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Fast Calculation of Electromagnetic Scattering in Anisotropic Multilayers and its Inverse Problem

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Cooperative works among

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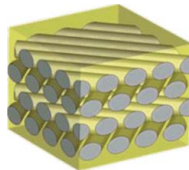
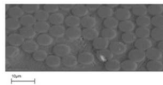
³ formerly in National University of Singapore (NUS)¹

ENDE Xi'an June 2014



1. Special thanks to X. Chen from NUS

Electromagnetic modeling of fiber-based composite structures



Motivation

- Accurate computational models of complex anisotropic multilayered composite structures
- Robust, fast, end-user's friendly imaging procedures

Forward modeling

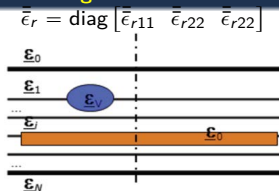


FIGURE: Damaged structure with uniaxial dielectric (glass-based) or conductive (graphite-based) multilayers

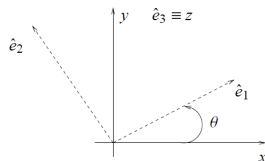


FIGURE: The transformation between the local and global coordinates by rotation matrix

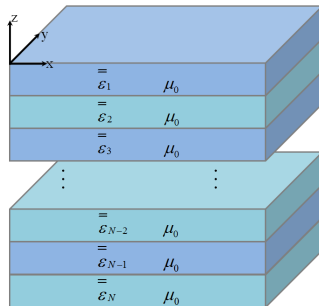
EM response of anisotropic multilayers to distributed sources

The state equation

$$\frac{d}{dz} \bar{\varphi}(z) = \bar{\bar{A}}_n \cdot \bar{\varphi}(z) + \bar{f}(z)$$

based on the 4-component vector :

$$\bar{\varphi}(k_x, k_y, z) = \begin{bmatrix} k_x \tilde{H}_x(k_x, k_y, z) + k_y \tilde{H}_y(k_x, k_y, z) \\ k_y \tilde{H}_x(k_x, k_y, z) - k_x \tilde{H}_y(k_x, k_y, z) \\ k_x \tilde{E}_x(k_x, k_y, z) + k_y \tilde{E}_y(k_x, k_y, z) \\ k_y \tilde{E}_x(k_x, k_y, z) - k_x \tilde{E}_y(k_x, k_y, z) \end{bmatrix}$$



The solution of the state equation

$$\bar{\varphi}(d_{n+1}) = e^{\bar{\bar{A}}_n(\delta_n)} \cdot \bar{\varphi}(d_n) + \int_{d_n}^{d_{n+1}} e^{\bar{\bar{A}}_n(\delta'_n)} \cdot \bar{f}(z') dz'$$

EM response of anisotropic multilayers to distributed sources

The new recurrence equation :

$$\bar{\varphi}(d_n) = \bar{\bar{\Omega}}_n \cdot \begin{bmatrix} \alpha_n \\ \beta_n \end{bmatrix}$$

New recurrence relations based on the propagator matrix method

- To efficiently calculate the spectral response of the laminate
- Capable of stably dealing with distributed source along z
- More efficient compared to the traditional Green's function method
- To numerically solve the state equation containing the tangential components of the fields

Two methods for calculating the scattered field

1st method

- Induced current integral equation (ICIE)
- windowing technique
- Padua interpolation-integration technique

2nd method

- Lippman-Schwinger integral formula
- Polarization tensor
- Padua interpolation-integration technique

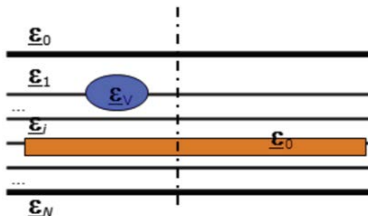


FIGURE: Damaged structure with uniaxial dielectric (glass-based) or conductive (graphite-based) multilayers

Discretization of the integral equation - 1st method

Induced current integral equation (ICIE)

$$\bar{\bar{\chi}}(\mathbf{r}) \cdot \mathbf{E}^{inc}(\mathbf{r}) = \frac{\mathbf{I}(\mathbf{r})}{-i\omega\epsilon_0} - \bar{\bar{\chi}}(\mathbf{r}) \cdot i\omega\mu_0 \int \bar{\bar{G}}(\mathbf{r}; \mathbf{r}') \cdot \mathbf{I}(\mathbf{r}') d\mathbf{r}'$$

By MoM

$$\begin{aligned} \sum_{v=1}^3 \chi_{u,v;m,n,p} \mathbf{E}_{v;m,n,p}^{inc} &= \frac{-1}{i\omega\epsilon_0} \sum_{m',n',p'} I_{m',n',p'}^{(u)} \psi_{m',n',p'}^{(u)}(\mathbf{r}_{m,n,p}) \\ &- \sum_{v=1}^3 \chi_{u,v;m,n,p} \sum_{\kappa=1}^3 \sum_{p'} \sum_{m',n'} \eta_{v\kappa;p;p';(m-m'),(n-n')} I_{m',n',p'}^{(\kappa)} \end{aligned}$$

By fast Fourier transform (FFT)

$$\bar{\bar{\xi}}_{v\kappa;p;p'} = \sum_{m',n'} \eta_{v\kappa;p;p';(m-m'),(n-n')} I_{m',n',p'}^{(\kappa)} = \text{IFFT} \left\{ \text{FFT} \left\{ \bar{\bar{\eta}}_{v\kappa;p;p'} \right\} \otimes \text{FFT} \left\{ {}_{(0)}\bar{\bar{I}}_{p'}^{(\kappa)} \right\} \right\}$$

The techniques for calculating the impedance matrix - 1st method

The impedance matrix :

$$\eta_{\nu\kappa;p;p'}(x, y) = i\omega\mu_0 \int_{\mathcal{D}} G_{\nu\kappa}[(x - x'), (y - y'); z_p; z'] \psi_{0,0,p'}^{(\kappa)}(\mathbf{r}') d\mathbf{r}'$$

After detouring the integral path to avoid branch cuts or singularities for the integral involving $\tilde{\eta}_{\nu\kappa;p;p'}(k_x, k_y)$, the DFT of $\tilde{\eta}'_{\nu\kappa;p;p'}$ (the windowed version of $\tilde{\eta}_{\nu\kappa;p;p'}$) can be constructed as

$$\begin{aligned} \hat{\eta}'_{\nu\kappa;p;p';\alpha,\beta} &= \frac{1}{4\pi^2\Delta x\Delta y} \exp\left(i\frac{2\pi\alpha}{M_t\Delta x}x_s + i\frac{2\pi\beta}{N_t\Delta y}y_s\right) \\ &\int_{-\infty}^{+\infty} d\sigma_x^R d\sigma_y^R \tilde{\eta}_{\nu\kappa;p;p'}[\sigma_x(\sigma_x^R, \sigma_y^R), \sigma_y(\sigma_x^R, \sigma_y^R)] \left| \frac{\partial(\sigma_x, \sigma_y)}{\partial(\sigma_x^R, \sigma_y^R)} \right| \times \\ &\left\{ \sum_{l_1, l_2=-\infty}^{+\infty} e^{i2\pi[l_1(x_s/\Delta x) + l_2(y_s/\Delta y)]} \tilde{w}\left[\frac{2\pi}{\Delta x}\left(\frac{\alpha}{M_t} + l_1\right) - \sigma_x(\sigma_x^R, \sigma_y^R), \frac{2\pi}{\Delta y}\left(\frac{\beta}{N_t} + l_2\right) - \sigma_y(\sigma_x^R, \sigma_y^R)\right] \right\} \end{aligned}$$

2-D Hamming window

$$\begin{aligned} w(x, y) &= \left\{ 0.54 + 0.46 \cos\left[\frac{(x - \Delta x/2)\pi}{a}\right] \right\} \\ &\times \left\{ 0.54 + 0.46 \cos\left[\frac{(y - \Delta y/2)\pi}{b}\right] \right\} \end{aligned}$$

Padua interpolation-integration technique - calculating fast oscillating integrals

- The goal is to compute the I-FT of fast oscillating spectrum in the $k_x - k_y$ plane

$$G(x, y) = \frac{1}{4\pi^2} \iint_{-\infty}^{\infty} \tilde{G}_0(k_x, k_y) e^{(ik_x x + ik_y y)} dk_x dk_y$$

- Interpolation of the non-oscillating part at the Padua points with Chebyshev's polynomial interpolant

$$\mathcal{L}_n \tilde{G}_0(k_x, k_y) = \sum_{k=0}^n \sum_{j=0}^k c_{j, k-j} \hat{T}_j(k_x) \hat{T}_{k-j}(k_y) - \frac{1}{2} c_{n,0} \hat{T}_n(k_x) T_0(k_y)$$

with weights $c_{j, k-j}$ computed using²

- Fourier transform of Chebyshev polynomials given by

$$\int_{-1}^1 \hat{T}_n(k_x) \exp(-ik_x x) dk_x$$

are managed using³

-
2. M. Caliari, S. De Marchi *et al.*, *Numer Algorithms*, **56**, 45-60, 2011
 3. V. Dominguez, I. G. Graham *et al.*, *IMA J Numer Anal*, **31**, 1253-1280, 2011

Padua interpolation-integration technique - calculating fast oscillating integrals

Alternative representation as self intersections and boundary contacts of the generating curve
 $\gamma(t) = (-\cos((n+1)t), -\cos(nt), t \in [0, \pi])$

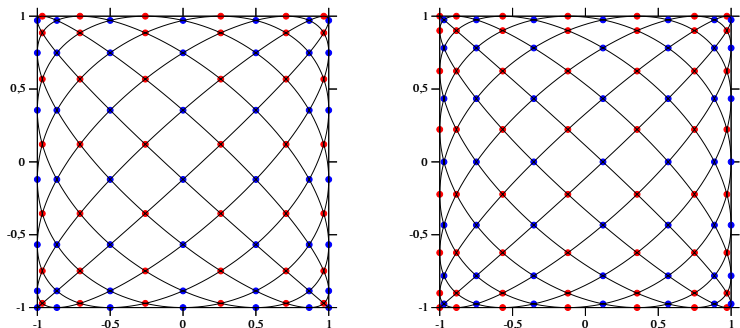


FIGURE: The Padua points with their generating curve for $n = 12$ (left, 91 points) and $n = 13$ (right, 105 points), also as union of two Chebyshev-Lobatto sub-grids (red and blue bullets). Image taken from ⁵

M. Caliari, S. De Marchi *et al.*, 5th European Congress of Mathematics - Amsterdam, July, 2008

Fast calculation of EM scattering problems - 2nd method

The Lippman-Schwinger integral formulation

$$\mathbf{E}^{sca}(\mathbf{r}) = i\omega\mu_0 \int \bar{\bar{G}}^{ee}(\mathbf{r}, \mathbf{r}') \cdot \bar{\bar{\chi}}(\mathbf{r}') \cdot \mathbf{E}^{tot}(\mathbf{r}') d\mathbf{r}'$$

where the contrast function

$$\bar{\bar{\chi}}(\mathbf{r}) = -i\omega\epsilon_0 \cdot (\bar{\bar{\epsilon}}_i - \bar{\bar{\epsilon}}_b)$$

$\bar{\bar{\epsilon}}_i$ is the permittivity tensor of an inclusion in the composite medium.

$\bar{\bar{\epsilon}}_b$ is the permittivity tensor of the composite medium in the global coordinate system.

The incident field is defined as

$$\begin{aligned} \mathbf{E}^{inc}(\mathbf{r}) &= i\omega\mu_0 \int \bar{\bar{G}}^{ee}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}_0(\mathbf{r}') d\mathbf{r}' \\ &= i\omega\mu_0 \bar{\bar{G}}^{ee}(\mathbf{r}, \mathbf{r}') \cdot \beta II \end{aligned}$$

Asymptotic formulation with polarization tensor - 2nd method

The Lippman-Schwinger integral formulation

When permittivity tensor of the inclusion $\bar{\bar{\epsilon}}_i = \bar{\bar{I}}\epsilon_i$ and its size is small enough, the scattered field can be derived into the asymptotic formulation.

$$\mathbf{E}^{sca}(\mathbf{r}) = i\omega\mu_0 \bar{\bar{G}}^{ee}(\mathbf{r}, \mathbf{r}_m) \cdot \bar{\bar{\varrho}} \cdot \mathbf{E}^{inc}(\mathbf{r}_m)$$

The polarization tensor

The polarization tensor in the local coordinate for the inclusion with volume V is :

$$\bar{\bar{\varrho}} = -i\omega\epsilon_0 V \cdot \begin{bmatrix} \alpha_l & 0 & 0 \\ 0 & \alpha_t & 0 \\ 0 & 0 & \alpha_t \end{bmatrix}$$

$$\alpha_l = \epsilon_{11} \frac{\epsilon_i - \epsilon_{11}}{\epsilon_{11} + L_l (\epsilon_i - \epsilon_{11})}$$

$$\alpha_t = \epsilon_{22} \frac{\epsilon_i - \epsilon_{22}}{\epsilon_{22} + L_t (\epsilon_i - \epsilon_{22})}$$

- L_l and L_t are dependent on the shape of inclusion.
- For a cubic inclusion, $L_l = c \arctan(c / \sqrt{1 + 2c})$ and $L_t = (1 - L_l) / 2$, where $c = \epsilon_{11} / \epsilon_{22}$.

Comparison of the scattered field by MoM and COMSOL - 1st Case

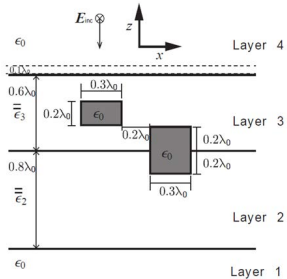
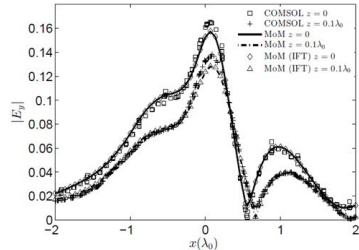
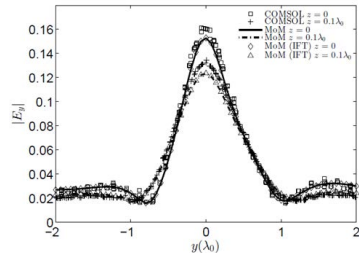


FIGURE: The Configuration of the 1st Case⁷

- freq=6 GHz
- $\bar{\epsilon}_2 = \epsilon_0 \text{diag}[3, 2, 2]$, rotation angle $\theta_2 = 30^\circ$
- $\bar{\epsilon}_3 = \epsilon_0 \text{diag}[4, 2.5, 2.5]$, rotation angle $\theta_3 = 60^\circ$



(a) Scattered electric fields along the x-axis.



(b) Scattered electric fields along the y-axis.

7. Y. Zhong, P.-P. Ding, M. Lambert, D. Lesselier, and X. Chen, Fast calculation of scattering by 3-D inhomogeneities in uniaxial anisotropic multilayers, *submitted to IEEE Trans. Antennas Propagat.*, 2014.

Comparison of the scattered field by MoM and asymptotic method - 2nd Case

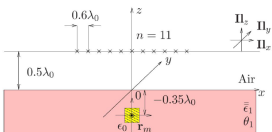


FIGURE: The Configuration of the 2nd Case

- freq=3 GHz
- $\bar{\epsilon}_1 = \epsilon_0 \text{diag} [2 + i0.3, 3 + i0.1, 3 + i0.1]$
- rotation angle $\theta = 60^\circ$
- 11 electric dipole sources with x/y/z polarization
- a cubic air scatterer with side length $0.1\lambda_0$

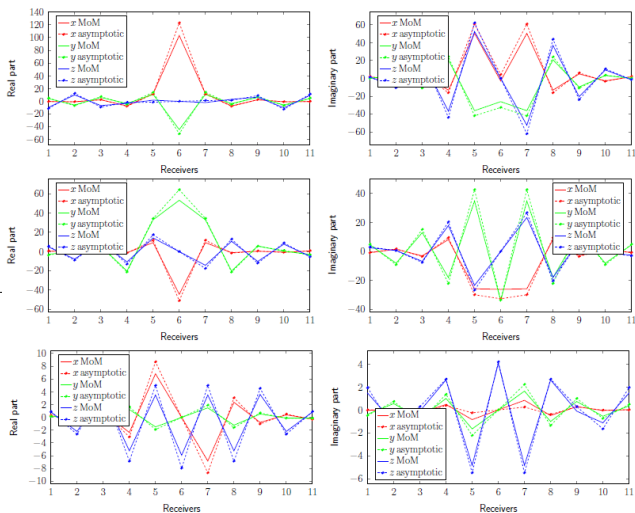


FIGURE: The scattered electric field with sources in x/y/z-polarization

Comparison of the scattered field by MoM and asymptotic method - 3rd Case

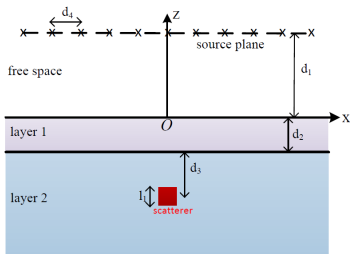


FIGURE: The Configuration of the 3rd Case

- freq = 3 GHz
- $d_1 = 0.5\lambda_0$; $d_2 = 0.2\lambda_0$; $d_3 = 0.35\lambda_0$; $d_4 = 0.2\lambda_0$
- layer 1 : $\bar{\epsilon}_1 = \epsilon_0 \text{diag} [2 + i0.3, 3 + i0.1, 3 + i0.1]$; rotation angle $\theta_1 = 60^\circ$
- layer 2 : $\bar{\epsilon}_2 = \epsilon_0 \text{diag} [4.5 + i0.2, 6 + i0.05, 6 + i0.05]$; rotation angle $\theta_2 = 45^\circ$
- 11 electric dipole sources with x polarization
- a cubic air scatterer with side length $0.1\lambda_0$

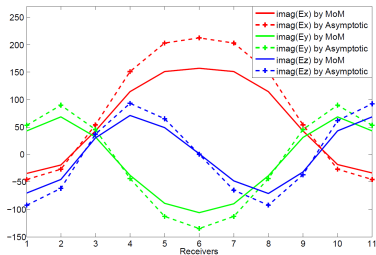
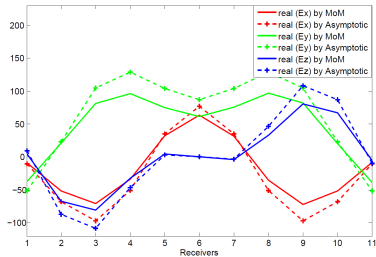


FIGURE: The scattered electric field with the x-polarization source located at $(0, 0, 0.5\lambda_0)$

MUSIC (Multiple Signal Classification) imaging method

Singular value decomposition

$$\mathbf{K} = \mathbf{U} \mathbf{S} \mathbf{V}^*$$

- Multistatic response matrix \mathbf{K} maps the currents at the source locations to the scattered fields measured at the detectors.
- Subspace is spanned by the singular vectors corresponding to different singular values.

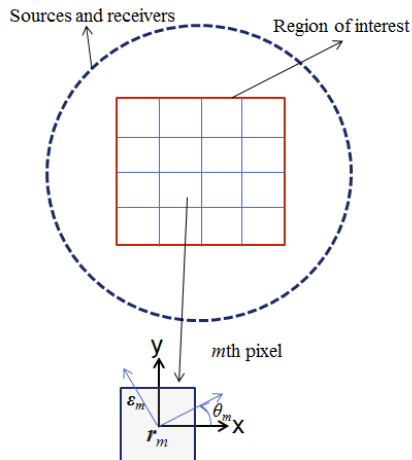


FIGURE: Damaged structure with uniaxial dielectric (glass-based) or conductive (graphite-based) multilayers

MUSIC (MULTiple Signal Classification) imaging method

Formulations

Standard MUSIC imaging method⁸

$$\phi(\mathbf{r}) = \frac{1}{\sum_{\sigma_j < \sigma_L} \sum_{v=1}^3 \left| \bar{u}_j^* \cdot \bar{G}_v(\mathbf{r}) \right|^2}$$

Enhanced MUSIC imaging method⁹

$$\phi(\mathbf{r}) = \frac{1}{1 - \sum_{\sigma_j > \sigma_L} \left| \bar{u}_j^* \cdot \bar{G}(\mathbf{r}) \cdot \bar{a}_{\text{test}} \right|^2}$$

with

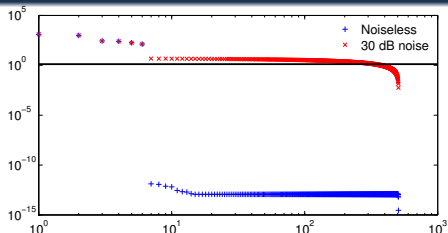
$$\bar{a}_{\text{test}} = \arg \max_{\bar{a}} \frac{\sum_{\sigma_j > \sigma_L} \left| \bar{u}_j^* \cdot \bar{G}(\mathbf{r}) \cdot \bar{a} \right|^2}{\left| \bar{G}(\mathbf{r}) \cdot \bar{a} \right|^2}$$

Choice of σ_L

- σ_i being ordered from the largest to the lowest value
- A threshold T arbitrarily chosen

$$\sigma_L = T \times \max_i (\sigma_i) \quad (1)$$

Example for two scatterers $T = 10^3$



Configuration of interest

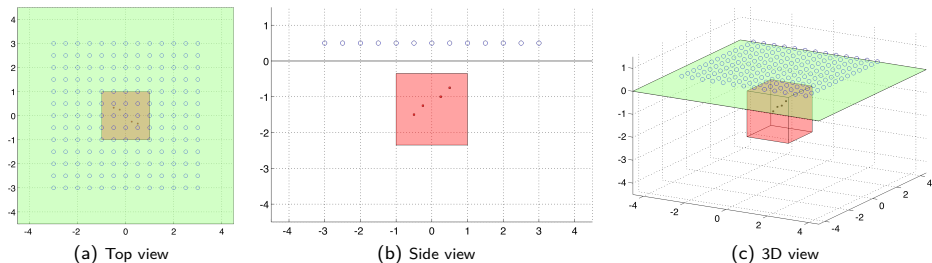


FIGURE: Testing configuration

Description of the configuration

Measurement configuration

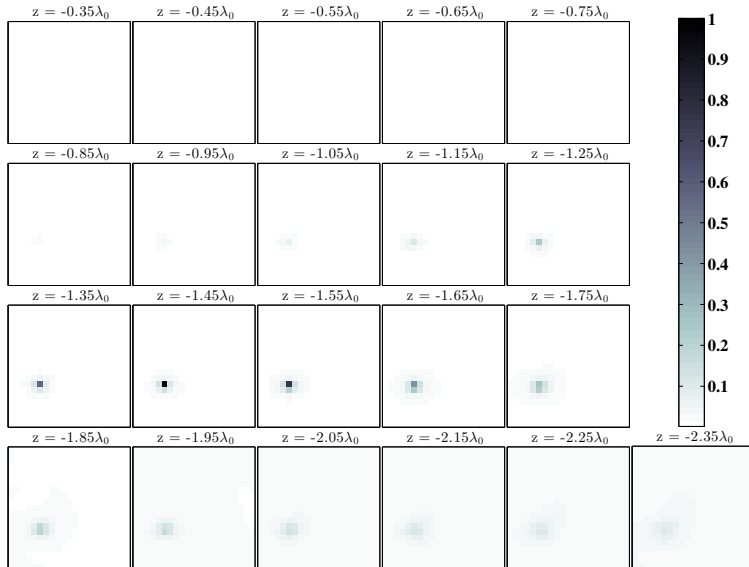
- location of sources = location of receivers (x/y/z polarization)
- $N_{\text{receivers}} = 13 \times 13$
- z position of receivers : $0.5\lambda_0$
- range of receivers in x-y plane : $[-3\lambda_0, 3\lambda_0]$

Region of interest (ROI)

- $N_{\text{cells}} = 21 \times 21 \times 21$
- range of ROI along z : $[-2.35\lambda_0, -0.35\lambda_0]$
- range of ROI in x-y plane : $[-\lambda_0, \lambda_0]$

The 1st case - one scatterer

plane cut representation



The 1st case - one scatterer

Isosurface = 0.5

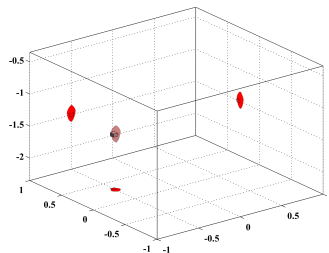
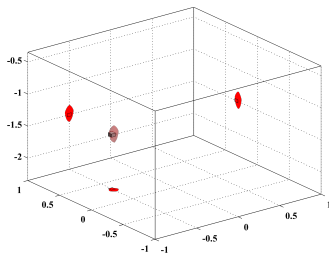


FIGURE: Imaging results by MUSIC for noiseless case (left figure) and 30 dB noisy case (right figure)

FIGURE: Influence of the choice of the isosurface

The 2nd case - two scatterers

Isosurface = 0.5

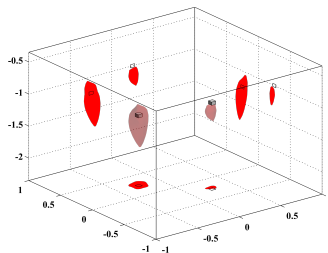
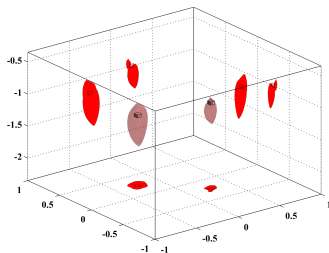


FIGURE: Imaging results by MUSIC for noiseless case (left figure) and 30 dB noisy case (right figure)

FIGURE: Influence of the choice of the isosurface

The 3rd case - three scatterers

Isosurface = 0.1

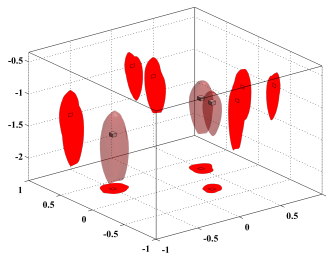
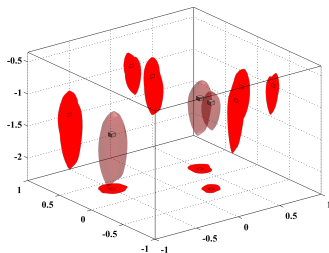


FIGURE: Imaging results by MUSIC for noiseless case (left figure) and 30 dB noisy case (right figure)

FIGURE: Influence of the choice of the isosurface

The 4th case - four scatterers

Isosurface = 0.1

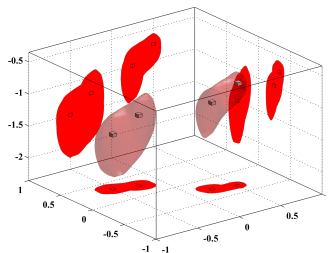
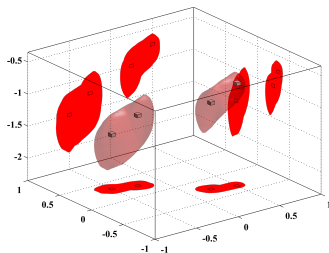


FIGURE: Imaging results by MUSIC for noiseless case (left figure) and 30 dB noisy case (right figure)

FIGURE: Influence of the
choice of the isosurface

Conclusions

Achievements

- Generalized and complete formulation of EM response & Green dyads for undamaged anisotropic multilayers (work at the whole range of frequency for all materials)
- Asymptotic formula-based calculation of EM response for 3-D damaged uniaxial multilayers

Challenges

- To speed up the interpolation and integration for large source-receiver arrays
- To handle delaminations at the interfaces as thin planar defects
- To extend NdT to detecting larger defects by using MUSIC as the first localization tool for non-linearized procedures
- To check the size range of defects possibly detected by the first-order modeling
- To put more endeavor on experiments for practical applications

Thank you & Questions?