EMC 2015
DRESDEN, AUGUST 16-22

Parametric Identification of Stochastic EMI Sources Based on Near-Field Measurements

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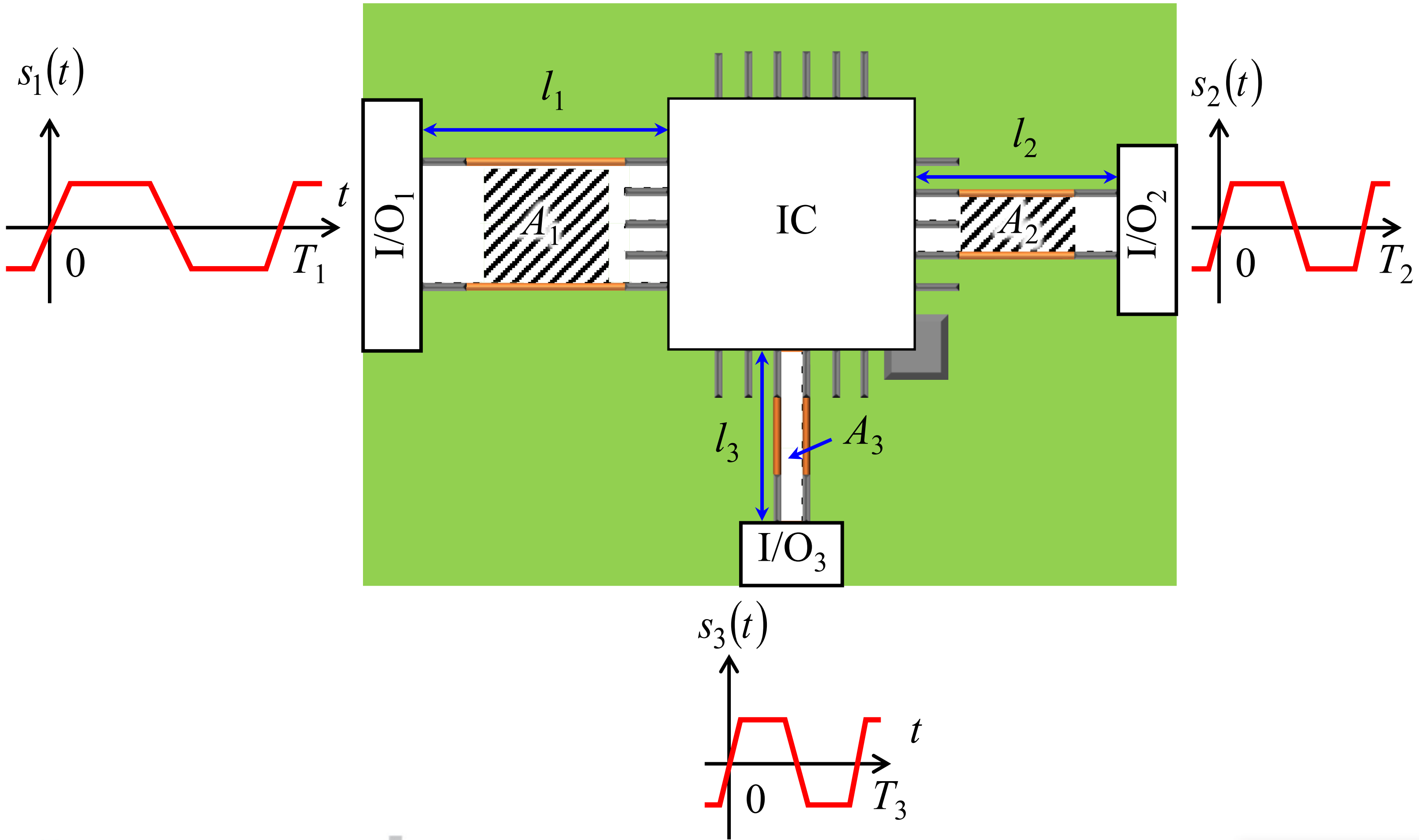
Outline

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

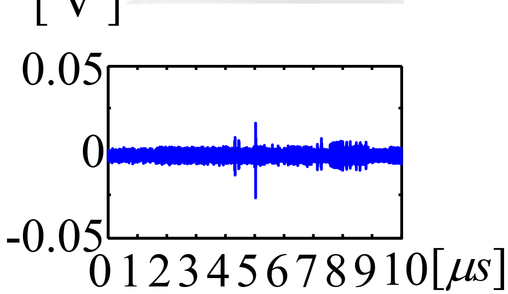
Motivation

- PCB as multi-input / multi-output DUT

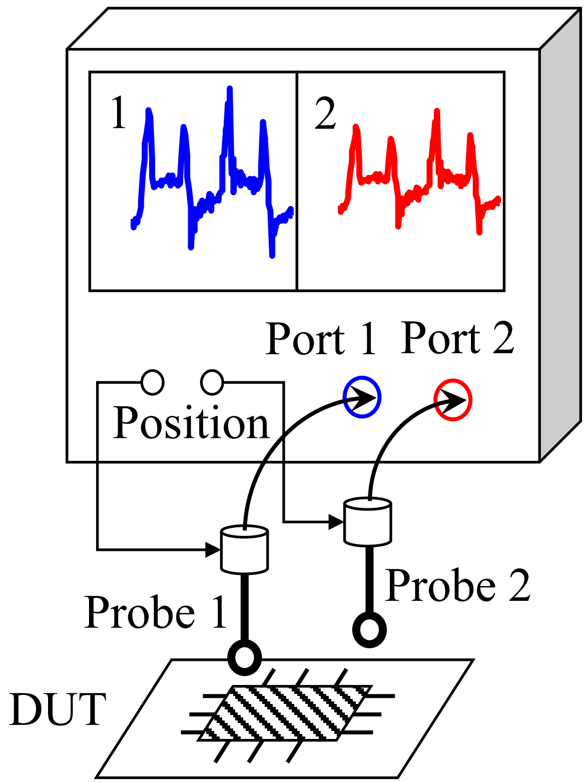


Motivation

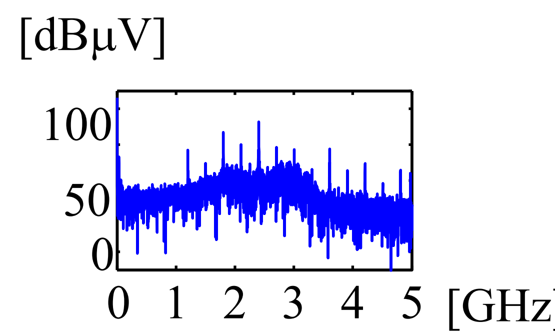
- Digital oscilloscope



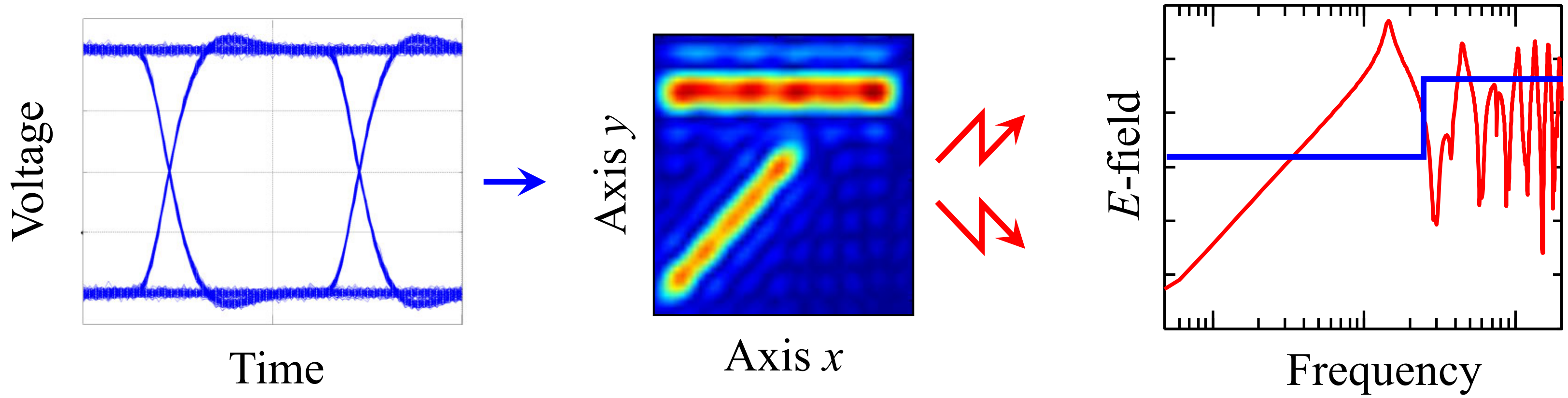
- 2-point scanning system of EMI sources



- Vector network analyzer



Motivation

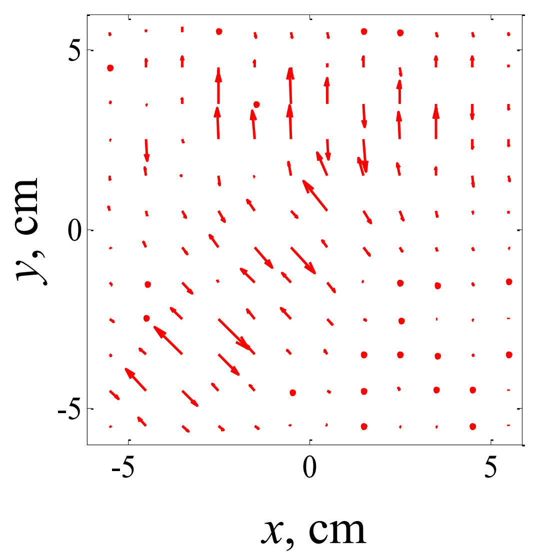


- ✓ We will concentrate on the localization of traces on the surface of the PCB. The reason is that such type of source can be used as a model of the information bearing signal transmitting between spatially separated blocks of the electronic device through transmission lines along the surface of PCB or some bus interface. The accurate localization and parameter estimation of such source could significantly improve the validity of the F-F spatial distribution of the information bearing EMI pattern.

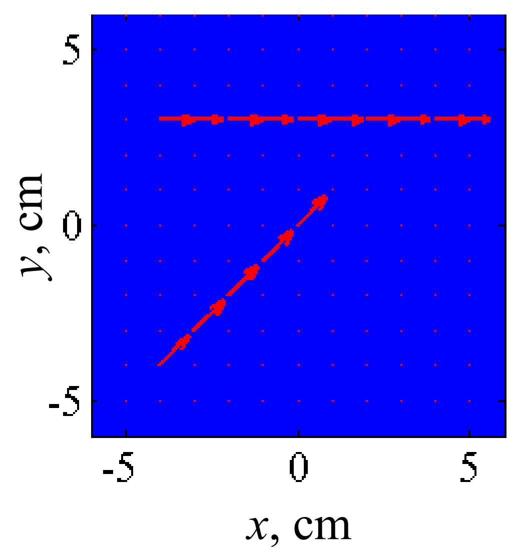
Motivation

✓ For the computation of the F-F EM radiation and for the recovering of the input electric current densities on the surface of the DUT it is sufficient to measure $H_\perp$-fields at the knots of the periodic array in the observation plane.

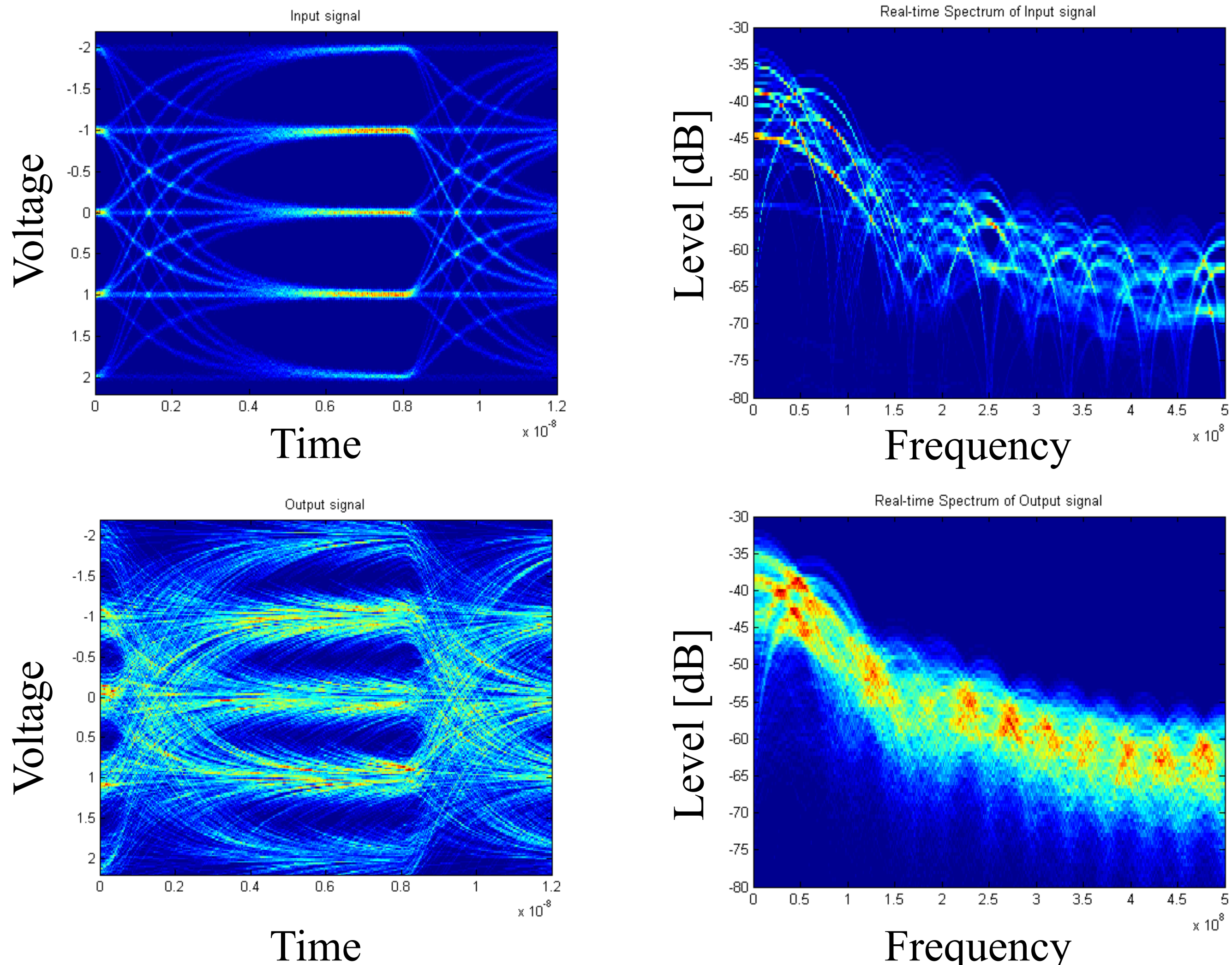
- $H_\perp$-field



- Map of dipoles



Characterization of stochastic EM radiated emission



Characterization of stochastic EM radiated emission

➢ Near-field received signal

$$y(t)=x(t)+w(t)=\sum_{i=1}^{N}s_{\alpha}(t,T_i)*g_i(t)+\sum_{j=1}^{M}s_{\tau}(t,T_j)*g_j(t)+w(t)$$

• PAM signal	$s_{\alpha}(t,T_i)=\sum_{n=-\infty}^{\infty}\alpha_n\cdot\delta(t-n\cdot T_i)$
• PPM signal	$s_{\tau}(t,T_i)=\sum_{n=-\infty}^{\infty}\delta(t-n\cdot T_i-\tau_n)$
• Impulse response	$g(t)=L^{-1}\left\{A\cdot p+K+\frac{\sum_{m=0}^{M}b_m\cdot p^m}{\sum_{n=0}^{N}a_n\cdot p^n}\right\},\quad M<N$
• Additive noise	$w(t)\in N(0,\sigma_w)$

Characterization of stochastic EM radiated emission

➢ Cyclo WSS process

✓ The discrete-time WSS process converted into the continuous-time random signal by its transition through the LTI dynamic system characterizing by the impulse response $g(t)$ which duration in general could be more then interval T of the initial WSS process.

- Generalized information signal
- LTI system
- EMI

$$\sum_{n=-\infty}^{\infty} \alpha_n \cdot \delta(t - nT - \tau_n) \longrightarrow \boxed{\text{Impulse response } g(t)} \longrightarrow \sum_{n=-\infty}^{\infty} \alpha_n \cdot g(t - nT - \tau_n)$$

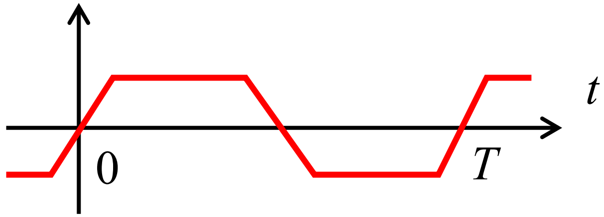
Characterization of stochastic EM radiated emission

- ✓ The binary information signal consists of two possible outcomes "1" and "0". A discrete Bernoulli distribution can represent it by assuming of two corresponding probabilities:

$$P\{1\} = p; \quad P\{0\} = 1 - p = q$$

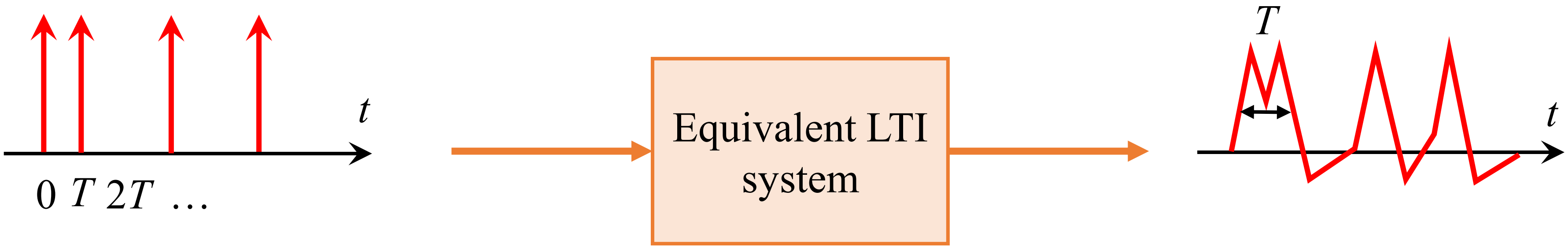
- ✓ Another important feature of the information signal is the synchronization by a clock generator with a repetition rate $1/T$.

  - Clock signal



Characterization of stochastic EM radiated emission

- Information signal
- Impulse response
- Received signal



✓ To transmit information between separate devices it must be converted into a continuous signal, which can be measured in the observation plane due to the radiation of its common mode. This stochastic signal exhibits the properties of the cyclo WSS process.

Characterization of stochastic EM radiated emission

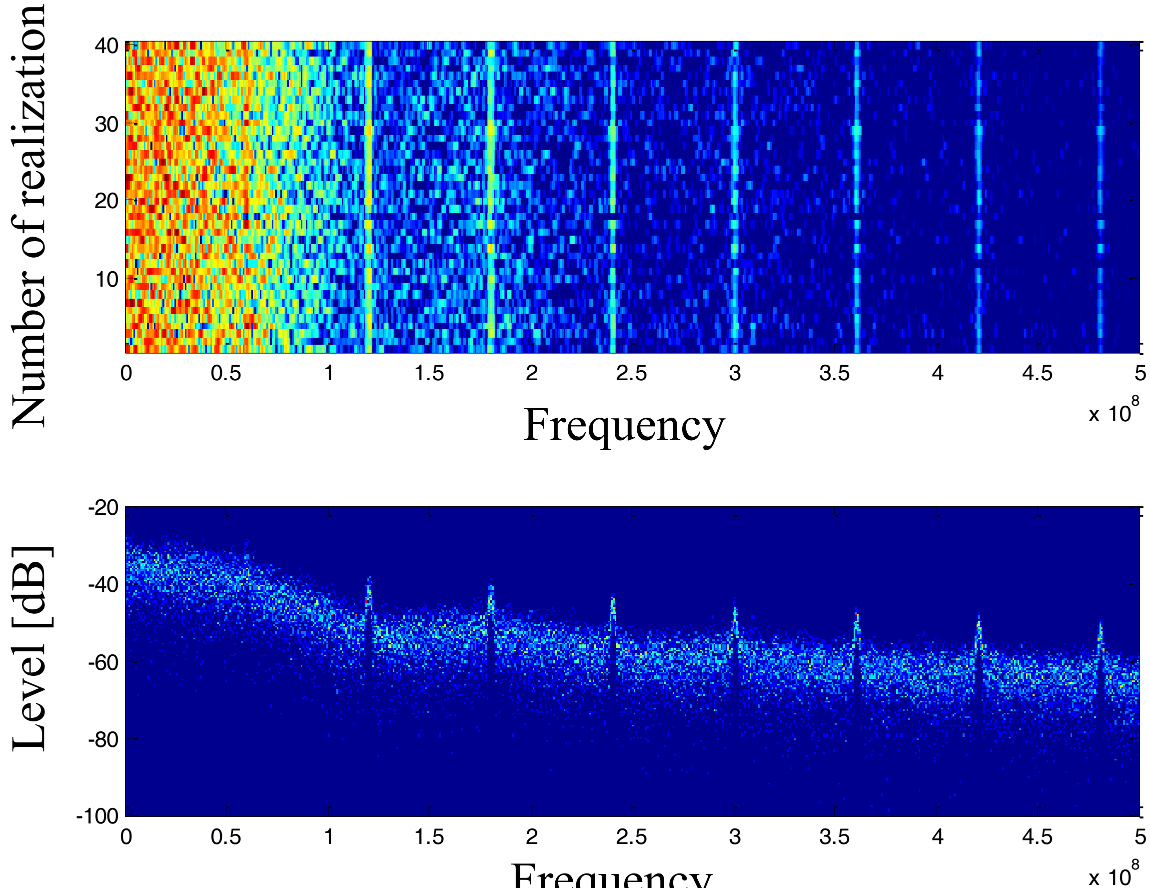
➢ Order of cyclo WSS process

•	Periodic mean value	$E\{x(t)\} = \sum_{k=1}^{N_1 \cdot M_1} C_1(t, T_k)$
•	Periodic mean power	$E\{x^2(t)\} = \sum_{k=1}^{N_2 \cdot M_2} C_2(t, T_k)$
	where	$C_{1,2}(t,T) = A_0 + \sum_{n=1}^{\infty} A_n \cdot \cos\left(2\pi \frac{n}{T} t + \theta_n\right)$

Characterization of stochastic EM radiated emission

➢ EMI

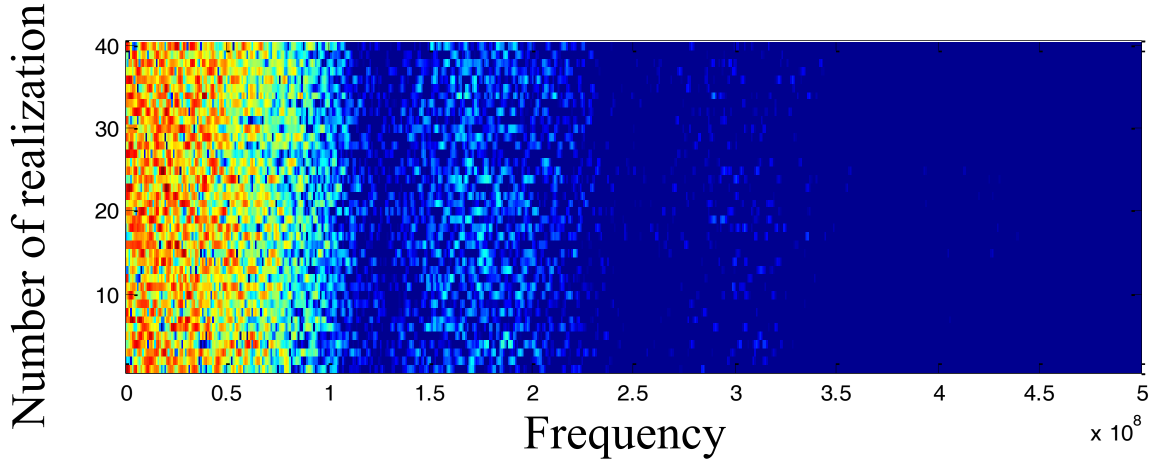
1st order CWSS

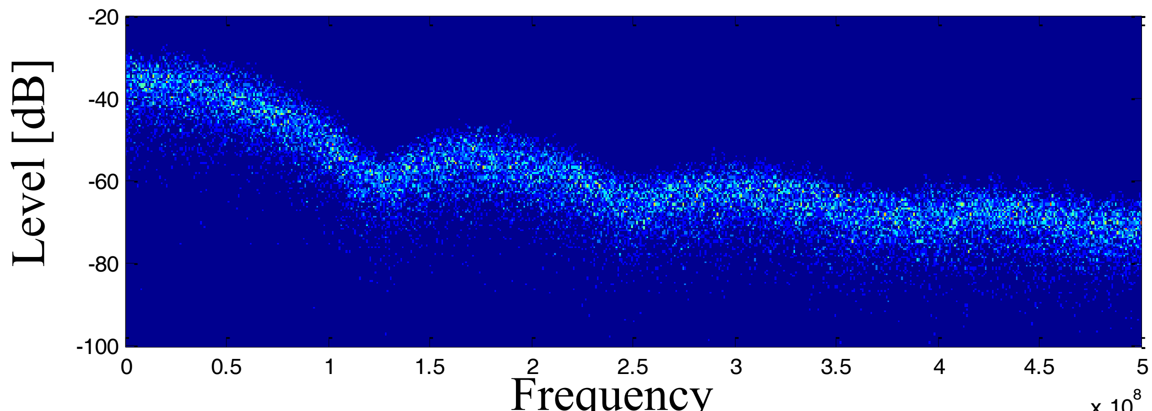


Characterization of stochastic EM radiated emission

➢ EMI

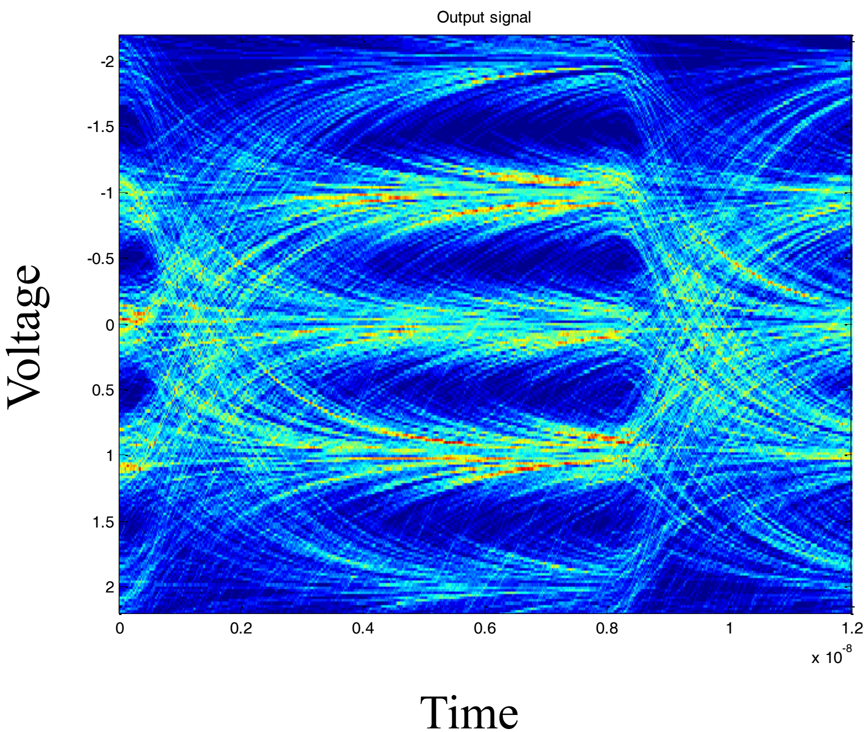
2nd order CWSS



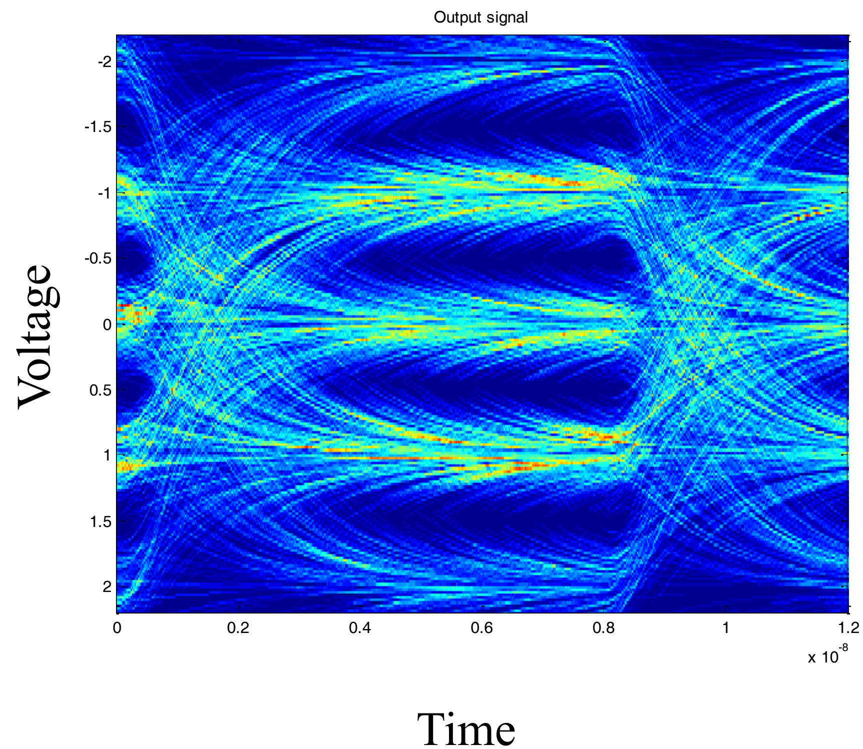


Characterization of stochastic EM radiated emission

- **EMI**
1st order CWSS



- **EMI**
2nd order CWSS



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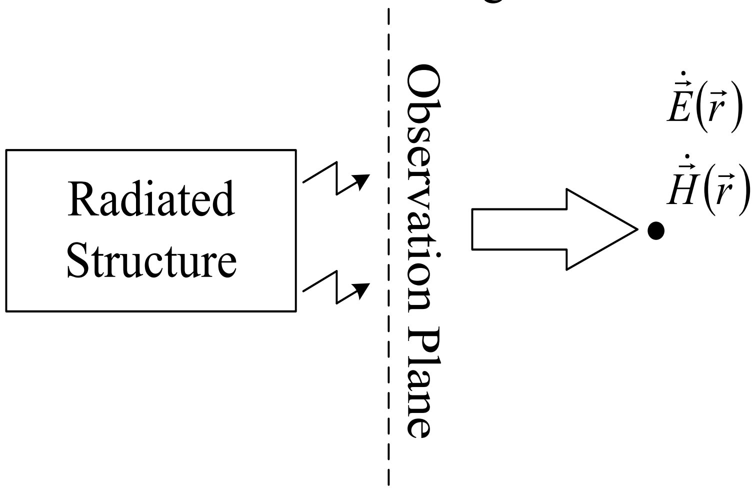
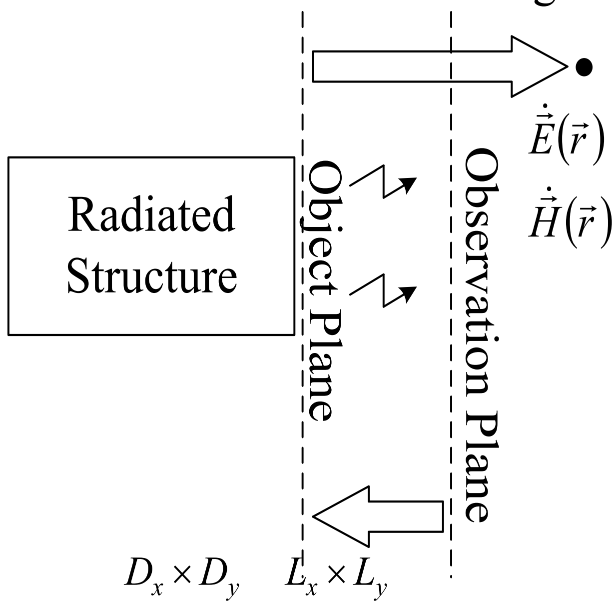
Non-parametric estimation of stochastic EMI sources

➢ Direct Reconstruction



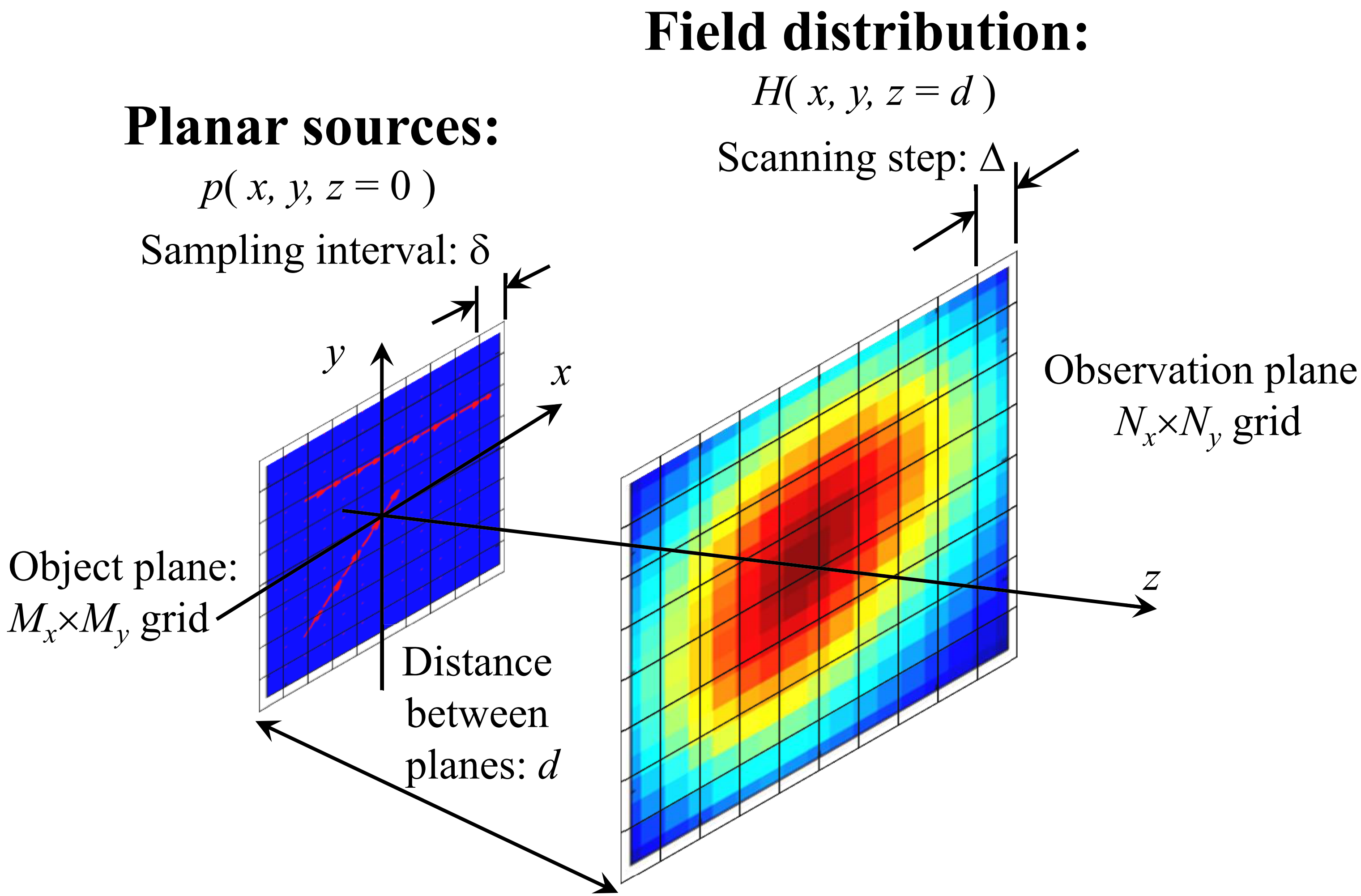
✓ Angular limitations

➢ Model-Based Approach



✓ The adequate model is need

Non-parametric estimation of stochastic EMI sources



Non-parametric estimation of stochastic EMI sources

✓ Nonparametric estimation of stochastic EMI sources produces the dipole moment parameters for all knots of the mesh in the object plane of the electronic device. The main topic of our research was to reconstruct the geometry of transmission lines designated for transferring the information signal between separated blocks of the electronic device.

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

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

$$\dot{p}_{\{x,y\}} = \frac{\dot{I} \cdot \Delta l_{\{x,y\}}}{j2\pi f}$$

Non-parametric estimation of stochastic EMI 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

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

- ✓ 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

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

Non-parametric estimation of stochastic EMI sources

➢ Cross-correlation Estimation

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

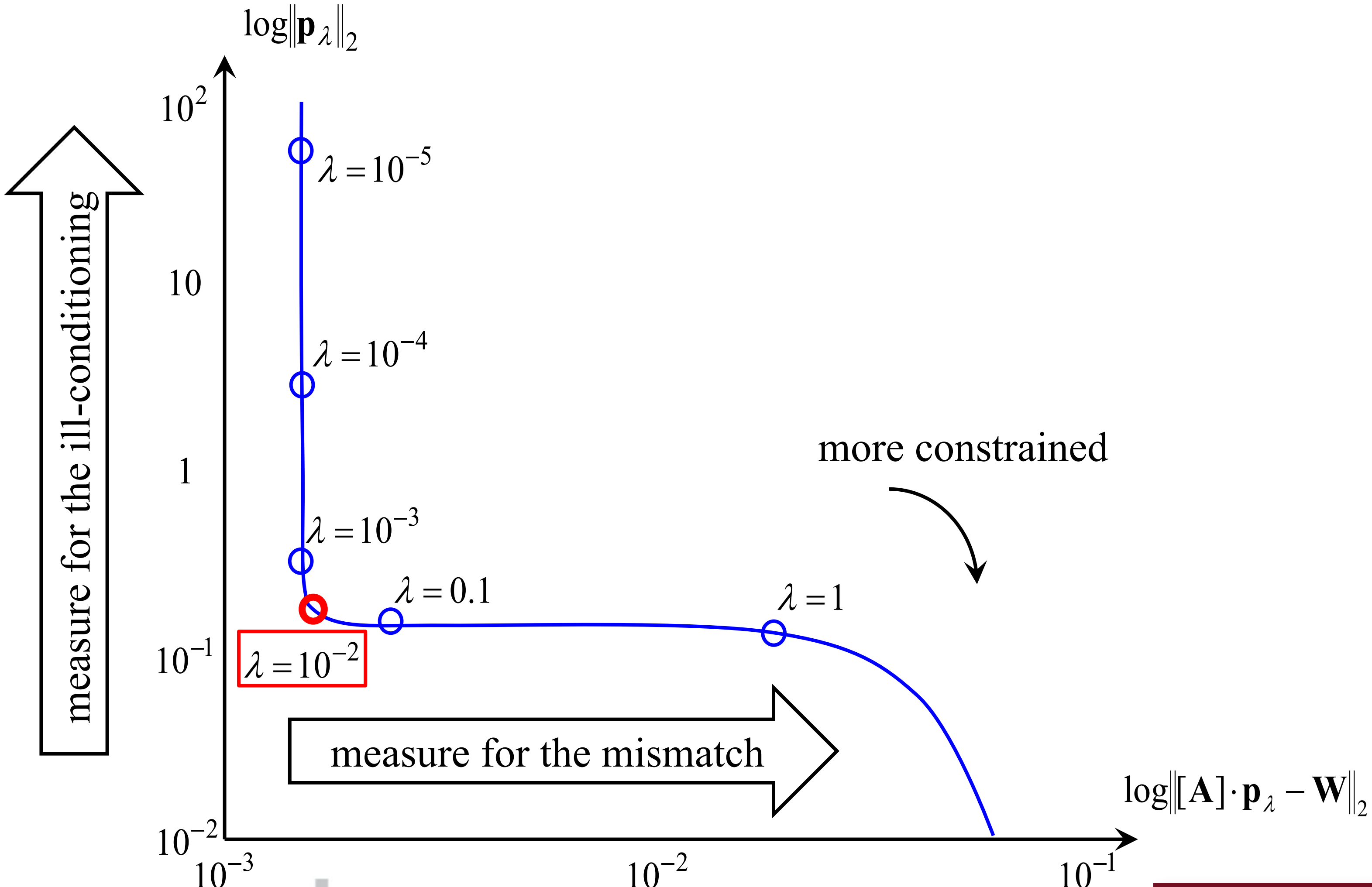
Non-parametric estimation of stochastic EMI sources

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

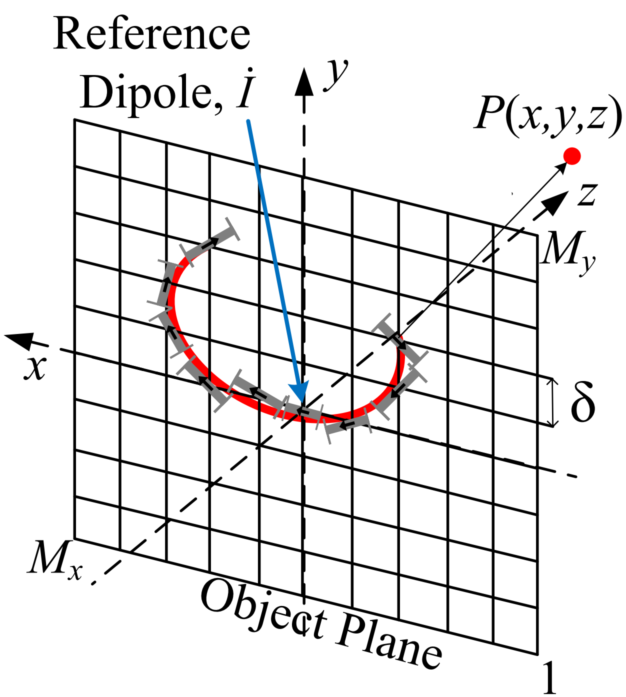
Non-parametric estimation of stochastic EMI sources

- Typical L-curve for an ill-posed problem



Parametric identification of stochastic EMI sources

- ✓ The distributed multi-dipole model of the EMI source consists of the linked together electric dipoles characterized by dipole moments for some predefined frequency of the harmonic current flowing through the transmission line.



- Model Parameters

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

- 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 of stochastic EMI sources

✓ Parametric identification procedure allows significantly reduce the number of the effective dipoles and linking them to form the geometry of the distributed stochastic EMI source.

- Space frequency-domain model of planar sources

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

where

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

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

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

Parametric identification of stochastic EMI sources

- Data Matrix $$\underset{M_D \times N_D}{[\mathbf{D}]} = \begin{pmatrix} [\mathbf{D}]_0 & [\mathbf{D}]_1 & \cdots & [\mathbf{D}]_{M_x-L} \\ [\mathbf{D}]_1 & [\mathbf{D}]_2 & \cdots & [\mathbf{D}]_{M_x-L+1} \\ \vdots & \vdots & \ddots & \vdots \\ [\mathbf{D}]_{L-1} & [\mathbf{D}]_L & \cdots & [\mathbf{D}]_{M_x-1} \end{pmatrix}, L \le \frac{M_x}{2}$$

where $$[\mathbf{D}]_v = \begin{pmatrix} \dot{G}[v,0] & \dot{G}[v,1] & \cdots & \dot{G}[v,M_y-J] \\ \dot{G}[v,1] & \dot{G}[v,2] & \cdots & \dot{G}[v,M_y-J+1] \\ \vdots & \vdots & \ddots & \vdots \\ \dot{G}[v,J-1] & \dot{G}[v,J] & \cdots & \dot{G}[v,M_y-1] \end{pmatrix}, J \le \frac{M_y}{2}$$

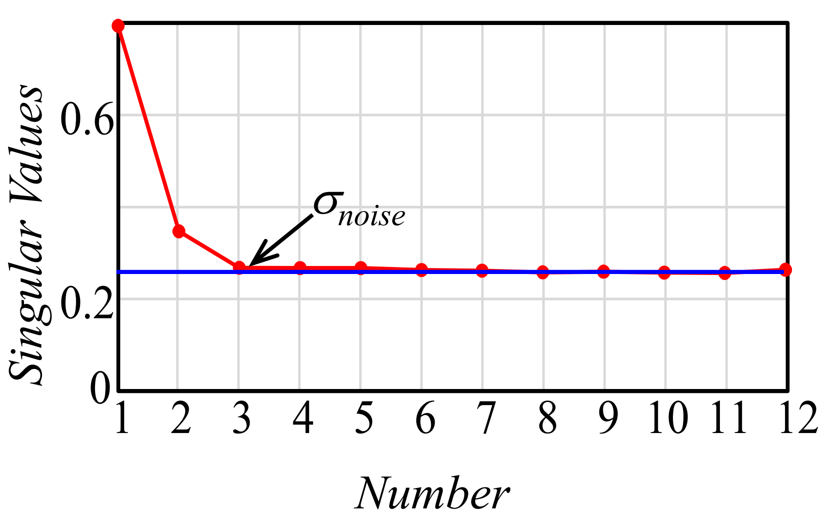
Parametric identification of stochastic EMI sources

➢ Model Order Selection

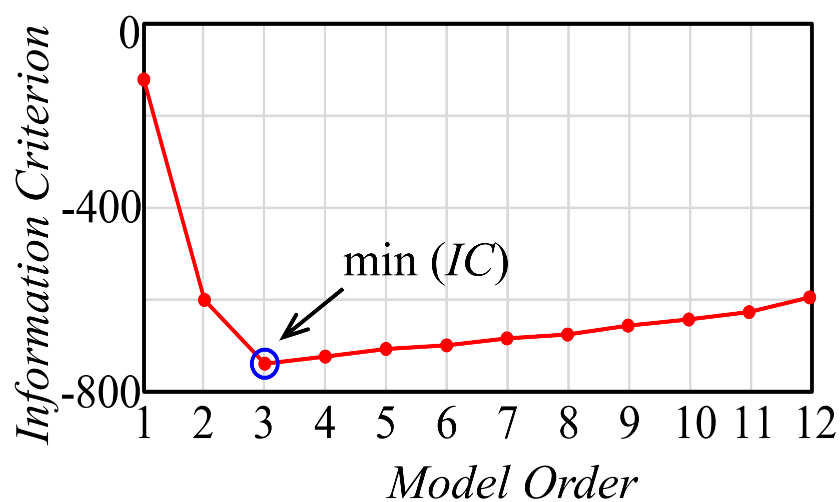
✓ The appropriate number of sources can be chosen using the information criteria such as Akaike information criterion (AIC) or Minimum Description Length (MDL) criterion. The general form of any information criteria looks as follows:

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

- Singular Value Decomposition



- Information Criterion



Parametric identification of stochastic EMI sources

- 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-coordinates

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

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

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

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

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

- y-coordinates

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

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

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

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

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

Parametric identification of stochastic EMI sources

- Complex amplitudes of dipole moments estimation:

- Minimum least squares algorithm $$\mathrm{diag}\begin{pmatrix} \dot{\alpha}_1 \\ \dot{\alpha}_2 \\ \vdots \\ \dot{\alpha}_{Order} \end{pmatrix} = \mathbf{Z}_L^{+} \cdot \mathbf{G} \cdot \mathbf{Z}_R^{+}$$

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

Parametric identification of stochastic EMI sources

- ✓ Finally the geometric parameters of dipoles such as delays and orientation in the object plane could be calculated from the estimated dipole moments. It allows predicting of the far field distribution for any information bearing stochastic signal flowing through the identified distributed EMI source.

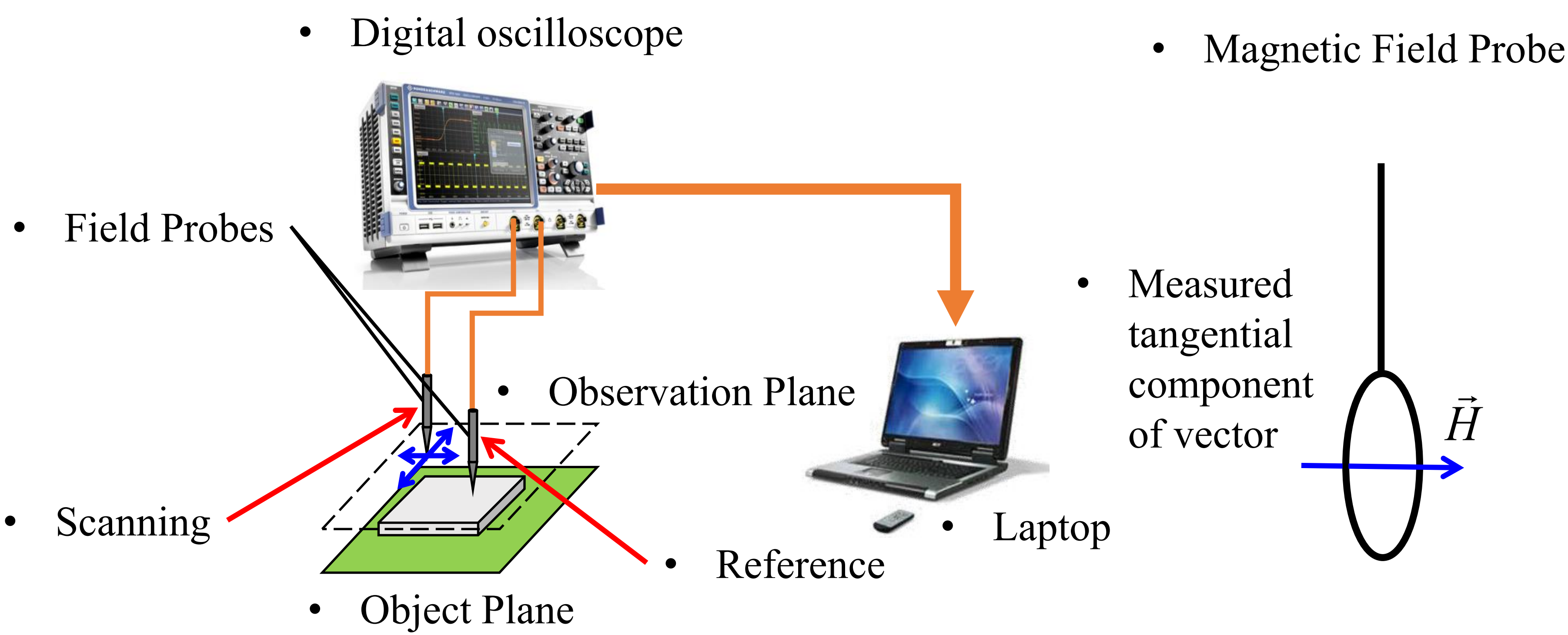
$$\dot{I} = \frac{j2\pi f_m \cdot \dot{\vec{p}}}{\Delta \vec{l}}$$

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

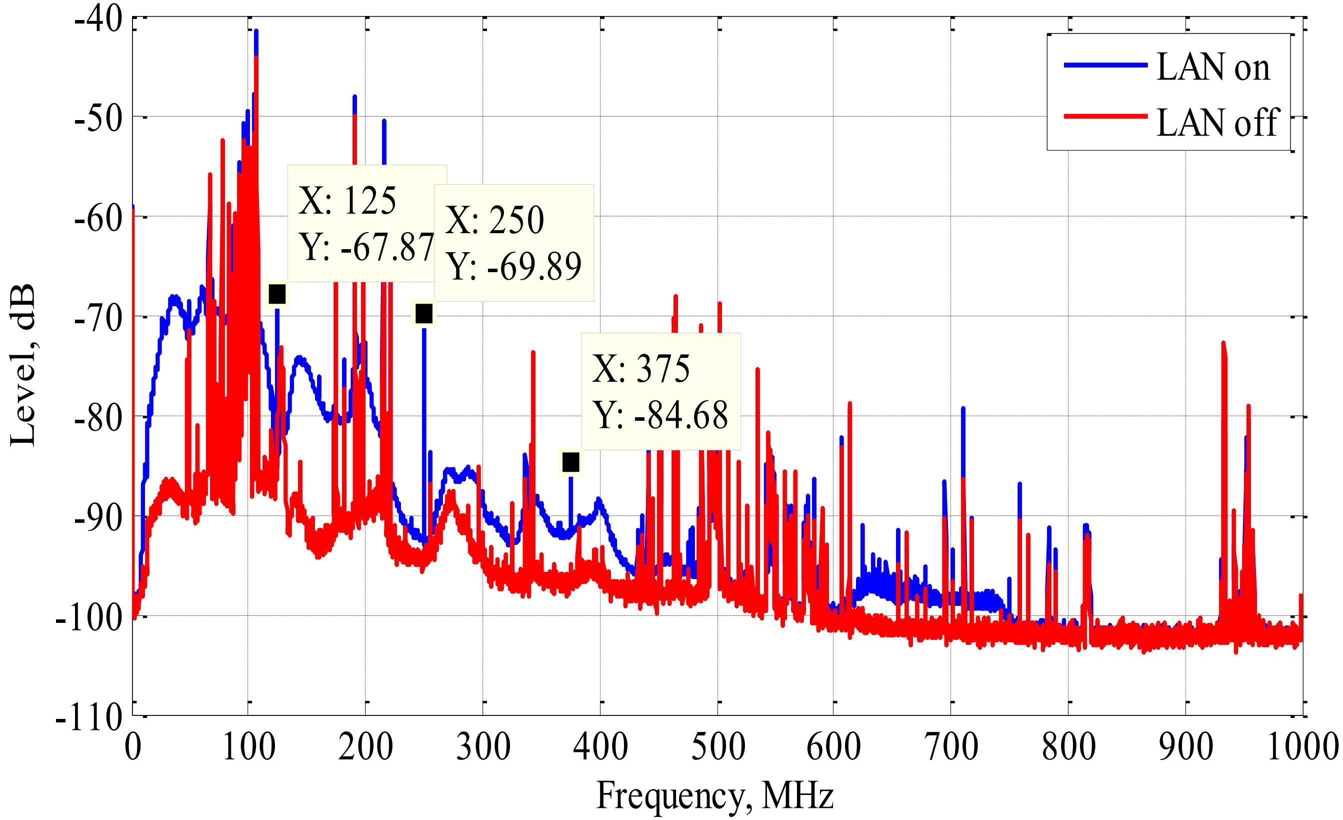
$$\Delta l_{\{x,y\}_s} = \frac{|\dot{\alpha}_{\{x,y\}_s}| \cdot 2\pi f_m}{|\dot{I}|}$$

Experimental Results

➢ Measurement setup

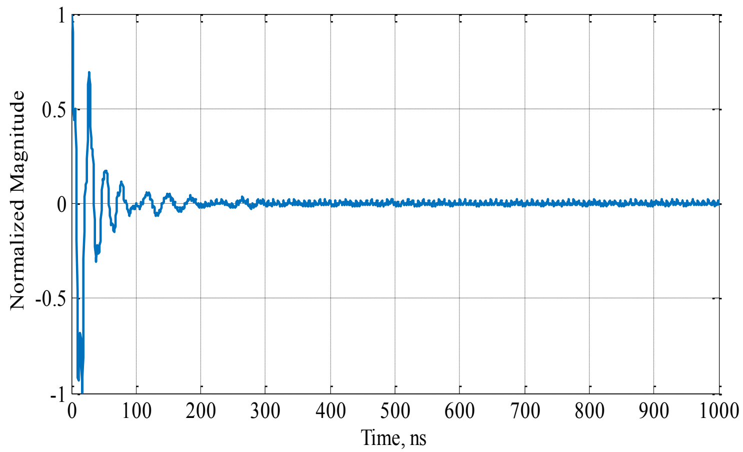


Experimental Results

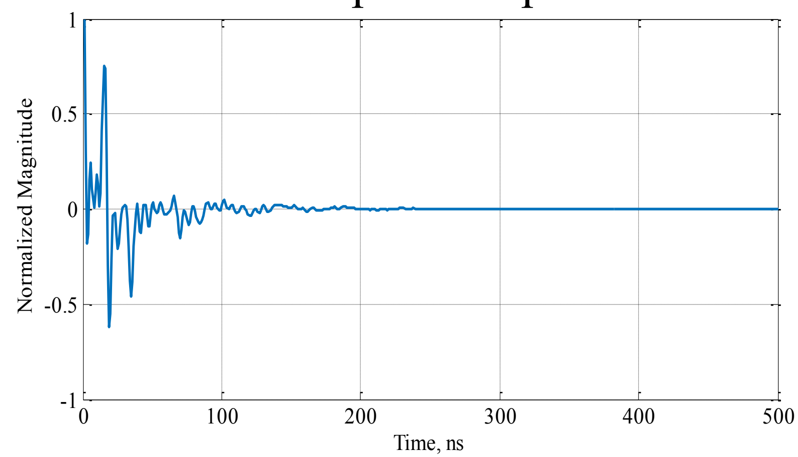


Experimental Results

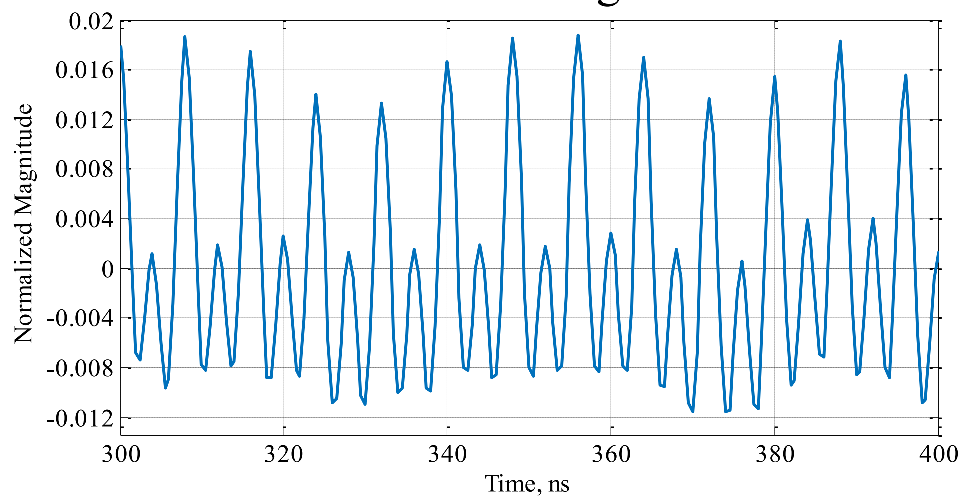
- Autocorrelation function



- Impulse response



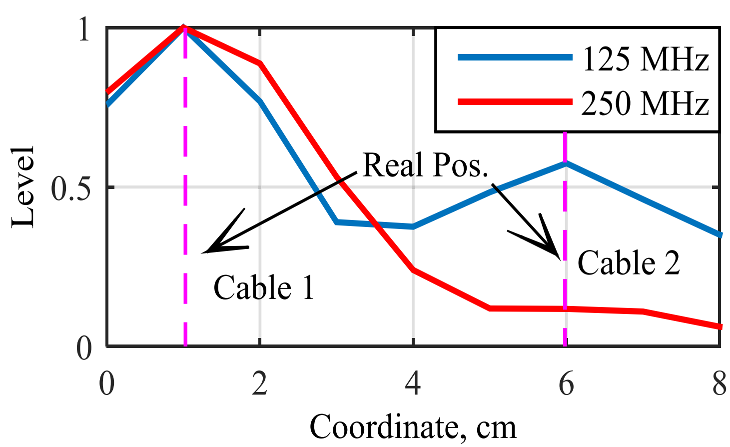
- Autocorrelation function region after this filtering



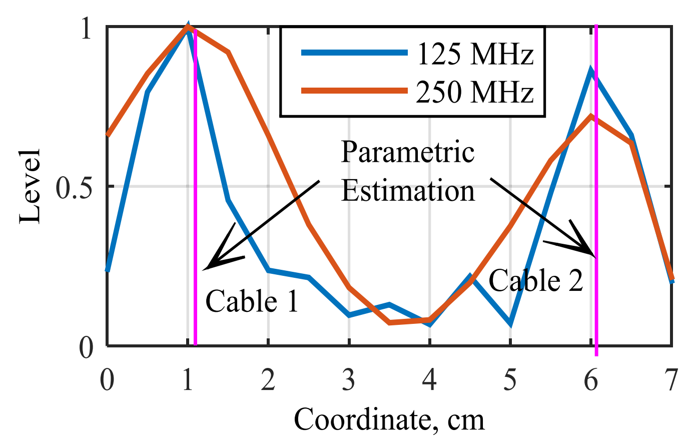
Experimental Results

✓ Comparison of cross-correlation spectra for mutually spaced WCSC sources

- Non-parametric ensemble averaging



- Parametric identification procedure



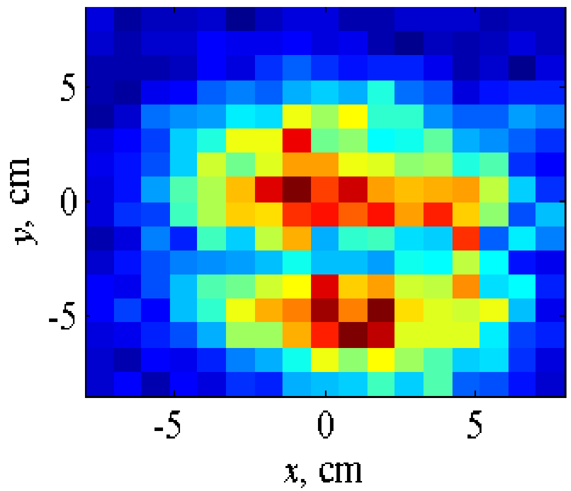
Experimental Results

➢ Measurement parameters

Frequency,	$f = 240$ MHz
Distance between observation plane and object plane,	$d = 3$ cm
Scanning step,	$\Delta = 1$ cm
Resolution in the object plane,	$\delta = 1$ cm
Number of scanning points,	15×16

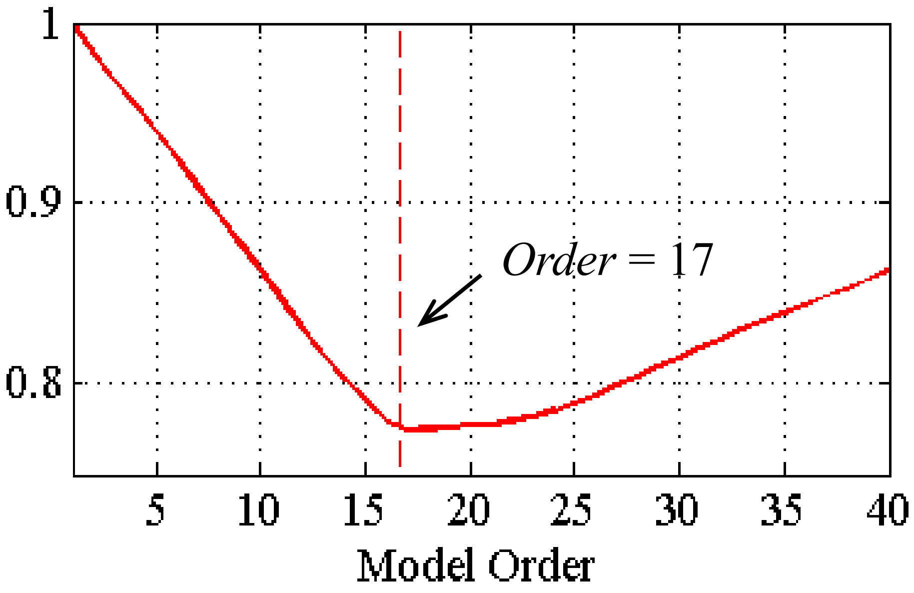
DUT: Monitor mainboard

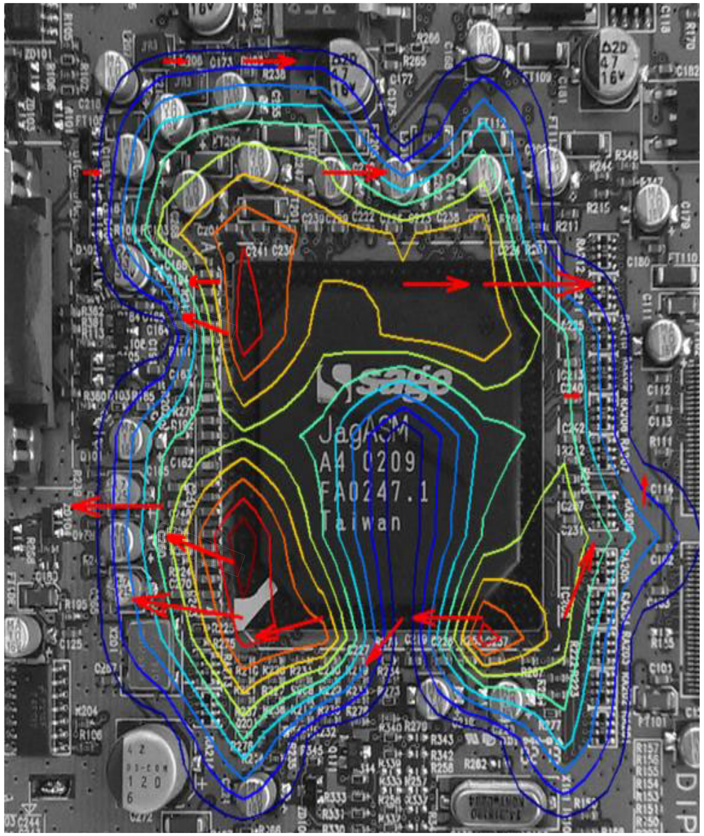
- Cross-correlation in the observation plane



Experimental Results

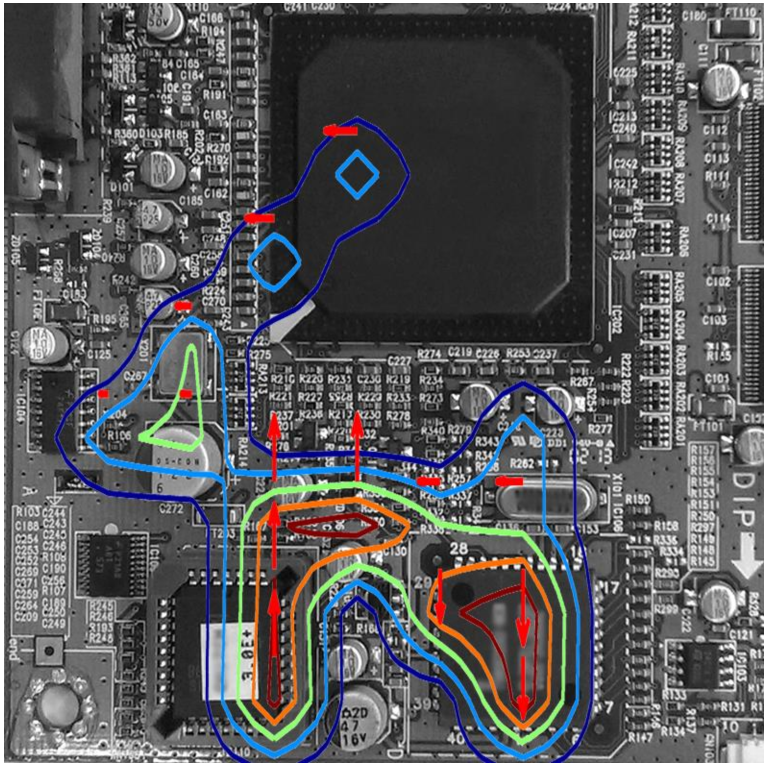
➢ **Localization Result** $f = 240$ **MHz**





Experimental Results

➤ **Localization Result** ***f* = 214.8 MHz**



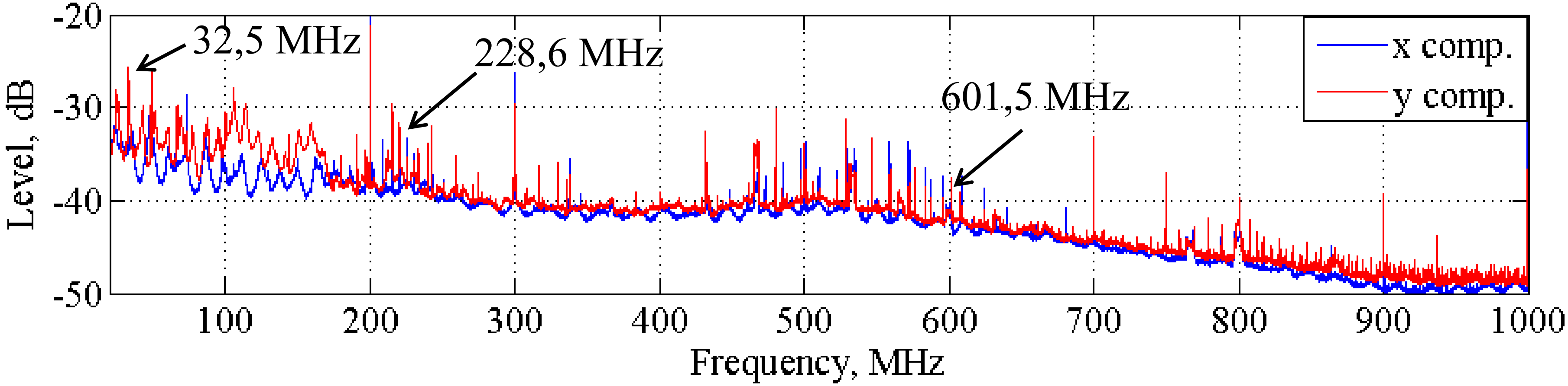
Experimental Results

➢ Measurement parameters

Frequency range,	$f = 1 \ldots 1000$ MHz
Distance between observation plane and object plane,	$d = 3.5$ cm
Scanning step,	$\Delta = 2$ cm
Resolution in the object plane,	$\delta = 2$ cm
Number of scanning points,	28×17

DUT: Notebook

- Autocorrelation spectrum of the H-field

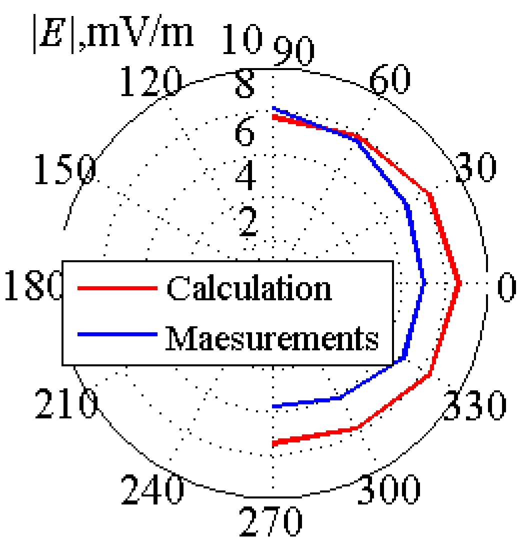


Experimental Results

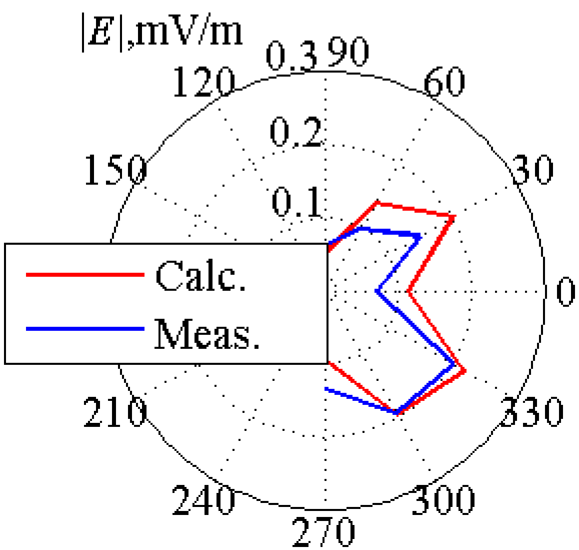
➢ Far-Field Pattern

Distance,	$r = 2$ m
Polarization,	Horizontal

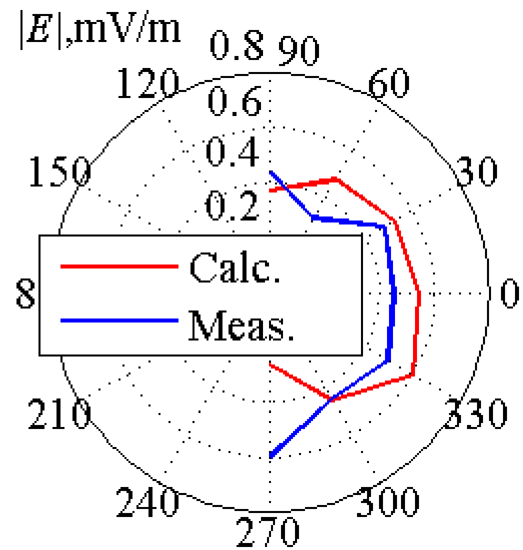
$f = 32{,}5$ MHz



$f = 601{,}5$ MHz



$f = 228{,}6$ MHz



Conclusion

- The N-F measurements of the stochastic fields radiating by PCB can be used for the prediction of the F-F distribution of the EMI containing the information bearing signal and for the localization of the stochastic CWSS EMI sources on the surface of the PCB or electronic device under test.
- The improvement of the localization accuracy could be archived by specific signal processing in addition to the conventional averaging technique for stochastic EM field.

Conclusion

- The proposed algorithm of Tikhonov regularization in conjunction with L-curve method allows the finding of the stable inverse reconstruction of the multi-dipole model distribution in the object plane
- Additional parametric identification procedure based on the model order selection in accordance with AIC and also on the 2 D Matrix Pencil Algorithm with subsequent fitting by MLS technique gives the geometrical configuration of the information bearing CWSS stochastic sources of the electronic device under test.
- Implemented simulations and measurement experiments verified the choice of the proposed signal processing algorithms for the purpose of the EM sources localization and the prediction of the far-field unintentional emissions pattern.