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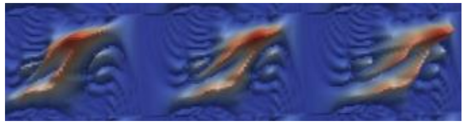

Spatial Localization of Unintentional Stochastic Radiation Sources

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at The George Green Institute of Electromagnetic Research,
The University of Nottingham

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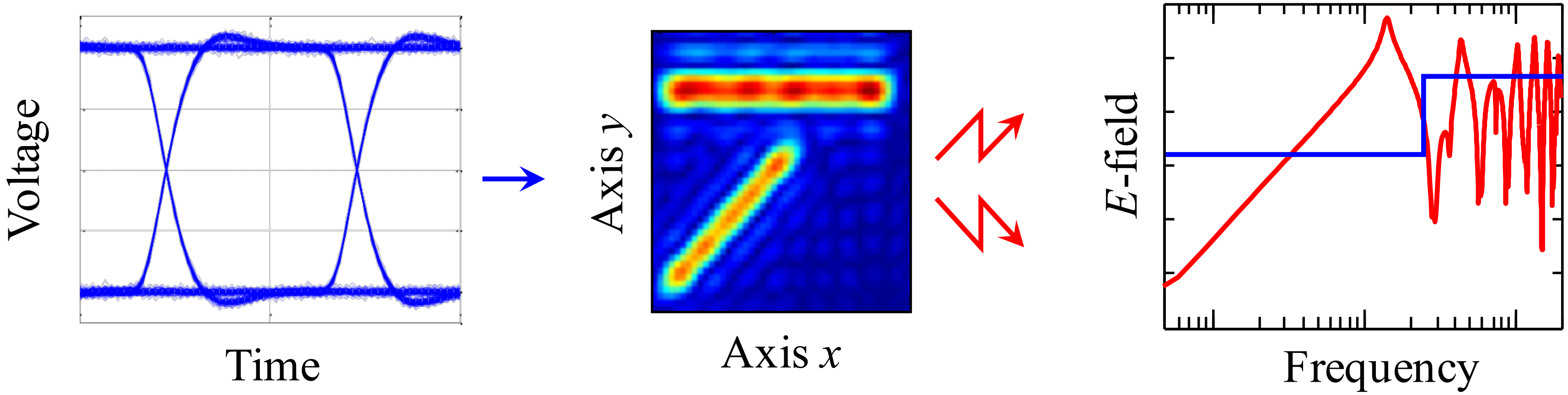
Outline

- Motivation
- Characterization of stochastic EM radiated emission
- Non-parametric estimation of stochastic EMI sources
- Parametric identification of stochastic EMI sources
- Experimental results
- Conclusion

Localization of signal traces



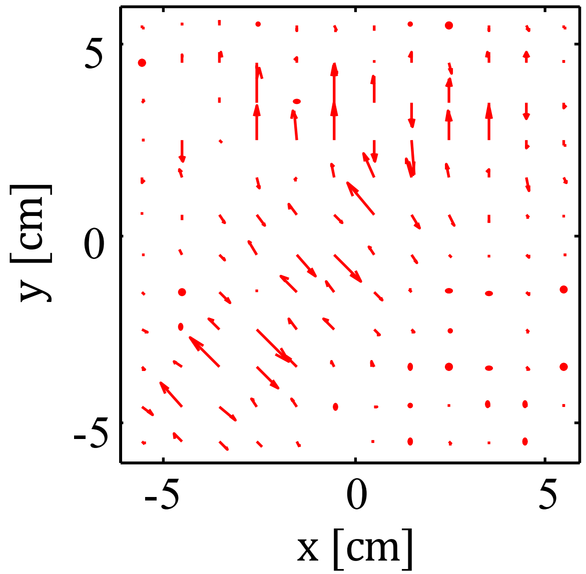
✓ The radiating source

✓ Equivalent sources on the surface of PCB

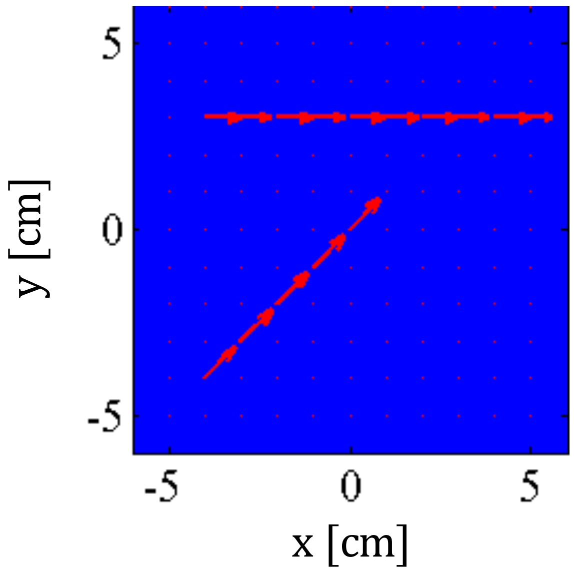
✓ The distribution of the radiated EM field

Field recovering

➢ H-field distribution



➢ Map of dipoles



- ✓ The source is the surface current distribution
- ✓ Radiating of the H-field polarized component
- ✓ Recovery of the linked electric dipoles

Outline

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- **Characterization of stochastic EM radiated emission**
- Non-parametric estimation of stochastic EMI sources
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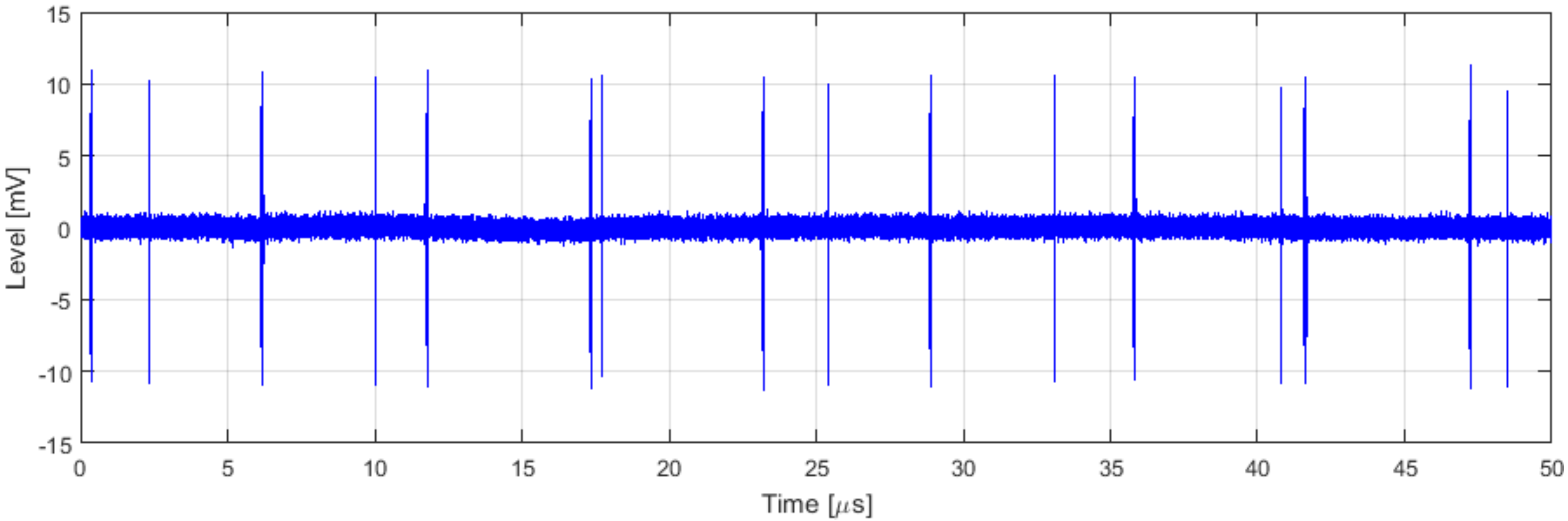
Stochastic EM radiated emission

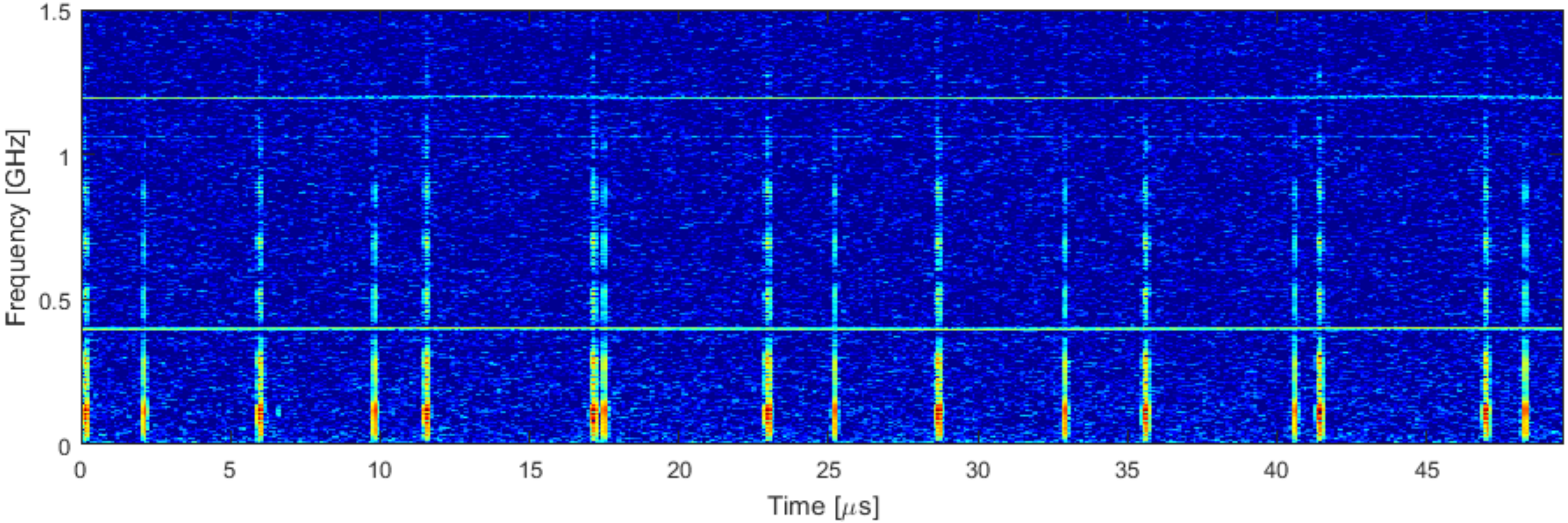
➢ Time-domain of EM emissions



- ✓ Short pulses with high amplitude
- ✓ Stationary clock synchronization sequence

Stochastic EM radiated emission

➢ Spectrogram of EM emissions

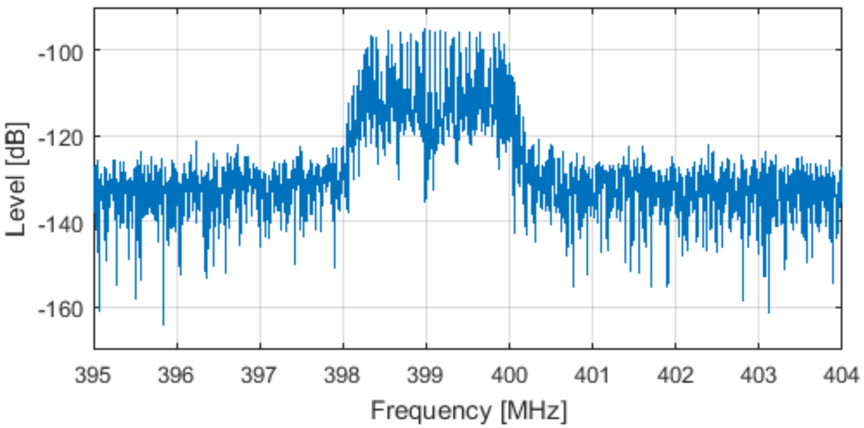


✓ Ultra wideband random pulse component
✓ Clock synchronization stationary deterministic waveform

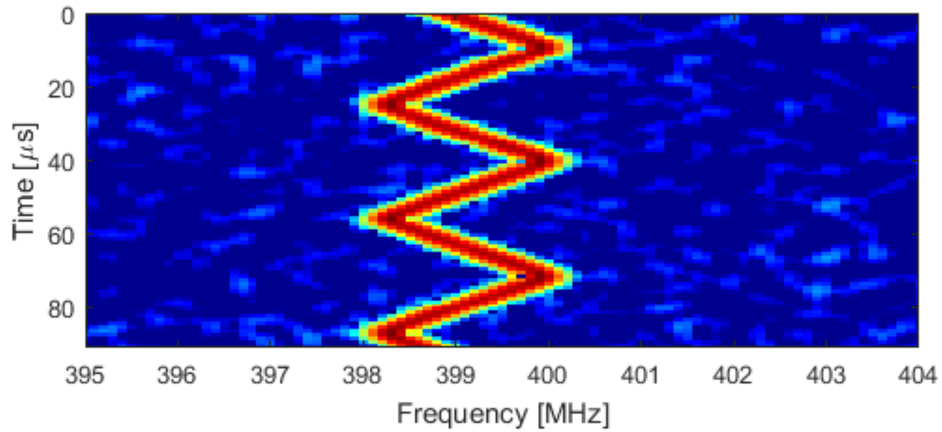
Stochastic EM radiated emission

➢ Central frequency 399 MHz

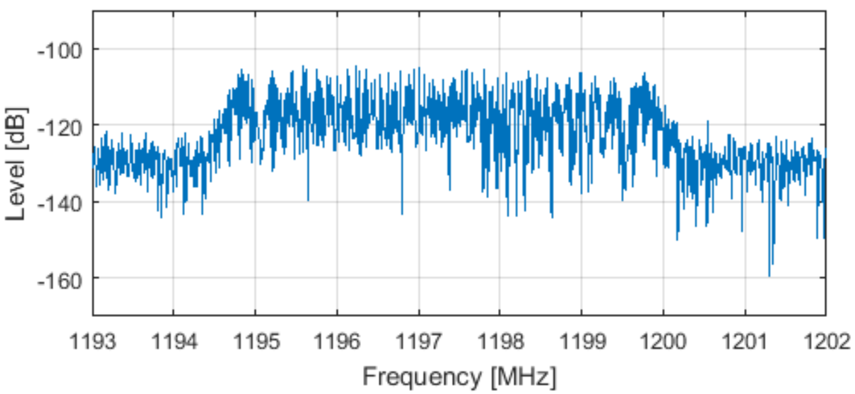
✓ Amplitude spectrum

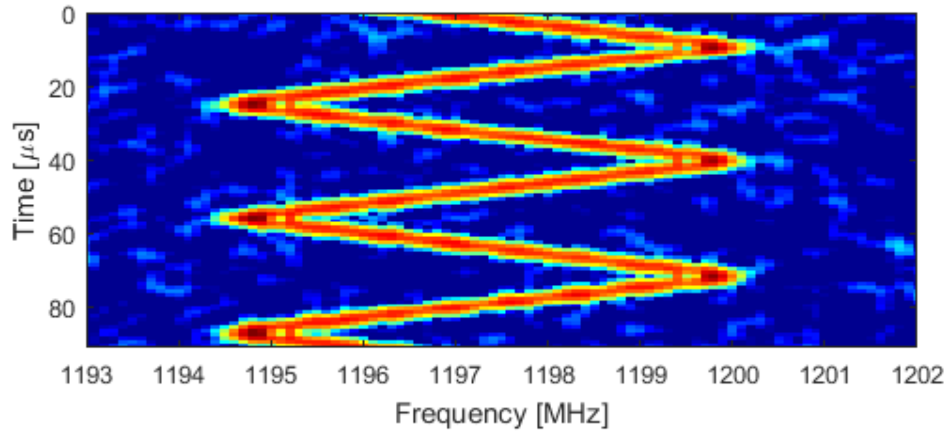


✓ Spectrum vs. time



➢ Central frequency 1197 MHz





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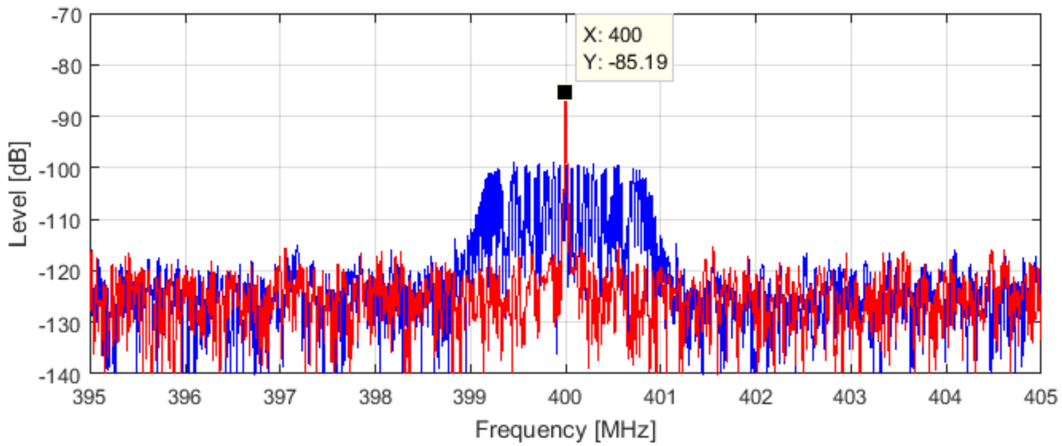
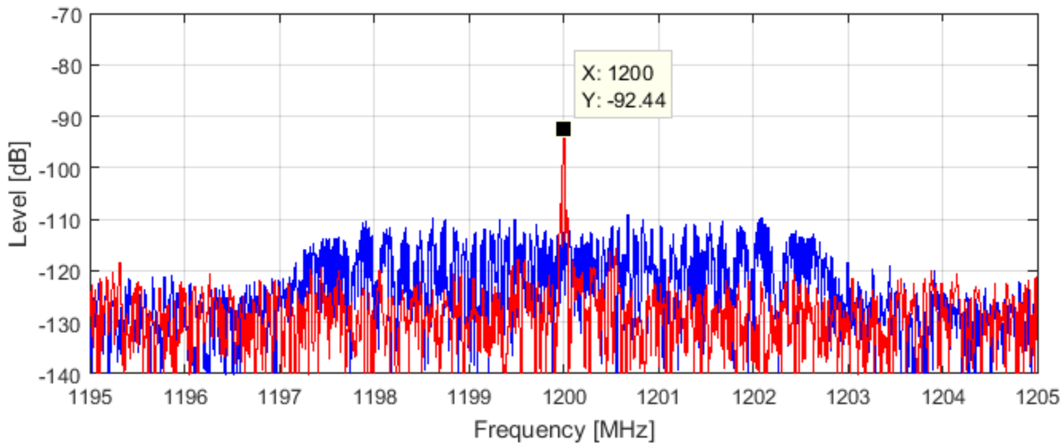
Stochastic EM radiated emission

- Central frequency 400 MHz



- Central frequency 1200 MHz



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- **Non-parametric estimation of stochastic EMI sources**
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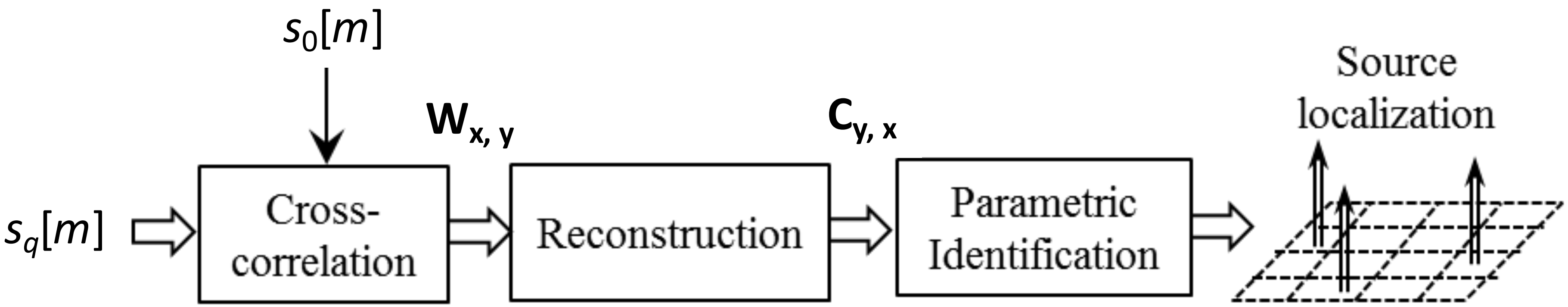
EMI sources localization

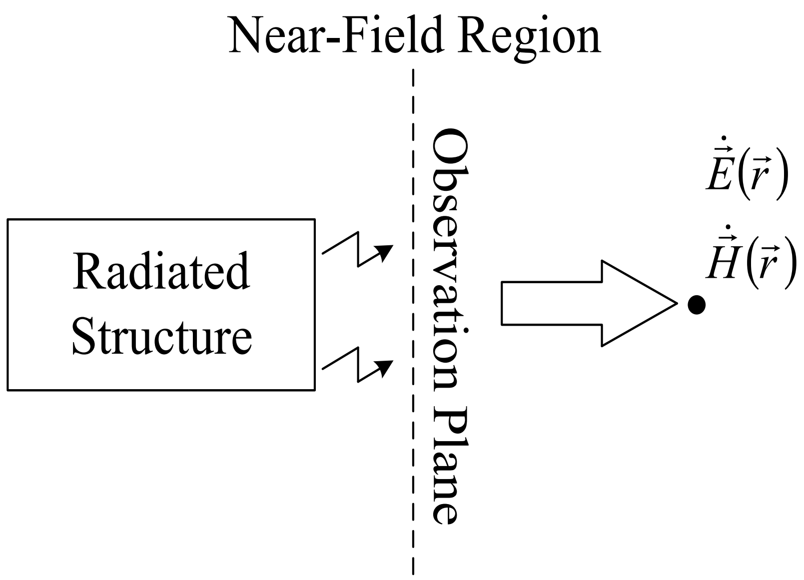
- Stochastic EMI sources localization algorithm



- ✓ $s_q[m]$ – measured spatial distribution
- ✓ $s_0[m]$ – reference component
- ✓ $W_{x,\,y}$ – cross-correlation matrix
- ✓ $C_{y,x}$ – inverse cross-correlation matrix

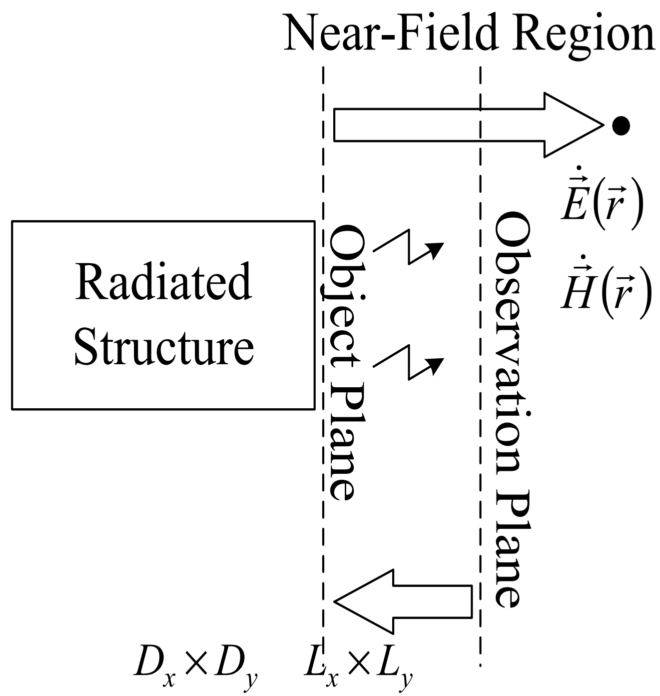
Estimation of stochastic sources

- ➢ **Direct reconstruction**



✓ **Angular limitations**

- ➢ **Model-Based Approach**

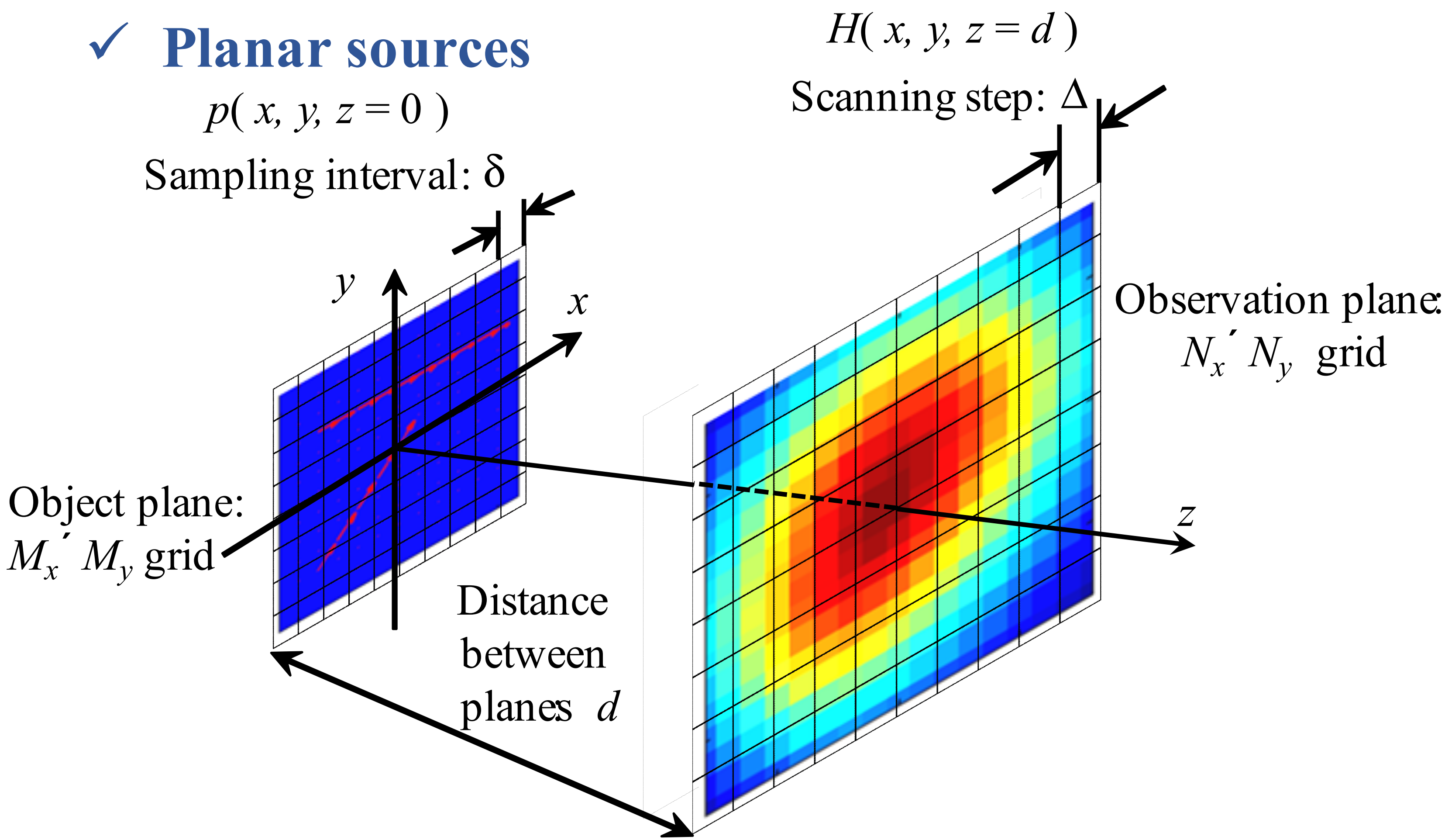


✓ **The adequate model is need**

Estimation of stochastic sources

✓ **Field distribution**

✓ **Planar sources**



Estimation of stochastic sources

➢ Electric dipole model

$$\dot{H}_x(\vec{r}) = \dot{I} \cdot \left[d \cdot \sum_{j=1}^{M_x \cdot M_y} \frac{e^{-j\left(kr_j + 2\pi f \tau_j\right)}}{4\pi r_j^2} \left(jk + \frac{1}{r_j} \right) \cdot \Delta l_{y_j} \right]$$

$$\dot{H}_y(\vec{r}) = -\dot{I} \cdot \left[d \cdot \sum_{j=1}^{M_x \cdot M_y} \frac{e^{-j\left(kr_j + 2\pi f \tau_j\right)}}{4\pi r_j^2} \left(jk + \frac{1}{r_j} \right) \cdot \Delta l_{x_j} \right]$$

$$\dot{p}_{\{x,y\}} = \frac{\dot{I} \cdot \Delta l_{\{x,y\}}}{j 2\pi f}$$

Estimation of stochastic sources

- ✓ The relations between the measured complex amplitudes of the tangential harmonic magnetic fields in the observation plane and the complex amplitude of the current are defined in accordance with the electric dipole model

$$\dot{\mathbf{H}}_\mathbf{x} = [\dot{\mathbf{G}}_\mathbf{x}] \cdot \dot{\mathbf{p}}_\mathbf{y} \qquad \dot{\mathbf{H}}_\mathbf{y} = [\dot{\mathbf{G}}_\mathbf{y}] \cdot \dot{\mathbf{p}}_x$$

- ✓ The complex amplitudes of the cross correlation spectra could be expressed by the following matrix expression

$$\dot{\mathbf{W}}_\mathbf{x} = \dot{\mathbf{H}}_\mathbf{x} \cdot \dot{H}_{0x}^* = [\dot{\mathbf{G}}_\mathbf{x}] \cdot \dot{\mathbf{p}}_\mathbf{y} \cdot \dot{H}_{0x}^* = [\dot{\mathbf{A}}_\mathbf{x}] \cdot \dot{\mathbf{p}}_\mathbf{y} \qquad \dot{\mathbf{W}}_\mathbf{y} = \dot{\mathbf{H}}_\mathbf{y} \cdot \dot{H}_{0y}^* = [\dot{\mathbf{A}}_\mathbf{y}] \cdot \dot{\mathbf{p}}_\mathbf{x}$$

- ✓ Obtained parameters of dipole moments in the object plane

$$\dot{\mathbf{p}}_\mathbf{y} = [\dot{\mathbf{A}}_\mathbf{x}]^+ \cdot \dot{\mathbf{W}}_\mathbf{x} \qquad \dot{\mathbf{p}}_\mathbf{x} = [\dot{\mathbf{A}}_\mathbf{y}]^+ \cdot \dot{\mathbf{W}}_\mathbf{y}$$

Estimation of stochastic sources

➢ Cross-correlation Estimation

• Complex amplitude of scanning probe	$\dot{H}_i^k = \frac{1}{N}\sum_{n=0}^{N-1} w_n \cdot H_i^k(t_n) \cdot e^{-j2\pi f_m t_n}, i = 1,2,...,N_x \times N_y$
• Complex amplitude of reference probe	$\dot{H}_0^k = \frac{1}{N}\sum_{n=0}^{N-1} w_n \cdot H_0^k(t_n) \cdot e^{-j2\pi f_m t_n}$
• Time samples	$t_n = n \cdot t_s, n = 0,1,...,N-1$
• Weighting coefficients of time window	w_n
• Frequencies	$f_m = \frac{m}{T}, m = 0,1,2,...$
• Cross-correlation coefficients	$\dot{W}_i = \frac{1}{K}\sum_{k=1}^{K} \dot{H}_i^k \cdot \dot{H}_0^{k*}$
• Complex coefficients	$\dot{G}_{i,j} = j2\pi f_m \cdot \frac{e^{-jkr_{ij}}}{4\pi r_{ij}} \left(jk + \frac{1}{r_{ij}} \right) \cdot d, j = 1,2,...,M_x \times M_y$

Estimation of stochastic sources

➢ Reconstruction of Dipole Moments

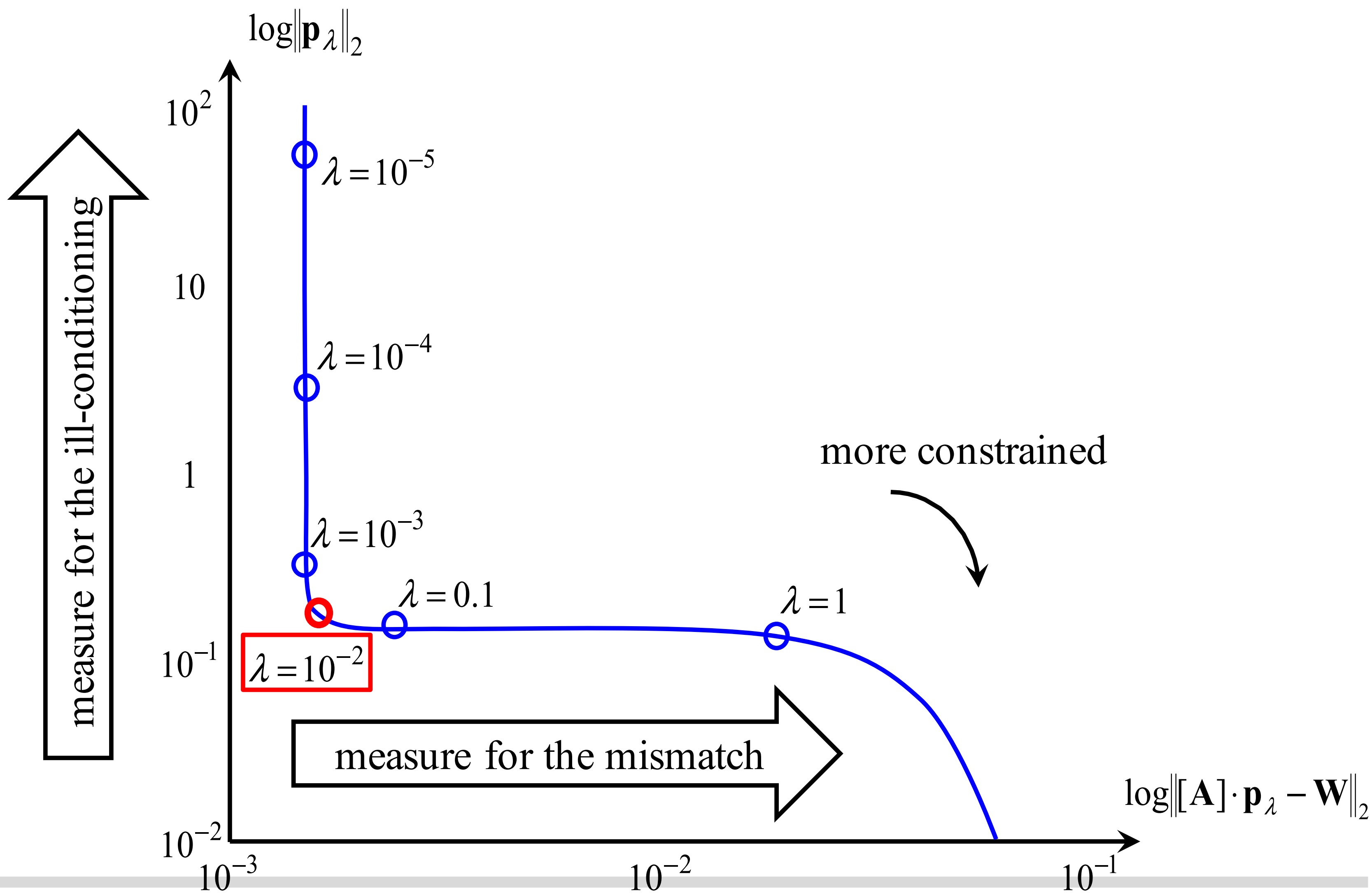
- Singular value decomposition $$[\mathbf{A}] = [\mathbf{U}] \cdot [\mathrm{diag}(\sigma_i)] \cdot [\mathbf{V}]$$
- Tikhonov regularization $$\mathbf{p}_\lambda = \arg\{\min_{\mathbf{b}}[(\|[\mathbf{A}]\cdot\mathbf{p} - \mathbf{W}\|_2)^2 + \lambda^2(\|\mathbf{p}\|_2)^2]\} = [\mathbf{V}][\mathbf{\Sigma}]_\lambda^H[\mathbf{U}]^H \cdot \mathbf{W}$$

where $$[\mathbf{\Sigma}]_\lambda^H = \left[\mathrm{diag}\left\{\frac{\sigma_i^2}{\sigma_i^2 + \lambda^2} \cdot \frac{1}{\sigma_i}\right\}\right]$$

- L-curve Method $$\lambda : \max_\lambda\left\{\mathrm{curv}\left(\log\left\|[\mathbf{A}]\cdot\mathbf{p}_\lambda - \mathbf{W}\right\|_2, \log\left\|\mathbf{p}_\lambda\right\|_2\right)\right\}$$

Estimation of stochastic sources

- Typical L-curve for an ill-posed problem



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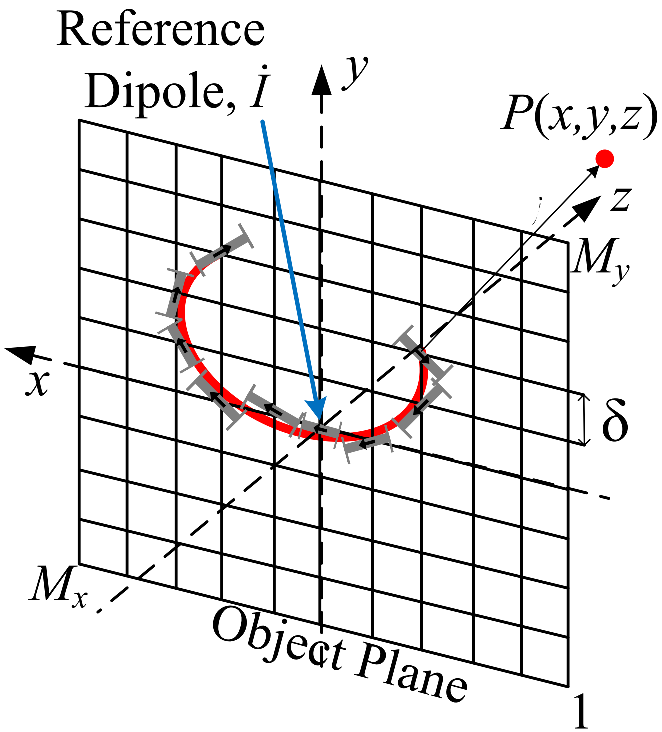
Parametric identification



✓ **Model parameters**

$$\mathbf{\Theta}_s = \begin{pmatrix} \Delta\vec{l}_s \\ \tau_s \end{pmatrix}$$

- s-th dipole orientation vector
- current delay in s-th dipole

$$s = 1,2,\ldots Order \qquad Order < (M_x \times M_y)$$

Parametric identification

➢ **Space frequency-domain model of planar sources**

$$\dot{G}[\nu,\mu]=\sum_{j=1}^{M_x\times M_y}\dot{p}_\lambda(x_j,y_j,z=0)\cdot \mathrm{e}^{-j2\pi\left(\frac{x_j}{D_x}\nu+\frac{y_j}{D_y}\mu\right)}=\dot{F}[\nu,\mu]+\dot{N}[\nu,\mu]$$

$$\dot{F}[\nu,\mu]=\sum_{s=1}^{Order}\dot{\alpha}_s\cdot \mathrm{e}^{-j\frac{2\pi\, x_s}{D_x}\nu}\cdot \mathrm{e}^{-j\frac{2\pi\, y_s}{D_y}\mu}=\sum_{s=1}^{Order}\dot{\alpha}_s\cdot \dot{z}_{x_s}^{\nu}\cdot \dot{z}_{y_s}^{\mu}$$

$$\nu=0,1,\ldots M_x-1$$

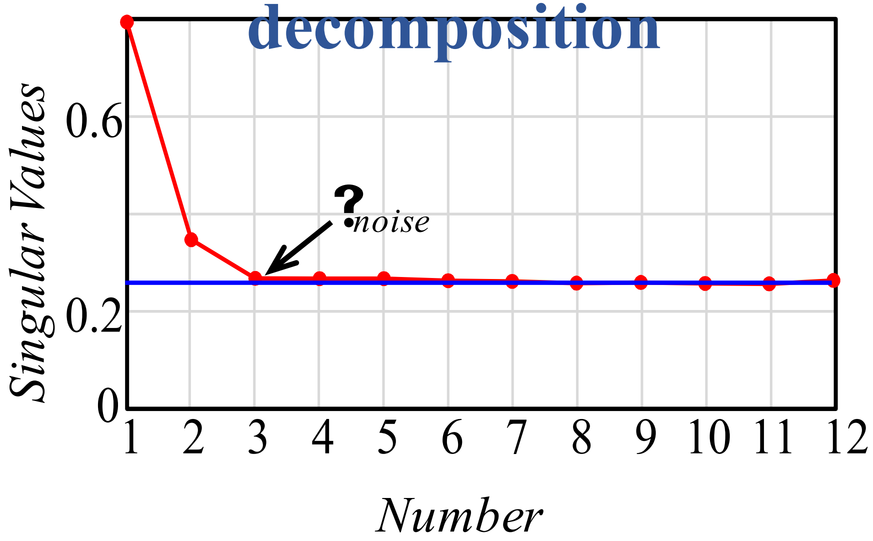
$$\mu=0,1,\ldots M_y-1$$

Parametric identification

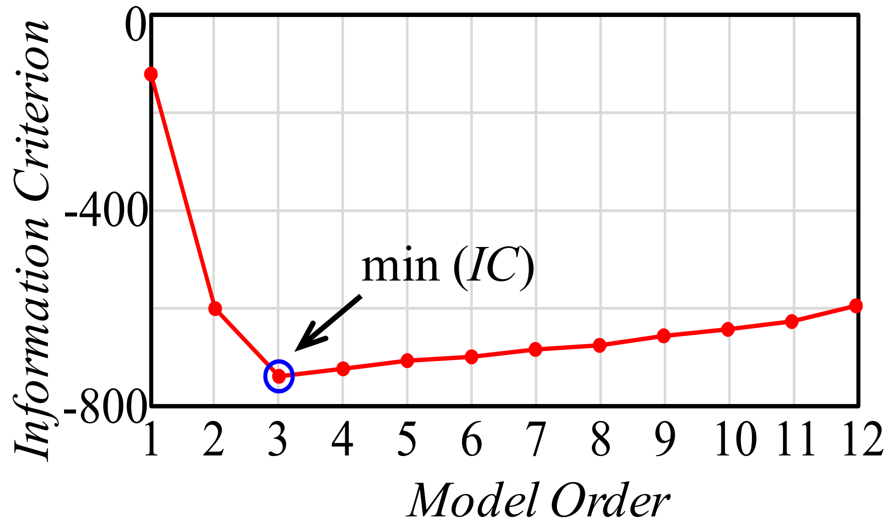
➢ Model Order Selection

$$Order = \arg\{\min[-2\ln(L_k(\mathbf{D},\tilde{\mathbf{\Theta}})) + r(k)f(N,k)]\}$$

✓ **Singular value decomposition**



✓ **Information criterion**



Parametric identification

- Effective source coordinates estimation

$$[\mathbf{D}]=[\mathbf{U}][\Sigma][\mathbf{V}]^H=[\mathbf{U}]_s[\Sigma]_s[\mathbf{V}]_s{}^H+[\mathbf{U}]_n[\Sigma]_n[\mathbf{V}]_n{}^H$$

✓ x-coordinate

$$[\mathbf{U}]_s=\begin{bmatrix}[\mathbf{U}]_{s1}\\ [\mathbf{U}]_{s1L}\end{bmatrix}=\begin{bmatrix}[\mathbf{U}]_{s2L}\\ [\mathbf{U}]_{s2}\end{bmatrix}$$

$$[\mathbf{M}]=[\mathbf{U}]_{s2}-\lambda\cdot[\mathbf{U}]_{s1}$$

$$[\mathbf{U}]_{s1}^{+}[\mathbf{U}]_{s2}=[\mathbf{Q}][\mathbf{Z}]_x[\mathbf{Q}]^{-1}$$

$$[\mathbf{Z}]_x=[\mathbf{Q}]^{-1}[\mathbf{U}]_{s1}^{+}[\mathbf{U}]_{s2}[\mathbf{Q}]$$

$$\mathbf{z}_x=\operatorname{diag}([\mathbf{Z}]_x)\Rightarrow \mathbf{x}=-D_x\frac{\arg\mathbf{z}_x}{2\pi}$$

✓ y-coordinate

$$[\mathbf{U}]_{sP}=[\mathbf{P}]\cdot[\mathbf{U}]_s=\begin{bmatrix}[\mathbf{U}]_{1P}\\ [\mathbf{U}]_{1PJ}\end{bmatrix}=\begin{bmatrix}[\mathbf{U}]_{2PJ}\\ [\mathbf{U}]_{2P}\end{bmatrix}$$

$$[\mathbf{M}]_P=[\mathbf{U}]_{2P}-\lambda\cdot[\mathbf{U}]_{1P}$$

$$[\mathbf{U}]_{1P}^{+}[\mathbf{U}]_{2P}=[\mathbf{Q}][\mathbf{Z}]_y[\mathbf{Q}]^{-1}$$

$$[\mathbf{Z}]_y=[\mathbf{Q}]^{-1}[\mathbf{U}]_{1P}^{+}[\mathbf{U}]_{2P}[\mathbf{Q}]$$

$$\mathbf{z}_y=\operatorname{diag}([\mathbf{Z}]_y)\Rightarrow \mathbf{y}=-D_y\frac{\arg\mathbf{z}_y}{2\pi}$$

Parametric identification

➢ Complex amplitudes of dipole moments

✓ **Minimum least squares algorithm**

$$\operatorname{diag}\begin{pmatrix} \dot{\alpha}_1 \\ \dot{\alpha}_2 \\ \vdots \\ \dot{\alpha}_{Order} \end{pmatrix} = \mathbf{Z}_L^{+} \cdot \mathbf{G} \cdot \mathbf{Z}_R^{+}$$

$$\mathbf{Z}_L = \begin{bmatrix} \dot{z}_{x_1} & \dot{z}_{x_2} & \cdots & \dot{z}_{x_{Order}} \\ \dot{z}_{x_1}^2 & \dot{z}_{x_2}^2 & \cdots & \dot{z}_{x_{Order}}^2 \\ \vdots & \vdots & & \vdots \\ \dot{z}_{x_1}^{M_x} & \dot{z}_{x_2}^{M_x} & \cdots & \dot{z}_{x_{Order}}^{M_x} \end{bmatrix} \quad \mathbf{Z}_R = \begin{bmatrix} \dot{z}_{y_1} & \dot{z}_{y_1}^2 & \cdots & \dot{z}_{y_1}^{M_y} \\ \dot{z}_{y_2} & \dot{z}_{y_2}^2 & \cdots & \dot{z}_{y_2}^{M_y} \\ \vdots & \vdots & & \vdots \\ \dot{z}_{y_{Order}} & \dot{z}_{y_{Order}}^2 & \cdots & \dot{z}_{y_{Order}}^{M_y} \end{bmatrix}$$

Parametric identification

- Geometric parameters of dipoles

$$\dot{I} = \frac{j2\pi f_m \cdot \dot{\vec{p}}}{\Delta \vec{l}}$$

$$\tau_s = -\frac{\arg\{j2\pi f_m \dot{\vec{p}}_s\}}{2\pi f_m}$$

$$\Delta l_{\{x,y\}_s} = \frac{|\dot{\alpha}_{\{x,y\}_s}| \cdot 2\pi f_m}{|\dot{I}|}$$

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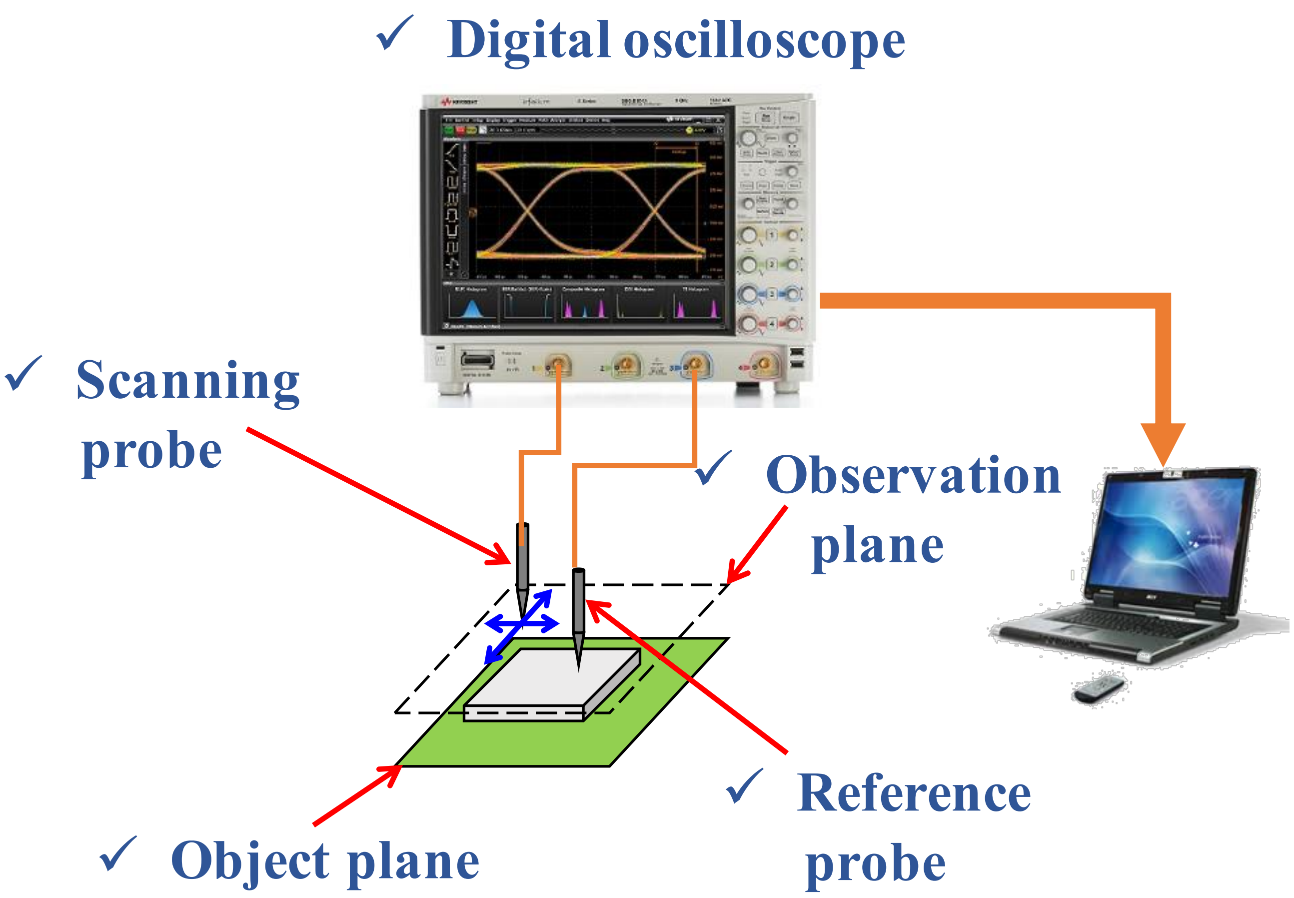
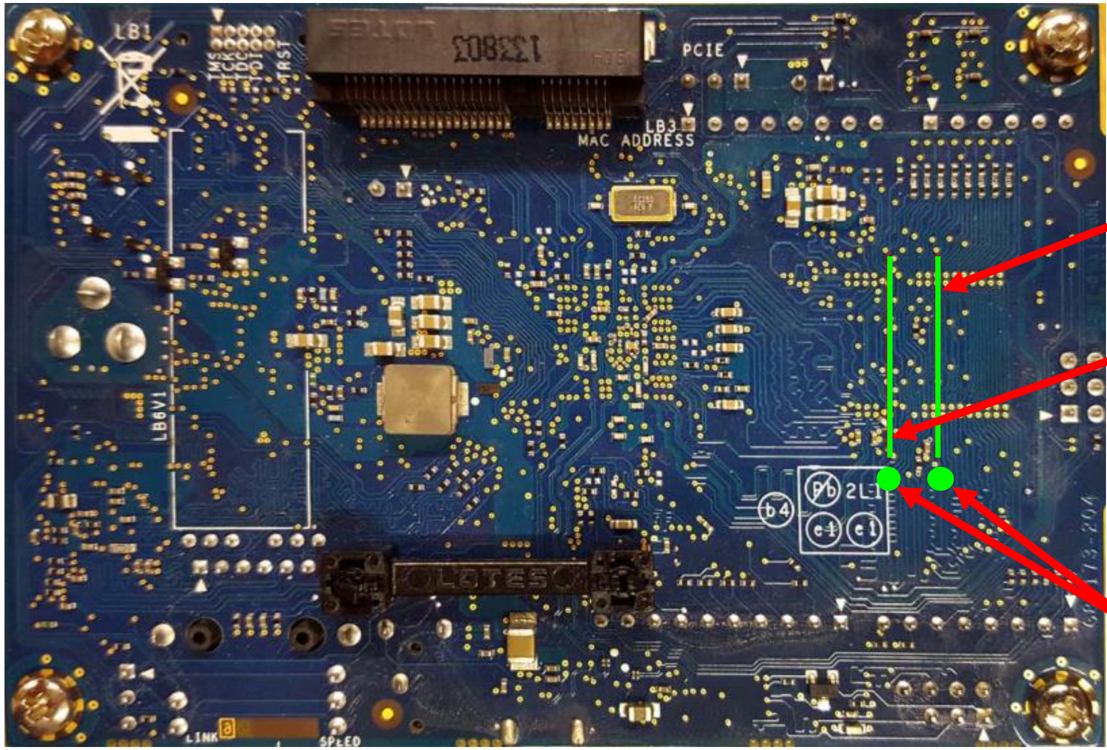
Measurement setup

- Time-domain measurement system



Experimental Results

➢ Line scanning

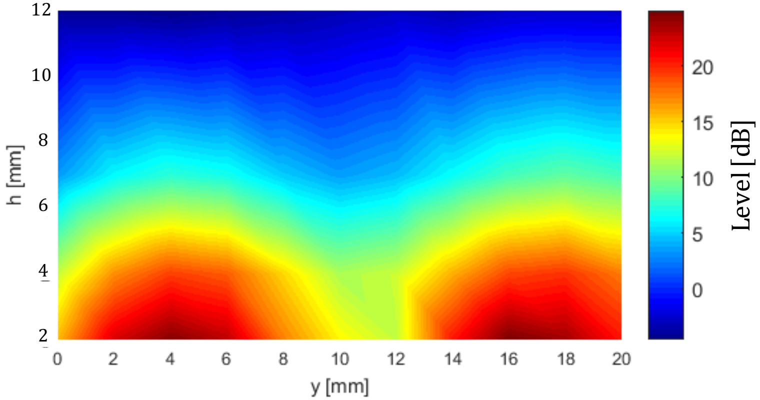


- ✓ Scanning path 20 mm
- ✓ Scanning step 2 mm

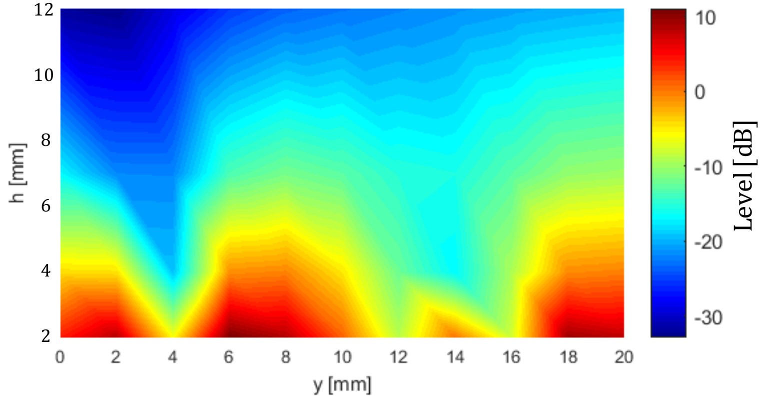
Experimental Results

- Spatial distribution of clock power, $F = 400$ MHz

✓ H_x probe polarization

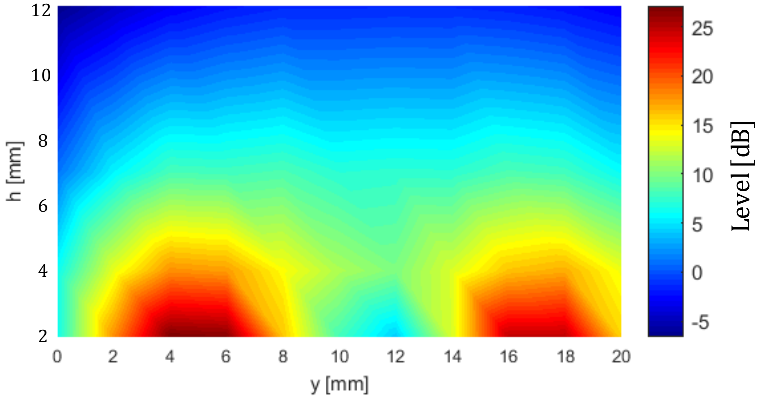


✓ H_y probe polarization

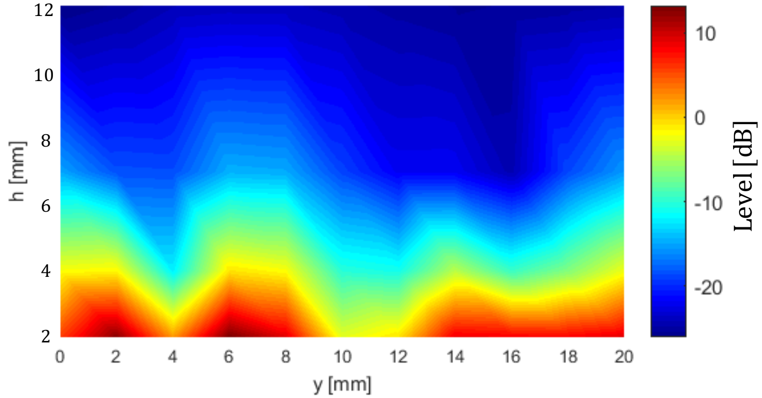


✓ Path 1

✓ H_x probe polarization



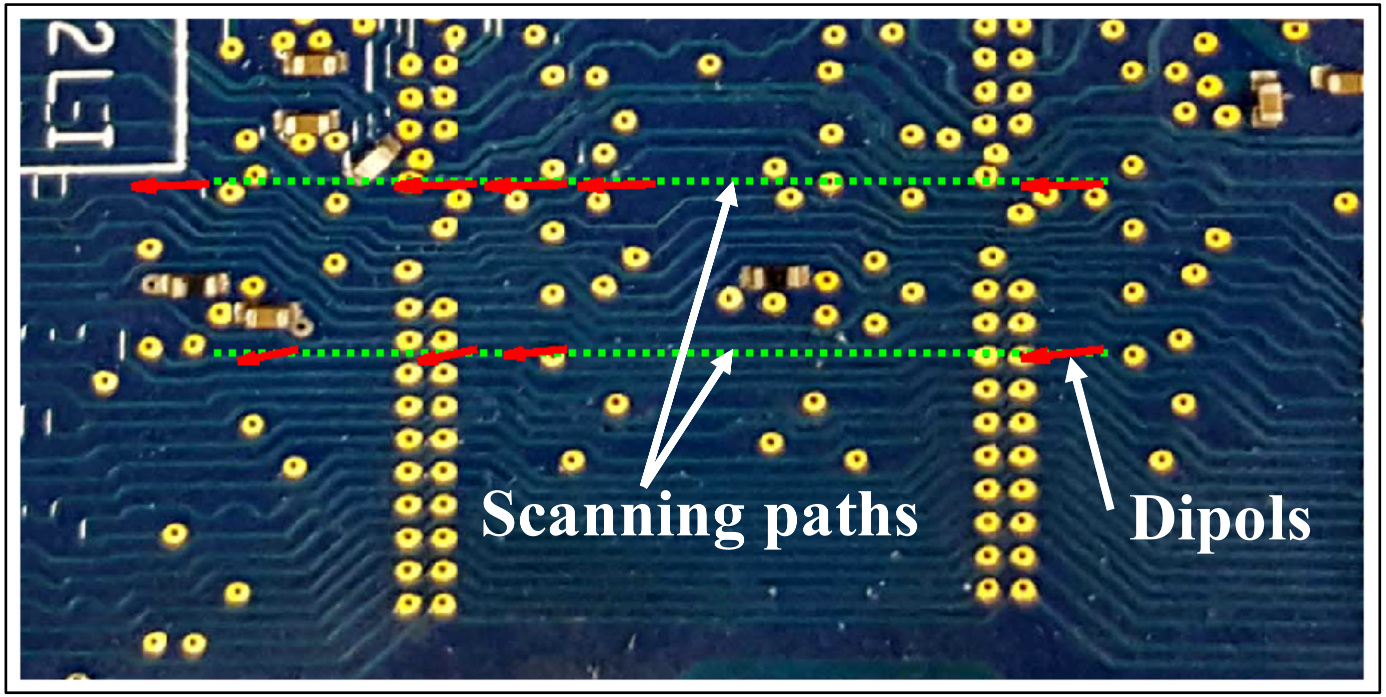
✓ H_y probe polarization



✓ Path 2

Experimental Results

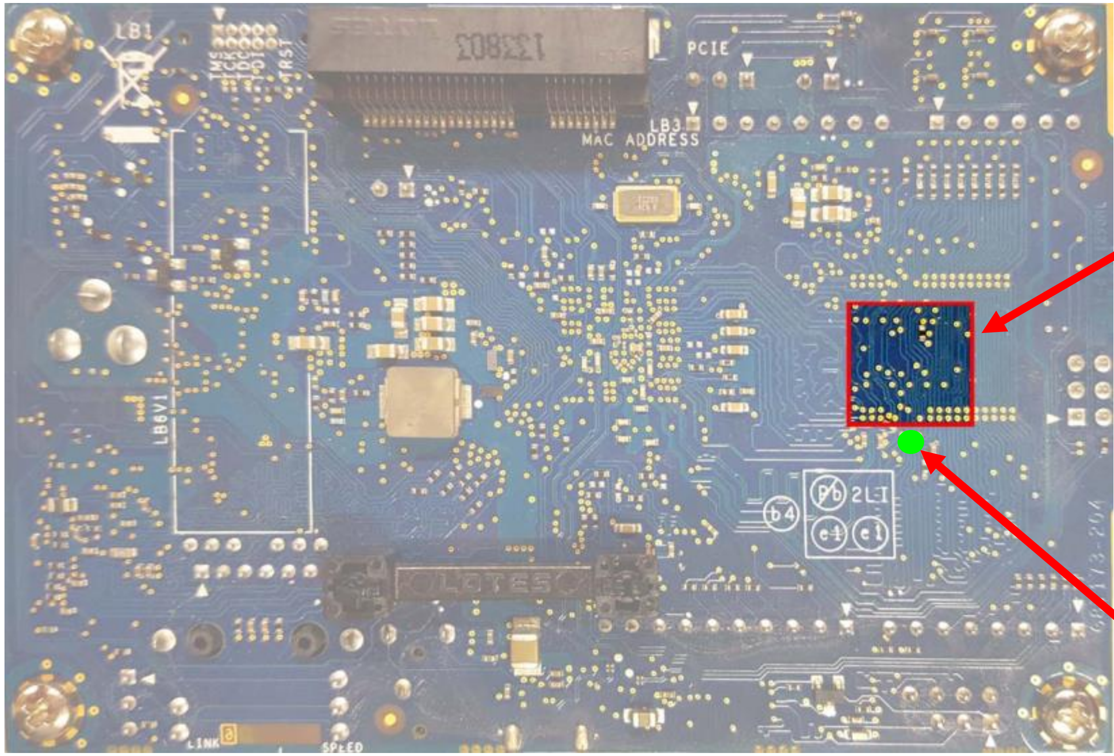
➢ Equivalent dipoles



✓ Model order 4-5

Experimental Results

➢ Area scanning



Scanning region

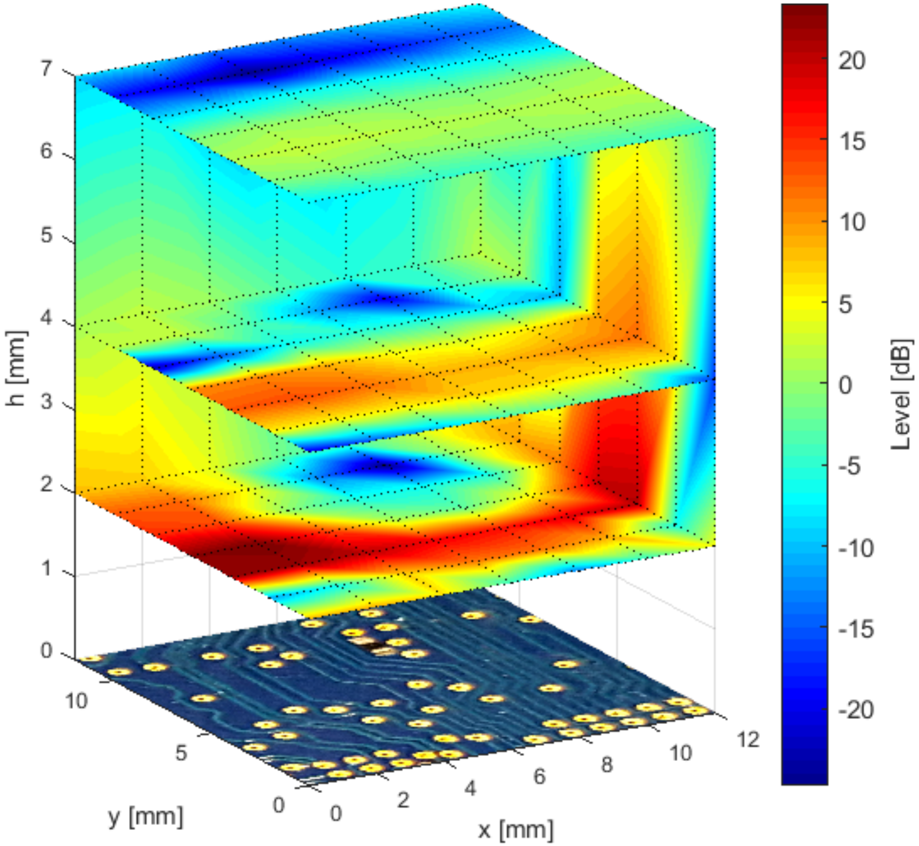
Reference probe position

- ✓ Scanning area 12x12 mm
- ✓ Scanning step 2 mm

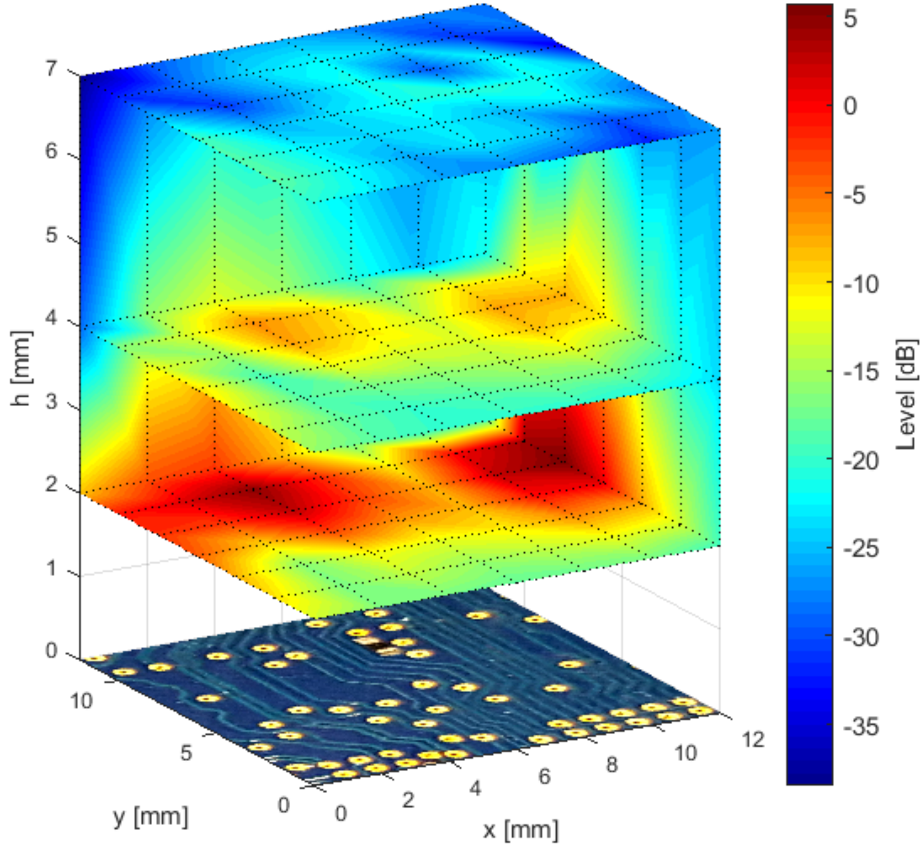
Experimental Results

➢ Spatial distribution of clock power at frequency 400 MHz in the volume over the PCB

✓ H_x probe polarization

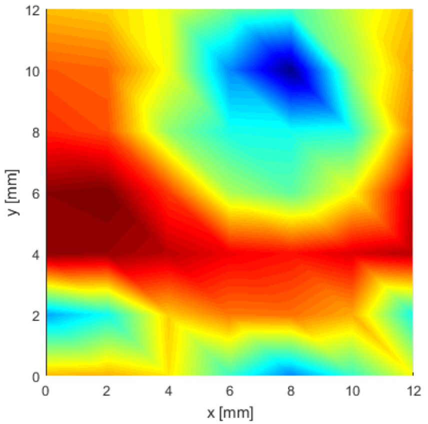


✓ H_y probe polarization

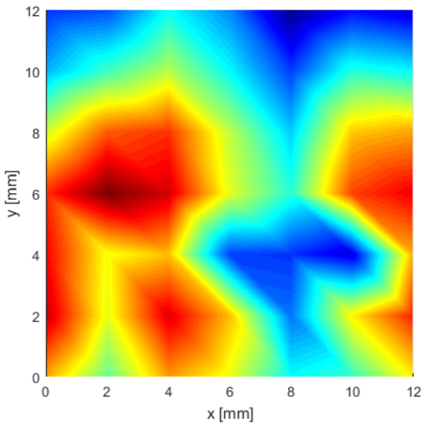


Experimental Results

- **Spatial distribution**
  - ✓ H_x

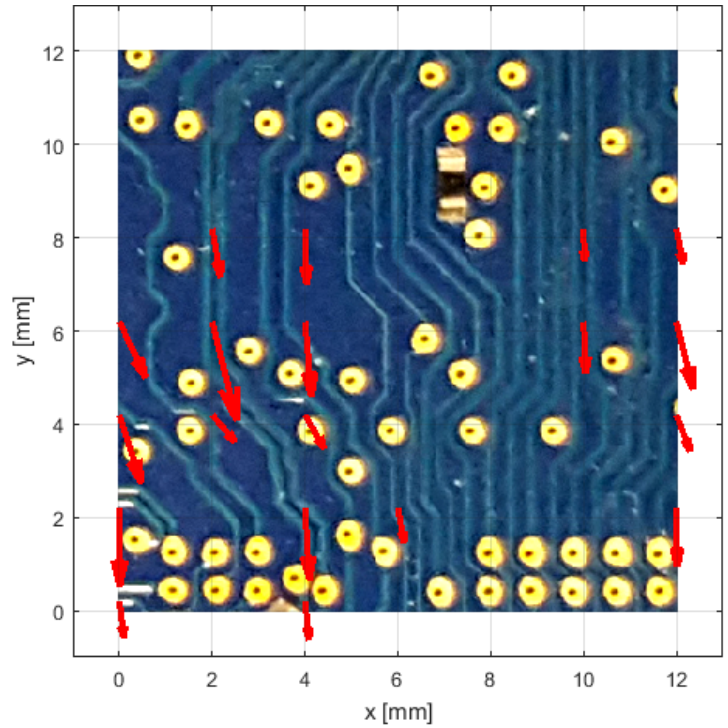


  - ✓ H_y



  - ✓ $h = 2$ mm, $F = 400$ MHz

- **Equivalent dipoles**



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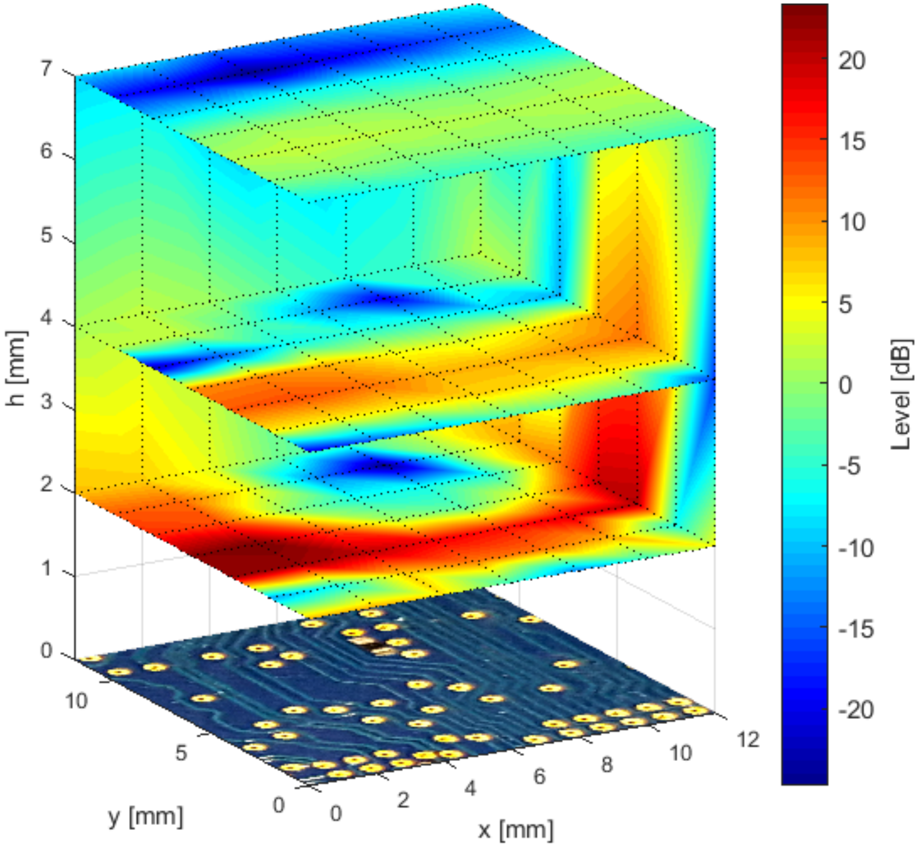
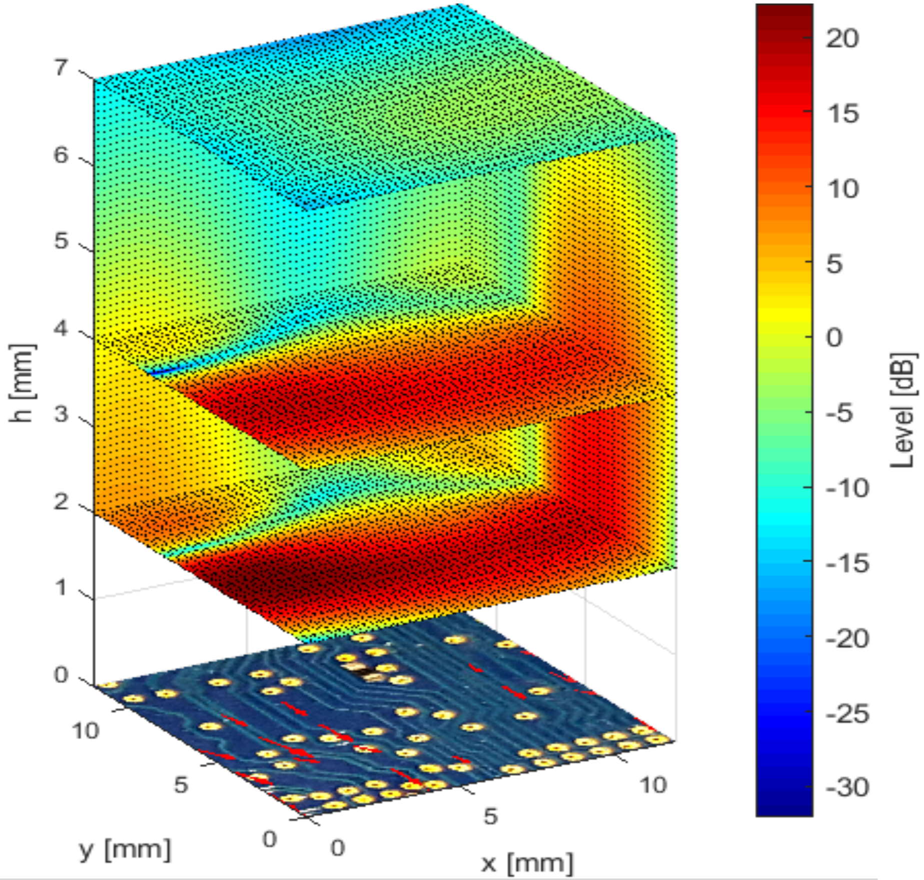
Experimental Results

➢ Comparison of experimental and predicted power distributions for H_x polarization

✓ Experimental



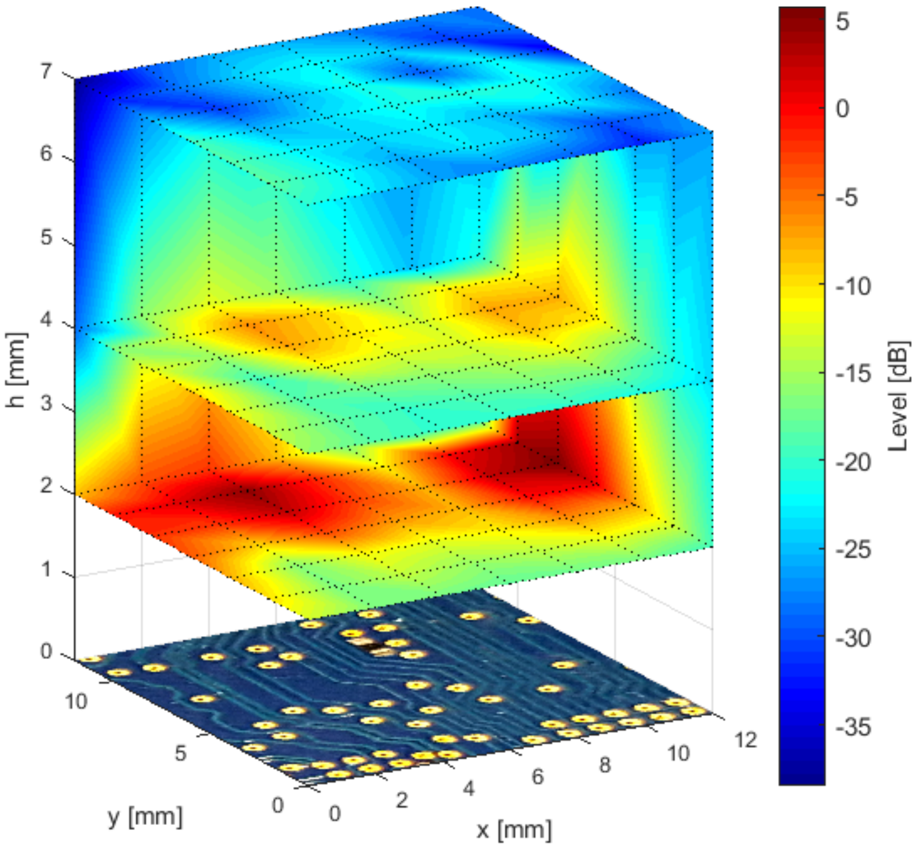
✓ Prediction



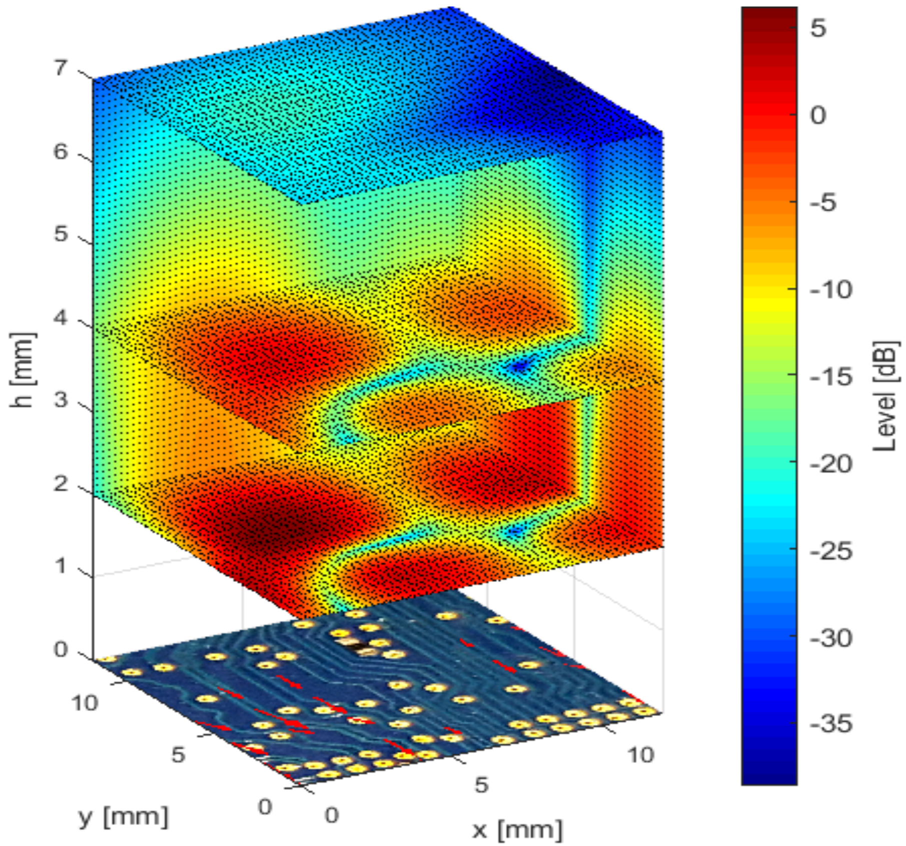
Experimental Results

➢ **Comparison of experimental and predicted power distributions for H_y polarization**

✓ **Experimental**



✓ **Prediction**



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Conclusion

- The near-field measurements of stochastic radiation from PCB can be used for the localization of EMI sources with predefined clock frequency.
- The improvement of the localization accuracy could be achieved by parametric identification procedure in addition to the conventional averaging and inverse technique for stochastic EM field.
- The proposed signal processing algorithms for the EMI sources localization and the approach for prediction of the enclose unintentional emissions pattern were verified by experimental measurements.

Thank you for your kind attention!

Questions?