EMC 2015
DRESDEN, AUGUST 16-22

Multipole-Based Macro-models for EMC and EMI System Analysis

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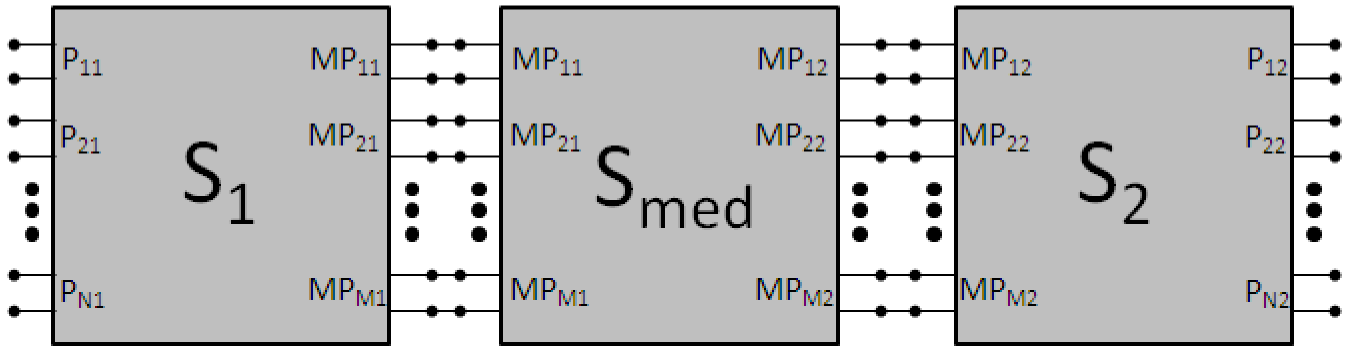
Introduction & Goals

Idea: Extended S-Matrix



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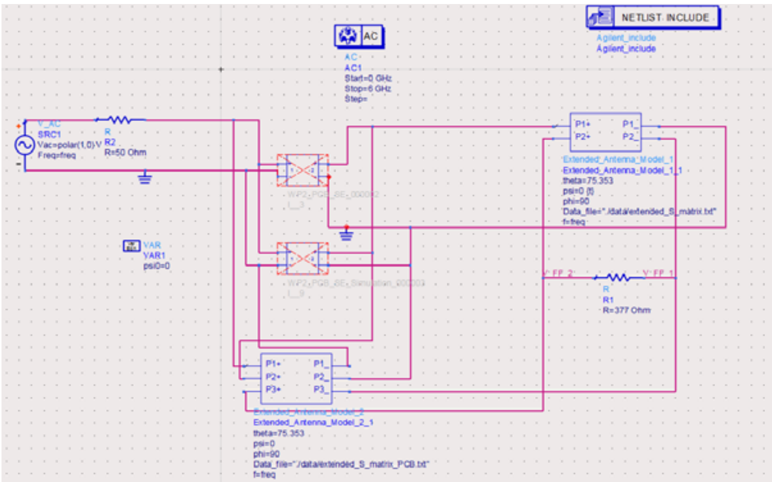

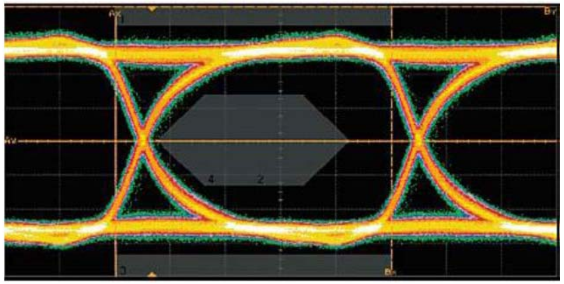

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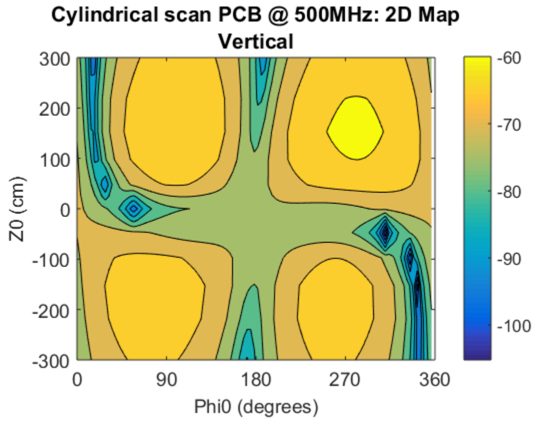

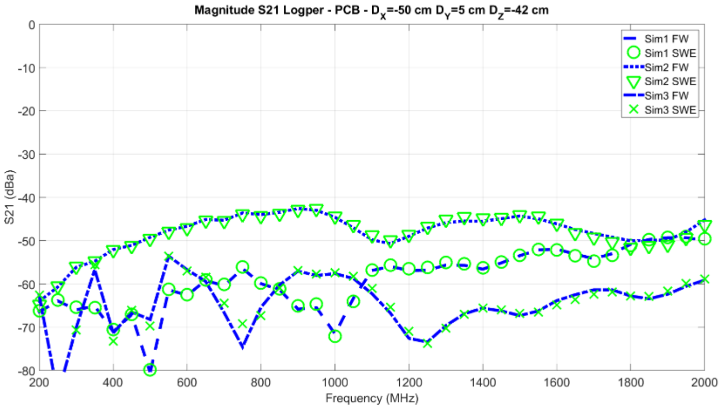

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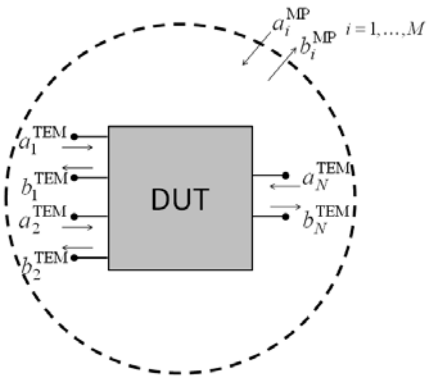
Introduction & Goals



Expansion in spherical waves

$$\vec{E}(r,\theta,\varphi) = \frac{k}{\sqrt{\eta}} \sum_{csmn} Q^{(c)}{}_{smn} \vec{F}^{(c)}{}_{smn}(r,\theta,\varphi)$$

$$\vec{H}(r,\theta,\varphi) = -ik\sqrt{\eta} \sum_{csmn} Q^{(c)}{}_{smn} \vec{F}^{(c)}{}_{3-s,mn}(r,\theta,\varphi)$$

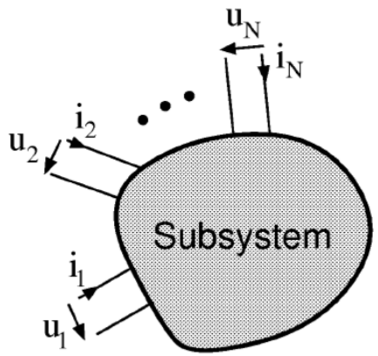
⬇

$$\begin{bmatrix} \Gamma & \boldsymbol{R} \\ \boldsymbol{T} & \boldsymbol{S} \end{bmatrix} \begin{bmatrix} a_{TEM} \\ a_i{}^{MP} \end{bmatrix} = \begin{bmatrix} b_{TEM} \\ b_i{}^{MP} \end{bmatrix}$$

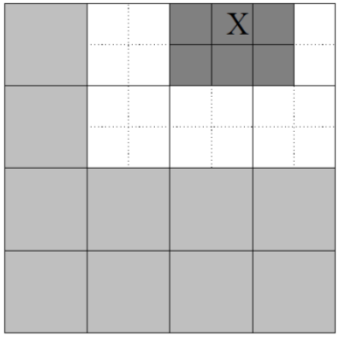
Similar types of expansions:

- Plane waves (e.g. Drogoudis, D.; Van Hese, J.; Boesman, B.; Pissoort, D., "Combined circuit/full-wave simulations for electromagnetic immunity studies based on an extended S-parameter formulation," Signal and Power Integrity (SPI), 2014 IEEE 18th Workshop on , vol., no., pp.1,4, 11-14 May 2014
- Cylindrical waves (e.g. Vandenbosch, G.A.E.; Demuynck, F.J., "The expansion wave concept. II. A new way to model mutual coupling in microstrip arrays," Antennas and Propagation, IEEE Transactions on , vol.46, no.3, pp.407,413, Mar 1998)

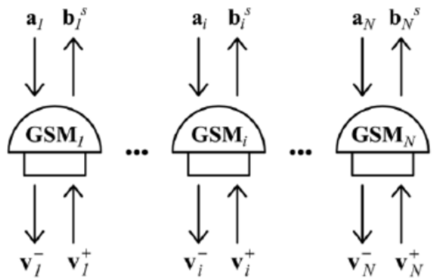
Current application of Spherical-Wave-Expansions



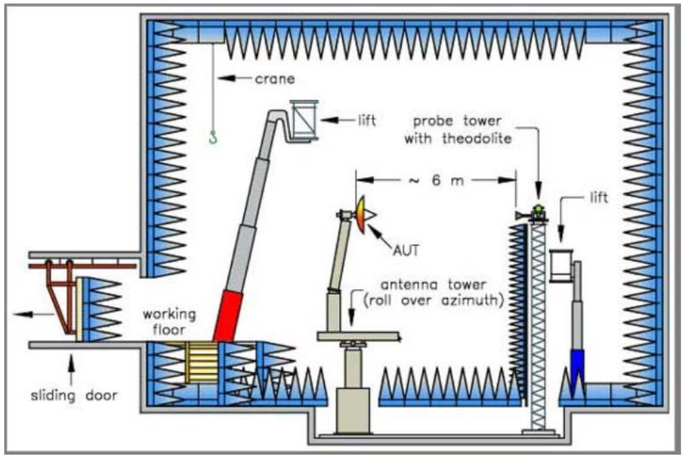
Integration in full-wave engines



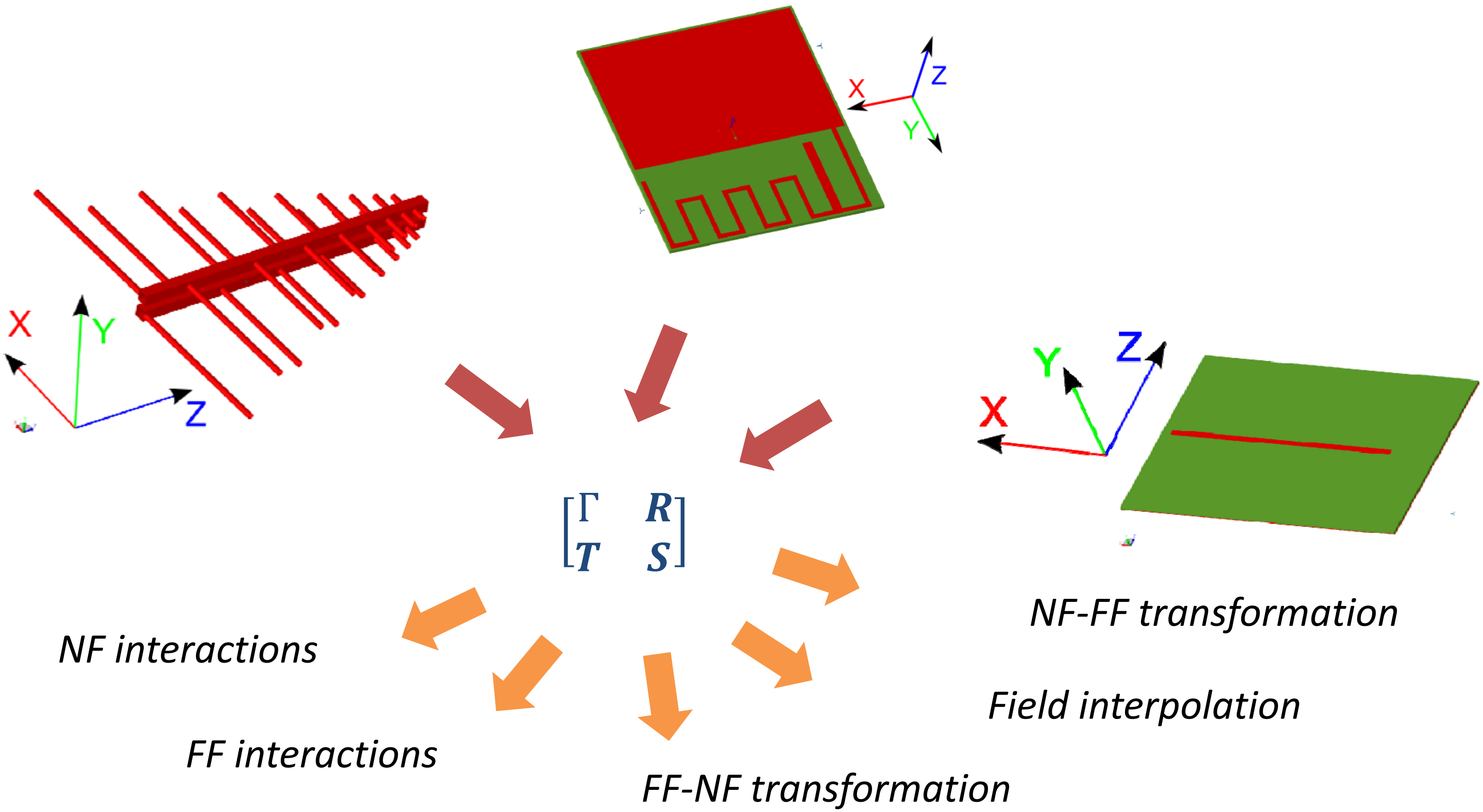
$d/_{\lambda}$ sufficiently large or $N = kr_0 + 10$



Integration in antenna analysis

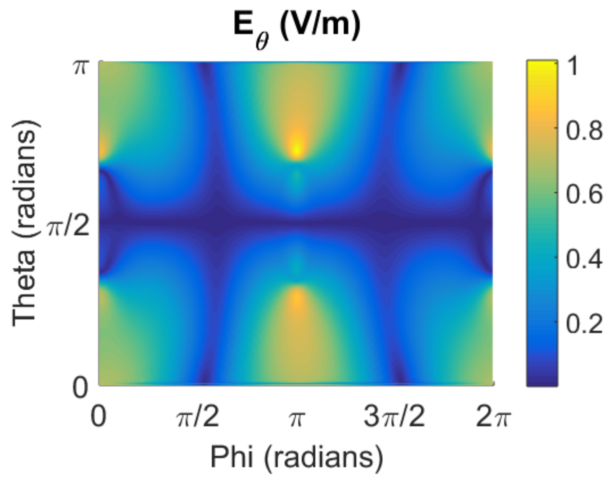


Library of SWE-based models



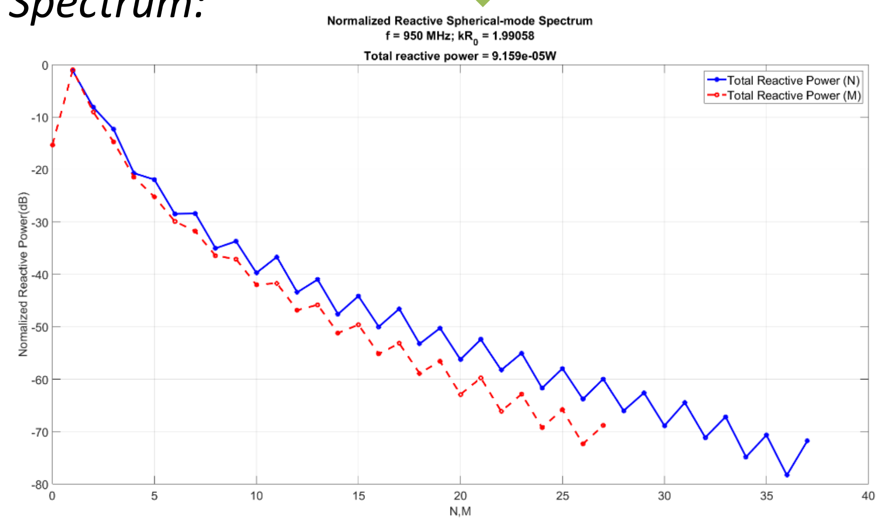
Building a SWE-based model

Tangential Near-fields on a DUT's minimum-sphere:



$$Q^{(3)}_{1mn} = \frac{\sqrt{\eta}}{k} \frac{(-1)^m}{\sqrt{2\pi n(n+1)}} \frac{1}{R^{(3)}_{1n}(kr)} \left(\frac{m}{|m|}\right)^{-m} \times$$
$$\{-(i \cdot m) I_1 (E_\theta(\theta,\phi)) - I_2 (E_\phi(\theta,\phi))\} \quad (2a)$$
$$Q^{(3)}_{2mn} = \frac{\sqrt{\eta}}{k} \frac{(-1)^m}{\sqrt{2\pi n(n+1)}} \frac{1}{R^{(3)}_{2n}(kr)} \left(\frac{m}{|m|}\right)^{-m} \times$$
$$\{-(i \cdot m) I_1 (E_\phi(\theta,\phi)) + I_2 (E_\theta(\theta,\phi))\} \quad (2b)$$

Reactive Energy Spectrum:



Extended S-Matrix:

$$\begin{bmatrix} \Gamma & \boldsymbol{R} \\ \boldsymbol{T} & \boldsymbol{S} \end{bmatrix} \begin{bmatrix} a_{TEM} \\ a_i{}^{MP} \end{bmatrix} = \begin{bmatrix} b_{TEM} \\ b_i{}^{MP} \end{bmatrix}$$

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Building a SWE-based model

- Solution of orthogonality integrals using **Chebyshev integration**:

$$I_1 = \int_0^\pi \tilde{f}(\theta, m) \frac{m\overline{P}_n^{|m|}(\cos\theta)}{\sin\theta} \sin\theta d\theta = \int_{-1}^{1} \sum_{k=0}^{k_{max}} y_k T_k(x) dx \quad (3a)$$

$$I_2 = \int_0^\pi \tilde{f}(\theta, m) \frac{d\overline{P}_n^{|m|}(\cos\theta)}{d\theta} \sin\theta d\theta = \int_{-1}^{1} \sum_{k=0}^{k'_{max}} y'_k T_k(x) dx \quad (3b)$$

Model with N=100 takes not more than 30s!

- Model complexity depends on chosen N:

$$\#S - parameters = 2N(N+2) + 2N(N+2)$$

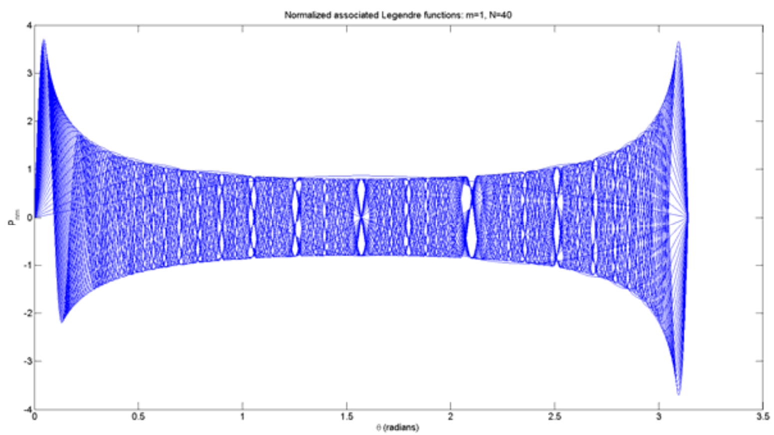
Radiation *Reception*

- *N* is the **'bandwidth'** of the DUT, which is derived automatically from the Reactive Energy Spectrum
- Scattering of the DUT is being neglected

Building a SWE-based model

Challenges:

- Efficient and stable recursion of Associated Legendre Functions (ALF's) and their derivatives
- Stable computation of reactive energy for high bandwidth
- Deriving a suitable **truncation criterion**

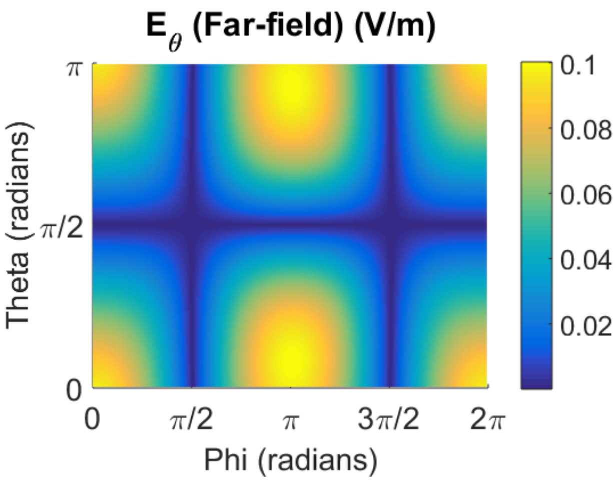


$$W_{reactive} = \frac{1}{4\omega} \sum_{smn} |Q^{(3)}_{smn}|^2 \int_{kr_0}^{\infty} \left\{ \left[R^{(3)}_{1n}(kr)\, R^{(4)}_{1n}(kr) + R^{(3)}_{2n}(kr)\, R^{(4)}_{2n}(kr) \right] (kr)^2 - 2 + n(n+1) \cdot z^{(3)}_n(kr)\, z^{(4)}_n(kr) \right\} d(kr) \qquad (8)$$

$$I_1^{n=10} = \frac{55}{kr} + \frac{1485}{kr^3} + \frac{77220}{kr^5} + \frac{4729725}{kr^7} + \frac{1297972675}{kr^9} + \frac{17878360500}{kr^{11}} + \frac{955215261000}{kr^{13}} + \frac{41910069576375}{kr^{15}} + \frac{1327152203251875}{kr^{17}} + \frac{22561587455281880}{kr^{19}}$$

Building a SWE-based model

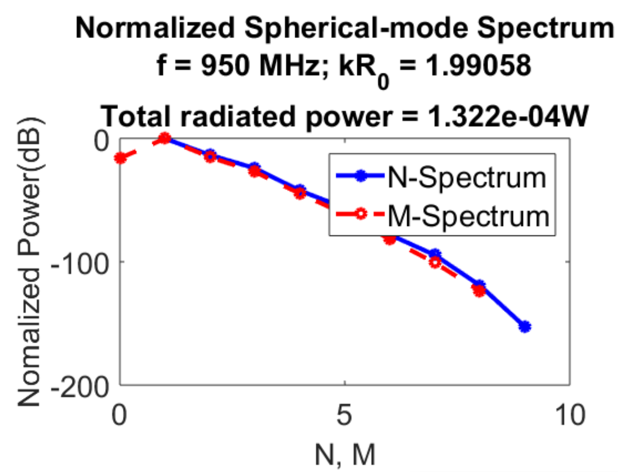
Minimize model complexity by *expanding tangential Far-fields:*



$$Q^{(3)}_{1mn} = \sqrt{\frac{\eta}{4\pi}}\,(-1)^{m+n+1}\sqrt{\frac{2}{n\,(n+1)}}\,(-i)^{n+1} \left(\frac{m}{|m|}\right)^{-m}\left\{-\left(i\cdot m\right) I_1\left(E_\theta\left(\theta,\phi\right)\right) - I_2\left(E_\phi\left(\theta,\phi\right)\right)\right\} \quad (4a)$$

$$Q^{(3)}_{2mn} = \sqrt{\frac{\eta}{4\pi}}\,(-1)^{m+n}\sqrt{\frac{2}{n\,(n+1)}}\,(-i)^{n} \left(\frac{m}{|m|}\right)^{-m}\left\{-\left(i\cdot m\right) I_1\left(E_\phi\left(\theta,\phi\right)\right) + I_2\left(E_\theta\left(\theta,\phi\right)\right)\right\} \quad (4b)$$

Radiated Power Spectrum:

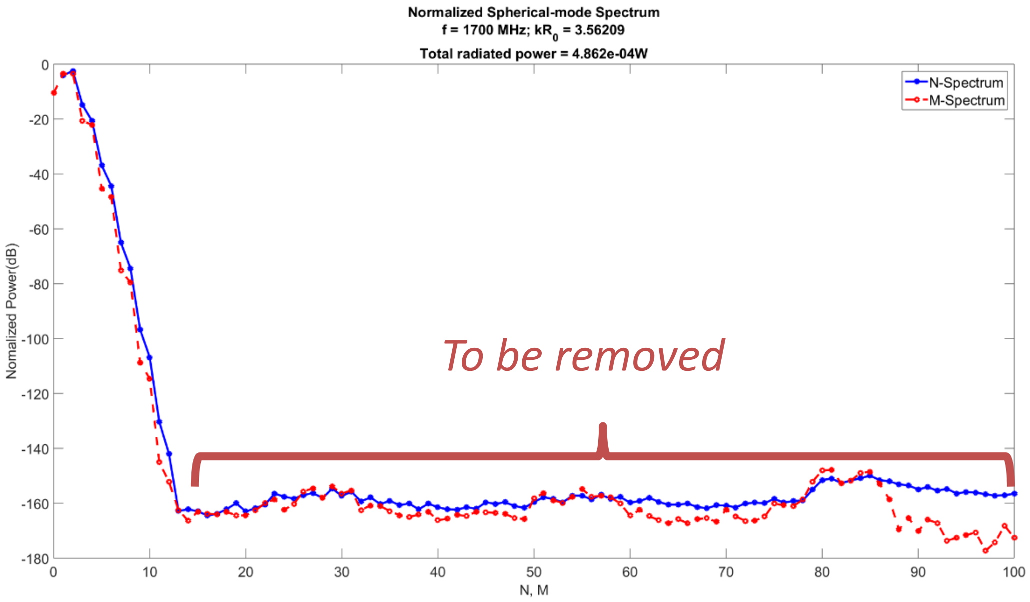


Extended S-Matrix:

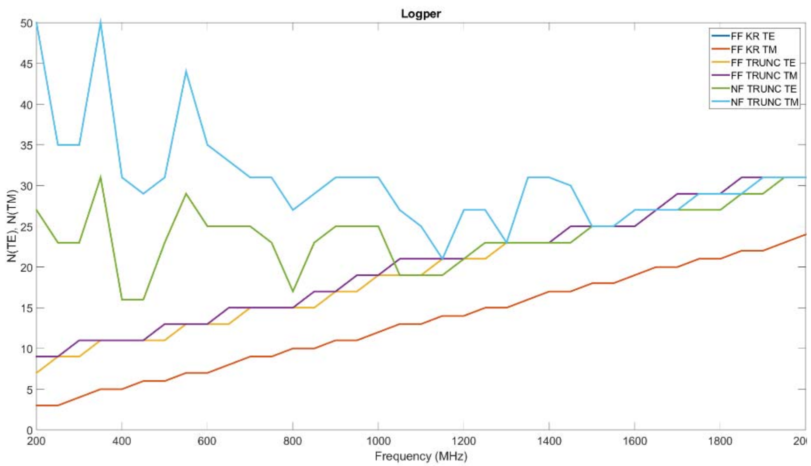
$$\begin{bmatrix} \Gamma & \boldsymbol{R} \\ \boldsymbol{T} & \boldsymbol{S} \end{bmatrix} \begin{bmatrix} a_{TEM} \\ a_i{}^{MP} \end{bmatrix} = \begin{bmatrix} b_{TEM} \\ b_i{}^{MP} \end{bmatrix}$$

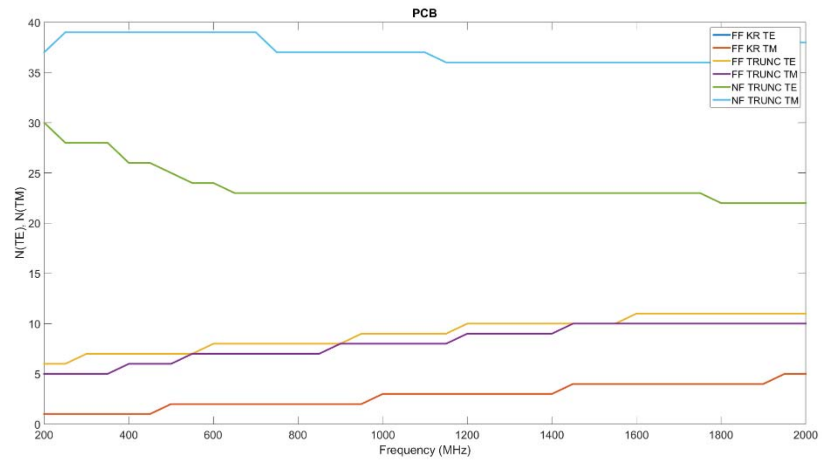
Building a SWE-based model

- Same **integration** technique as in case of expanding **Near-field** data.
- Truncation criterion based on removing *erroneous* modes:



Building a SWE-based model





- **Far-field**: Truncation corresponds to ~ $N = kr_0 + n_1$

Constant between 5 and 10

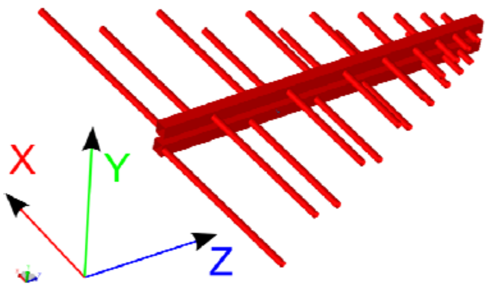
Propagation constant

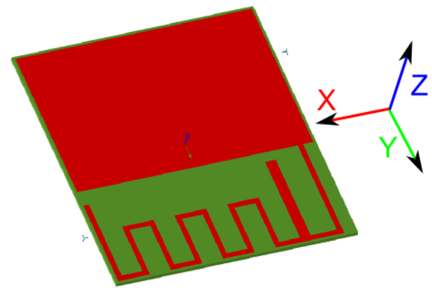
Radius of the minimum-sphere

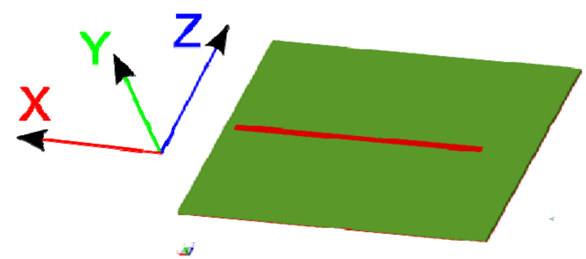
- **Near-field**: An additional number of modes incorporates the presence of reactive energy

Applications of SWE-based models

Recall:







$$\begin{bmatrix} \Gamma & \boldsymbol{R} \\ \boldsymbol{T} & \boldsymbol{S} \end{bmatrix}$$

NF interactions

FF interactions

FF-NF transformation

Field interpolation

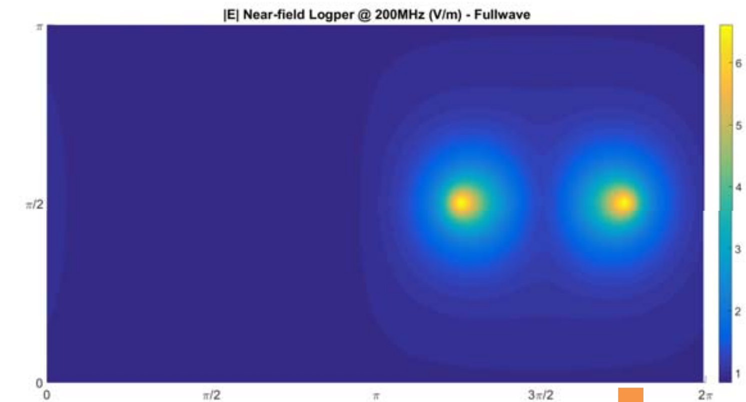
NF-FF transformation

Field interpolation & transformation

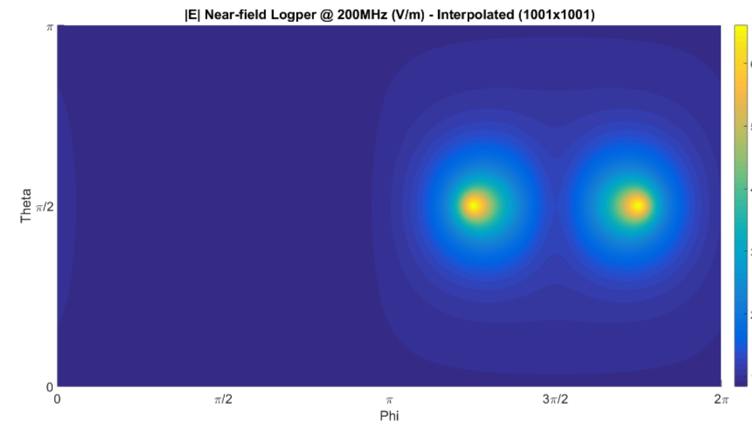
- See: Boesman B; Pissoort D; Gielen G; Vandenbosch G.A.E, "Fast and Efficient Near-field to Near-field and Near-field to Far-field Transformation based on the Spherical Wave Expansion," Accepted for 2015 International Symposium on Electromagnetic Compatibility, Aug. 2015.

- General work-flow:
  - ❑ SWE macro-model available
  - ❑ Inverse Discrete Cosine Transform (IDCT) in θ
  - ❑ Inverse Discrete Sine Transform (IDST) in θ
  - ❑ Inverse Fast Fourier Transform (IFFT) in ϕ

Field interpolation & transformation

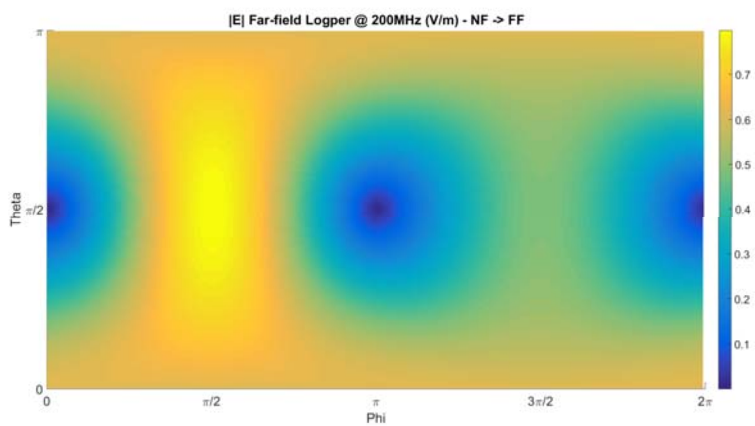


Increased resolution

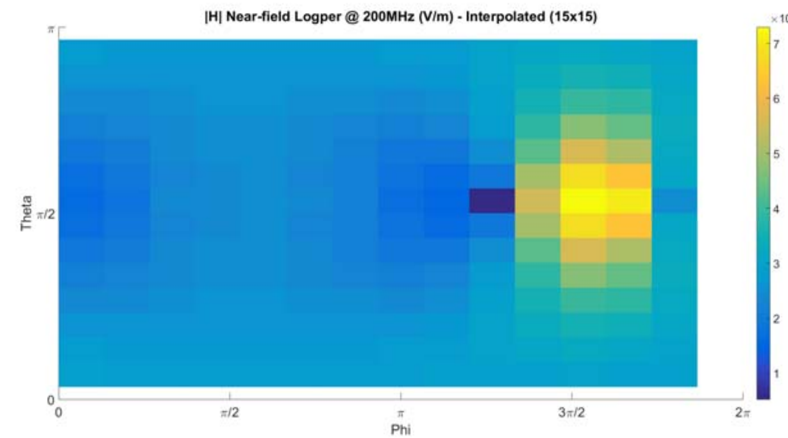


$$\begin{bmatrix} \Gamma & \boldsymbol{R} \\ \boldsymbol{T} & \boldsymbol{S} \end{bmatrix}$$

NF to FF transformation



Decreased resolution



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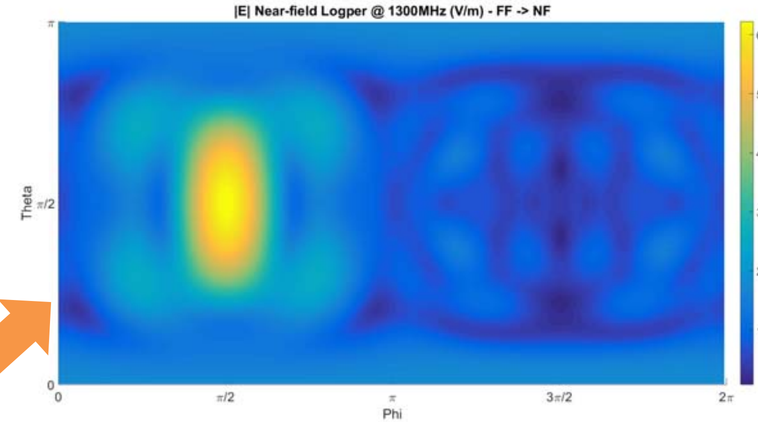
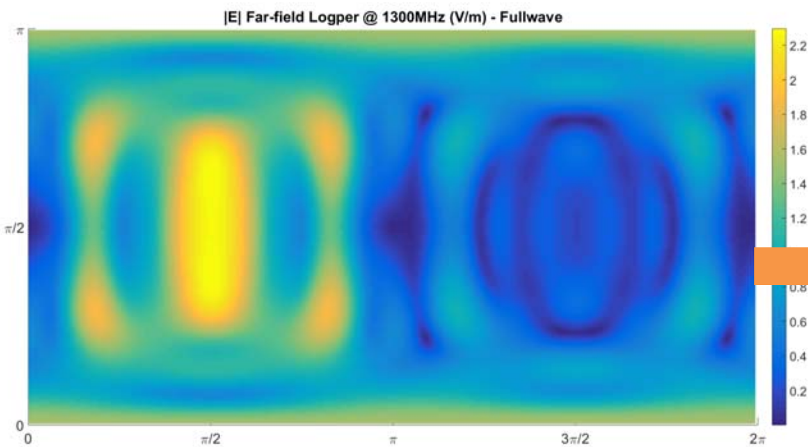
Field interpolation & transformation

FF to NF transformation

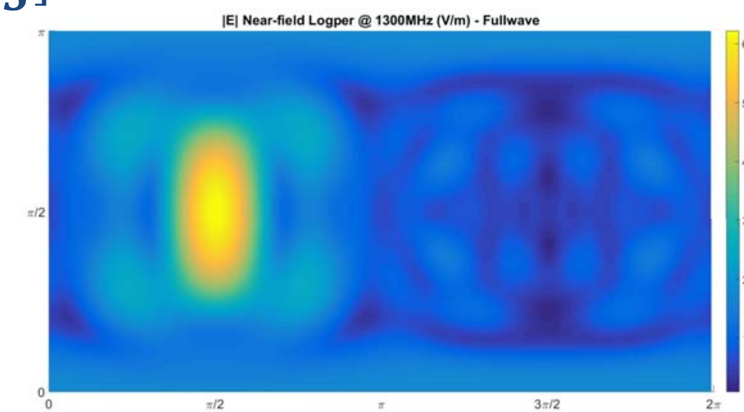


Fullwave Far-field



$$\begin{bmatrix} \Gamma & \boldsymbol{R} \\ \boldsymbol{T} & \boldsymbol{S} \end{bmatrix}$$

Fullwave Near-field



Field interpolation & transformation

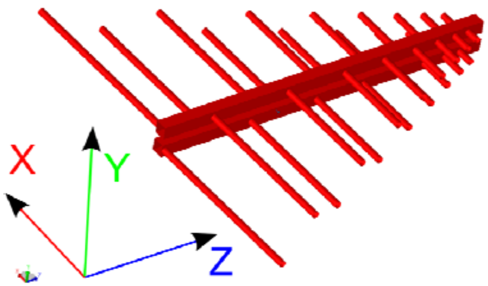
TABLE I. SUMMARY OF COMPUTATION TIMES AND DISK SPACE FOR INTERPOLATION AND TRANSFORMATION OF NEAR-FIELD AND FAR-FIELD DATA.

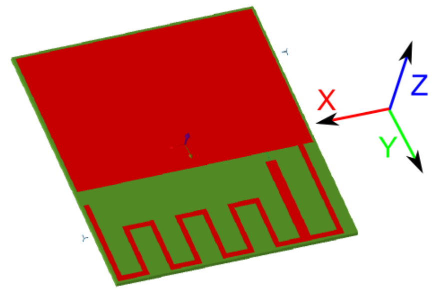
	NF @200MHz			FF @1300MHz
	N=50	N=75	N=100	N = 26
SWE	9.9s	22.5s	39.1s	1.4s
Disk space	1.8Mb	4.1Mb	7.2Mb	0.5Mb
NF Interp. 2500	22.7s	24.2s	28.2s	-
NF Interp. 1000	3.4s	5.0s	7.8s	-
NF Interp. 500	2.2s	3.7s	6.5s	-
FF Transform. 2500	8.0s	9.1s	11.4s	7.4s
FF Transform. 1000	1.4s	2.6s	4.0s	0.9s
FF Transform. 500	0.9s	1.9s	3.5s	0.4s

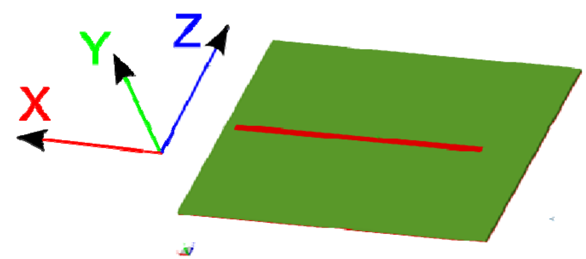
- ***No field data*** *to be stored*
- ***Fast*** *reconstruction, interpolation and transformation*
- *Noise* ***filtering***

Applications of SWE-based models

Recall:







$$\begin{bmatrix}\Gamma & \boldsymbol{R}\\ \boldsymbol{T} & \boldsymbol{S}\end{bmatrix}$$

NF-FF transformation

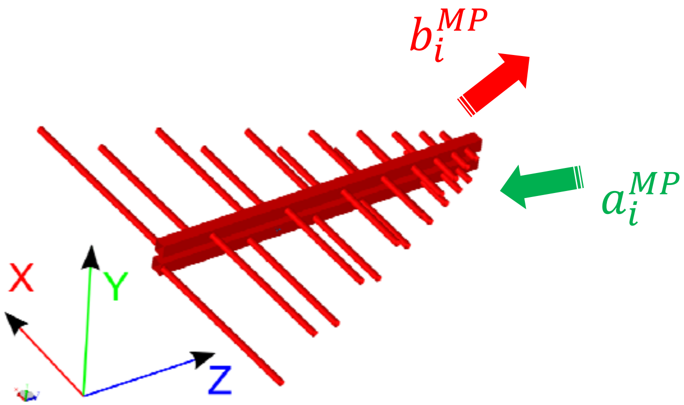
NF interactions

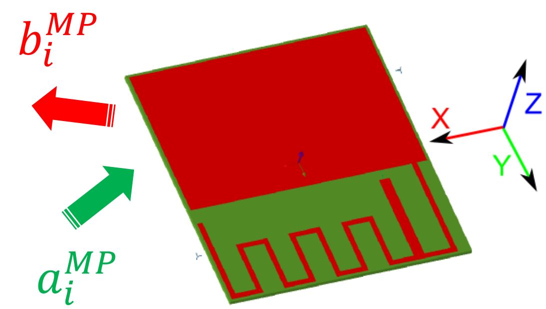
Field interpolation

FF interactions

FF-NF transformation

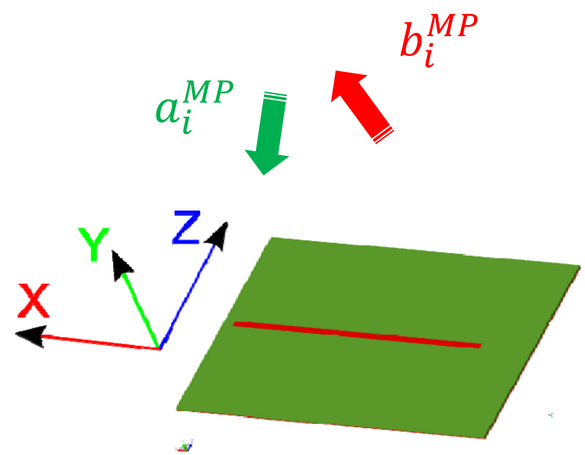
S-Parameter simulations





$$\begin{bmatrix} Translation & \ddots & \\ & \ddots & \ddots \\ \ddots & & Rotation \\ & \ddots & \end{bmatrix} \begin{bmatrix} \vdots \\ a_i^{MP} \\ \vdots \end{bmatrix} = \begin{bmatrix} \vdots \\ b_i^{MP} \\ \vdots \end{bmatrix}$$

S_{med}



S-Parameter simulations

$$S_{21} = [S_{inc}^{dut2}]\,[E_{-\phi_0}]\,[D_{-\theta_0}]\,[C_{+kA}]\,[D_{+\theta_0}]\,[E_{+\phi_0}]\,[S_{rad}^{dut1}] \quad (16a)$$

$$S_{12} = [S_{inc}^{dut1}]\,[E_{-\phi_0}]\,[D_{-\theta_0}]\,[C_{-kA}]\,[D_{+\theta_0}]\,[E_{+\phi_0}]\,[S_{rad}^{dut2}] \quad (16b)$$

but …

- Use **sparse** matrix formulations
- **Truncate** computations where-ever possible
- Extensively use **symmetries**

See: Boesman, B.; Pissoort, D.; Gielen, G.; Vandenbosch, G., "A circuit approach to compute near-field interactions based on an efficient implementation of the spherical wave expansion," *Electromagnetic Compatibility (EMC Europe), 2014 International Symposium on* , vol., no., pp.91,96, 1-4 Sept. 2014

S-Parameter simulations

- **Translation** of spherical waves:
  - ❑ Most computionally intensive step
  - ❑ Must be repeated for each frequency
  - ❑ Use Z-axis

- Concept of **translation vectors**:
  - ❑ Independent of frequency and distance
  - ❑ Allow to efficiently derive the full translation matrix (matter of seconds)

$$C'^{\mu n}_{\mu\nu,1} = \frac{1}{2} i^{(n-\nu)} \sqrt{\frac{2}{n(n+1)\nu(\nu+1)}} i^{(-p)} \tag{8a}$$

$$\{n(n+1) + \nu(nu+1) - p(p+1)\} \overline{a}(\mu, n, -\mu, \nu, p)$$

$$C'^{\mu n}_{\mu\nu,2} = \frac{1}{2} i^{(n-\nu)} \sqrt{\frac{2}{n(n+1)\nu(\nu+1)}} i^{(-p)} \tag{8b}$$

$$\{2i\mu\} \overline{a}(\mu, n, -\mu, \nu, p)$$

(8c)

'Normalized' Gaunt coefficients

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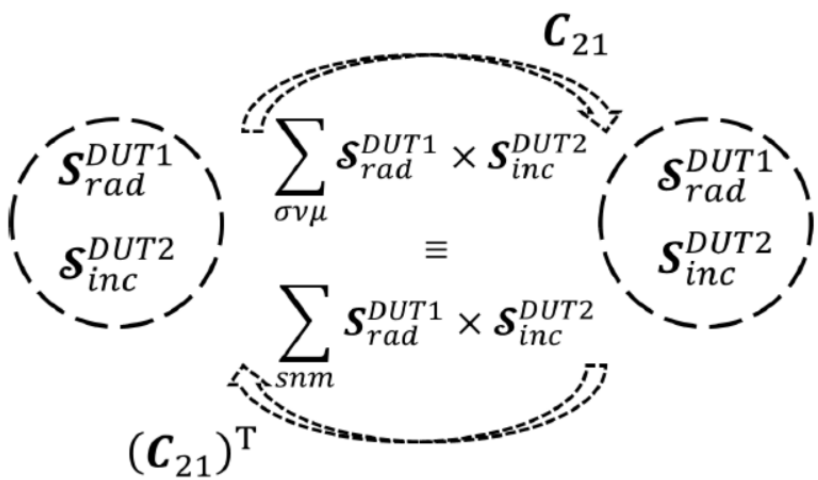
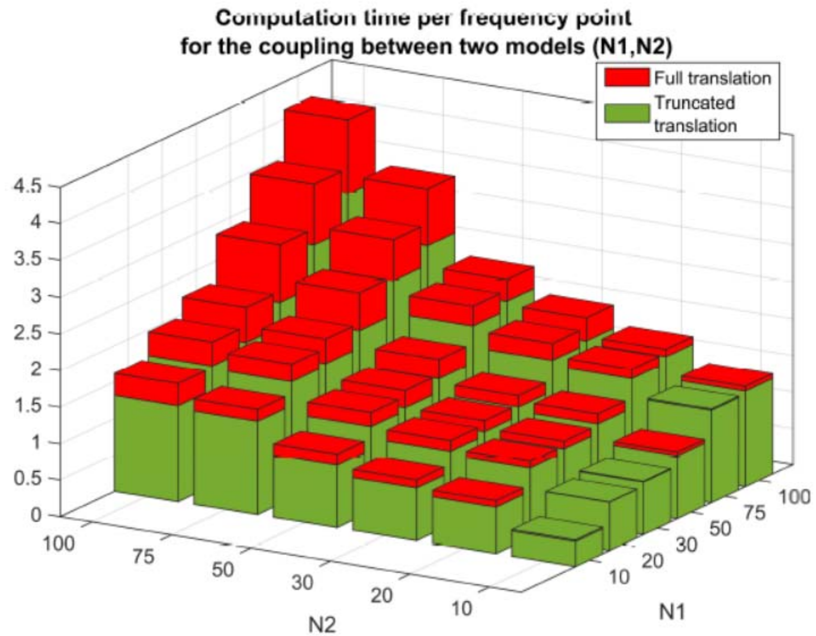
S-Parameter simulations

- **Arbitrary translations**: align the translation axis with the Z-axis
- **Rotation** of spherical waves:
  - ❑ Orders do not mix, sparse matrices
  - ❑ Efficient (FFT-based) algorithms

- Two ways to translate a set of spherical waves:

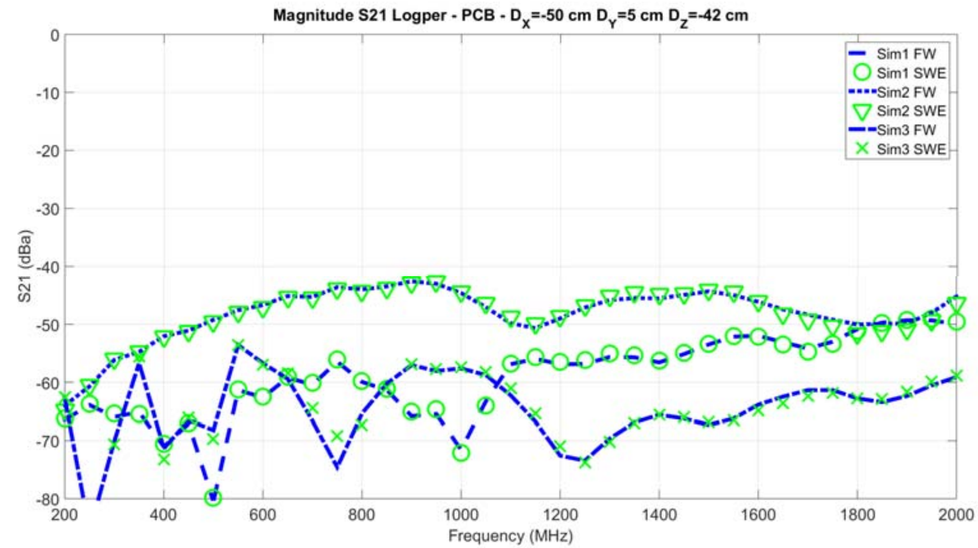


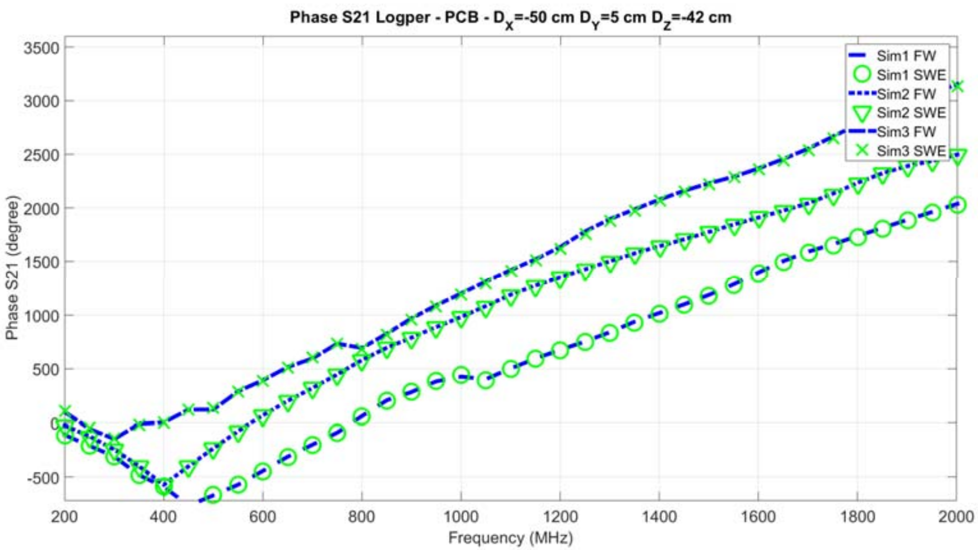
S-Parameter simulations

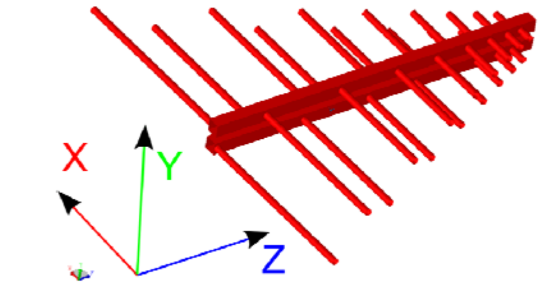


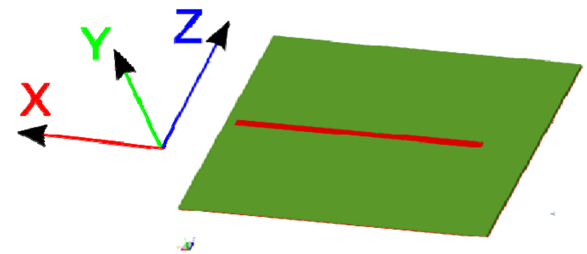
It's crucial to minimize the applied models' bandwidths

S-Parameter simulations using NF-models









Sim1: dX = 65cm; dY = 0cm; dZ = 0cm
Sim2: dX = 50cm; dY = 5cm; dZ = 42cm
Sim3: dX = -50cm; dY = 5cm, dZ = -42cm

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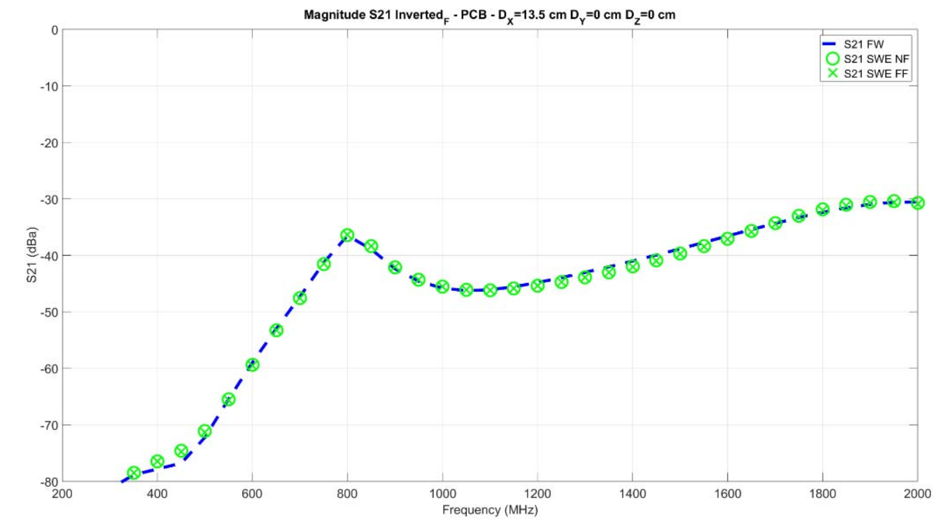
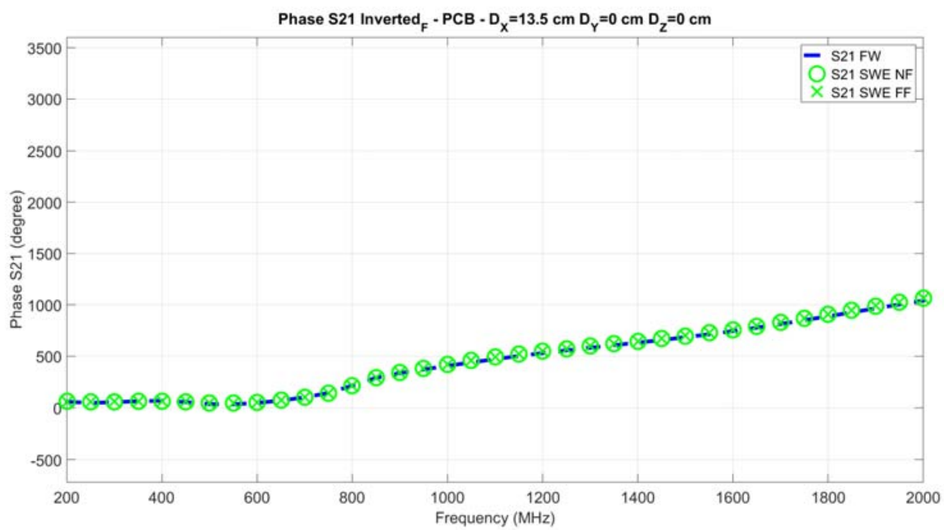
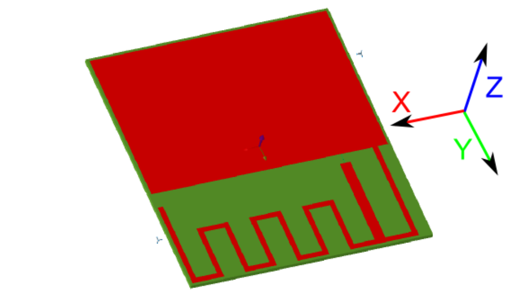
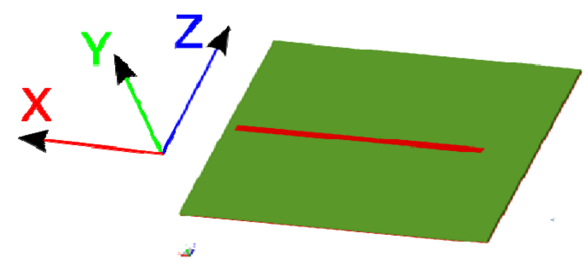
S-Parameter simulations using FF-models









dX = 13,5cm; dY = 0cm; dZ = 0cm

Each green dot represents a sufficiently converged result!

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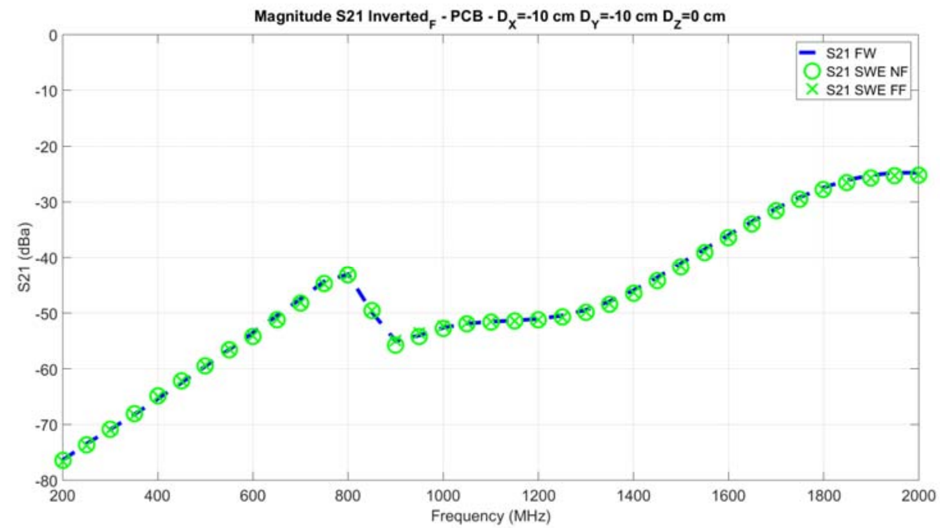
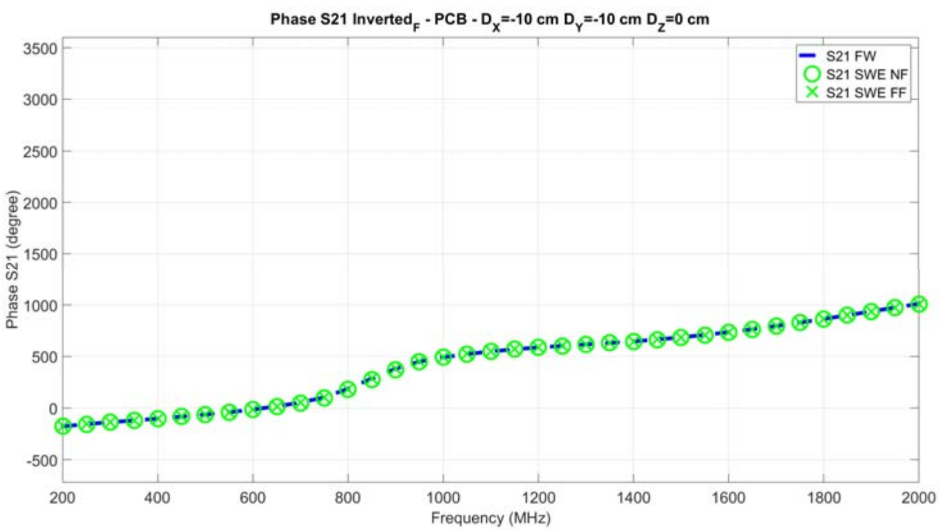
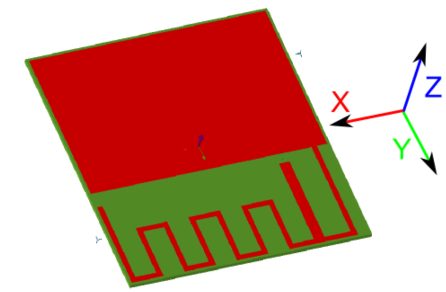
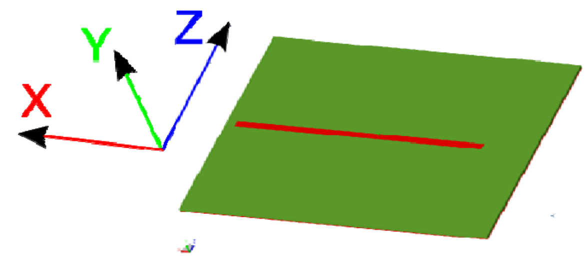
S-Parameter simulations using FF-models









dX = -10cm; dY = -10cm; dZ = 0cm

Each green dot represents a sufficiently converged result!

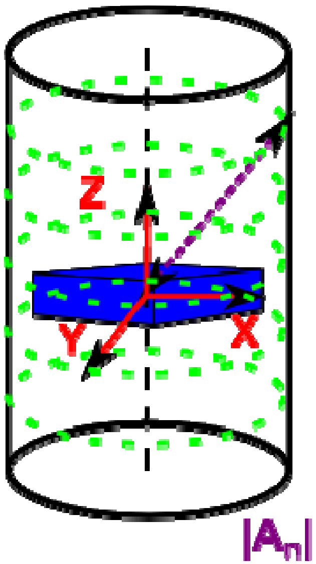
S-Parameter simulations

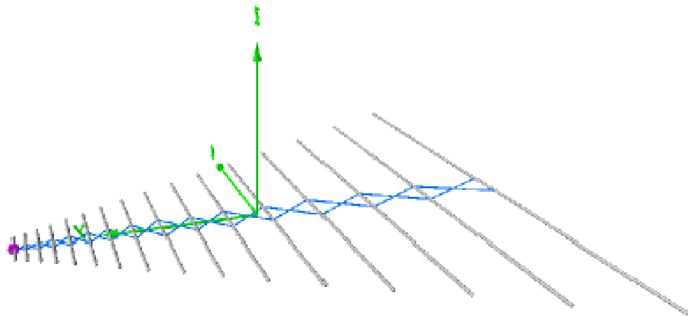
TABLE I
COMPUTATION TIME NEAR-FIELD COUPLING PER FREQUENCY POINT (IN SECONDS, 37 FREQUENCY POINTS)

	Logper - PCB	Inverted F - PCB
SWE NF	24,1	51,8
SWE NF TRUNC	17,0	21,5
SWE FF	13,0	9,6
FDTD 4 GPU's	185,0	104,0
FDTD CPU 8 threads	3249,0	1294,0
FDTD CPU 1 thread	8299,0	3410
FEM CPU 8 cores	10772,0	1005,0

- **FF-models** seem to convergence in a lot of cases, even when computing near-field interactions between these models.
- **NF-models** can be **truncated** prior to simulation: $N_{trunc} = \lceil kr_0 \rceil + \lceil {}^1/_6\,(N - kr_0) \rceil$

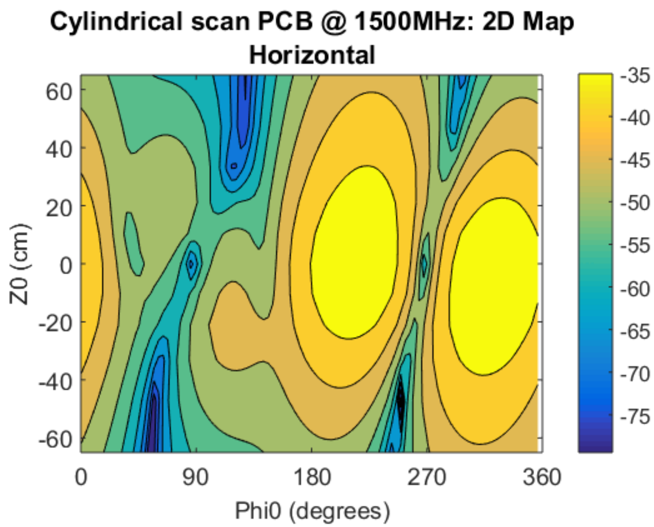
Cylindrical scan of a DUT





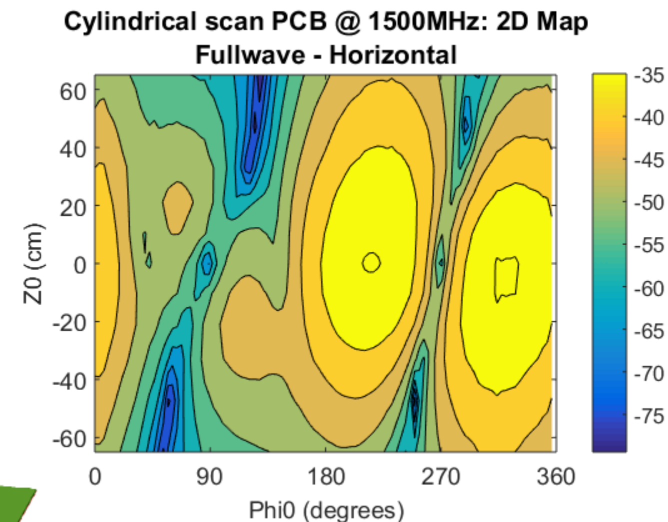
$$b_i = a_j^{DUT} \sum_{\mu'=-N}^{N} e^{i\mu'\chi_0} \sum_{m=-N}^{N} e^{im\varphi_0} \left[\sum_{s=1}^{2} \sum_{n=1}^{N} S^{DUT}_{rad,j,\{smn\}} \cdot \sum_{\mu=-N}^{N} d^{n}_{\mu m}(\vartheta_0) \cdot \sum_{\nu=\max(|\mu|,|\mu'|,1)}^{N} d^{n}_{\mu\mu'}(\vartheta_0) \left\{ \sum_{\sigma=1}^{2} C^{sn(3)}_{\sigma\mu\nu}(kA) S^{Antenna}_{inc,i,\{\sigma\mu'\nu\}} \right\} \right]$$

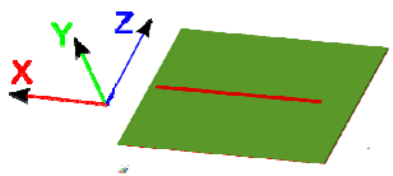
Cylindrical scan(1): PCB

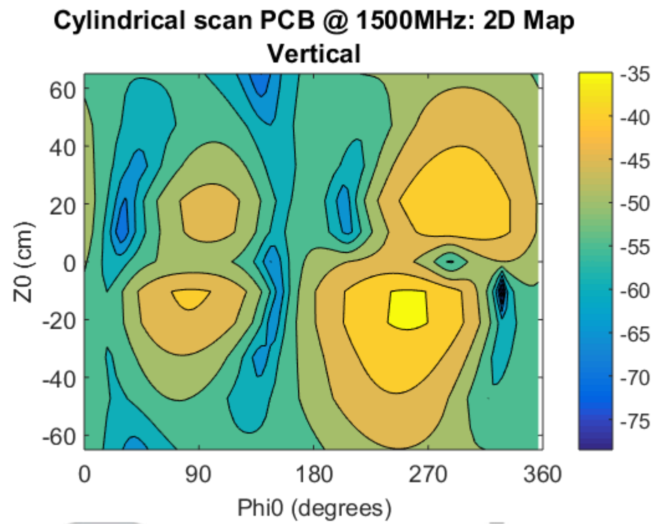


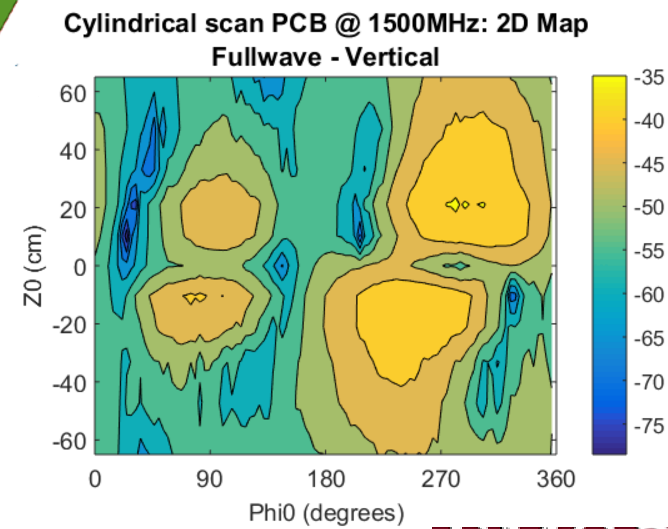
R=65cm

NF-models

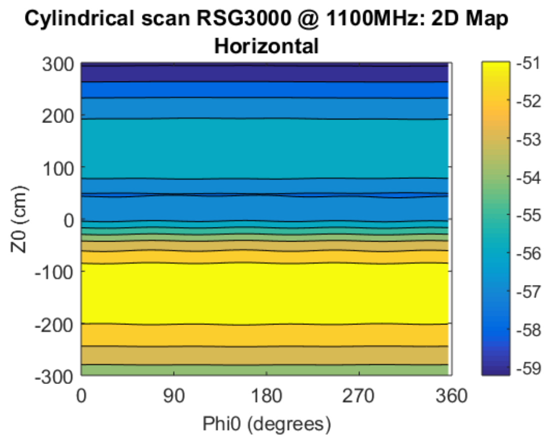


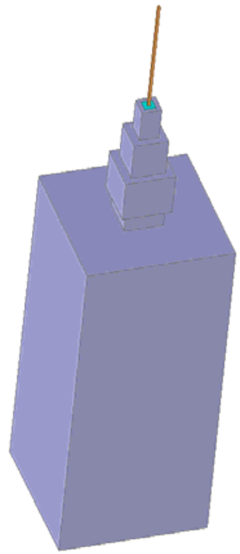


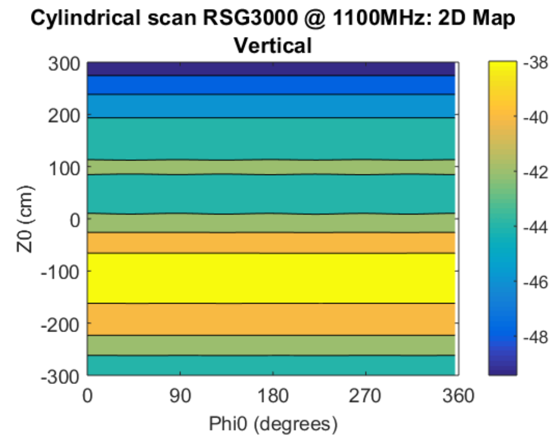


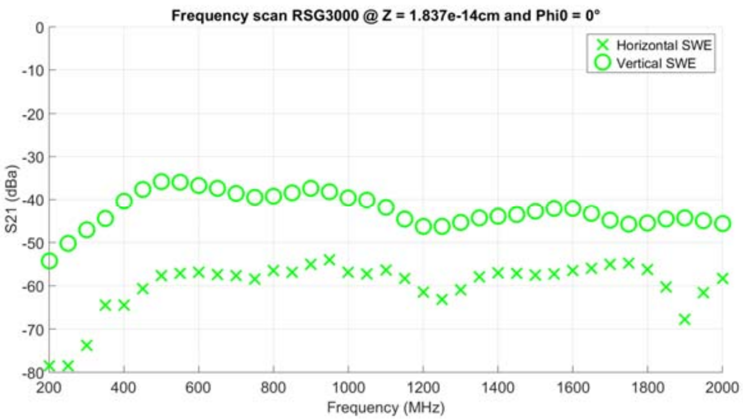


Cylindrical scan(2): RSG3000



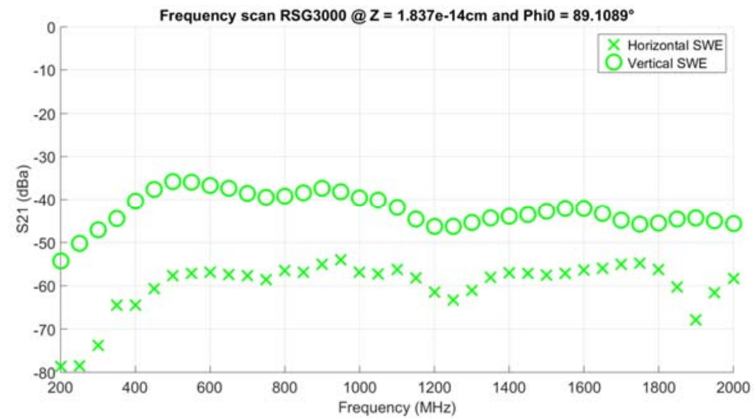






R=3m

FF-models



Cylindrical scan of a DUT

TABLE II
COMPUTATION TIME CYLINDRICAL SCAN (IN SECONDS)

	Logper - PCB	Logper - RSG3000
SWE NF	110,2	162,3
SWE NF TRUNC	50.1	55,4
SWE FF	-	47,9
FDTD 4 GPU's	$>$ 1day	$>$ 1 day

- Combination of S-Parameter simulation and FFT

- Very **high performance** compared to Full-wave simulation techniques
- Can be implemented in **existing circuit solvers**.
- Important applications in fast EMC analysis.

Conclusions

- SWE-based models can be based on:
  - ❑ **Near-field** data
  - ❑ **Far-field** data
- Several applications are presented
  - ❑ Efficient field **transformation** & **interpolation**
  - ❑ **S-Parameter** simulations for radiation
  - ❑ Fast **Cylindrical scan** of a DUT
- Simulation times about 0,5s per frequency point, with minor memory consumption
- Future work:
  - ❑ Incorporation of (infinite) groundplane beneath DUT
  - ❑ Frequency sweep

Thank you for your attention!

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