FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF INFORMATION TECHNOLOGY
RESEARCH GROUP ELECTROMAGNETICS

COMPARISON OF TWO NOVEL INTEGRAL EQUATION APPROACHES FOR LOSSY CONDUCTOR MODELING

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OUTLINE

- Motivation
- Calderón preconditioned HDC method
- 3-D differential surface admittance operator
- Examples
- Conclusions

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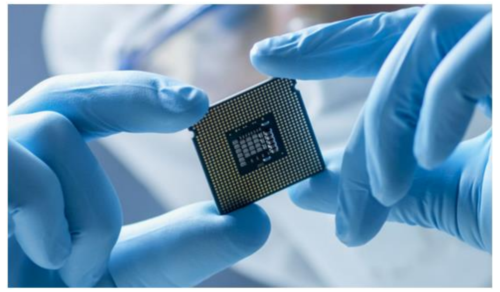
MOTIVATION

Industries



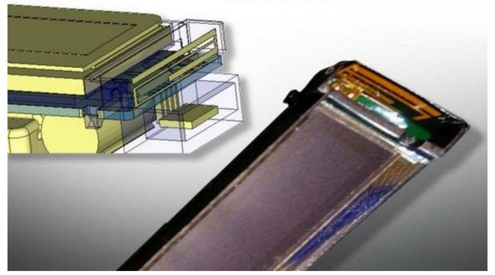
Semiconductors

5G to IoT

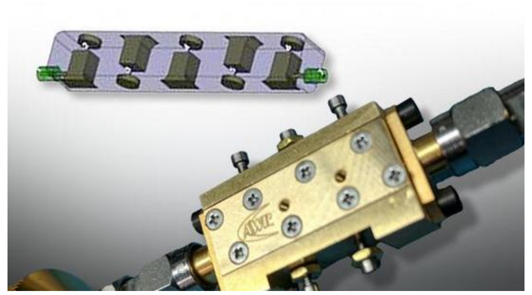
Automotive

Aerospace and Defense

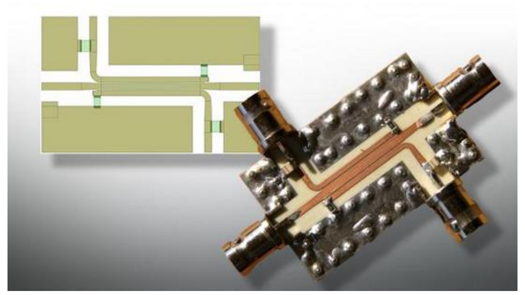
Devices & Components



Antennas

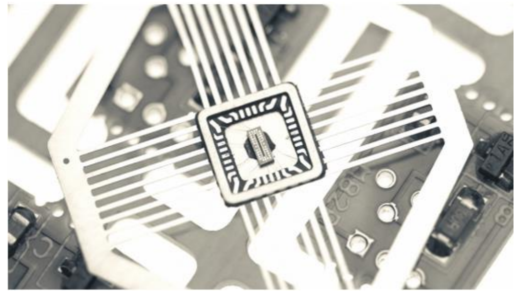


Filters

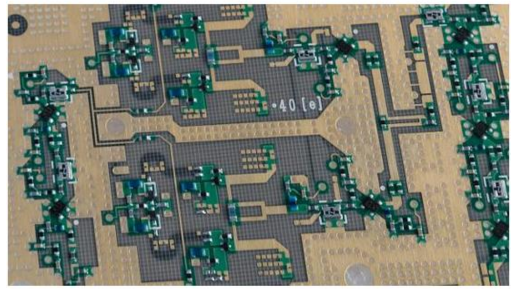


Passive components

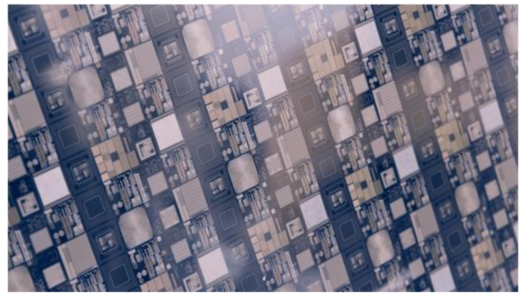
Technologies



MMICs



RF PCBs



Next generation ICs

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MOTIVATION

Industries

onduct

5G to IoT

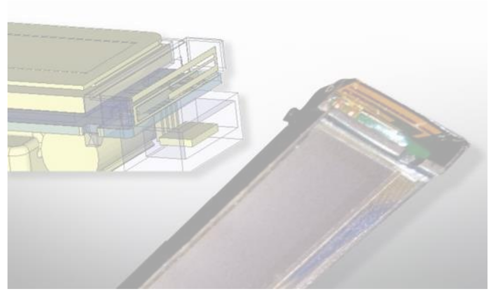
Aerospace and De

Smarter

Smaller

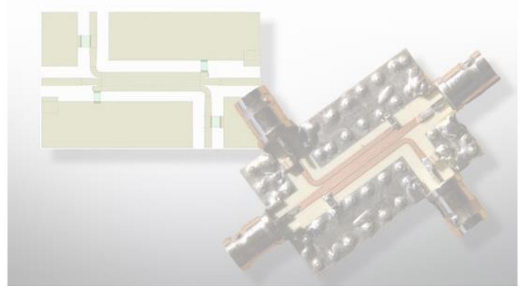
Faster

Devices & Components



Antennas

Filters



Passive components

Technologies

Increasing need for accurate simulations

Next generation ICs

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BOUNDARY INTEGRAL EQUATIONS

Calderón preconditioned PMCHWT Method	
Only surface discretization	Dense system matrix
Automatic inclusion radiation condition	~~Low-frequency & dense-mesh breakdown~~
Scalable through MLFMM	Difficulty numerical computation for lossy conductors

But for materials with a high dielectric contrast (HDC), e.g. good conductors, conditioning problems return

Calderón preconditioned PMCHWT Method for HDC materials	
Only surface discretization	Dense system matrix
Automatic inclusion radiation condition	Low-frequency & dense-mesh breakdown
Scalable through MLFMM	Difficulty numerical computation for lossy conductors

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THIS WORK

- Two single-source boundary integral equation (BIE) solutions that both focus on one crucial aspect:
  - Method 1: A Calderón preconditioned (CP) BIE that does not break down in the presence of HDC materials
  - Method 2: A 3-D differential surface admittance (DSA) operator that tackles the difficulty of numerically integrating the Green's function inside highly conductive dielectrics.

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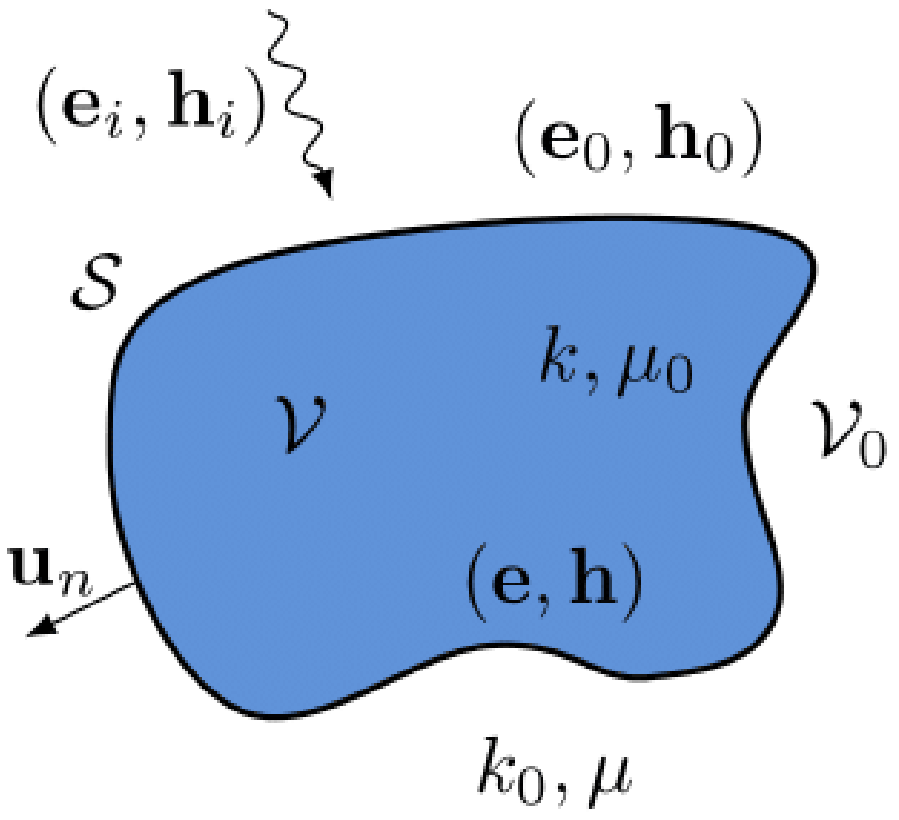
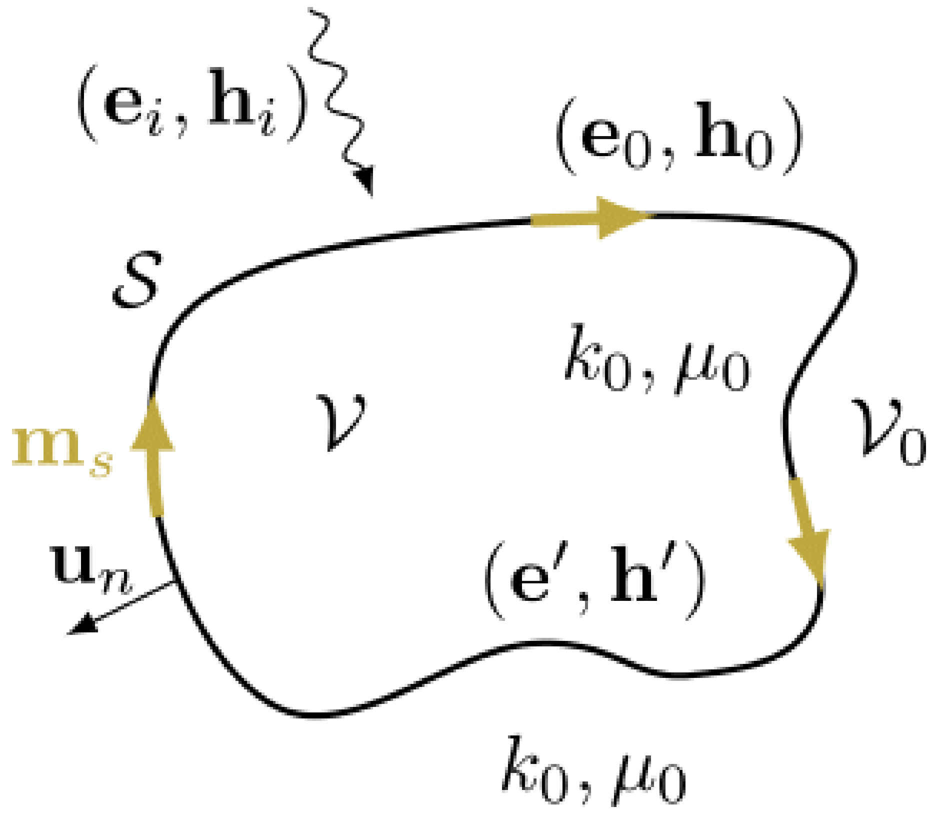
CALDERÓN PRECONDITIONER FOR HDC MEDIA



Field equivalence



On the boundary $\mathcal{S}$:

$$(\mathcal{K}_0 + \frac{1}{2})\mathbf{m}_s + \mathbf{u}_n \times \mathbf{e} = \mathbf{u}_n \times \mathbf{e}_i$$

$$\frac{1}{\eta_0}\mathcal{T}_0\mathbf{m}_s - \mathbf{u}_n \times \mathbf{h} = -\mathbf{u}_n \times \mathbf{h}_i$$

$\mathcal{K}_0$ = Magnetic field integral operator in $\mathcal{V}_0$

$\mathcal{T}_0$ = Electric field integral operator in $\mathcal{V}_0$

η_0 = Impedance of background medium

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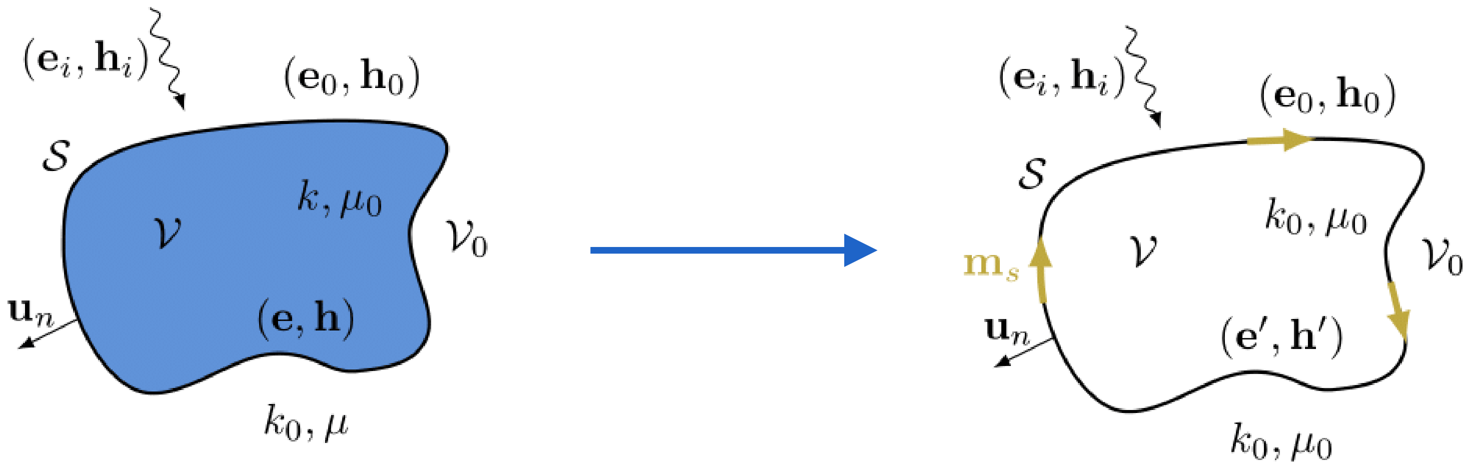
CALDERÓN PRECONDITIONER FOR HDC MEDIA

Introduction of the Poincaré-Steklov operator, results in a solvable system by eliminating $\mathbf{u}_n \times \mathbf{h}$:

$$\mathcal{P}\left(\mathbf{u}_n \times \mathbf{e}\right) = \mathbf{u}_n \times \mathbf{h}$$



$$(\mathcal{K}_0 + \frac{1}{2})\mathbf{m}_s + \mathbf{u}_n \times \mathbf{e} = \mathbf{u}_n \times \mathbf{e}_i$$

$$\frac{1}{\eta_0}\mathcal{T}_0\mathbf{m}_s - \mathcal{P}\left(\mathbf{u}_n \times \mathbf{e}\right) = -\mathbf{u}_n \times \mathbf{h}_i$$

$$\mathcal{P} = -\frac{1}{\eta}\mathcal{T}^{-1}\left(\mathcal{K} + \frac{1}{2}\right)$$

$\mathcal{K} =$ Magnetic field integral operator in $\mathcal{V}$

$\mathcal{T} =$ Electric field integral operator in $\mathcal{V}$

$\eta =$ Impedance of original medium

$\mathcal{P} =$ Poincaré-Steklov operator of the original medium

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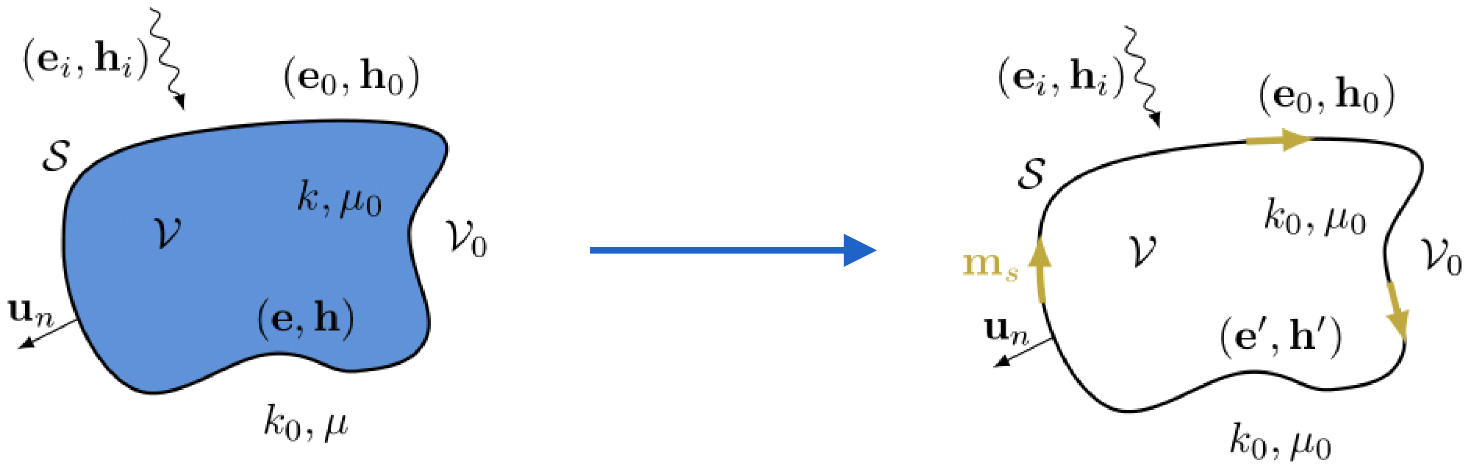
CALDERÓN PRECONDITIONER FOR HDC MEDIA

$$\begin{pmatrix} \mathcal{K}_0 + \frac{1}{2} & -1 \\ \frac{\mathcal{T}_0}{\eta_0} & \mathcal{P} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{m}_s \\ -\mathbf{u}_n \times \mathbf{e} \end{pmatrix} = \begin{pmatrix} \mathbf{u}_n \times \mathbf{e}_i \\ -\mathbf{u}_n \times \mathbf{h}_i \end{pmatrix}$$



Introduction Calderón preconditioner (CP):

- Eliminates ill-conditioning
- Avoids calculation $\mathcal{T}^{-1}$ in Poincaré-Steklov operator

$$\begin{pmatrix} 1 & 0 \\ 0 & -\eta\mathcal{T} \end{pmatrix}$$

$$\begin{pmatrix} \mathcal{K}_0 + \frac{1}{2} & -1 \\ -\frac{\eta}{\eta_0}\mathcal{T}\mathcal{T}_0 & \mathcal{K} + \frac{1}{2} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{m}_s \\ -\mathbf{u}_n \times \mathbf{e} \end{pmatrix} = \begin{pmatrix} \mathbf{u}_n \times \mathbf{e}_i \\ \eta\mathcal{T}\left(\mathbf{u}_n \times \mathbf{h}_i\right) \end{pmatrix}$$

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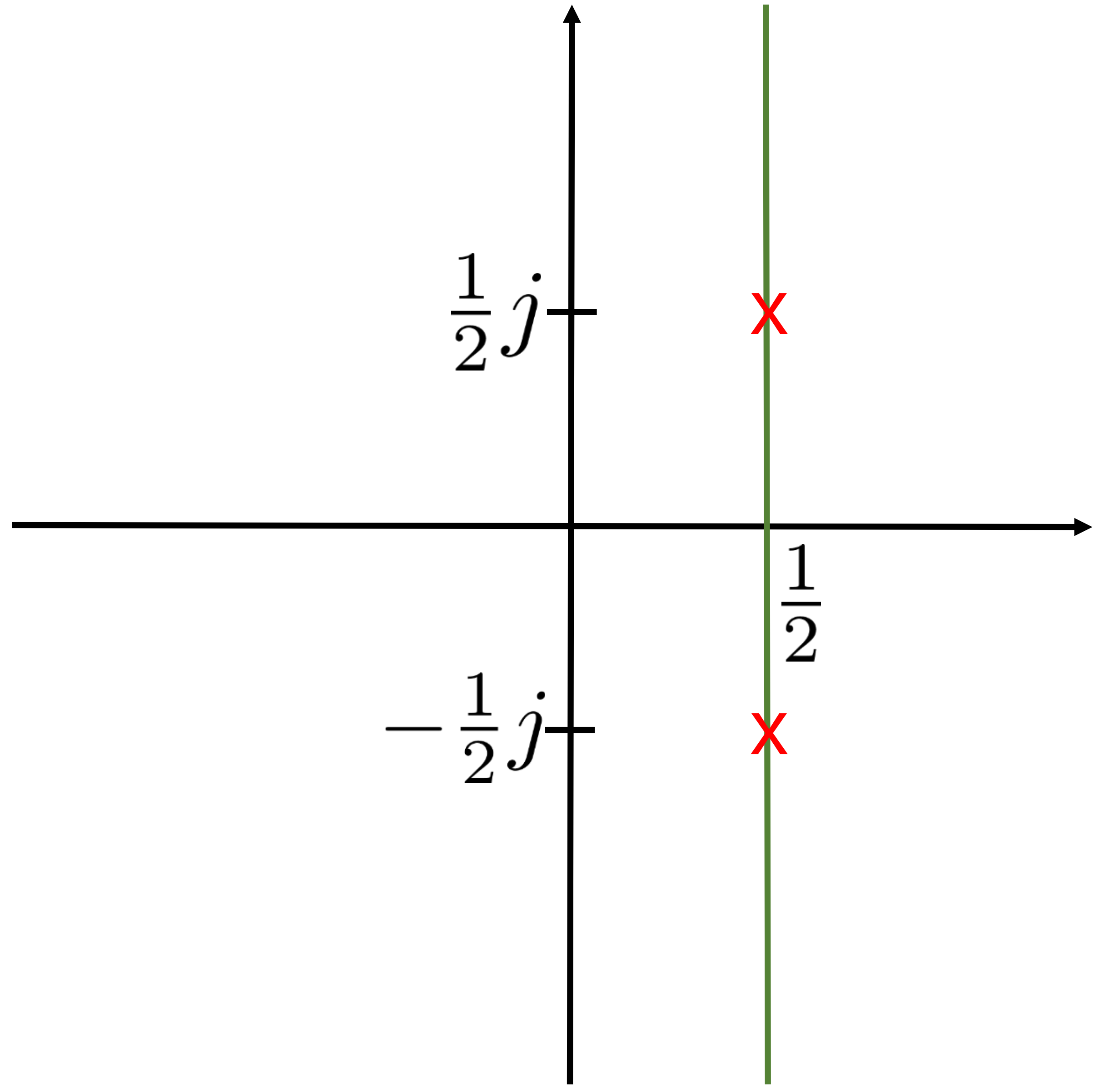
SPECTRAL PROPERTIES

Eigenvalue accumulation points:

$$\lambda = \frac{1}{2} \pm \frac{1}{2}\sqrt{\frac{\epsilon_0}{\epsilon}}\,j$$

$$\lambda = \frac{1}{2} \pm \frac{1}{2}\sqrt{\frac{\mu}{\mu_0}}\,j$$



$\mathcal{V}_0 =$ vacuum: $\epsilon_{r,0} = 1$

$\mathcal{V} =$ vacuum: $\epsilon_r = 1$

✔ conditioning $\sim \frac{\lambda_{max}}{\lambda_{min}}$

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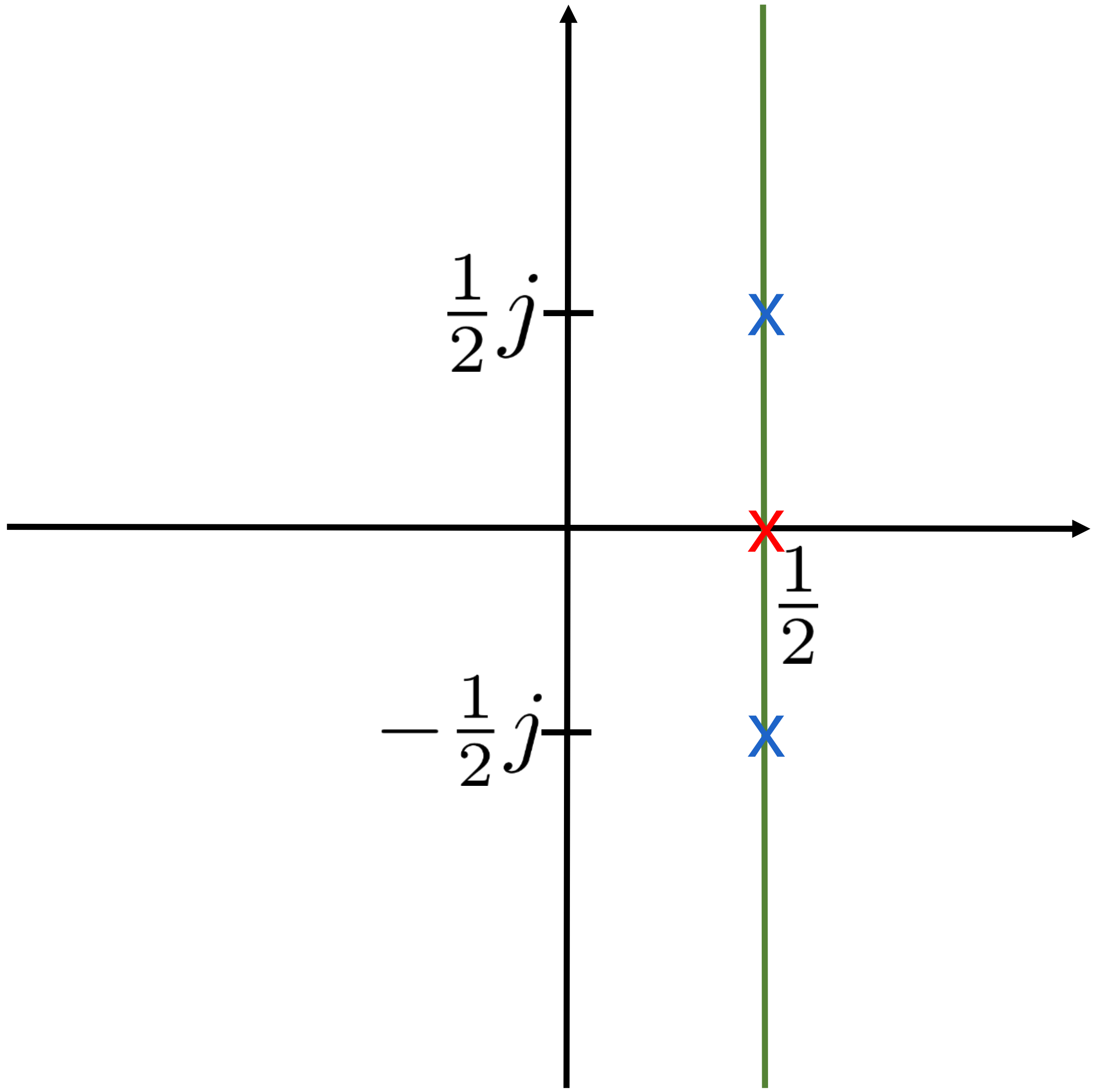
SPECTRAL PROPERTIES

Eigenvalue accumulation points:

$$\lambda = \frac{1}{2} \pm \frac{1}{2}\sqrt{\frac{\epsilon_0}{\epsilon}}j$$

$$\lambda = \frac{1}{2} \pm \frac{1}{2}\sqrt{\frac{\mu}{\mu_0}}j$$



$\mathcal{V}_0 =$ vacuum: $\epsilon_{r,0} = 1$

$\mathcal{V} =$ copper: $|\epsilon_r| >> 1$

conditioning $\sim \frac{\lambda_{max}}{\lambda_{min}}$

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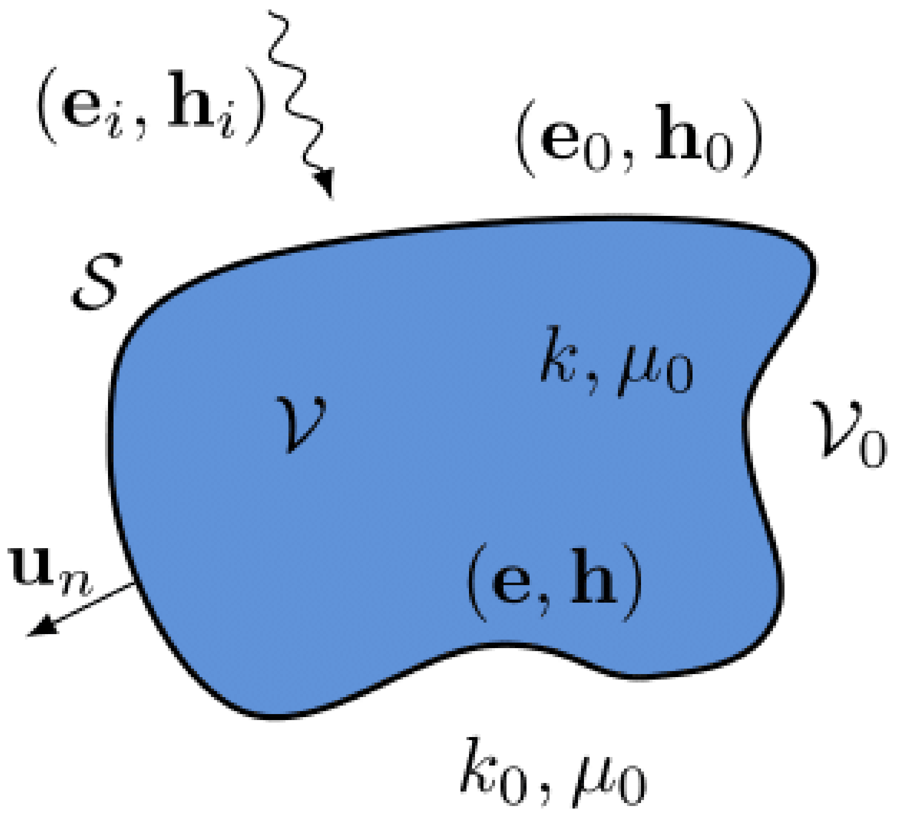
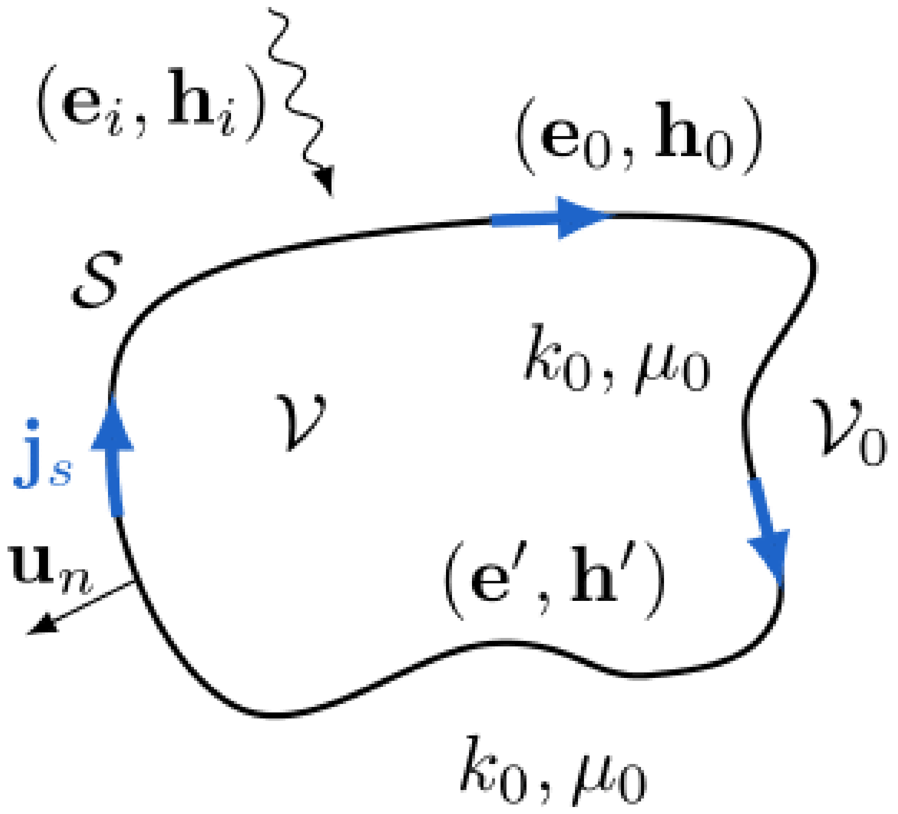
3-D DIFFERENTIAL SURFACE ADMITTANCE OPERATOR



Field equivalence



On the boundary $\mathcal{S}$:

$$\mathcal{P}\left(\mathbf{u}_n \times \mathbf{e}\right) = \mathbf{u}_n \times \mathbf{h}$$

$\mathcal{P} =$ Poincaré-Steklov operator of the original medium

On the boundary $\mathcal{S}$:

$$\mathcal{P}_0\left(\mathbf{u}_n \times \mathbf{e}'\right) = \mathbf{u}_n \times \mathbf{h}'$$

$\mathcal{P}_0 =$ Poincaré-Steklov operator of the background medium

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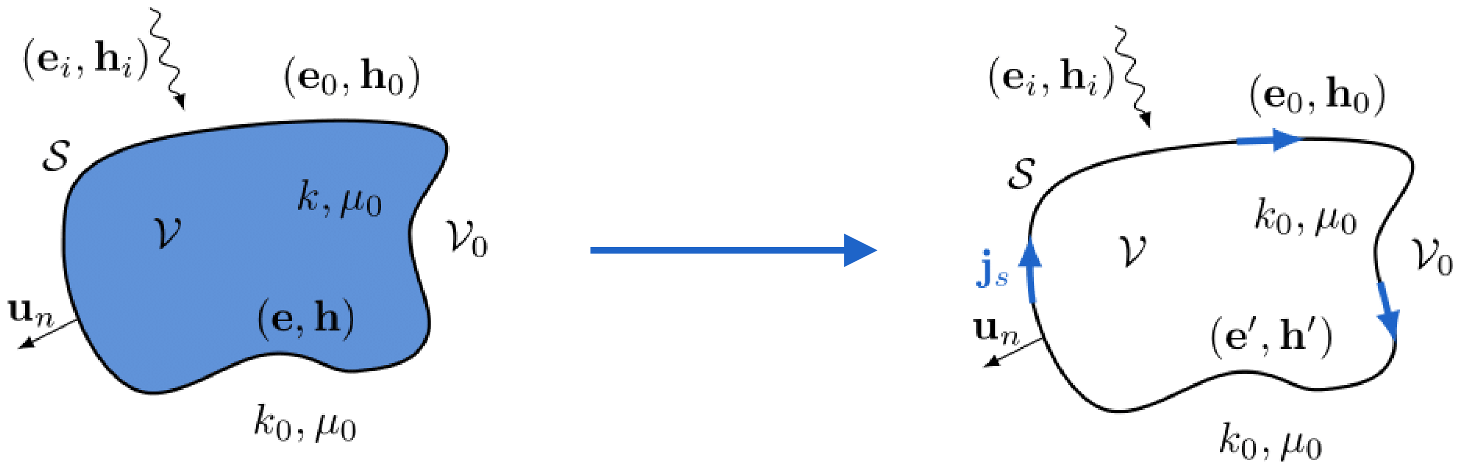
3-D DIFFERENTIAL SURFACE ADMITTANCE OPERATOR

Through the boundary conditions in both situations, both PS operators can be combined to:



$$\mathbf{j}_s = (\mathcal{P} - \mathcal{P}_0)\,(\mathbf{u}_n \times \mathbf{e}) = \mathcal{Y}\,(\mathbf{u}_n \times \mathbf{e})$$

The electric field integral equation (EFIE) completes the system of equations

$$\eta_0 \mathcal{T} \mathbf{j}_s + \mathbf{u}_n \times \mathbf{e} = \mathbf{u}_n \times \mathbf{e}_i$$

$\mathcal{Y}$ could be computed directly, but the computation of $\mathcal{P}$ involves bothersome numerical integrals ⊗

Novel alternative method that avoids these integrals… ✓

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$\mathcal{Y} =$ Differential surface admittance operator

3-D DIFFERENTIAL SURFACE ADMITTANCE OPERATOR

$$\mathcal{Y}[\mathbf{x}] = \eta \sum_{\nu} \frac{\mathcal{K}_\nu}{\mathcal{N}_\nu^2} \left[\int_{\mathcal{S}} (\mathbf{u}_n \times \mathbf{h}_{mnp}) \cdot \mathbf{x} \, \mathrm{d}S \right] (\mathbf{u}_n \times \mathbf{h}_{mnp})$$

η: $(k^2 - k_0^2)/j\omega\mu_0$

$\mathcal{K}_\nu / \mathcal{N}_\nu^2$: Normalization constant

$\mathbf{u}_n \times \mathbf{h}_{mnp}$: Magnetic eigenmodes

- ✓ Valid for all materials (including good conductors) over a broad frequency range
- ✓ Does not rely on the Green's function in the medium
  $\Rightarrow$ integrals are material independent
- ✗ Requires eigenmodes of the volume $\mathcal{V}$
  $\Rightarrow \mathcal{V}$ should be a canonical shape

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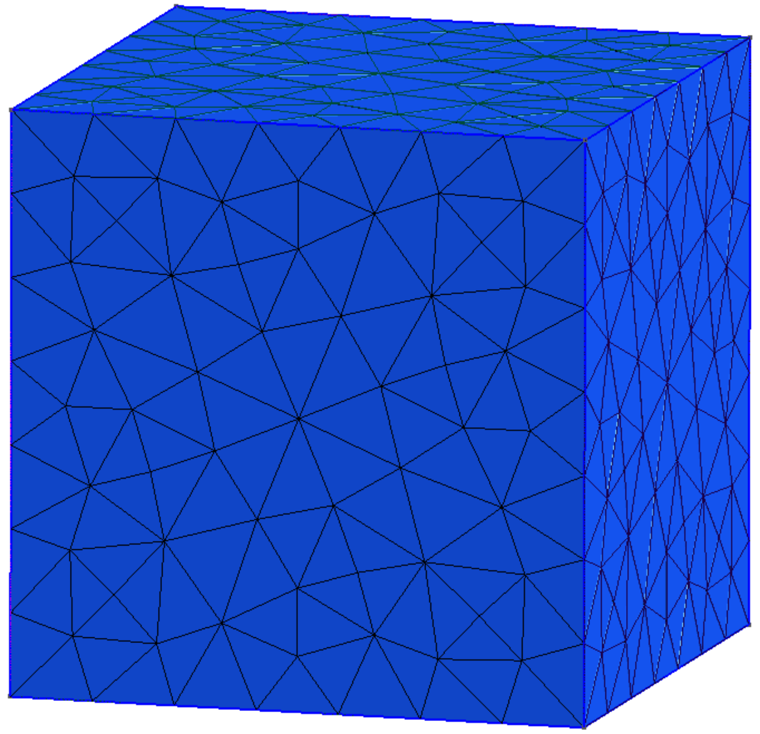
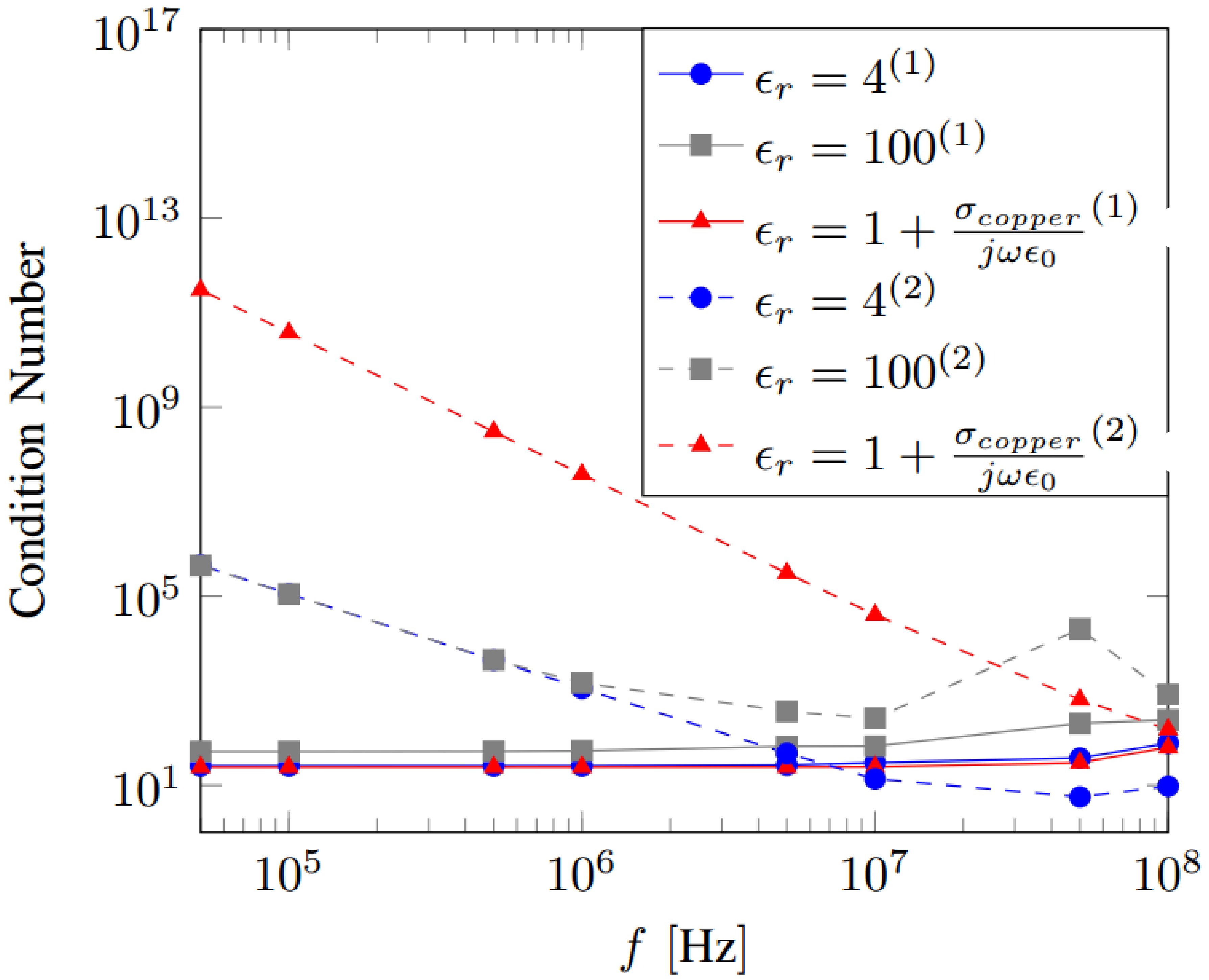
VALIDATION METHOD 1



Side = 2 m



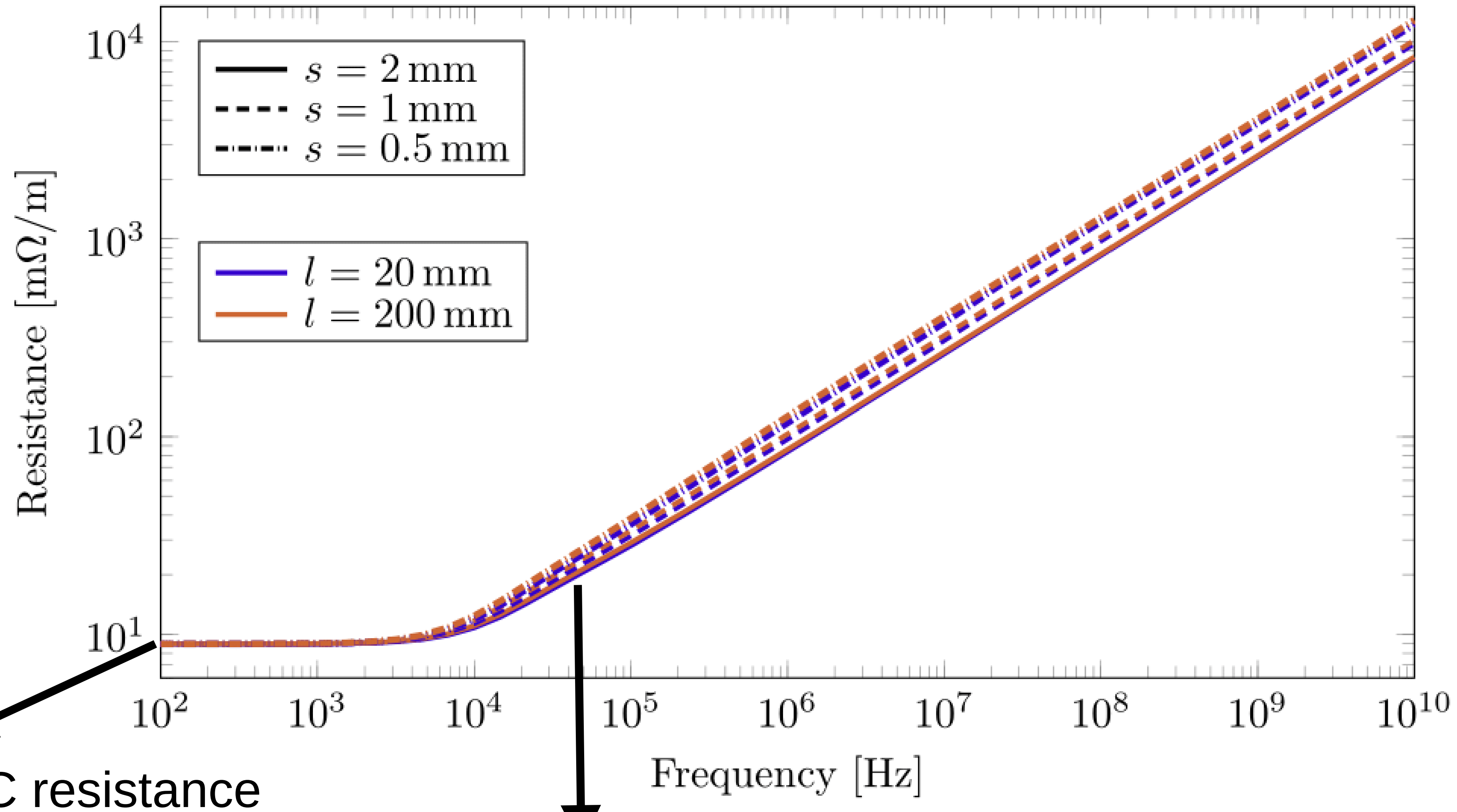
Low frequency breakdown does not occur: Condition number converges for decreasing frequency

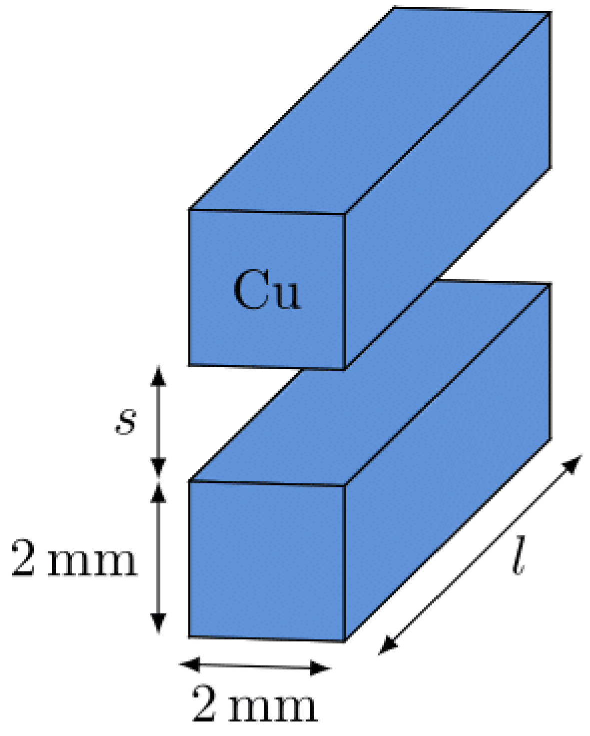
Full line = method 1

Dashed line = CP-PMCHWT

VALIDATION METHOD 2 (1)

Normalized resistance = total resistance (3-D) / length





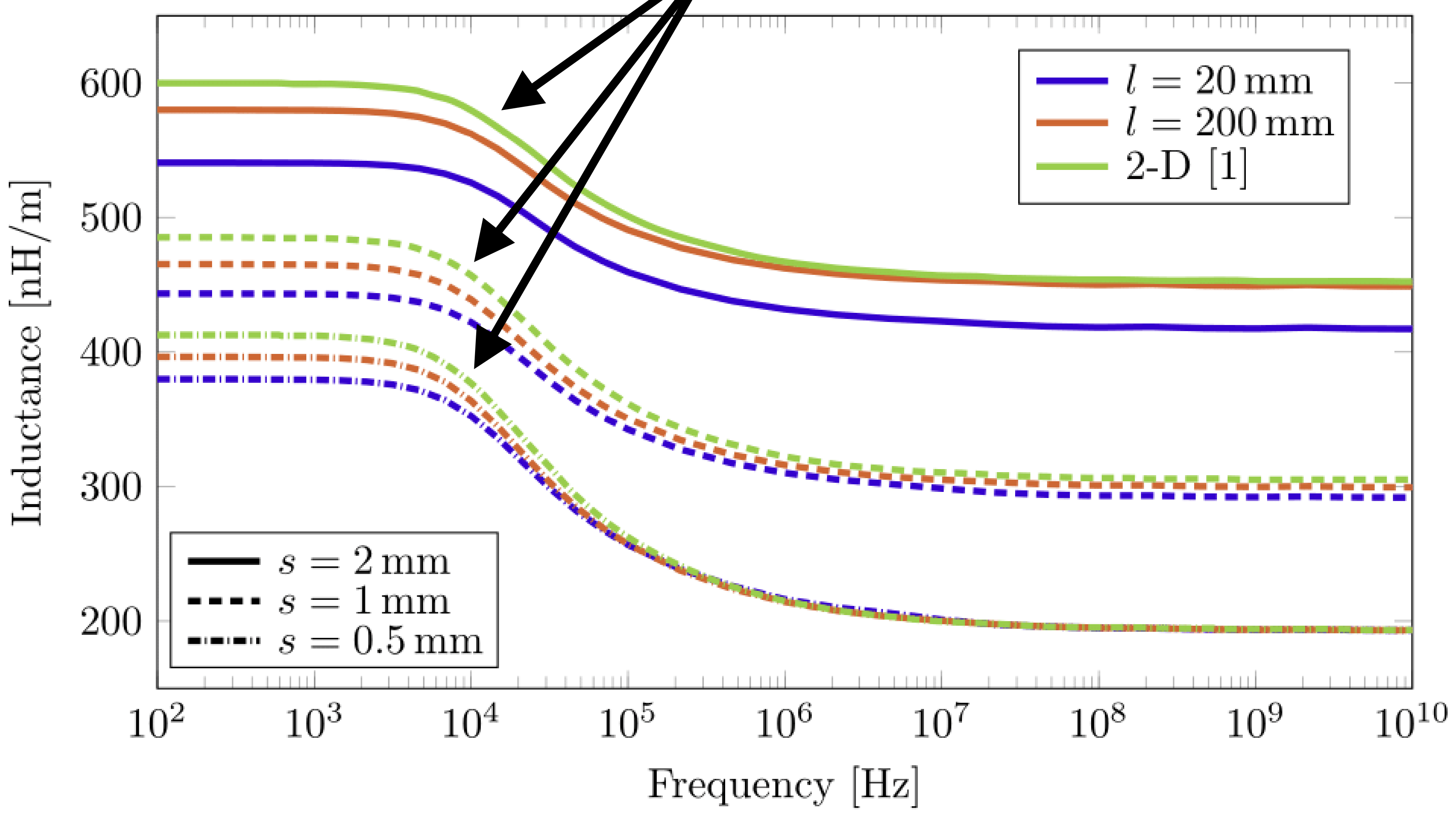
Pouillet DC resistance

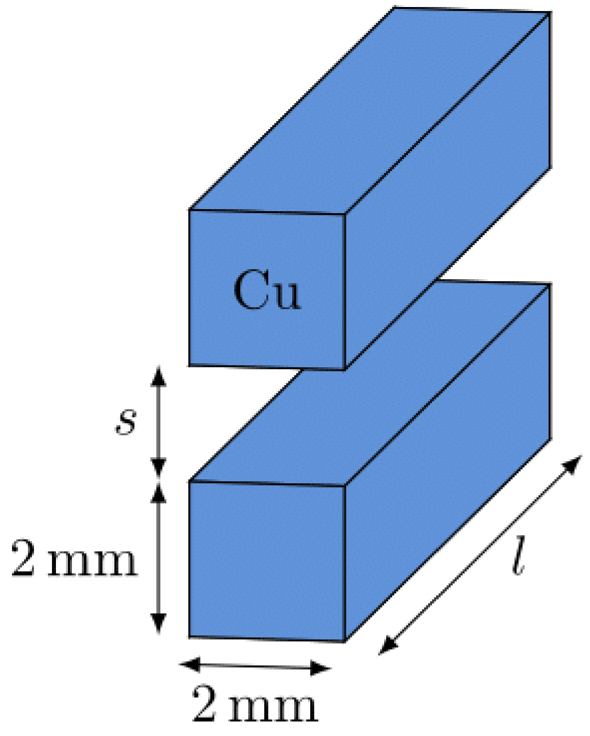
Proximity effect → fan out

VALIDATION METHOD 2 (2)

Normalized inductance

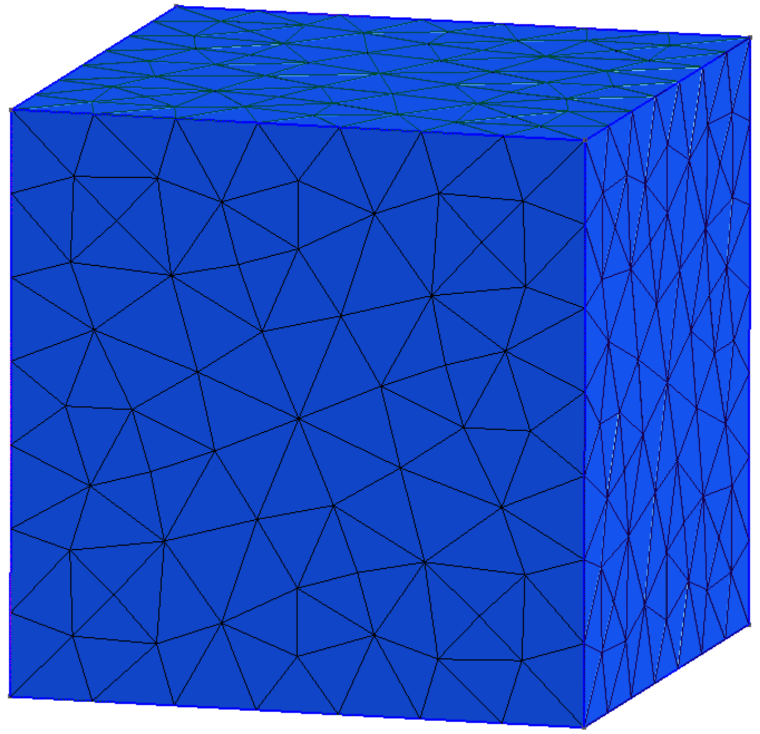
Increasing length → 2-D results



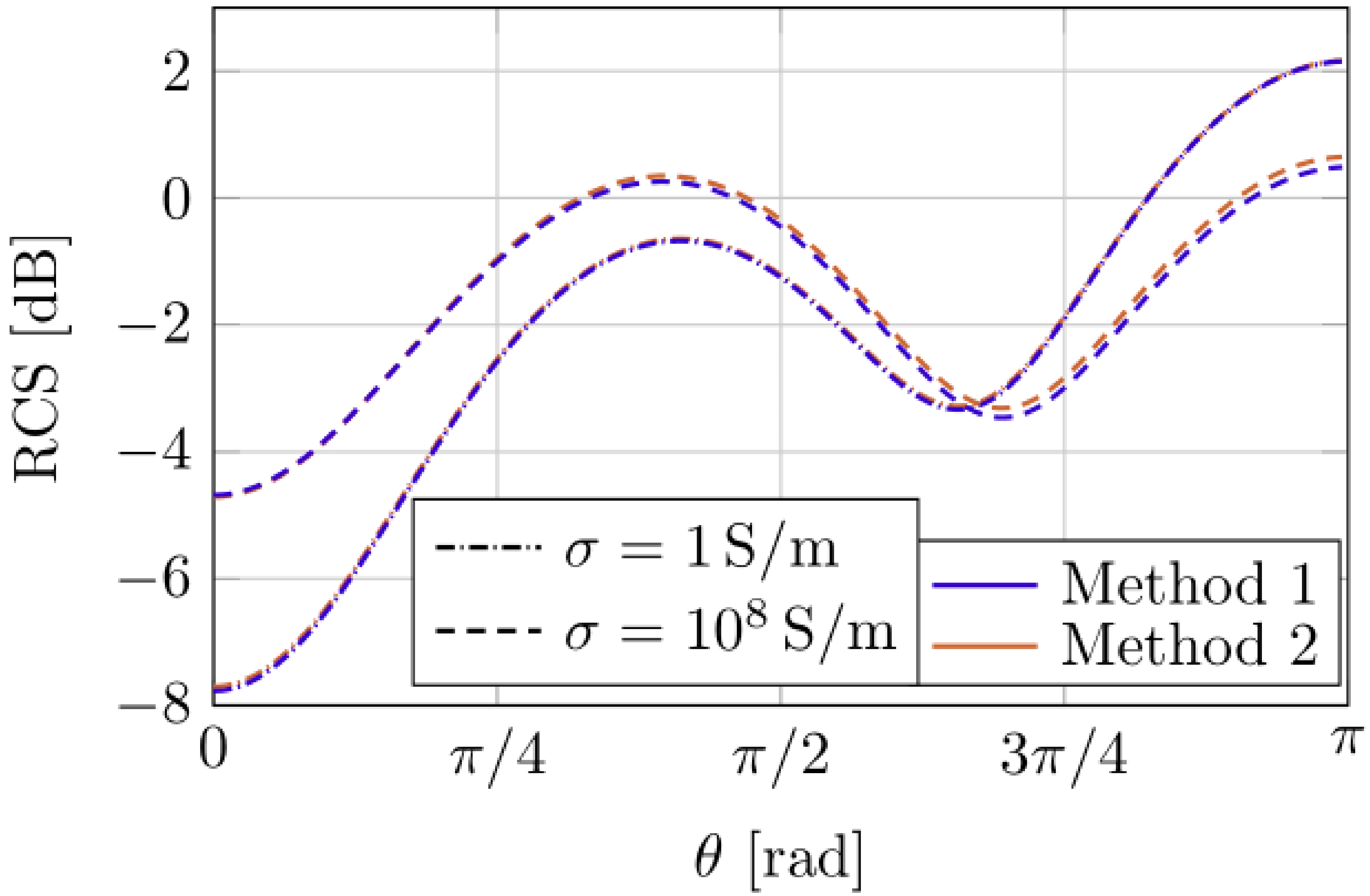


[1] D. De Zutter and L. Knockaert, IEEE MTT, vol. 53, pp. 2526-2538 (2005)

COMPARISON METHOD 1 & 2: CUBE SCATTERING



Side = 0.5 m   Frequency = 200 MHz



mesh elements:

Method 1: 936 (generated triangular mesh)

Method 2: 432 (structured rectangular mesh)

Very good agreement between both methods

Small deviation due to course mesh

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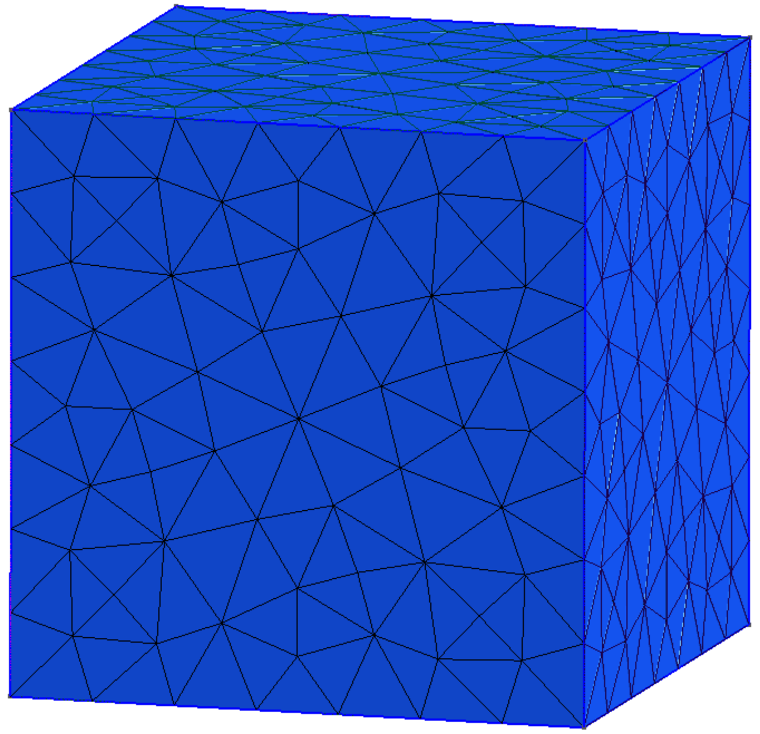
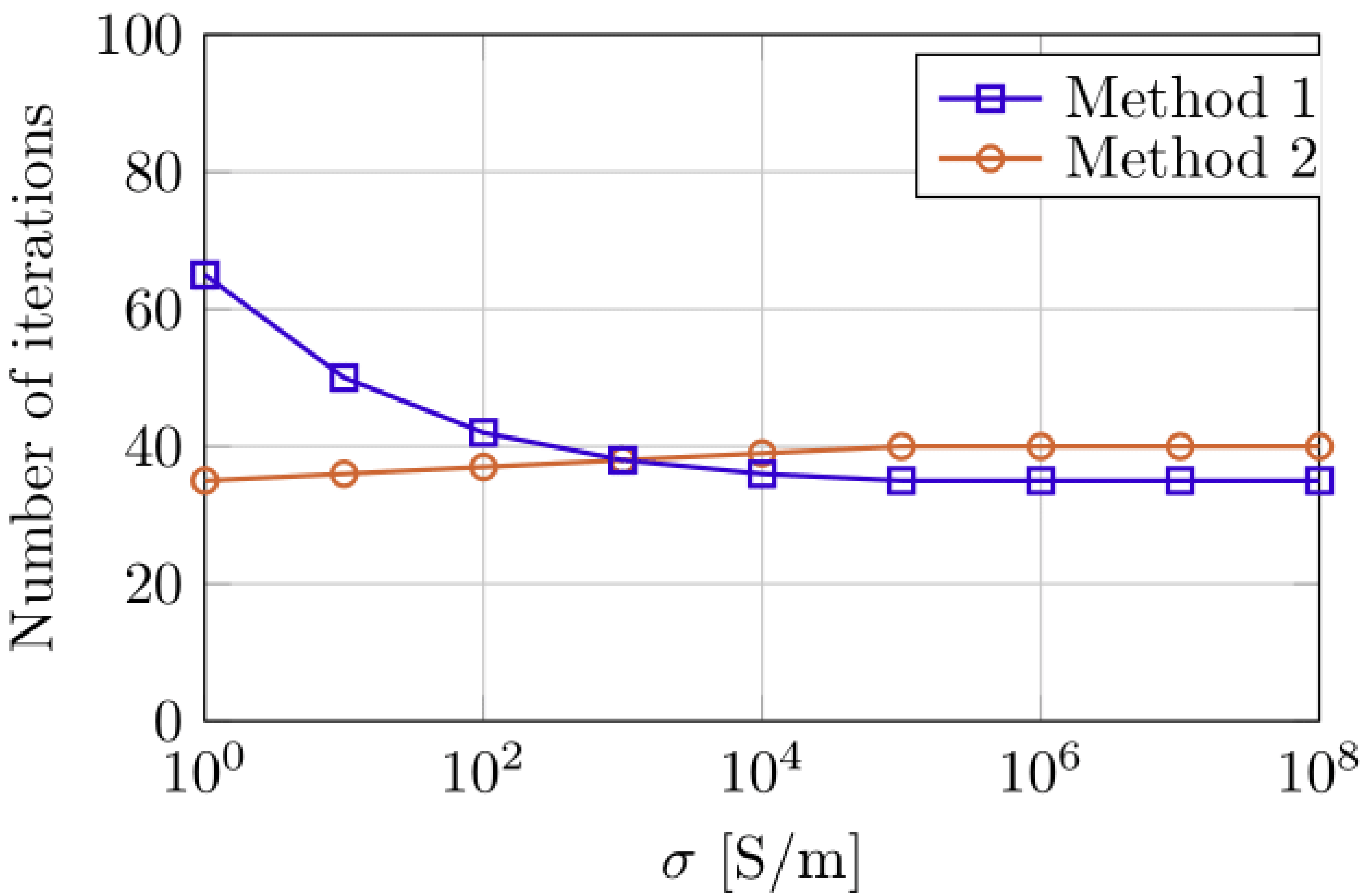
COMPARISON METHOD 1 & 2: CUBE SCATTERING



Side = 0.5 m   Frequency = 200 MHz



mesh elements:

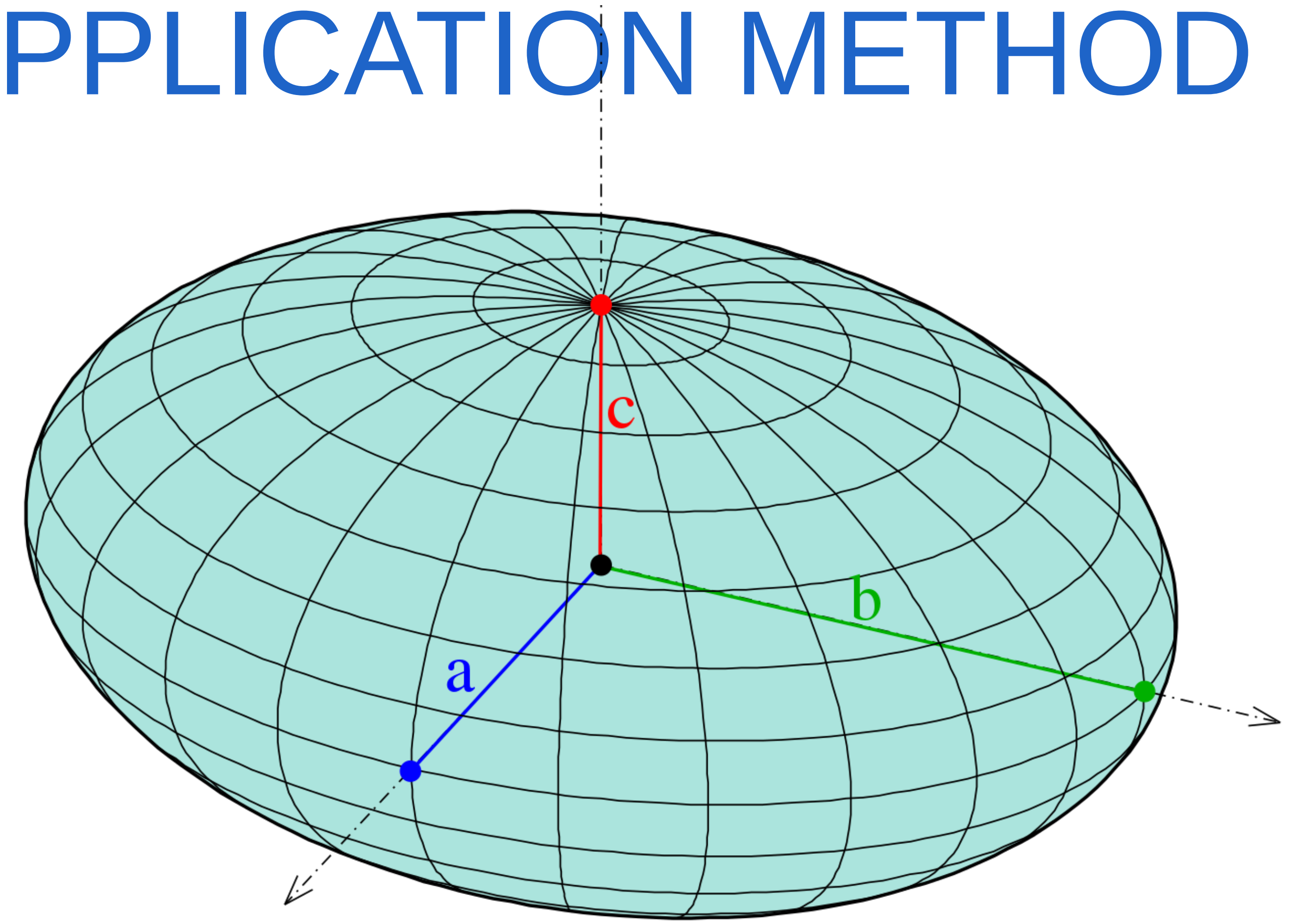
Method 1: 936 (generated triangular mesh)

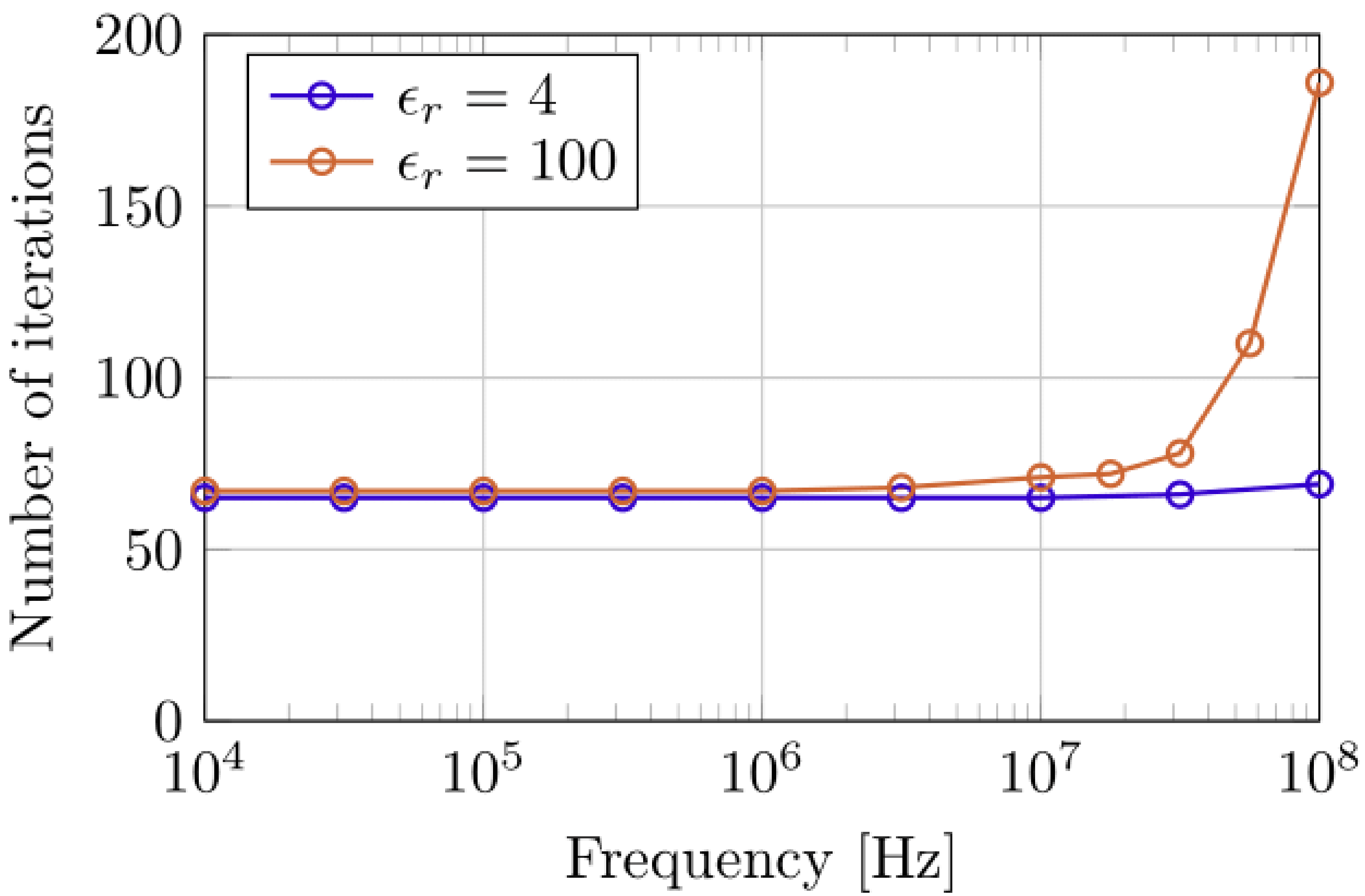
Method 2: 432 (structured rectangular mesh)

Similar # iterations for solution

Method 1 outperforms method 2 for HDC despite larger system matrix

APPLICATION METHOD 1: ELLIPSOID SCATTERING





a = 0.6 m, b= = 0.4 m, c = 0.2 m

Frequency = 200 MHz

Stable number of iterations over a wide frequency range

Increase for HDC at highest frequency due to internal resonances

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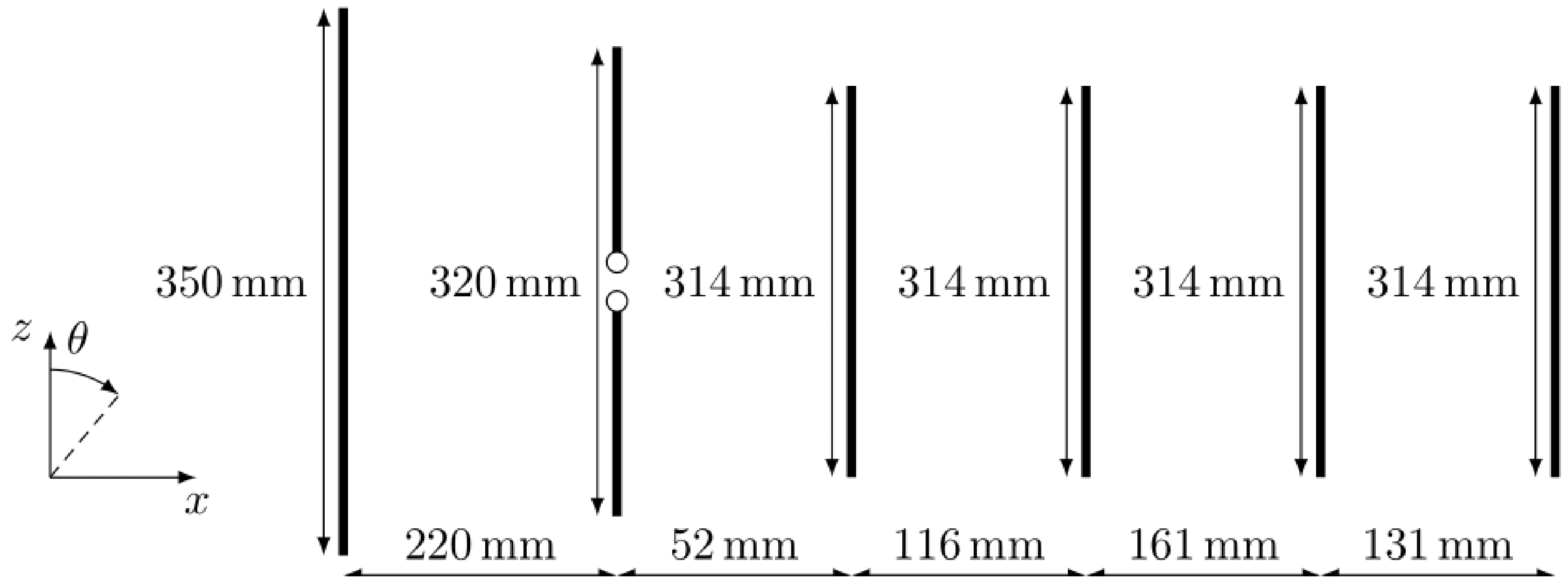
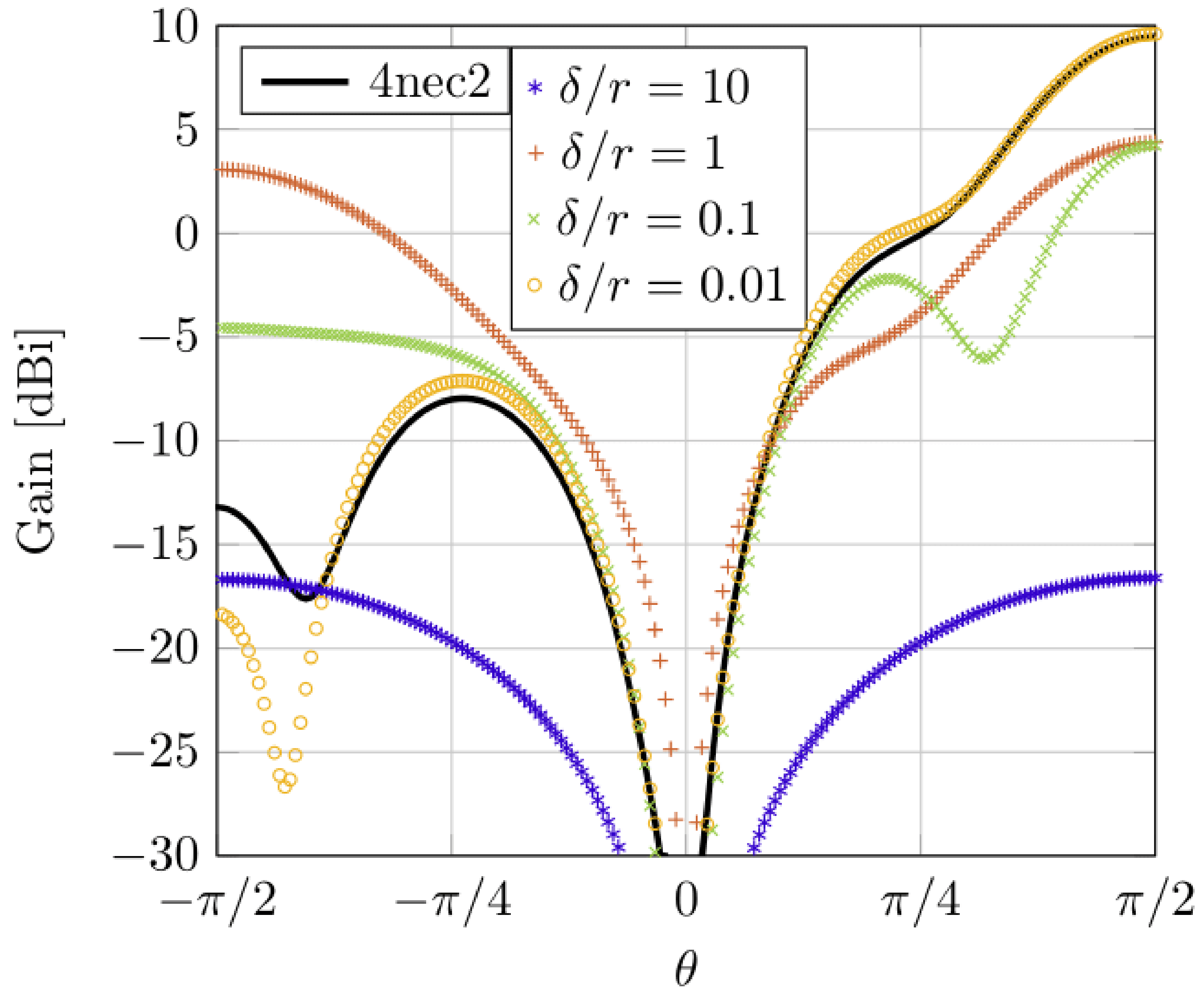
APPLICATION METHOD 2: YAGI-UDA





Frequency = 434 MHz
(ISM band)

For poor conductive elements, parasitic elements are transparent → responsive resembles (inefficient) dipole

Once skin effect appears, gain increases and Yagi-Uda operation starts shaping the gain pattern

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CONCLUSIONS

- Two novel boundary integral equation methods
  - Single-source formulations
  - Well equipped to handle good conductors & HDC
- New Calderón preconditioner
  - No low-frequency or dense-mesh breakdown for HDC
- 3-D differential surface admittance operator
  - No cumbersome integrals involving HDC's Green's function
  - Broadband model

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