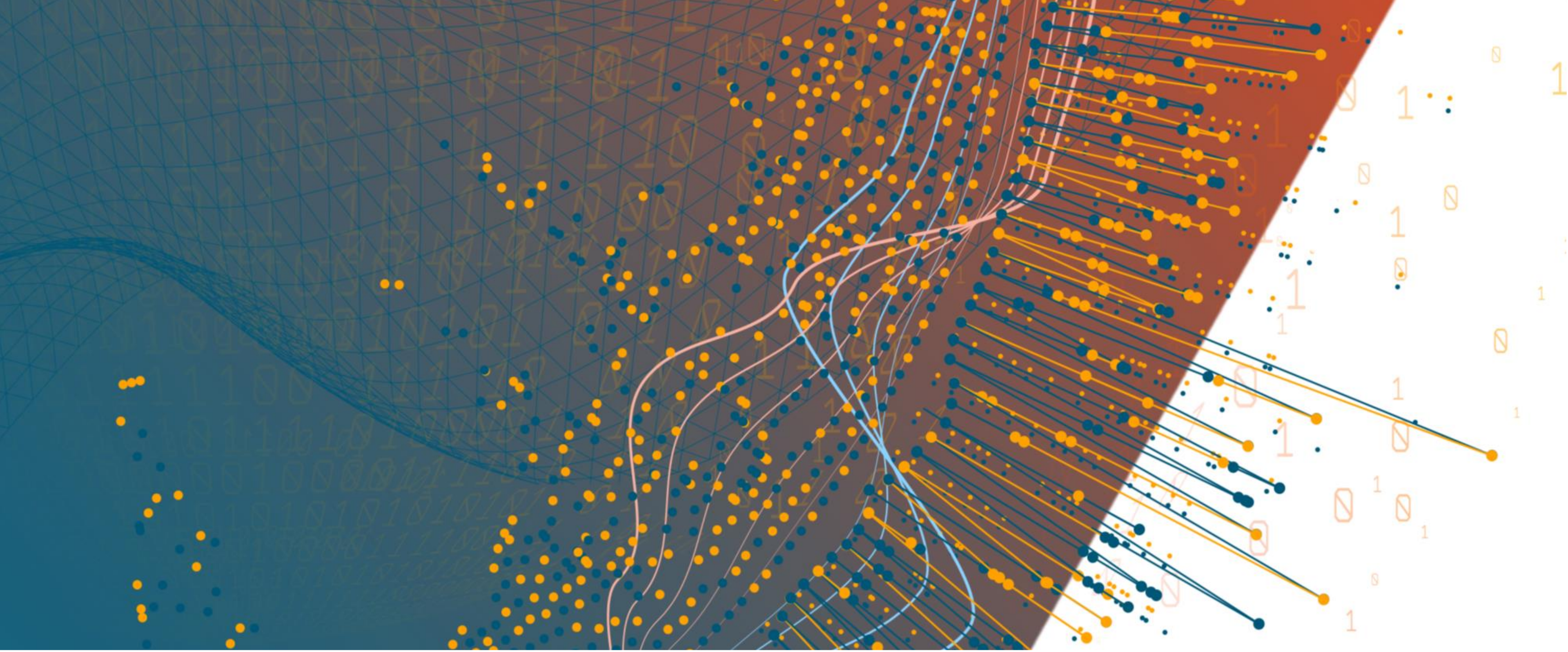


ANTENNA MODELING AND SIMULATION TECHNIQUES

Dr. C.J. Reddy – VP Business Development – Electromagnetics, Altair

October 2020

Outline

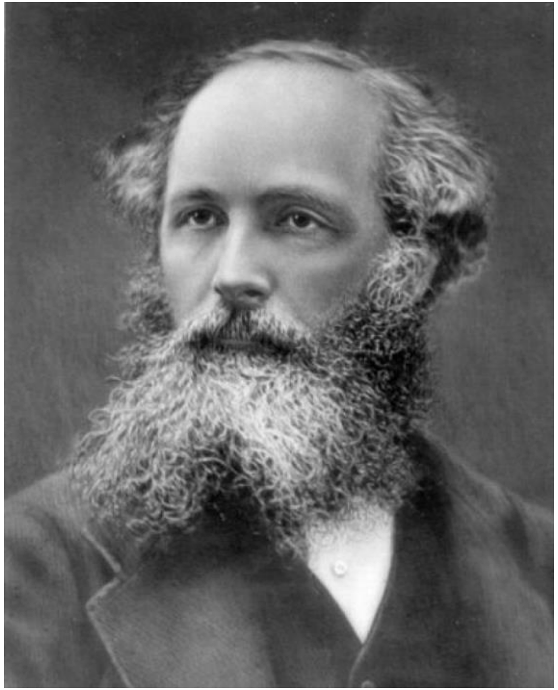
- Introduction to Antenna Analysis
- Computational Electromagnetics (CEM)
- CEM Solver Technologies for Antenna Modeling
  - Full wave Solutions (MoM, MLFMM, FEM, FDTD)
  - Asymptotic Solutions (PO, RL-GO, UTD)
  - Hybrid Solutions
- Antenna Arrays
  - Infinite Arrays
  - Finite Arrays
- Advanced Topics
  - Characteristic Mode Analysis – CMA
  - Machine Learning for Antenna Design and Optimization
- Antenna Modeling and Simulation in Education and Further Reading

INTRODUCTION TO ANTENNA ANALYSIS

Electromagnetics

Maxwell's equations for electromagnetism have been called the ***"second great unification in physics"*** after the first one realized by Isaac Newton.

James Clerk Maxwell
(1831-1879)



Maxwell's Equations

$$\vec{\nabla} \times \vec{H} = \vec{J}_v + \varepsilon \frac{d\vec{E}}{dt}$$

$$\vec{\nabla} \times \vec{E} = -\vec{M}_v - \mu \frac{d\vec{H}}{dt}$$

$$\vec{\nabla} \bullet \vec{H} = \frac{1}{\mu} \sigma_m$$

$$\vec{\nabla} \bullet \vec{E} = \frac{1}{\varepsilon} \sigma_e$$

$$\mathbf{E} = -j\omega\mu\mathbf{A} + \frac{1}{j\omega\epsilon}\nabla(\nabla \cdot \mathbf{A})$$

$$\mathbf{E} = -j\omega\mu \int_V d\mathbf{r}'\mathbf{G}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}(\mathbf{r}')$$

$$\mathbf{G}(\mathbf{r},\mathbf{r}') = \frac{1}{4\pi}\left[\mathbf{I} + \frac{\nabla\nabla}{k^2}\right] G(\mathbf{r},\mathbf{r}')$$

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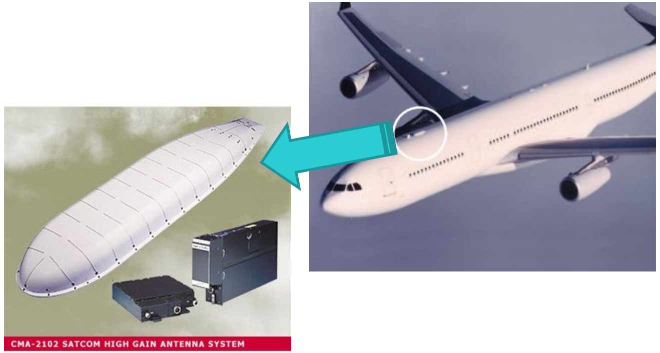
Invention of Radio

Guglielmo Marconi (1874 – 1937)

- 12 December 1901, using a 500-foot antenna for reception, the message was received at Signal Hill in St John's, Newfoundland (now part of Canada) signals transmitted by a high-power station at Poldhu, Cornwall, England
- The distance between the two points was about 2,200 miles (3,500 km).

- Founded **Marconi's Wireless Telegraph Company** of Canada in 1903
- Later Renamed as “Canadian Marconi Company” in 1925
- Now called **CMC Electronics**, a wholly owned subsidiary of Esterline Corporation - http://www.cmcelectronics.ca



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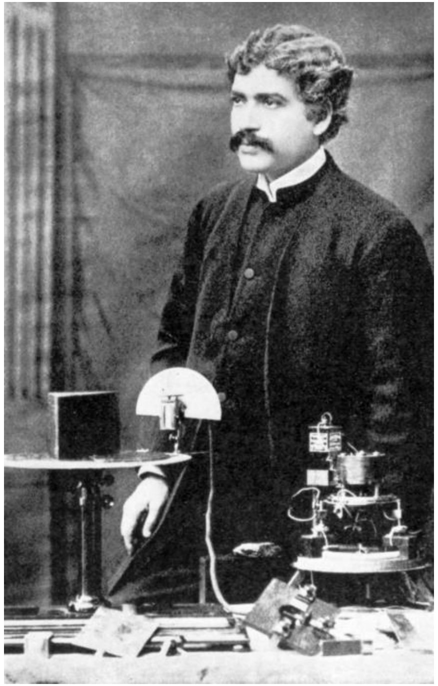
Invention of Radio

Jagadish Chandra Bose (1858 – 1937)



- During a November 1894 public demonstration at Town Hall of Kolkata, Bose ignited gunpowder and rang a bell at a distance using millimetre range wavelength microwaves.
- Bose wrote in a Bengali essay, Adrisya Alok (**Invisible Light**),

"The invisible light can easily pass through brick walls, buildings etc. Therefore, messages can be transmitted by means of it without the mediation of wires."

On **14 September 2012**, Bose's experimental work in millimetre-band radio was recognized as an **IEEE Milestone in Electrical and Computer Engineering**, the first such recognition of a discovery in India

http://theinstitute.ieee.org/technology-focus/technology-history/first-ieee-milestones-in-india/

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Antennas Today…

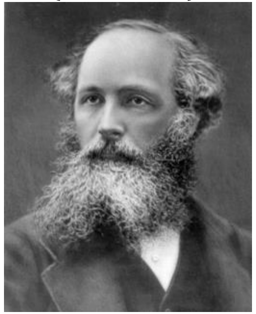
Analyzing Antennas

- Based on Solving Governing Equations of underlying Physics
- Expressed in the form of Differential or integral Equations
- Solution of Governing Equations based on various Boundary Conditions of a specific problem
- Analytical Solutions are possible when the problem at hand is simple enough to apply boundary conditions

Maxwell's Equations for Electromagnetics

Name	Integral equations	Differential equations
Gauss's law	$\oint\!\!\oint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oint\!\!\oint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot \mathrm{d}\boldsymbol{l} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_\Sigma \mathbf{B}\cdot\mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{l} = \mu_0\left(\iint_\Sigma \mathbf{J}\cdot\mathrm{d}\mathbf{S} + \varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_\Sigma \mathbf{E}\cdot\mathrm{d}\mathbf{S}\right)$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial \mathbf{E}}{\partial t}\right)$

James Clerk Maxwell
(1831-1879)



https://en.wikipedia.org/wiki/Maxwell's_equations

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Analyzing Antennas

Solving Maxwell's Equations

- Electromagnetic field behavior is governed by Maxwell's equations
- Expressed in terms of fields (E, H) and sources (J, M)

$$\vec{\nabla} \times \vec{H} = \vec{J}_v + \varepsilon \frac{d\vec{E}}{dt}$$

$$\vec{\nabla} \times \vec{E} = -\vec{M}_v - \mu \frac{d\vec{H}}{dt}$$

$$\vec{\nabla} \bullet \vec{H} = \frac{1}{\mu} \sigma_m$$

$$\vec{\nabla} \bullet \vec{E} = \frac{1}{\varepsilon} \sigma_e$$

Solving for Electric Field in terms of Vector Potential **A** which is obtained using Free Space Green's Function, **G**

$$\mathbf{E} = -j\omega\mu\mathbf{A} + \frac{1}{j\omega\epsilon}\nabla(\nabla \cdot \mathbf{A})$$

$$\mathbf{E} = -j\omega\mu \int_V d\mathbf{r}'\mathbf{G}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}(\mathbf{r}')$$

$$\mathbf{G}(\mathbf{r},\mathbf{r}') = \frac{1}{4\pi}\left[\mathbf{I} + \frac{\nabla\nabla}{k^2}\right] G(\mathbf{r},\mathbf{r}')$$

A = Vector Potential
G = Green's Function

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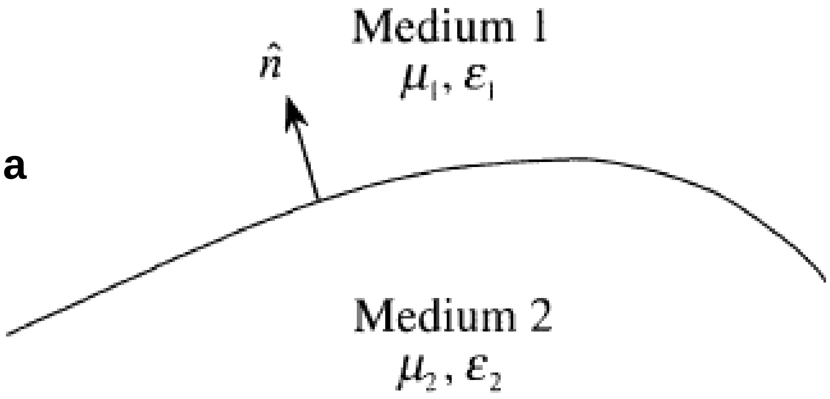
Analyzing Antennas

Solving Maxwell's Equations

- **A complete description of an EM problem should include information about**
  - ✓ **Differential/Integral equations (Maxwell's equations)**
  - ✓ **Boundary conditions**

- **Tangential components of an E field is continuous across an interface and zero on a perfectly conducting (PEC) surface**

- **Tangential component of an H field is discontinuous across an interface (where a surface current exists)**



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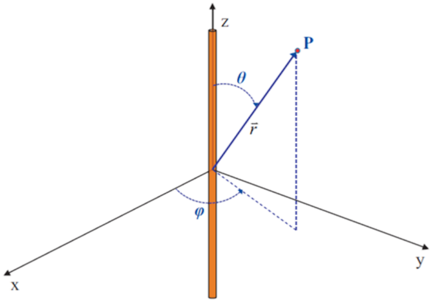
Antennas – Analytical Approach

Dipole Antenna



Vector Potential $\mathbf{A}(x,y,z) = \frac{\mu}{4\pi}\int_c \mathbf{I_e}(x',y',z')\frac{e^{-jkR}}{R}dl'$

$l \ll \lambda$ $\mathbf{I_e}$ is constant $\mathbf{I_0}$ (typically length is less than λ/50) ⇒ $\mathbf{A}(x,y,z) = \hat{z}\frac{\mu I_0 l}{4\pi r}e^{-jkr}$

l is in the range of λ/50 to λ/10

$$\mathbf{I_e}(x'=0,y'=0,z') = \begin{cases} \hat{z}I_0\left(1-\frac{2}{l}z'\right), & 0 \le z' \le l/2 \\ \hat{z}I_0\left(1+\frac{2}{l}z'\right), & -l/2 \le z' \le 0 \end{cases}$$

⇒

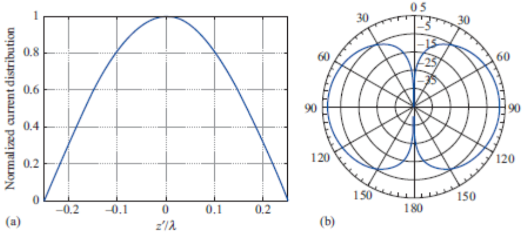
$$\mathbf{A}(x,y,z) = \frac{\mu}{4\pi}\left[\hat{z}\int_{-l/2}^{0} I_0\left(1+\frac{2}{l}z'\right)\frac{e^{-jkR}}{R}dz' + \hat{z}\int_{0}^{l/2} I_0\left(1-\frac{2}{l}z'\right)\frac{e^{-jkR}}{R}dz'\right]$$

l > λ/10

$$\mathbf{I_e}(x'=0,y'=0,z') = \begin{cases} \hat{z}\, I_0 \sin\left[k\left(\frac{l}{2}-z'\right)\right], & 0 \le z' \le l/2 \\ \hat{z}\, I_0 \sin\left[k\left(\frac{l}{2}+z'\right)\right], & -l/2 \le z' \le 0 \end{cases}$$

⇒ ??? Gets more complicated

Current Distribution



Directivity

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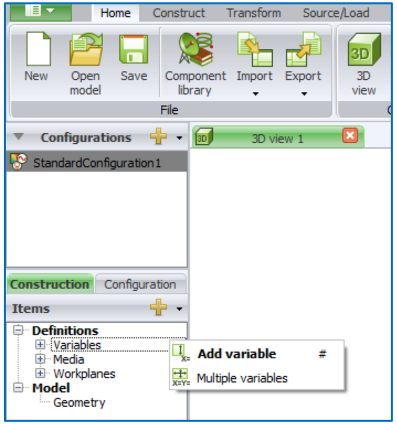
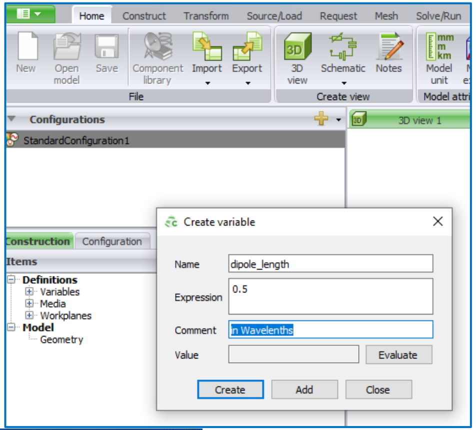
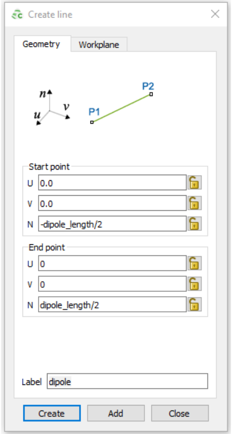
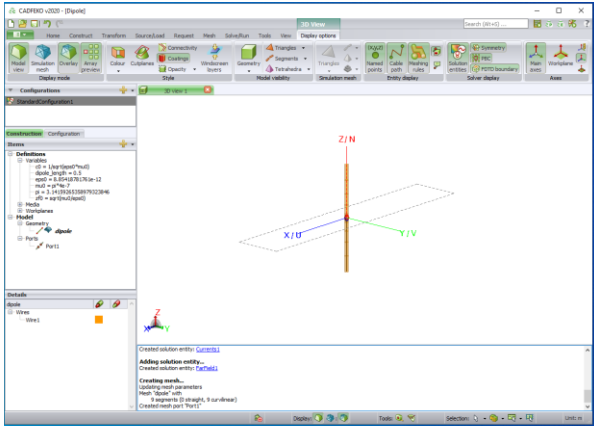
Analyzing Antennas – Modeling and Simulation

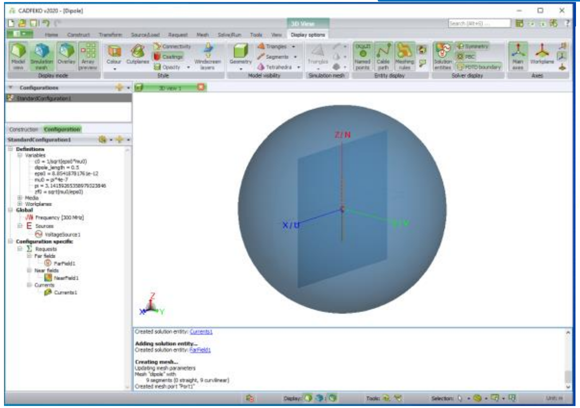
Dipole Antenna

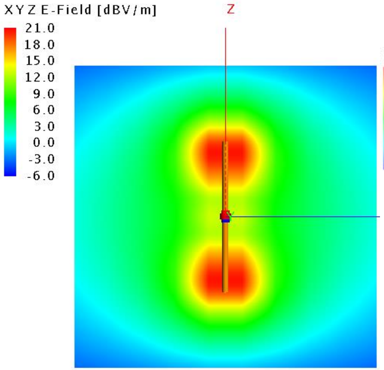


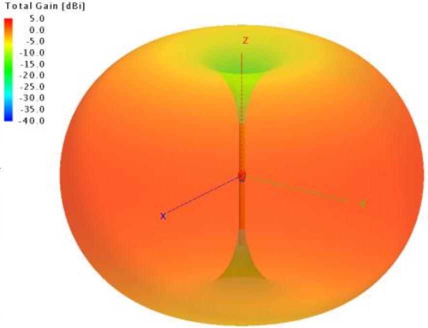


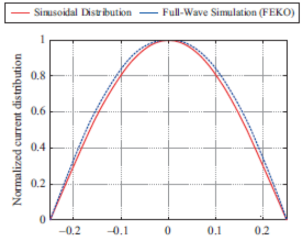












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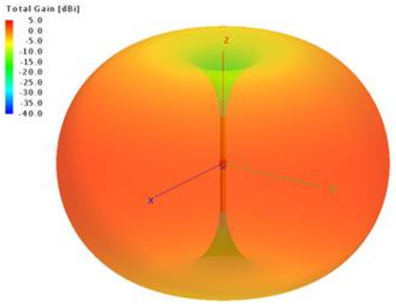
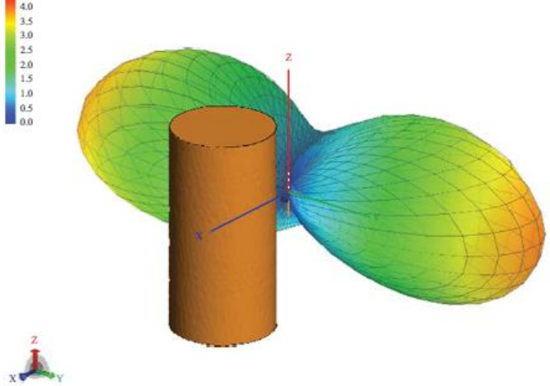
Analyzing Antennas – Modeling and Simulation

Dipole Antenna with Surrounding Environment

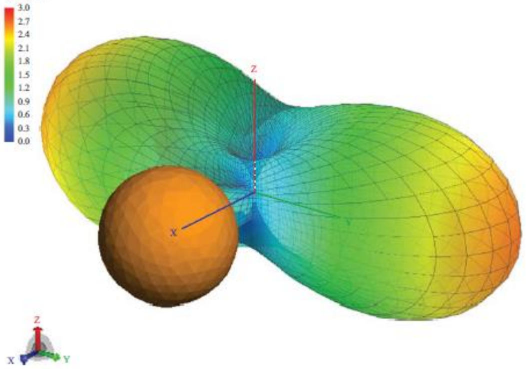
By itself



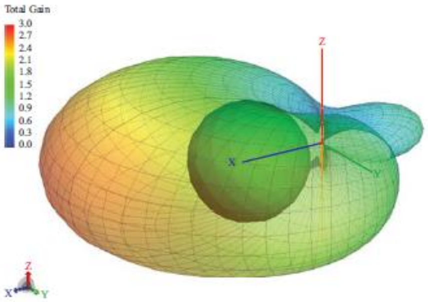
Infront of a Conducting Cylinder



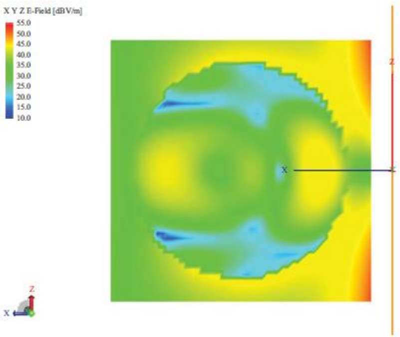
Infront of a Conducting Sphere



Infront of a Dielectric Sphere



Electric Field through the Dielectric Sphere



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COMPUTATIONAL ELECTROMAGNETICS

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Computational Electromagnetics (CEM)

- CEM is the numerical solution of Maxwell's equations
  - CEM has become an indispensable industrial tool

Computational cost (CPU time & memory) must be as low as possible

Computer modeling

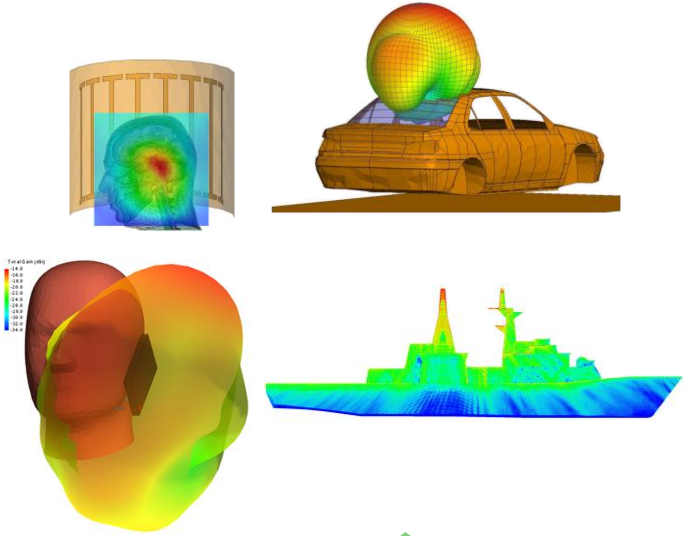
$$\vec{\nabla} \times \vec{H} = \vec{J}_v + \varepsilon \frac{d\vec{E}}{dt}$$

$$\vec{\nabla} \times \vec{E} = -\vec{M}_v - \mu \frac{d\vec{H}}{dt}$$

$$\vec{\nabla} \bullet \vec{H} = \frac{1}{\mu}\sigma_m$$

$$\vec{\nabla} \bullet \vec{E} = \frac{1}{\varepsilon}\sigma_e$$

CEM tool



Numerical analysis

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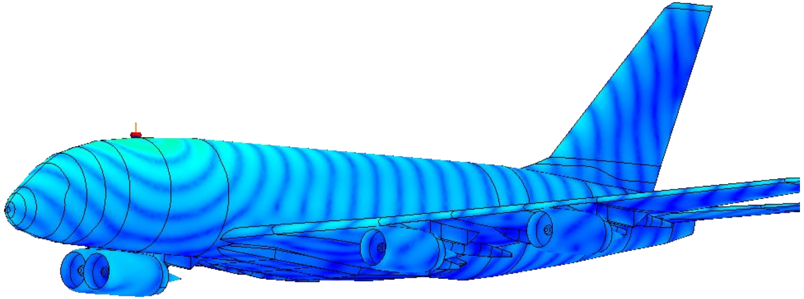
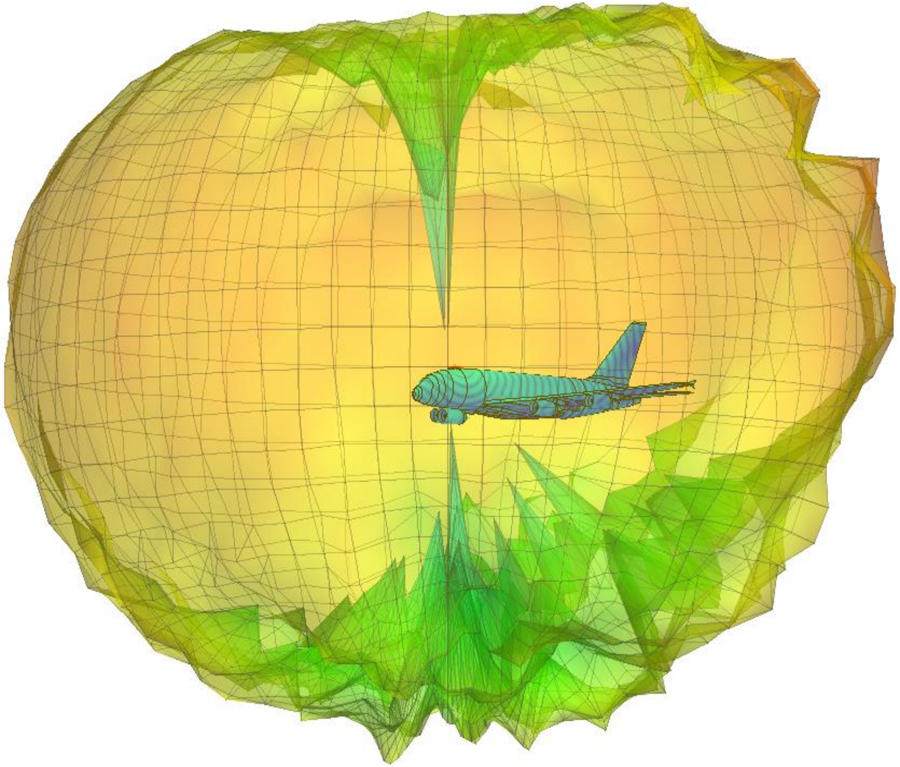
Computational Electromagnetics (CEM)

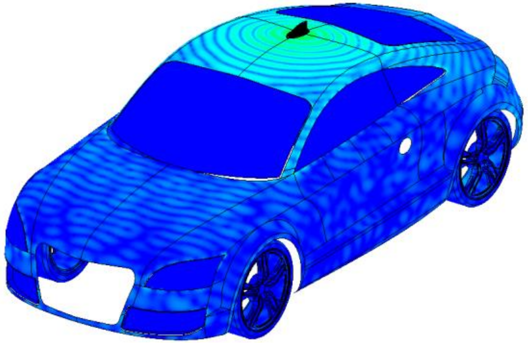
120MHz VHF Comm Antenna

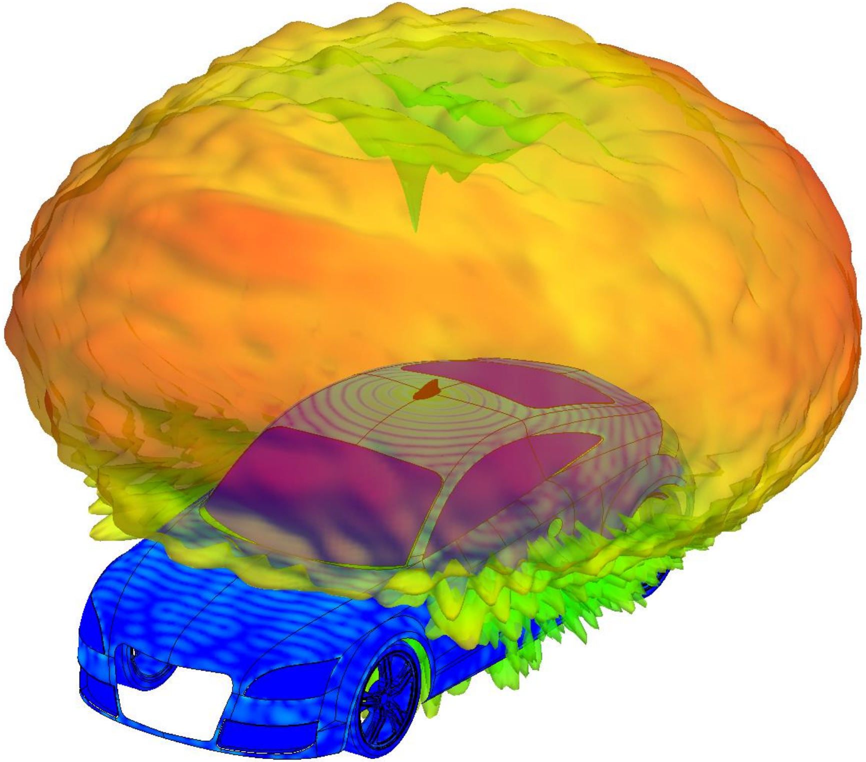




Computational Electromagnetics (CEM)

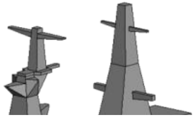
1.8GHz LTE Antenna

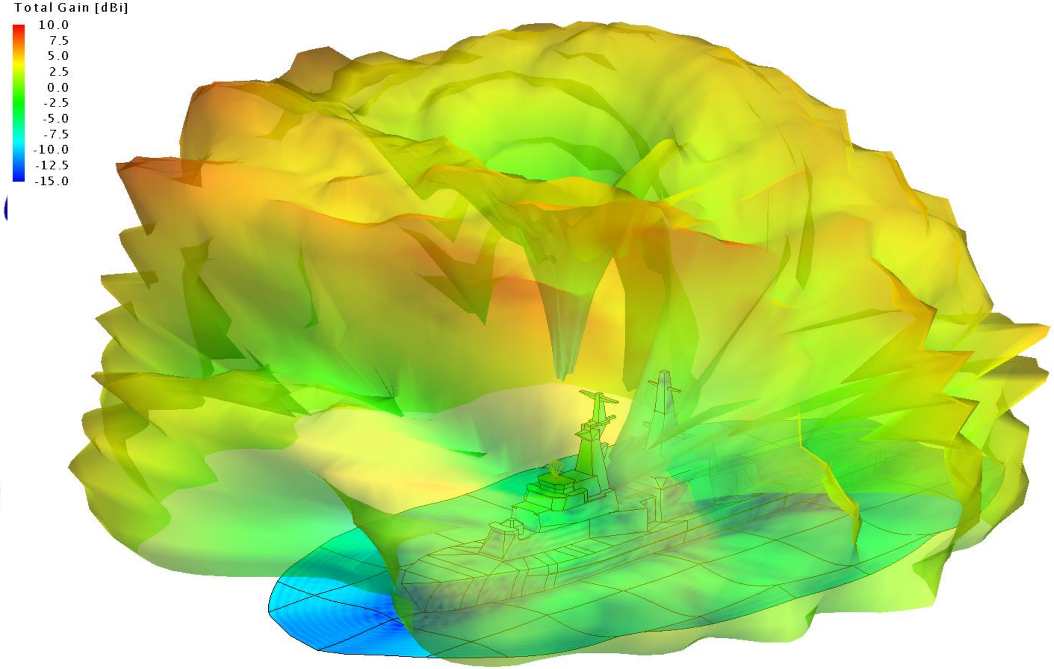


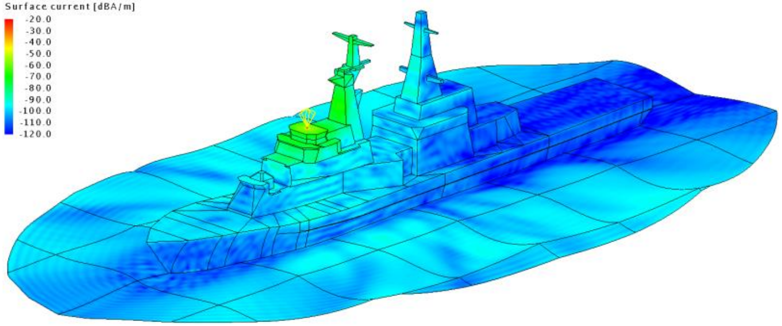


Computational Electromagnetics (CEM)

100MHz – Monocone Antenna







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Altair Antenna Simulation Solutions

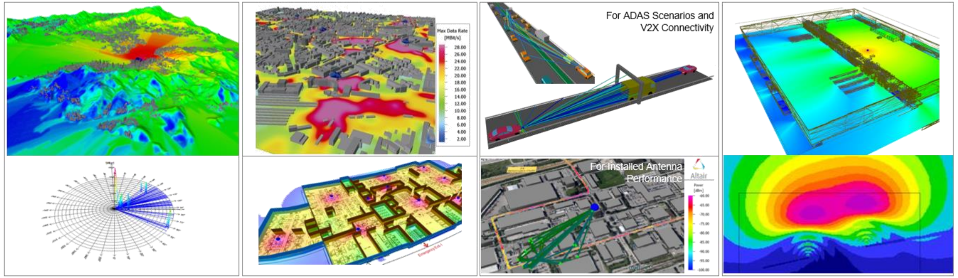
Altair Feko

High Frequency EM Simulations

https://altairhyperworks.com/product/Feko

Altair WinProp

Wave Propagation & Radio Network Planning



https://altairhyperworks.com/product/Feko/WinProp-Propagation-Modeling

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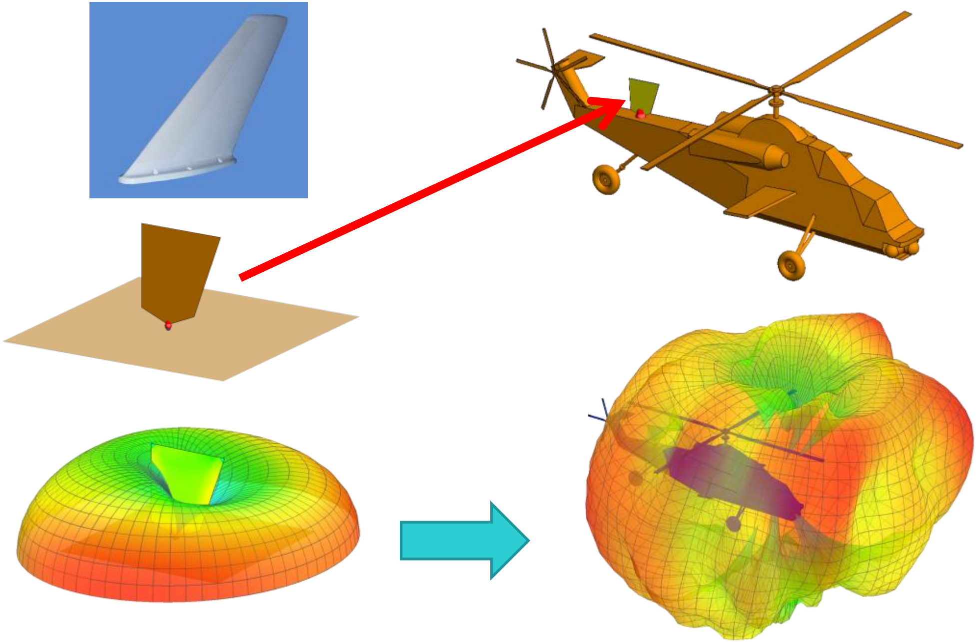
Antennas in Product Development

Altair Feko - High Frequency EM Simulations

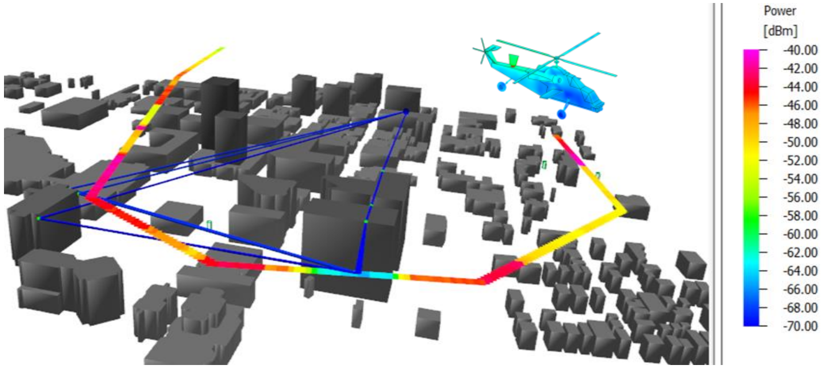
Antenna Design

Antenna Placement



Altair WinProp - Wave Propagation & Wireless Network Planning

Virtual Flight Test



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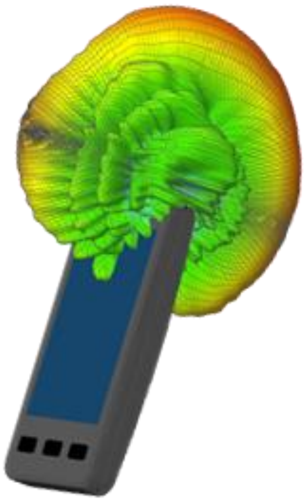
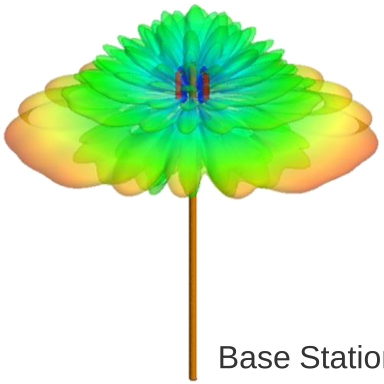
Antennas in Product Development

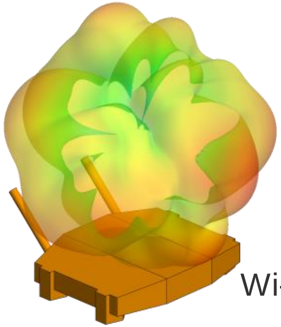
Altair Feko - High Frequency EM Simulations



Mobile Device



Base Station



Wi-fi Router

Altair WinProp - Wave Propagation & Wireless Network Planning

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CEM SOLVER TECHNOLOGIES

CEM Solver Technologies

A basic knowledge of CEM Solver Technologies is required to understand the advantages and disadvantages of each and how these affect their applicability to solve different classes of antenna problems.

- **Full Wave Solutions**
  - Method of Moments (MoM)
  - Multilevel Fast Multipole Method (MLFMM)
  - Finite Element Method (FEM)
  - Finite Difference Time Domain (FDTD)

Full wave solutions solve Maxwell Equations accurately and provide reliable results provided a good CAD model and mesh is available.

- **Asymptotic Solutions**
  - Physical Optics (PO)
  - Large Element Physical Optics (LE-PO)
  - Ray Lunching Geometrical Optics (RL-GO) (also known as Shooting and Bouncing Ray – SBR method)
  - Uniform Theory of Diffraction (UTD)

Asymptotic solutions also solve Maxwell Equations, but with appropriate assumptions and approximations. They also can provide reasonably accurate results, provided the approximations and assumptions are properly considered during the simulation process.

CEM Solver Technologies

- **Hybrid Solutions**
  - FEM/MoM/MLFMM
  - MoM/PO
  - MLFMM/PO
  - MoM/LE-PO
  - MLFMM/LE-PO
  - MoM/RL-GO
  - MoM/UTD

While full wave solutions are accurate, they are computationally expensive when applied to electrically large structures.

While asymptotic solutions may provide an alternative, they may not be suitable for modeling complex antenna geometries.

↓

Hybrid solutions that combine, both full wave and asymptotic solutions can facilitate simulation of electrically large antenna problems with less computational resources, but at the same time providing required accuracy.

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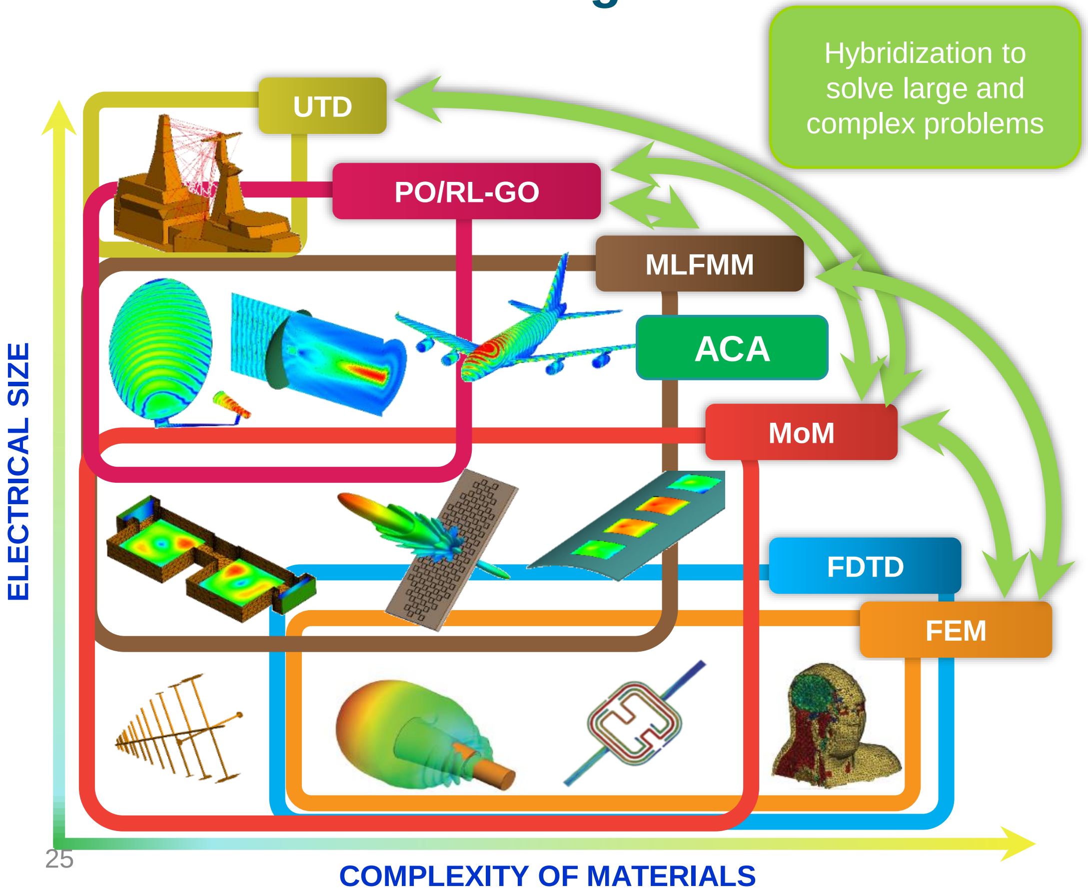
CEM Solver Technologies



Asymptotic Solutions
(high-frequency approximation)

Full-wave Solutions

(physically rigorous solution)

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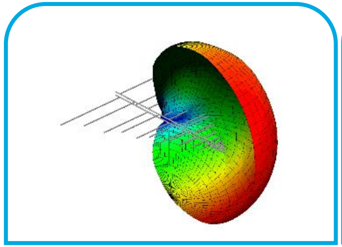
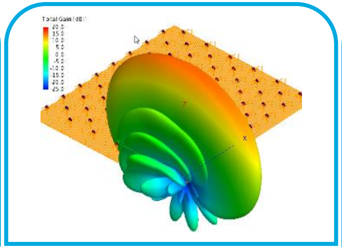
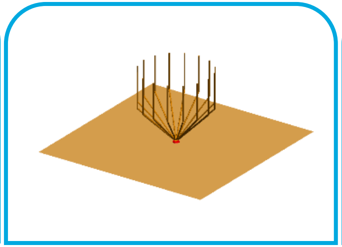
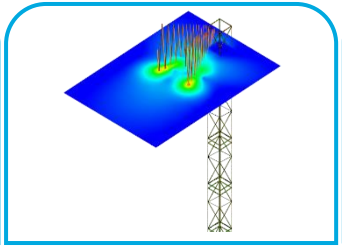
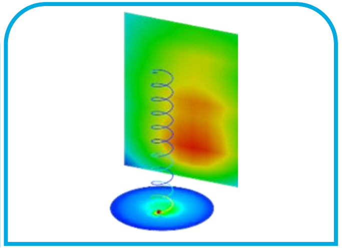
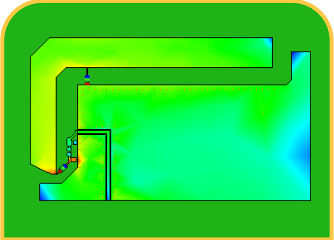
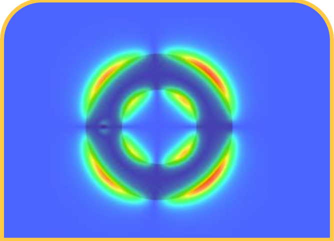
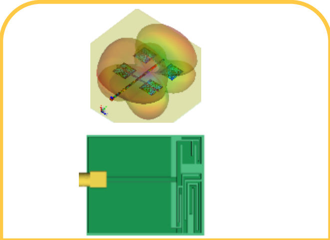
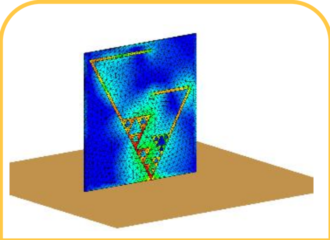
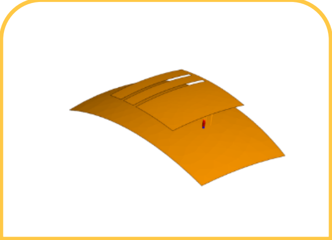
Antennas

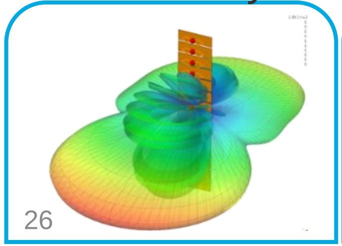
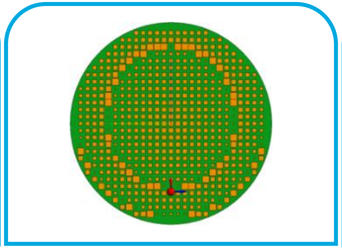
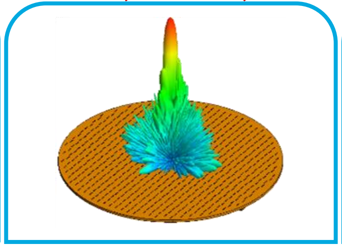
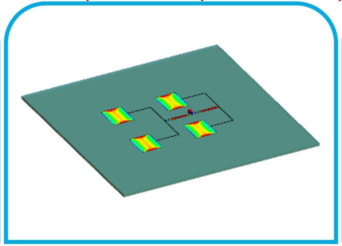
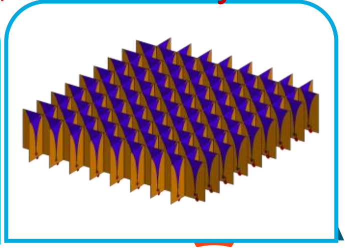
Wire Antennas – MoM and MLFMM

Planar Antennas – Planar Green's Function, MoM, FEM, FDTD

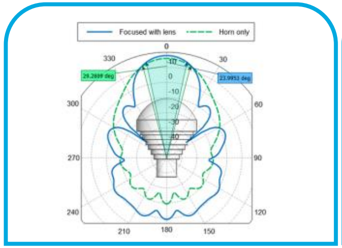






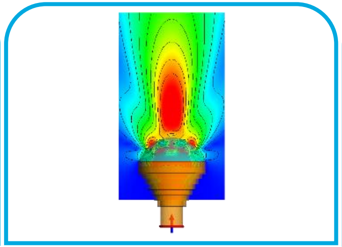
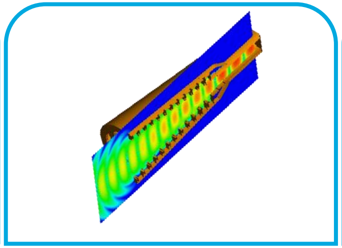
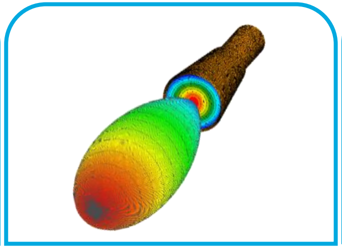
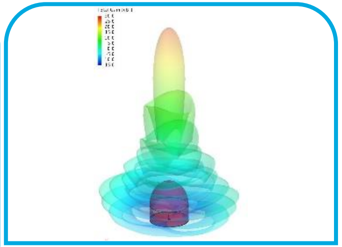
Antenna Arrays – Planar Green's Function, MoM, MLFMM, FEM, FDTD, Finite Array Tool

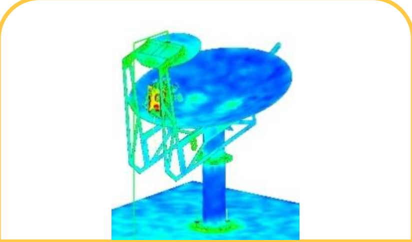
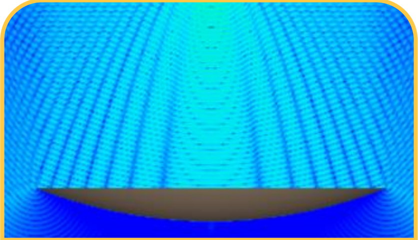
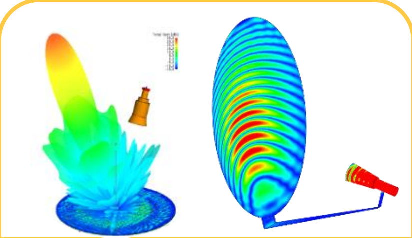
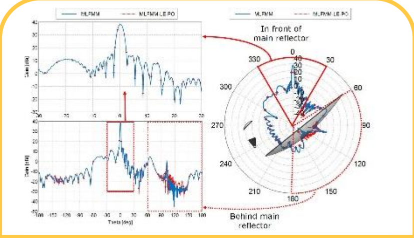
Antennas

Horns, Apertures and Lenses – MoM, MLFMM, FEM and RL-GO

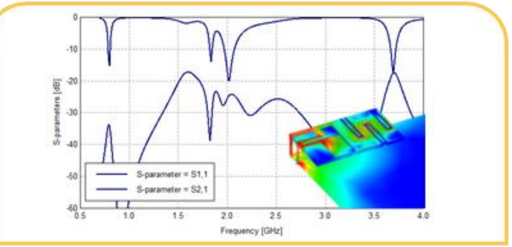


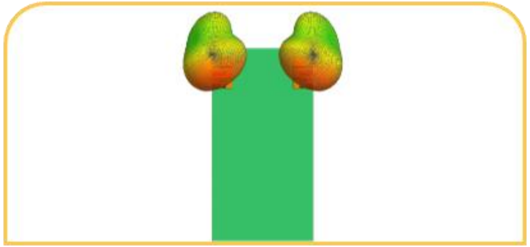
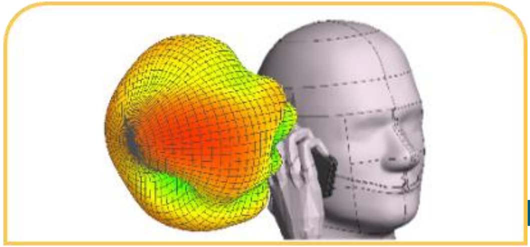





Reflector Antennas – MLFMM, PO, LE-PO, RL-GO

Mobile and Wireless Antennas – MoM, FEM, FDTD



FULL WAVE SOLUTIONS

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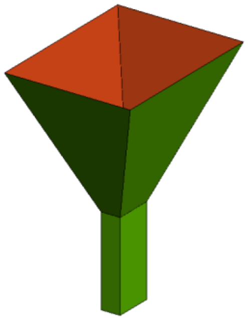
Full Wave Solutions

	Field method **(Differential form of Maxwell's Equations)**	**Source method** **(Integral form of Maxwell's Equations)**
Base	Electromagnetic fields	Currents and charges
Equations	Differential equations	Integral equations
Discretization	Volumetric (Tetrahedral, Voxels etc)	Surface (segments and triangles)
Radiation Boundary (open problem)	Special Absorbing Boundary Conditions (ABCs) must be introduced ("Air Box" around the radiating structure.)	Exact treatment by using free space Green's Function (No "Air Box" Needed)
Solutions	Finite Element methods (FEM) Finite Difference Time Domain (FDTD)	Method of Moments (MoM) Adaptive Cross Approximation (ACA) Multilevel Fast Multipole Method (MLFMM)

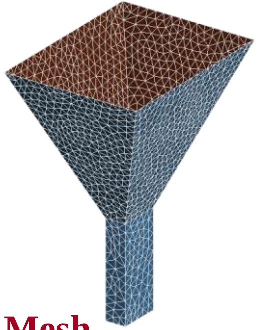
METHOD OF MOMENTS

Method of Moments (MoM)



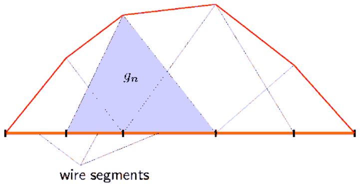
Geometry

- 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



Mesh

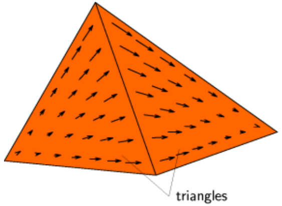
$$Z\ I = V$$



Linear Basis Functions on wire segments

Z = NXN complex matrix
I = Unknown current vector
V = Known Excitation vector

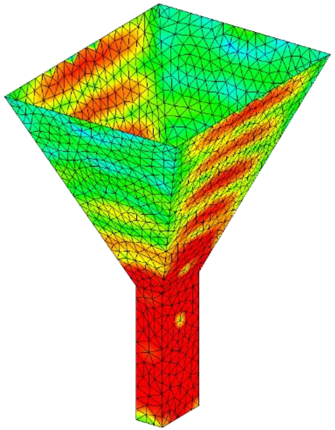
- Solving this equation, unknown currents on each triangle is found



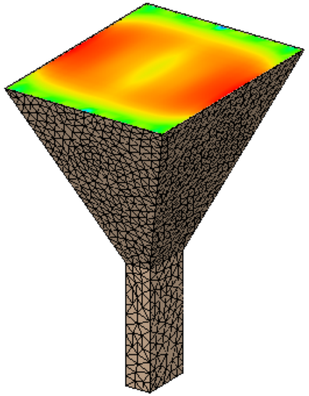
RWG Basis Functions on triangles

Method of Moments (MoM)

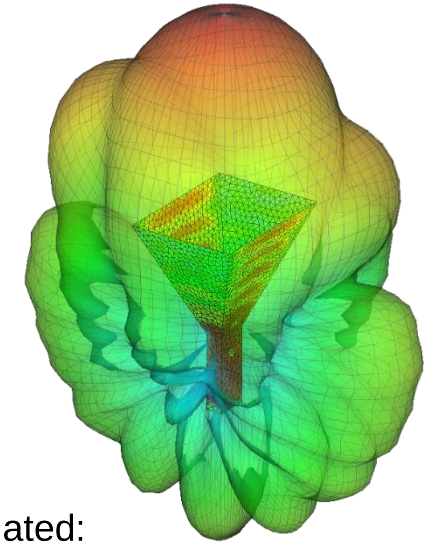
Surface Currents



Near Fields



Radiation Patterns



Antenna Characteristics can be found from the currents calculated:

- Near- or Far-fields
- Input impedances
- S-parameters etc

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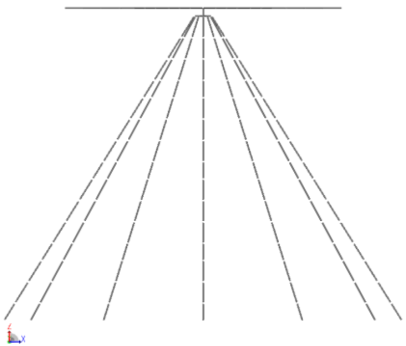
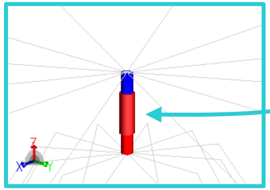
MoM Examples - Wire Discone Antenna

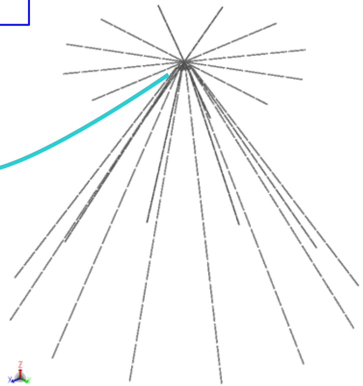
- Lowest -10 dB S11 frequency = 50 MHz



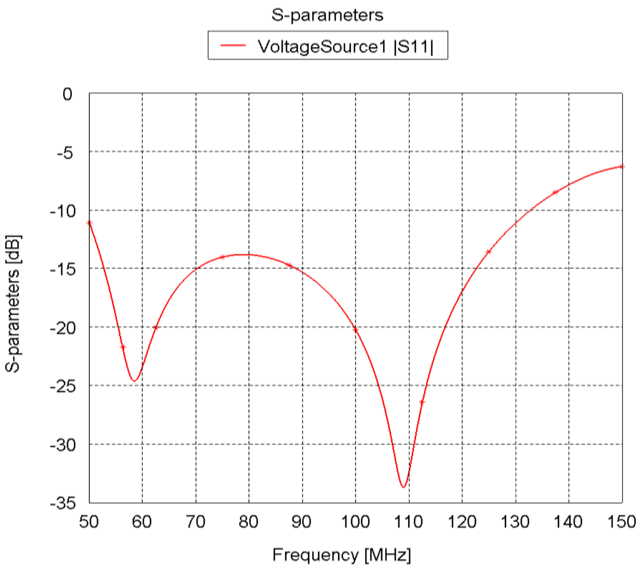


Feeding with voltage source at wire port

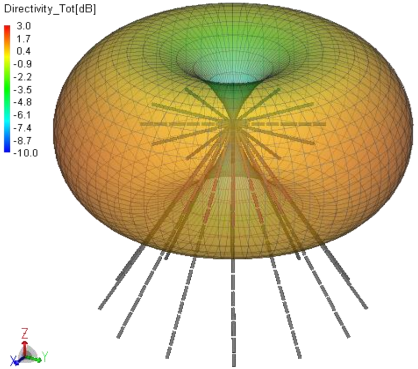
MoM mesh

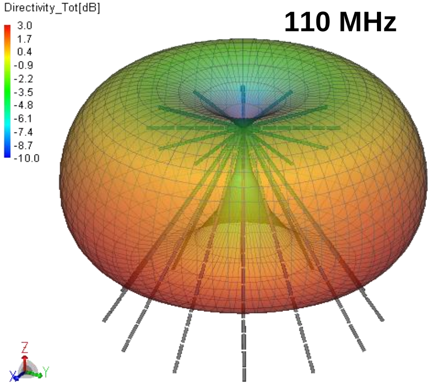


S11 vs. frequency



60 MHz





110 MHz

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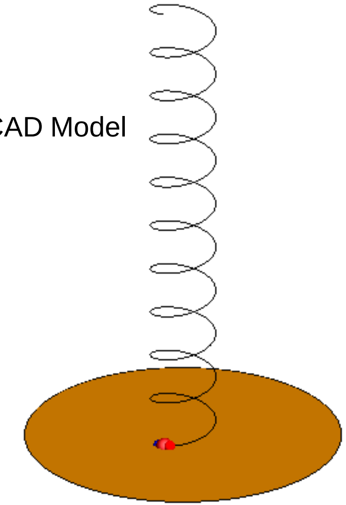
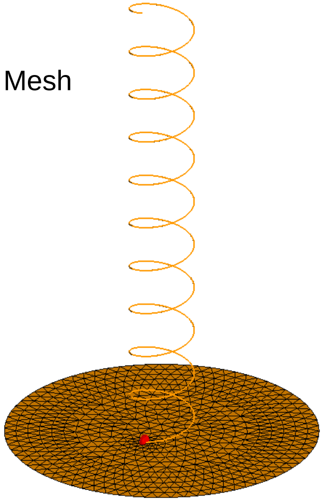
MoM Examples – Broadband Helix

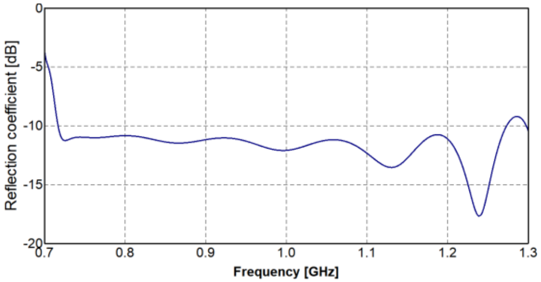
Frequency Band: 800MHz to 1.2 GHz

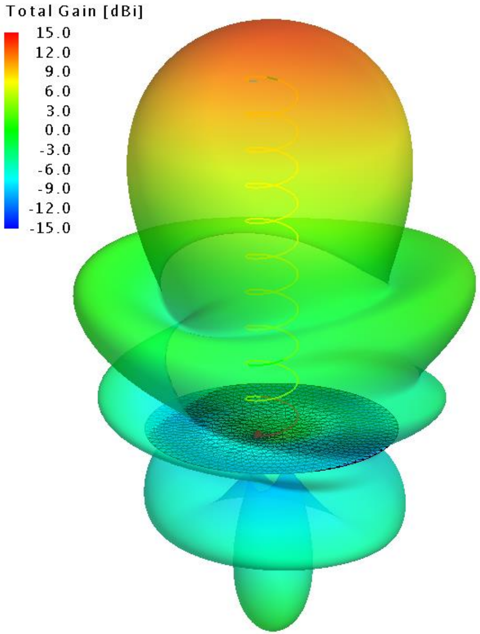
CAD Model



MoM Mesh







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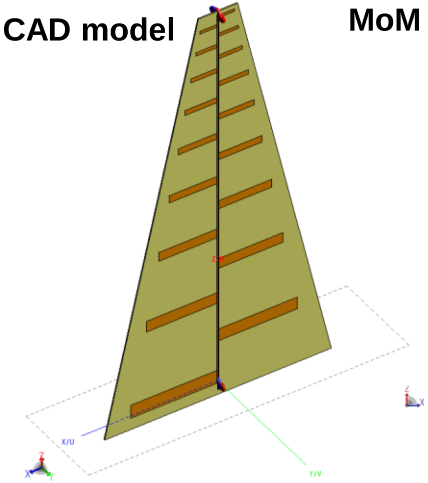
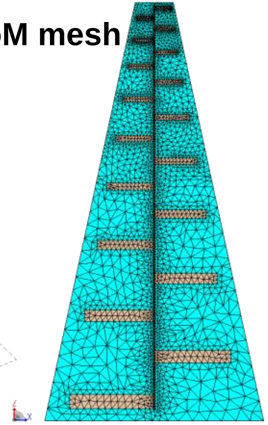
MoM Examples - Printed Log Periodic Antenna

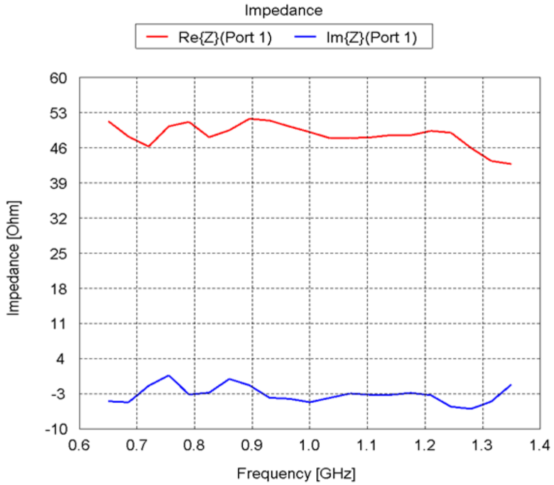
- **Finite substrate:**
  - FR4
  - h = 1.5 mm
  - ε_r = 4.35
  - 18 elements
- **Design:**
  - Center frequency = 1 GHz
  - Bandwidth = 70%
  - Gain = 9 dBi

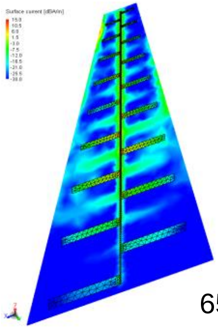
CAD model



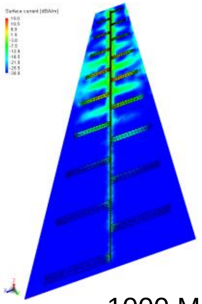
MoM mesh



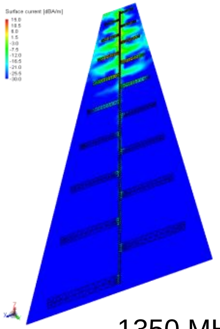




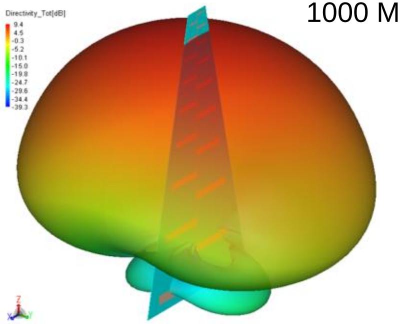
650 MHz



1000 MHz



1350 MHz



1000 MHz

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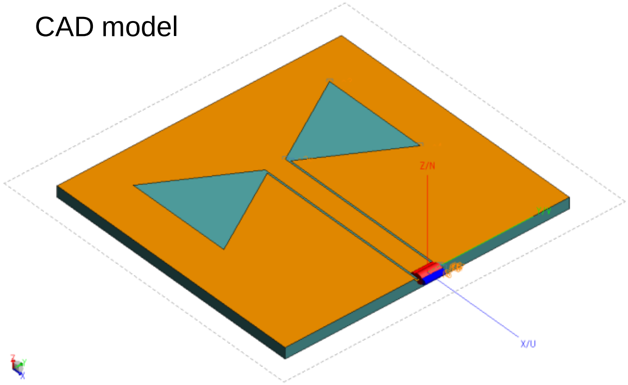
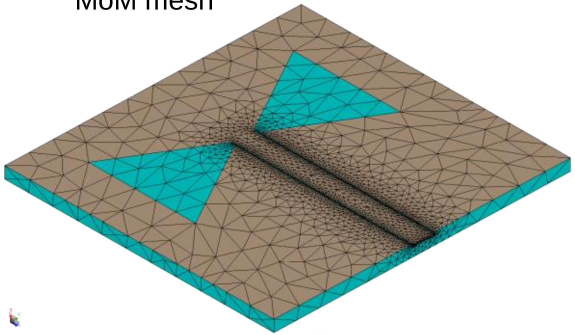
MoM Examples – CPW fed Bowtie Antenna

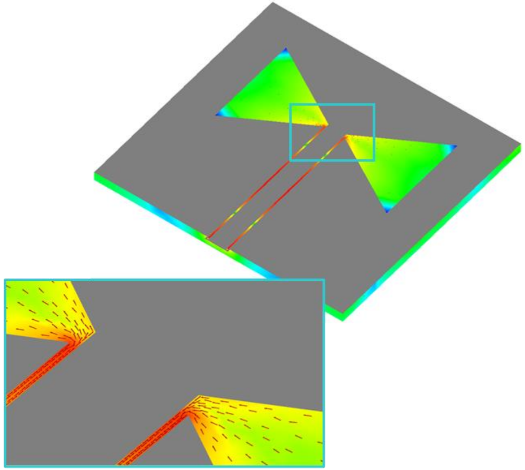
- **Finite substrate:**
  - Rogers – RT/duroid - 5880
  - h = 1.575 mm
  - ε_r = 2.2
- **Design:**
  - Center frequency = 9 GHz
  - 50 Ω
  - Expect wide band match

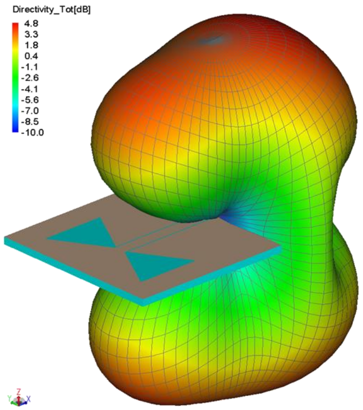
CAD model

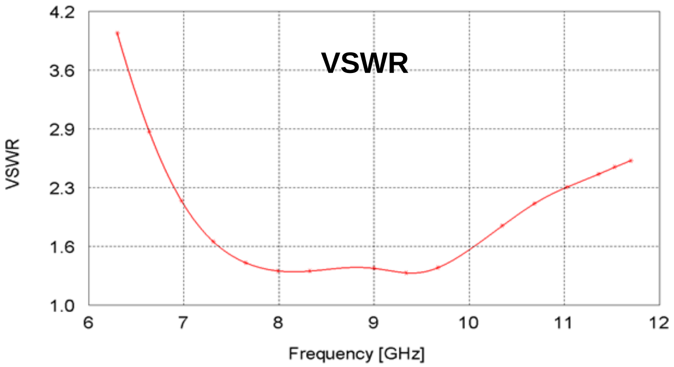


MoM mesh









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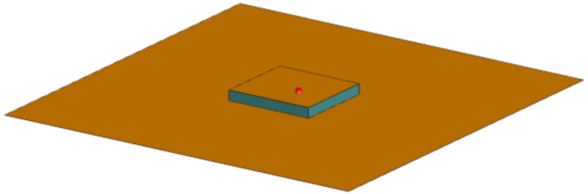
MoM Examples – Microstrip Patch Antenna

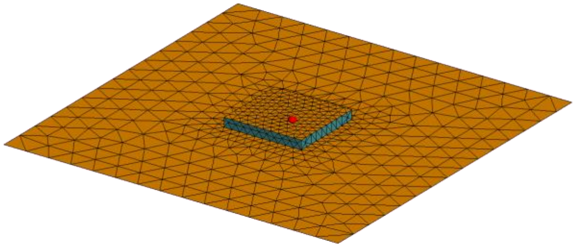
- **Finite substrate:**
  - h = 7.5 mm
  - ε_r = 2.0
  - Ground Plane = 277 mm

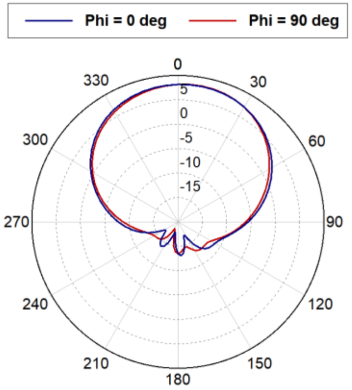
- **Design:**
  - Frequency = 1.62 GHz
  - 50 Ω

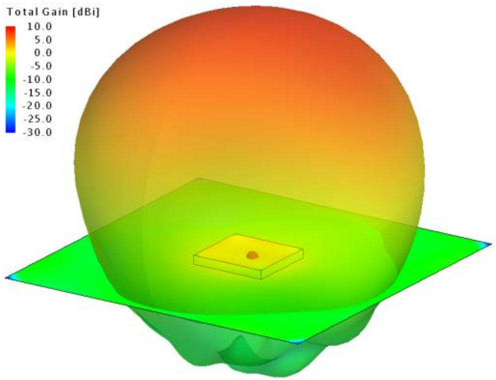
CAD model

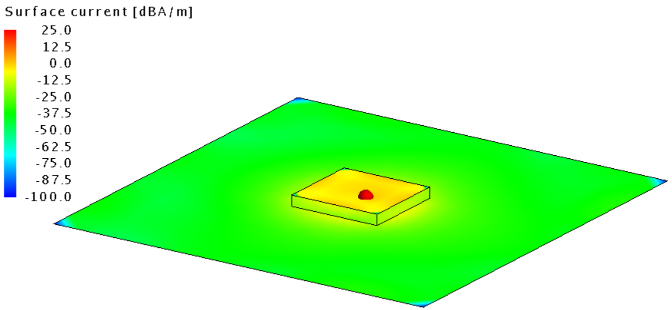


MoM mesh









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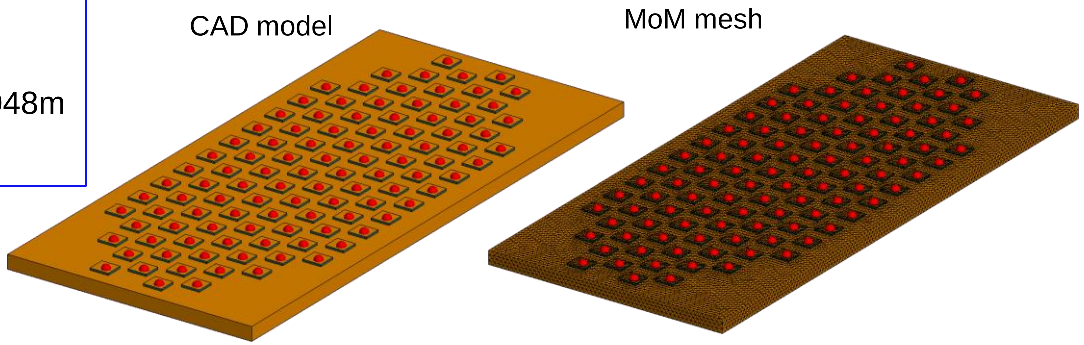
MoM Examples – Microstrip Patch Antenna Array

Array:

- 106 elements
- Size of the Panel = 1.8796m x 0.8636m x 0.048m
- Frequency = 1.62 GHz



Triangles: 47,148
Number of Unknowns = 131,565

Z Matrix Size = 131, 565 x 131, 565 (Complex numbers)

MoM Memory Requirement = 125 GBs

Limitation of Computer Hardware used:

Dell Precision 5720
3.70GHz quad core 64-bit processor with 4 cores
Memory of 64GBs
Microsoft Windows 10 Operating System.
(< US $3,000)

→ **MLFMM**

MULTILEVEL FAST MULTIPOLE METHOD
MLFMM

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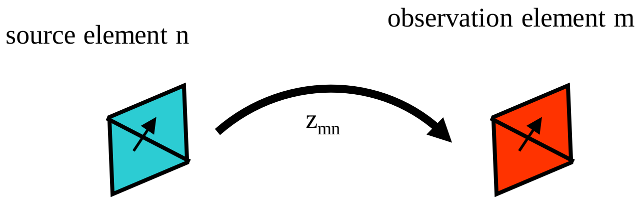
Computational Complexity of MoM

MoM based on the solution of a system of linear equations

$$\mathbf{Z}\,\mathbf{I} = \mathbf{V} \quad \Rightarrow \quad \mathbf{I} = \mathbf{Z}^{-1}\,\mathbf{V}$$

Impedance matrix Z describes interaction of n.th element with m.th element

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



→ LU-decomposition requires $O\,(N^3)$ operations and $O\,(N^2)$ memory

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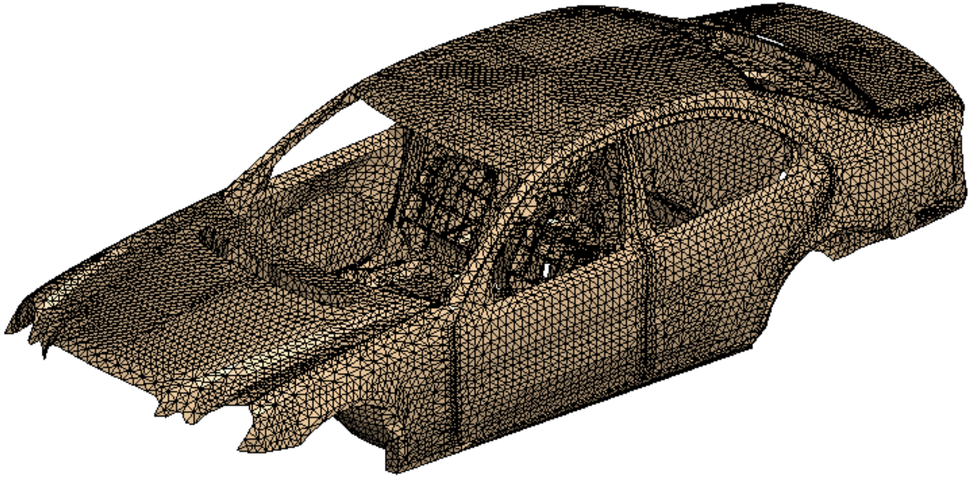
Resource Requirement

Example:
Automotive simulation
at 2 GHz instead of 1 GHz:

$$f \longrightarrow 2f$$
$$N \longrightarrow 4N$$

Complexity	Factor
$O(N^3)$	64
$O(N^2)$	16
$O(N)$	4
$O(N \log N)$	$4 \cdot \left(1 + \frac{\log 4}{\log N}\right) < 5$
$O(N \log^2 N)$	$4 \cdot \left(1 + \frac{2\log 4}{\log N} + \frac{\log^2 4}{\log^2 N}\right) < 6$



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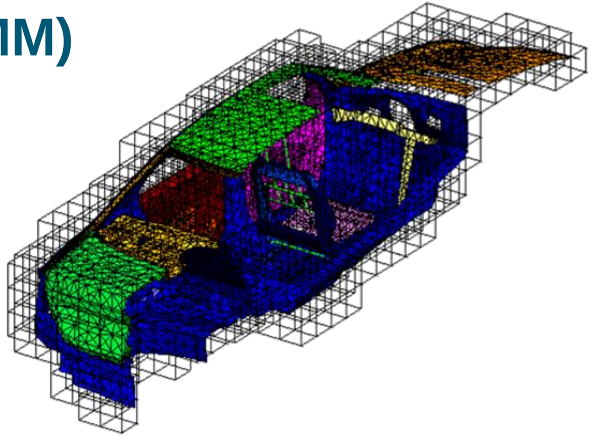
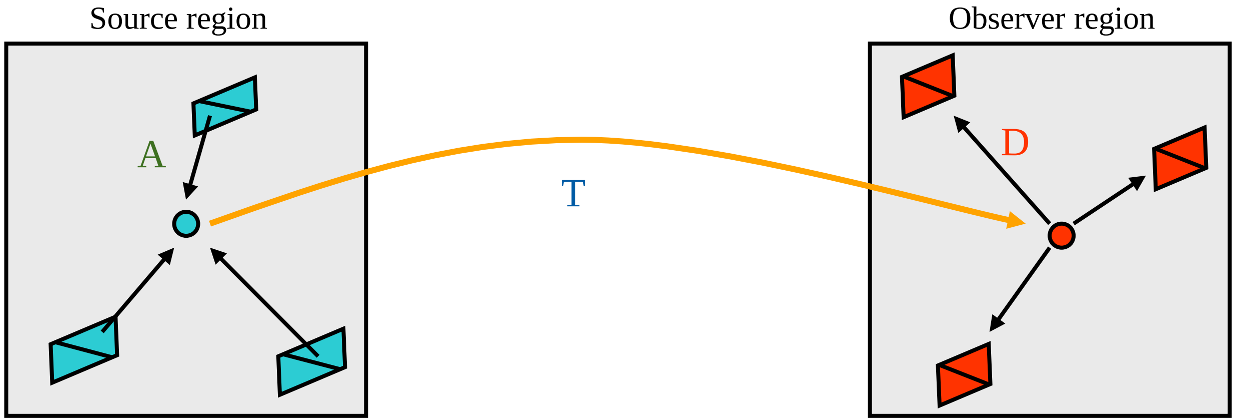
Multilevel Fast Multipole Method (MLFMM)

- **Multilevel implementation**:
  - Divide space into boxes
  - Aggregation (A)
  - Translation (T)
  - Disaggregation (D)





Resource Requirement

Example:
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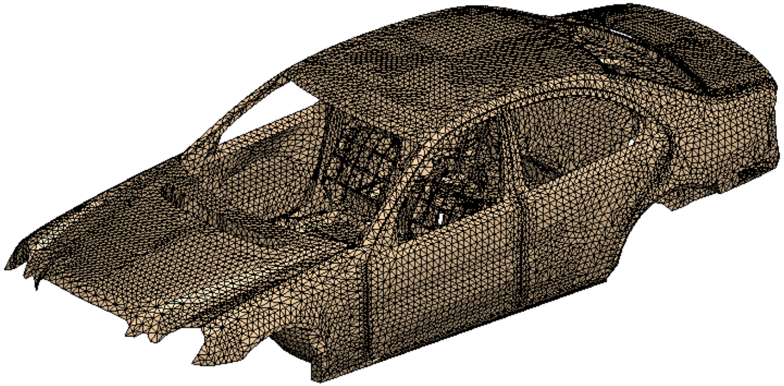
at 2 GHz instead of 1 GHz:

$f \longrightarrow 2f$

$N \longrightarrow 4N$



Complexity	Factor
$O(N^3)$	64
$O(N^2)$	16
$O(N)$	4
$O(N \log N)$	$4 \cdot \left(1 + \frac{\log 4}{\log N}\right) < 5$
$O(N \log^2 N)$	$4 \cdot \left(1 + \frac{2\log 4}{\log N} + \frac{\log^2 4}{\log^2 N}\right) < 6$

→ MLFMM

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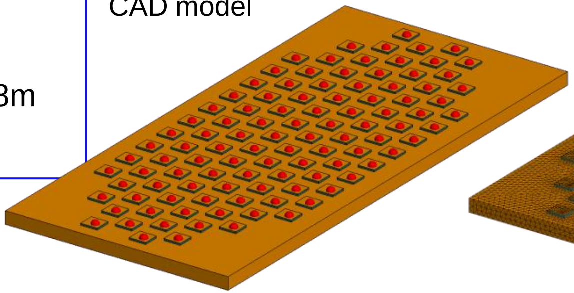
MLFMM – Microstrip Patch Antenna Array

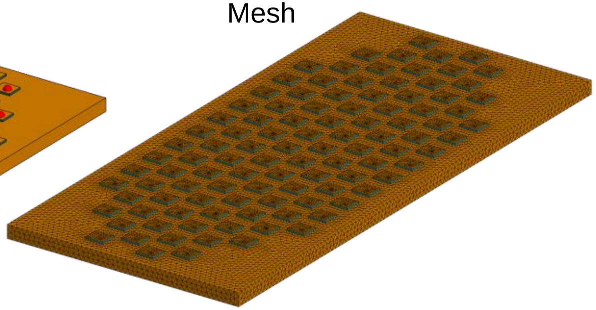
Array:

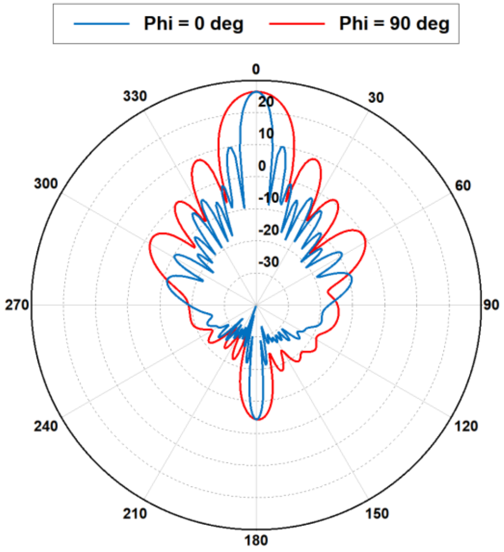
- 106 elements
- Size of the Panel = 1.8796m x 0.8636m x 0.048m
- Frequency = 1.62 GHz

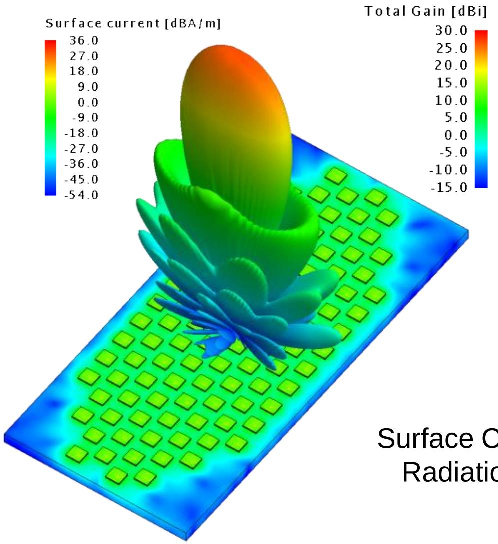
CAD model



Mesh







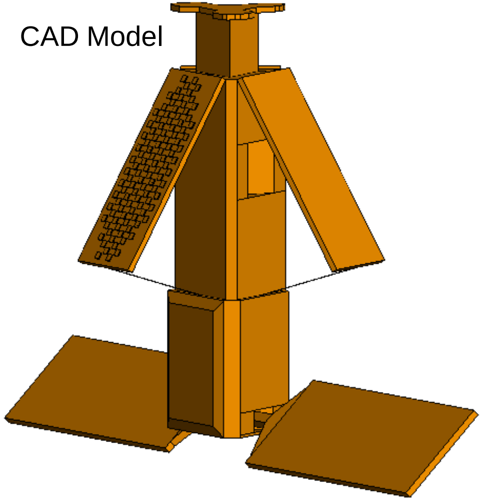
Surface Currents and Radiation Pattern

Triangles: 47,148
Number of Unknowns = 131,565

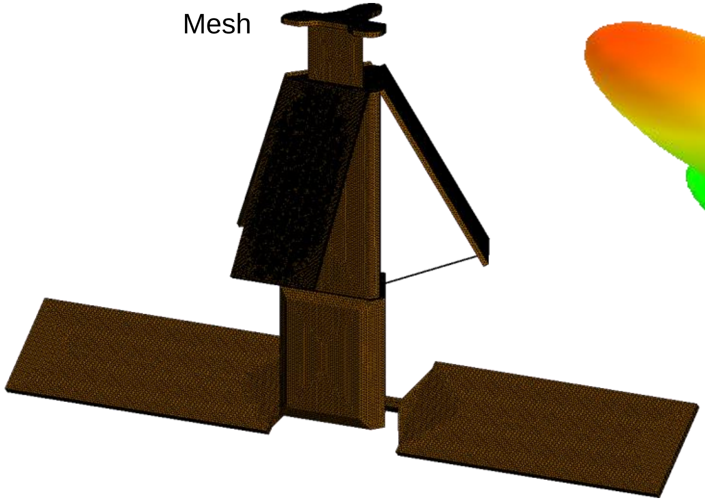
Z Matrix Size = 131, 565 x 131, 565 (Complex numbers)
MoM Memory Requirement = 125 GBs
MLFMM Memory Requirement = 11 GBs !!
10 mins !!

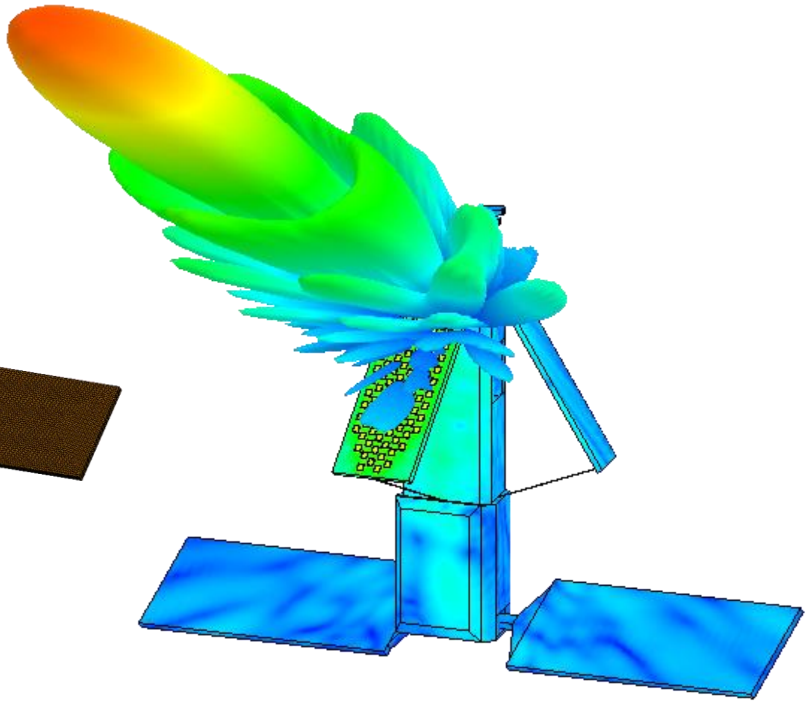
MLFMM – Microstrip Patch on A Satellite

CAD Model



Mesh





Triangles: 216,909

Number of Unknowns = 376, 722
Z Matrix Size = 376, 722 x 376, 722 (Complex numbers)
MoM Memory Requirement ~ 1 TBs

MLFMM Memory Requirement = 11 GBs !! In 47 mins !!

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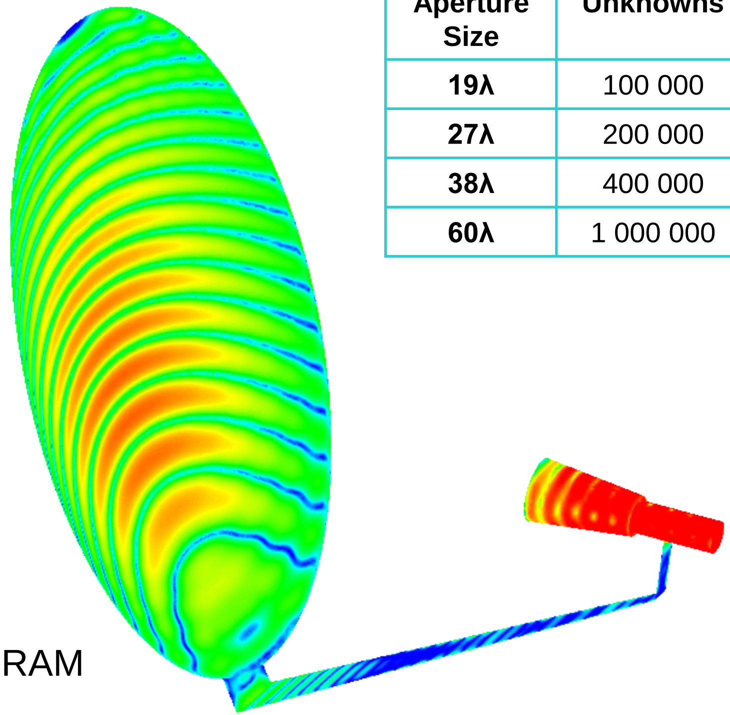
MLFMM - Analysis of a Reflector Antenna

- **Problem description:**
  - Offset parabolic reflector
  - Cylindrical horn
  - Support structure
  - 12.5 GHz
  - **18 inch aperture (19 λ)**
- **Solution:**
  - 94 000 unknowns
  - Solved with MLFMM
  - 1.2 GByte RAM
  - MoM solution would require 134 GByte RAM

Aperture Size	Unknowns	Memory
19λ	100 000	1 GB
27λ	200 000	2 GB
38λ	400 000	4.5 GB
60λ	1 000 000	12 GB



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FINITE ELEMENT METHOD
FEM, FEM/MOM AND FEM/MLFMM

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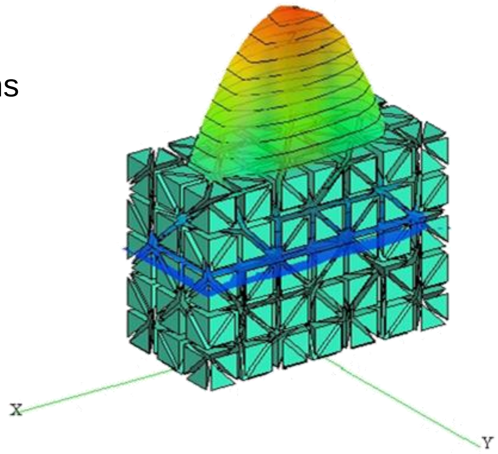
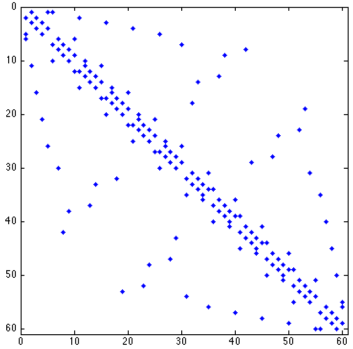
What is the FEM?

- **FEM** = Finite Element Method
- **Full-wave method**
- Solves the differential form of **Maxwell's equations**:
  - Volume discretization
  - Generates Sparse matrix
- **Advantages:**
  - Well-suited to highly inhomogeneous regions
  - 3D Anisotropic Materials
  - Memory efficient

- **Disadvantages of using only FEM**:
  - Numerical dispersion
  - Entire problem space discretized
  - Requires a solution to a large set of linear equations
  - No intrinsic radiation boundary condition as with MoM
  - Requires artificial Absorbing Boundaries (normally referred to as “Air Box” for radiation problems





Sparse Matrix

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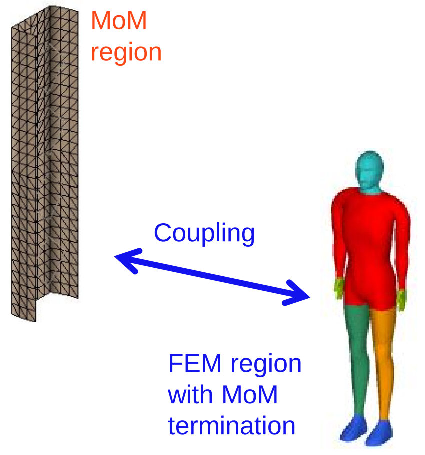
What is Hybrid FEM-MoM?

- **MoM** is ideal for radiation and coupling analysis
- **MoM/SEP →** not optimal for HIGHLY inhomogeneous, geometrically complex dielectric bodies
- **FEM-MoM** uses surface integral equation as radiation boundary condition to FEM (tangential field continuity)
- Not unnecessary to discretize of **3D free-space ("white space")**
- **Best of both worlds:**
  - Use FEM for efficient modelling of inhomogeneous dielectrics
  - Use MoM for efficient, accurate modelling of complex wires, metallic surfaces, sources of radiation and open spaces
- **FEM-MLFMM** is same as **FEM-MoM →** more efficient for electrically large MoM

Example: base station radiation hazard analysis



$$\hat{n} \times \vec{E}^{\mathrm{FEM}}\Big|_{\partial\Omega} = \hat{n} \times \vec{E}^{\mathrm{MoM}}\Big|_{\partial\Omega}$$

$$\vec{J}_s^{\,\mathrm{FEM}} = -\vec{J}_s^{\,\mathrm{MoM}}$$

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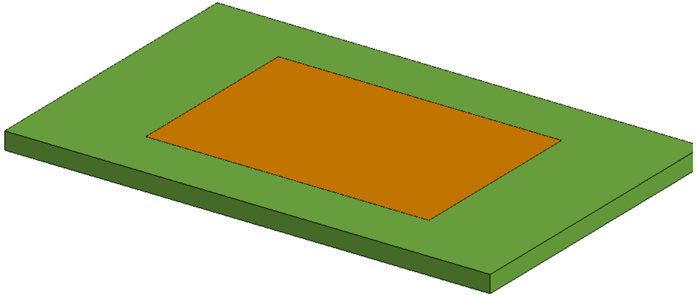
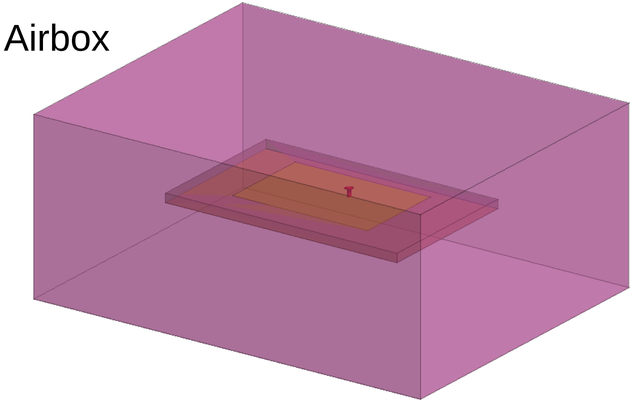
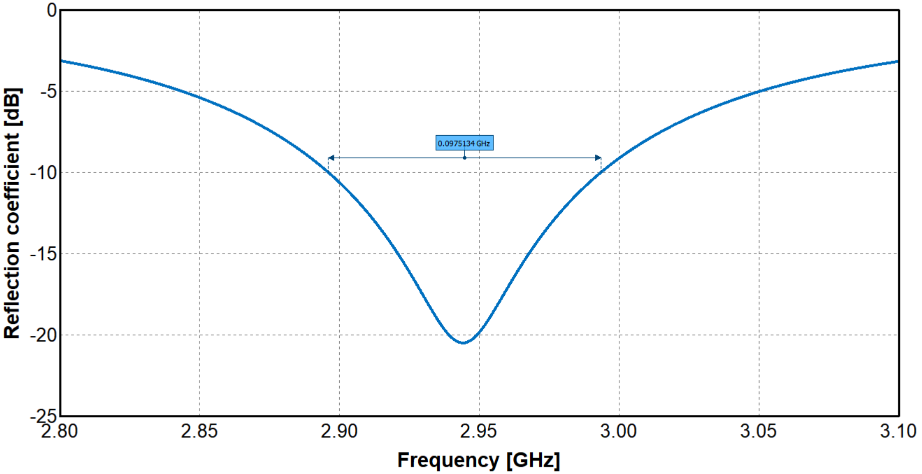
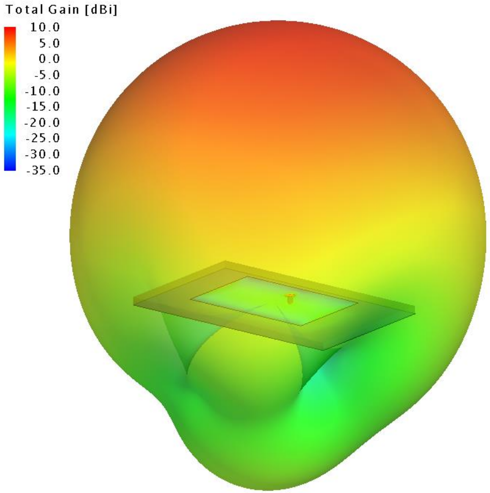
FEM Example – Microstrip Patch Antenna

Design:
ε_r=2.2
Patch = 31.18 x 46.64
Substrate = 50 x 80 x 2.87
Frequency ~ 2.8 to 3.1 GHz

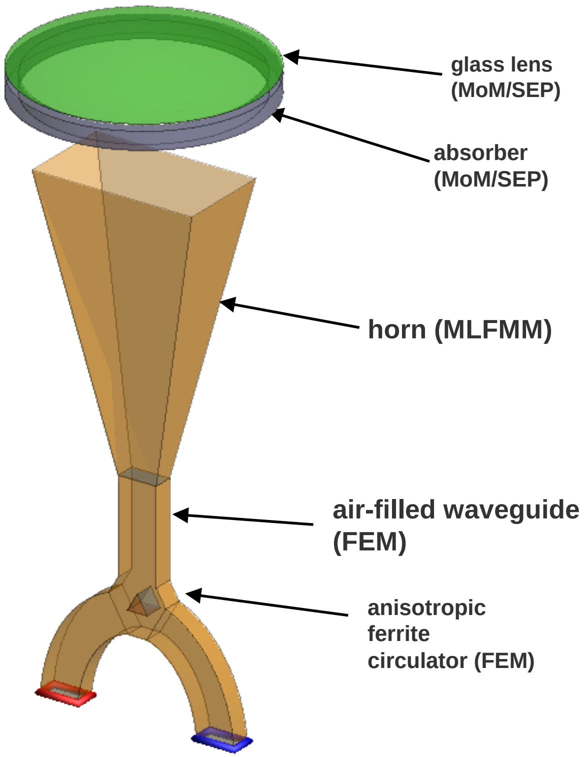




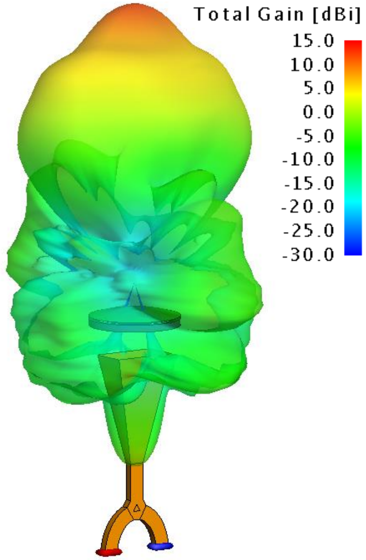


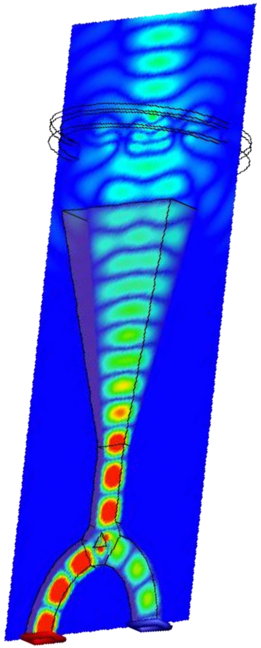


Hybrid FEM-SEP-MoM (MLFMM)



- Strengths of the Hybrid **FEM-SEP-MoM (MLFMM)**
  - Well suited to models with inhomogeneous dielectrics and large homogeneous dielectrics
  - Combines strengths of **FEM** and **SEP** and **MoM/MLFMM** solutions !





FINITE DIFFERENCE TIME DOMAIN METHOD
FDTD

Finite Difference Time Domain - FDTD

- Solves the differential form of Maxwell's equations
- Volume discretization
- Traditional advantages
  - Inhomogeneous materials easily accommodated.
  - 3D Anisotropic Materials
  - Memory efficient
  - GPU Friendly
- Traditional disadvantages
  - Boundary condition application as a stair step.
  - Numerical dispersion of propagating waves
  - Entire problem space discretised.
  - Structured mesh.
  - Run-time dependant on time taken for energy to propagate out of problem space.

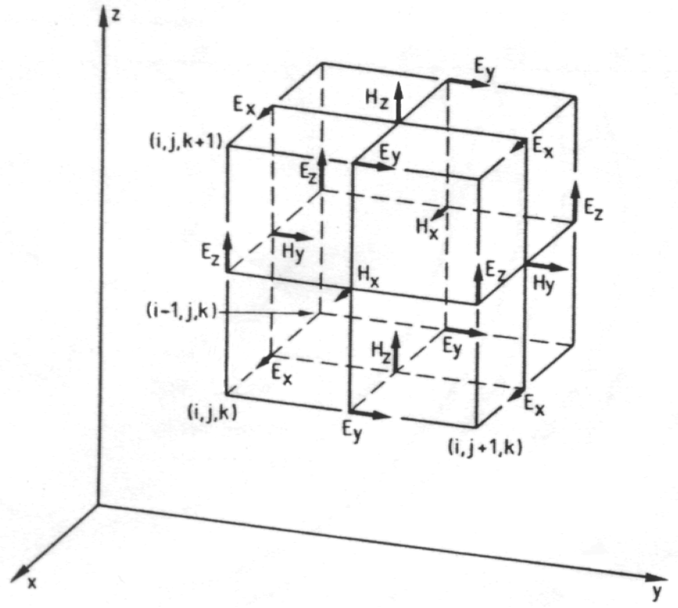


Image from: Gerrit Mur, “Absorbing boundary conditions for the Finite-Difference Approximation of the Time-Domain Electromagnetic-Field Equations”, IEEE Transactions on Electromagnetic compatibility, Vol. EMC-23, Nov 1981

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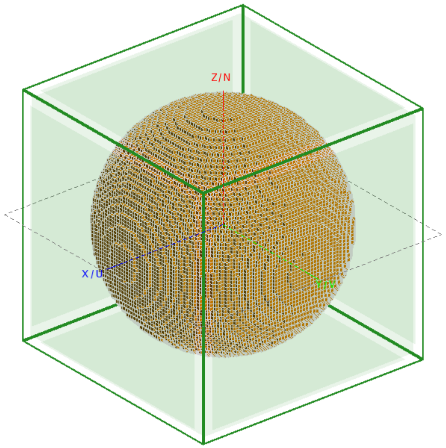
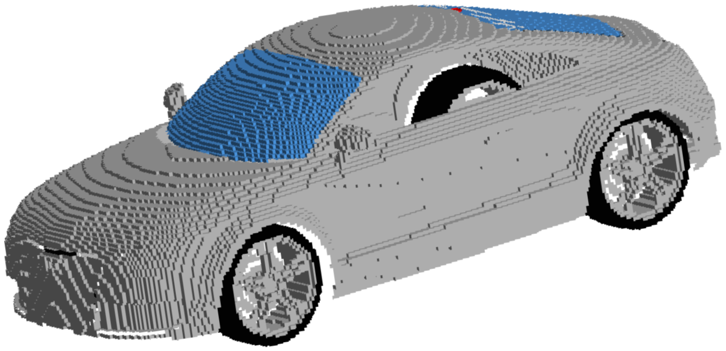
FDTD - Voxel Mesh Generator



- Discretization of models into voxel elements for FDTD solution
- Supports non-uniform meshing of geometry and mesh parts
- Aligned to key points and boundaries
- Mesh settings
  - Standard / fine / coarse auto setting
    - Observes simulation frequency and material properties
  - Custom setting
  - Advanced settings
    - Growth rate
    - Aspect ratio
    - Handling of small geometry features



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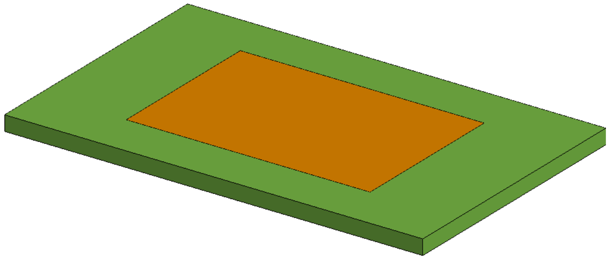
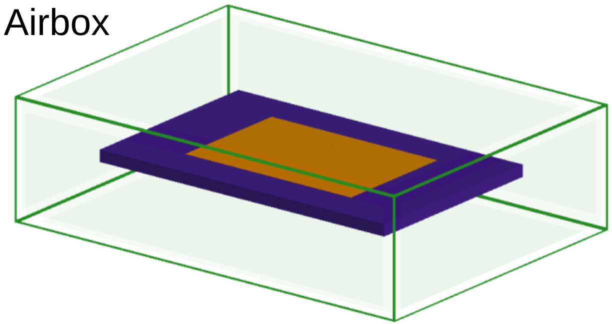
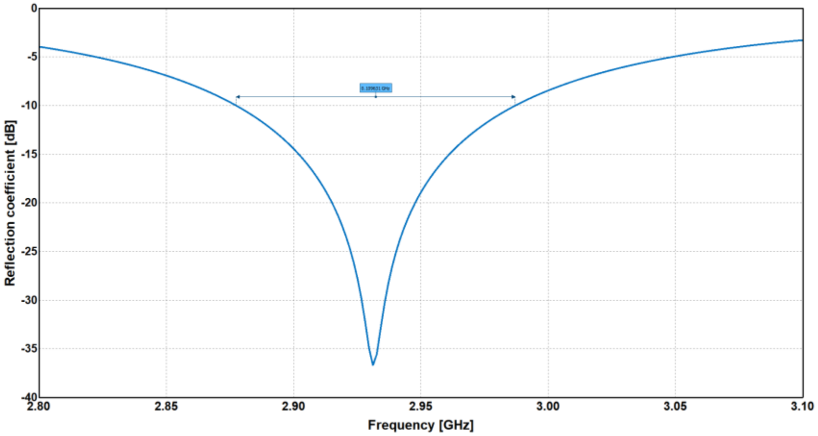
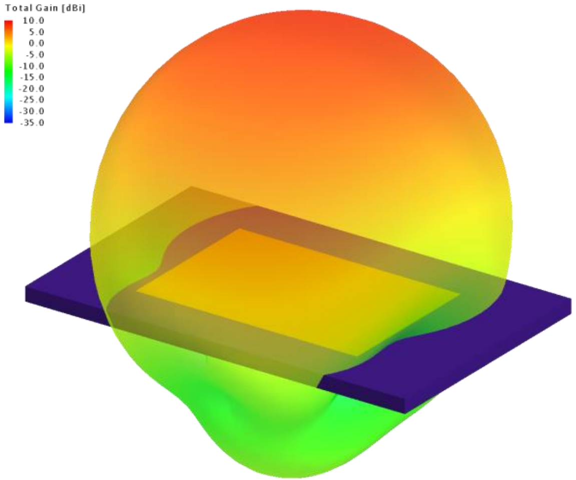
FDTD Example – Microstrip Patch Antenna

Design:
ε_r=2.2
Patch = 31.18 x 46.64
Substrate = 50 x 80 x 2.87
Frequency ~ 2.8 to 3.1 GHz







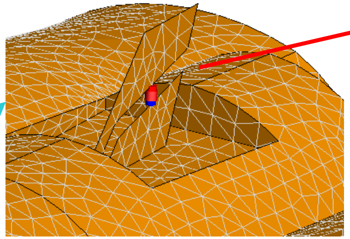


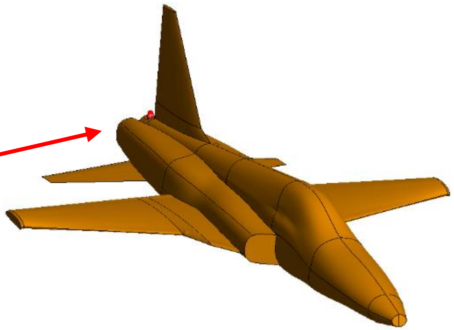
ASYMPTOTIC AND HYBRID SOLUTIONS

Asymptotic Methods Motivation and Application

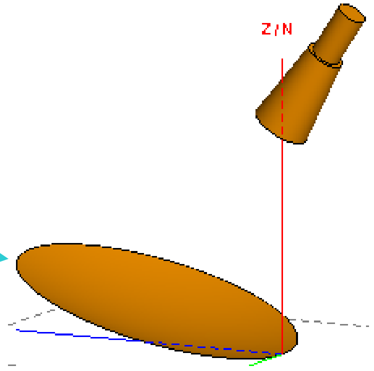
- **Motivation:**
  - To solve extremely large models
  - Larger than MoM or MLFMM can solve

- with available computational resources



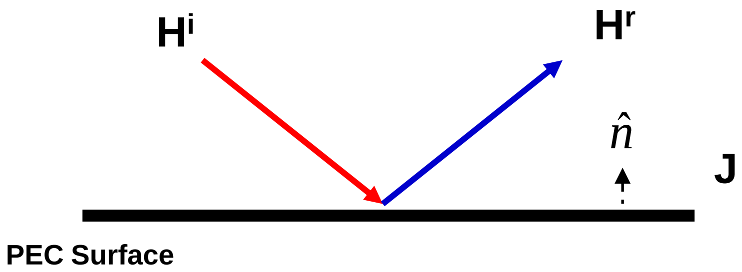


- **Conditions of applicability:**
  - Radiator/source is localized
  - Radiator/source is far away
  - Structure features are large in terms of wavelength
  - Typically used for antenna placement or scattering analysis



HYBRID MOM/PO

Physical Optics (PO)



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

$$\mathbf{J}(\mathbf{r}) = 2\hat{n} \times \mathbf{H}^i(\mathbf{r})$$

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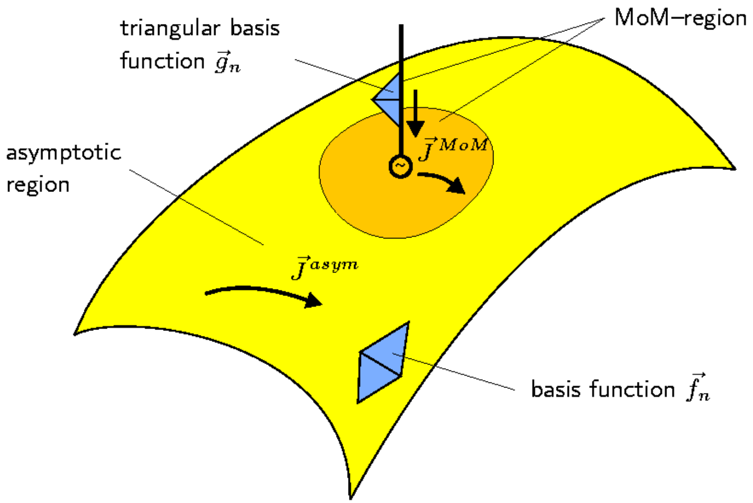
Hybrid MoM/Physical Optics (PO) Technique

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

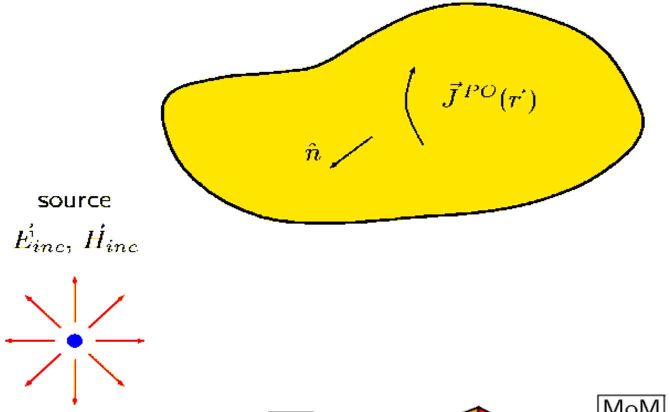
$$\vec{\mathcal{E}}\left\{\vec{J}^{MoM}\right\}_{tan} + \vec{\mathcal{E}}\left\{\vec{J}^{asym}\right\}_{tan} = -\vec{E}_{i,tan}$$

Discretization of Currents in MoM/PO

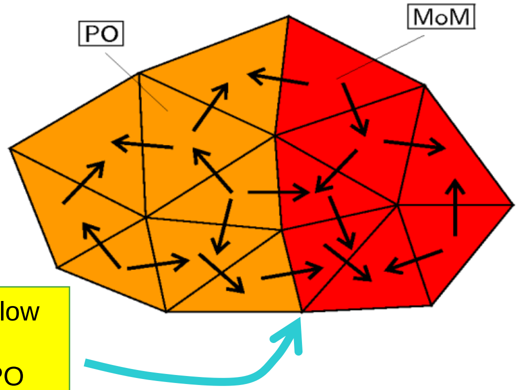
- PO currents represented exactly like MoM currents
- Triangular mesh
- Same basis functions

$$\vec{J}^{\,\mathrm{PO}} = \sum_{n=1}^{N} \alpha_n . \vec{f}_n$$

- Meshing guidelines
  - Same as for metallic MoM



PO Unknowns **N**: MoM Unknowns **M**

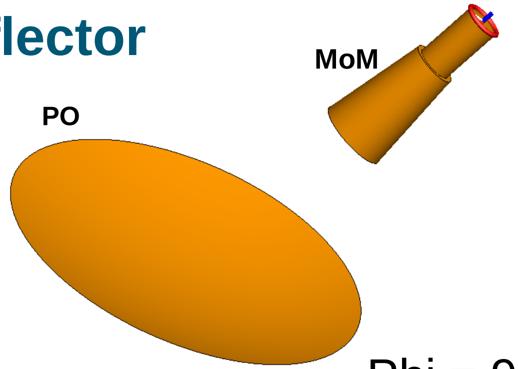


Continuous current flow on the boundary between MoM and PO regions

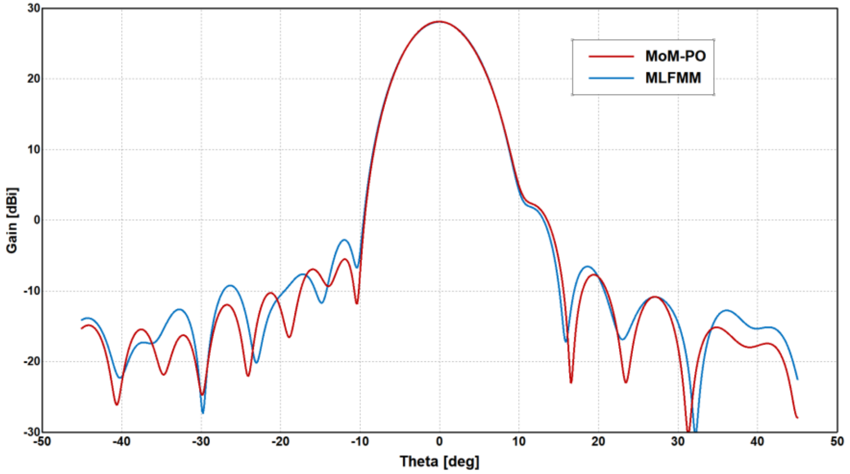
Storage Requirement
MXM – MoM Matrix
NXM – MoM/PO Coupling Matrix

Hybrid MoM/PO Example – Offset Reflector

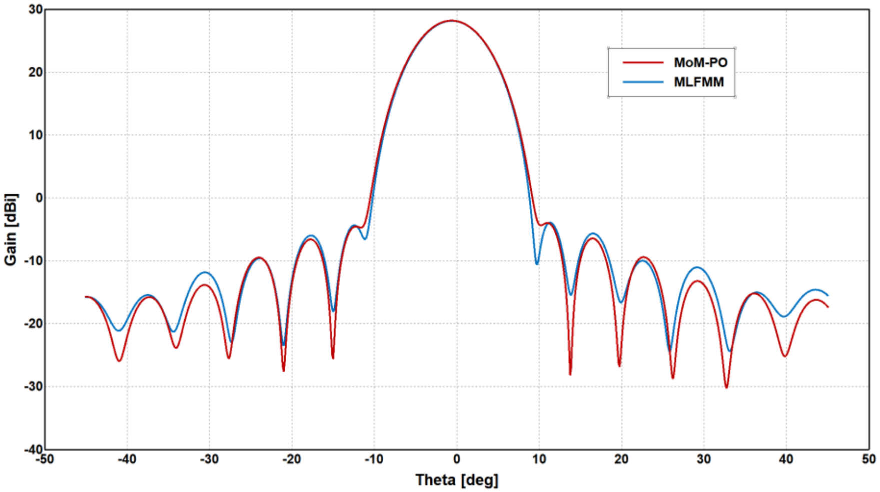
Frequency: 6.25 GHz
Offset reflector diameter ≈ 10.4λ
Focal distance: ≈ 5.7 λ



Phi = 0 deg



Phi = 90 deg



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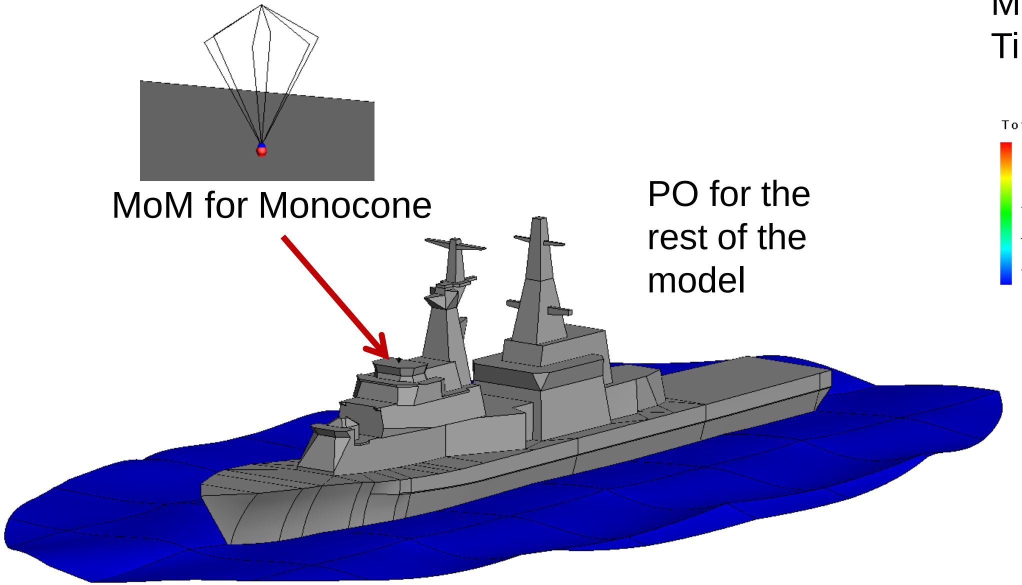
Hybrid MoM/PO Example - Monocone on Ship at 500MHz

Frequency	Length	Width	Height
500MHz	200 λ	23.3 λ	61.7 λ



MoM for Monocone

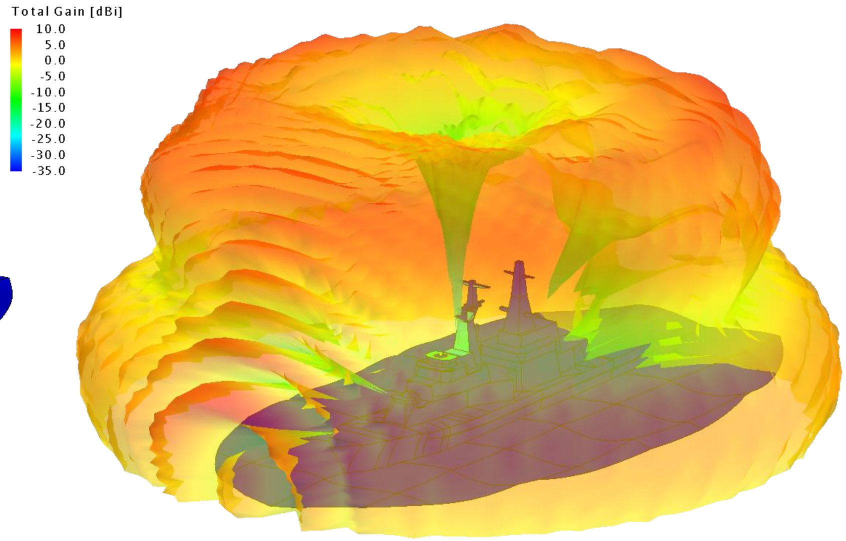
PO for the rest of the model

MoM-PO Hybrid - Coupled

Number of Triangles: 3,513,348

Memory Required: **33 GBs**

Time: **1.1 hours**



Large Element PO Formulation (LE-PO)

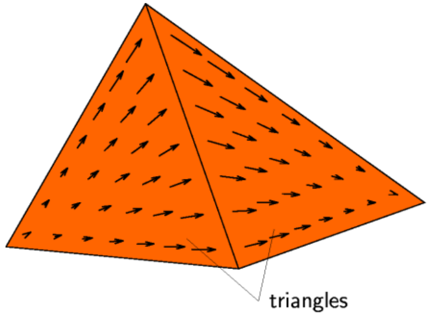
Electrically large triangular patches for PO:

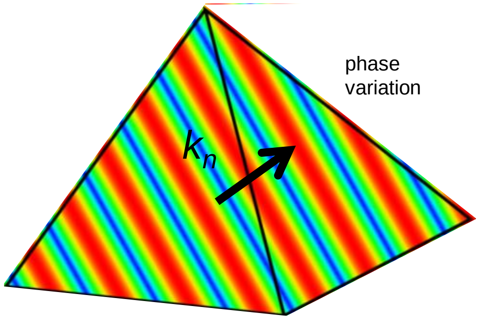
- Traditional RWG (Rao-Wilton-Glisson) basis functions f_n require electrically small mesh elements ($\lambda/6$ .. $\lambda/12$):

$$\vec{f}_n(r) = \begin{cases} \frac{l_n}{2A_n^+}\vec{p}_n^{\,+}, & r \text{ in } T_n^+ \\ \frac{l_n}{2A_n^-}\vec{p}_n^{\,-}, & r \text{ in } T_n^- \\ 0 & \text{otherwise,} \end{cases}$$

- Incorporation of linear phase term into basis function allows the use much larger mesh elements (several λ):

$$\vec{f}_n^{ph}(r) = \begin{cases} \frac{l_n}{2A_n^+}\vec{p}_n^{\,+} \cdot e^{-jk_n\cdot(\vec{p}_n^{\,+}-\vec{p}_{nc}^{\,+})}, & r \text{ in } T_n^+ \\ \frac{l_n}{2A_n^-}\vec{p}_n^{\,-} \cdot e^{-jk_n\cdot(\vec{p}_n^{\,-}-\vec{p}_{nc}^{\,-})}, & r \text{ in } T_n^- \\ 0 & \text{otherwise,} \end{cases}$$





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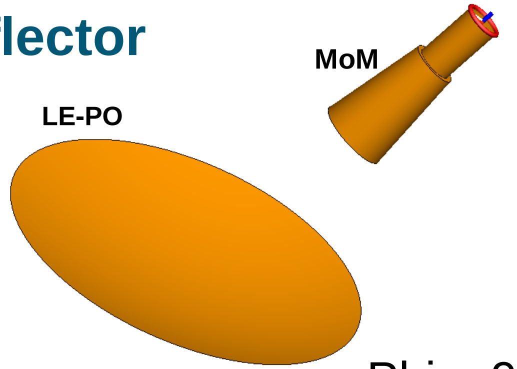
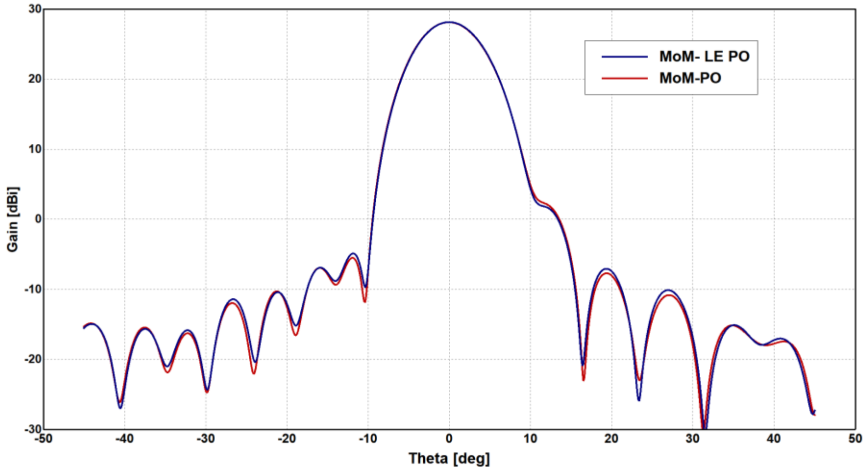
Hybrid MoM/PO Example – Offset Reflector

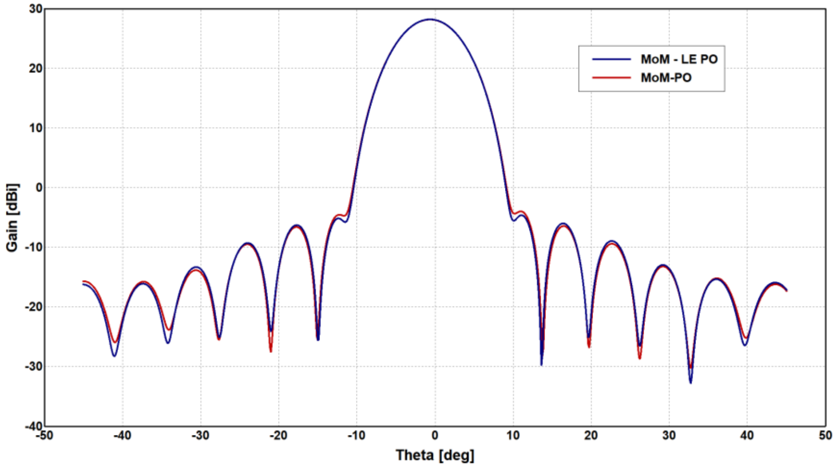
Frequency: 6.25 GHz
Offset reflector diameter ≈ 10.4λ
Focal distance: ≈ 5.7 λ



Phi = 0 deg



Phi = 90 deg



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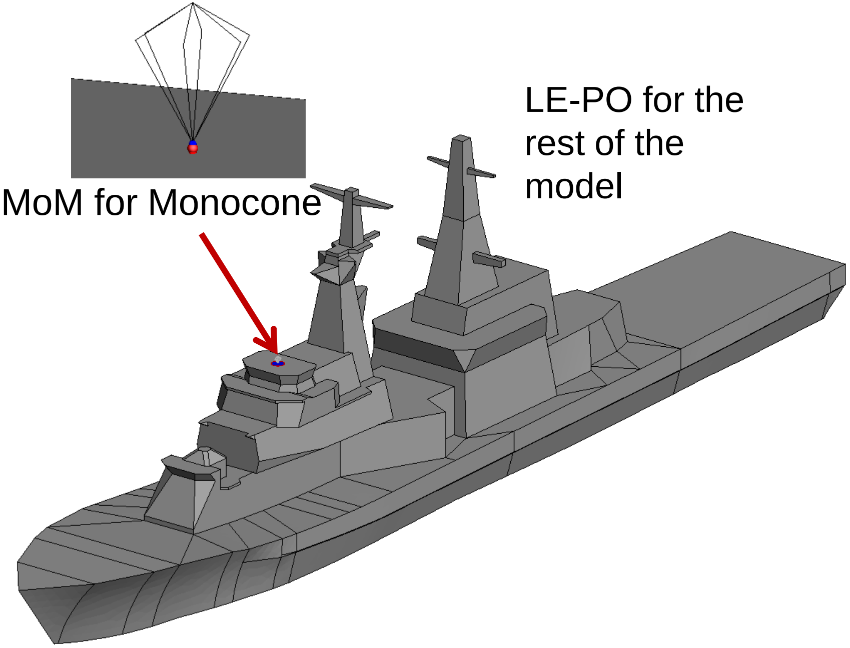
Monocone on Ship at 500MHz

Frequency	Length	Width	Height
500MHz	200 λ	23.3 λ	61.7 λ



MoM for Monocone

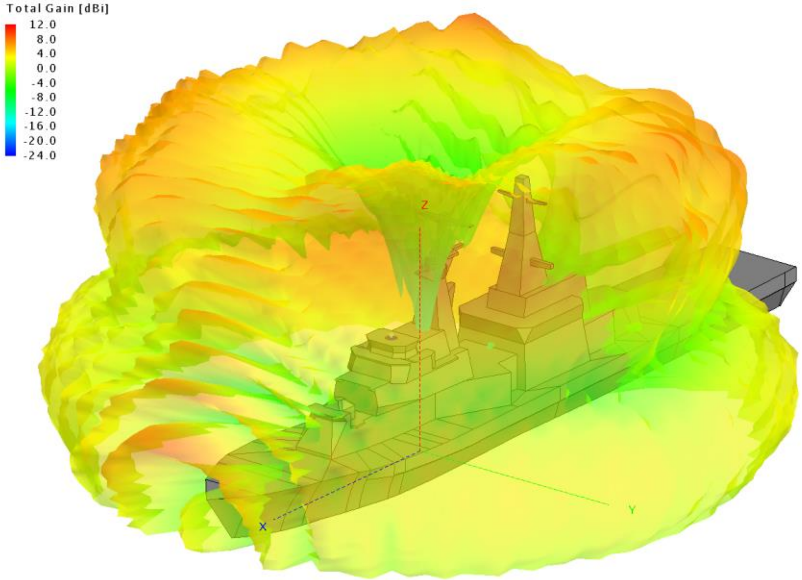
LE-PO for the rest of the model

MoM-LE-PO Hybrid - Coupled

Number of Triangles: 10,974

Memory Required: **238MBs (33GBs for PO)**

Time: **2.7 mins (1.1 hours for PO)**



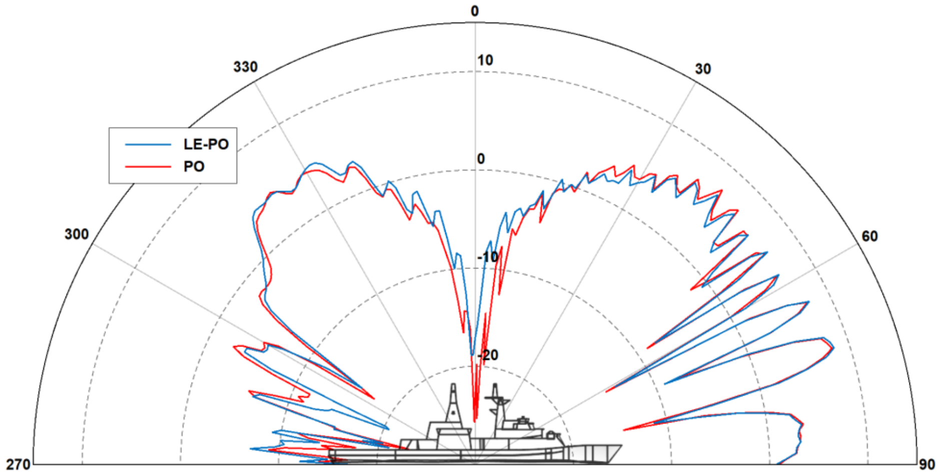
Monocone on Ship at 500MHz

Frequency	Length	Width	Height
500MHz	200 λ	23.3 λ	61.7 λ

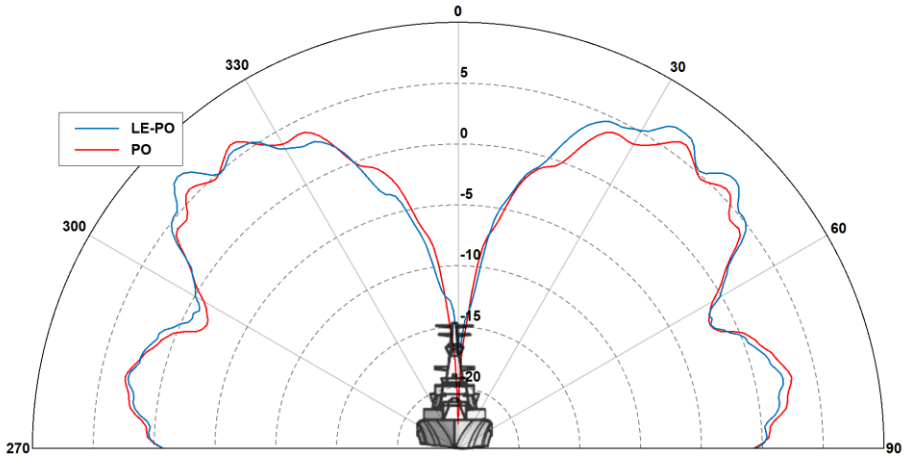
MoM-LE-PO Hybrid - Coupled

Number of Triangles: 10,974
Memory Required: **238MBs**
Time: **2.7 mins**

Phi = 0 degs



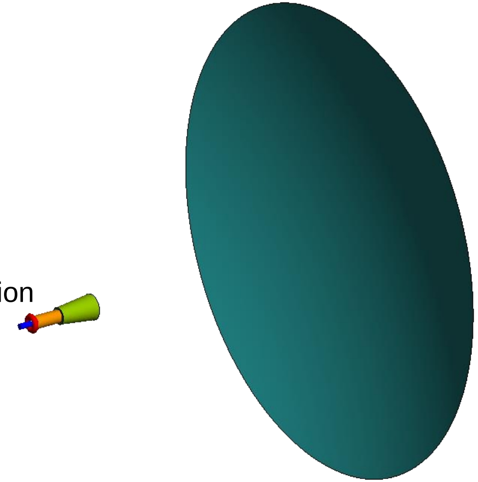
Phi = 90 degs



Iterative Hybrid MoM/PO or MLFMM/PO

PO region (or LE-PO)
J_{PO} = currents on PO region

MoM region (MLFMM)
J_{MoM} = currents on MoM region



1) Solve MoM/MLFMM problem ignoring PO region Compute J_{PO} from the scattered magnetic field caused by J_{MoM}
2) The scattered electric field caused by J_{PO} then radiates back into the MoM region and modifies the excitation vector
3) With the new excitation vector, repeat from 2) until J_{MoM} has reached convergence

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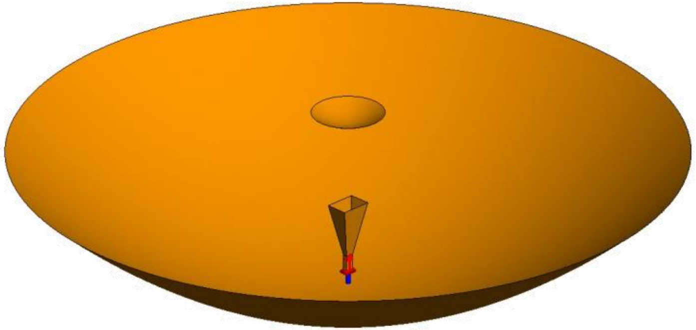
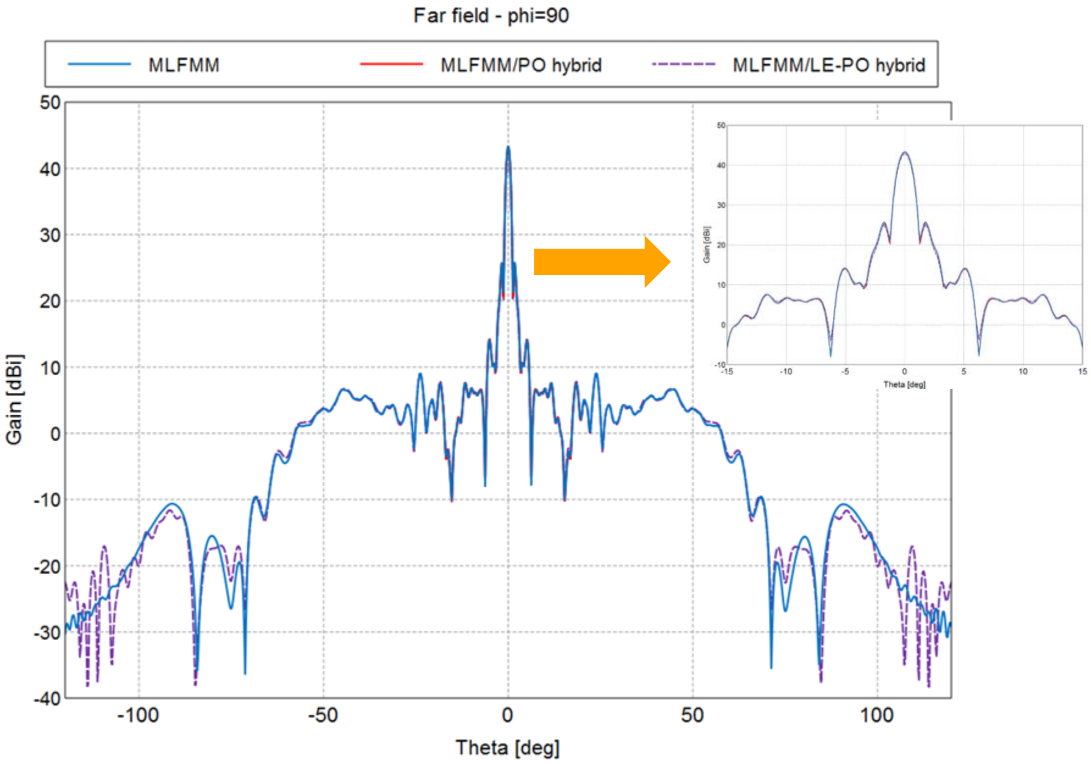
Cassegrain Reflector Antenna

MLFMM – Feed Horn + Sub reflector
LE-PO - Reflector



Full MLFMM: **0.786 hours, 12.4 GByte**
Hybrid MLFMM/LE-PO: **0.129 hours, 0.43 GByte**

Intel(R) Core(TM) i7-3770K CPU @ 3.50GHz; 4 parallel processes



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HYBRID MOM/RL-GO

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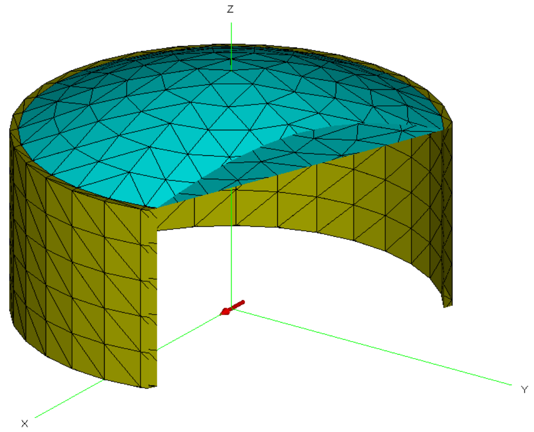
Ray-Launching Geometrical Optics (RL-GO)



- **Aimed at solution of electrically very large** (> 20 λ) **structures**
- E.g. **Lenses, reflectors, large scatterers**
- **GO = Geometrical Optics**
- **Ray-launching,** optical – Also known as Shooting and Bouncing Ray (SBR) Method
- Interaction with **MoM structures** via ray-launching principles

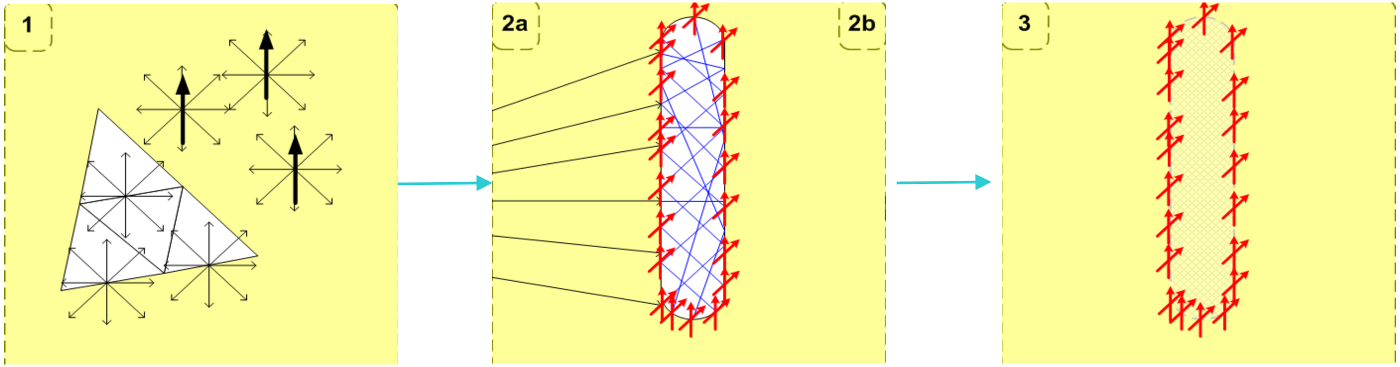
- **Advantages:**
  - Explore RL-GO when PO has failed
  - Mesh can be very coarse (as opposed to PO) – no mesh storage problem
  - Good for smooth, large structures

- **Disadvantages:**
  - Grazing incidence means that RL-GO sources will be sparsely placed, forcing very fine launching increment
  - Reduced accuracy with many multiple reflections

MoM / RL-GO formulation

- From each source ray tubes are launched at incremental spacing, covering all directions
- Where a ray tube hits a surface, **J-sources** (and/or M-sources for dielectrics) are placed on the surface, based on plane wave approximation
- As a ray tube bounces between surfaces, a source(s) is added at every interaction point
- **Total solution field = incident fields + all RL-GO sources** (reflected fields)

MoM sources and a dielectric body scenario



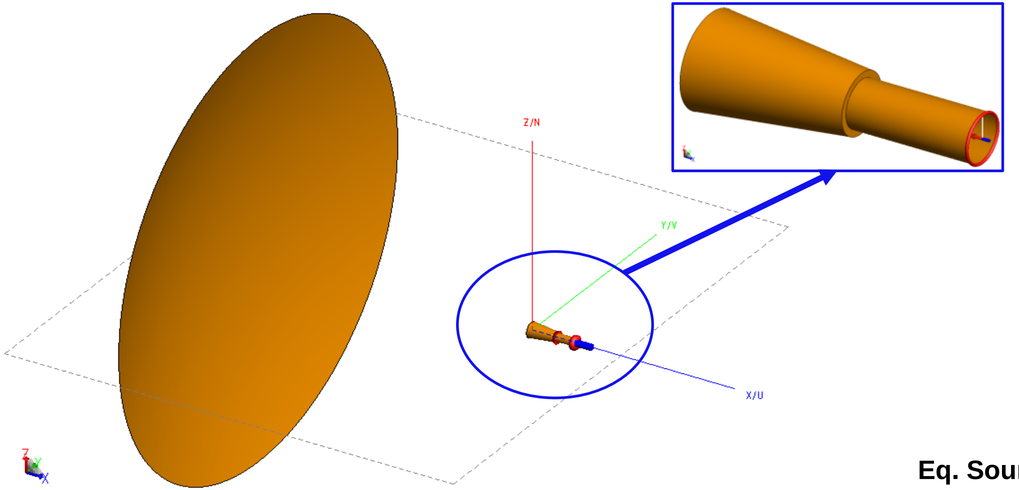
MoM triangles and radiating point sources

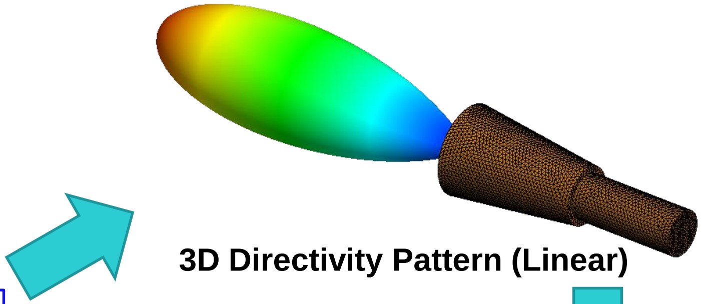
Interactions with dielectric; Huygens sources placed on dielectric boundary

Equivalence principle: Huygens sources radiating in free space

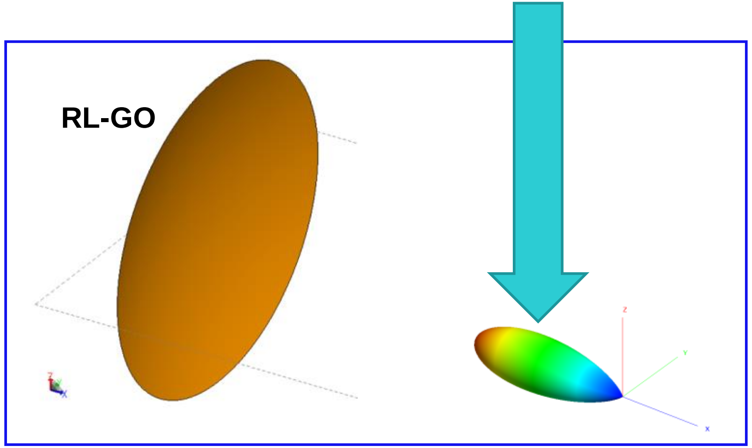
RL-GO Example: Reflector Antenna

- **Parabolic reflector**
- **Circular horn antenna feed**
- **Fundamental waveguide mode excitation**
- 8 GHz
- **Reflector aperture** = 36 λ





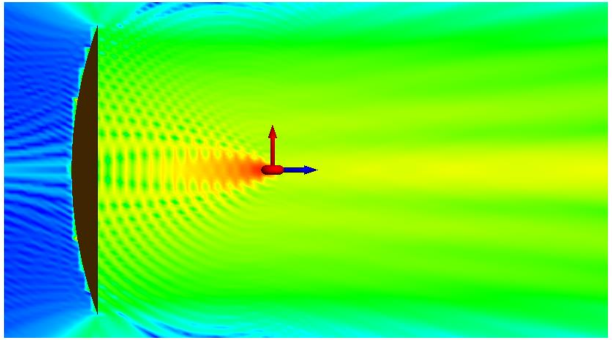
3D Directivity Pattern (Linear)



Eq. Source Replacing Feed Horn (Far field pattern or Spherical Modes)

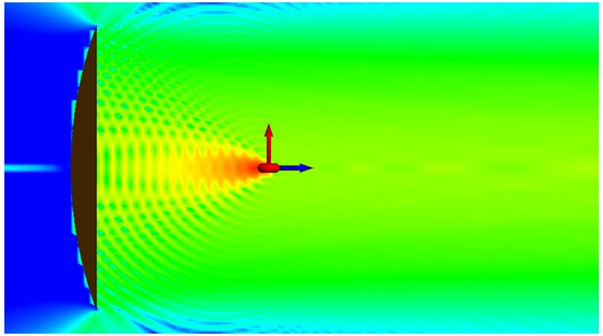
RL-GO Example: Reflector Antenna

Near Fields



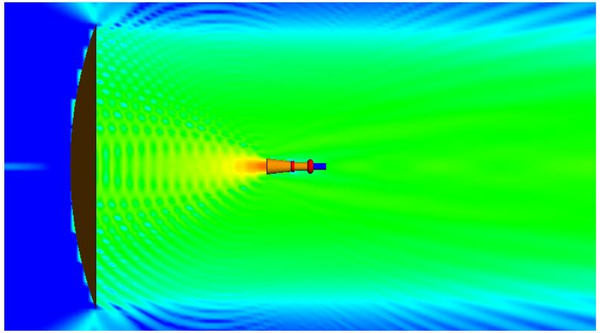
RL-GO with Eq Source

Memory: 62 MBs
CPU Time: 4 mins



MLFMM with Eq Source

Memory: 4 GBs
CPU Time: 3 mins



MLFMM with Horn Feed

Memory: 4.4 GBs
CPU Time: 7 mins

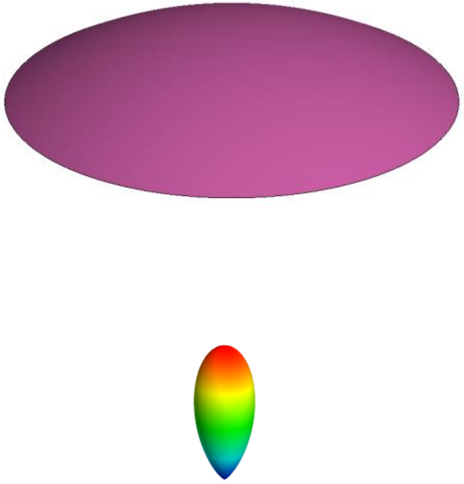
RL-GO Example: Lens Antenna

Dielectric Lens Antenna

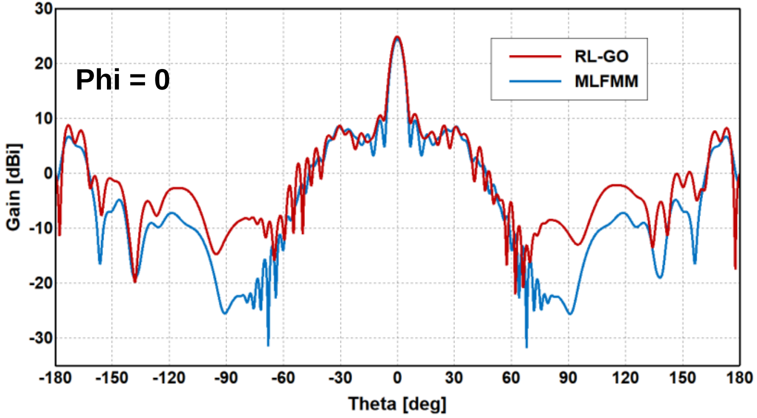
Frequency: 30GHz
Diameter = 10cm

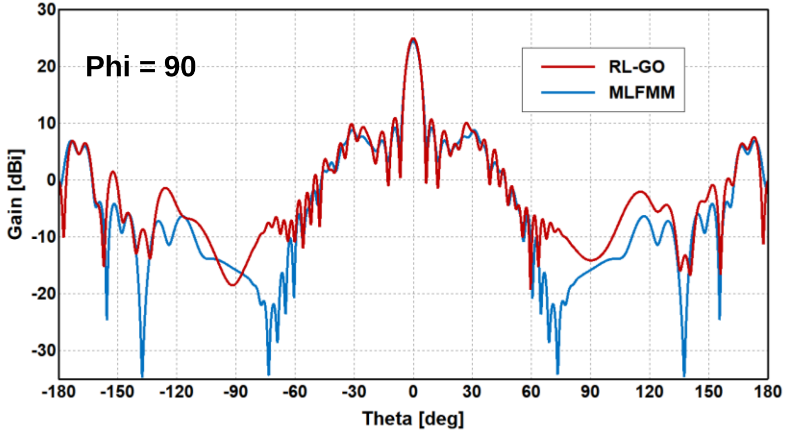
$\varepsilon_r = 6$
Tan $\delta = 0.005$

RL-GO



$$E_x = \cos^4(\theta) \text{ where } 0 \le \theta \le \frac{\pi}{2}$$





MLFMM
Memory: 15.3GBs
CPU Time: 8mins

RL-GO
Memory: 97 MBs
CPU Time: 11 secs

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HYBRID MOM/UTD

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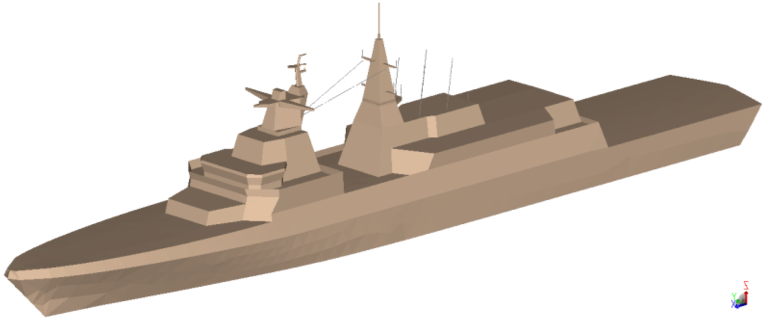
Uniform Theory of Diffraction (UTD) - Motivation

- **PO and RL-GO can be computationally expensive when:**
  - Problem extremely large in wavelengths (>1,000s of wavelengths)
  - Diffraction is important
  - Multiple interactions involving reflections and diffractions are important
- **For such problems UTD may be suitable**
- **UTD is based on field ray tracing using reflection, diffraction, and creeping wave calculations**
- **Computational Complexity remains constant if the problem is suitable for UTD**



method	formulation	CPU–time	memory
MoM	current–based	$f^{4 \ldots 6}$	f^4
PO	current–based	f^2	f^0
UTD	ray–based	f^0	f^0

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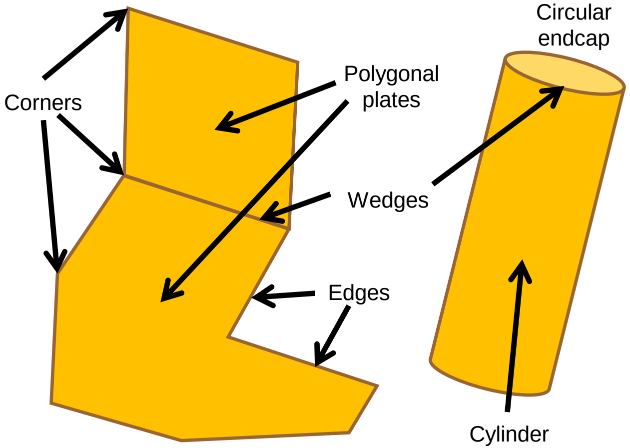
Uniform Theory of Diffraction (UTD)

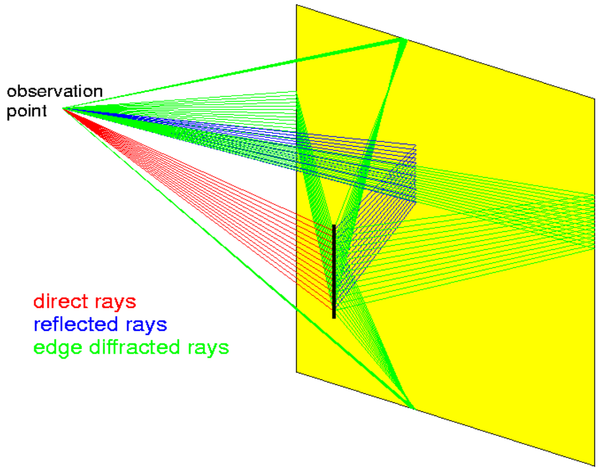
Geometry restrictions:

- PEC or lossy metal structures
- Also PEC with coatings/thin dielectric sheet
- Must consist of flat polygonal plates
- Single cylinder allowed
- Edge length/diameter of plates must be > 1λ
- "Mesh" is the same as the plates (i.e. CAD)

Types of rays considered:

- Direct rays
- Reflected rays (also multiple edge)
- Edge diffracted rays
- Corner diffracted rays
- Combinations/multiples of reflections and diffractions
- Creeping rays





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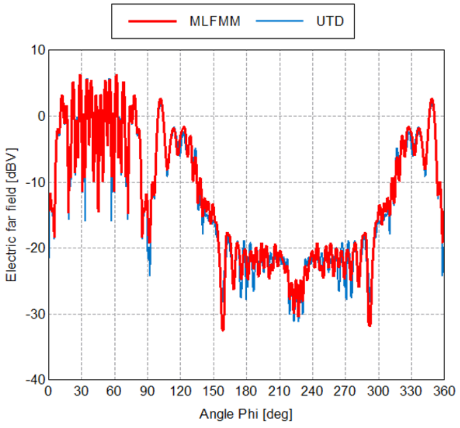
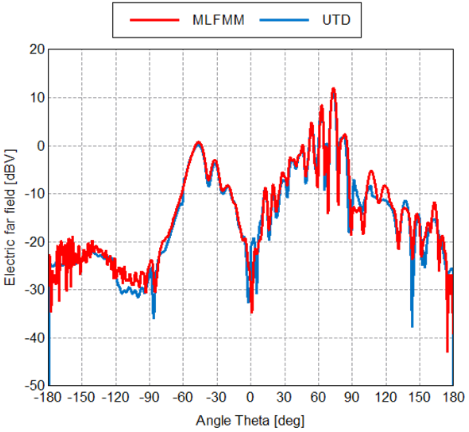
Hybrid MoM/UTD - Satellite Structure

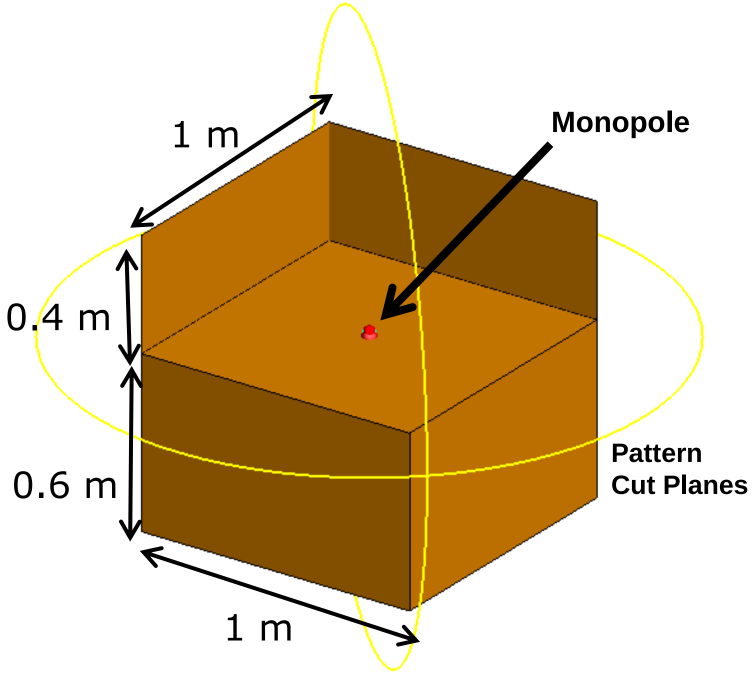
- Geometry consists of rectangular plates
- Box structure with two reflector panels
- Well suited for MoM-UTD Hybrid Method
- Excitation: single 1⁄4 λ monopole (MoM)

6GHz

1 m = 20 λ



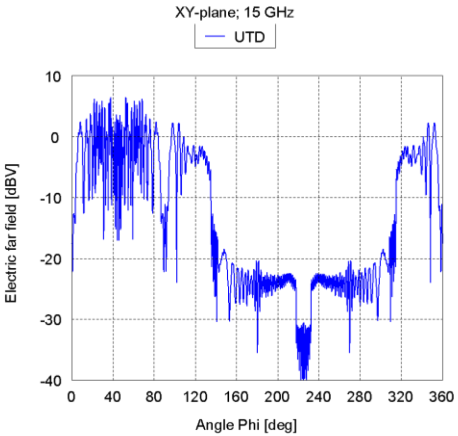


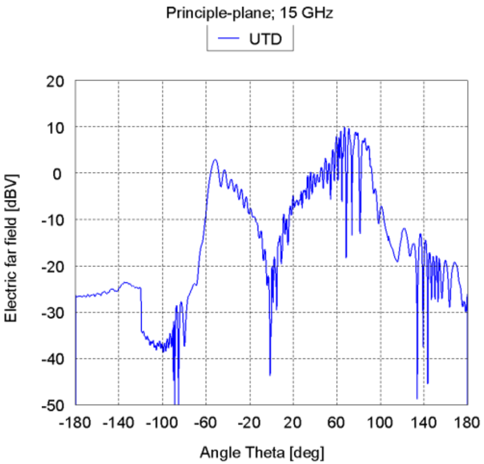


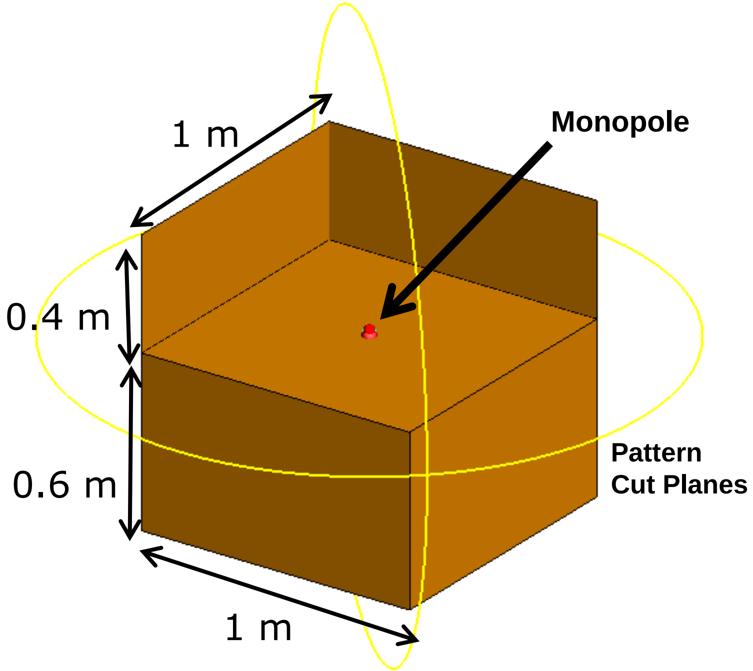
Hybrid MoM/UTD - Satellite Structure

15GHz

1 m = 50 λ







Method	6 GHz	15 GHz
MLFMM	14.1 GByte	---
UTD	**1.0 MByte**	**1.0 MByte**

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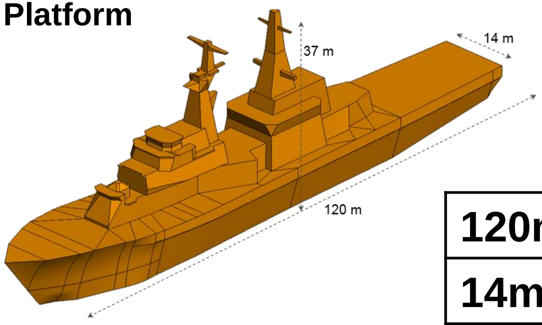
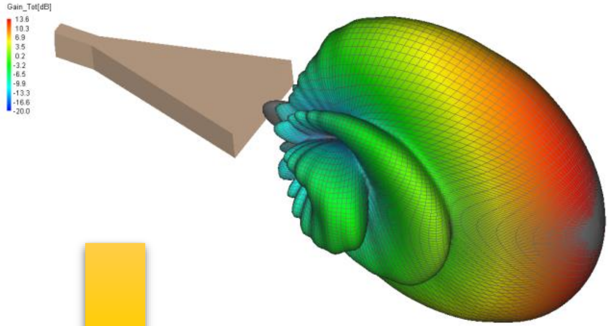
UTD Example - Radar on a ship Deck

Platform

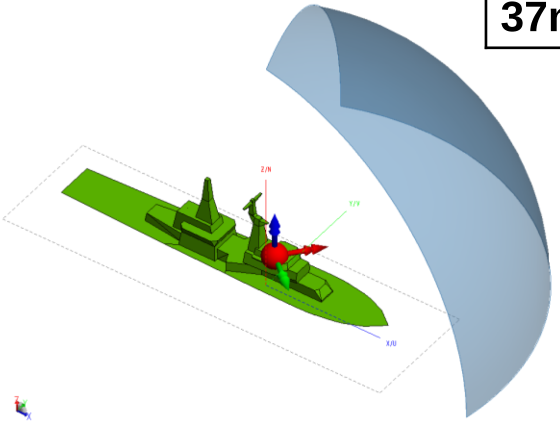


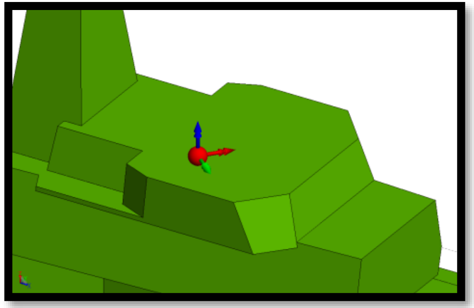
Representative Radar Antenna @ 10GHz



10GHz

120m	4,000 λ
14m	467 λ
37m	1,233 λ

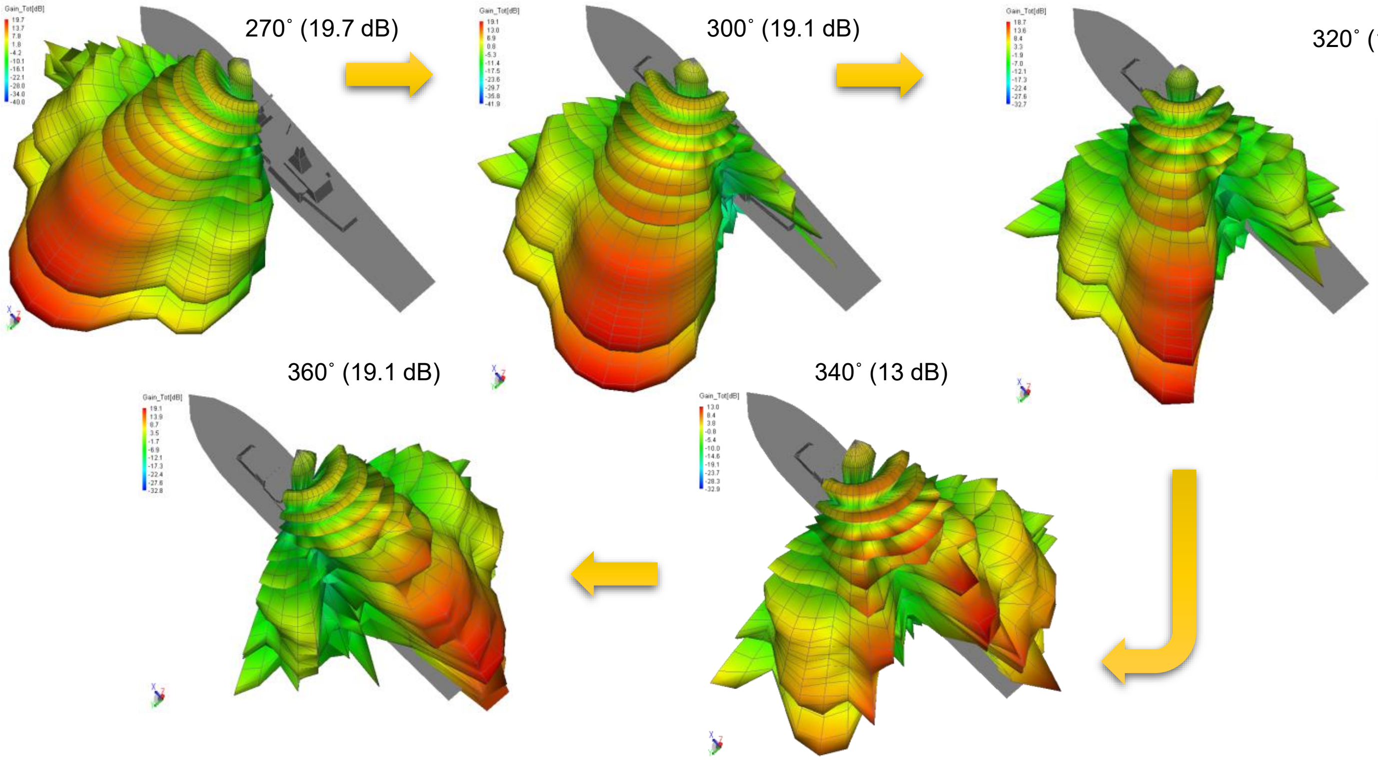




- Import as pattern point source to location 50 cm above deck
- Specify far-field calculation in front of antenna (-60˚, +60˚)

RADIATION PATTERN VS. AZIMUTH SCAN ANGLE

- **At 340˚ worst tower blockage evident (peak pattern gain shown in parenthesis)**



Radiation pattern as a function of scan angle

Computational cost (laptop, single process):

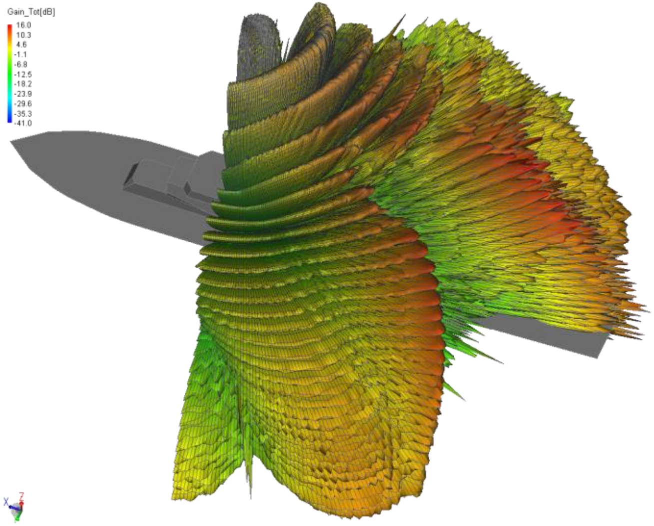
2 Mbytes

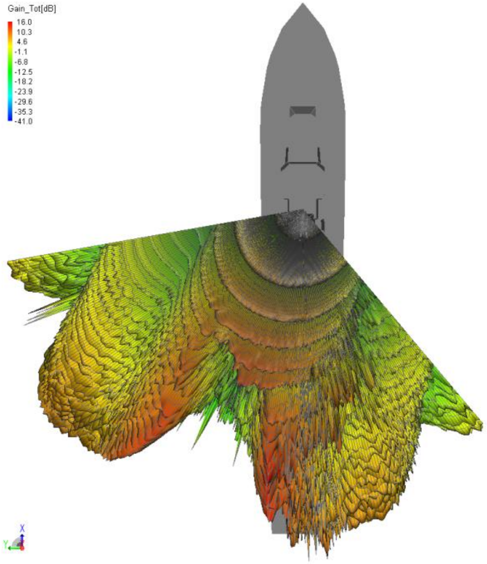
6 min/pattern

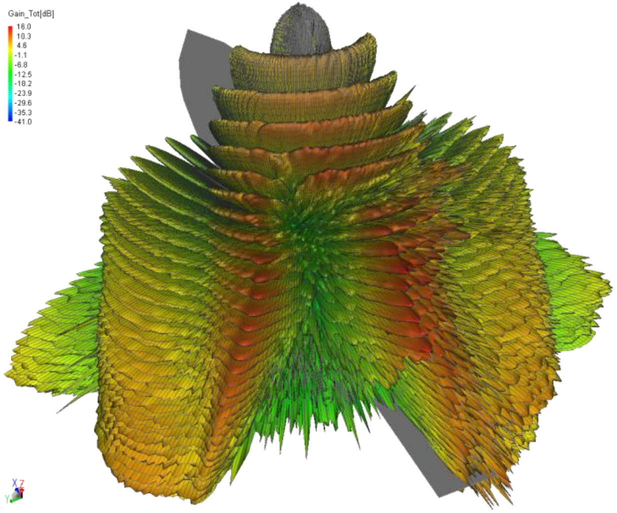
UTD - Detailed Analysis of Pattern at 340˚

- **Recalculate at 340˚ - much finer far-field sampling**
- **Lobes due to path gain now all resolved**
  - **Antenna is 16.67λ above deck**
- **Computational cost (laptop, single process): 2 Mbytes, 6 hours**

10GHz





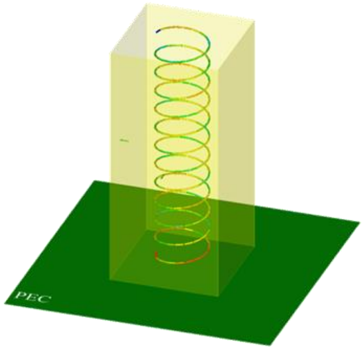


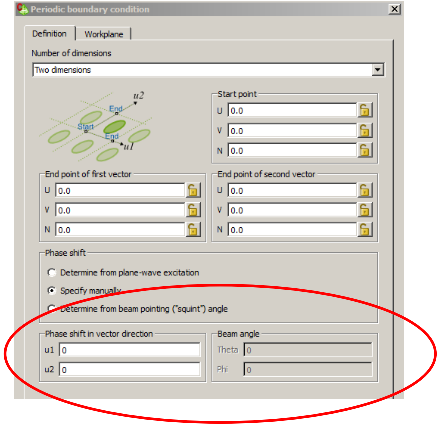
ANTENNA ARRAYS

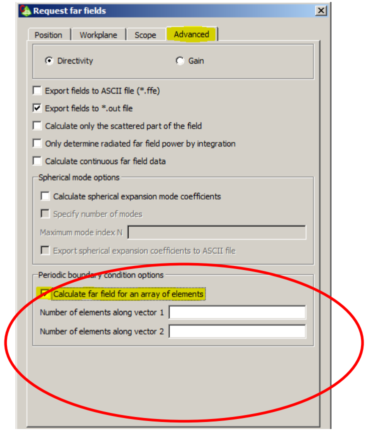
Arrays Using Periodic Boundary Conditions (PBCs)

FEM or MoM can be used for infinite Periodic structures using PBCs

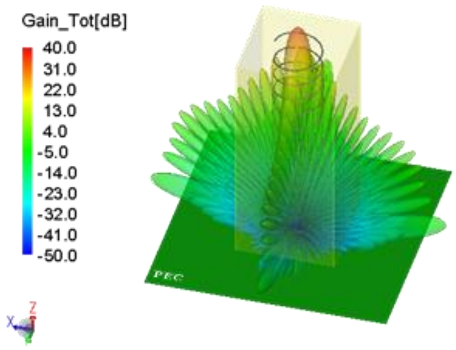
Helix Antenna Array Simulation



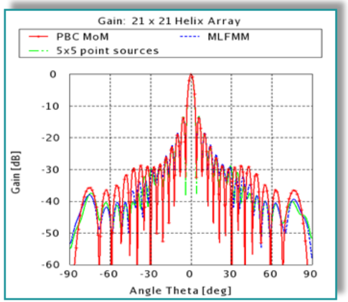




21 x 21 Array



- Radiation pattern analysis for arbitrarily large arrays (1D or 2D rectangular arrays)
- Simulate single element of array, integrate for antenna pattern using array factor



Solution Method	Memory
PBC	0.5 MByte
MLFMM	4.5 GBs

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FINITE ANTENNA ARRAYS
DOMAIN GREENS FUNCTION METHOD - DGFM

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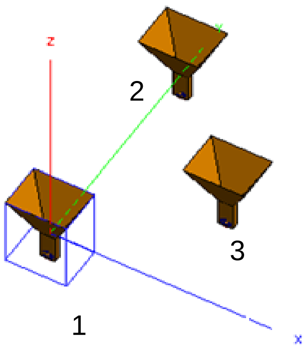
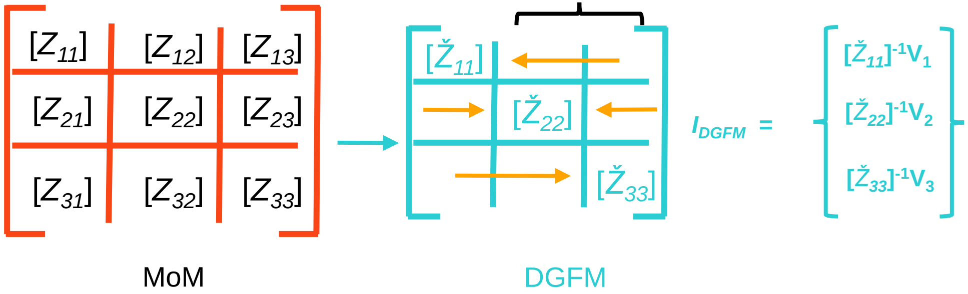
DGFM – Efficient Method for Finite Antenna Arrays

- **Analysis Based on Solving One Array Element at a Time**
  - Accounts for **Edge Effects** of Finite Arrays
  - **Mutual Coupling** is Accounted for When Calculating Self-Interaction Matrix of the Element by Using a Modified Green's Function
  - **The Computational Complexity** Scales Much Better – By Solving Smaller Matrix Equations



Coupling terms $[Z_{12}]$ and $[Z_{13}]$ included in $[\check{Z}_{11}]$



Daniel J. Ludick et al, Efficient Analysis of Large Aperiodic Antenna Arrays Using the Domain Green's Function Method, IEEE Trans. On Antennas and Propagation, pp. 1579-1587, April 2014.

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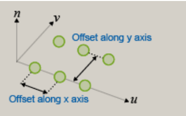
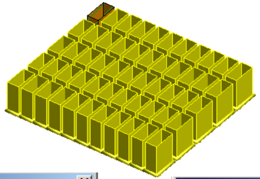
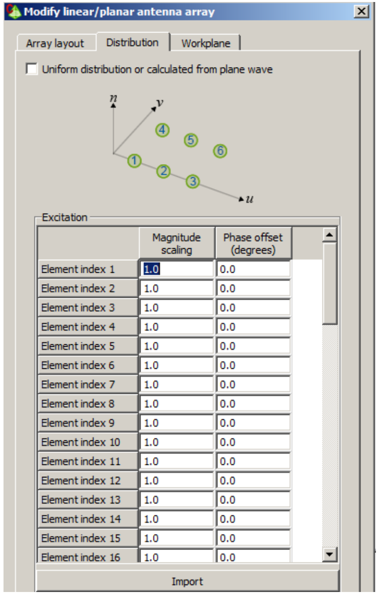
DGFM – Efficient Method for Finite Antenna Arrays

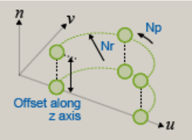
- **Linear array**

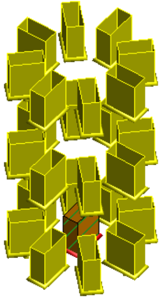


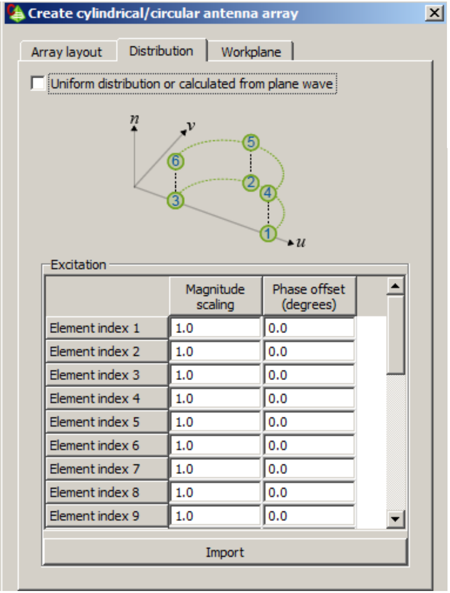




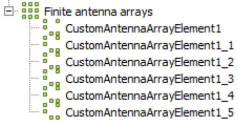
- **Circular or cylindrical**

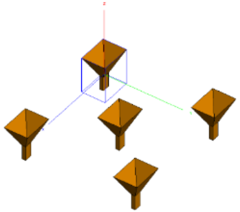


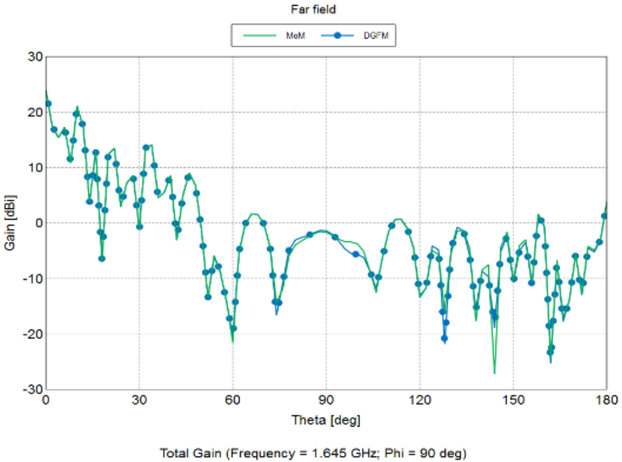




- **Custom array**







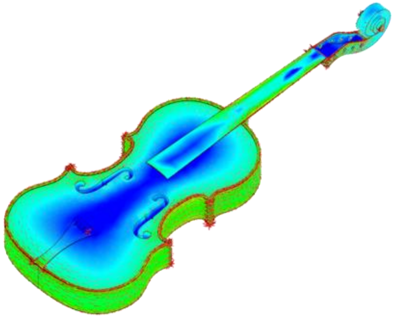
	MoM	DGFM
CPU time	1.5 hours	28.7 min
Total Memory Usage	7.54 GByte	319.4 MByte

ADVANCED TOPICS

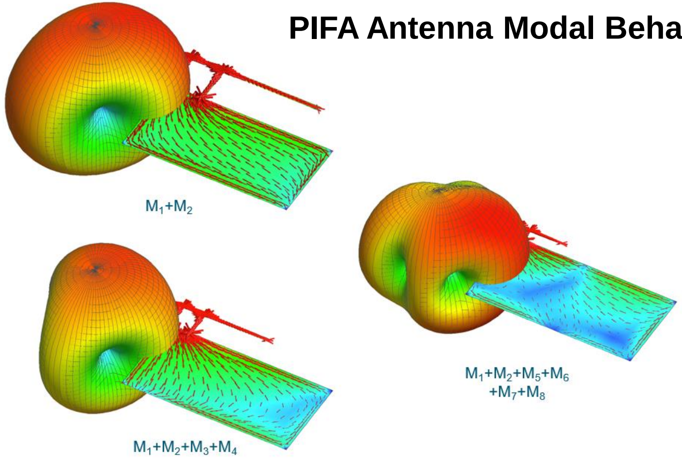
CMA – Characteristic Mode Analysis

- **CMA gives you fundamental physical insights that a driven simulation doesn't give you.**
- **CMA can help in antenna design: how to modify the shape, where to place excitations and loads.**

"Putting Physics Back into Simulations"



PIFA Antenna Modal Behavior



M. Vogel, G. Gampala, D. Ludick, and C. J. Reddy, "Characteristic mode analysis: putting physics back into simulation," IEEE Antennas and Propagation Magazine, vol. 57, no. 2, pp. 307–317, 2015.

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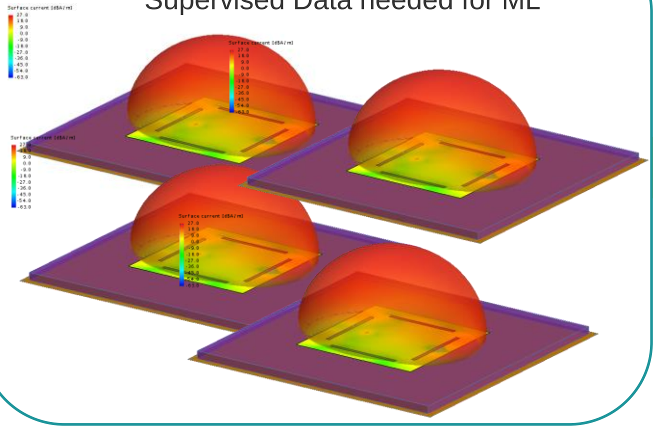
Machine Learning for Antenna Design and Optimization

"Machine learning is a field of study that gives computers the ***ability to learn without being explicitly programmed****. " - Arthur Samuel, Computer Scientist 1959*

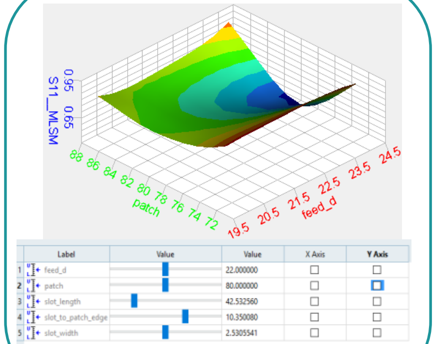
Alternative Description:
Machine learning is a family of algorithms that help make predictions from data sets

Simulation data with multiple variables
Supervised Data needed for ML



Machine Learning with Regression

Build a mathematical model that defines the goal (Return Loss of the Antenna etc.) as function of geometry variables



Mathematical Model

Optimize using ML Model

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Machine Learning for Antenna Design and Optimization

Antenna Design and Optimization Using Machine Learning

On-Demand Short Course

Machine learning is a method of data analysis that automates analytical model building. As the complexity of antennas increases each day, antenna designers can take advantage of machine learning to generate trained models for their physical antenna designs and perform fast and intelligent optimization on these trained models. Using the trained models, different optimization algorithms and goals can be run quickly, in seconds, that can be utilized for comparison studies, stochastic analysis for tolerance studies etc.

This short course presents the process of fast and intelligent optimization by adopting the Design of Experiments (DOE) and Machine Learning using Altair FEKO. We discuss specific examples that showcase the advantages of using ML for antenna design and optimization.

Access Short Course

Speakers

Dr. C.J. Reddy
Vice President, Business Development - Electromagnetics

Dr. Reddy was awarded the US National Research Council (NRC) Resident Research Associateship at NASA Langley Research Center. He is currently a Fellow of IEEE, ACES and AMTA and has published 37 journal papers, 77 conference papers and 18 NASA Technical Reports to date.

Gopinath Gampala
Technical Regional Manager

Gopi graduated from University of Mississippi with a Master's degree in computational electromagnetics in 2007 and working in the field of CAE since then. He is a member of IEEE and published extensively on topics like High-impedance surfaces, Low-profile antennas, LTE, Radomes, Characteristic Mode Analysis, 5G and Machine Learning.

https://web.altair.com/antenna-design-optimization-machine-learning-ondemand

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ANTENNA MODELING AND SIMULATION IN EDUCATION

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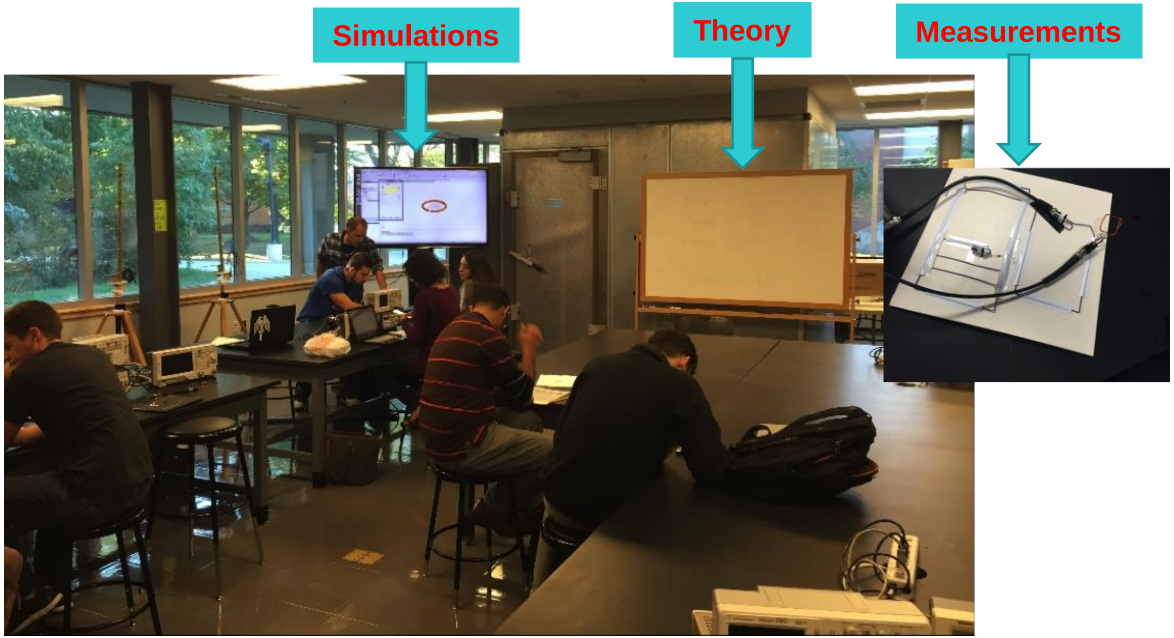
Fusing Theory and Simulations in Lab

University of Michigan – Dearborn

- Simulate the “experiment” with Altair Feko
- Correlate simulation results with theory
- Experiment in the lab
- Correlate measured lab data with theory and simulations



Altair Blog: https://blog.altair.com/innovation-in-education-fusing-simulations-with-theory-and-experiments/

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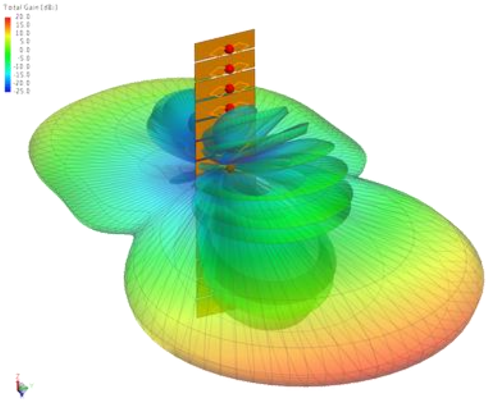
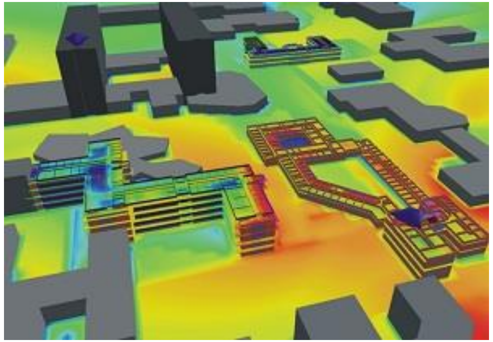
ALTAIR UNIVERSITY

Altair Feko Student Edition



Feko – Comprehensive Electromagnetic Simulations

Free for Students and Faculty to Download at



WinProp – Wave Propagation and Radio Network Planning Tool

https://altairuniversity.com/feko-student-edition/

altairuniversity@altair.com

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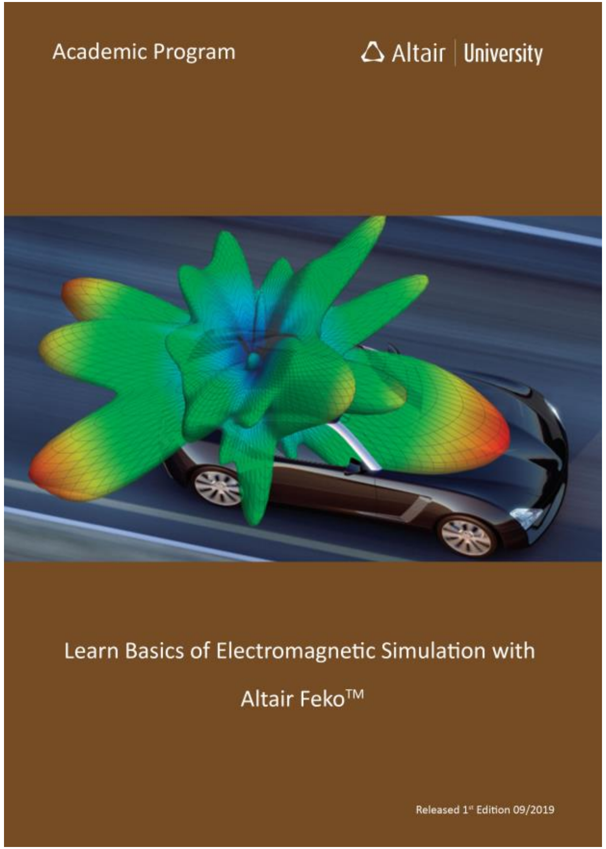
Feko Free eBook



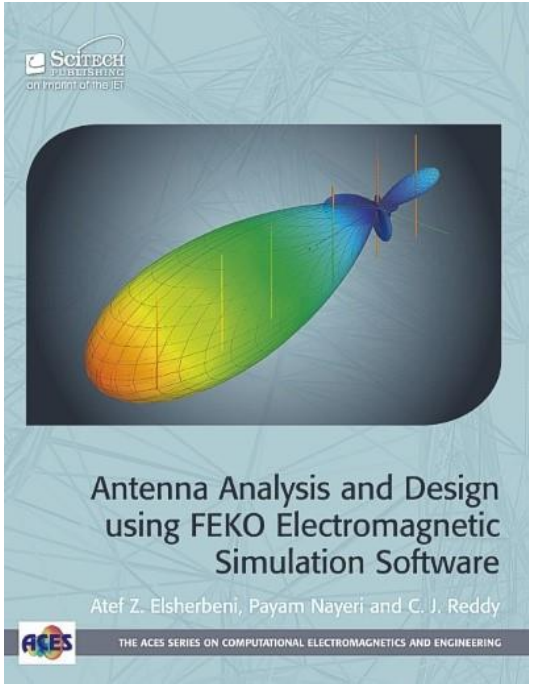
Learn Electromagnetic Simulation with Altair Feko

Altair Feko is an environment to solve electromagnetic problems. This book takes the reader through the basics of broad spectrum of EM problems, including antennas, the placement of antennas on electrically large structures, microstrip circuits, RF components, the calculation of scattering as well as the investigation of electromagnetic compatibility (EMC). The concepts are explained with examples and step-by-step tutorials after each section. Moreover, the users will also be guided with videos to make the learning experience fast and effective.

DOWNLOAD the Free eBook

https://altairuniversity.com/free-ebook-electromagnetic-simulation-feko/

Book - Antenna Analysis & Design using FEKO EM Simulation Software – Atef Elsherbeni, Payam Nayeri and C.J. Reddy



"Education through Simulations".

1. Introduction
2. Wire Dipole and Monopole Antennas
3. Wire Loop Antennas
4. Microstrip Patch Antennas
5. Microstrip Based Filters and Feed Networks
6. Broadband Dipole Antennas
7. Traveling Wave and Broadband Antennas
8. Frequency Independent Antennas
9. Horn Antennas
10. Reflector Antenna

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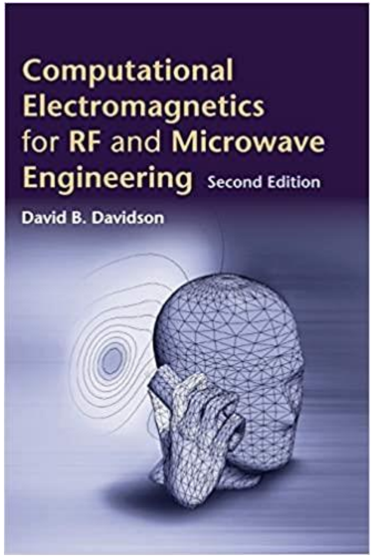
Further Reading on Modeling and Simulation Methods

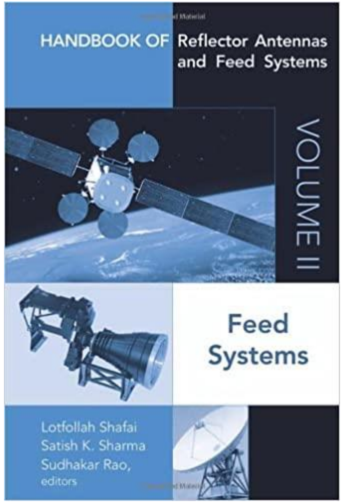


Computational Electromagnetics for RF and Microwave Engineering
2nd Edition
David B. Davidson
Cambridge University Press

Handbook of Reflector Antennas and Feed Systems Volume II
Feed Systems
Sudhakar Rao, Lotfollah Shafai, Satish K. Sharma
Artech House

CHAPTER 2
Numerical Methods

Kubilay Sertel, Ohio State University
C. J. Reddy, EM Software & Systems (EMSS) USA Inc.



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Questions

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