Combining Differential/Integral Methods and Time/Frequency Domain Analysis to Solve Complex Antenna Problems

IEEE Long Island Section MTT-S

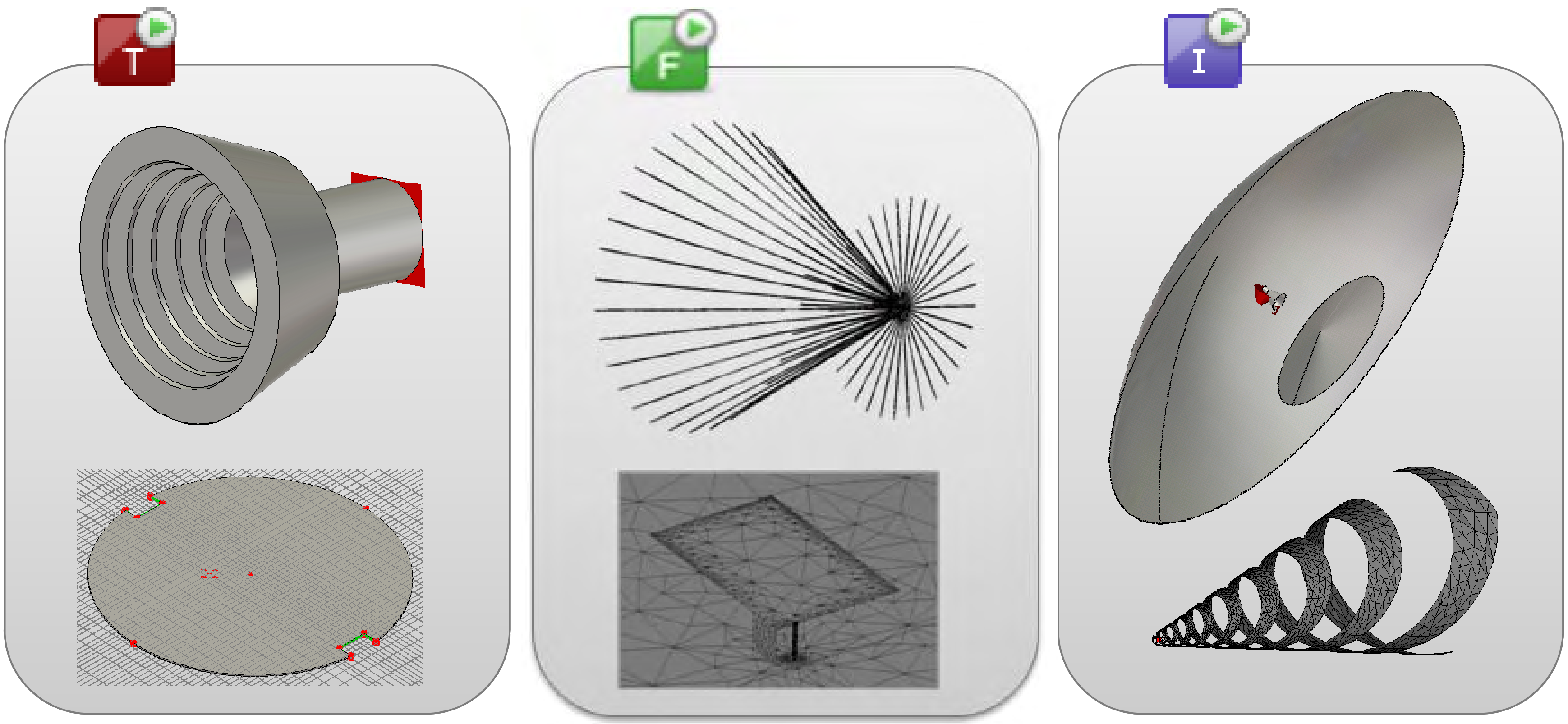
Jan. 27, 2011

Overview of Presentation

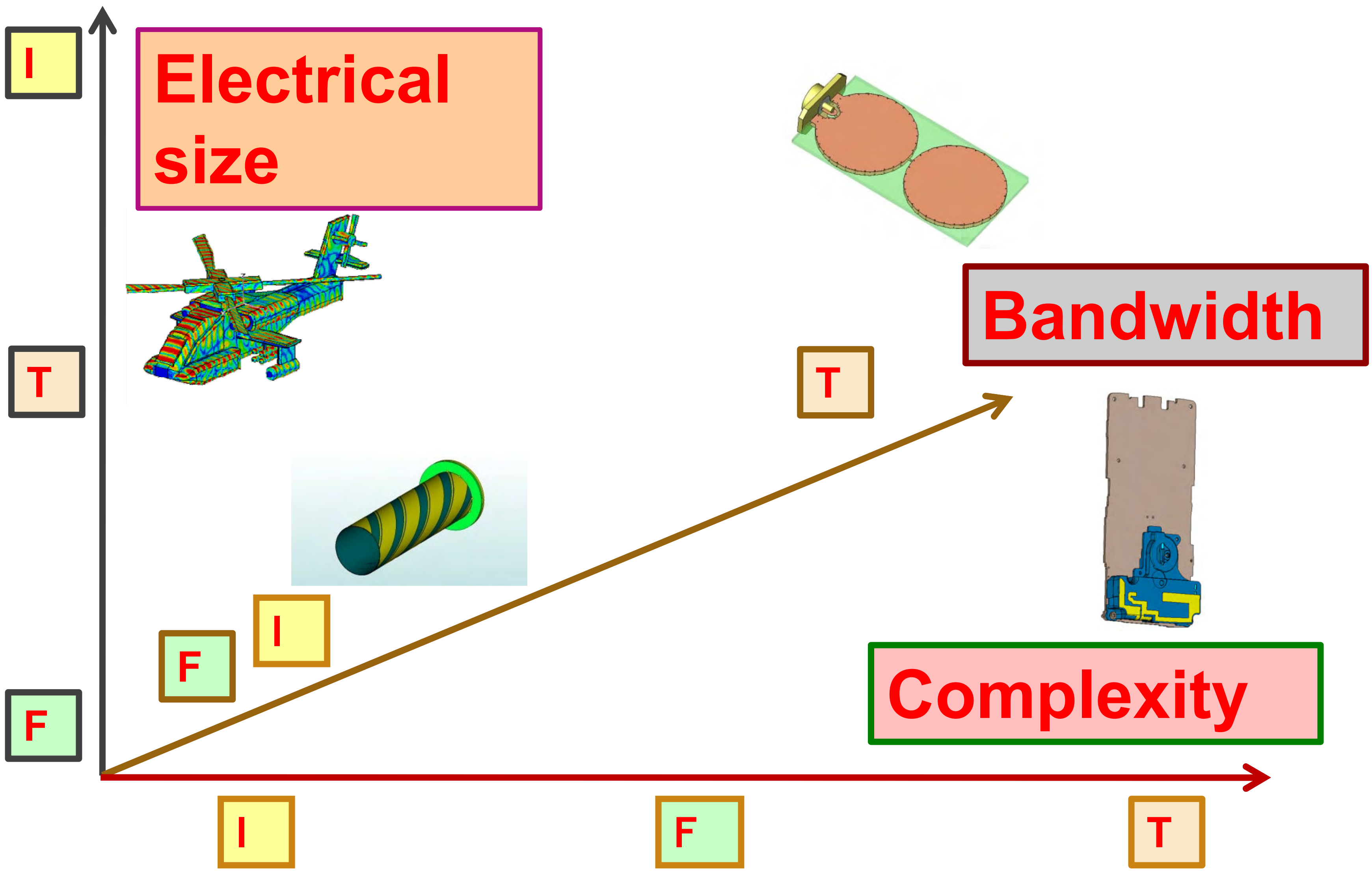
- Antenna design challenges
  - diversity in electrical size, bandwidth and complexity
- Differential and integral-equation based numerical methods
  - Compare approaches
- Time-domain and frequency-domain analysis
  - Advantages and disadvantages
- Combining methods
  - Improve design productivity/efficiency
- Summary

Antenna Simulation

- Different antenna types require different solver technologies.



Antenna Applications
Electrical Size, bandwidth and Complexity

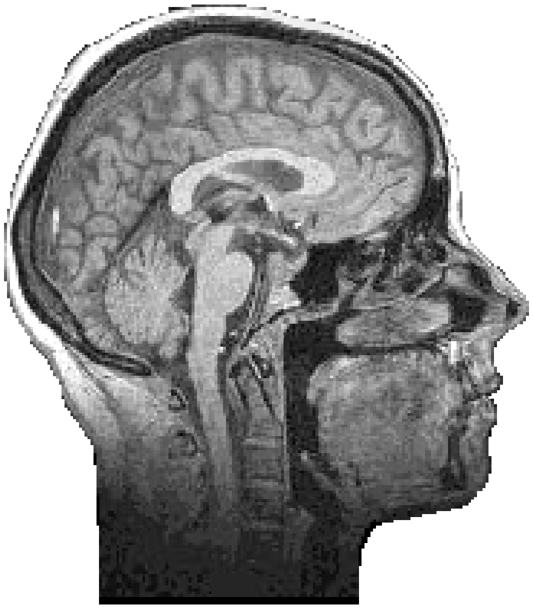


Comparing EM solver techniques

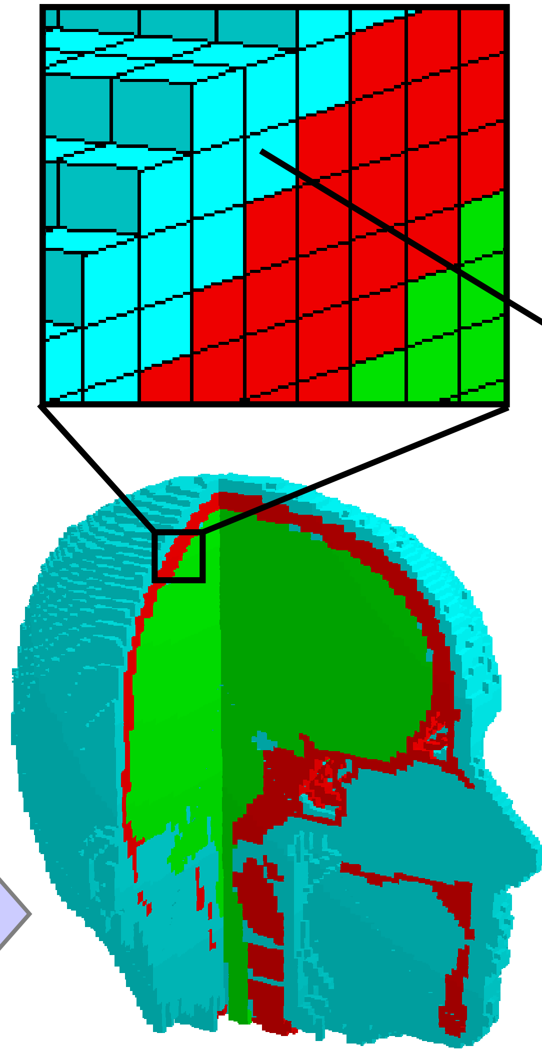
DIFFERENTIAL AND INTEGRAL METHODS

Time-Domain Method: FIT

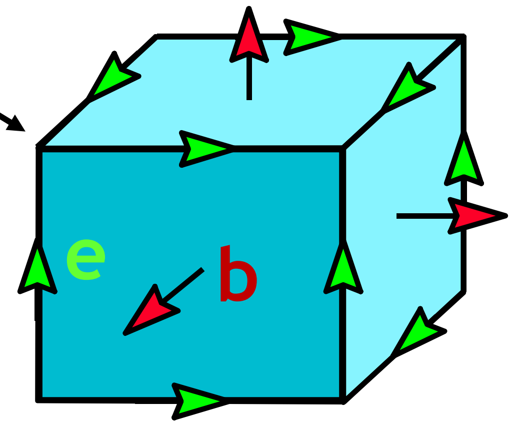
MRI data of a human head



Digitizing



Allocation of field components



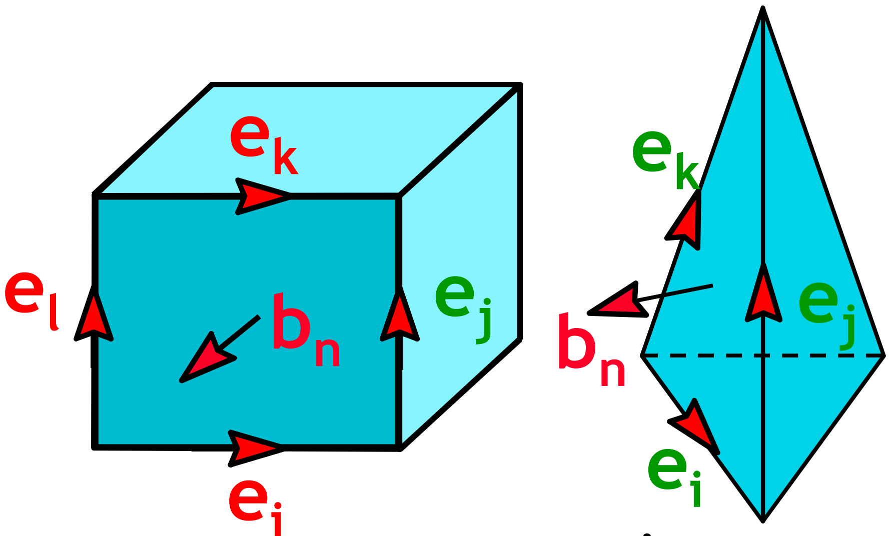
Each "brick" with different material properties

The Finite Integration Technique

Discretizing each Maxwell Equation

$$\oint_{\delta A} \mathrm{E}\; d\mathrm{s} = -\iint_{A} \dot{\mathrm{B}}\; d\mathrm{A}$$

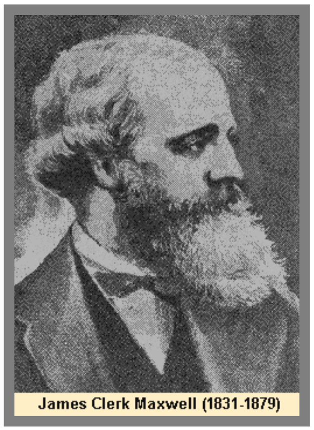
$$\mathrm{C}\mathrm{e} = -\dot{\mathrm{b}}$$



$$e_i + e_j - e_k \boxed{- e_l} = -\dot{b}_n$$

$$\underbrace{\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ 1 & 1 & -1 & -1 \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}}_{\mathrm{C}} \underbrace{\begin{bmatrix} e_i \\ e_j \\ e_k \\ e_l \end{bmatrix}}_{\mathrm{e}} = \underbrace{-\frac{d}{dt} \begin{bmatrix} \cdot \\ b_n \\ \cdot \end{bmatrix}}_{-\dot{\mathrm{b}}}$$

Maxwell Grid Equations



James Clerk Maxwell (1831-1879)

$$\oint_{\partial A} \vec{E}\cdot d\vec{s} = -\frac{\partial}{\partial t}\iint_{A} \vec{B}\cdot d\vec{A}$$

$$\oint_{\partial A} \vec{H}\cdot d\vec{s} = \iint_{A}\left(\frac{\partial \vec{D}}{\partial t} + \vec{J}\right)\cdot d\vec{A}$$

$$\oint\!\!\!\oint_{\partial V} \vec{B}\cdot d\vec{A} = 0$$

$$\oint\!\!\!\oint_{\partial V} \vec{D}\cdot d\vec{A} = Q$$

Maxwell's equations (1876)

$$C e = -\dot{b}$$

$$\tilde{C} h = \dot{d} + j$$

$$\tilde{S} d = q$$

$$S b = 0$$

Grid equations (1977)

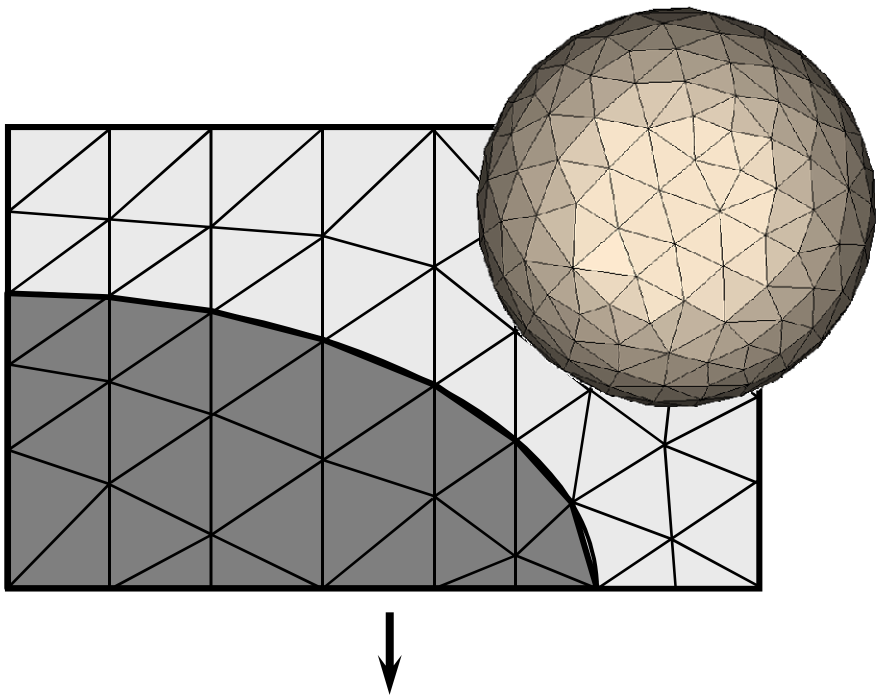
$$\mathit{div\ curl} = 0$$

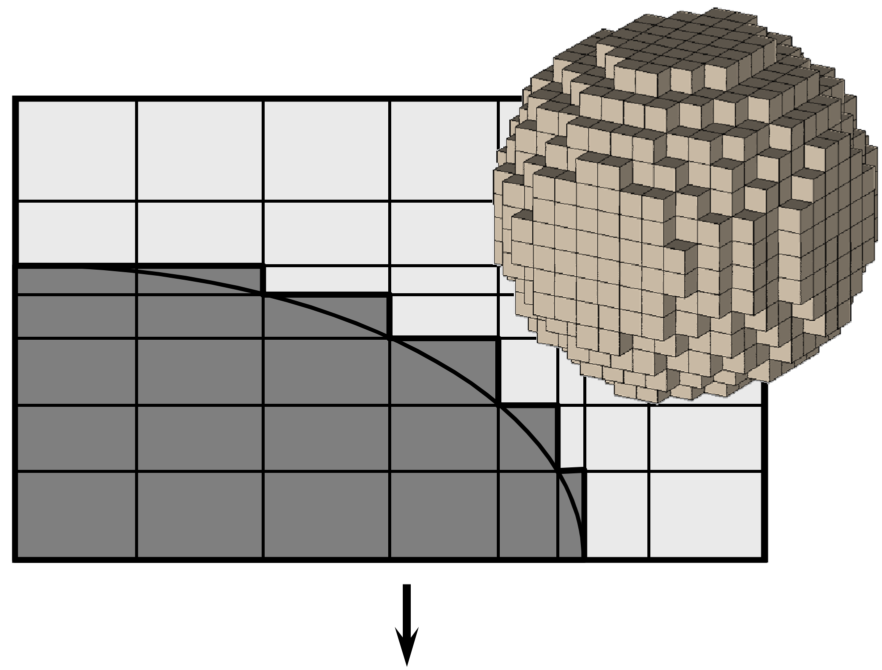
$$\mathit{curl\ grad} = 0$$

$$S C = 0$$

$$\tilde{C} S^{T} = 0$$

Geometry Approximation





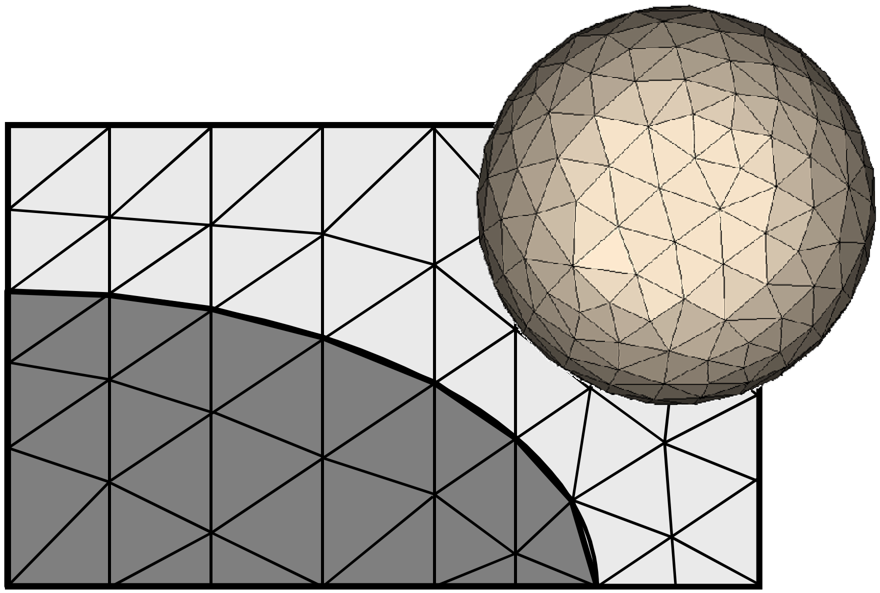
Tetrahedral Meshing FEM

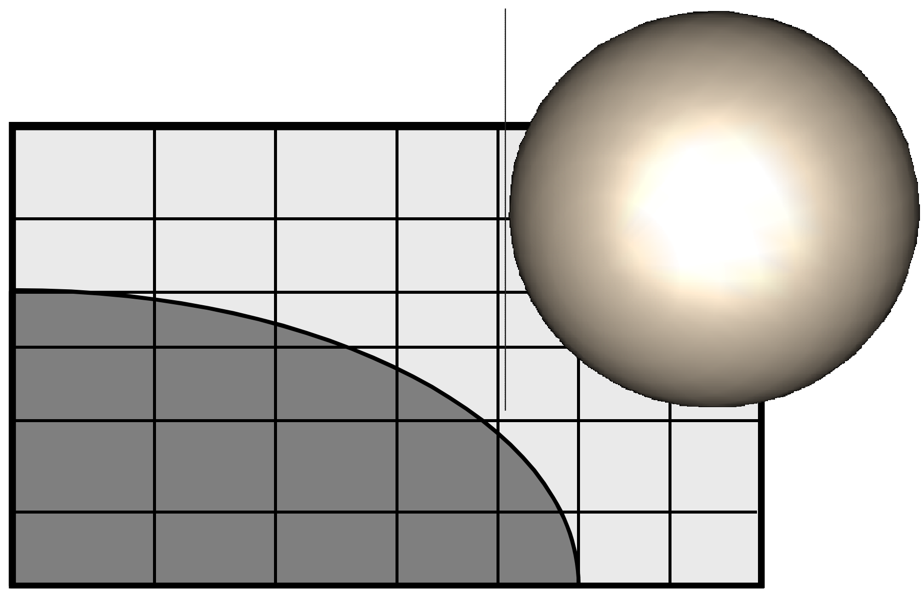
+ good geometry approximation
- higher memory requirements
- lower speed for big problems

Standard FDTD, TLM

- stair-case geometry approximation
+ low memory requirements
+ high speed for big problems

Geometry Approximation





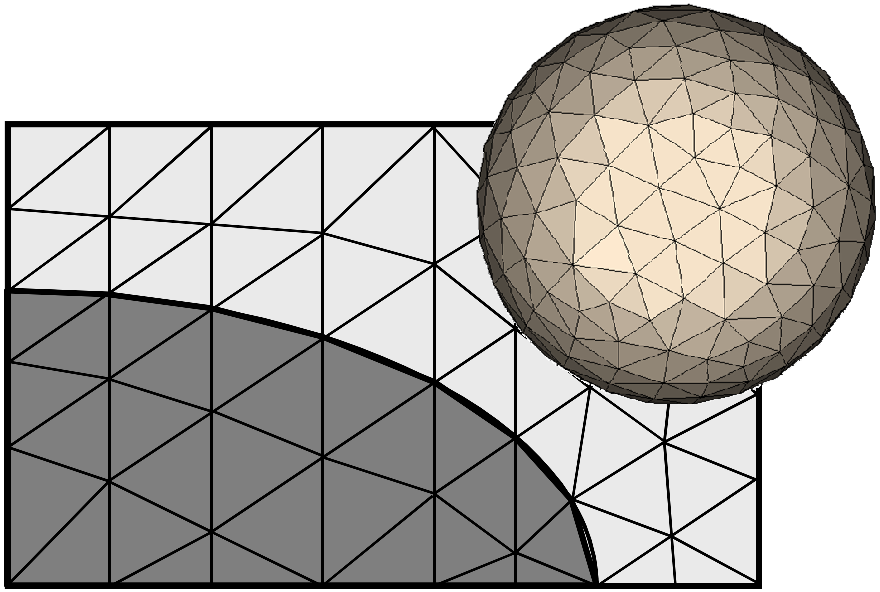
Tetrahedral Meshing

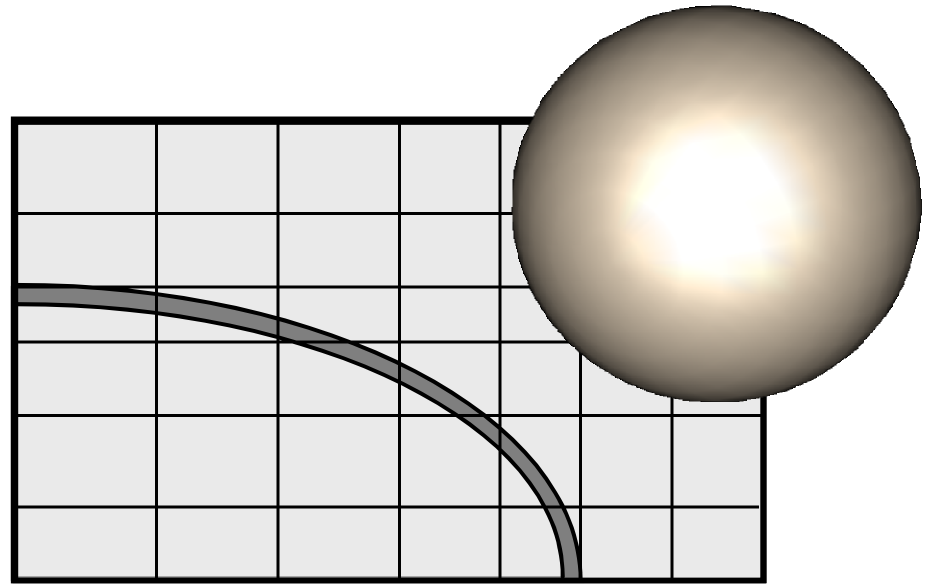
\+ good geometry approximation
- higher memory requirements
- lower speed for big problems

Hexahedral + PBA

\+ excellent geometry approximation
\+ low memory requirements
\+ high speed for big problems

Frequency Domain + Time Domain





TET-Mesh in Freq. Domain

☺ Electrically small structures

☺ Highly resonant structures

☺ Arbitrary material dispersion

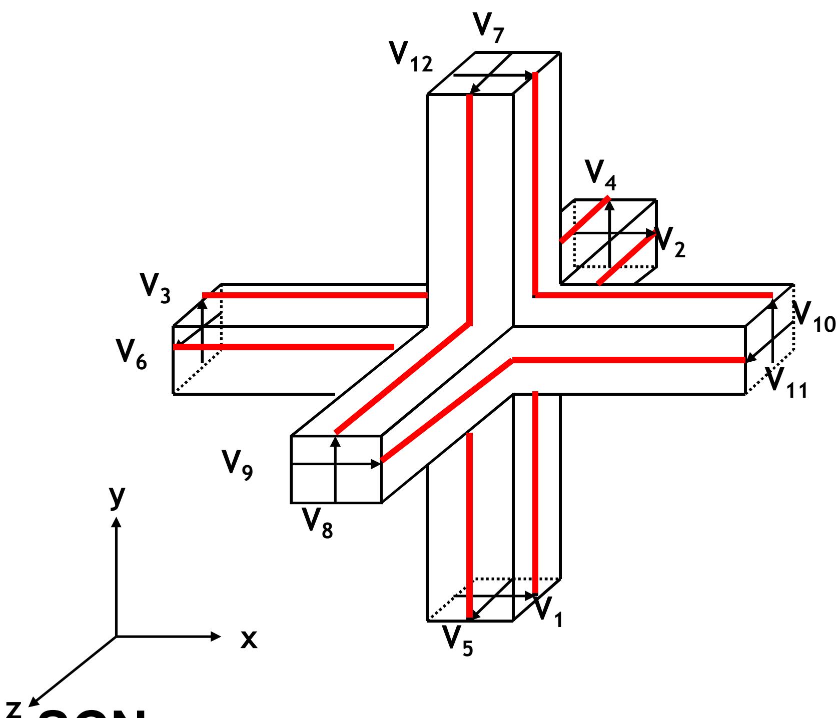
PBA-Mesh in Time Domain

☺ Electrically large structures

☺ Low memory

☺ Broadband Solution

Differential Time-Domain Method: TLM



SCN

Symmetrical Condensed Node

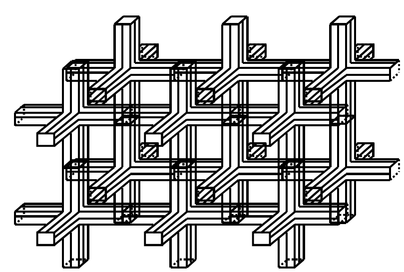
Johns P.B. 1987 [3]

The simplest form of 3D TLM uses 12 transmission lines to model a cube of empty space.

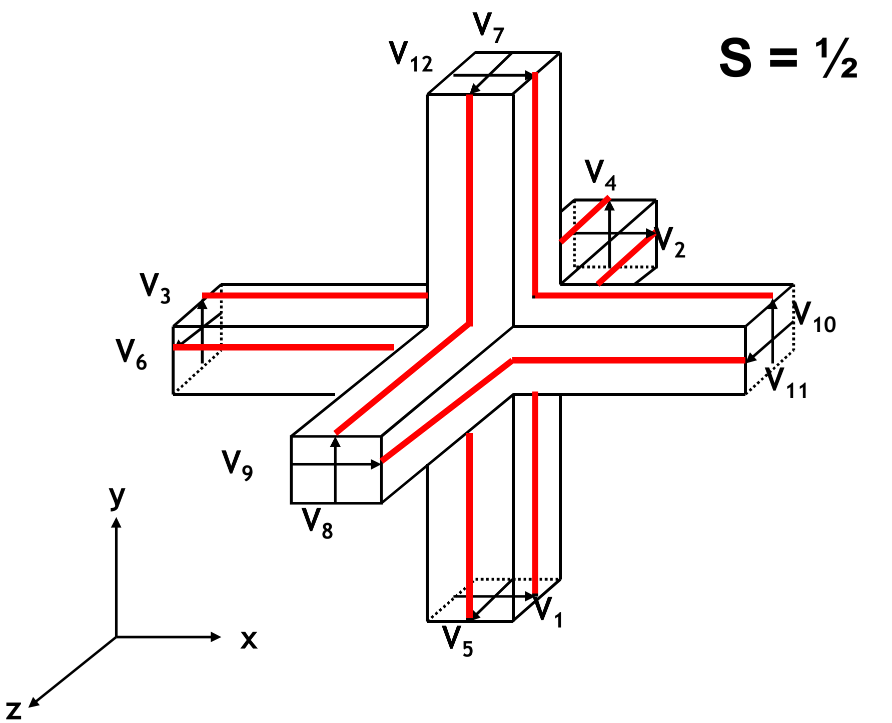
The two polarizations in each direction of propagation are carried on two orthogonal pairs of transmission-lines.

Single grid for E and H fields.

The link lines have the same characteristic impedance Z_o



Scattering in 3D SCN

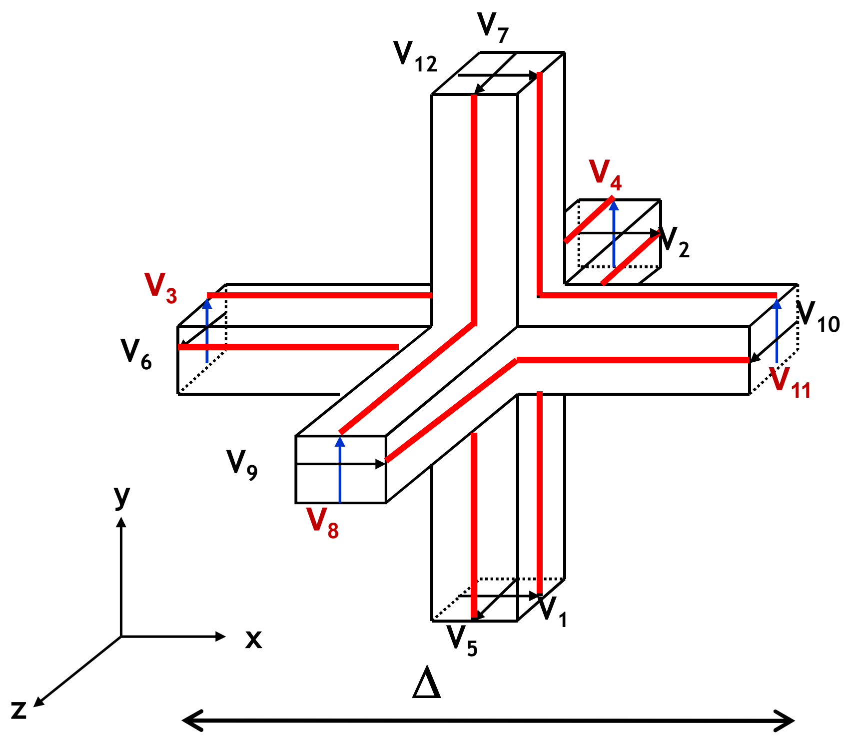


$$S = \frac{1}{2}\begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & -1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

The SCN scattering equation $V^r = SV^i$ contains a 12 x 12 matrix

Incident and reflected fields are known at all boundaries

Calculating Fields in the SCN



$E_x = (V_1^i + V_2^i + V_9^i + V_{12}^i) / 2\Delta$

$E_y = (V_3^i + V_4^i + V_8^i + V_{11}^i) / 2\Delta$

$E_z = (V_5^i + V_6^i + V_7^i + V_{10}^i) / 2\Delta$

$H_x = (V_4^i - V_8^i + V_7^i - V_5^i) / 2 Z_0\Delta$

$H_y = (V_6^i - V_{10}^i + V_9^i - V_2^i) / 2 Z_0\Delta$

$H_z = (V_1^i - V_{12}^i + V_{11}^i - V_3^i) / 2 Z_0\Delta$

All 6 field components referenced to center of node

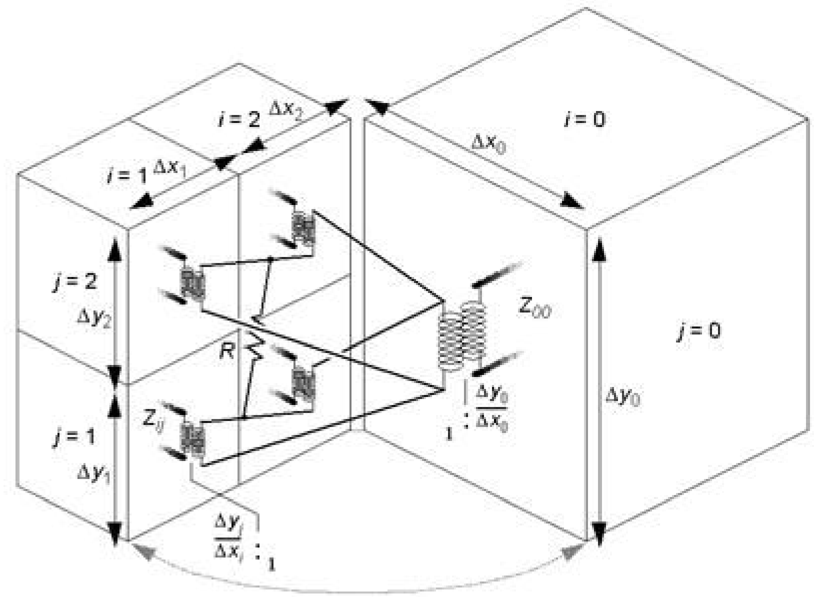
Hexahedral Octree Meshing in TLM

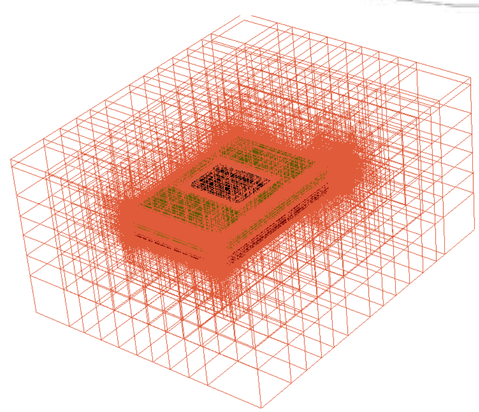
Multi-Grid Interface

- The interface is defined as an electrical connection
- Time-step is the same in both the coarse and fine grids
- The connection guarantees stability and is lossless
- The connection supports correct propagation at any angle to the interface

Cell count can be reduced by 97% using Octree meshing

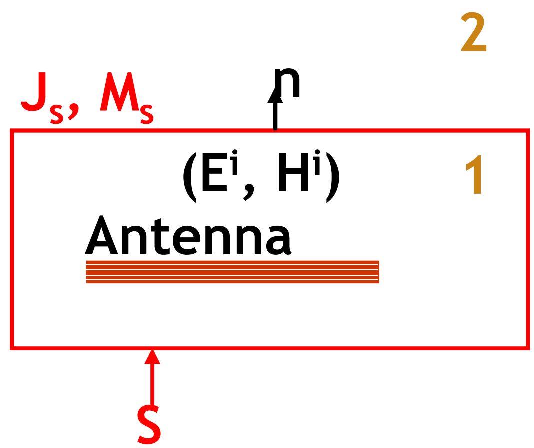
Cell Interface Circuit





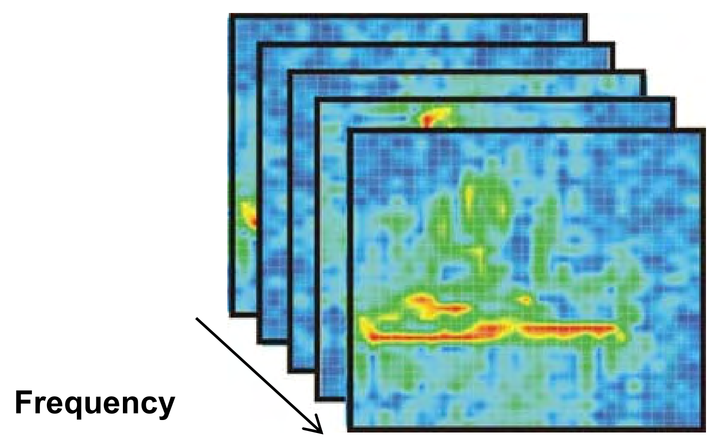
Broadband Equivalent Source (ES)

- The Equivalent Source is based on the “Equivalence Theorem”
- A closed surface S divides a region (1) containing sources from a source-free region (2)
- The EM field outside of S can be replaced by a distribution of electric and magnetic current densities (J_s, M_s) over the surface S
- The Equivalent Source captures the spatial variation and frequency dependency of antenna radiation
- Time domain waveform is synthesized based on the frequency content provided in the near field scan data



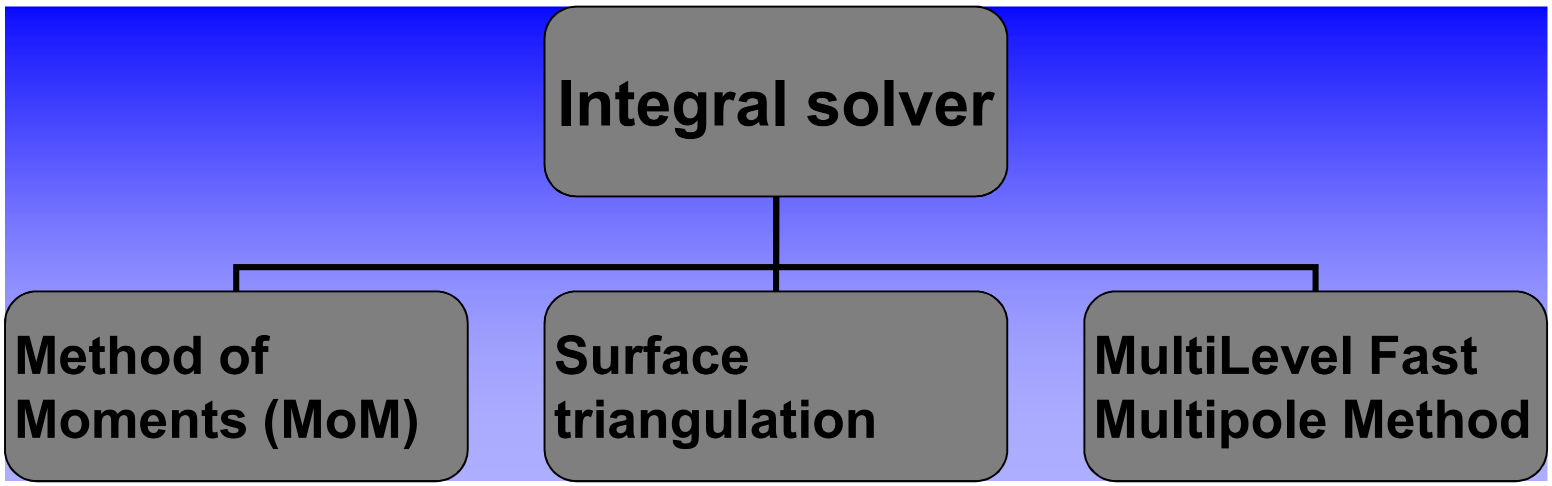
Electric Current $J_s = n \times H^i$

Magnetic Current $M_s = -n \times E^i$



Integral Equation Solvers

- Overview

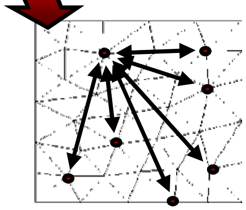


Integral Equation Solvers

Integral solver

- **Method of Moments (MoM)**
- **Surface triangulation**
- **MultiLevel Fast Multipole Method**

- Discretization by MoM
- Applies Green's function
- Open Boundary integral formulation
- N^2 for memory and N^3 for solver time



$$E(r) = -i\omega\mu \int_S \left[g(r-r')J(r') + \gamma^{-2}\nabla g(r-r')\nabla' \cdot J(r') \right] dS$$

Integral Equation Solvers

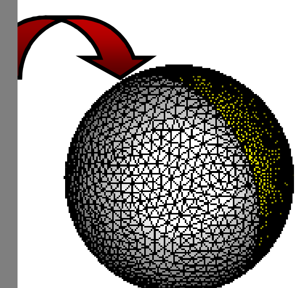
Integral solver

Method of Moments (MoM)

Surface triangulation

MultiLevel Fast Multipole Method

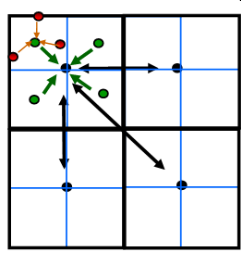
- Only surface mesh necessary
- Uses triangles
- Fewer elements than in Volume methods



Integral Equation Solvers

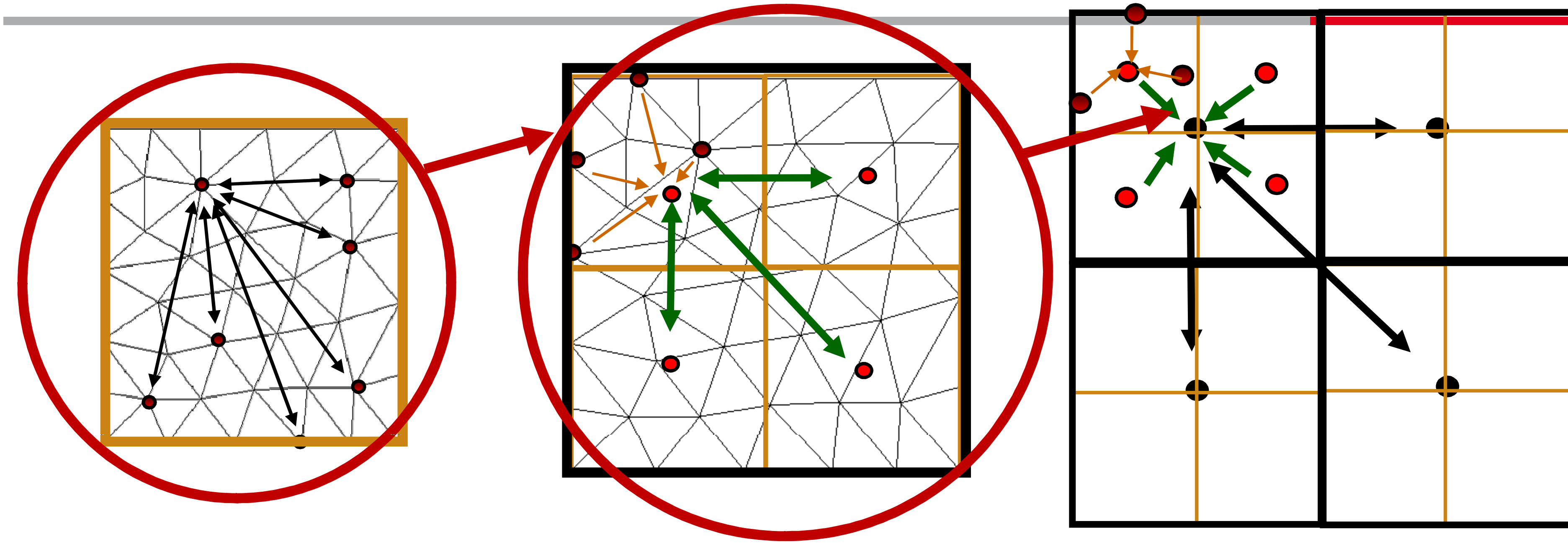
Integral solver

- Method of Moments (MoM)
- Surface triangulation
- MultiLevel Fast Multipole Method



- Iterative solver
- Recursive scheme to combine coupling
- O(N logN) for operations & memory

MLFMM in a nut shell



MoM

FMM

MLFMM

Every element
couples to
all other elements
→ dense matrices

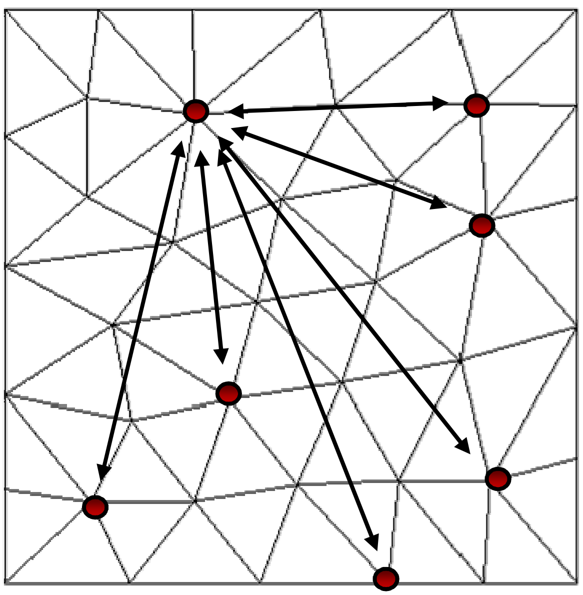
Use boxes to
combine coupling
→ sparser matrices

Recursive
scheme

Multi-Level Fast Multipole Method

<u>Overview</u>

- Based on the Method of Moments
- Steady-state simulation → energy storage is not a problem
- Solving for surface currents → Fields obtained via Green's Function
- Triangular Surface Mesh: single frequency meshing and results
- One simulation solves all ports
- Specialized for electrically very large structures



MLFMM solvers are ideal for electrically very large structures (>10λ).

Well suited applications: Radar cross-section, antenna placement.

Structures smaller than 10λ are better suited for time domain solvers.

Comparing the simulation domains

TIME-DOMAIN VS. FREQUENCY-DOMAIN

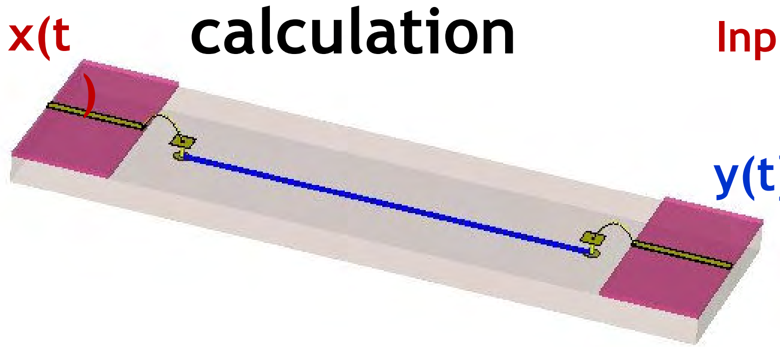
Statics, Frequency-Domain and Time-Domain

Maxwell Grid Equations

- $\frac{\partial}{\partial t} = 0$
  - E-static
  - M-static
  - J-static
  - Tracking+ Spacecharge
- $\frac{\partial}{\partial t} \mapsto i\omega$
  - Frequency Domain (j>0)
  - Eigenvalue Problem (j=0)
- $\frac{\partial}{\partial t} \neq 0$
  - Implicit
  - Explicit Time Domain
  - PIC

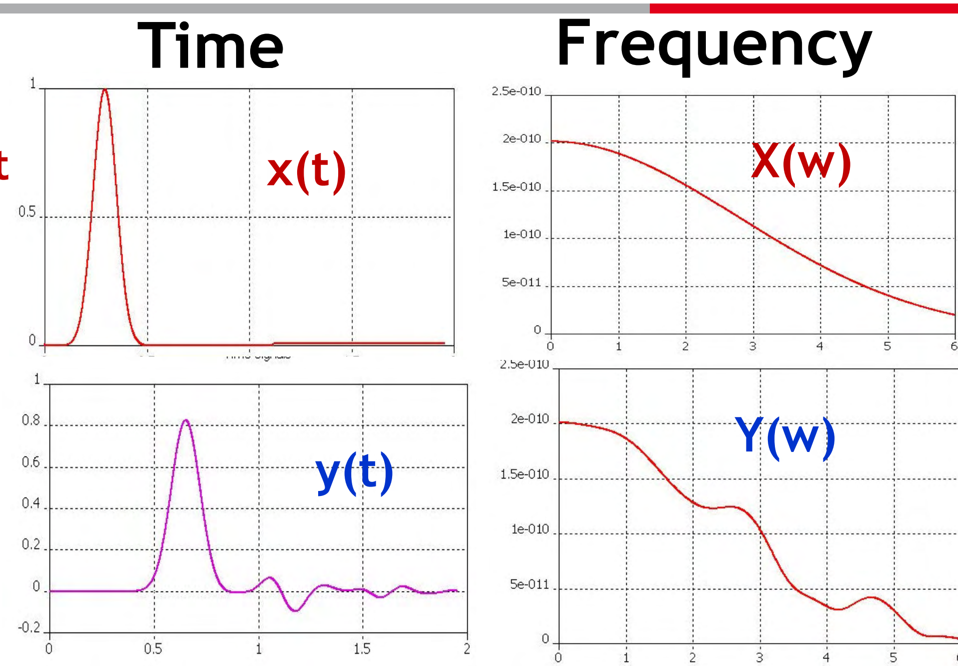
Time Domain Methods

Time Domain calculation



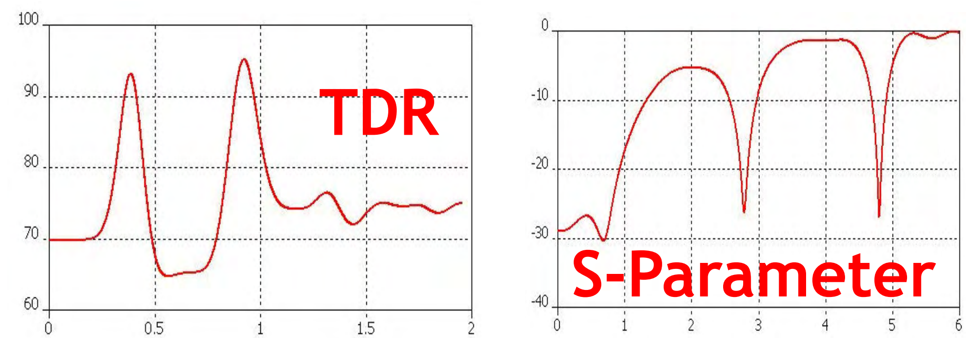
Input

Output



Monitoring of the time domain signals

Transfer



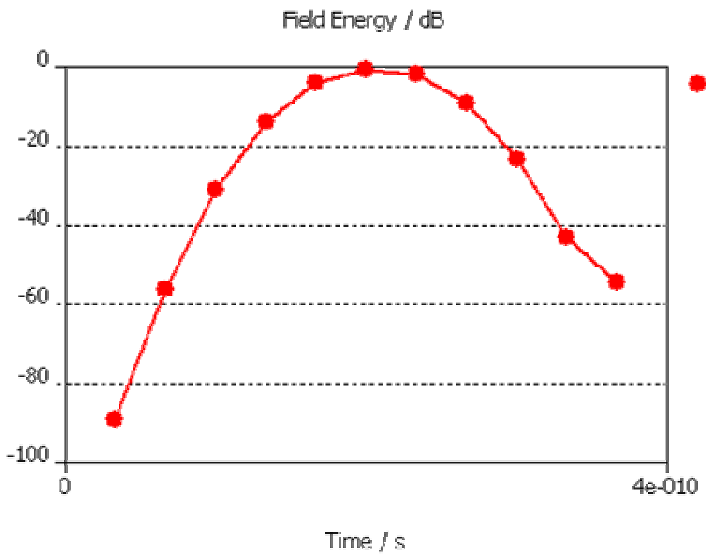
Broadband information (e.g 0-6 GHz)

after one single run by means of a FFT

Time Domain Analysis

<u>Overview</u>

- Arbitrary input signal
- Inject energy and watch it leave
- Solve for unknowns without matrix inversion
- Hexahedral Mesh: Broadband meshing and results
- Simulation is performed on a port-by-port basis
- Smaller mesh cells = longer solve times
- Energy storage for high Q structures prolongs simulation time

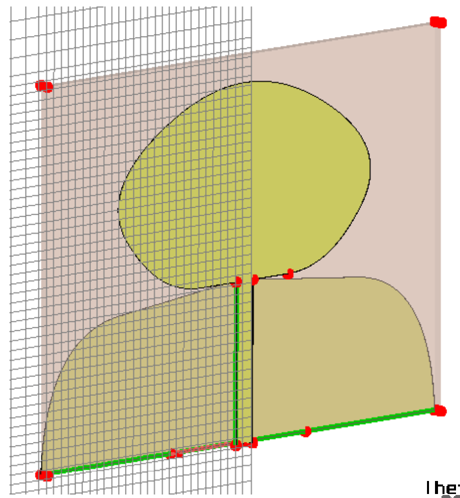


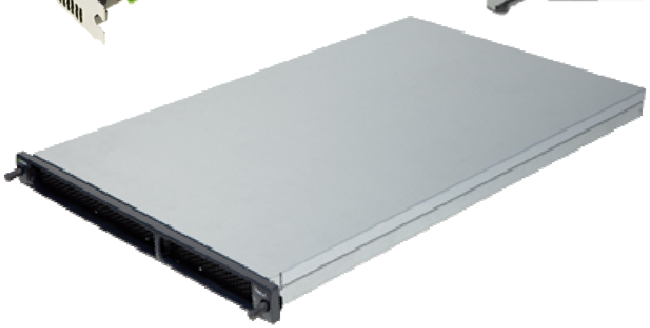
Well suited applications: Broadband, electrically large structures.

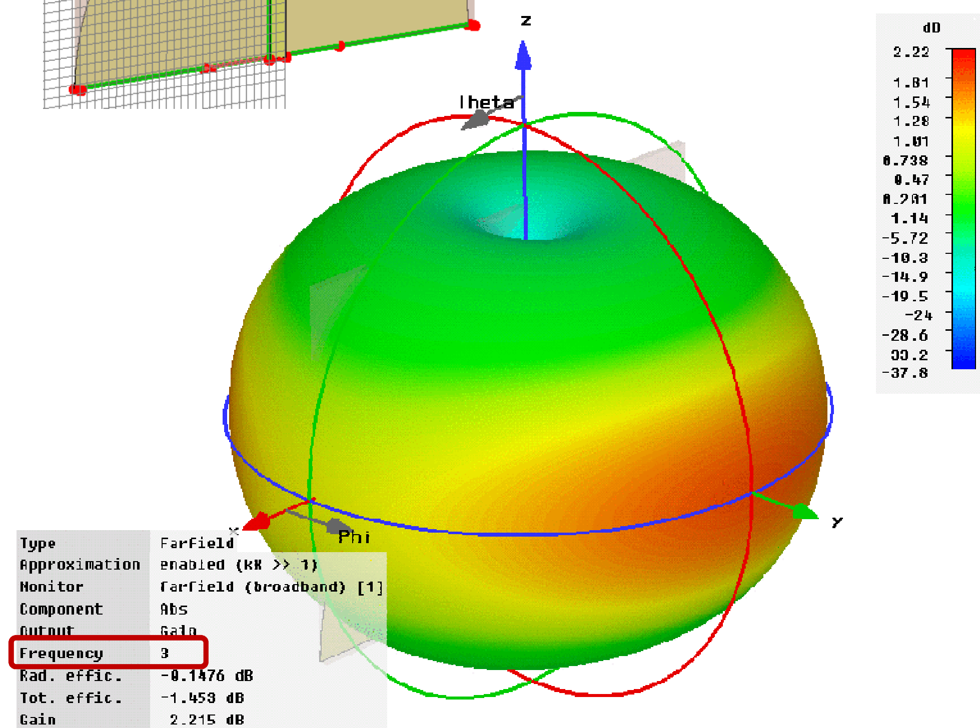
Highly resonant, electrically small structures may be better suited to a frequency domain solver.

Transient Solver

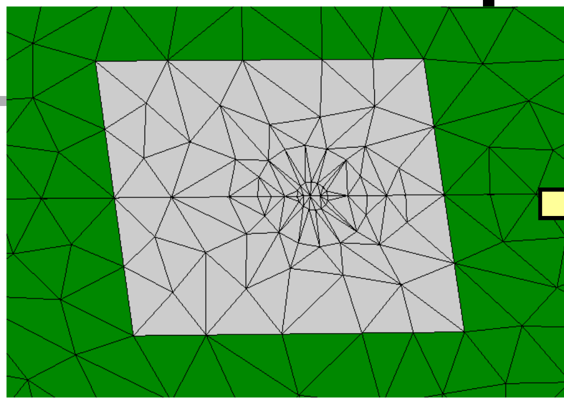
- PBA meshing
- Broadband
- Linear memory
- GPU acceleration

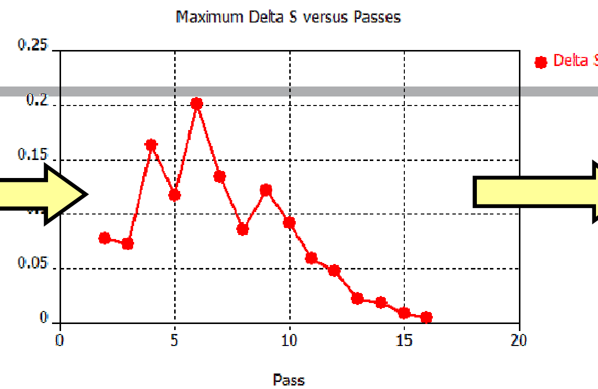


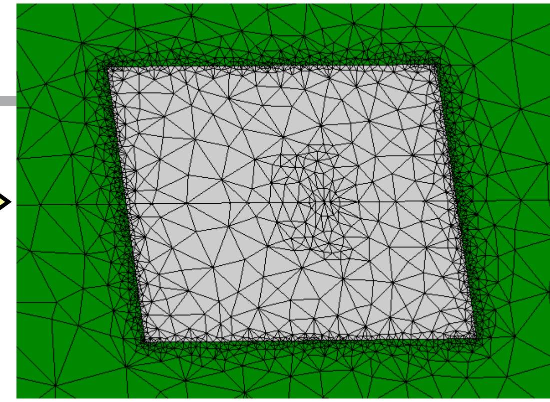




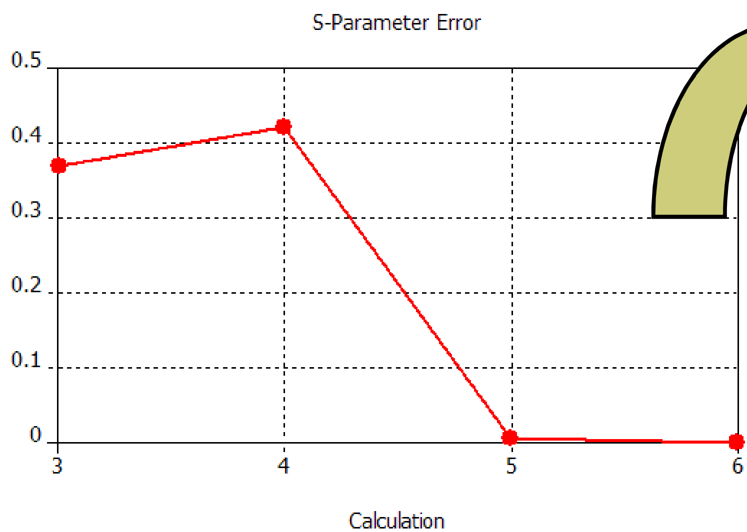
Frequency Domain Methods



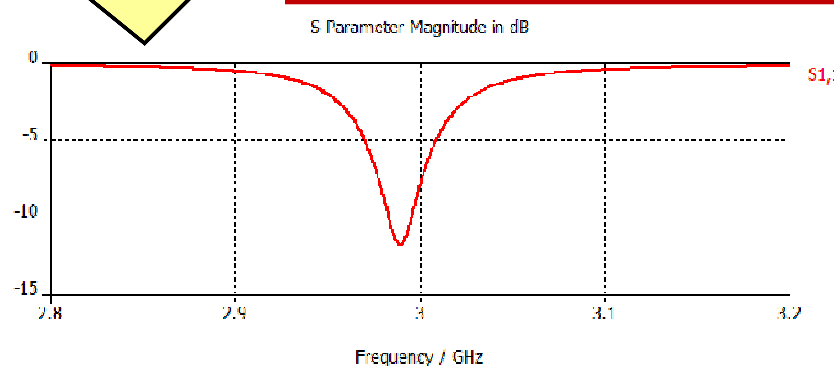




- Simulation performed at steady-state
- Adaptively refine the mesh at discrete frequencies
- Simulate multiple frequency points to obtain broadband behavior
- Simulation stops when S-parameters stop changing



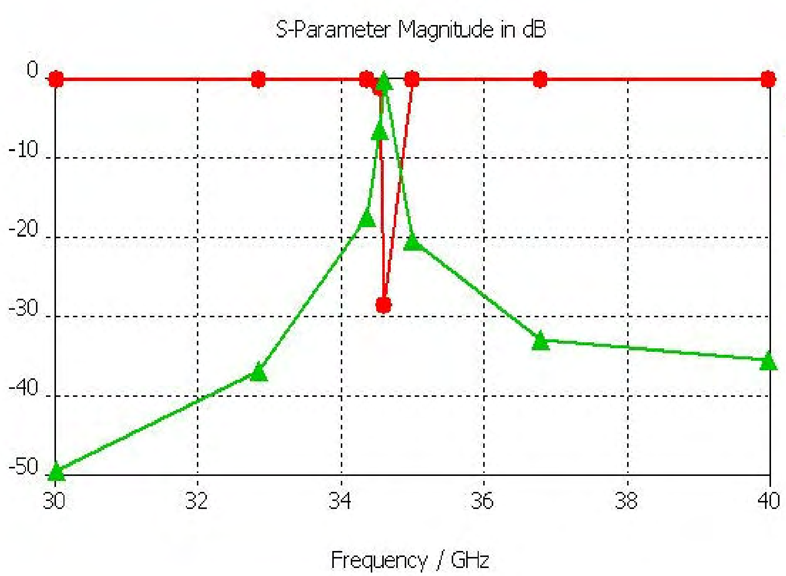
- Hexahedral or Tetrahedral mesh
- Frequency Domain Results only
- One frequency per simulation



Frequency Domain Analysis

<u>Overview</u>

- Assumed time-harmonic fields → Single frequency excitation
- Steady-state simulation → energy storage is not a problem
- Matrix inversion required for solution
- Tetrahedral Mesh: Single frequency meshing and results
- One simulation <u>can</u> solve all ports in one pass
- Small mesh cells have no effect on simulation time
- Number of mesh cell is the most significant indication of simulation time

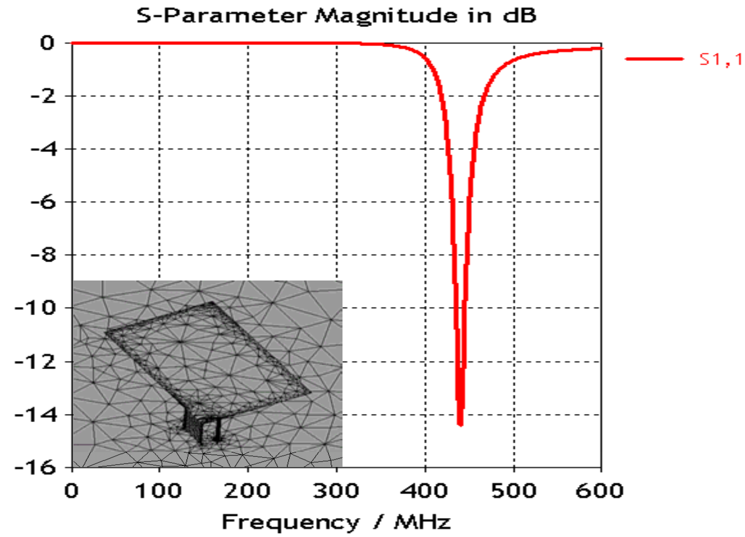


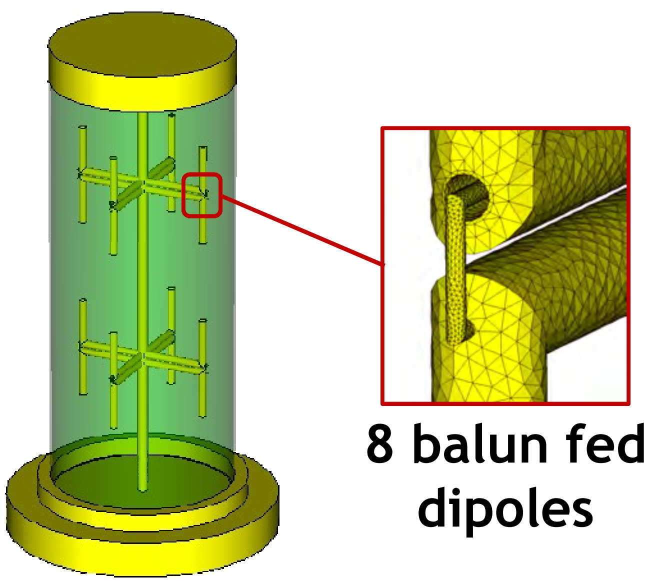
Well suited applications: Narrowband, electrically small structures.

Limited computational resources make it necessary to use a time domain solver for electrically large structures.

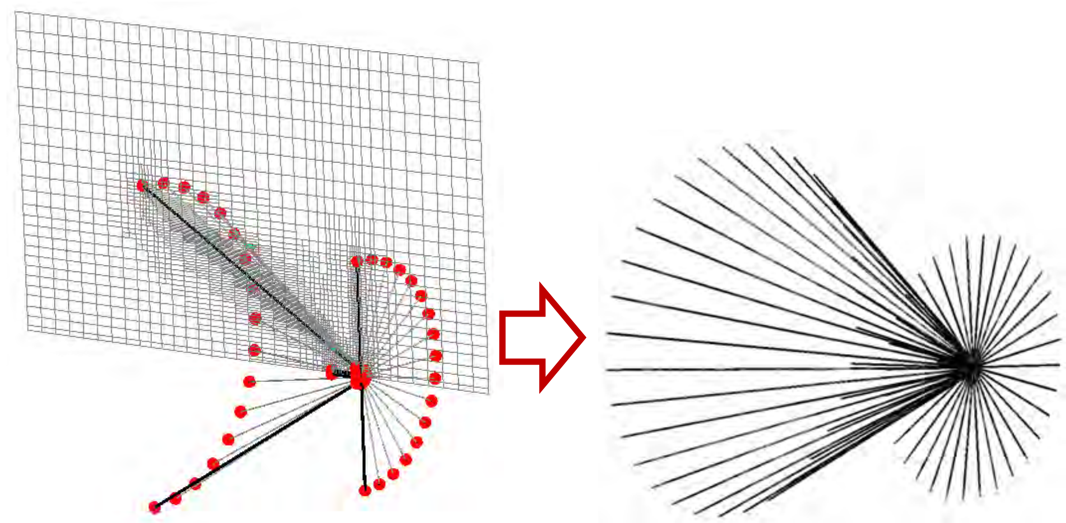
Frequency Solver

- Single frequency
- Electrically small
- Tetrahedral mesh
- Multiple ports





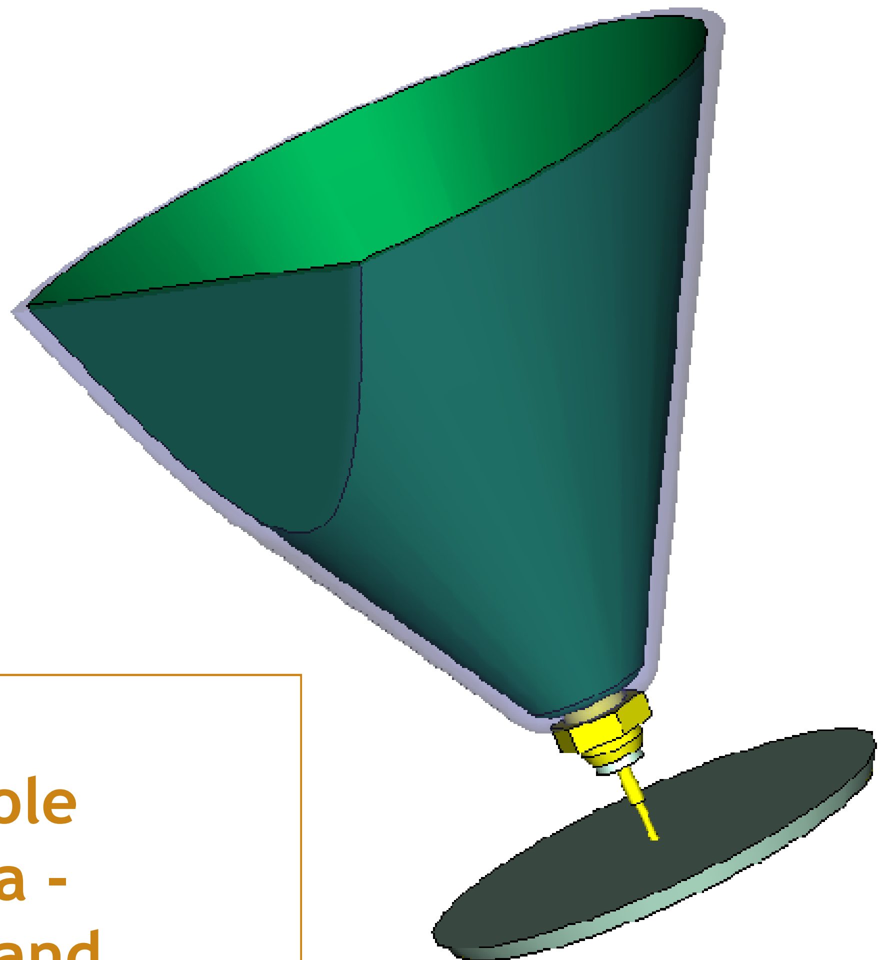
8 balun fed dipoles



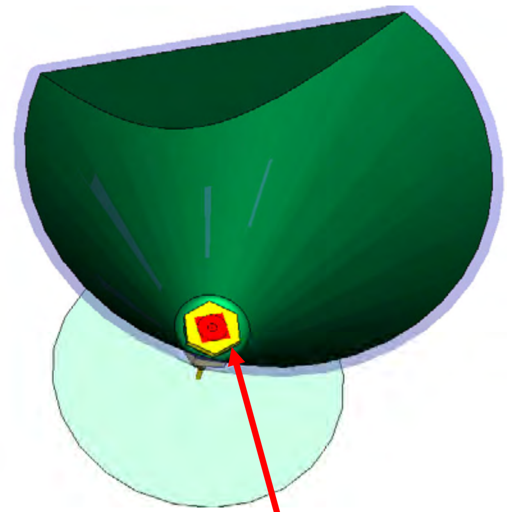
Applying differential/integral and time/frequency domain methods to antenna design problems

APPLYING THE DIFFERENT TECHNIQUES

Validation Example: Conical Monopole

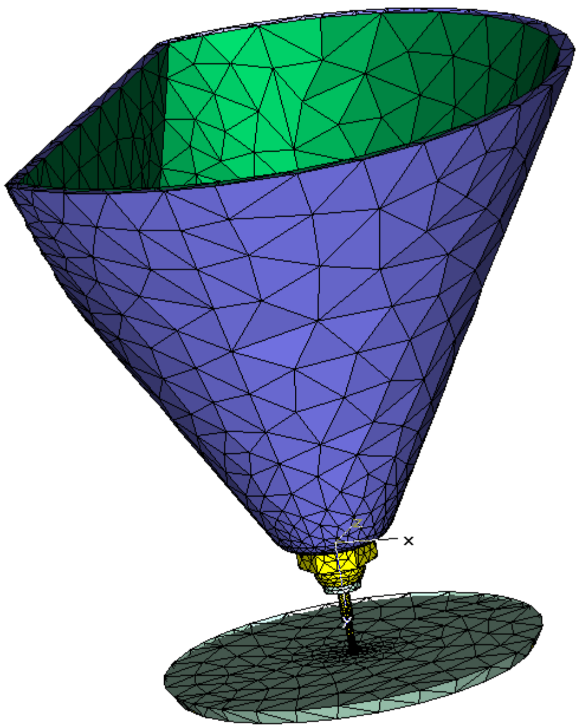


Conical monopole antenna - broadband

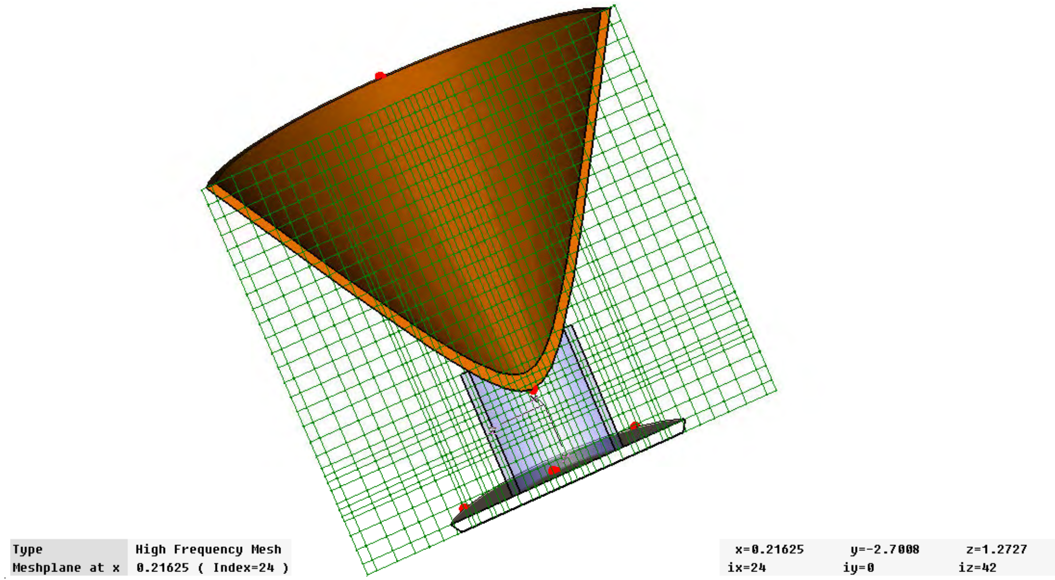


Wave guide port excitation

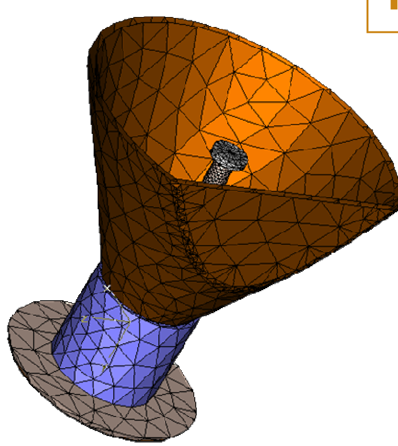
Mesh Types



Surface Mesh



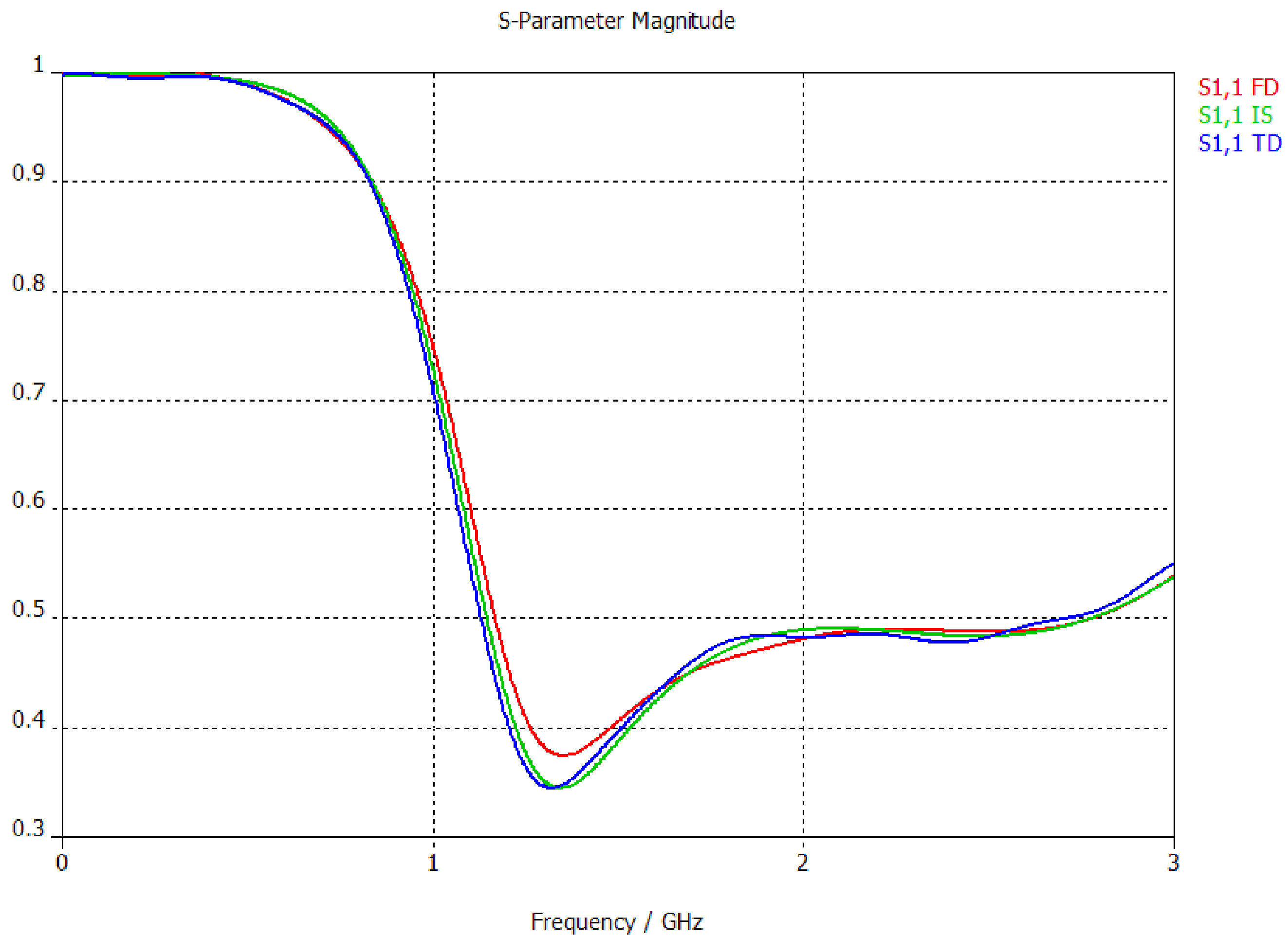
Hexahedral Mesh



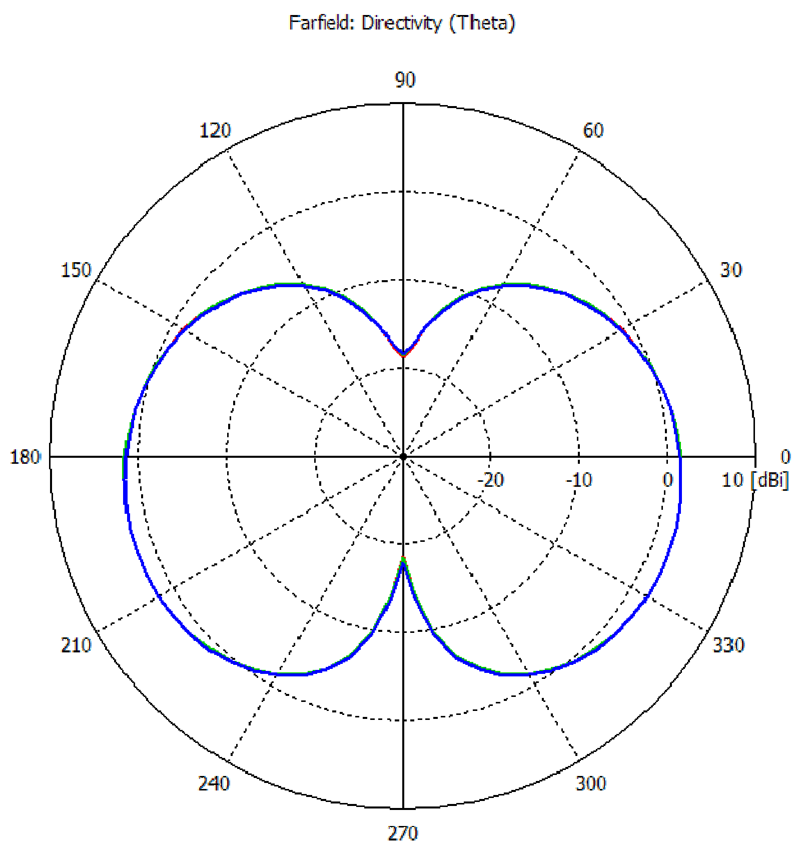
Tetrahedral volume Mesh

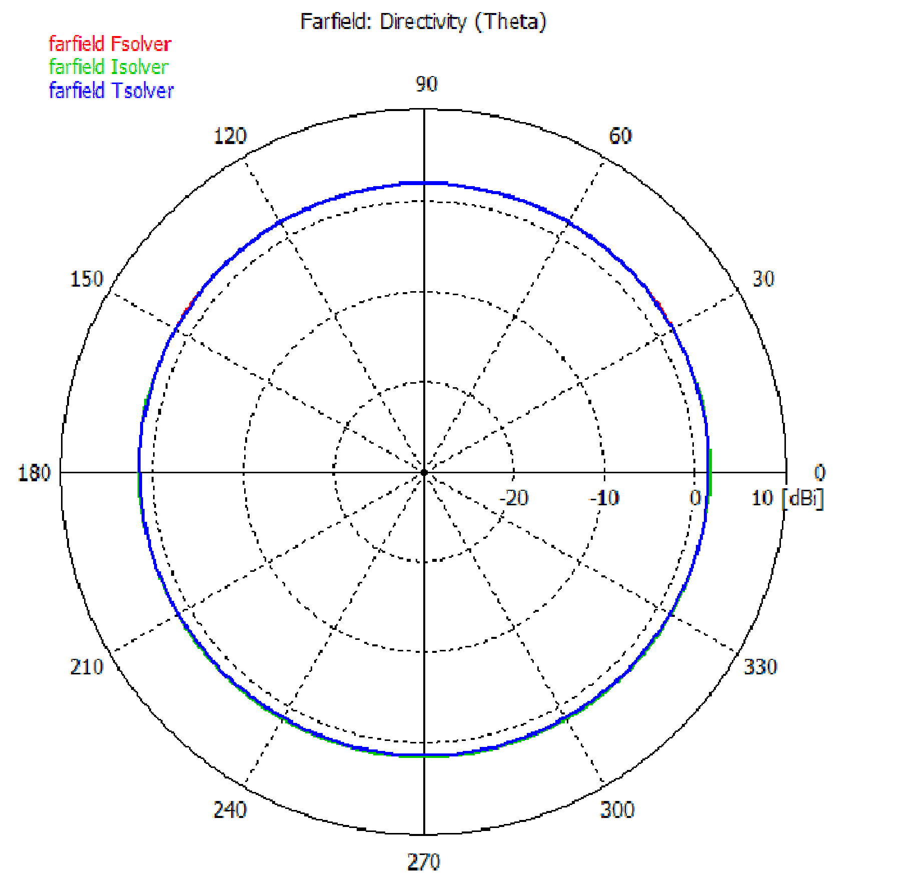
Type High Frequency Mesh

Result Comparison – S parameters



Result Comparison – Far Field





Phi=90

Theta=0-360

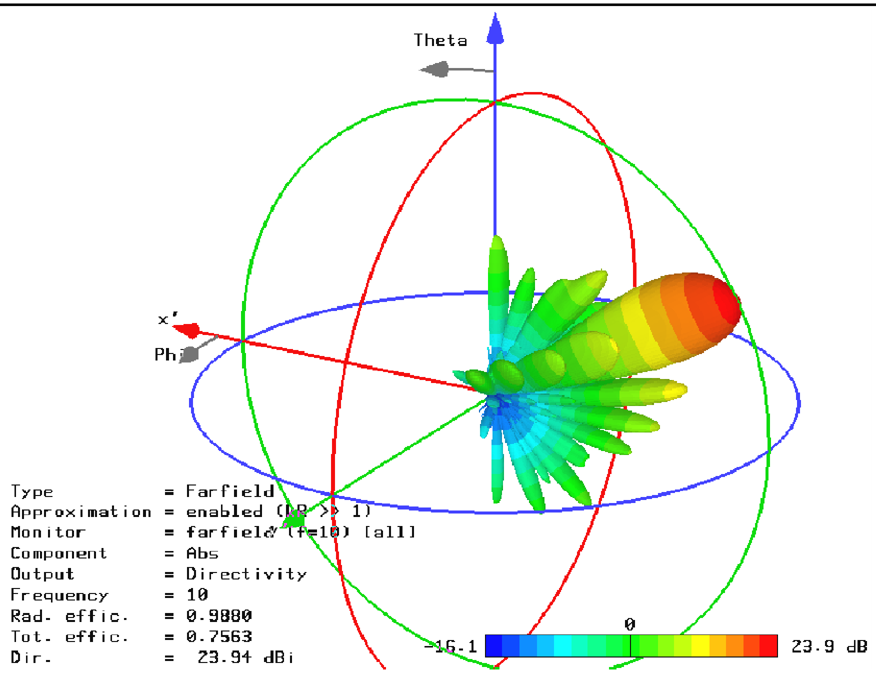
Phi=0

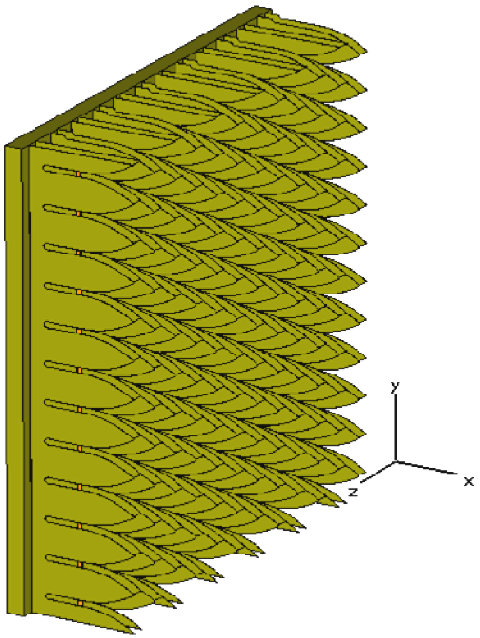
Theta=0-360

Time-Domain Solver Example: Phased Array

Finite Array of 138 Flared Slot Line Radiators

The slot lines are excited by striplines which are fed by coax lines though the ground plane. The array is modeled with an infinite perfect electrical conducting surface in front. The elements of the array are on a hexagonal lattice.

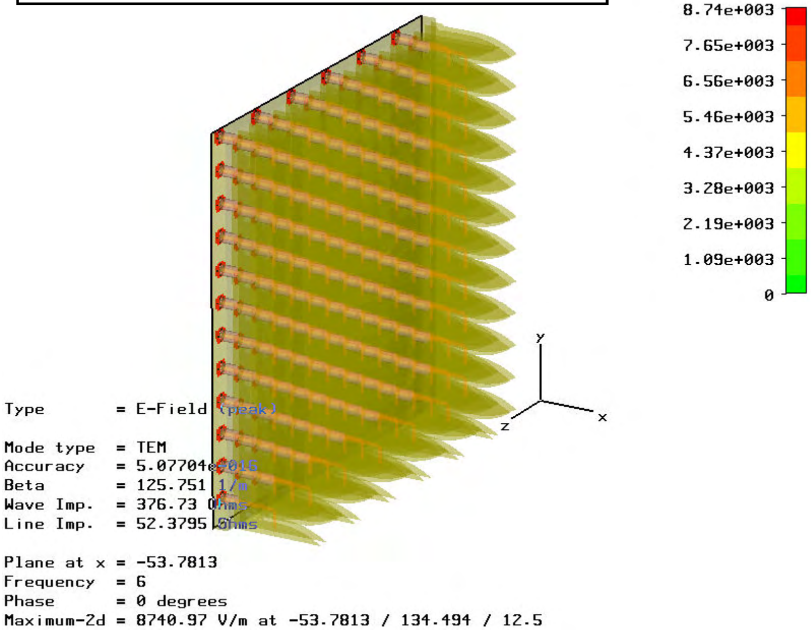


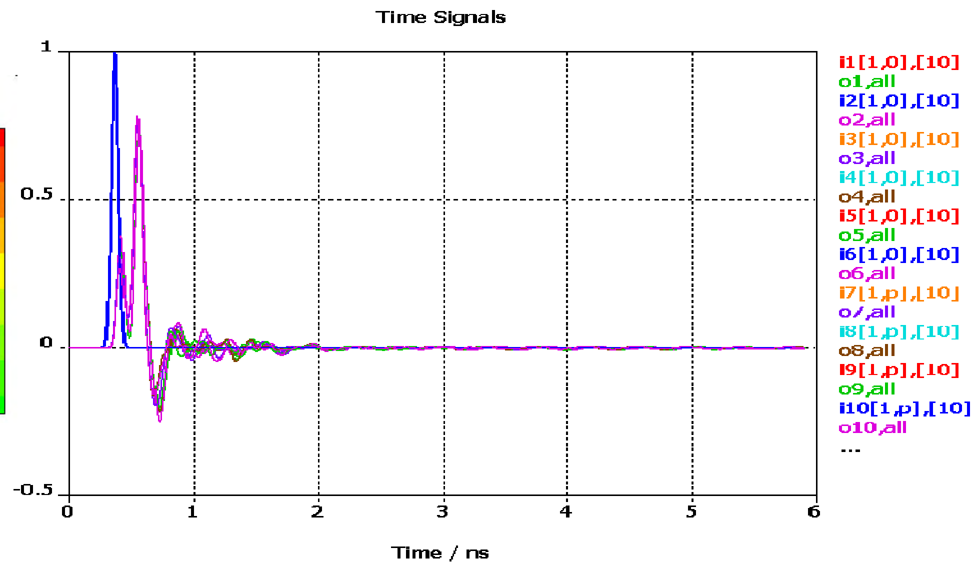


CST MWS simulation by Sonnet USA

Time-Domain Solver Example: Phased Array

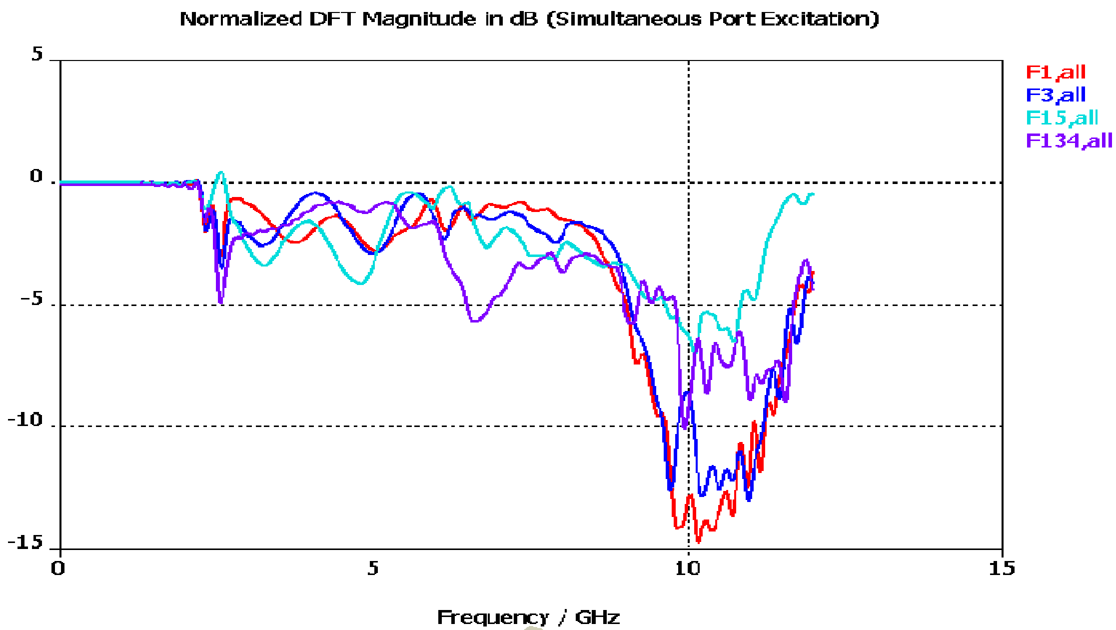
Each of the 138 coax lines are excited with their normal mode (TEM). The coax lines are near 50 ohms.





The coax lines are simultaneously excited with a broadband Gaussian pulse. This is done so that broad band s-parameters can be obtained. The return signals at the various ports is also monitored. This simulation required 400 Mbytes of RAM and < 1 hr on a 2.1 GHz laptop.

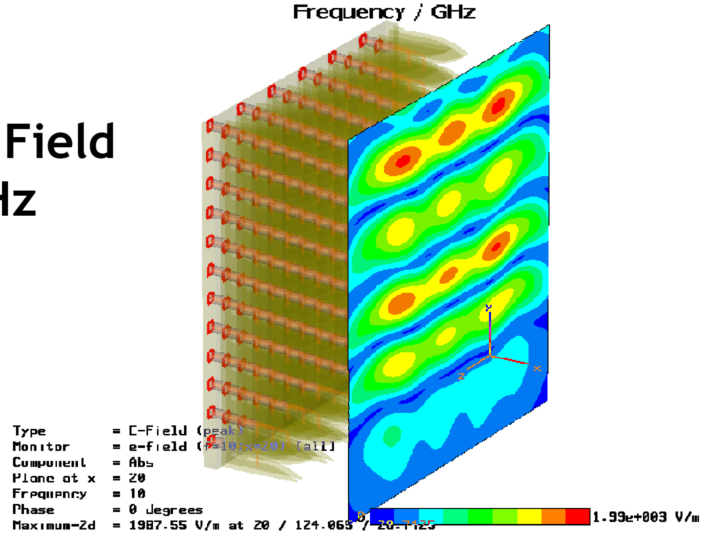
Time-Domain Solver Example: Phased Array



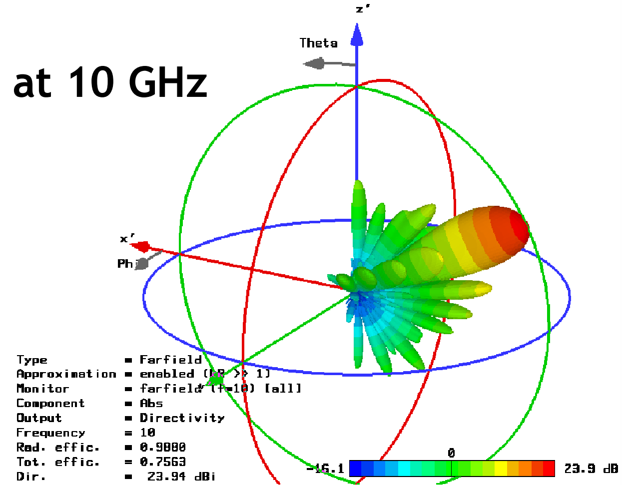
All ports are excited so you cannot get a standard S_{nn} for the array but rather a set of "driven" returns.

Note that the driven return at an element can go positive if it is coupling energy out of neighboring elements.

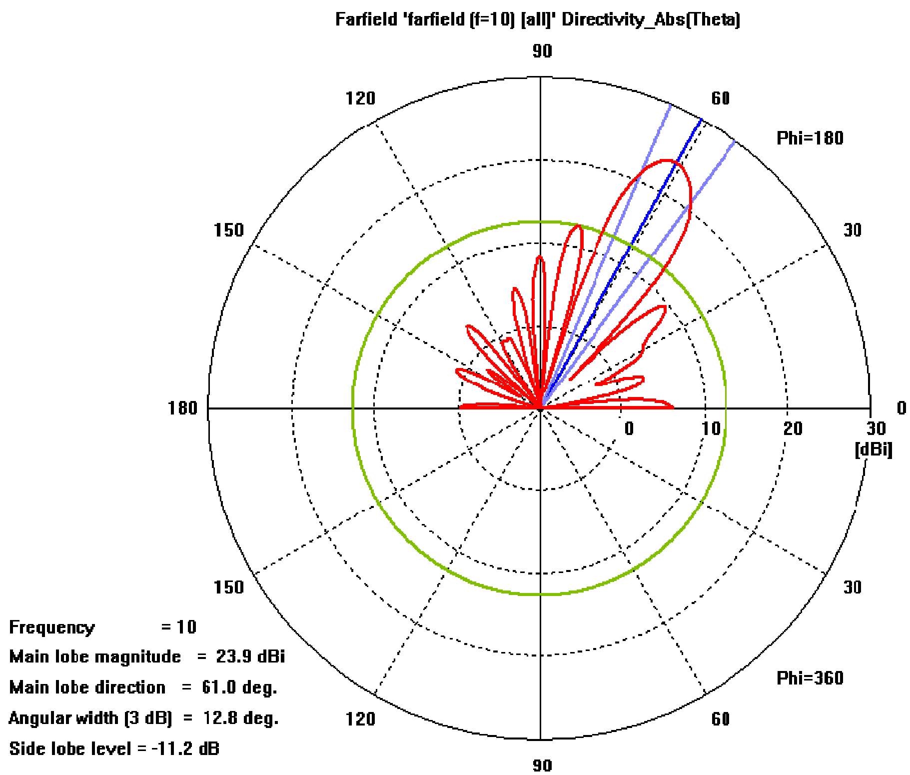
Electric Field at 10 GHz



Far Field at 10 GHz



Time-Domain Solver Example: Phased Array



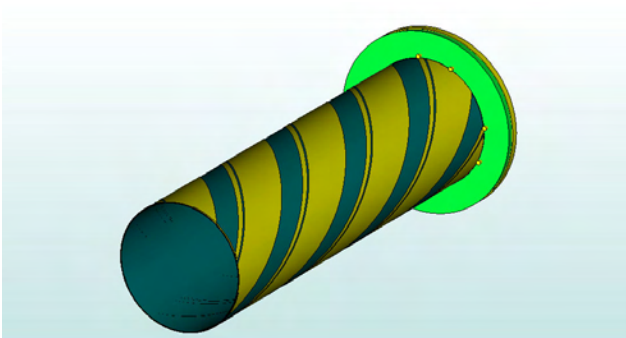
1) The main beam is at 61 degrees, not 60 degrees as calculated from the array function.

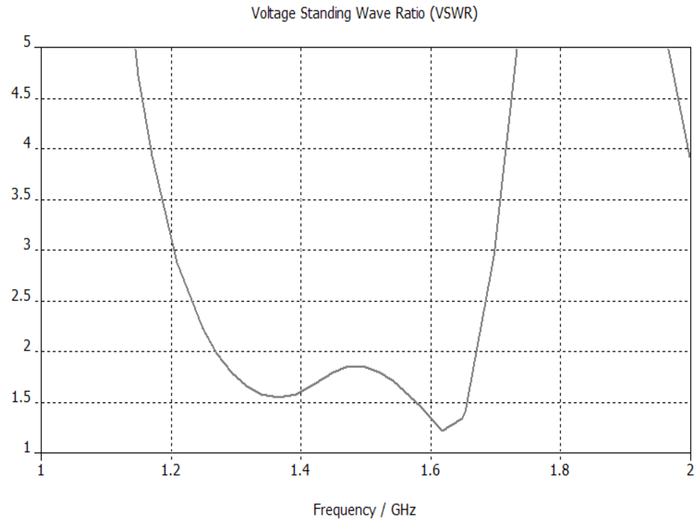
2) This deviation comes from several sources: the finite size of the array, the element pattern, and element to element coupling.

3) The side lobe level is -11.2 dB relative to the main beam. To suppress this, we could amplitude weight the excitations.

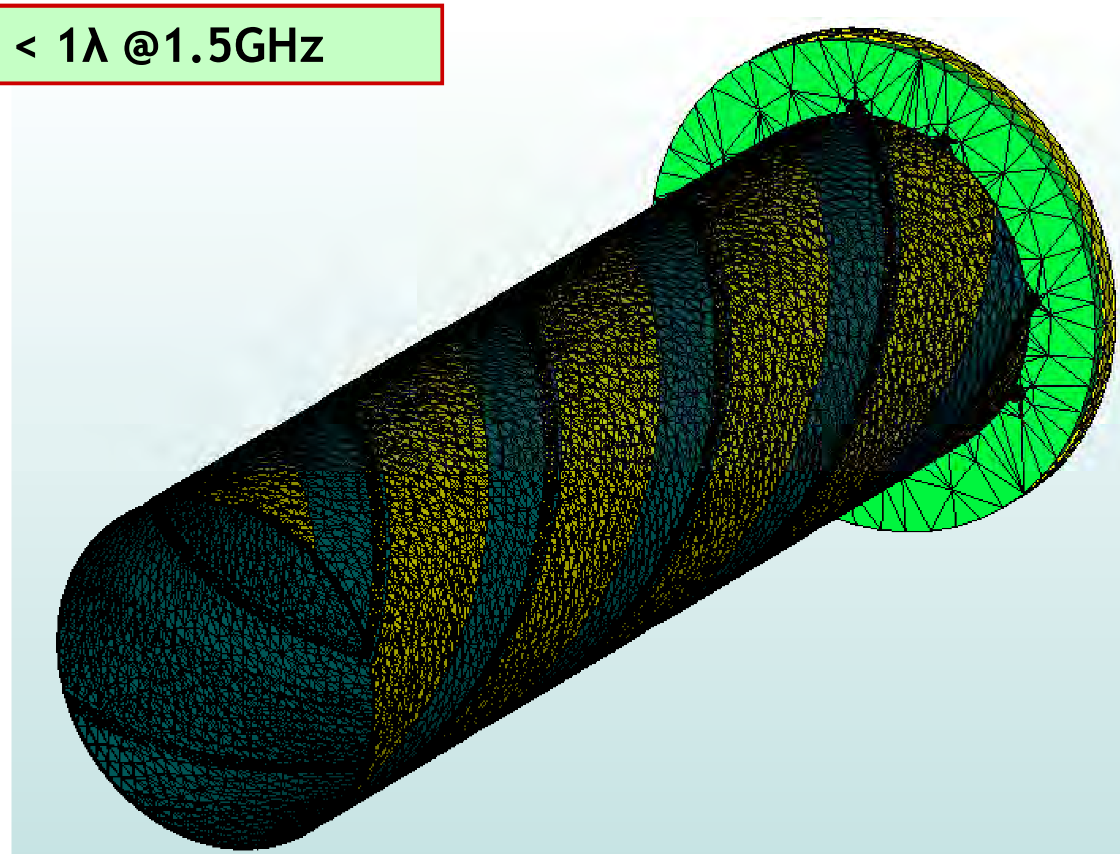
4) A Taylor, cosine or other weighting is often used to drop the strength of the excitations at the edges of the array and suppress the side lobes.

Frequency-Domain Solver Example: PQHA





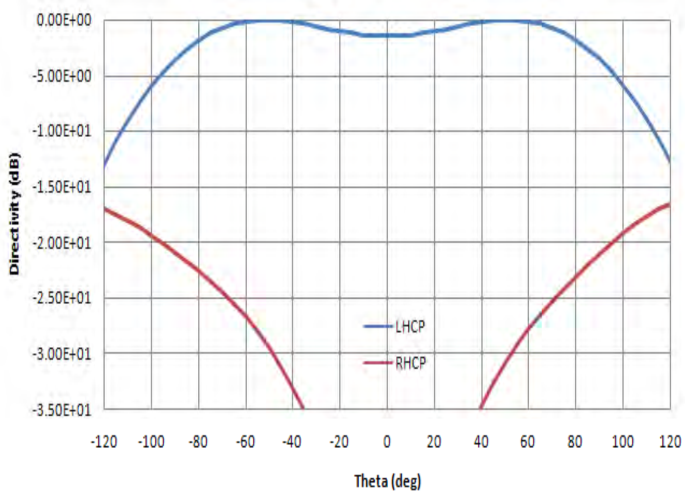
< 1λ @1.5GHz

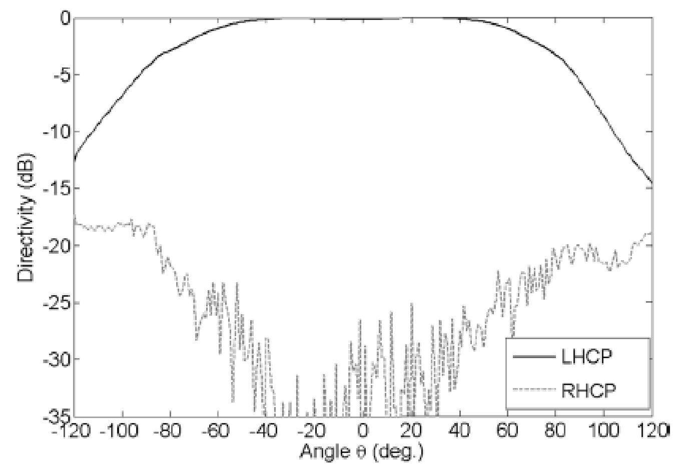


[#] Y. Letestu and A. Sharaiha, "Broadband Folded Printed Quadrifilar Helical Antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 54, No. 7, pp. 1600-1604, May 2006

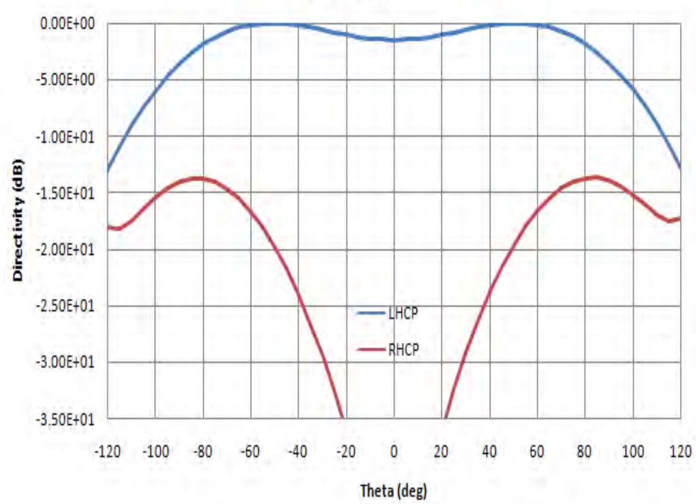
Frequency-Domain Solver Example: PQHA

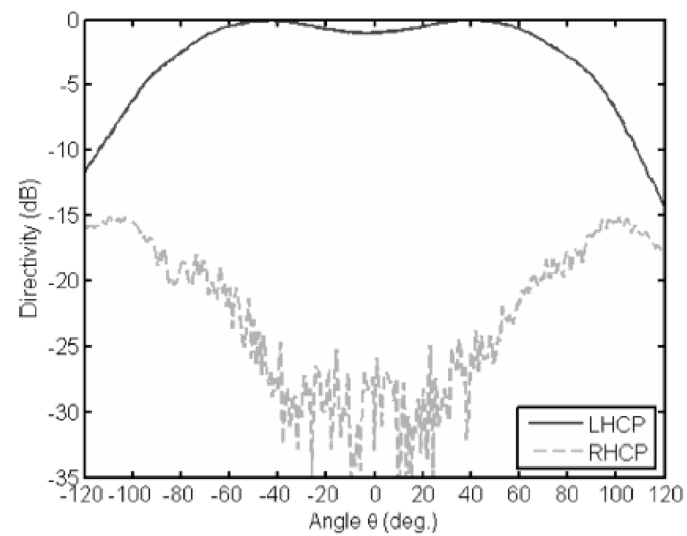
1.4 GHz



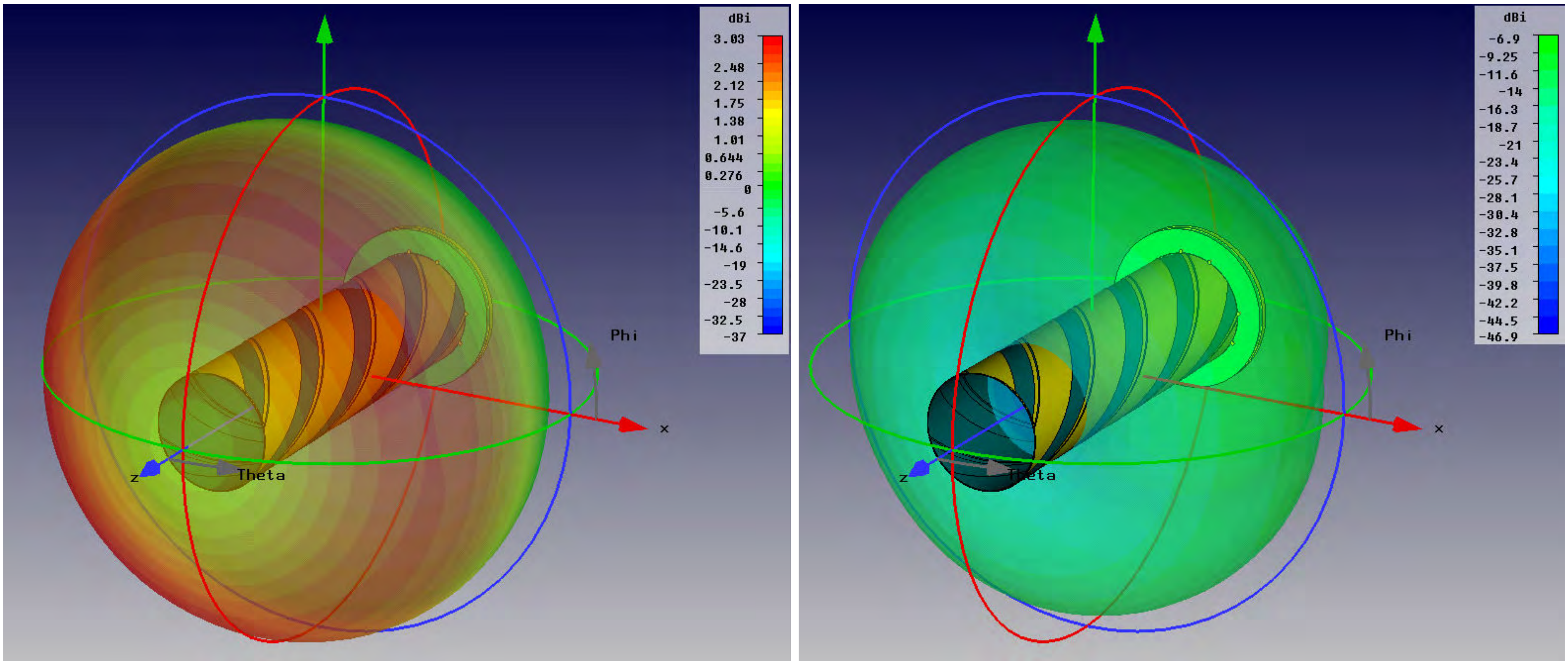


1.6 GHz



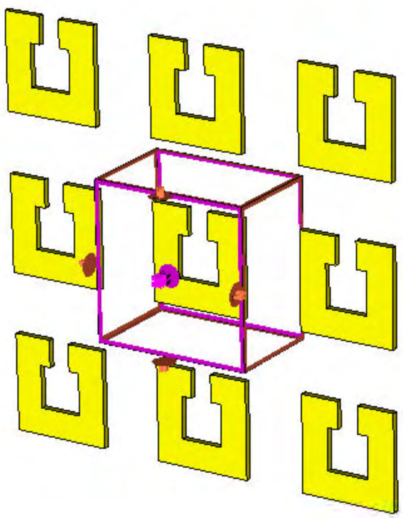


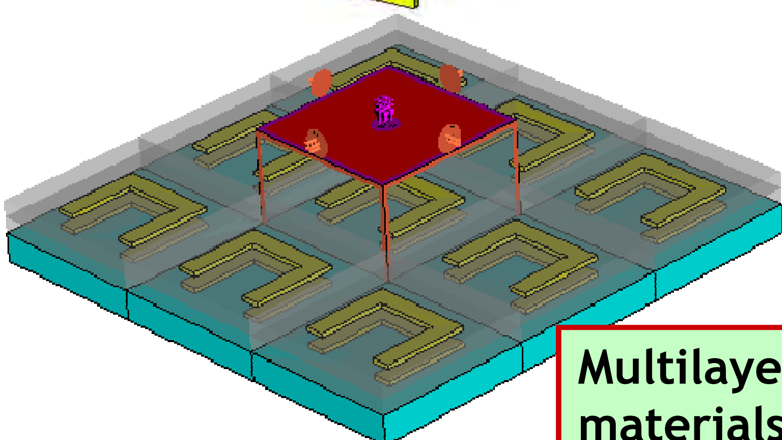
Frequency-Domain Solver Example: PQHA

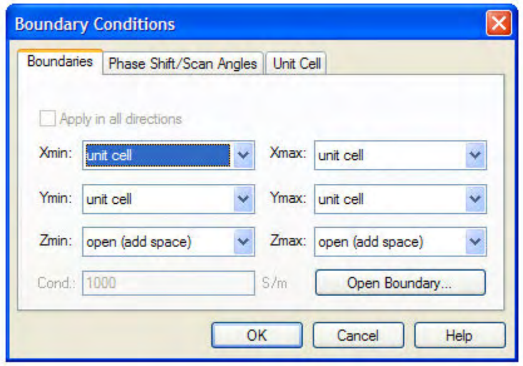


LHC and RHC patterns
10 dB minimum discrimination between circular polarizations

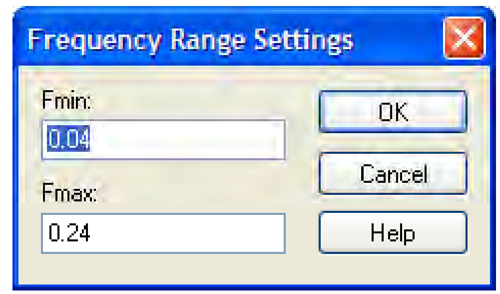
Frequency-Domain Solver Example: Metamaterials

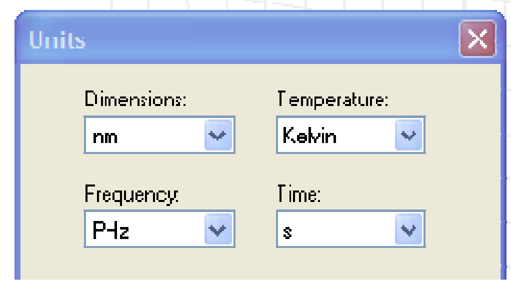






Unit cell and floquet-port modes

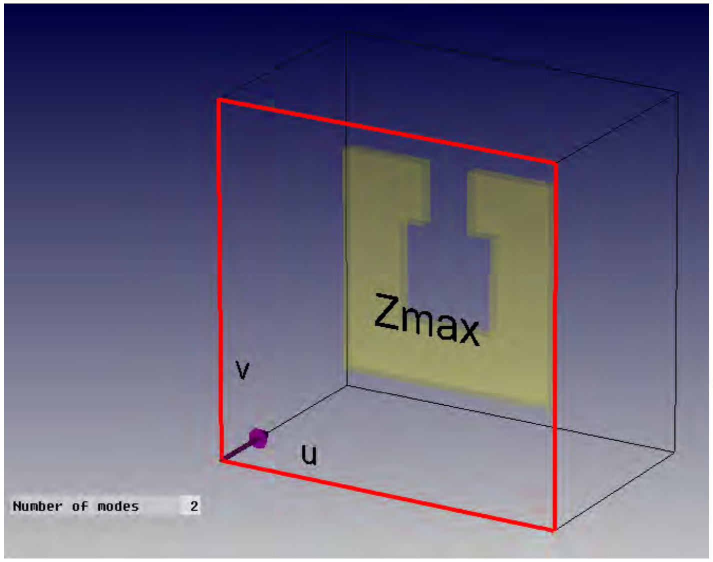


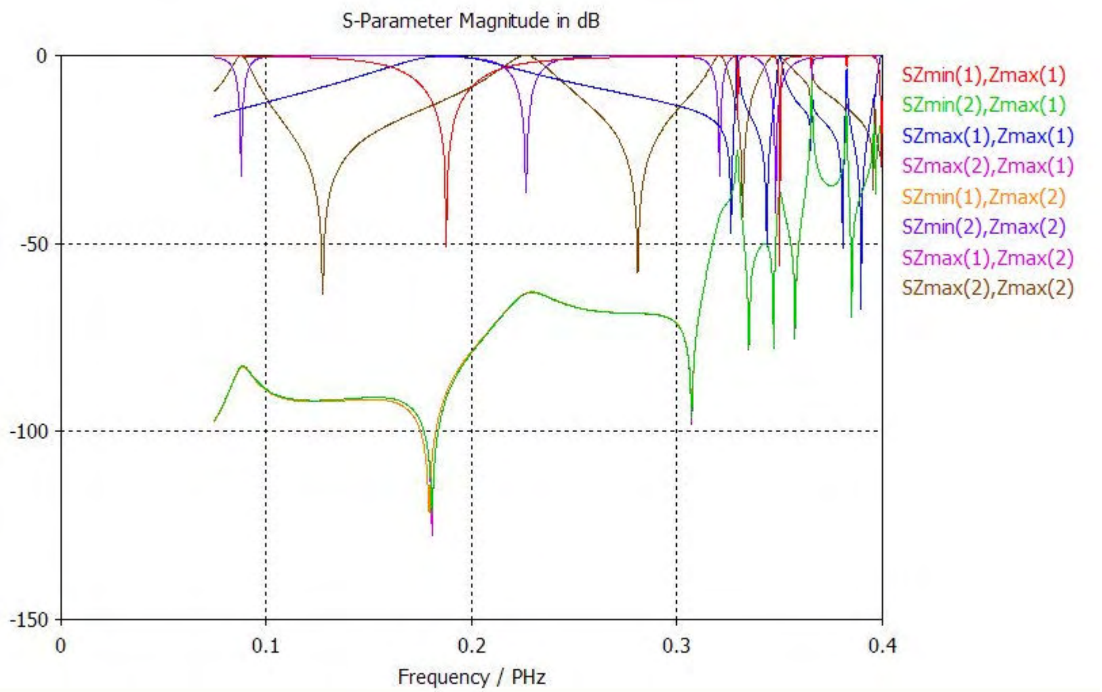


Multilayered meta-materials

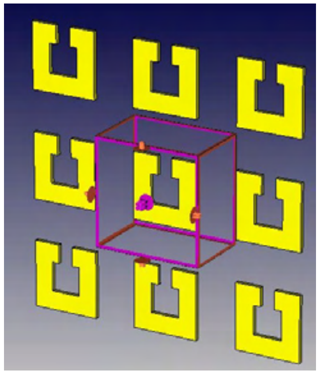
S.Linden at Al, "Magnetic response of metamaterials at 100 Terahertz", Science vol.26 Nov.2004

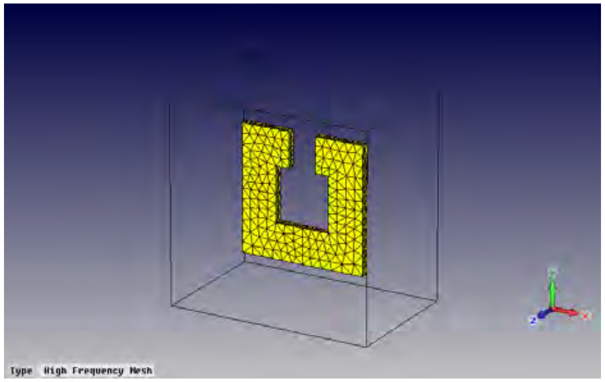
Floquet port and S-parameters results



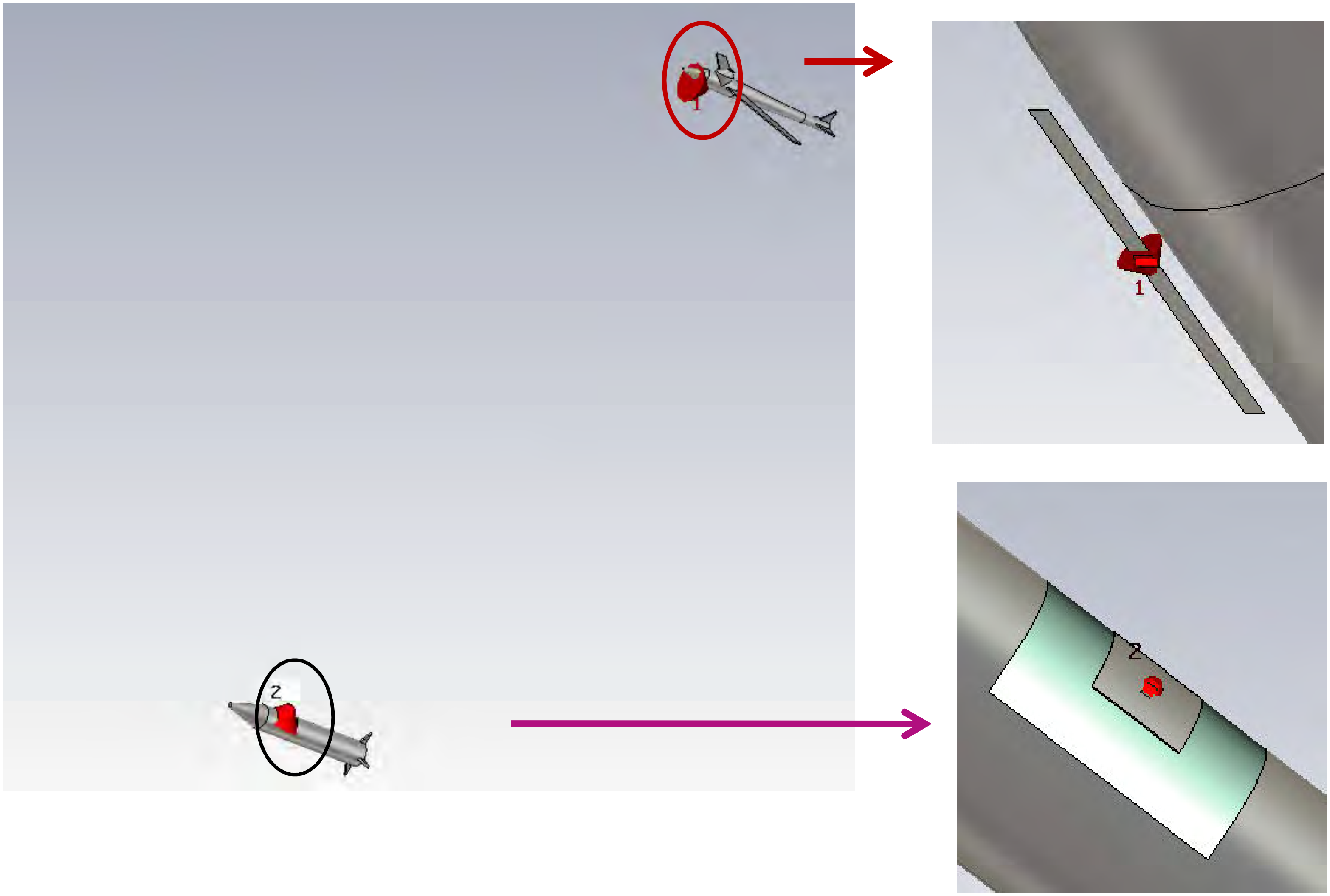


Unit cell

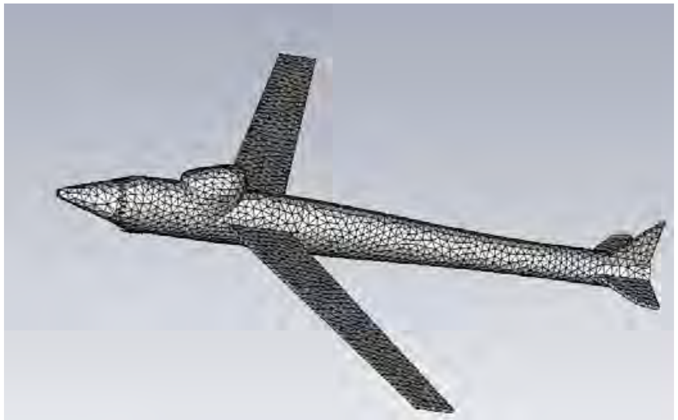


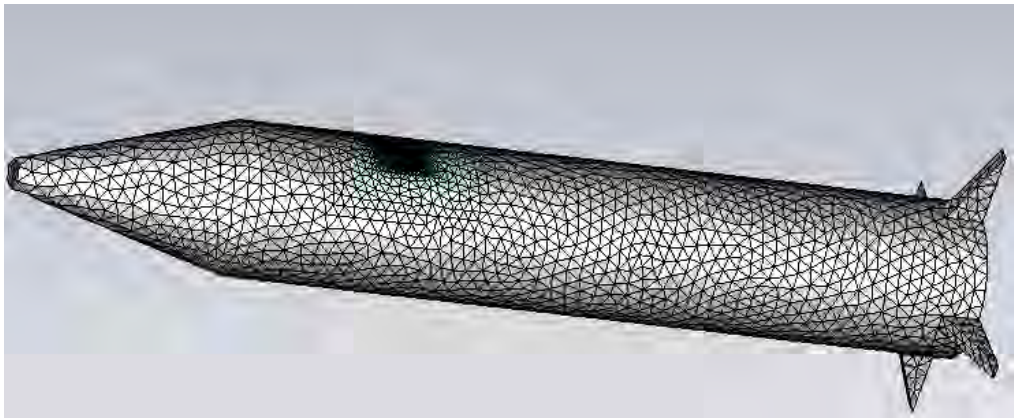


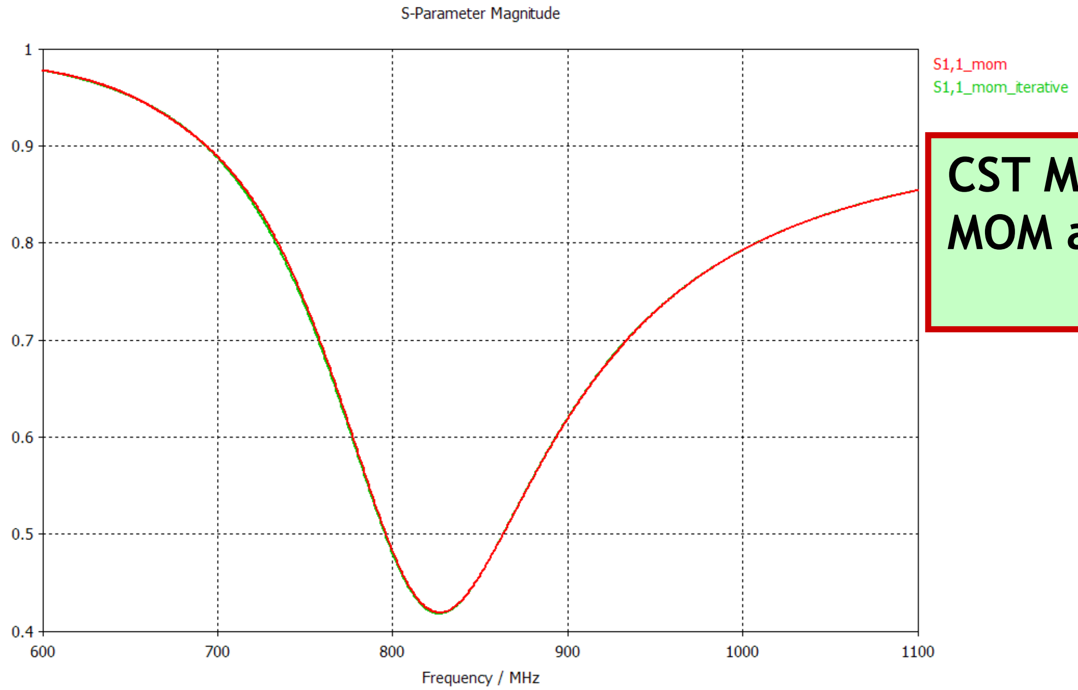
MoM Solver Example: Glider and missile



MoM Solver Example: Glider and missile

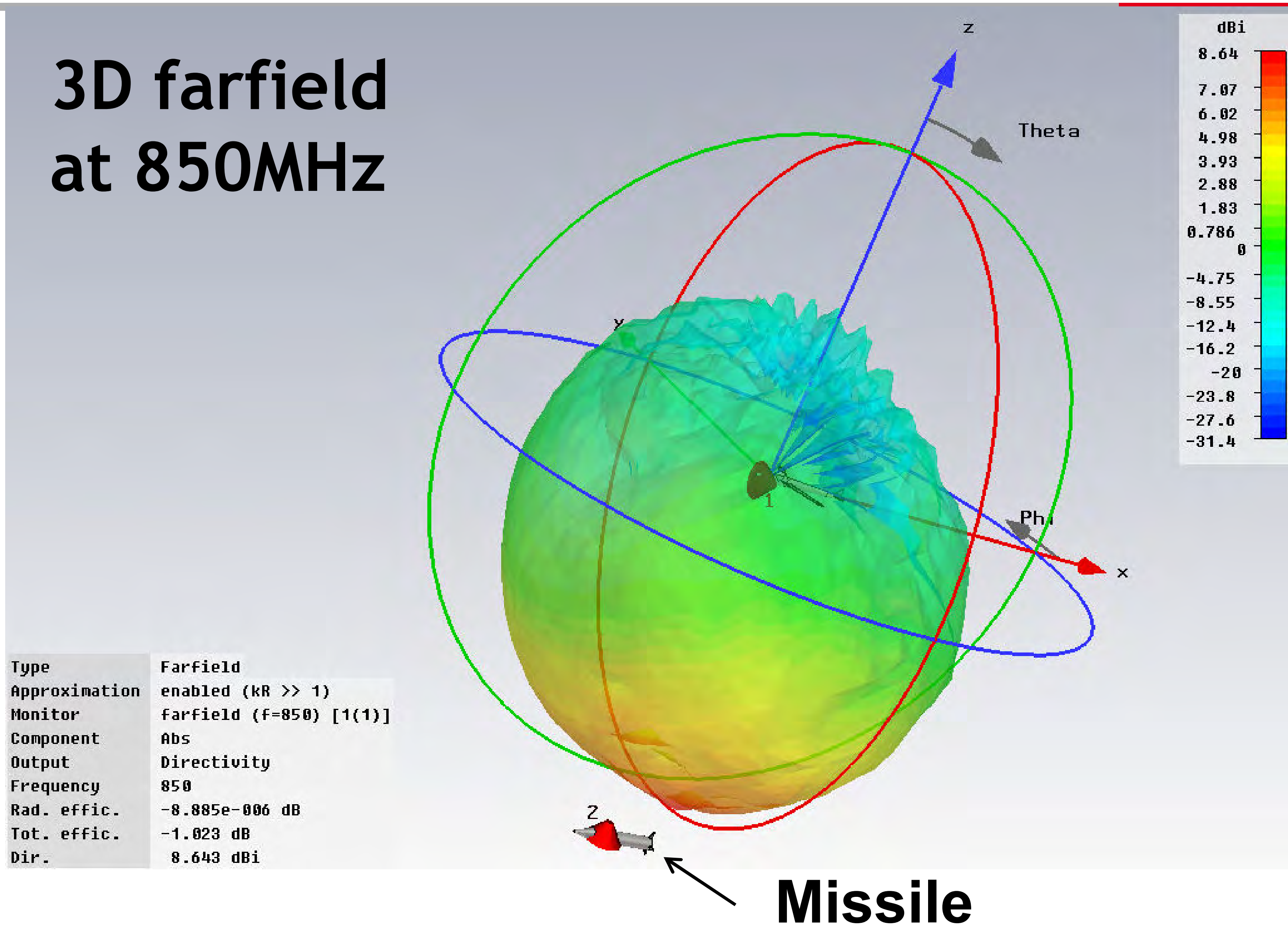




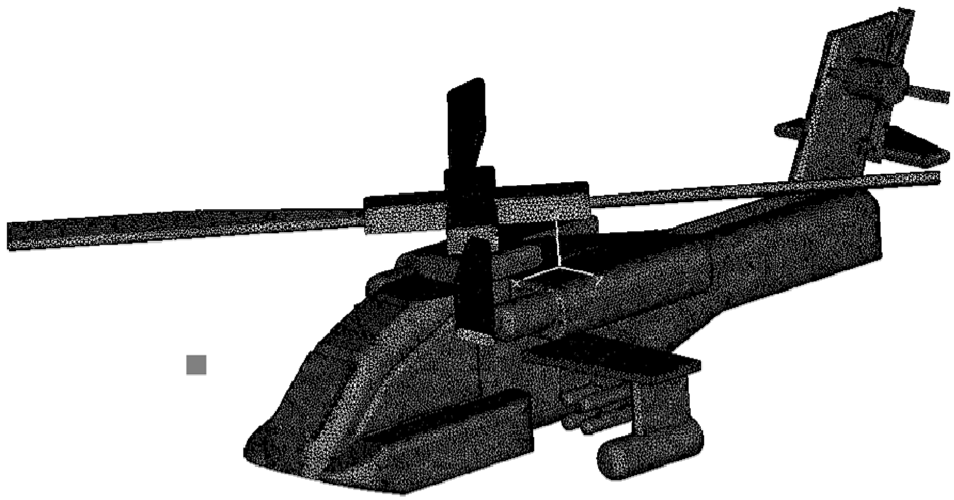


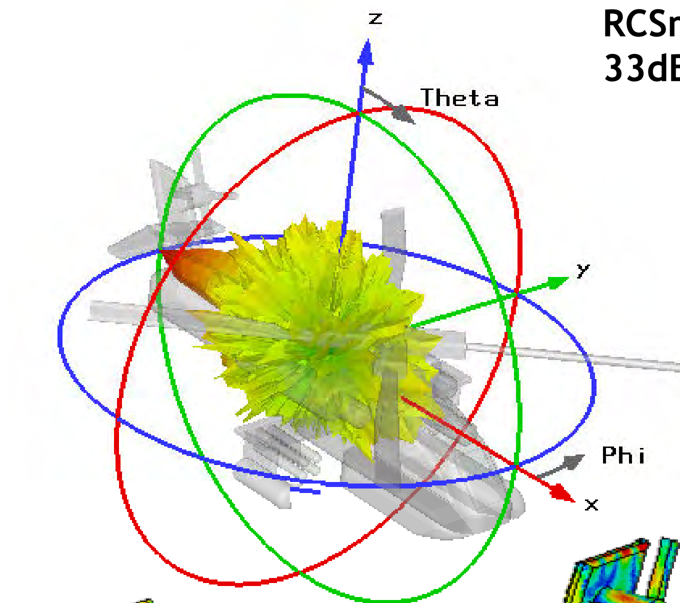
CST MWS
MOM and MLFMM S11

MoM Solver Example: Glider and missile



MLFMM Solver Example: Apache Helicopter



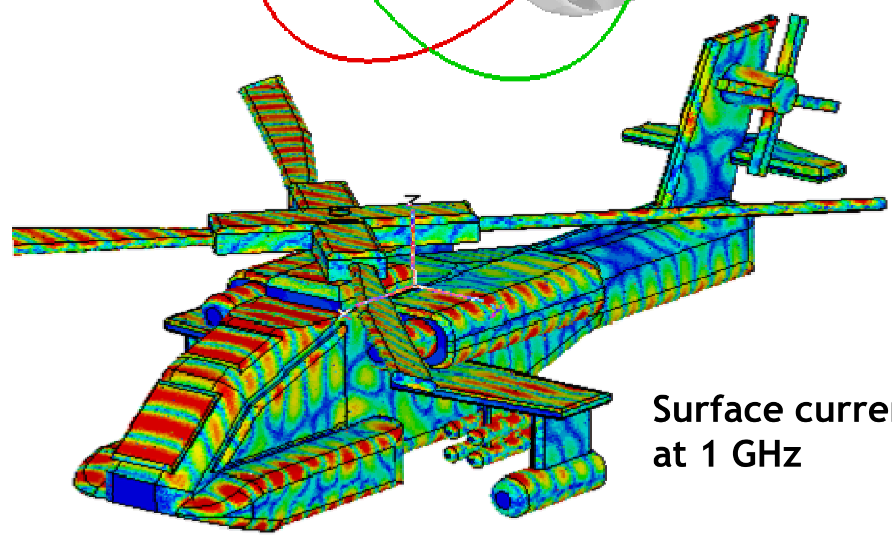


RCSmax = 33dBsm

7.30m x 6.10m x 2.30m ⇔ 25λ x 21λ x 8λ at 1 GHz ⇔ 175λ x 147λ x 56λ at 7 GHz

880k Surface mesh cells, 1st order MLFMM

Plane wave illumination from front



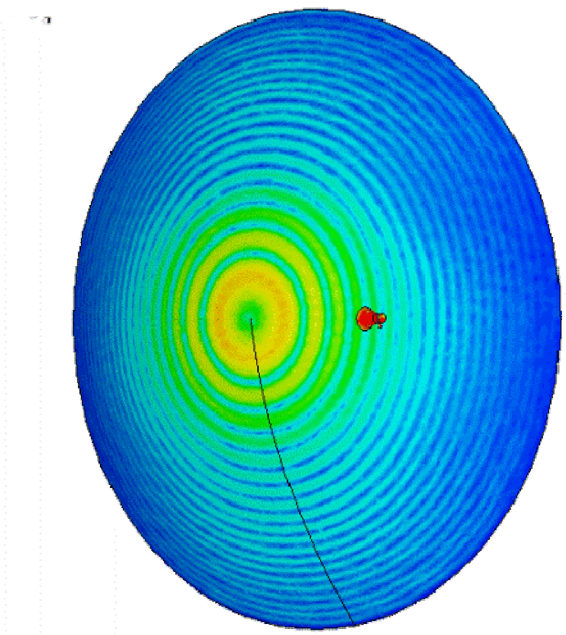
Surface currents at 1 GHz

Combining different techniques to simulate installed antenna performance

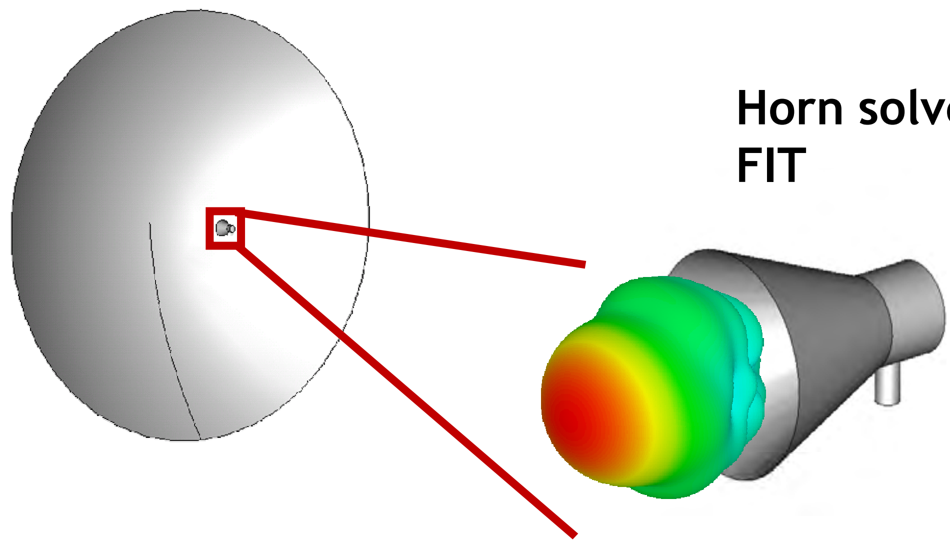
COMBINING DIFFERENT TECHNIQUES

Combined FIT/MLFMM Example: Horn with Dish

Dish solved using MLFMM

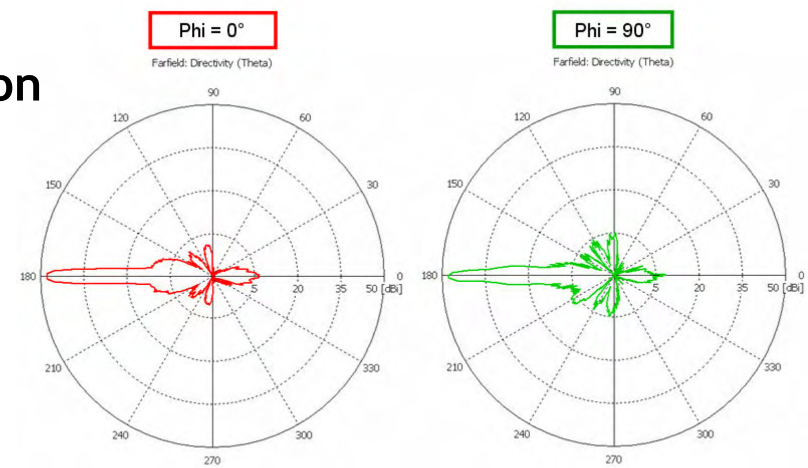


$15\ \lambda$ @ 30 GHz

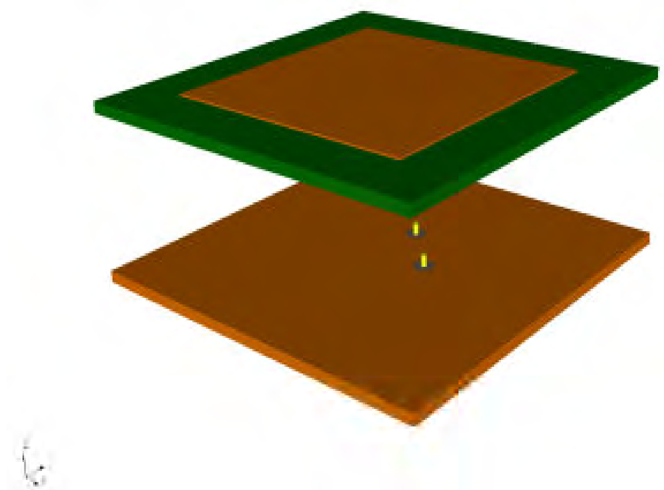


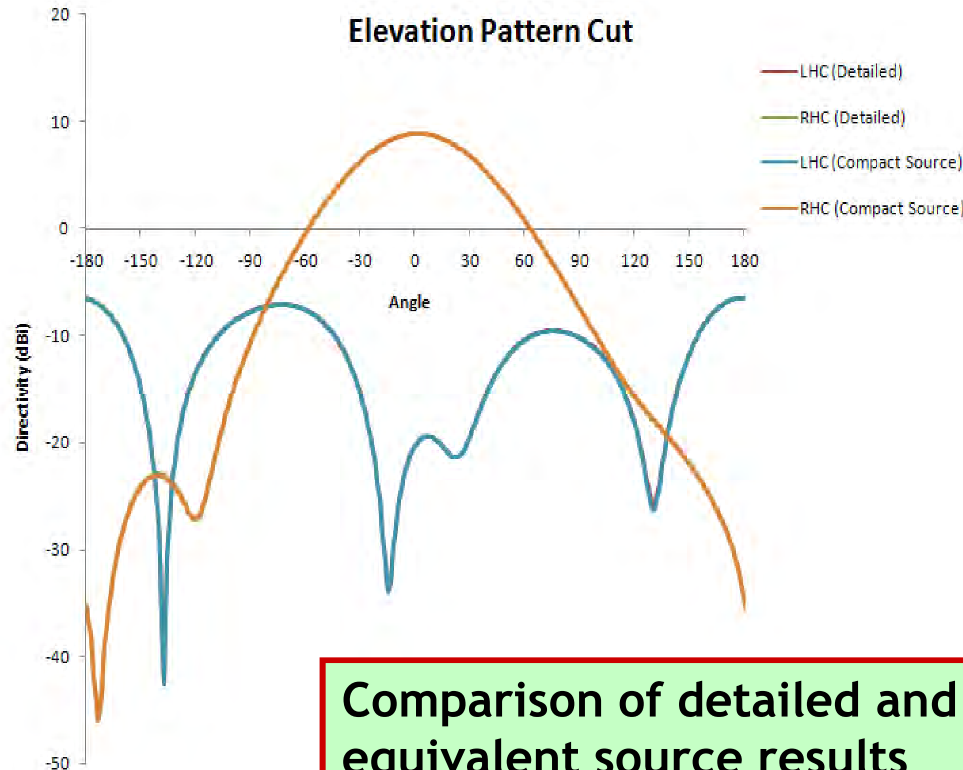
Horn solved using FIT

Radiation pattern

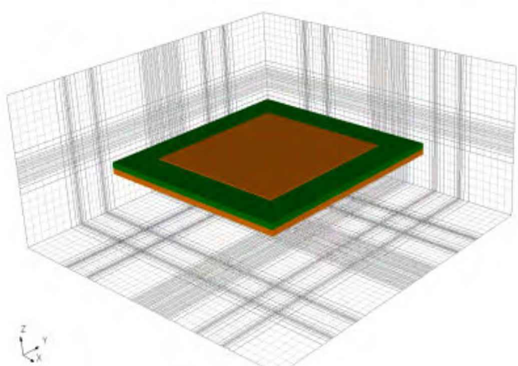


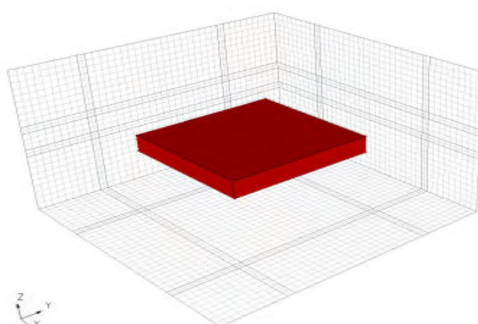
Combined TLM/ES Analysis: GPS Patch Antenna



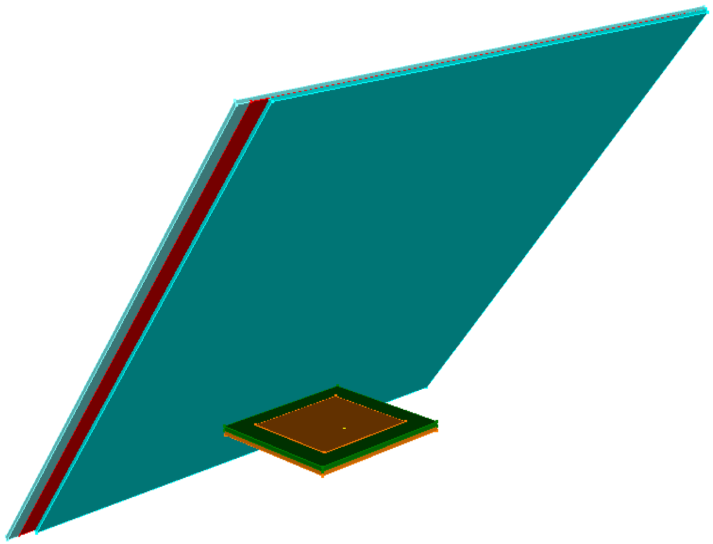


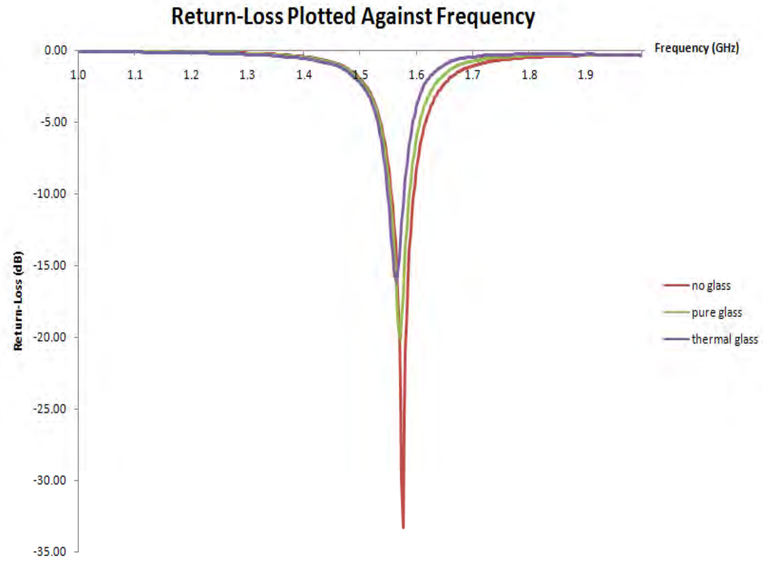
Comparison of detailed and equivalent source results

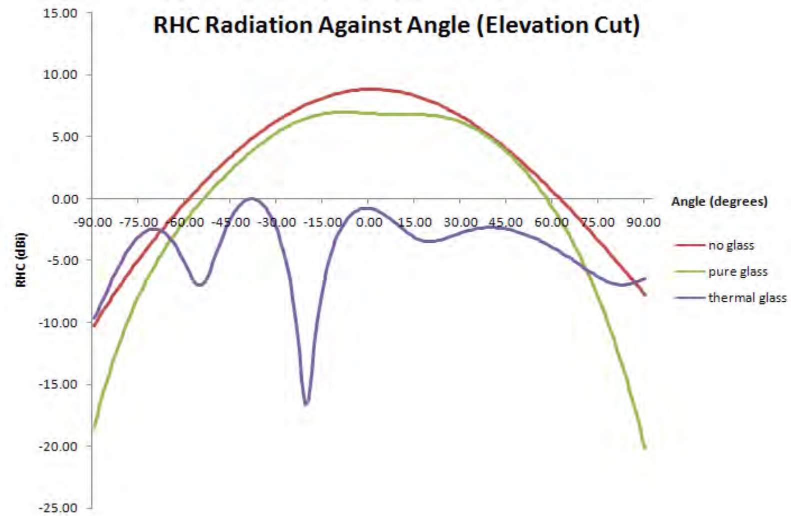




Combined TLM/ES Analysis: GPS Patch Antenna

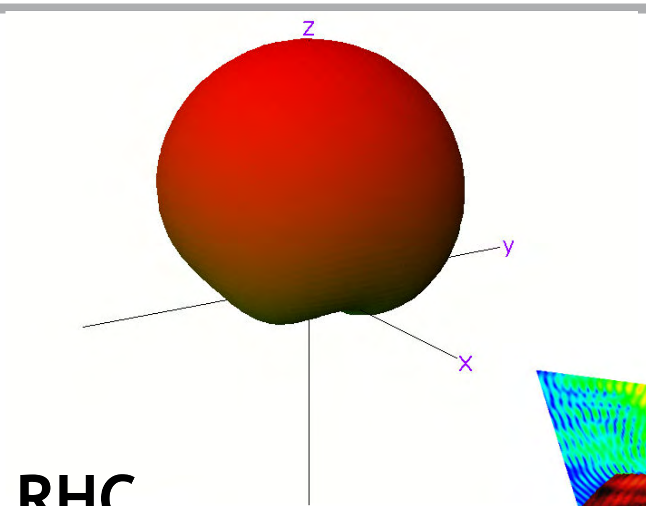




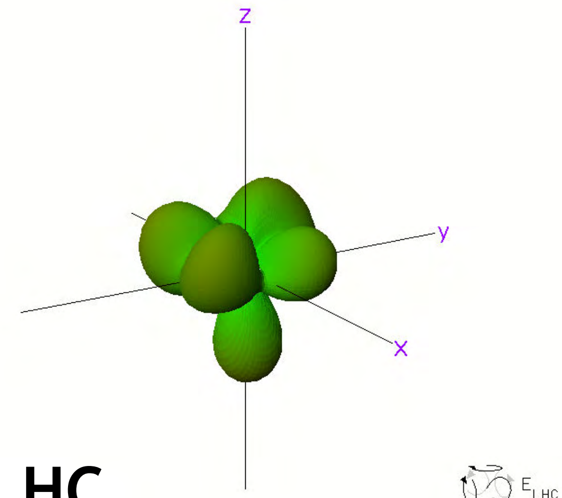


Impact of thermal glass on radiation pattern

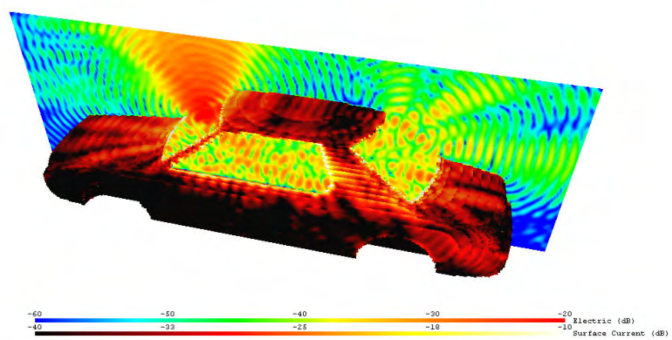
Combined TLM/ES Analysis: GPS Patch Antenna



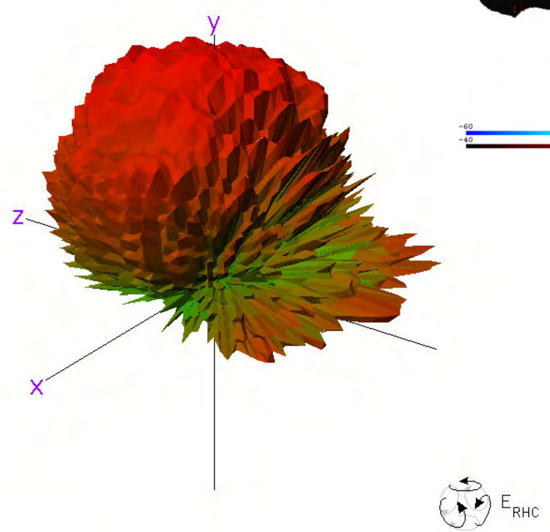
Antenna in free space



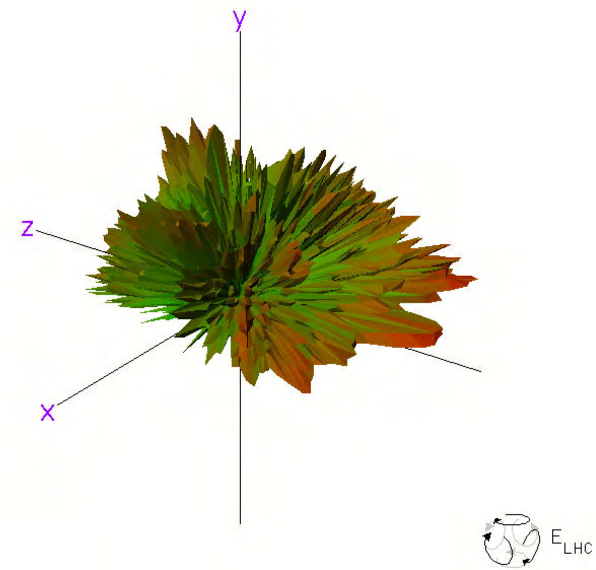
RHC



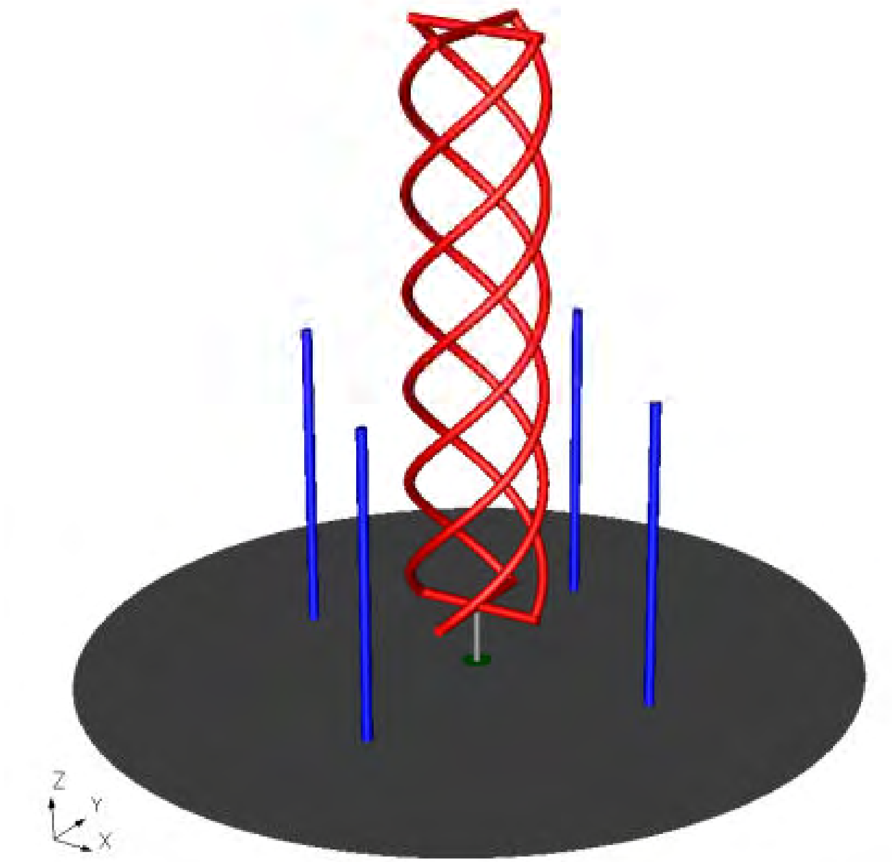
LHC



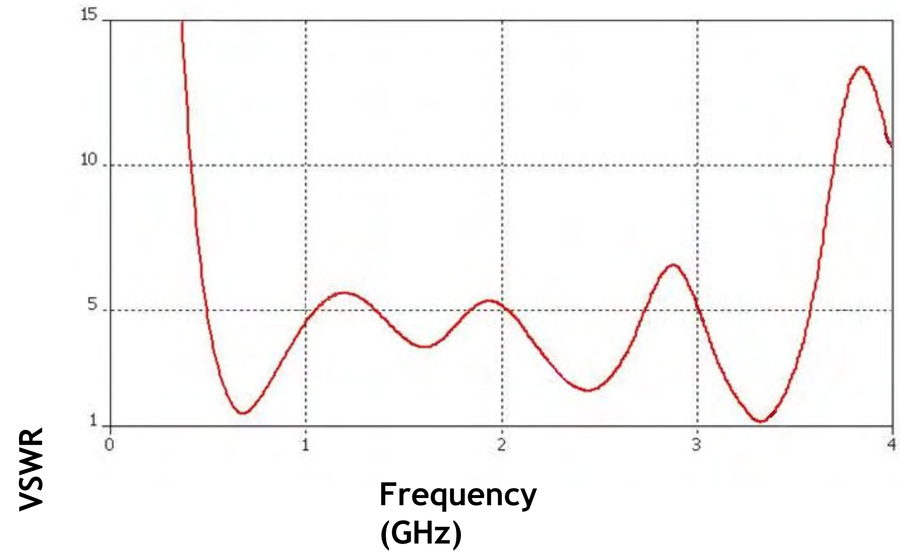
Antenna in car

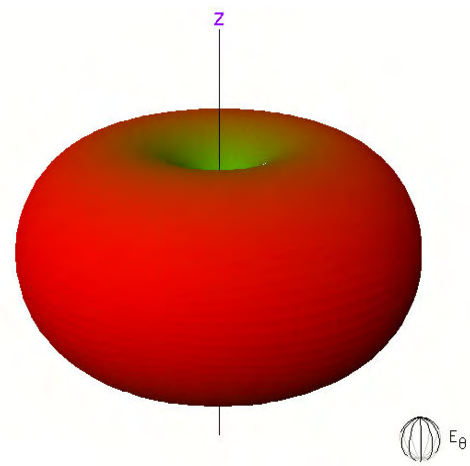


Combined TLM/ES Example: UWB Antenna on Humvee

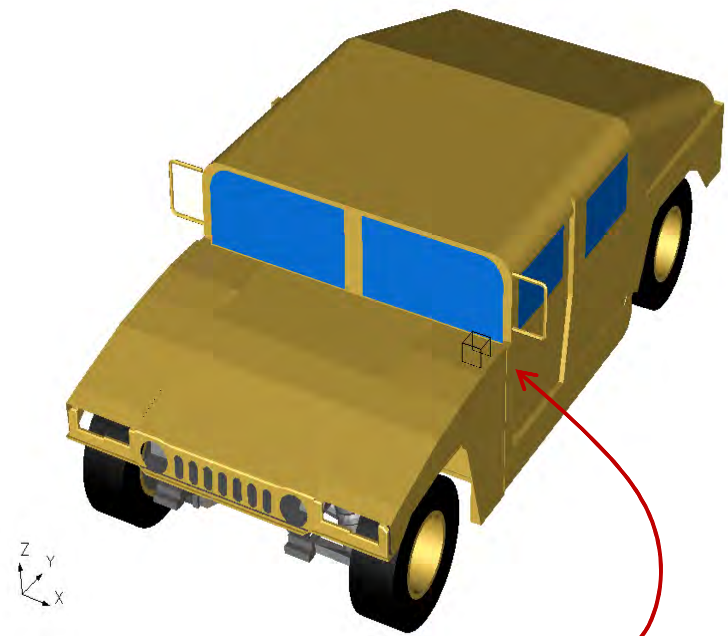


10.2 million cells and a minimum cell size of 0.6mm in the detailed model

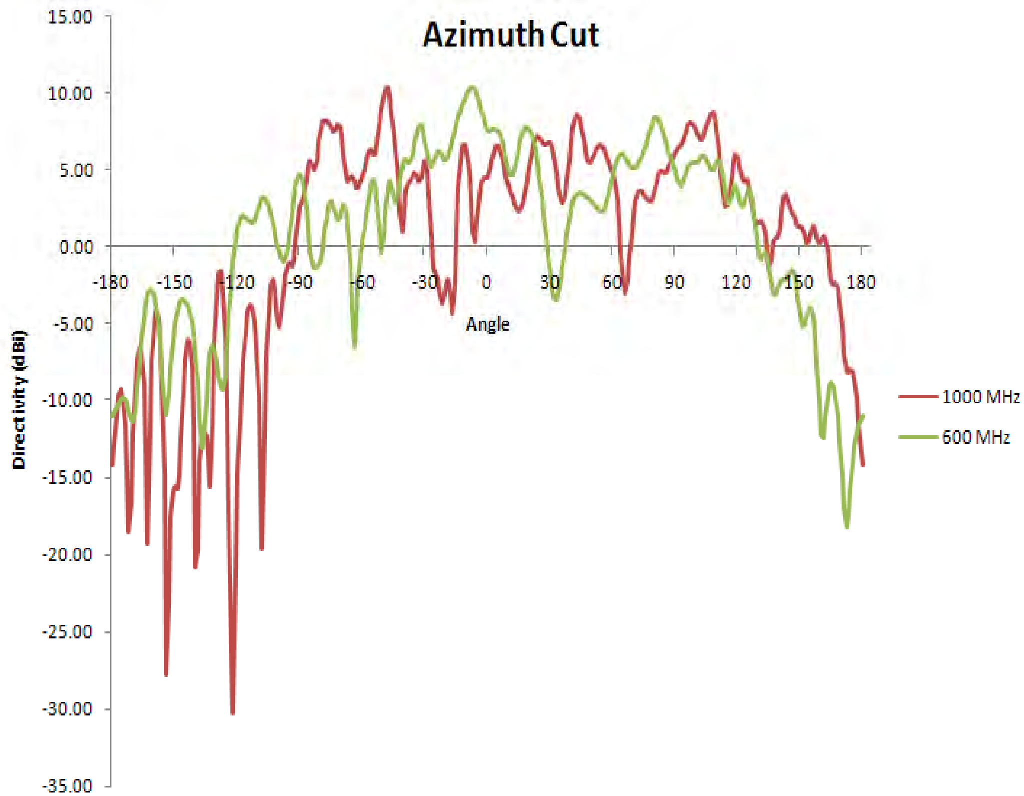




Combined TLM/ES Example: UWB Antenna on Humvee

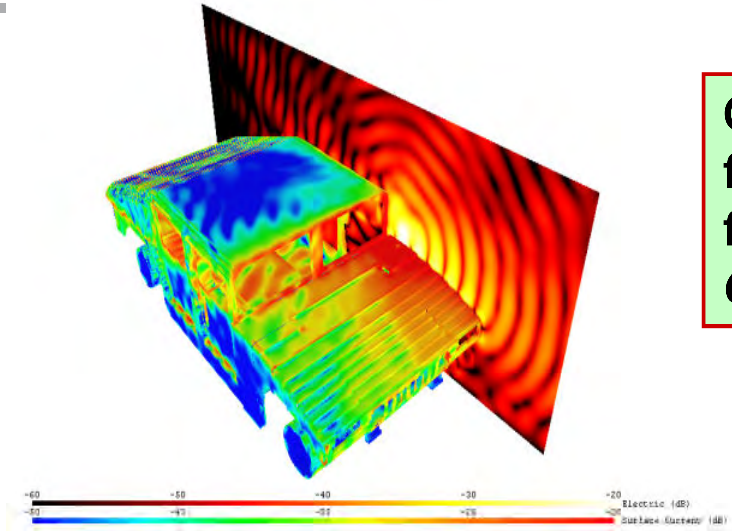


Equivalent source model

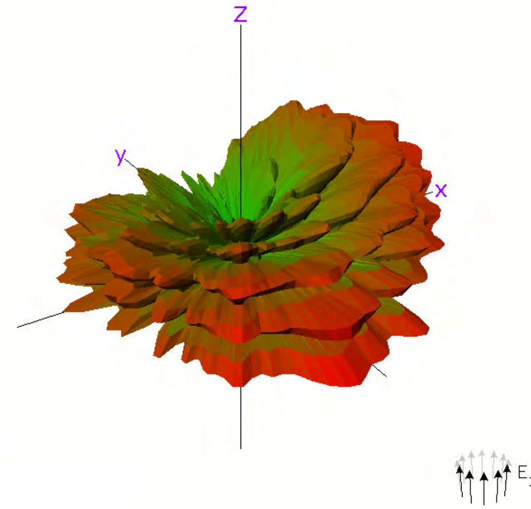


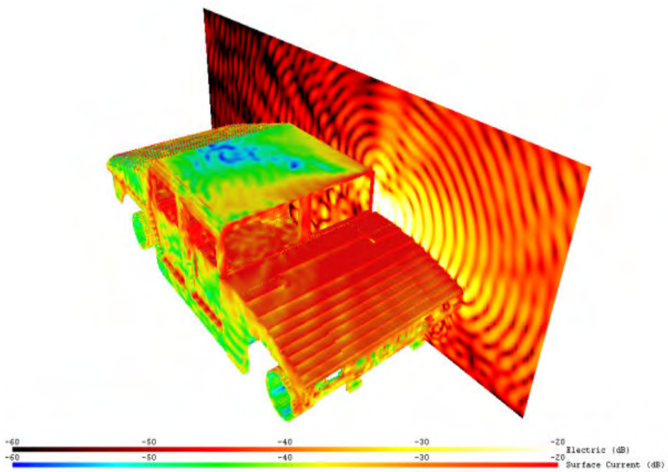
Azimuth pattern at 600 and 1000 MHz

Combined TLM/ES Example: UWB Antenna on Humvee

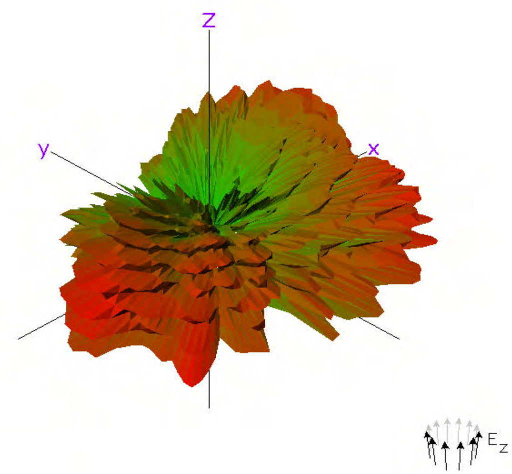


Currents and fields and 3D far-field pattern at 600 MHz





Currents and fields and 3D far-field pattern at 1000 MHz



Summary

- Huge variety in electrical size, bandwidth and complexity of antenna structures is a challenge for designers:
  - No one numerical method can efficiently cover the entire application spectrum
  - Utilize time/frequency and differential/integral solver techniques to improve productivity and efficiency
- EM analysis is increasingly required to assess installed antenna performance
  - Combinations of different numerical techniques can make such problems much more tractable