Advanced Computational Tools for Antenna Placement Studies

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www.emssusa.com
Problem/Issue

Antenna and Antenna Array Analysis on various platforms

• Antenna Element Design
• Array Design
• In-situ analysis of the array integrated on platforms
Problem/Issue

EM Analysis tools are required for

- Design of antenna elements
- Array analysis
- *In-situ* performance analysis of antenna arrays mounted on aircraft, shipboard and ground platforms
Problem/Issue

Radiation pattern and surface currents of a microstrip patch array with corporate feed.

Characterisation of a horn-fed reflector antenna.

Studying VHF antenna placement on a naval platform.

Computational model of a car with integrated windscreen antenna.

Specification of cable paths for automotive cable coupling analysis.

Automotive EMC measurement installation with log periodic source.

Radiation hazard analysis for personal radios carried inside an automobile. The human phantoms are modelled with the FEM, while the antennas and bodywork are modelled with the MoM.
Computational Electromagnetics

- Numerical solution based on approximation of currents and/or fields
- Desirable properties of CEM methods:
  - Approximation may be reduced in order to increase accuracy, approaching the analytical result
  - Computational cost (CPU time & memory) must be as low as possible
Numerical Techniques

- **Method of Moments**
  - Antenna Element Design

- **Multilevel Fast Multipole Method (MLFMM)**
  - Antenna/Array Design/Platform Analysis

- **Hybrid MoM/Physical Optics (PO)**
  - Platform Analysis

- **Hybrid MoM/Uniform Theory of Diffraction (UTD)**
  - Platform Analysis
EM Simulation Map: CEM Methods

- UTD
- PO/GO
- MLFMM
- MOM
- FEM

Electrical Size vs. Complexity of Materials
EM Simulation Map: CEM Methods

- **Asymptotic Methods** (high-frequency approximation)
  - UTD
  - PO/GO
- **Full-wave Methods** (physically rigorous solution)
  - MLFMM
  - MOM
  - FEM

Hybridization to solve large and complex problems
Method of Moments

- Create CAD Model of the geometry
- Create surface mesh – triangles
- Applying the equivalence principle, electric or magnetic currents assumed to be unknowns
- RWG basis functions are used
- A set of linear equations are formed

\[ Z \mathbf{I} = \mathbf{V} \]

\( Z \) = NXN complex matrix
\( \mathbf{I} \) = Unknown current vector
\( \mathbf{V} \) = Known Excitation vector

- Solving this equation, unknown currents on each triangle is found
Method of Moments

Antenna Characteristics can be found from the currents calculated:
- Near- or Far-fields
- Input impedances
- S-parameters etc

Surface Currents
Near Fields
Radiation Patterns
Very Thin Low-Profile Antenna Using Novel High Impedance Surface (HIS) Ground Plane

Three Dual-Band Miniaturized Inverted F Antennas Integrated in a PDA for MIMO Applications

2006 IEEE APS Symposium

Wireless LAN (WLAN)
2.45GHz and 5.2GHz

Prototype

FEKO Model

Figure 1: Simulation models for planar (a) and buckled (b) antennas

Three Dual-Band Miniaturized Inverted F Antennas Integrated in a PDA for MIMO Applications

2006 IEEE APS Symposium

Design and Analysis of a Novel Pent-band Antenna for Handheld Applications

GSM 800/900/1800/1900 and UMTS 2200

Design and Analysis of a Novel Pent-band Antenna for Handheld Applications

Accurate Simulation of Rotman Lens

Antenna Placement on Electrically Platform

ATR-42 (Avions de Transport Regional)

Fig. 1. CAD model of ATR42 aircraft.

Antenna Placement on Electrically Platform

VHF Antennas – 126MHz

\( \lambda /8 \) mesh, 4,245 triangles

Calculations with MoM using Magnetic Symmetry
MLFMM – no symmetry is used

Measurements with 1/12\textsuperscript{th} scale model

Antenna Placement on Electrically Platform

VHF Com Antennas – 126MHz
Top Antenna Patterns

Fig. 3. Directivity in the $\phi = 0^\circ$ (top position).

Fig. 4. Directivity in the $\phi = 90^\circ$ (top position).

Antenna Placement on Electrically Platform

VHF Com Antennas – 126MHz
Bottom Antenna Patterns


Fig. 5. Directivity in the $\phi = 0^\circ$ (bottom position).

Fig. 6. Directivity in the $\phi = 90^\circ$ (bottom position).
# Memory/CPU requirement for the MoM

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Electrical Size of Aircraft</th>
<th>Unknowns</th>
<th>Peak Memory</th>
<th>CPU-time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>length</td>
<td>wingspan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 MHz</td>
<td>9.7 (\lambda)</td>
<td>5.3 (\lambda)</td>
<td>5,874</td>
<td>542.6 MB</td>
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<td>8 (\lambda)</td>
<td>14,189</td>
<td>3.0 GB</td>
</tr>
<tr>
<td>450 MHz</td>
<td>21.75 (\lambda)</td>
<td>12 (\lambda)</td>
<td>29,389</td>
<td>13.0 GB</td>
</tr>
<tr>
<td>600 MHz</td>
<td>29 (\lambda)</td>
<td>16 (\lambda)</td>
<td>44,627</td>
<td>30.0 GB</td>
</tr>
</tbody>
</table>


[Image: Surface current (dBAm)]
MoM based on the solution of a system of linear equations

\[
Z \mathbf{I} = \mathbf{V} \quad \Rightarrow \quad \mathbf{I} = Z^{-1} \mathbf{V}
\]

Impedance matrix \( Z \) describes interaction of \( n.\text{th} \) element with \( m.\text{th} \) element

\[
Z = \begin{bmatrix}
* & * & * & * & * & * \\
* & * & * & * & Z_{mn} & * \\
* & * & * & * & * & * \\
* & * & * & * & * & * \\
* & * & * & * & * & * \\
* & * & * & * & * & *
\end{bmatrix}
\]

\( Z \) I = \mathbf{V} \quad \Rightarrow \quad \mathbf{I} = Z^{-1} \mathbf{V}

\( \rightarrow \) LU-decomposition requires \( O(N^3) \) operations and \( O(N^2) \) memory
Example:
Automotive simulation
at 2 GHz instead of 1 GHz:

\[ f \quad \rightarrow \quad 2f \]
\[ N \quad \rightarrow \quad 4N \]

<table>
<thead>
<tr>
<th>Complexity</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( O(N^3) )</td>
<td>64</td>
</tr>
<tr>
<td>( O(N^2) )</td>
<td>16</td>
</tr>
<tr>
<td>( O(N) )</td>
<td>4</td>
</tr>
<tr>
<td>( O(N \log N) )</td>
<td>(&lt; 5 )</td>
</tr>
<tr>
<td>( O(N \log^2 N) )</td>
<td>(&lt; 6 )</td>
</tr>
</tbody>
</table>
MoM Solution Acceleration

Adaptive Cross-Approximation:
- Effective for:
  - Low-frequency problems (sub-wavelength geometric detail)
  - Planar Greens function problems
- Large savings in memory and runtime over traditional implementation

Hardware Acceleration:
- **Parallelization**
  - Multi-core
  - Multi-CPU
  - Cluster
- **Graphical Processing Unit (GPU)**
  - NVIDIA CUDA enabled
Multilevel Fast Multipole Method (MLFMM)

- **Multilevel implementation:**
  - Divide space into boxes
  - Aggregation (A)
  - Translation (T)
  - Disaggregation (D)
Example:
Automotive simulation at 2 GHz instead of 1 GHz:
\[ f \rightarrow 2f \]
\[ N \rightarrow 4N \]

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</tr>
<tr>
<td>(O(N))</td>
<td>4</td>
</tr>
<tr>
<td>(O(N \log N))</td>
<td>(4 \left(1 + \frac{\log 4}{\log N}\right) &lt; 5)</td>
</tr>
<tr>
<td>(O(N \log^2 N))</td>
<td>(4 \left(1 + \frac{2 \log 4}{\log N} + \frac{\log^2 4}{\log^2 N}\right) &lt; 6)</td>
</tr>
</tbody>
</table>

MLFMM
Memory requirement for the MLFMM

General scaling of the MLFMM:

Memory

\( N \log(N) \)

CPU time

\( N \log^2(N) \)

→ Confirmed by examples
Possible with MLFMM

Asymptotic predictions of memory usage for the MoM with and without MLFMM.

<table>
<thead>
<tr>
<th>N</th>
<th>MoM</th>
<th>MLFMM</th>
<th>Application</th>
</tr>
</thead>
</table>
| 100 000 | 75 GByte | 1 GByte | • Military aircraft at 690 MHz  
  • Ship (115 m x 14 m) at 107 MHz  
  • Reflector antenna with aperture size 19\(\lambda\) |
| 200 000 | 300 GByte | 2 GByte | • Military aircraft at 960 MHz  
  • Ship (115 m x 14 m) at 150 MHz  
  • Reflector antenna with aperture size 27\(\lambda\) |
| 400 000 | 1.2 TByte | 4.5 GByte | • Military aircraft at 1.37 GHz  
  • Ship (115 m x 14 m) at 214 MHz  
  • Reflector antenna with aperture size 38\(\lambda\) |
| 1 000 000 | 7.5 TByte | 12 GByte | • Military aircraft at 2.2 GHz  
  • Ship (115 m x 14 m) at 340 MHz  
  • Reflector antenna with aperture size 60\(\lambda\) |
Comparison between MoM and MLFMM at 600 MHz

## Memory/CPU requirement for the MLFMM

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Electrical Size of Aircraft</th>
<th>Un_knowns</th>
<th>Peak Memory</th>
<th>CPU-time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>length wingspan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600 MHz</td>
<td>29 λ 16 λ</td>
<td>89,866</td>
<td>1.3 GB</td>
<td>20.0 min</td>
</tr>
<tr>
<td>1 GHz</td>
<td>48.3 λ 26.7 λ</td>
<td>407,648</td>
<td>3.7 GB</td>
<td>1.1 hours</td>
</tr>
<tr>
<td>2 GHz</td>
<td>96.6 λ 53.3 λ</td>
<td>1,320,430</td>
<td>10.5 GB</td>
<td>3 hours</td>
</tr>
<tr>
<td>3 GHz</td>
<td>145 λ 80 λ</td>
<td>2,736,834</td>
<td>21.4 GB</td>
<td>7 hours</td>
</tr>
</tbody>
</table>

Physical Optics

\[ J(r) = \hat{n} \times H(r) = \hat{n} \times \left[ H^i(r) + H^r(r) \right] \]

\[ J(r) = 2\hat{n} \times H^i(r) \]
Hybrid MoM/Physical Optics (PO) Technique

Decomposition of domain into MoM and asymptotic region

Two types of coupling:

- $J^{MoM}$ radiates $H$ causing asymptotic currents
- $J^{asym}$ radiates $E$ which must be considered in the MoM integral equation

\[
\vec{E} \left\{ J^{MoM} \right\}_{\tan} + \vec{E} \left\{ J^{asym} \right\}_{\tan} = -\vec{E}_{i,tan}
\]
Validation of FEKO for Electrically Large Problem

Air Traffic Control Antenna at 1GHz

$\lambda/5$ Mesh with 193,212 triangles
MoM/PO Hybrid Technique
Measurements – scale model

Validation of FEKO for Electrically Large Problem

Air Traffic Control Antenna at 1GHz

Fig. 8. Directivity in the $\phi = 0^\circ$.

Fig. 9. Directivity in the $\phi = 90^\circ$. 
Comparison between MLFMM and MoM/PO at 3 GHz

## Memory/CPU requirement for the MoM/PO


<table>
<thead>
<tr>
<th>Frequency</th>
<th>Electrical Size of Aircraft</th>
<th>Unknowns</th>
<th>Peak Memory</th>
<th>CPU-time</th>
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<tr>
<td></td>
<td>length</td>
<td>wingspan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>145 λ</td>
<td>80 λ</td>
<td>808,336</td>
<td>570.0 MB</td>
</tr>
<tr>
<td>8 GHz</td>
<td>387 λ</td>
<td>213 λ</td>
<td>5,075,060</td>
<td>4.0 GB</td>
</tr>
<tr>
<td>15 GHz</td>
<td>725 λ</td>
<td>400 λ</td>
<td>17,271,199</td>
<td>16.0 GB</td>
</tr>
<tr>
<td>20 GHz</td>
<td>967 λ</td>
<td>533 λ</td>
<td>30,437,010</td>
<td>30.9 GB</td>
</tr>
</tbody>
</table>
## Summary of MoM, MLFMM, and MoM/PO

<table>
<thead>
<tr>
<th>frequency</th>
<th>MoM symmetry (mesh size -- $\lambda/8$)</th>
<th>Electrical Size</th>
<th># of Unknowns</th>
<th>Peak Memory</th>
<th>CPU-time</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>14,189</td>
<td>3.0 GB</td>
<td>29.0 min</td>
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<td>12 $\lambda$</td>
<td>29,389</td>
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<td>3.0 hours</td>
</tr>
<tr>
<td>600 MHz</td>
<td>29 $\lambda$</td>
<td>16 $\lambda$</td>
<td>44,627</td>
<td>30.0 GB</td>
<td>9.1 hours</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>frequency</th>
<th>MLFMM (mesh size -- $\lambda/8$)</th>
<th>length</th>
<th>wingspan</th>
<th># of Unknowns</th>
<th>Peak Memory</th>
<th>CPU-time</th>
</tr>
</thead>
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<td>89,866</td>
<td>1.3 GB</td>
<td>20.0 min</td>
<td></td>
</tr>
<tr>
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<td>48.3 $\lambda$</td>
<td>26.7 $\lambda$</td>
<td>407,648</td>
<td>3.7 GB</td>
<td>1.1 hours</td>
<td></td>
</tr>
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<td>10.5 GB</td>
<td>3.0 hours</td>
<td></td>
</tr>
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<td>3 GHz</td>
<td>145 $\lambda$</td>
<td>80 $\lambda$</td>
<td>2,736,834</td>
<td>21.4 GB</td>
<td>7.0 hours</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>frequency</th>
<th>MoM/PO symmetry (mesh size -- $\lambda/6$)</th>
<th>length</th>
<th>wingspan</th>
<th># of Unknowns</th>
<th>Peak Memory</th>
<th>CPU-time</th>
</tr>
</thead>
<tbody>
<tr>
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<td>145 $\lambda$</td>
<td>80 $\lambda$</td>
<td>808,336</td>
<td>570.0 MB</td>
<td>8.0 min</td>
<td></td>
</tr>
<tr>
<td>8 GHz</td>
<td>387 $\lambda$</td>
<td>213 $\lambda$</td>
<td>5,075,060</td>
<td>4.0 GB</td>
<td>1.4 hours</td>
<td></td>
</tr>
<tr>
<td>15 GHz</td>
<td>725 $\lambda$</td>
<td>400 $\lambda$</td>
<td>17,271,199</td>
<td>16.0 GB</td>
<td>8.9 hours</td>
<td></td>
</tr>
<tr>
<td>20 GHz</td>
<td>967 $\lambda$</td>
<td>533 $\lambda$</td>
<td>30,437,010</td>
<td>30.9 GB</td>
<td>20.1 hours</td>
<td></td>
</tr>
</tbody>
</table>
Modern High Performance Computing

2-Node Cluster
Intel Xeon E5-2650 2.0GHz 8-core 20MB cache
Each Node: 2 CPUs (16 cores), 256GB RAM
Total: 4 CPUs (32 cores), 512 GB RAM
Infiband Interconnect

Under $20,000
# Resource Requirements

<table>
<thead>
<tr>
<th>Method</th>
<th>Frequency</th>
<th>Triangles</th>
<th>Unknowns</th>
<th>Memory</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOM</td>
<td>950MHz</td>
<td>162 524</td>
<td>121 537</td>
<td>222.1 GB</td>
<td>4.7 hr</td>
</tr>
<tr>
<td>MLFMM</td>
<td>950MHz</td>
<td>162 524</td>
<td>243 726</td>
<td>11.6 GB</td>
<td>0.1 hr</td>
</tr>
<tr>
<td>MLFMM</td>
<td>7.00 GHz</td>
<td>8 193 402</td>
<td>12 289 643</td>
<td>220.8 GB</td>
<td>2.6 hr</td>
</tr>
<tr>
<td>PO</td>
<td>7.00 GHz</td>
<td>5 119 950</td>
<td>3 838 847</td>
<td>36.9 GB</td>
<td>0.5 hr</td>
</tr>
<tr>
<td>PO</td>
<td>3 GHz</td>
<td>145 λ</td>
<td>80 λ</td>
<td>808 336</td>
<td>.57 GB</td>
</tr>
<tr>
<td>PO</td>
<td>8 GHz</td>
<td>387 λ</td>
<td>213 λ</td>
<td>5 075 060</td>
<td>4.0 GB</td>
</tr>
<tr>
<td>PO</td>
<td>15 GHz</td>
<td>725 λ</td>
<td>400 λ</td>
<td>17 271 199</td>
<td>16.0 GB</td>
</tr>
<tr>
<td>PO</td>
<td>20 GHz</td>
<td>967 λ</td>
<td>533 λ</td>
<td>30 437 010</td>
<td>31.0 GB</td>
</tr>
<tr>
<td>PO</td>
<td>45 GHz</td>
<td>2175 λ</td>
<td>1200 λ</td>
<td>108 435 565</td>
<td>128.0 GB</td>
</tr>
<tr>
<td>PO</td>
<td>60 GHz</td>
<td>2901 λ</td>
<td>1599 λ</td>
<td>191 095 846</td>
<td>248.0 GB</td>
</tr>
</tbody>
</table>
950 MHz: $\phi = 0^\circ$
950 MHz: $\phi = 90^\circ$
$7 \text{ GHz: } \phi = 0^\circ$
7 GHz: $\phi = 90^\circ$
Ray based hybrid method (MoM / UTD)

PO too expensive for very large (in terms of wavelengths) objects

FEKO offers the UTD (Uniform Theory of Diffraction)

<table>
<thead>
<tr>
<th>method</th>
<th>formulation</th>
<th>CPU–time</th>
<th>memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoM</td>
<td>current–based</td>
<td>$f^4...6$</td>
<td>$f^4$</td>
</tr>
<tr>
<td>PO</td>
<td>current–based</td>
<td>$f^2$</td>
<td>$f^0$</td>
</tr>
<tr>
<td>UTD</td>
<td>ray–based</td>
<td>$f^0$</td>
<td>$f^0$</td>
</tr>
</tbody>
</table>
Ray based hybrid method (MoM / UTD)

UTD applied to polygonal plates or a cylinder

Consideration of
- direct ray
- reflected rays (also multiple)
- edge diffracted rays
- corner diffracted rays
- combinations of reflections and diffractions
- multiple diffractions
- creeping rays
25 by 25 Array on Shipboard

- Ship
  - Length: 115 m
  - Width: 14 m
  - Height: 22 m
- Electrical size at 1.77 GHz
  - Length: 679 $\lambda$
  - Width: 82 $\lambda$
  - Height: 159 $\lambda$

MoM Unknowns: 32 millions
25 by 25 Array on Shipboard

- Instead, UTD is used
  - Peak memory: 8.4MB
- Runtime for each angle
  - 18.4 seconds
25 by 25 Array on Shipboard

Ship board array

Array in free space
Summary

Hybrid Methods are required for in-situ analysis.
Summary

• Successful demonstration of antenna design, array analysis and placement of arrays on electrically large structures
• Use of various electromagnetic analysis techniques demonstrated
• It is possible to design antenna elements/array and carry out in-situ analysis of antennas/array on platforms using commercial EM analysis tools.

Simulations in this presentation are done using

www.feko.info