Higher-Order Finite Element Electromagnetics Code for HPC Environments

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International Conference on Computational Science

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Antecedents

- 20 years of experience on numerical methods for EM.
  - Curl-conforming basis functions.
  - Non-standard mesh truncation technique (FE-IIEE).
  - Adaptivity: *h* and *hp*.
  - Hybridization with MoM, PO/PTD and GTD/UTD.

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- User-friendly.
- Efficient use of HPC in electromagnetics.

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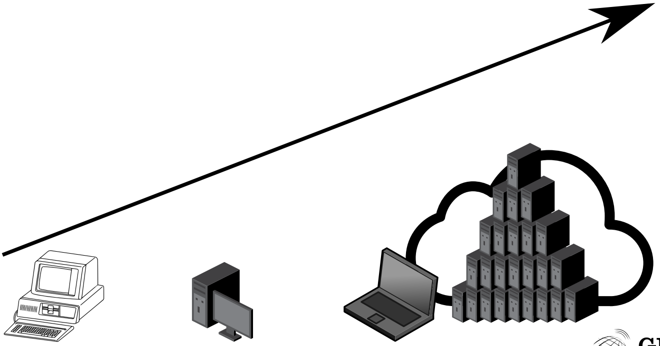

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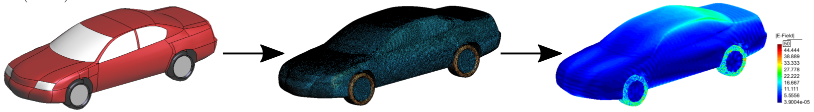
$$\vec{\nabla} \times \left(f_r^{-1} \times \vec{V}\right) - k_0^2 g_r \vec{V} = -jk_0 H_0 \vec{P} + \nabla \times f_r^{-1} \vec{Q}$$

$$\mathbf{LHS} g_i = \overrightarrow{RHS}$$

$$\vec{E} = \sum_i^n g_i \vec{N}_i$$



Outline

- Electromagnetic modeling features.
- Computational features and implementation.

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- Numerical results.

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Wave equation

$$\nabla \times \left(\bar{\bar{f}}_r^{-1} \nabla \times \mathbf{V} \right) - k_0^2 \, \bar{\bar{g}}_r \, \mathbf{V} = -jk_0 h_0 \, \mathbf{P} - \nabla \times \left(\bar{\bar{f}}_r^{-1} \mathbf{L} \right) \quad \text{in} \quad \Omega^{\text{FEM}}$$

$$\hat{\mathbf{n}} \times \mathbf{V} = \mathbf{\Psi}_{\text{D}} \qquad \text{over } \Gamma_{\text{D}}$$

$$\hat{\mathbf{n}} \times \left(\bar{\bar{f}}_r^{-1} \nabla \times \mathbf{V} \right) = \mathbf{\Psi}_{\text{N}} \qquad \text{over } \Gamma_{\text{N}}$$

$$\hat{\mathbf{n}} \times \left(\bar{\bar{f}}_r^{-1} \nabla \times \mathbf{V} \right) + \gamma \, \hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathbf{V} = \mathbf{\Psi}_{\text{C}} \qquad \text{over } \Gamma_{\text{C}}$$

	$\mathbf{V}$	$\bar{\bar{f}}_r$	$\bar{\bar{g}}_r$	h	$\mathbf{P}$	$\mathbf{L}$	Γ_{D}	Γ_{N}
Form. **E**	$\mathbf{E}$	$\bar{\bar{\mu}}_r$	$\bar{\bar{\epsilon}}_r$	η	$\mathbf{J}$	$\mathbf{M}$	Γ_{PEC}	Γ_{PMC}
Form. **H**	$\mathbf{H}$	$\bar{\bar{\epsilon}}_r$	$\bar{\bar{\mu}}_r$	$\frac{1}{\eta}$	$\mathbf{M}$	$-\mathbf{J}$	Γ_{PMC}	Γ_{PEC}

Variational formulation: Galerkin Method

Find $\mathbf{V} \in \mathbf{H}(\text{curl})$ such that

$$c(\mathbf{F},\mathbf{V}) = l(\mathbf{F}), \qquad \forall\, \mathbf{F} \in \mathbf{H}(\text{curl})_0$$

$$c(\mathbf{F},\mathbf{V}) = \int_\Omega (\nabla \times \mathbf{F}) \cdot \left(\bar{\bar{f}}_r^{\,-1} \nabla \times \mathbf{V}\right) d\Omega - k_0^2 \int_\Omega (\mathbf{F} \cdot \bar{\bar{g}}_r\, \mathbf{V})\, d\Omega \;+\; \gamma \int_{\Gamma_C} (\hat{\mathbf{n}} \times \mathbf{F}) \cdot (\hat{\mathbf{n}} \times \mathbf{V})\, d\Gamma_C$$

$$l(\mathbf{F}) = -jk_0 h_0 \int_\Omega \mathbf{F} \cdot \mathbf{P}\, d\Omega \;-\; \int_{\Gamma_N} \mathbf{F} \cdot \boldsymbol{\Psi}_N\, d\Gamma_N - \int_{\Gamma_C} \mathbf{F} \cdot \boldsymbol{\Psi}_C\, d\Gamma_C \;-\; \int_\Omega \mathbf{F} \cdot \nabla \times \left(\bar{\bar{f}}_r^{\,-1} \mathbf{L}\right) d\Omega$$

$$\mathbf{H}(\text{curl})_0 = \{\mathbf{W} \in \mathbf{H}(\text{curl}),\ \hat{\mathbf{n}} \times \mathbf{W} = 0 \ \text{ on } \ \Gamma_D\}$$
$$\mathbf{H}(\text{curl}) = \{\mathbf{W} \in L^2,\ \nabla \times \mathbf{W} \in L^2\}$$

EM features

- Periodic Boundary Conditions.
- Systematic approach for basis functions.

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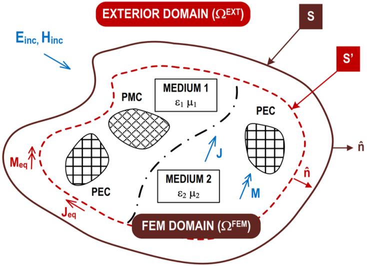

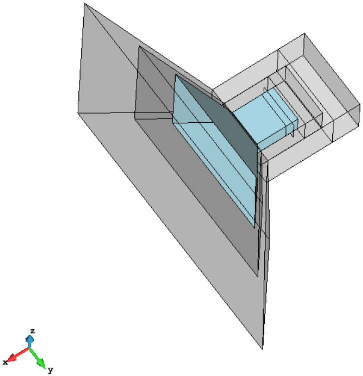

Mesh Truncation with FE-IIEE

[width=angle=0] Images/FEMImplemen$_{l}$*uise*4 − *eps* − *converted* − *to*

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Computational Features

- FORTRAN 2003.
- Set of automatic tests.

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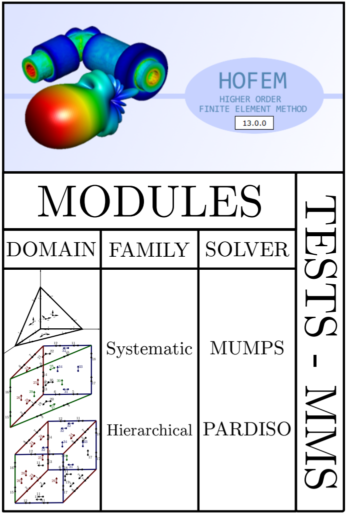
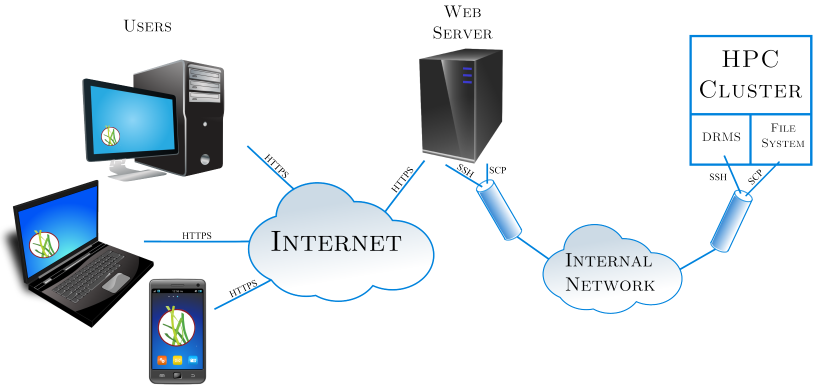
Design by blocks



Posidonia: In-house HPCaaS Solution (i)

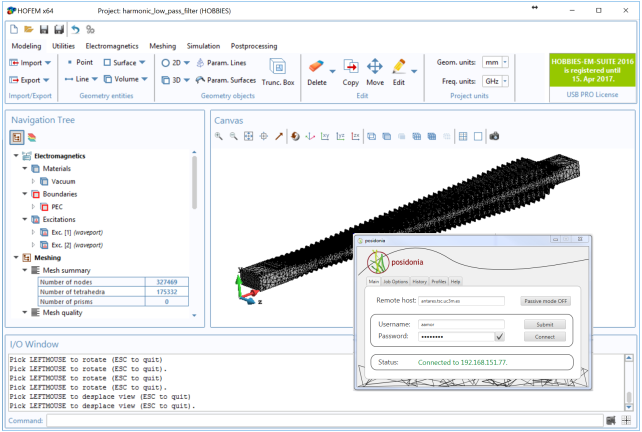


Posidonia: In-house HPCaaS Solution (ii)

- Features:
  - Remote job sumission.
  - Repository.
  - Notifications.
  - Profiles
- Design:
  - *User friendliness*.
  - Efficiency.
  - Generality.
  - Security.
  - Mobility.

A. Amor-Martin, I. Martinez-Fernandez, L. E. Garcia-Castillo. “Posidonia: A Tool for HPC and Remote Scientific Simulations”. *IEEE Antennas and Propagation Magazine*, 6:166–177, Dec. 2015.

GUI


HOFEM x64
Project: harmonic_low_pass_filter (HOBBIES)
Modeling
Utilities
Electromagnetics
Meshing
Simulation
Postprocessing
Import
Export
Import/Export
Point
Surface
Line
Volume
Geometry entities
2D
3D
Param. Lines
Param. Surfaces
Trunc. Box
Geometry objects
Delete
Copy
Move
Edit
Geom. units:
mm
Freq. units:
GHz
Project units
HOBBIES-EM-SUITE 2016
is registered until
15. Apr 2017.
USB PRO License
Navigation Tree
Electromagnetics
Materials
Vacuum
Boundaries
PEC
Excitations
Exc. [1] (waveport)
Exc. [2] (waveport)
Meshing
Mesh summary
Number of nodes 327469
Number of tetrahedra 175332
Number of prisms 0
Mesh quality
Canvas
posidonia
Main
Job Options
History
Profiles
Help
Remote host:
antares.tsc.uc3m.es
Passive mode OFF
Username:
aamor
Password:
Submit
Connect
Status:
Connected to 192.168.151.77.
I/O Window
Pick LEFTMOUSE to rotate (ESC to quit)
Pick LEFTMOUSE to rotate (ESC to quit).
Pick LEFTMOUSE to rotate (ESC to quit)
Pick LEFTMOUSE to rotate (ESC to quit).
Pick LEFTMOUSE to desplace view (ESC to quit)
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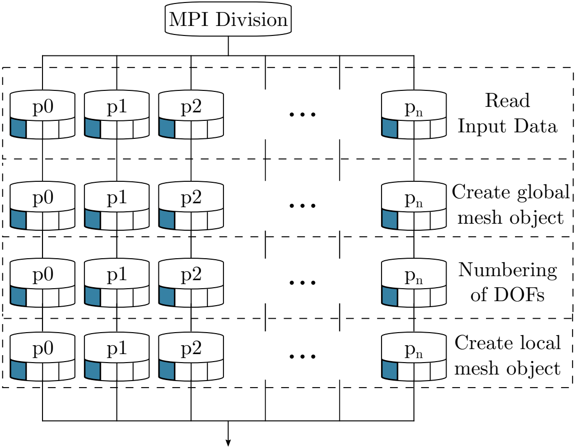
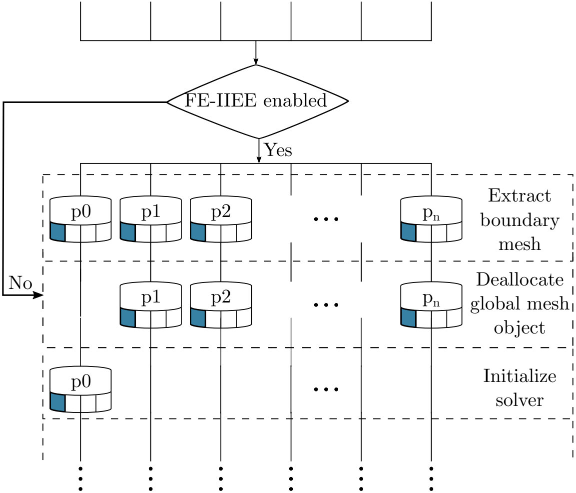
Command:

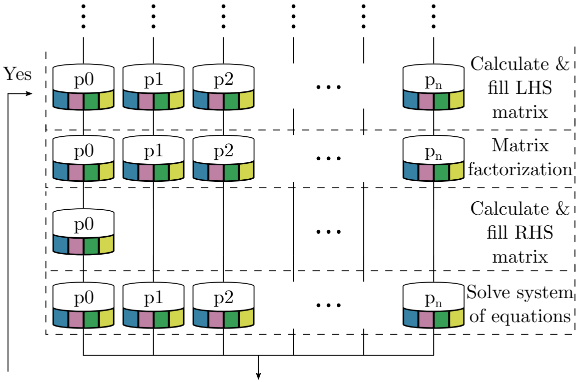
Flowchart (i)


MPI Division
p0
p1
p2
...
p_n
Read Input Data
Create global mesh object
Numbering of DOFs
Create local mesh object

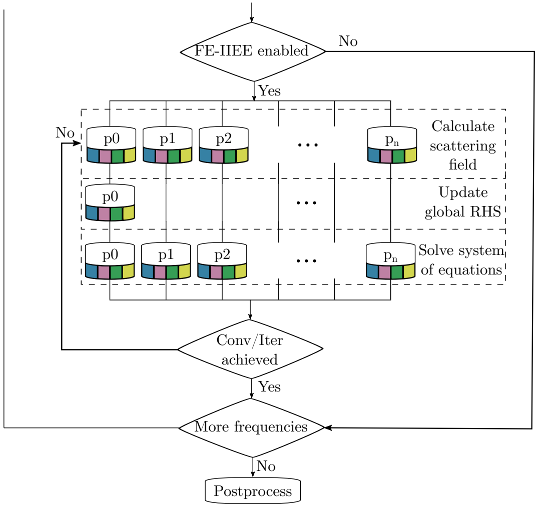
Flowchart (ii)



Flowchart (iii)



Flowchart (and iv)



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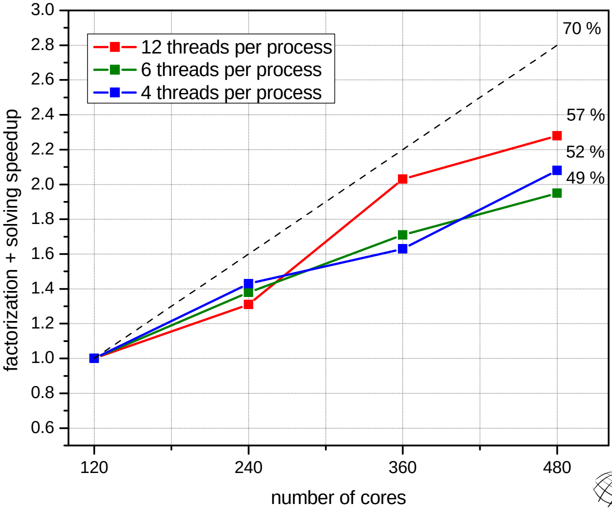
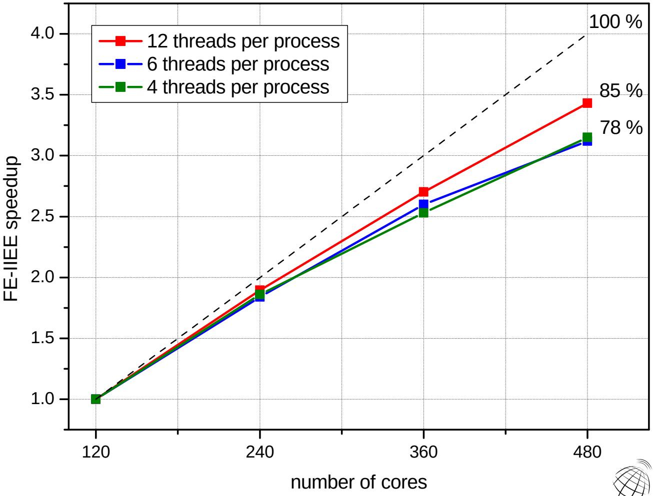
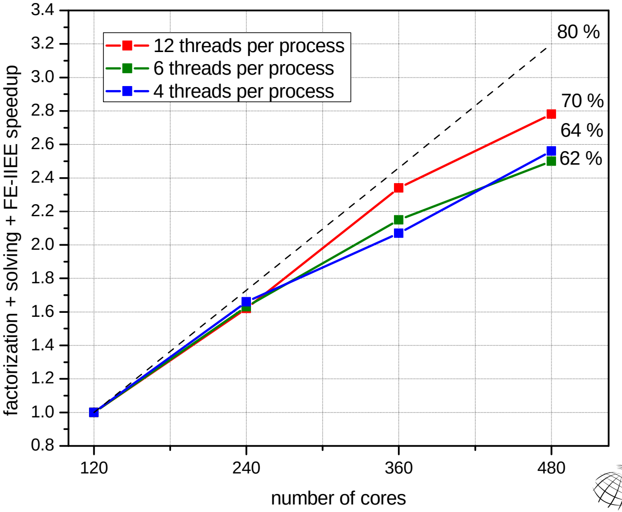
Speedup (i)


12 threads per process
6 threads per process
4 threads per process
70 %
57 %
52 %
49 %
factorization + solving speedup
number of cores
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
120
240
360
480

Speedup (ii)


12 threads per process
6 threads per process
4 threads per process
100 %
85 %
78 %
FE-IIEE speedup
4.0
3.5
3.0
2.5
2.0
1.5
1.0
120
240
360
480
number of cores

Speedup (and iii)

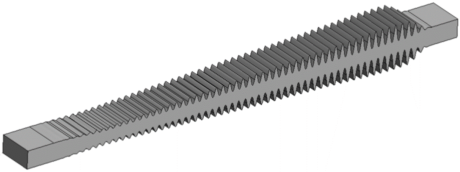


HPC Environment: Cluster of Xidian University (XDHPC)

- 140 compute nodes
  - Two twelve-core Intel Xeon 2690 V2 2.2 GHz CPUs
  - 64 GB of RAM
  - 1.8 TB of hard disk
- 56 Gbps InfiniBand network.

Waveguide problem (i)

- Analysis of harmonic low pass filter with higher-order mode suppresion.
- Analysis between 10 and 16 GHz.
- Total length: 218 mm.
- Total mesh elements: 324,532 tetrahedra.
- Total unknowns: 2,204,894.
- Simulation time: 7.3 min per frequency.



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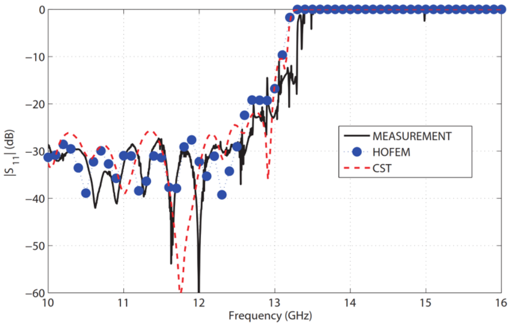
Waveguide problem (ii)



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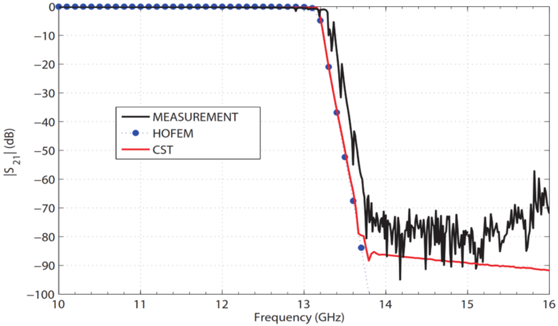
Waveguide problem (and iii)



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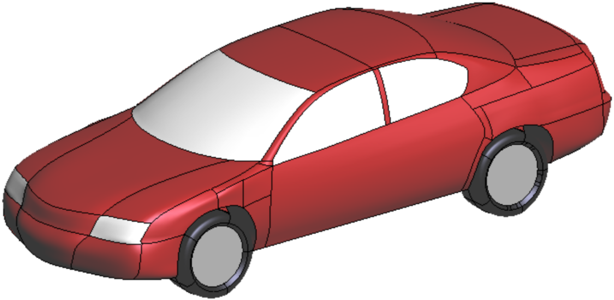
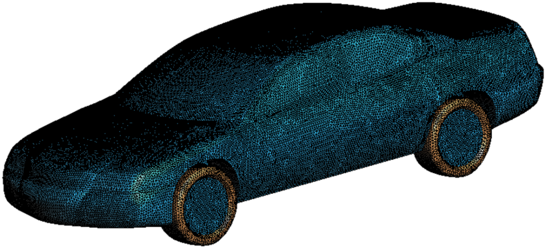
Scattering problem: Chevrolet Impala (i)

- RCS calculation at 1.5 GHz.
- Tyres modeled as dielectric material ($\varepsilon_r = 40$).
- Several incident planewaves around the car.



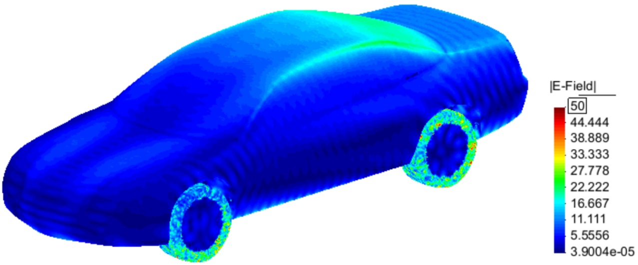
Scattering problem: Chevrolet Impala (ii)

- Simulation time: 59 min with 46 compute nodes.
- Total mesh elements: 2,651,970 tetrahedra.
- Total unknowns: 17,277,620.



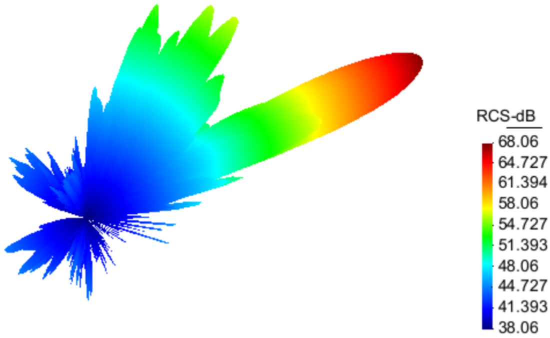
Scattering problem: Chevrolet Impala (iii)

- 3D representation of total E-field over the car at 1.5 GHz.
- Incident planewave from the trunk of the car.



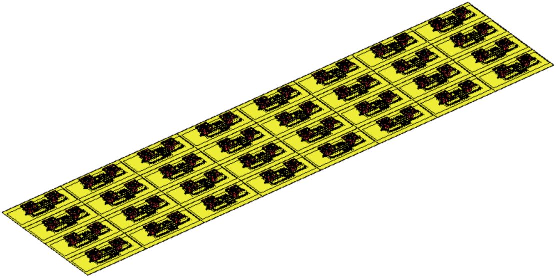
Scattering problem: Chevrolet Impala (and iv)

- 3D representation of RCS in dB at 1.5 GHz.
- Incident planewave in front of the car.



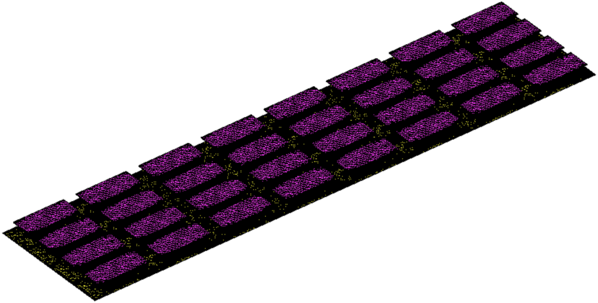
Radiation problem: Base Station Antenna (i)

- Analysis between 2 and 3 GHz.
- Total length: 1.6 m.
- Total mesh elements: 6,861,740 tetrahedra.
- Total unknowns: 45,121,862.



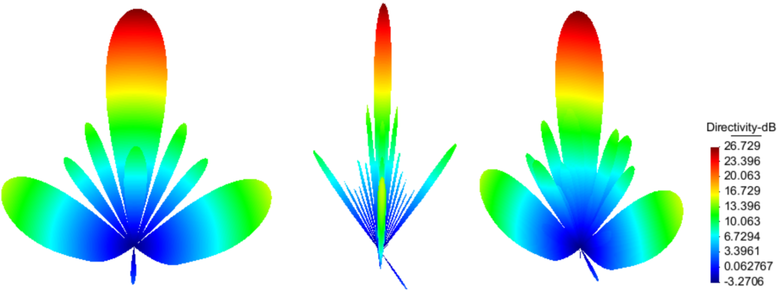
Radiation problem: Base Station Antenna (ii)

- Simulation time: 5.5 hours per frequency.
- Using 48 compute nodes and 1,152 CPU cores.
- Out-of-core simulation using 1.89 TB RAM.



Radiation problem: Base Station Antenna (iii)

- 3D representation of directivity at 2.6 GHz when every element is excited.



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Conclusions

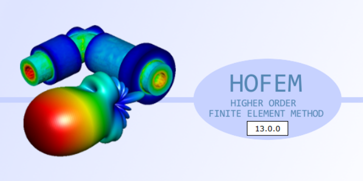
- HPC EM simulator.
- Several tens of millions of unknowns.
- More than one thousand cores used.
- 70% scalability.

Future Work

- Work in Progress:
  - Hierarchical basis functions of variable order p.
  - h-adaptivity $\Rightarrow$ support for *hp* meshes.
- Future Work:
  - Conformal and non-conformal DDM.
  - Hybrid (direct + iterative) solver.

Thank you for your attention!

Higher-Order Finite Element Electromagnetics Code for HPC Environments



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