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Asymptotic modeling of the multiple electromagnetic wave scattering by small spheres

Justine Labat, Victor Péron, Sébastien Tordeux

PhD student in Applied Mathematics

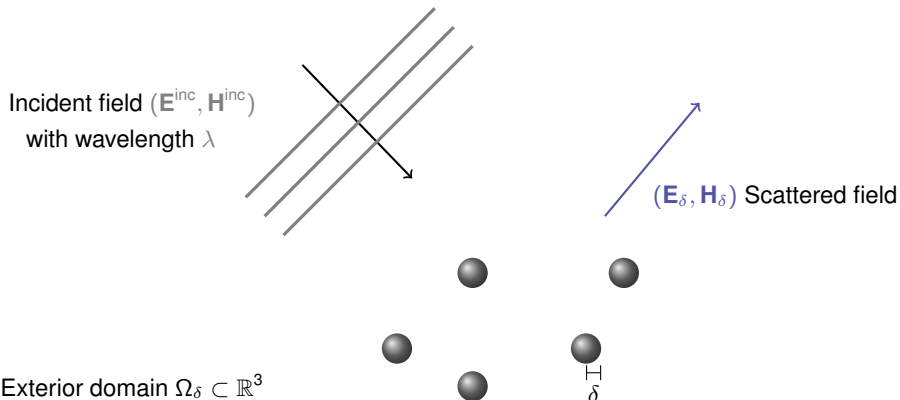
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6th European Conference on Computational Mechanics (ECCM 6)
7th European Conference on Computational Fluid Dynamics (ECFD 7)

Glasgow, June, 14th 2018

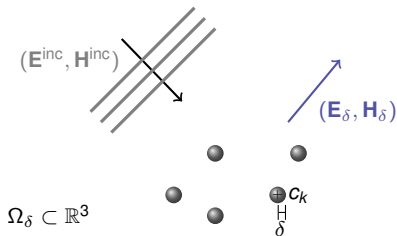


3D-Multiple Scattering Problem by Small Spheres



Asymptotic assumption : $\delta \ll \lambda$

Model Problem



- Time-harmonic domain
- Homogeneous & isotropic medium Ω_δ
- Perfect conductors $\mathcal{B}(c_k, \delta)$, $k = 1 \dots N_{\text{obs}}$

Time-harmonic Maxwell equations

$$\begin{cases} \mathbf{curl} \mathbf{E}_\delta - i\kappa \mathbf{H}_\delta = 0 & \text{in } \Omega_\delta \\ \mathbf{curl} \mathbf{H}_\delta + i\kappa \mathbf{E}_\delta = 0 & \text{in } \Omega_\delta \end{cases}$$

$$\text{with } \kappa^2 = \omega^2 \mu (\varepsilon + \frac{i\sigma}{\omega}), \Im(\kappa) \geq 0$$

Boundary condition

$$\mathbf{n} \times \mathbf{E}_\delta = -\mathbf{n} \times \mathbf{E}^{\text{inc}} \quad \text{on } \partial\Omega_\delta$$

Silver-Müller radiation condition

$$r(\mathbf{H}_\delta \times \hat{\mathbf{x}} - \mathbf{E}_\delta) \xrightarrow[r \rightarrow \infty]{} 0 \quad \text{unif. in } \hat{\mathbf{x}} = \frac{\mathbf{x}}{r}$$

Mathematical well-posedness

For any $\mathbf{E}^{\text{inc}} \in \mathbf{H}_{\text{loc}}(\mathbf{curl}, \Omega_\delta)$ there exist a unique solution $(\mathbf{E}_\delta, \mathbf{H}_\delta) \in \mathbf{H}_{\text{loc}}(\mathbf{curl}, \Omega_\delta)^2$ to the exterior Maxwell problem.

Approaches and Objectives

- Asymptotic models



H. Ammari, M.S. Vogelius, D. Volkov (2001)

Asymptotic formulas for perturbations in the electromagnetic fields due to the presence of inhomogeneities of small diameter II. The full Maxwell equations



D.P. Challa, G. Hu, M. Sini (2013)

Multiple scattering of electromagnetic waves by finitely many point-like obstacles



D.V. Korikov, B.A. Plamenevskii (2017)

Asymptotics of solutions for stationary and nonstationary Maxwell systems in a domain with small holes

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Asymptotics of solutions for stationary and nonstationary Maxwell systems in a domain with small holes

- High-order numerical solution



[M. Ganesh, S.C. Hawkins \(2009\)](#)

A high-order algorithm for multiple electromagnetic scattering in three dimensions



[H. Barucq, J. Chabassier, H. Pham, S. Tordeux \(2017\)](#)

Numerical robustness of single-layer method with Fourier basis for multiple obstacle acoustic scattering in homogeneous media

Asymptotic models

- ✗ Restricted to small obstacles
- ✓ Low computational cost
- ✓ Meshless method

Motivations

Asymptotic models

- ✗ Restricted to small obstacles
- ✓ Low computational cost
- ✓ Meshless method

Multiple scattering



Foldy-Lax model

- ✓ Interactions taken into account
- ✓ Low computational cost
- ✓ Meshless method

Superposition
principle



Born approximation

- ✗ No interaction between the obstacles
- ✓ Low computational cost
- ✓ Meshless method

Motivations

Asymptotic models

- ✗ Restricted to small obstacles
- ✓ Low computational cost
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Superposition principle

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- ✗ No interaction between the obstacles
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Multiple scattering

Foldy-Lax model

- ✓ Interactions taken into account
- ✓ Low computational cost
- ✓ Meshless method

High-order numerical solution

- ✗ High computational cost
 - ✗ volumical methods FEM, DG, ...
 - ~ boundary element methods
- ✗ Mesh refinement
- ✓ High-order spectral method

Outline

1. Asymptotic expansions for the single electromagnetic scattering

- First terms of the asymptotics
- Numerical results

2. Multiple electromagnetic scattering by small spheres

- Born approximation
- Foldy-Lax approximation
- Preliminary numerical results

3. Conclusions and perspectives

Outline

1. Asymptotic expansions for the single electromagnetic scattering

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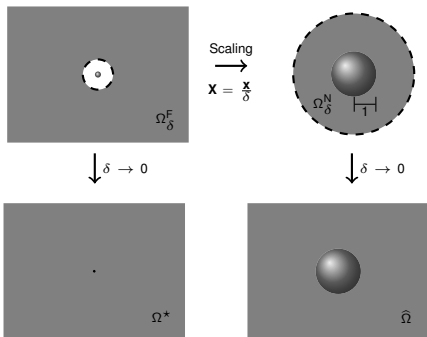
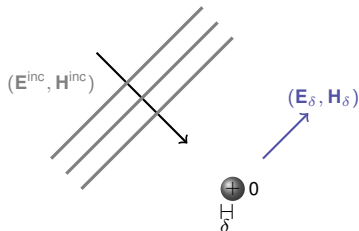
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Approximation for Single Scattering

Method of **matched asymptotic expansions**

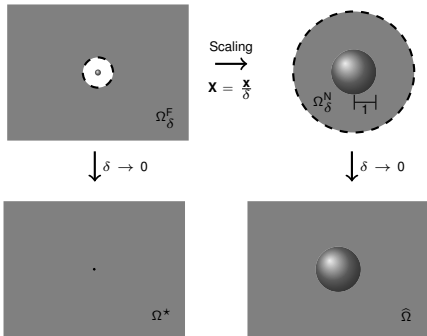
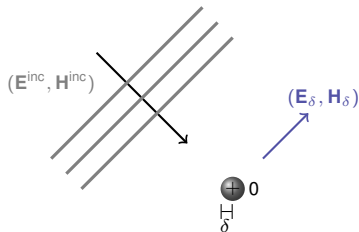
- Domain decomposition
- Local approximations
- Matching procedure



Approximation for Single Scattering

Method of **matched asymptotic expansions**

- Domain decomposition
- **Local approximations**
- Matching procedure



Asymptotic expansions

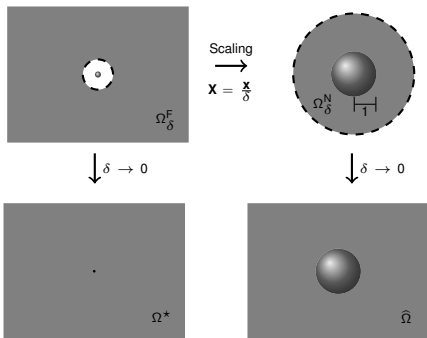
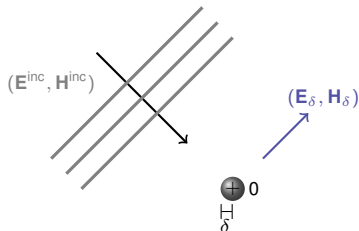
Far field expansion in $\Omega^* = \mathbb{R}^3 \setminus \{0\}$

Near field expansion in $\hat{\Omega} = \mathbb{R}^3 \setminus \overline{\mathcal{B}(0,1)}$

Approximation for Single Scattering

Method of **matched asymptotic expansions**

- Domain decomposition
- Local approximations
- **Matching procedure**



Asymptotic expansions

Far field expansion in $\Omega^* = \mathbb{R}^3 \setminus \{0\}$

Near field expansion in $\hat{\Omega} = \mathbb{R}^3 \setminus \overline{\mathcal{B}(0, 1)}$

Near field \implies Far field

Near Field Expansion

$$\mathbf{E}_\delta(\delta\mathbf{X}) = \widehat{\mathbf{E}}_0(\mathbf{X}) + \delta\widehat{\mathbf{E}}_1(\mathbf{X}) + \delta^2\widehat{\mathbf{E}}_2(\mathbf{X}) + \dots$$

0-order (static **dipole**)

$$\widehat{\mathbf{E}}_0(\mathbf{X}) = \frac{1}{|\mathbf{X}|^3} \left(3(\mathbf{e}_r \cdot \mathbf{E}^{\text{inc}}(0))\mathbf{e}_r - \mathbf{E}^{\text{inc}}(0) \right)$$

1-order (static **quadrupole** + static **dipole**)

$$\widehat{\mathbf{E}}_1(\mathbf{X}) = -\frac{1}{|\mathbf{X}|^4} \gamma_t \left(\mathbf{J}_{\text{Einc}}^{\text{sym}}(0)\mathbf{e}_r \right) + \frac{3}{2|\mathbf{X}|^4} (\mathbf{e}_r \cdot \mathbf{J}_{\text{Einc}}(0)\mathbf{e}_r)\mathbf{e}_r - \frac{i\kappa}{2|\mathbf{X}|^2} \mathbf{H}^{\text{inc}}(0) \times \mathbf{e}_r$$

with $\gamma_t \mathbf{u} = \mathbf{u} - (\mathbf{e}_r \cdot \mathbf{u})\mathbf{e}_r$ and $\mathbf{J}^{\text{sym}} = \frac{1}{2}(\mathbf{J} + \mathbf{J}^T)$ symmetric Jacobian

2-order

$$\widehat{\mathbf{E}}_2(\mathbf{X}) = \text{octupole} + \text{quadrupole} + \text{dipole}$$

Near Field Expansion

$$\mathbf{E}_\delta(\delta\mathbf{X}) = \widehat{\mathbf{E}}_0(\mathbf{X}) + \delta\widehat{\mathbf{E}}_1(\mathbf{X}) + \delta^2\widehat{\mathbf{E}}_2(\mathbf{X}) + \dots$$

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with $\gamma_t \mathbf{u} = \mathbf{u} - (\mathbf{e}_r \cdot \mathbf{u})\mathbf{e}_r$ and $\mathbf{J}^{\text{sym}} = \frac{1}{2}(\mathbf{J} + \mathbf{J}^T)$ symmetric Jacobian

2-order

$$\widehat{\mathbf{E}}_2(\mathbf{X}) = \text{**octupole**} + \text{**quadrupole**} + \text{**dipole**}$$

Far Field Expansion I

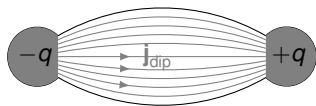
$$\mathbf{E}_\delta(\mathbf{x}) = \delta^3 \tilde{\mathbf{E}}_3(\mathbf{x}) + \delta^5 \tilde{\mathbf{E}}_5(\mathbf{x}) + \dots$$

3-order (time-harmonic **dipole**)

$$\tilde{\mathbf{E}}_3(\mathbf{x}) = -\frac{\kappa^3}{2} h_1^{(1)}(\kappa r) \mathbf{e}_r \times \mathbf{H}^{\text{inc}}(0) - \kappa^3 \tilde{h}_1^{(1)}(\kappa r) \gamma_t \mathbf{E}^{\text{inc}}(0) - 2\kappa^3 \frac{h_1^{(1)}(\kappa r)}{i\kappa r} (\mathbf{e}_r \cdot \mathbf{E}^{\text{inc}}(0)) \mathbf{e}_r$$

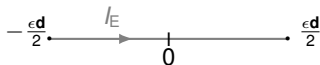
with $h_n^{(1)}$ spherical Hankel of 1st kind and $\tilde{h}_n^{(1)}(z) = \frac{h_n^{(1)}(z) + z h_n^{(1)'}(z)}{iz}$

Time-Harmonic Electromagnetic Dipole



\mathbf{j}_{dip} electric current

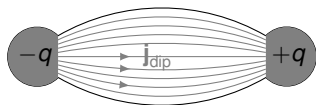
Ideal configuration



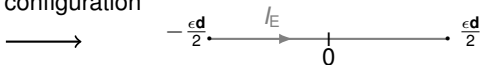
$\mathbf{d} \in \mathbb{R}^3$, ϵ small parameter

- Punctual charges with $q = \frac{1}{\epsilon}$
- Filiform current (\mathbf{d}, I_E)
- Charge conservation $I_E = -i\omega q$

Time-Harmonic Electromagnetic Dipole

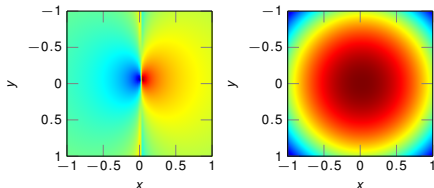


Ideal configuration



$\mathbf{d} \in \mathbb{R}^3$, ϵ small parameter

\mathbf{j}_{dip} electric current



Time-harmonic electric potential V and magnetic potential \mathbf{A} (x -component) in the xy -plane

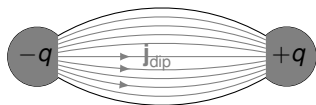
$\epsilon \rightarrow 0$

- Punctual charges with $q = \frac{1}{\epsilon}$
- Filiform current (\mathbf{d}, l_E)
- Charge conservation $l_E = -i\omega q$

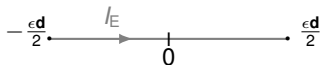
$$\mathcal{E}_{\text{dip}}^{\text{elec}}[\mathbf{d}] = -\nabla V + i\kappa \mathbf{A}$$

$$\mathcal{H}_{\text{dip}}^{\text{elec}}[\mathbf{d}] = \text{curl } \mathbf{A}$$

Time-Harmonic Electromagnetic Dipole

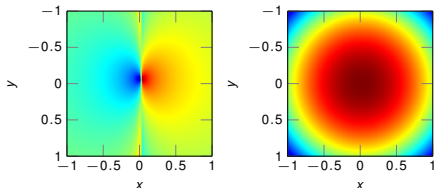


Ideal configuration



$\mathbf{d} \in \mathbb{R}^3$, ϵ small parameter

\mathbf{j}_{dip} electric current



Time-harmonic electric potential V and magnetic potential \mathbf{A} (x -component) in the xy -plane

$\epsilon \rightarrow 0$

- Punctual charges with $q = \frac{1}{\epsilon}$
- Filiform current (\mathbf{d}, I_E)
- Charge conservation $I_E = -i\omega q$

$$\boldsymbol{\mathcal{E}}_{\text{dip}}^{\text{elec}}[\mathbf{d}] = -\nabla V + i\kappa \mathbf{A}$$

$$\boldsymbol{\mathcal{H}}_{\text{dip}}^{\text{elec}}[\mathbf{d}] = \text{curl } \mathbf{A}$$

\longrightarrow

Magnetic dipole

$$\boldsymbol{\mathcal{H}}_{\text{dip}}^{\text{mag}}[\mathbf{d}] = \boldsymbol{\mathcal{E}}_{\text{dip}}^{\text{elec}}[\mathbf{d}]$$

$$\boldsymbol{\mathcal{E}}_{\text{dip}}^{\text{mag}}[\mathbf{d}] = -\boldsymbol{\mathcal{H}}_{\text{dip}}^{\text{elec}}[\mathbf{d}]$$

Far Field Expansion II

$$\mathbf{E}_\delta(\mathbf{x}) = \delta^3 \tilde{\mathbf{E}}_3(\mathbf{x}) + \delta^5 \tilde{\mathbf{E}}_5(\mathbf{x}) + \dots$$

3-order

$$\tilde{\mathbf{E}}_3 = \mathcal{E}_{\text{dip}}^{\text{elec}} [4\pi \mathbf{E}^{\text{inc}}(0)] + \mathcal{E}_{\text{dip}}^{\text{mag}} [-2\pi \mathbf{H}^{\text{inc}}(0)]$$

5-order

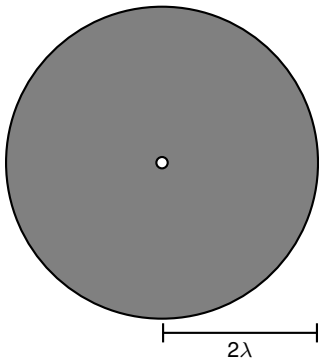
$$\tilde{\mathbf{E}}_5(\mathbf{x}) = \frac{3\kappa^2}{10} \mathcal{E}_{\text{dip}}^{\text{elec}} [4\pi \mathbf{E}^{\text{inc}}(0)](\mathbf{x}) - \frac{3\kappa^2}{5} \mathcal{E}_{\text{dip}}^{\text{mag}} [-2\pi \mathbf{H}^{\text{inc}}(0)](\mathbf{x}) + \text{time-harmonic quadrupole}$$

Collected dipolar model

$$\mathbf{E}_\delta^{\text{Col}}(\mathbf{x}) = \left(\delta^3 + \frac{3\kappa^2 \delta^5}{10} \right) \mathcal{E}_{\text{dip}}^{\text{elec}} [4\pi \mathbf{E}^{\text{inc}}(0)](\mathbf{x}) + \left(\delta^3 - \frac{3\kappa^2 \delta^5}{5} \right) \mathcal{E}_{\text{dip}}^{\text{mag}} [-2\pi \mathbf{H}^{\text{inc}}(0)](\mathbf{x})$$

Simulation Description

3D Whole domain



Small parameter

$$\delta \in \left\{ \frac{1}{10^p}, p = 0.5 : 0.1 : 4 \right\}$$

Physical parameters

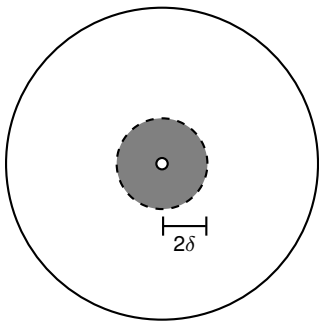
- $\varepsilon = \mu = 1.0, \sigma = 0$
- $\lambda = 5.0,$
 $\omega = \kappa = \frac{2\pi}{5.0} \approx 1.26$

Incident plane wave

- $\mathbf{E}^{\text{inc}} = \vec{p} \exp(-i\vec{k} \cdot \mathbf{x})$
- $\mathbf{H}^{\text{inc}} = \frac{1}{i\kappa} \text{curl } \mathbf{E}^{\text{inc}}$
- $\vec{p} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \vec{k} = \begin{pmatrix} 0 \\ 0 \\ \kappa \end{pmatrix}$

Simulation Description

Near field domain



Small parameter

$$\delta \in \left\{ \frac{1}{10^p}, p = 0.5 : 0.1 : 4 \right\}$$

Physical parameters

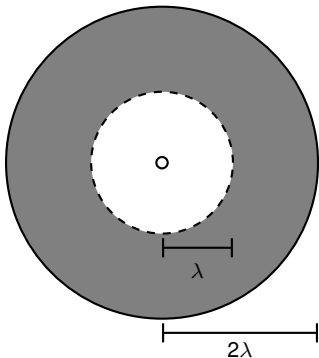
- $\varepsilon = \mu = 1.0, \quad \sigma = 0$
- $\lambda = 5.0,$
 $\omega = \kappa = \frac{2\pi}{5.0} \approx 1.26$

Incident plane wave

- $\mathbf{E}^{\text{inc}} = \vec{p} \exp(-i\vec{k} \cdot \mathbf{x})$
- $\mathbf{H}^{\text{inc}} = \frac{1}{i\kappa} \text{curl } \mathbf{E}^{\text{inc}}$
- $\vec{p} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \vec{k} = \begin{pmatrix} 0 \\ 0 \\ \kappa \end{pmatrix}$

Simulation Description

Far field domain



Small parameter

$$\delta \in \left\{ \frac{1}{10^p}, p = 0.5 : 0.1 : 4 \right\}$$

Physical parameters

- $\varepsilon = \mu = 1.0, \quad \sigma = 0$
- $\lambda = 5.0,$
 $\omega = \kappa = \frac{2\pi}{5.0} \approx 1.26$

Incident plane wave

- $\mathbf{E}^{\text{inc}} = \vec{p} \exp(-i\vec{k} \cdot \mathbf{x})$
- $\mathbf{H}^{\text{inc}} = \frac{1}{i\kappa} \text{curl } \mathbf{E}^{\text{inc}}$
- $\vec{p} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \vec{k} = \begin{pmatrix} 0 \\ 0 \\ \kappa \end{pmatrix}$

Near field approximations

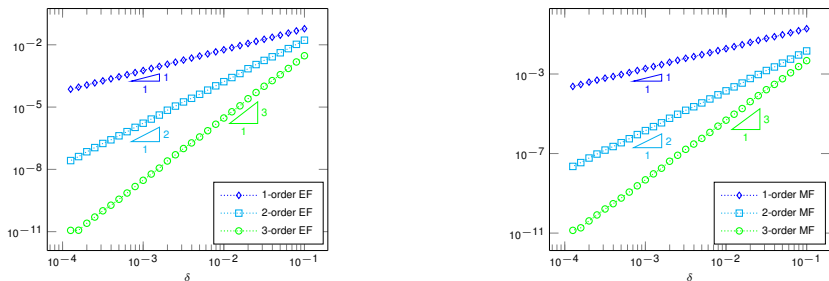
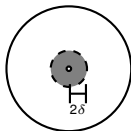


Figure: Relative $L^2(\Omega_\delta^{2\delta})$ -errors for electric near field (left) magnetic near field (right)



$$\text{1-order EF : } \|\mathbf{E}_\delta - \widehat{\mathbf{E}}_0(\frac{\cdot}{\delta})\|_{L^2(\Omega_\delta^{2\delta})} / \|\mathbf{E}_\delta\|_{L^2(\Omega_\delta^{2\delta})}$$

$$\text{2-order EF : } \|\mathbf{E}_\delta - \widehat{\mathbf{E}}_0(\frac{\cdot}{\delta}) - \delta \widehat{\mathbf{E}}_1(\frac{\cdot}{\delta})\|_{L^2(\Omega_\delta^{2\delta})} / \|\mathbf{E}_\delta\|_{L^2(\Omega_\delta^{2\delta})}$$

$$\text{3-order EF : } \|\mathbf{E}_\delta - \widehat{\mathbf{E}}_0(\frac{\cdot}{\delta}) - \delta \widehat{\mathbf{E}}_1(\frac{\cdot}{\delta}) - \delta^2 \widehat{\mathbf{E}}_2(\frac{\cdot}{\delta})\|_{L^2(\Omega_\delta^{2\delta})} / \|\mathbf{E}_\delta\|_{L^2(\Omega_\delta^{2\delta})}$$

Far field approximations

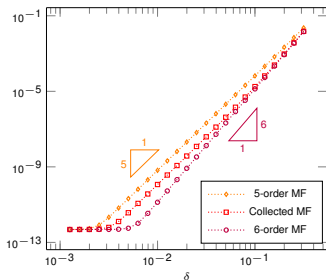
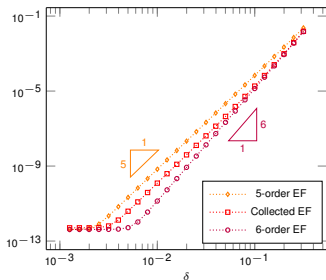
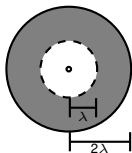


Figure: Absolute $L^2(\Omega_\lambda^{2\lambda})$ -errors for electric far field (left) magnetic far field (right)



$$\text{5-order EF : } \|\mathbf{E}_\delta - \delta^3 \tilde{\mathbf{E}}_3\|_{L^2(\Omega_\lambda^{2\lambda})}$$

$$\text{6-order EF : } \|\mathbf{E}_\delta - \delta^3 \tilde{\mathbf{E}}_3 - \delta^5 \tilde{\mathbf{E}}_5\|_{L^2(\Omega_\lambda^{2\lambda})}$$

Outline

1. Asymptotic expansions for the single electromagnetic scattering

- First terms of the asymptotics
- Numerical results

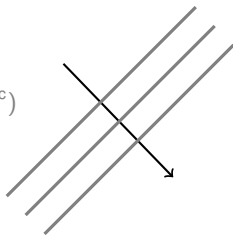
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- Foldy-Lax approximation
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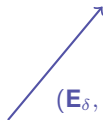
3. Conclusions and perspectives

3D-Multiple Scattering Problem by Small Spheres

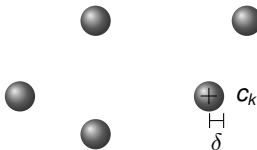
Incident field $(\mathbf{E}^{\text{inc}}, \mathbf{H}^{\text{inc}})$
with wavelength λ



$(\mathbf{E}_\delta, \mathbf{H}_\delta)$ Scattered field



Exterior domain $\Omega_\delta \subset \mathbb{R}^3$



$$\Omega_\delta = \mathbb{R}^3 \setminus \bigcup_{k=1}^{N_{\text{obs}}} \overline{\mathcal{B}(c_k, \delta)}$$

Born Approximation

$$\mathbf{E}_{\delta}^{\text{Born}}(\mathbf{x}) = \sum_{k=1}^{N_{\text{obs}}} \mathbf{E}_{\delta,k}(\mathbf{x})$$

$$\mathbf{H}_{\delta}^{\text{Born}}(\mathbf{x}) = \sum_{k=1}^{N_{\text{obs}}} \mathbf{H}_{\delta,k}(\mathbf{x})$$

- Each obstacle is modeled as a **dipolar source** around c_k

$$\mathbf{E}_{\delta,k}(\mathbf{x}) = \mathcal{E}_{\text{dip}}^{\text{elec}}[\mathbf{d}_{\delta,k}^{\text{E}}](\mathbf{x} - c_k) + \mathcal{E}_{\text{dip}}^{\text{mag}}[\mathbf{d}_{\delta,k}^{\text{H}}](\mathbf{x} - c_k)$$

$$\mathbf{H}_{\delta,k}(\mathbf{x}) = \mathcal{H}_{\text{dip}}^{\text{elec}}[\mathbf{d}_{\delta,k}^{\text{E}}](\mathbf{x} - c_k) + \mathcal{H}_{\text{dip}}^{\text{mag}}[\mathbf{d}_{\delta,k}^{\text{H}}](\mathbf{x} - c_k)$$

- The directions $\mathbf{d}_{\delta,k}^{\text{E}}$ and $\mathbf{d}_{\delta,k}^{\text{H}}$ depend on the **nature** of the obstacles

Born Approximation

$$\mathbf{E}_\delta^{\text{Born}}(\mathbf{x}) = \sum_{k=1}^{N_{\text{obs}}} \mathbf{E}_{\delta,k}(\mathbf{x})$$

$$\mathbf{H}_\delta^{\text{Born}}(\mathbf{x}) = \sum_{k=1}^{N_{\text{obs}}} \mathbf{H}_{\delta,k}(\mathbf{x})$$

- Each obstacle is modeled as a **dipolar source** around c_k

$$\mathbf{E}_{\delta,k}(\mathbf{x}) = \mathcal{E}_{\text{dip}}^{\text{elec}}[\mathbf{d}_{\delta,k}^{\text{E}}](\mathbf{x} - c_k) + \mathcal{E}_{\text{dip}}^{\text{mag}}[\mathbf{d}_{\delta,k}^{\text{H}}](\mathbf{x} - c_k)$$

$$\mathbf{H}_{\delta,k}(\mathbf{x}) = \mathcal{H}_{\text{dip}}^{\text{elec}}[\mathbf{d}_{\delta,k}^{\text{E}}](\mathbf{x} - c_k) + \mathcal{H}_{\text{dip}}^{\text{mag}}[\mathbf{d}_{\delta,k}^{\text{H}}](\mathbf{x} - c_k)$$

- The directions $\mathbf{d}_{\delta,k}^{\text{E}}$ and $\mathbf{d}_{\delta,k}^{\text{H}}$ depend on the **nature** of the obstacles

Case of perfectly conducting spheres

- 3-order approximation

$$\mathbf{d}_{\delta,k}^{\text{E}} = 4\pi\delta^3 \mathbf{E}^{\text{inc}}(c_k) \quad \mathbf{d}_{\delta,k}^{\text{H}} = -2\pi\delta^3 \mathbf{H}^{\text{inc}}(c_k)$$

- Corrected dipolar approximation

$$\mathbf{d}_{\delta,k}^{\text{E}} = 4\pi\delta^3 \left(1 + \frac{3(\kappa\delta)^2}{10}\right) \mathbf{E}^{\text{inc}}(c_k)$$

$$\mathbf{d}_{\delta,k}^{\text{H}} = -2\pi\delta^3 \left(1 - \frac{3(\kappa\delta)^2}{5}\right) \mathbf{H}^{\text{inc}}(c_k)$$

Important restrictions

- Very small obstacles
- Small number of obstacles
- No interaction taken into account

Foldy-Lax Approximation

$$\mathbf{E}_\delta^{\text{Foldy}}(\mathbf{x}) = \sum_{k=1}^{N_{\text{obs}}} \mathbf{E}_{\delta,k}(\mathbf{x})$$

$$\mathbf{H}_\delta^{\text{Foldy}}(\mathbf{x}) = \sum_{k=1}^{N_{\text{obs}}} \mathbf{H}_{\delta,k}(\mathbf{x})$$

- Each obstacle is modeled as a **dipolar source** around c_k

$$\mathbf{E}_{\delta,k}(\mathbf{x}) = \boldsymbol{\varepsilon}_{\text{dip}}^{\text{elec}} [\mathbf{d}_{\delta,k}^{\text{E}}](\mathbf{x} - c_k) + \boldsymbol{\varepsilon}_{\text{dip}}^{\text{mag}} [\mathbf{d}_{\delta,k}^{\text{H}}](\mathbf{x} - c_k)$$

$$\mathbf{H}_{\delta,k}(\mathbf{x}) = \boldsymbol{\mathcal{H}}_{\text{dip}}^{\text{elec}} [\mathbf{d}_{\delta,k}^{\text{E}}](\mathbf{x} - c_k) + \boldsymbol{\mathcal{H}}_{\text{dip}}^{\text{mag}} [\mathbf{d}_{\delta,k}^{\text{H}}](\mathbf{x} - c_k)$$

Case of perfectly conducting spheres

- 3-order approximation

$$\mathbf{d}_{\delta,k}^{\text{E}} = 4\pi\delta^3 \left(\mathbf{E}^{\text{inc}}(c_k) + \sum_{\substack{\ell=1 \\ \ell \neq k}}^{N_{\text{obs}}} \mathbf{E}_{\delta,\ell}(c_k) \right) \quad \mathbf{d}_{\delta,k}^{\text{H}} = -2\pi\delta^3 \left(\mathbf{H}^{\text{inc}}(c_k) + \sum_{\substack{\ell=1 \\ \ell \neq k}}^{N_{\text{obs}}} \mathbf{H}_{\delta,\ell}(c_k) \right)$$

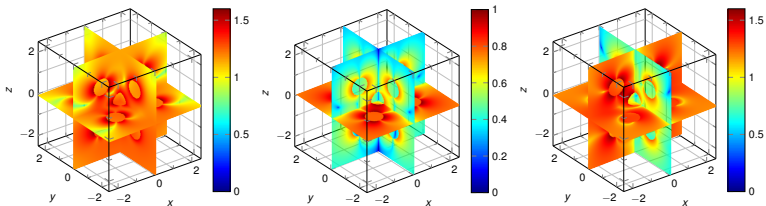
- Corrected dipolar approximation

$$\mathbf{d}_{\delta,k}^{\text{E}} = 4\pi\delta^3 \left(1 + \frac{3(\kappa\delta)^2}{10} \right) \left(\mathbf{E}^{\text{inc}}(c_k) + \sum_{\substack{\ell=1 \\ \ell \neq k}}^{N_{\text{obs}}} \mathbf{E}_{\delta,\ell}(c_k) \right) \quad \mathbf{d}_{\delta,k}^{\text{H}} = -2\pi\delta^3 \left(1 - \frac{3(\kappa\delta)^2}{5} \right) \left(\mathbf{H}^{\text{inc}}(c_k) + \sum_{\substack{\ell=1 \\ \ell \neq k}}^{N_{\text{obs}}} \mathbf{H}_{\delta,\ell}(c_k) \right)$$

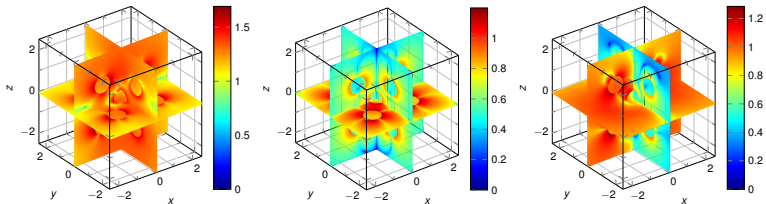
First Numerical Results

13 obstacles ; $d_{jk} \approx 1.0$; $\delta = 0.4$

Born approximation



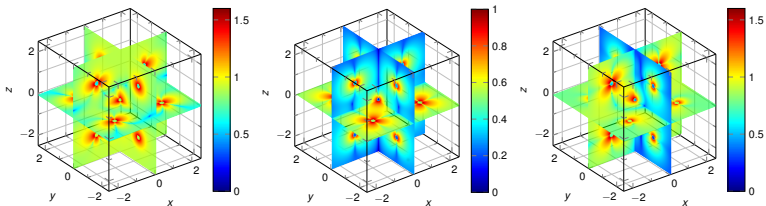
Foldy-Lax approximation



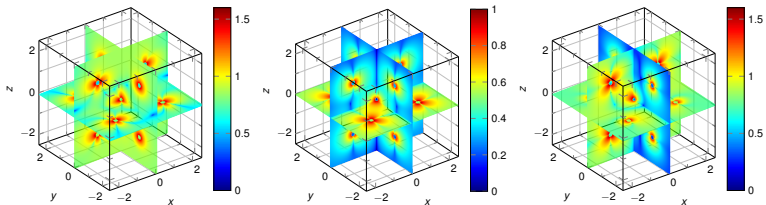
First Numerical Results

13 obstacles ; $d_{jk} \approx 1.25$; $\delta = 0.1$

Born approximation



Foldy-Lax approximation



Outline

1. Asymptotic expansions for the single electromagnetic scattering

- First terms of the asymptotics
- Numerical results

2. Multiple electromagnetic scattering by small spheres

- Born approximation
- Foldy-Lax approximation
- Preliminary numerical results

3. Conclusions and perspectives

Conclusions and Perspectives

Conclusions and on-going works

- Single scattering
 - ✓ Derivation of first terms of asymptotics for one sphere
 - ✓ Numerical validation



J. Labat, V. Péron, S. Tordeux (Inria Research Report n°9169, 2018)

Asymptotic Modeling of the Electromagnetic Scattering by Small Spheres Perfectly Conducting.

- Multiple scattering
 - ✓ Born approximation
 - ✓ Foldy-Lax approximation
 - ~ Numerical validation of Born and Foldy-Lax models with **finite element solutions**
 - ~ High-order spectral method

Perspectives

- Single scattering
 - ✗ Justification of matched asymptotic expansions
 - ✗ Extension to obstacles of arbitrary shape
- Multiple scattering
 - ✗ Justification of Foldy-Lax approximation
 - ✗ Justification of the high-order spectral method