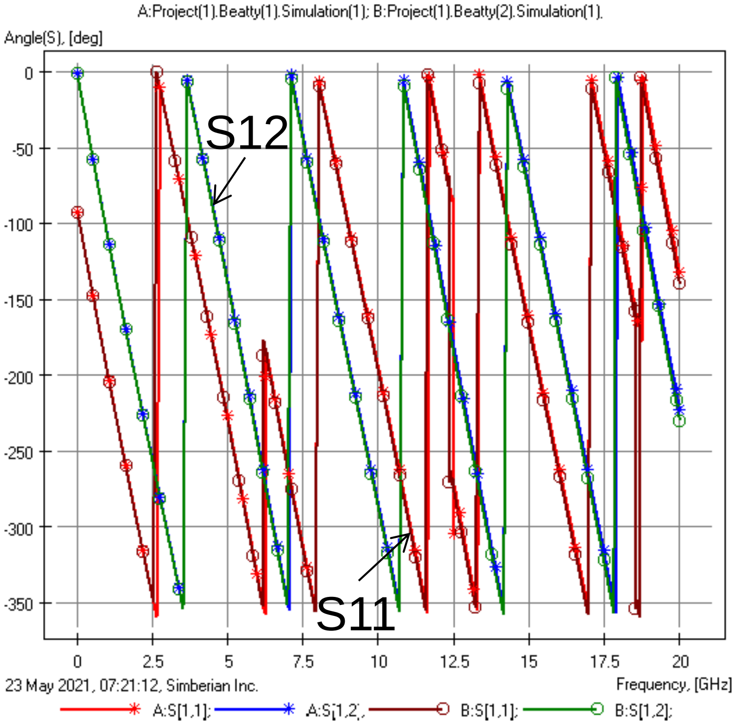




Beatty: Bode Plots for Small Difference

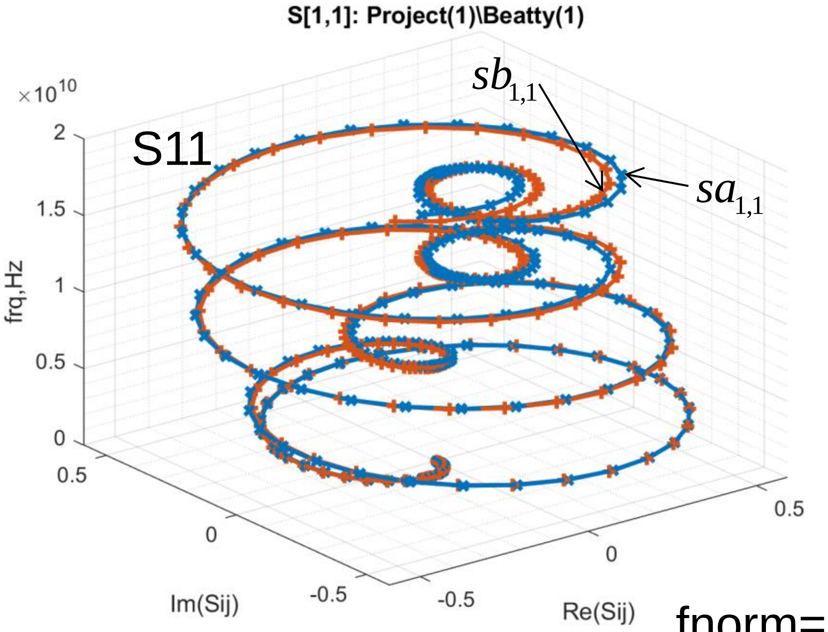
Delay in 25 Ohm section 80 ps vs 81 ps

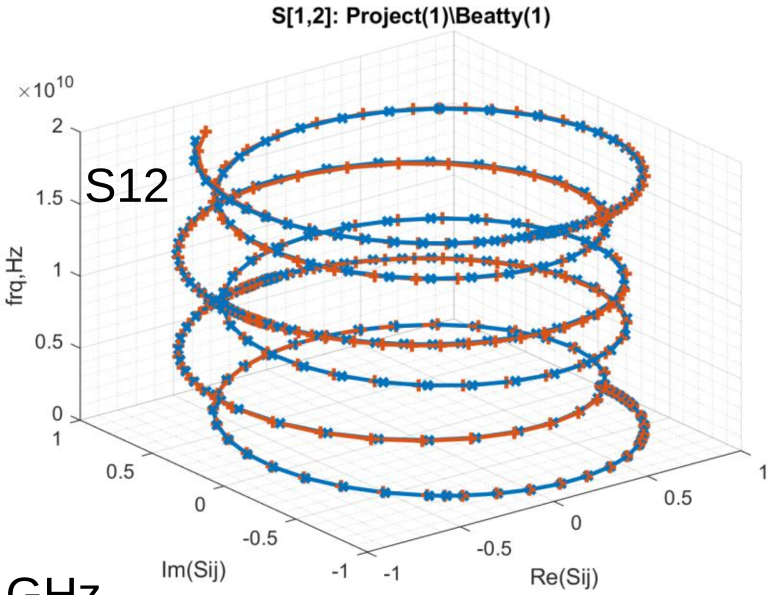




Beatty: Similarity of 3D Spiral Plots and SPS

Delay in 25 Ohm section 80 ps vs 81 ps





fnorm=1GHz

SPS11=95.35%

SPS12=94.94%

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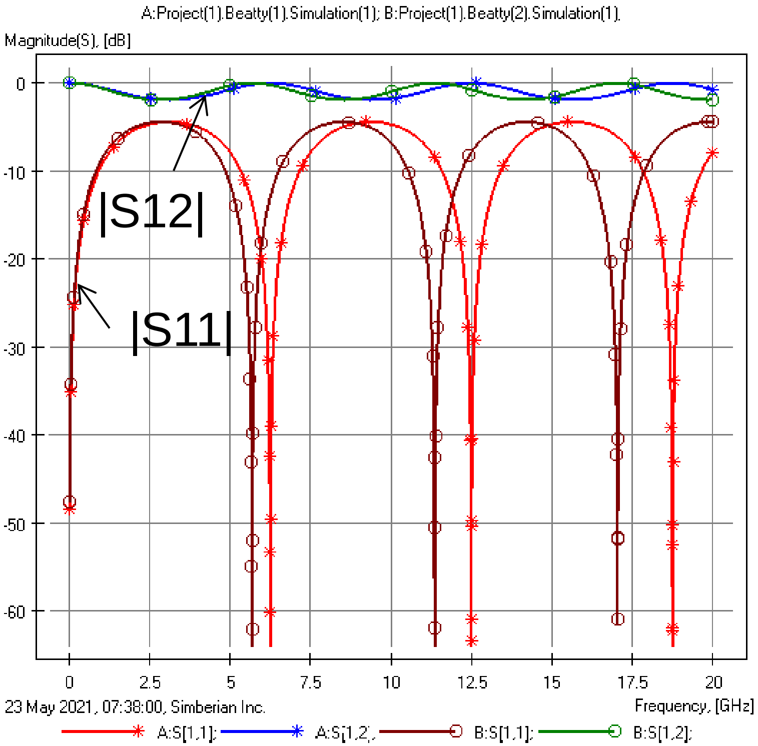
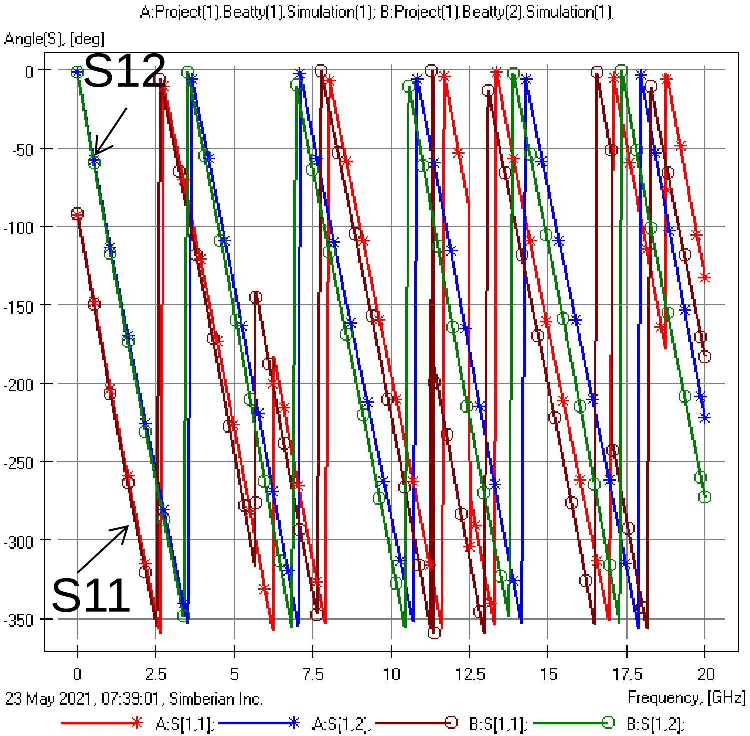
Beatty: Bode Plots for Large Difference

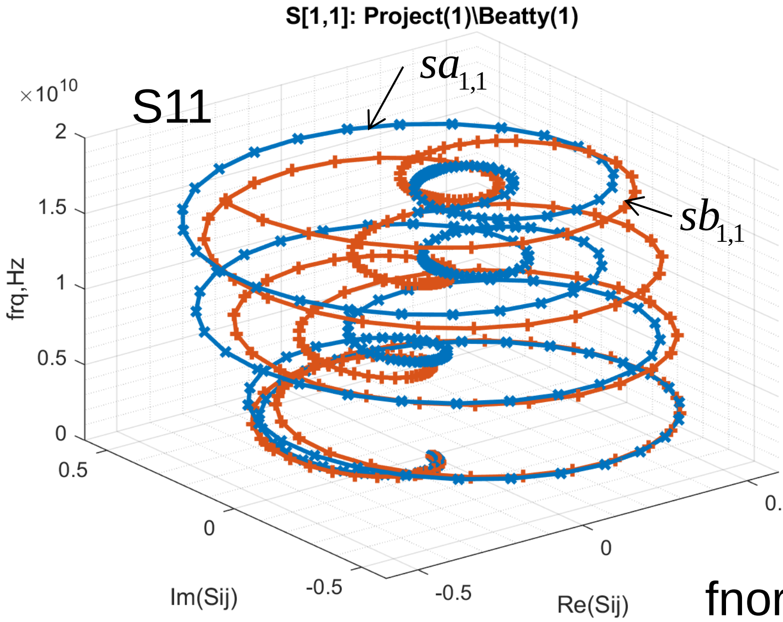
Delay in 25 Ohm section 80 ps vs 88 ps

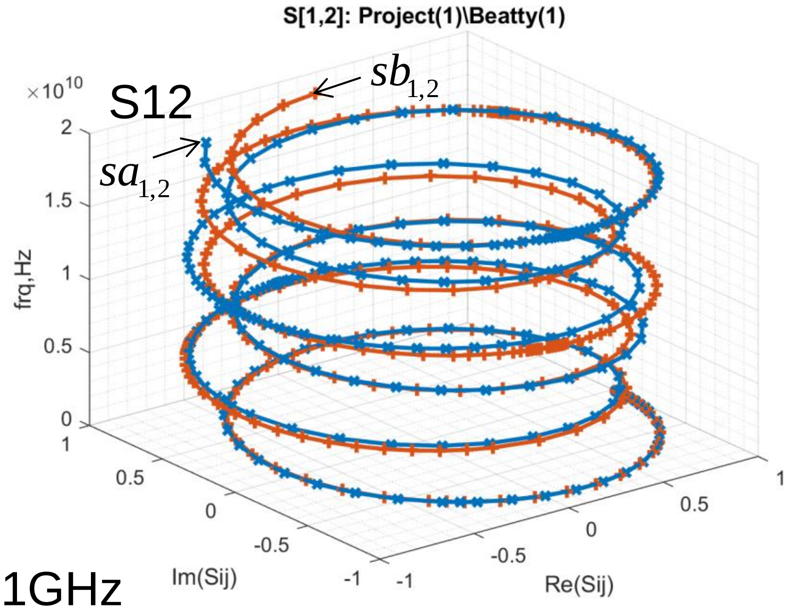




Beatty: Similarity of 3D Spiral Plots and SPS

Delay in 25 Ohm section 80 ps vs 88 ps





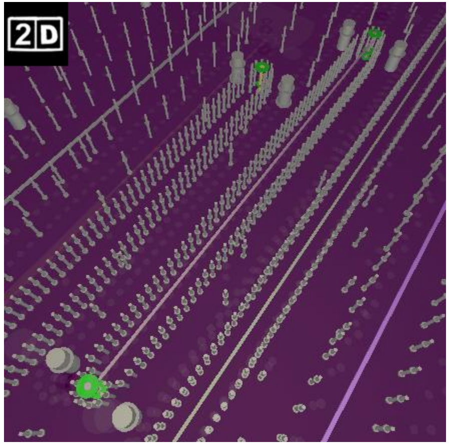
fnorm=1GHz

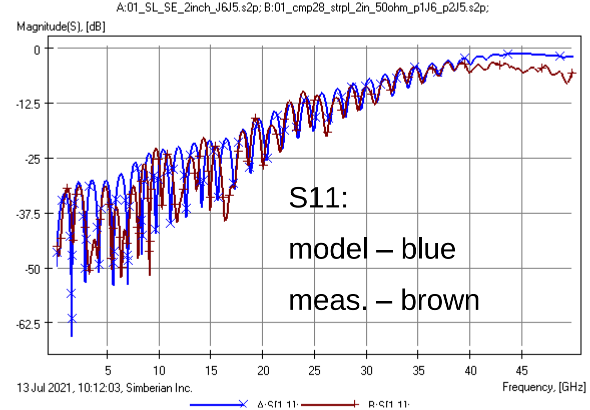
SPS11=70.02%

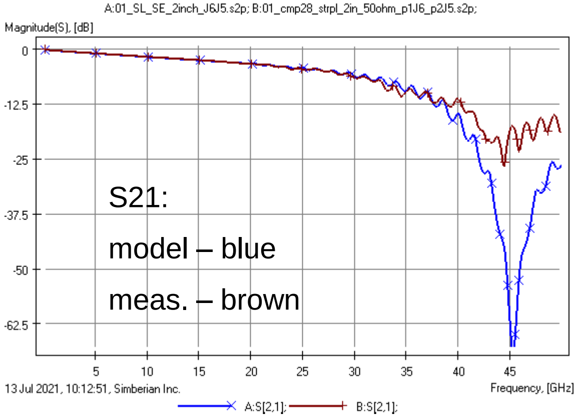
SPS12=70.15%

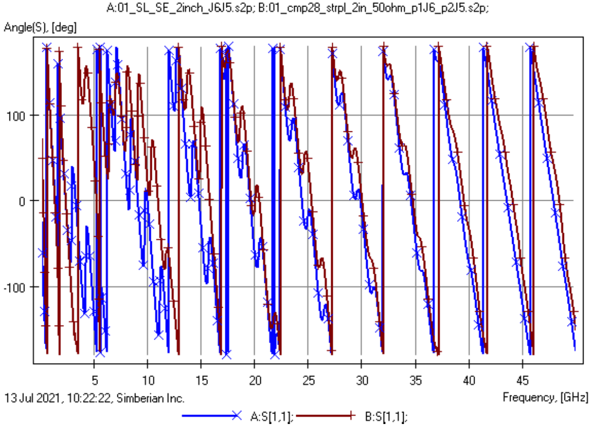
CMP-28: 2-inch strip segment

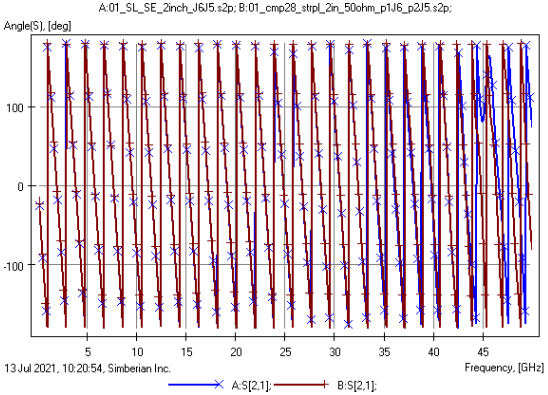
Designed and Measured by Wild River Technology
Modeled with Simbeor
Guide to CMP-28/32 Simbeor Kit, CMP-28 Rev. 4, Sept. 2014.



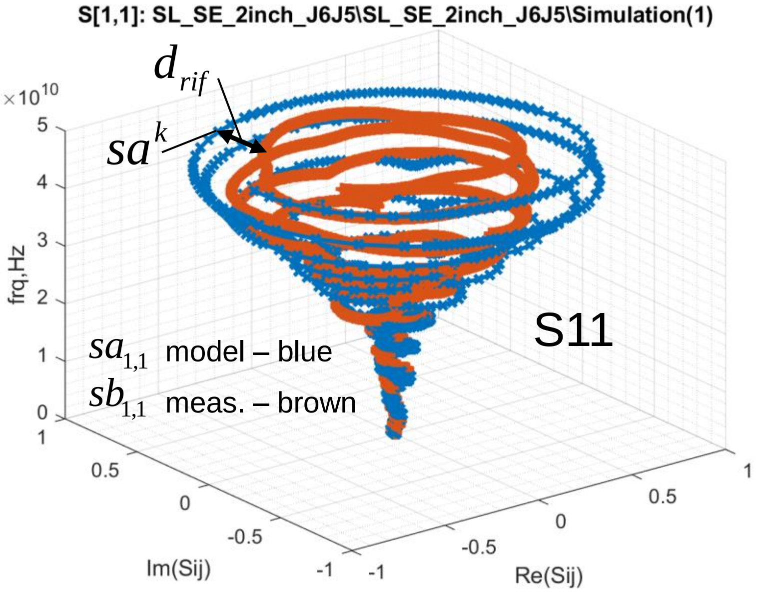




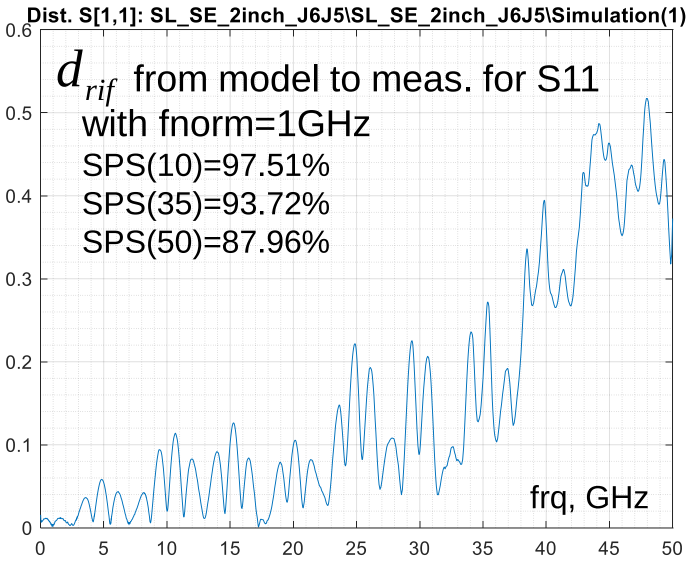




CMP-28: 2-inch Strip Segment - S11



MHD and SPS



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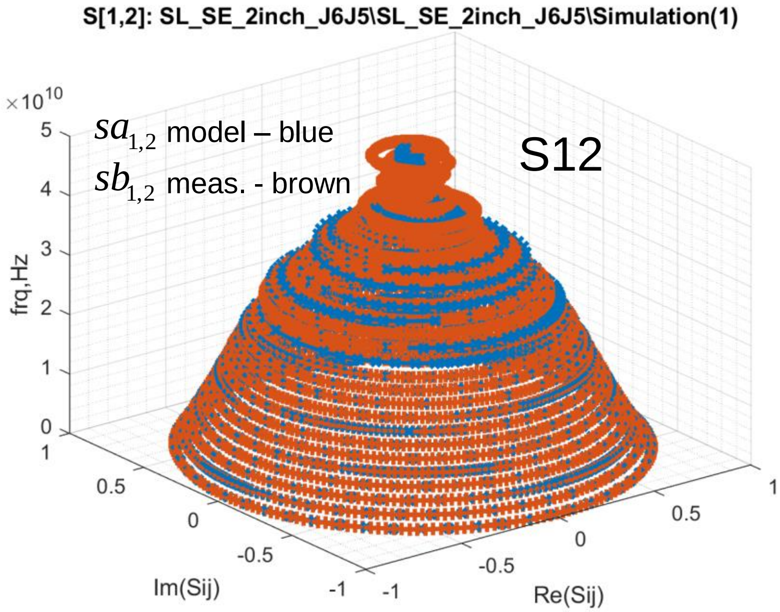
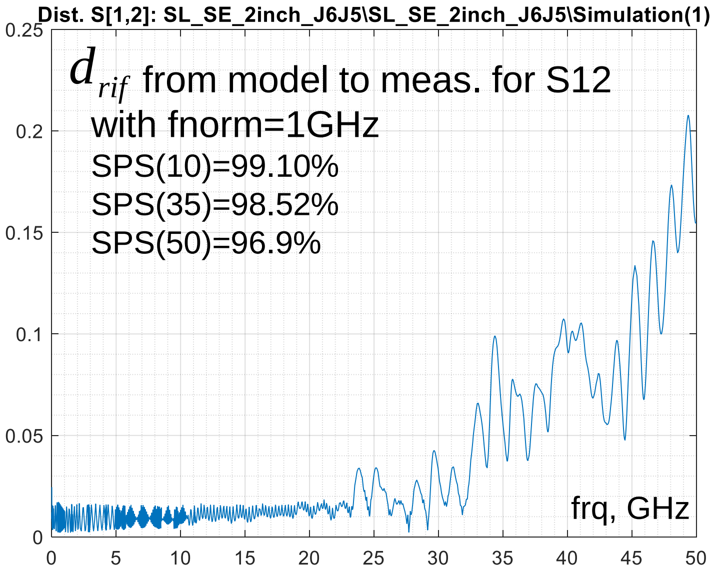
CMP-28: 2-inch Strip Segment – S12

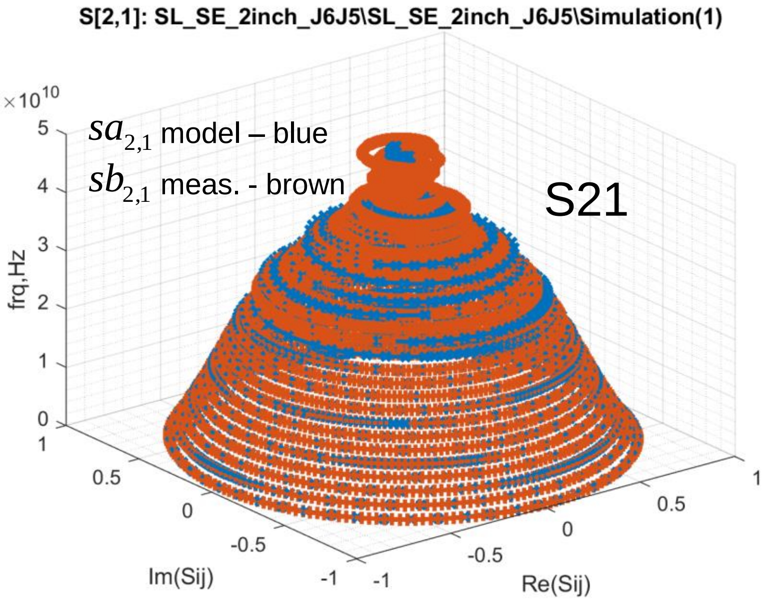
MHD and SPS

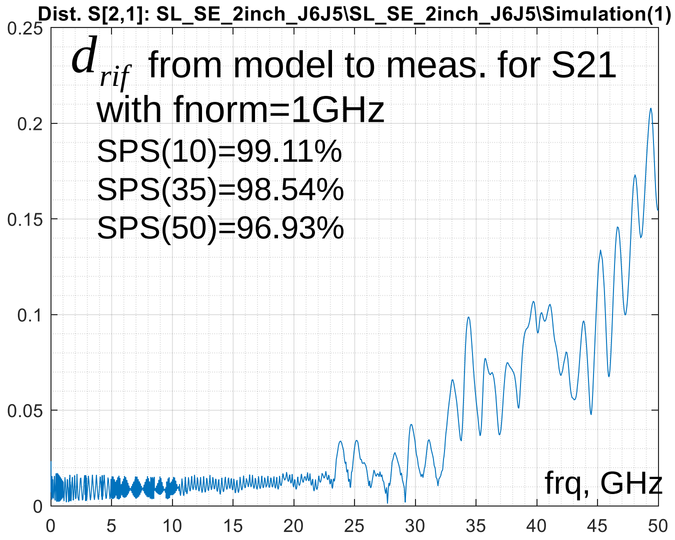




CMP-28: 2-inch Strip Segment – S21

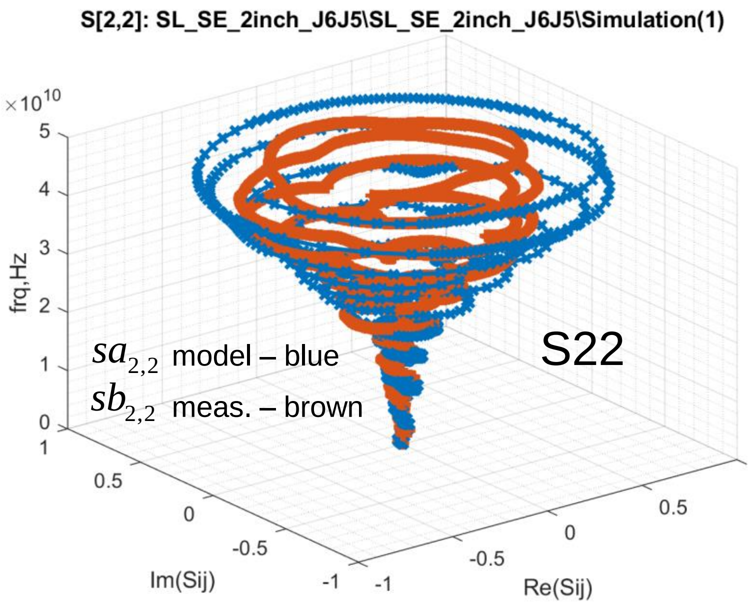
MHD and SPS

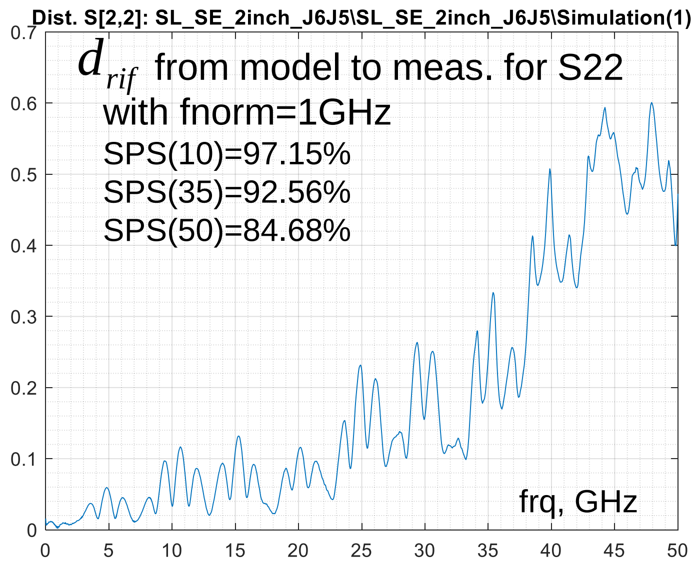




CMP-28: 2-inch Strip Segment – S22

MHD and SPS





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Normalization Frequency and Sampling

CMP-28: 2 inch strip line case

fnorm defines unit along the frequency axis and allows comparison of non-identically sampled data sets

Identical sampling in model and measurement:
(5000 points from 10 MHz to 50 GHz), frqmax=35GHz

fnorm	SPP11	SPP12	SPP21	SPP22	SPP
1 MHz	92.5219	97.5969	97.6797	90.5733	90.5733
10 MHz	92.5219	97.5969	97.6797	90.5733	90.5733
100 MHz	92.5219	97.5969	97.6797	90.5733	90.5733
1 GHz	92.8275	98.3235	98.344	91.1202	91.1202

Small dependency on fnorm with the identical sampling

Adaptive model sampling (1525 points from 10 MHz to 50 GHz), equidistant measurement (5000 points from 10 MHz to 50 GHz), frqmax=35GHz

fnorm	SPP11	SPP12	SPP21	SPP22	SPP
1 MHz	0	0	0	0	0
10 MHz	73.0803	74.6885	74.7012	72.457	72.457
100 MHz	92.6053	96.4737	96.5211	91.3543	91.3543
1 GHz	93.7131	98.5223	98.5417	92.5639	92.5639

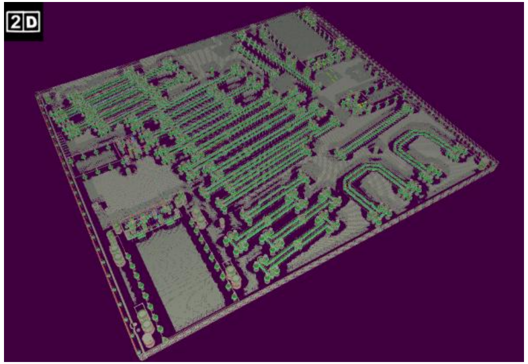
Small dependency on fnorm from 100 MHz to 1 GHz with the non-identical sampling

CMP-28 – Complete Picture

		Single-ended			Mixed-mode		
Model	Measurement	SPS_SE 10 GHz	SPS_SE 35 GHz	SPS_SE 50 GHz	SPS_MM 10 GHz	SPS_MM 35 GHz	SPS_MM 50 GHz
SL_SE_2inch_J6J5	cmp28_strpl_2in_50ohm_p1J6_p2J5_s2p	97.1513	92.5639	84.677	n/a	n/a	n/a
SL_SE_8inch_J7J8	cmp28_strpl_8inch_p1J7_p2J8_s2p	97.8176	91.8262	80.9387	n/a	n/a	n/a
SL_SE_Beatty_25Ohm_J28J27	cmp28_strpl_Beatty_25ohm_p1J28_p2J27_s2p	98.3164	91.7525	81.1544	n/a	n/a	n/a
SL_SE_Resonator_J23J24	cmp28_strpl_resonator_p1J23_p2J24_s2p	98.5621	92.8552	82.7012	n/a	n/a	n/a
SL_SE_Via_Capacitive_J18J17	cmp28_strpl_via_capacitive_p1J18_p2J17_s2p	94.9476	91.1739	82.8437	n/a	n/a	n/a
SL_SE_Via_Backdrilled_J14J13	cmp28_strpl_via_backdrilled_p1J14_p2J13_s2p	97.1172	90.8311	82.0804	n/a	n/a	n/a
SL_SE_2inch_Capacitive_J9J10	cmp28_strpl_2in_Capacitive_p1J10_p2J09_s2p	97.7805	93.0992	87.3275	n/a	n/a	n/a
SL_SE_2inch_Inductive_J11_J12	cmp28_strpl_2in_Inductive_p1J12_p2J11_s2p	97.8352	93.8351	87.8757	n/a	n/a	n/a
SL_DF_2inch	cmp28_strpl_diff_2inch_J39J40J35J36_s4p	95.9985	91.087	83.0354	96.0773	91.2115	83.5488
SL_DF_6inch	cmp28_strpl_diff_6inch_J47J48J43J44_s4p	96.8208	93.0776	85.1746	96.6165	93.2208	85.3854
MS_SE_2in_J1_J2	cmp28_mstrp_2in_p1J1_p2J2	97.9111	94.7303	91.8845	n/a	n/a	n/a
MS_SE_8in_J4_J3	cmp28_mstrp_8inch_p1J4_p2J3	97.6372	95.3771	91.645	n/a	n/a	n/a
MS_SE_Beatty_25Ohm_J25_J26	cmp28_mstrp_Beatty_25ohm_p1J25_p2J26	96.5268	93.3182	89.9407	n/a	n/a	n/a
MS_SE_Resonator_J21_J22	cmp28_mstrp_resonator_p1J21_p2J22	98.0708	94.1929	90.5811	n/a	n/a	n/a
MS_SE_GND_Voids_J74_J75	cmp28_gnd_voids_p1J74_p2J75	97.6512	88.4187	83.5582	n/a	n/a	n/a
MS_SE_GraduateCoplanar_J70_J69	cmp28_graduate_coplanar_p1J70_p2J69	97.6924	94.4118	91.4621	n/a	n/a	n/a
MS_SE_Via_Inductive_J15_J16	cmp28_mstrp_via_inductive_p1J15_p2J16	96.6664	93.596	90.0153	n/a	n/a	n/a
MS_SE_Via_Capasitive_J19_J20	cmp28_mstrp_via_capacitive_p1J19_p2J20	96.5088	93.969	90.1057	n/a	n/a	n/a
MS_SE_Via_Pathology_J65_J66	cmp28_via_pathology_p1J65_p2J66	97.2525	91.9582	88.486	n/a	n/a	n/a
MS_DF_2inch	cmp28_mstrp_diff_2inch_J38J37J34J33	95.4645	93.3429	90.407	95.2326	93.3716	90.771
MS_DF_6inch	cmp28_mstrp_diff_6inch_J46J45J42J41	95.5751	93.9318	90.9123	95.63	93.9971	91.0086
MS_DF_GND_Cutout	cmp28_mstrp_diff_gnd_cutout_J59J60J55J56	94.4506	91.4807	88.7113	94.488	89.9057	87.5165
MS_DF_Vias	cmp28_mstrp_diff_vias_J49J50J51J52	95.6808	91.6811	88.4878	95.6215	89.4264	86.7044

EvR-1 Validation Platform and Brackets

SPS Brackets:
[99, 100] **Good**
[90, 99) **Acceptable**
[80, 90) **Inconclusive**
[0, 80) **Bad**



Model	Measurement	SPS_SE 10 GHz	SPS_SE 30 GHz	SPS_SE 50 GHz	SPS_MM 10 GHz	SPS_MM 30 GHz	SPS_MM 50 GHz
bottom_5cm	BOTTOM_5CM_2_4MM	96.8794	93.8748	91.0964	96.8487	94.3083	91.0312
bottom_10cm	BOTTOM_10CM_2_4MM	97.3225	93.3726	89.9538	97.2836	94.2057	90.4303
c1_vias	C1_2_4MM	96.5812	89.8957	87.6369	96.4881	84.5651	83.0403
c2_vias	C2_2_4MM	97.7527	94.1594	92.0496	97.5927	93.5917	91.1854
c3_vias	C3_2_4MM	96.6935	90.4189	89.9007	96.4762	88.1249	88.883
C4_VIAS	C4_VIA_HIROSE_IFBW_500HZ	91.8131	81.6629	80.329	n/a	n/a	n/a
C5_VIAS	C5_VIA_HIROSE_IFBW_500HZ	93.6226	80.9815	76.027	n/a	n/a	n/a
INNER6_5cm	INNER6_5CM_2_4MM	97.9282	95.2488	93.5004	98.1915	96.1638	93.0851
INNER6_10cm	INNER6_10CM_2_4MM	98.0079	96.2949	94.3676	98.0913	96.8311	92.9737
F1_AC0402	F1_2_4MM	95.6116	89.9624	88.5524	93.5732	87.0771	85.2955
F2_AC0201	F2_2_4MM	95.4258	87.1843	87.8359	93.8553	82.6032	83.0044
F3_DecapShorted	F3_2_4MM	96.6008	88.994	86.8609	96.1133	85.2825	84.8707
G1	G1_2_4MM	97.58	94.7692	92.4024	96.3346	92.5155	91.5084
G2	G2_2_4MM	97.5394	96.027	94.4308	97.2923	96.1297	94.1932
D2_Beatty6	D2_BEATTY_25OHM_INNER6	97.6913	95.5578	92.1797	n/a	n/a	n/a
E1_MeanderStraight	E1_Meander_10cm_Hirose_co	91.9887	80.8534	75.3068	n/a	n/a	n/a
NNER1_5cm	INNER1_5CM_2_4MM	98.3749	95.226	90.7426	98.4463	95.8208	91.1003
INNER1_10cm	INNER1_10CM_2_4MM	98.272	94.9564	90.6877	98.4756	95.7491	90.8221
INNER2_5cm	INNER2_5CM_2_4MM	97.7826	94.7072	92.4632	97.9628	95.1115	91.8582
INNER2_10cm	INNER2_10CM_2_4MM	97.5838	95.8042	94.5077	97.92	96.3239	93.2927
INNNER3_5cm	INNER3_5CM_2_4MM	98.0741	95.856	95.0785	98.2038	96.0933	95.0072
INNNER3_10cm	INNER3_10CM_2_4MM	97.6933	96.6618	95.6197	97.9462	96.93	95.3461
D1_BEATTY	D1_BEATTY_25OHM_INNER1	96.7996	91.9662	90.3091	n/a	n/a	n/a

M. Marin, Y. Shlepnev, 40 GHz PCB Interconnect Validation: Expectation vs. Reality, DesignCon2018, January 31, 2018, Santa Clara, CA. - #2018_01 at https://www.simberian.com/AppNotes.php

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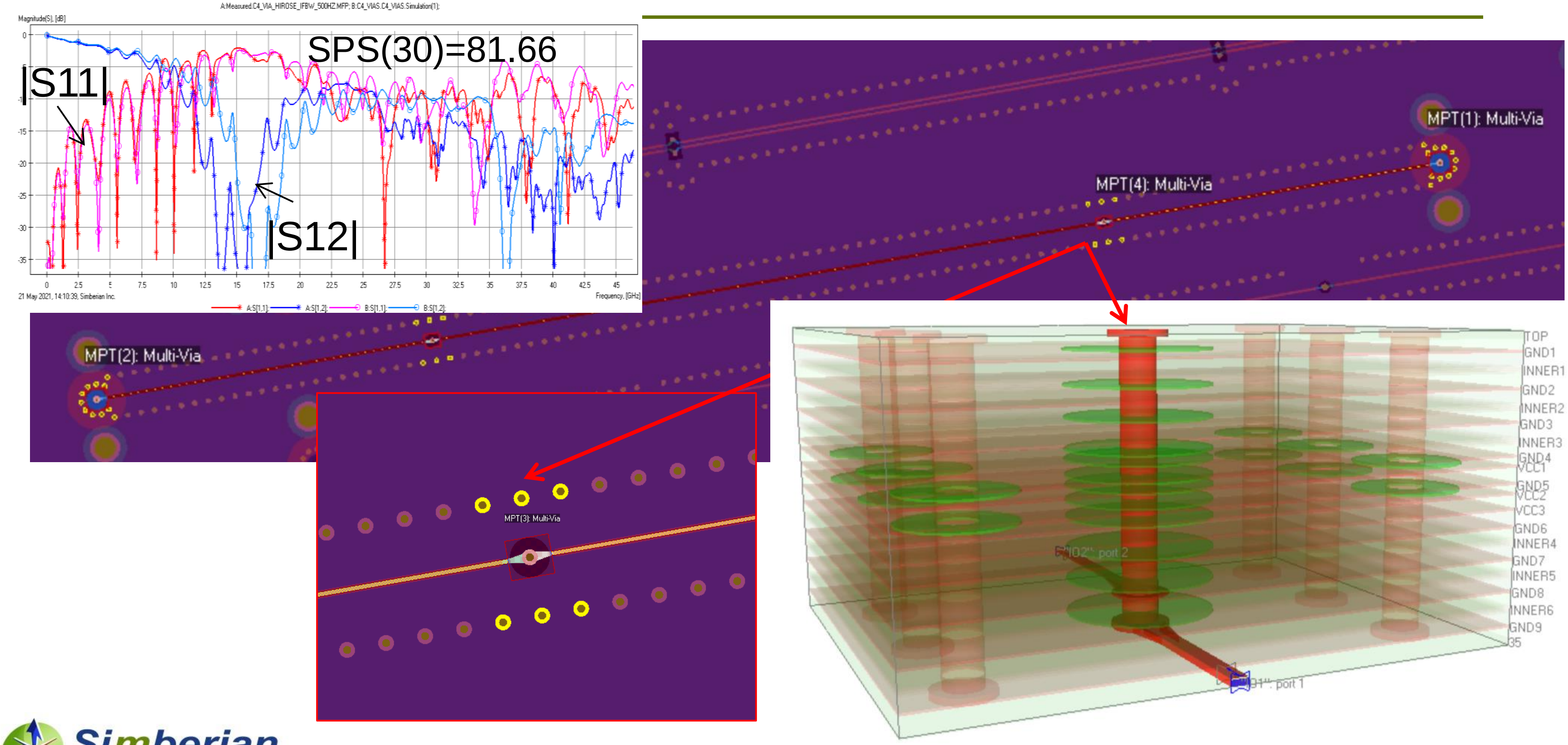
EvR-1: C4_VIAS - Long Stubs and Localization Problem



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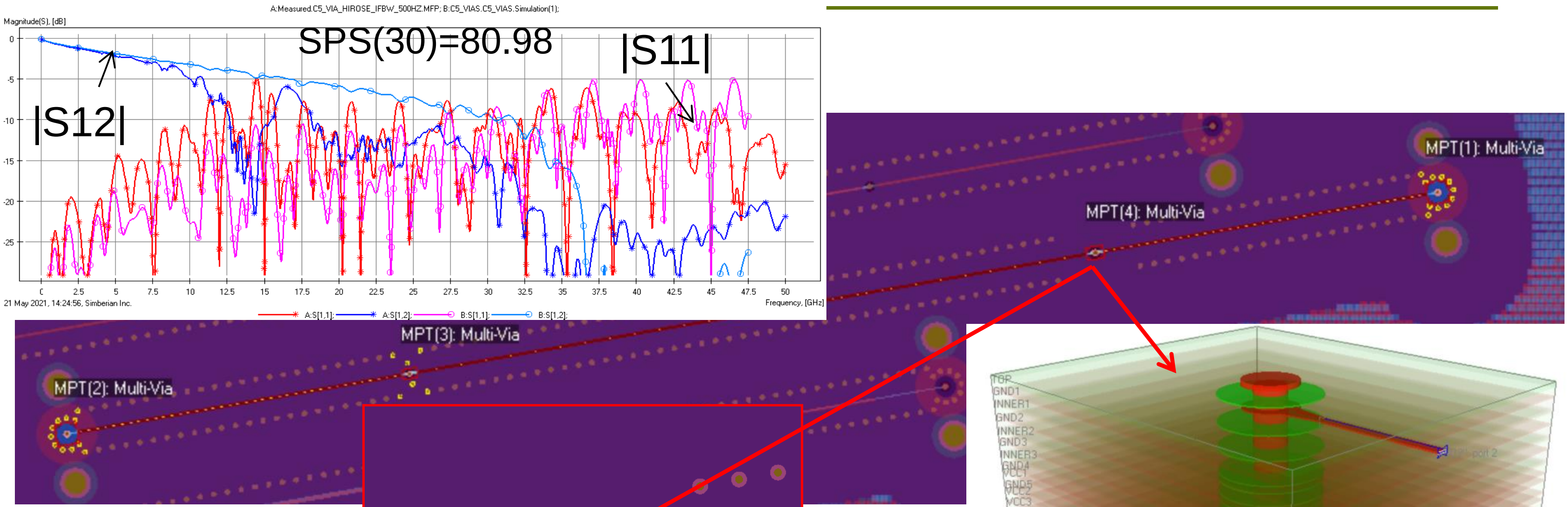
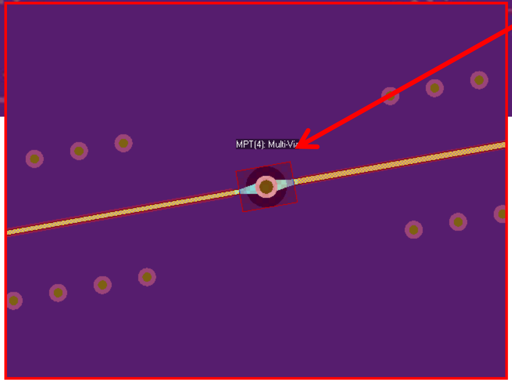
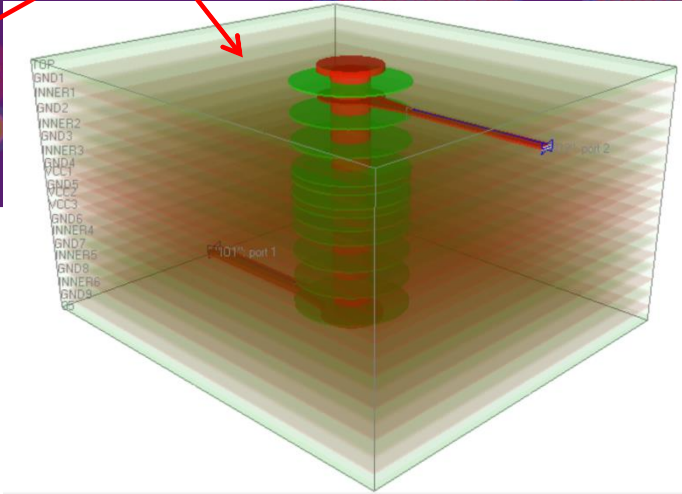
EvR-1: C5_VIAS – No Localization







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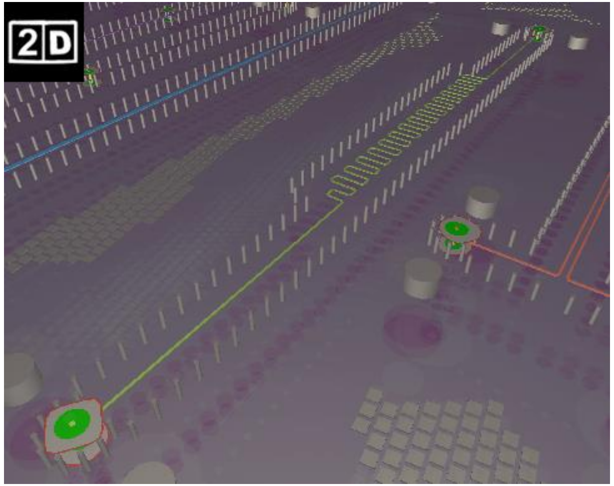
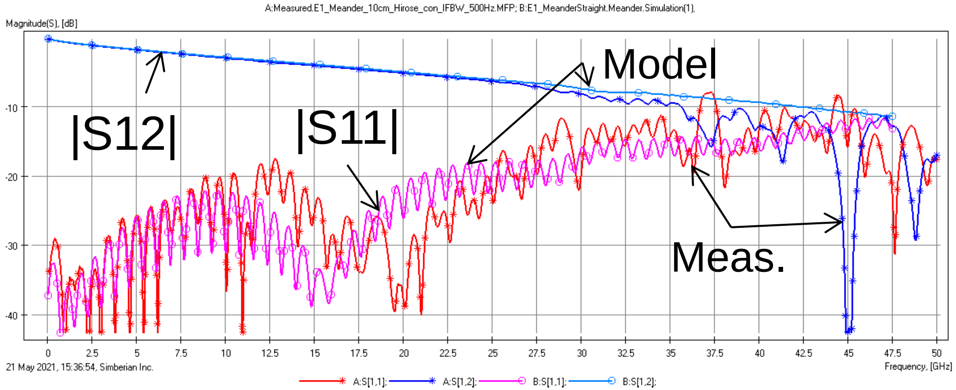
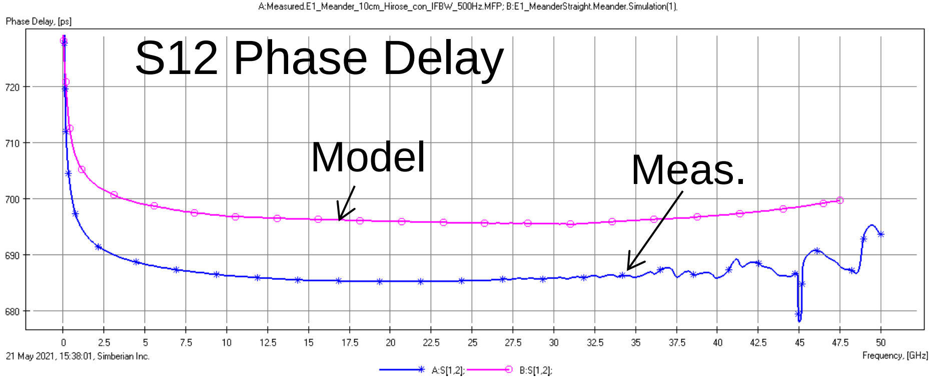
EvR-1: Meander – Sensitivity to Delay

SPS(30)

95.3805	80.7767
80.7744	96.0296







Other Applications: Finding Measurement Matching Model

The largest SPS values are for models that created for corresponding measured structures – SPS(30) with fnorm=1GHz

Model\Meas	'cmp28_strpl_2in_50ohm_p1J6_p2J5_s2p'	'cmp28_strpl_8inch_p1J7_p2J8_s2p'	'cmp28_strpl_Beatty_25ohm_p1J28_p2J27_s2p'	'cmp28_strpl_resonator_p1J23_p2J24_s2p'
SL_SE_2inch_J6J5	92.4394	63.4563	61.6764	48.7333
SL_SE_8inch_J7J8	46.7434	91.8262	62.2733	58.5501
SL_SE_Beatty_25Ohm_J28J27	54.1567	73.3791	91.7525	58.1063
SL_SE_Resonator_J23J24	47.8512	59.0499	57.4813	92.8552

All are 2-port S-parameters

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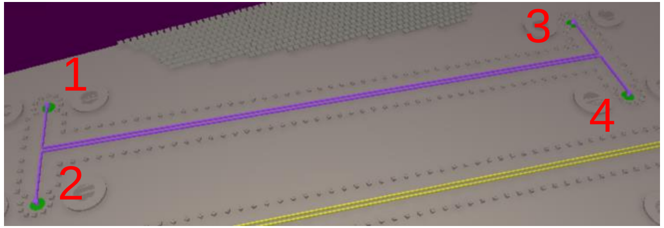
Other Applications: Finding Port Mapping



Modeled: 1—3, 2—4;
Measured: 1—2, 3—4;

Wrong port mapping or no mapping

bottom_5cm vs. BOTTOM_5CM_2_4MM:
SPS=34.2403%

93.8649	35.9115	34.2403	97.6833
35.9042	94.3134	97.9695	34.3053
34.2412	97.9843	94.7716	35.8398
97.7408	34.3058	35.8304	95.2950

With correct model port mapping
1->1,2->3, 3->2, 4->4

bottom_5cm vs. BOTTOM_5CM_2_4MM:
SPS=93.8649%

93.8649	98.1029	97.4252	97.6833
98.1014	94.7709	97.9843	95.8049
97.4376	97.9695	94.3135	98.0679
97.7408	95.8234	98.0640	95.2950

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Conclusion

- A new S-parameters similarity SPS metric is defined through modified Hausdorff distance in 3D RIF space
- The metric is intuitive, simple to implement, computationally straightforward and robust
- Tiers or levels can be introduced for a particular application domain
- It may compliment FSV as the first-pass quick and easy evaluation of S-parameters similarity
- See details and code snippets are in Simberian App Note #2021_05: Y. Shlepnev, S-Parameters Similarity Metric, May 24, 2021