# Computational Electromagnetics in Antenna Analysis and Design

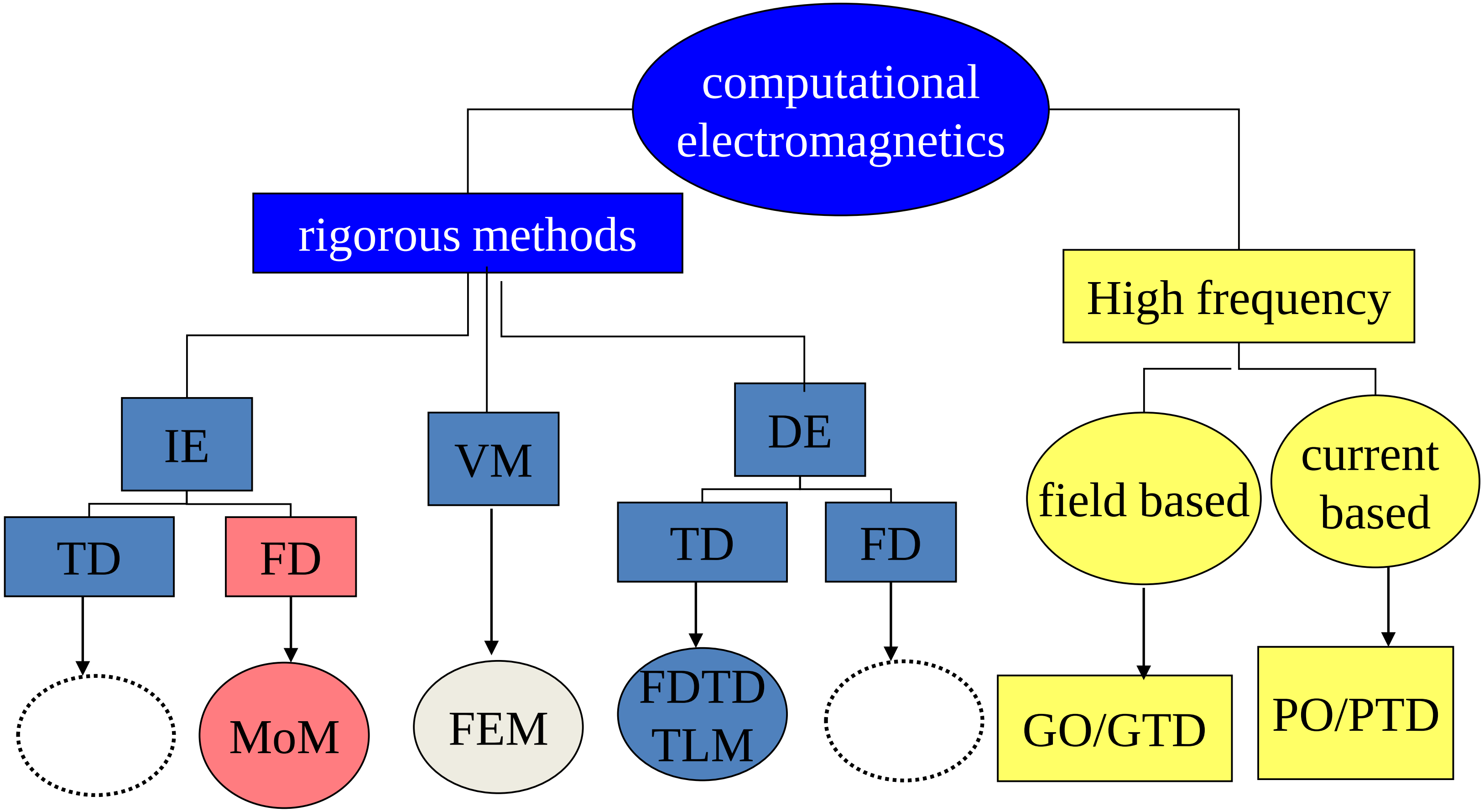
➢It is rare for real-life EM problems to fall neatly into a class that can be solved by the analytical methods presented in the preceding lectures. Classical approaches may fail if:

- the material is not linear and cannot be linearized without seriously affecting the result
- the solution region is complex (i.e. the various boundaries do not coincide with any well described coordinate system).
- the boundary conditions are time-dependent
- the medium is inhomogeneous or anisotropic

➢Whenever a problem with such complexity arises, numerical solutions must be employed.

➢Fortunately there are a large number of very good commercial programs available for solving antenna problems.

# Computational Electromagnetics


computational electromagnetics

rigorous methods

High frequency

IE

VM

DE

field based

current based

TD

FD

TD

FD

MoM

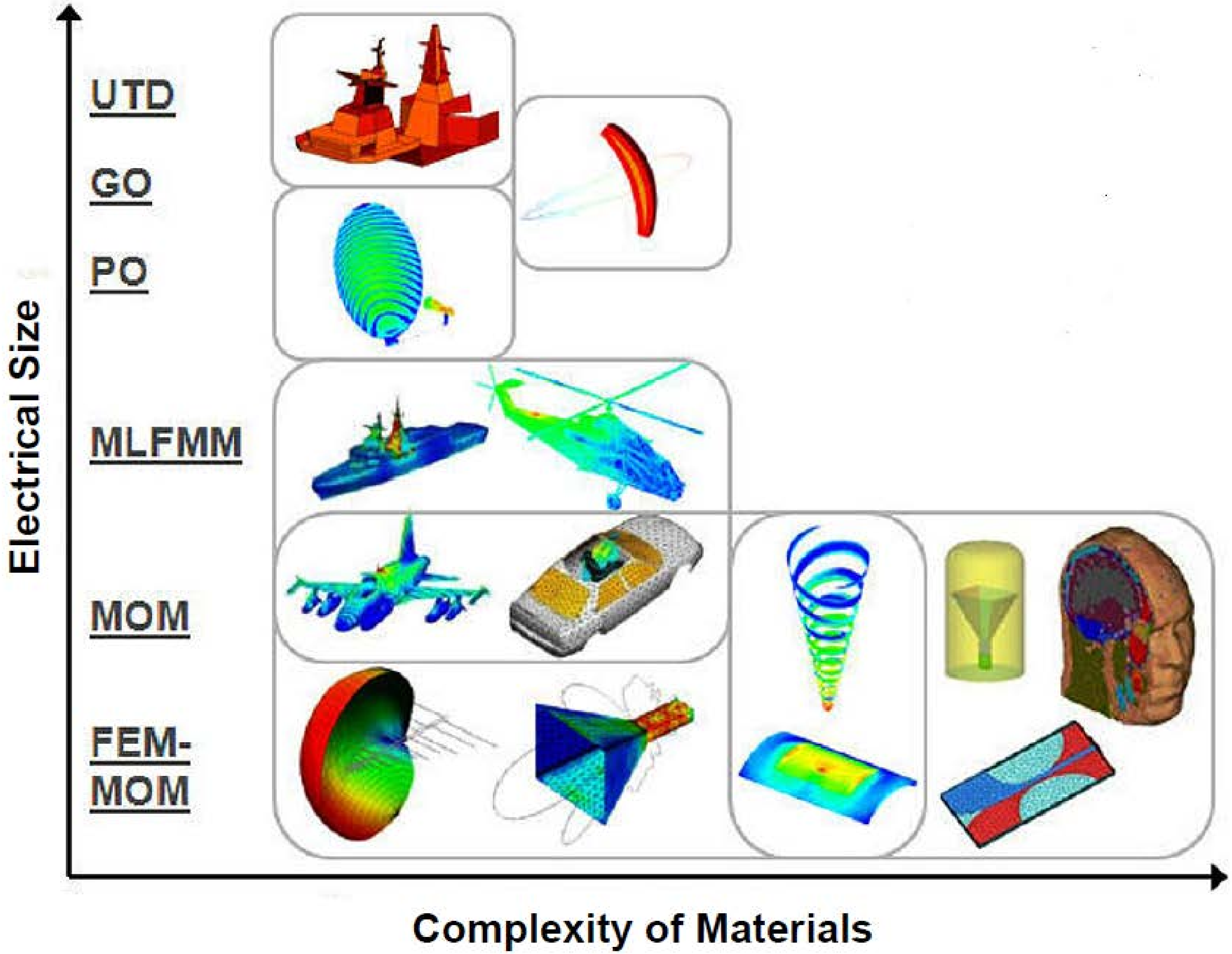
FEM

FDTD TLM

GO/GTD

PO/PTD

# The Universe of Antenna Modeling Methods



UTD

GO

PO

MLFMM

MOM

FEM-MOM

Electrical Size

Complexity of Materials

Courtesy of EMSS

# Computational Electromagnetics

- **Method of moments (MoM)**
  - A method for solving integro-differential equations such as Hallen's or Pocklington's equation at a given frequency
  - Earliest and longest legacy of software codes for antenna modeling
  - BRACT, WIRA, AMP, NEC, NEC-2, NEC-3, NEC-4, MiniNEC, ELNEC, EZNEC, winNECPlus, 4nec2, FEKO, WIPL-D, Zeland IE3D
- **Finite element method (FEM)**
  - Best for design of small antennas of complex structure
  - Ansoft HFSS
- **Finite difference time-domain method (FDTD)**
  - Time-domain method
  - Best for design of small antennas for broadband applications
  - CST Microwave Studio, Zeland Fidelity, Faustus MEFiSTo
- **Geometric, physical, and uniform theories of diffraction**
  - Best for electrically large antennas

# Comparison of Methods

| | Domain | Generality | Accuracy | Memory N= number of elements | Antenna Types |
|---|---|---|---|---|---|
| MoM | Frequency | Homogeneous or discretely homogeneous regions | Very accurate | @($N^2$) | All but harder for large reflector antennas |
| FDTD | Time (all frequencies in one run) | Very general. inhomogeneous, dispersive, anisotropic | Moderately accurate | @(N) | All but harder for large reflector antennas |
| FEM | Frequency | Very general. inhomogeneous, dispersive, anisotropic | Very accurate | @(N log N) | All but harder for large reflector antennas |
| High Frequency Methods | Frequency | Only good for structures much larger than the wavelength | Only accurate for large structures | @(N) | Only good for large antennas (mostly used for reflectors) |

# Goal of all of these methods

Approximate these

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \vec{M} \qquad \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

$$\nabla \cdot \vec{D} = \rho \qquad \nabla \cdot \vec{B} = \rho_m$$

With this

$$[A] \cdot [x] = [b]$$

# The Method of Moments

# Originators

I.G. Bubnov
1872-1919

Leonid Vitaliyevich Kantorovich
1912-1986

Jack H. Richmond
1922-1990

Boris Grigoryevich Galerkin
1871-1945

Gleb Pavlovich Akilov
1924-1964

Roger F. Harrington
1925-

# Equations for Obtaining the Current Along a Wire

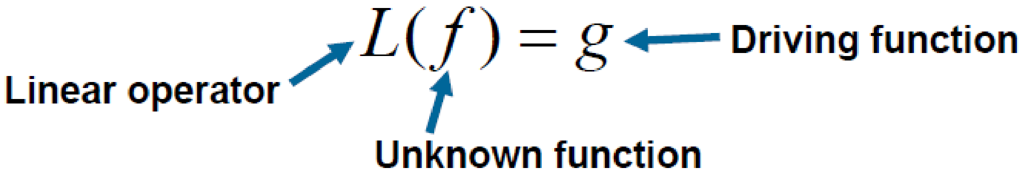
- **Pocklington's equation (1897)**

$$\int_{-l/2}^{l/2} I_z(z')\left[\left(\frac{\partial^2}{\partial z^2}+k^2\right)G(z,z')\right]dz' = -j\omega\varepsilon\, E_z^i(\rho=a)$$

- **Hallen's equation (1938)**

$$\int_{-l/2}^{l/2} I_z(z')\frac{e^{-jkR}}{4\pi R}\,d\,z' = -j\sqrt{\frac{\varepsilon}{\mu}}\left[B_1\cos(kz)+C_1\sin(k\,|\,z\,|)\right]$$

- **General form**



$$L(f) = g$$

**Linear operator**

**Unknown function**

**Driving function**

# Integro-Differential Equations Made Simple

- Start with an equation. The analysis problem is to find *f*

$$L(f) = g$$

- Assume *f* can be expanded as a weighted sum of basis functions

$$L(f) = L\left(\sum_n a_n f_n\right) = g$$

- Set all projections (via test functions) of left and right sides equal

$$\sum_n a_n L(f_n \bullet \phi_m) = g \bullet \phi_m$$

- Write as a matrix equation

$$\begin{bmatrix} L(f_1 \bullet \phi_1) & \cdots & L(f_N \bullet \phi_1) \\ \vdots & \ddots & \vdots \\ L(f_1 \bullet \phi_M) & \cdots & L(f_N \bullet \phi_M) \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix} = \begin{bmatrix} g \bullet \phi_1 \\ \vdots \\ g \bullet \phi_M \end{bmatrix}$$

# The Solution

- **Solve for the vector of expansion coefficients**

$$\begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix} = \begin{bmatrix} L(f_1 \bullet \phi_1) & \cdots & L(f_N \bullet \phi_1) \\ \vdots & \ddots & \vdots \\ L(f_1 \bullet \phi_M) & \cdots & L(f_N \bullet \phi_M) \end{bmatrix}^{-1} \begin{bmatrix} g \bullet \phi_1 \\ \vdots \\ g \bullet \phi_M \end{bmatrix}$$

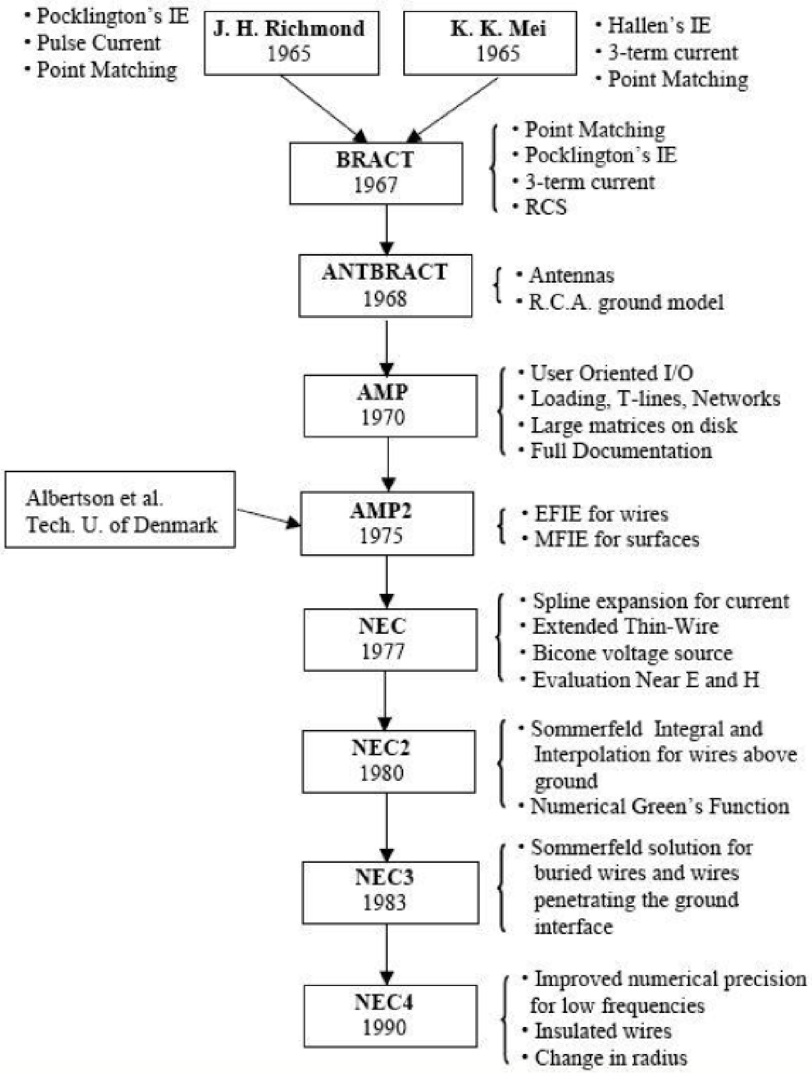
- **Obtain *f***

$$f = \sum_n a_n f_n = \begin{bmatrix} f_1 & \cdots & f_N \end{bmatrix} \begin{bmatrix} L(f_1 \bullet \phi_1) & \cdots & L(f_N \bullet \phi_1) \\ \vdots & \ddots & \vdots \\ L(f_1 \bullet \phi_M) & \cdots & L(f_N \bullet \phi_M) \end{bmatrix}^{-1} \begin{bmatrix} g \bullet \phi_1 \\ \vdots \\ g \bullet \phi_M \end{bmatrix}$$

# Principle MoM Computer Codes

- BRACT & ANTBRACT – Developed late 1960’s at MBAssociates, San Ramon
- WIRA – Developed early 1970’s by M. Andreasen, F. Harris and R. Tanner at TCI
- AMP/AMP2 – Developed mid 1970’s by G. Burke at MBAssociates, San Ramon
- NEC-1 (1979) – Added more accurate current expansions; multiple wire junctions; thick wires
- NEC-2 (1981) – Sommerfield-Norton ground interaction for wire structures above lossy ground; numerical Green's function allows modifying without repeating whole calculation
- NEC-3 (1985) – Buried wires
- NEC-4 (1992) – Improved accuracy for stepped-radius wires and electrically-small segments, end caps and insulated wires, catenary-shaped wires, improved error detection
- Zeland IE3D (1992) – Adaptive meshing, developed by Dr. Jian-Xiong Zheng. Company in Fremont, CA
- WIPL-D (ca 2000) – Advanced MoM for wires, plates, and dielectrics based on work of A.R. Djordjevic, B.M. Kolundzija, U. Belgrade, Serbia
- FEKO (ca 2000) – Hybrid method developed by U. Jakobus at EMSS, Stellenbosch. South Africa

# The Development of NEC



- Pocklington's IE
- Pulse Current
- Point Matching

**J. H. Richmond**
1965

**K. K. Mei**
1965

- Hallen's IE
- 3-term current
- Point Matching

**BRACT**
1967

- Point Matching
- Pocklington's IE
- 3-term current
- RCS

**ANTBRACT**
1968

- Antennas
- R.C.A. ground model

**AMP**
1970

- User Oriented I/O
- Loading, T-lines, Networks
- Large matrices on disk
- Full Documentation

Albertson et al.
Tech. U. of Denmark

**AMP2**
1975

- EFIE for wires
- MFIE for surfaces

**NEC**
1977

- Spline expansion for current
- Extended Thin-Wire
- Bicone voltage source
- Evaluation Near E and H

**NEC2**
1980

- Sommerfeld Integral and Interpolation for wires above ground
- Numerical Green's Function

**NEC3**
1983

- Sommerfeld solution for buried wires and wires penetrating the ground interface

**NEC4**
1990

- Improved numerical precision for low frequencies
- Insulated wires
- Change in radius

# EZNEC http://www.eznec.com/

- **Developed by Roy Lewallen, W7EL**
- **Now in version 5.0**
- **Six products available**

| | |
|---|---|
| EZNEC v.5 demo program | $0 (free) |
| EZNEC-ARRL v.3 & v.4 | $45 (on ARRL Antenna Book CD-ROM) |
| EZNEC v.5 | $90 |
| EZNEC+ v.5 | $140 |
| EZNEC Pro/2 v.5 | $500 |
| EZNEC Pro/4 v.5 | $650 (sold only to NEC-4 licensees) |

- **EZNEC includes either the NEC-2 or NEC-4 engines**
- **NEC-4 license for qualified US academic and noncommercial users can be obtained from Lawrence Livermore National Laboratory for $300. This probably includes you!**
  - Form at: https://ipo.llnl.gov/technology/software/documents/NEC.pdf

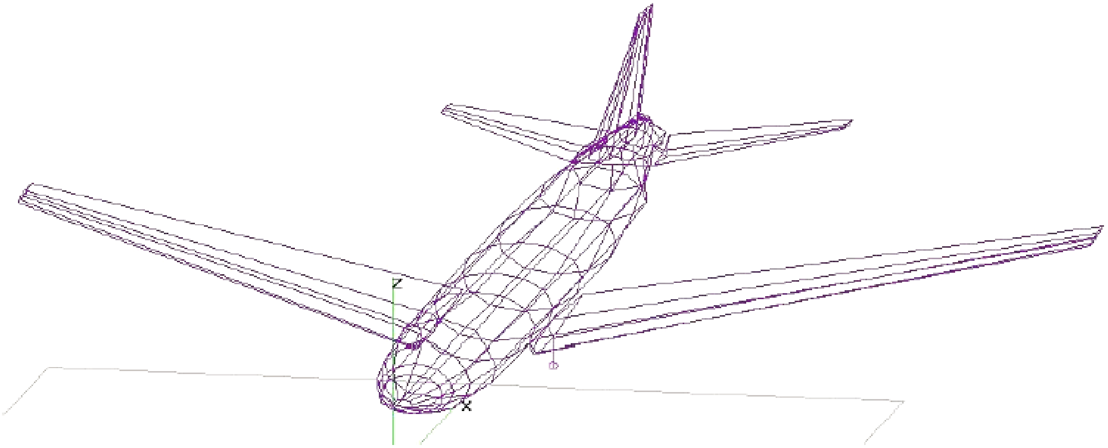
# Key Parts of EZNEC

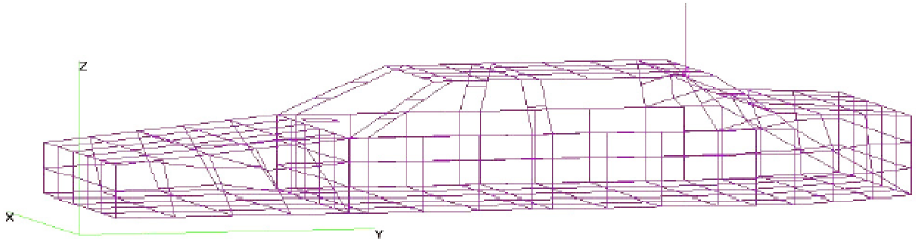
- **Specifying the antenna model**
    - Wire geometry (including radials)
    - Excitation sources
    - Wire loads
    - Transmission lines
    - Ground type and parameters
    - Frequency or sweep range
- **Specifying the desired outputs**
    - Radiation pattern crossection at a given frequency
    - Gain in a specific direction
    - Pattern beamwidth
    - Front-to-back ratio
    - Front-to-rear ratio
    - Impedance
    - SWR
    - Output data files for other programs

# 4nec2 http://home.ict.nl/~arivoors/

- **A free full-featured GUI for NEC-2 and NEC-4**
- **Written and supported by Arie Voors, Netherlands**
- **Runs under Windows 2000 and XP**
- **Includes standard EZNEC models as .nec files**
- **Comes with NEC-2 executables but can use NEC-4 executable**
- **Comes configured for up to 11,000 segments but can be increased by to any number by recompiling the NEC-2 or NEC- source codes**
- **Two versions**
    - 4nec2 – limited to machine memory
    - 4nec2X – uses virtual memory for bigger problems
- **Has 3D graphics and two optimizers**
    - Gradient descent optimizer
    - Genetic optimizer
- **Permits writing NEC script, thereby giving access to all NEC-2 and NEC-4 commands**

# 4nec2 Wire-Grid Models of Boeing 747 and Automobile





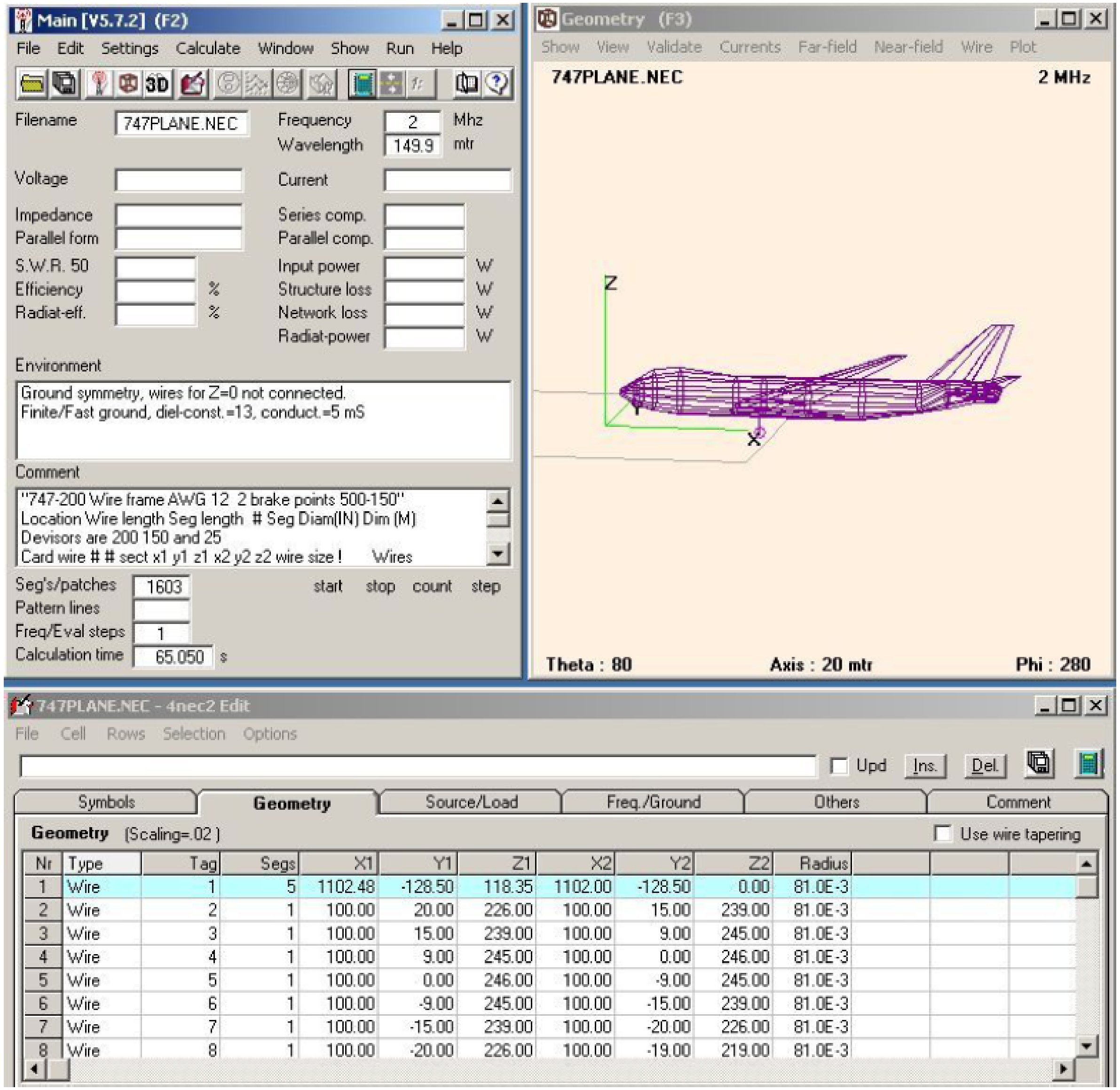
# 4nec2 Screen Displays

Main screen

Geometry screen

Edit screen

Wire tab



Filename 747PLANE.NEC
Frequency 2 Mhz
Wavelength 149.9 mtr
Voltage
Current
Impedance
Series comp.
Parallel form
Parallel comp.
S.W.R. 50
Input power W
Efficiency %
Structure loss W
Radiat-eff. %
Network loss W
Radiat-power W

Environment

Ground symmetry, wires for Z=0 not connected.
Finite/Fast ground, diel-const.=13, conduct.=5 mS

Comment

"747-200 Wire frame AWG 12 2 brake points 500-150"
Location Wire length Seg length # Seg Diam(IN) Dim (M)
Devisors are 200 150 and 25
Card wire # # sect x1 y1 z1 x2 y2 z2 wire size ! Wires

Seg's/patches 1603
Pattern lines
Freq/Eval steps 1
Calculation time 65.050 s
start stop count step

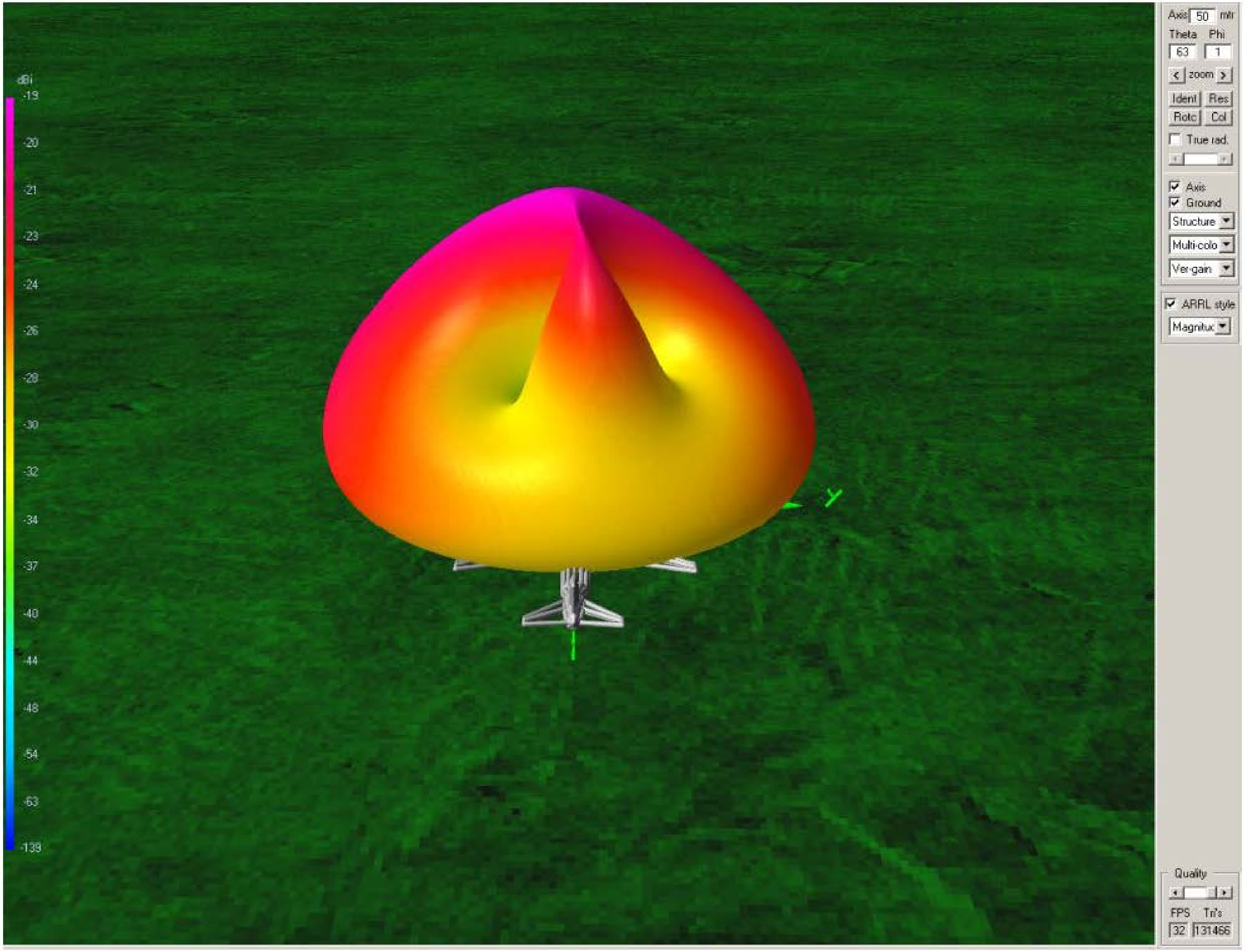
747PLANE.NEC 2 MHz

Theta : 80 Axis : 20 mtr Phi : 280

**Geometry** (Scaling=.02 )

| Nr | Type | Tag | Segs | X1 | Y1 | Z1 | X2 | Y2 | Z2 | Radius |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Wire | 1 | 5 | 1102.48 | -128.50 | 118.35 | 1102.00 | -128.50 | 0.00 | 81.0E-3 |
| 2 | Wire | 2 | 1 | 100.00 | 20.00 | 226.00 | 100.00 | 15.00 | 239.00 | 81.0E-3 |
| 3 | Wire | 3 | 1 | 100.00 | 15.00 | 239.00 | 100.00 | 9.00 | 245.00 | 81.0E-3 |
| 4 | Wire | 4 | 1 | 100.00 | 9.00 | 245.00 | 100.00 | 0.00 | 246.00 | 81.0E-3 |
| 5 | Wire | 5 | 1 | 100.00 | 0.00 | 246.00 | 100.00 | -9.00 | 245.00 | 81.0E-3 |
| 6 | Wire | 6 | 1 | 100.00 | -9.00 | 245.00 | 100.00 | -15.00 | 239.00 | 81.0E-3 |
| 7 | Wire | 7 | 1 | 100.00 | -15.00 | 239.00 | 100.00 | -20.00 | 226.00 | 81.0E-3 |
| 8 | Wire | 8 | 1 | 100.00 | -20.00 | 226.00 | 100.00 | -19.00 | 219.00 | 81.0E-3 |

# 4nec2 3D Pattern of Antenna on 747 – Vert Pol



Axis 50 mtr

Theta 63 Phi 1

☐ True rad.

☑ Axis

☑ Ground

☑ ARRL style

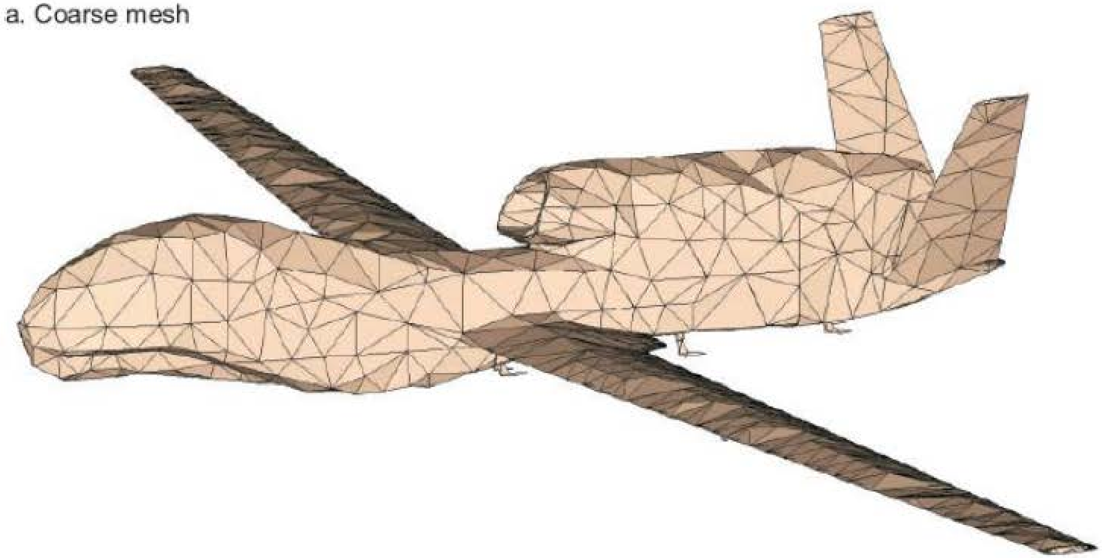
FPS 32 Tri's 131466

# FEKO http://www.feko.info/

- Developed and sold by EM Software & Systems (EMSS), South Africa
- Switches automatically among multiple "engines" like a Toyota Prius
- Main method is MoM/SIE, but has MoM/VIE, FEM, FMM, and several optics approximations
- Capabilities similar to WIPL-D: lossy conductors, dielectric and magnetic materials, near and farfield calculations, optimizer
- Curved surfaces are approximated by many flat triangles
- Triangle surface meshing and low-order basis functions give heavy computation burden, hence the need for multiple engines
- Has infinite Sommerfeld-Norton ground
- Limited LITE version of interest to Radio Amateurs
    - FEKO LITE – Free download from http://www.feko.info/sales

# FEKO Model of Global Hawk (RQ-4A)

a. Coarse mesh



b. Refined mesh

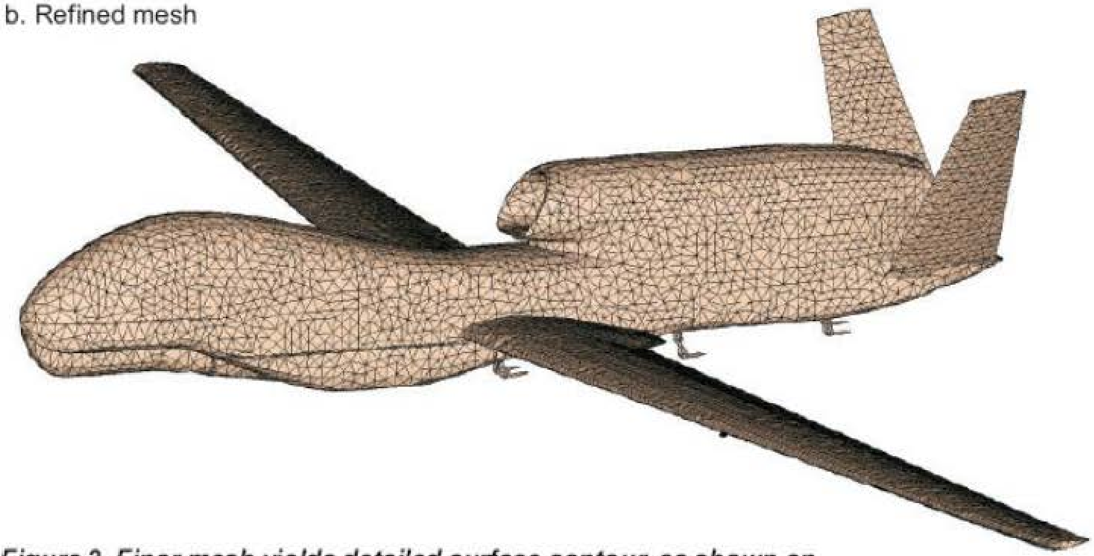


*Figure 2. Finer mesh yields detailed surface contour, as shown on*

# FEKO Pattern of Horn Antenna in Wing Pod

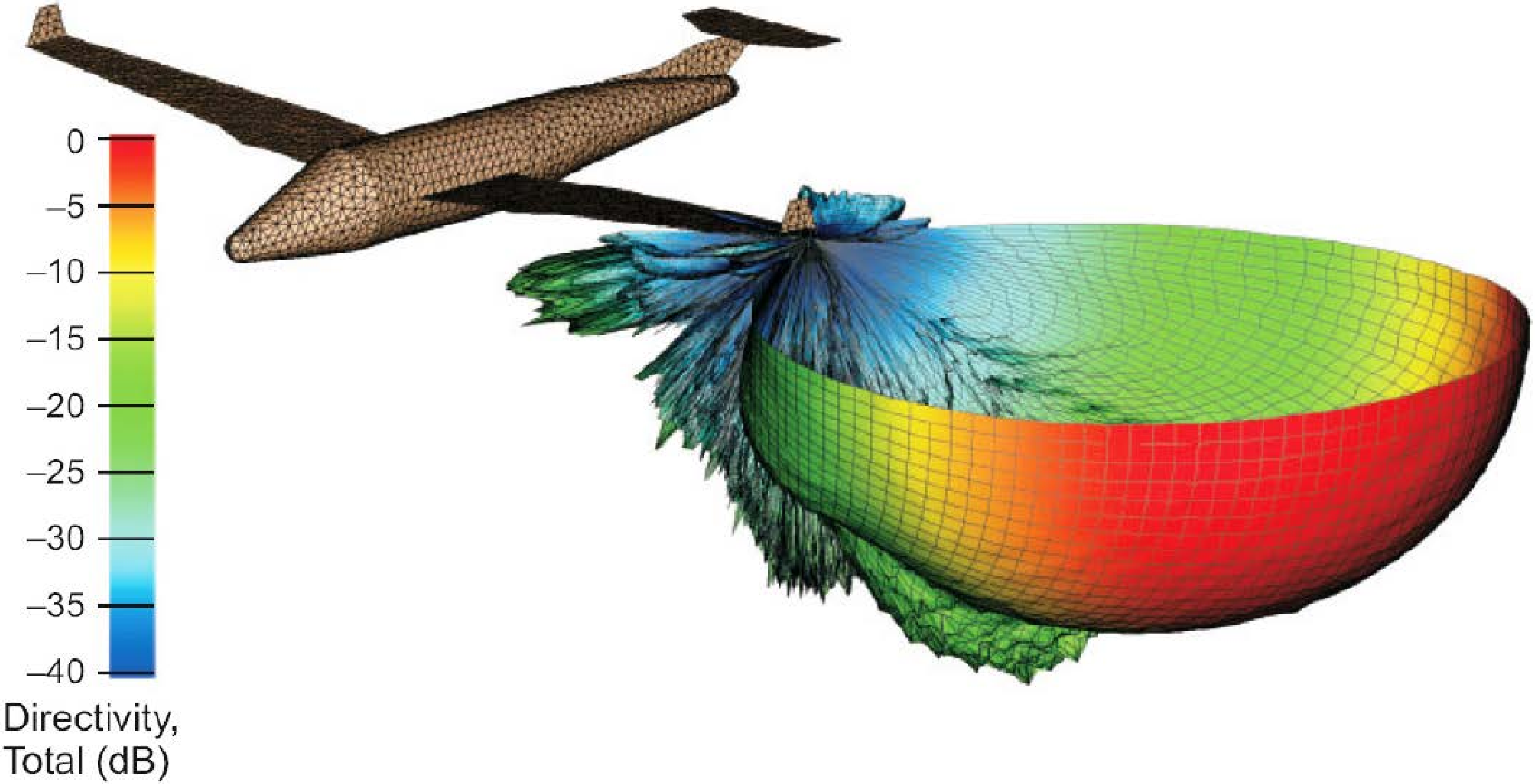
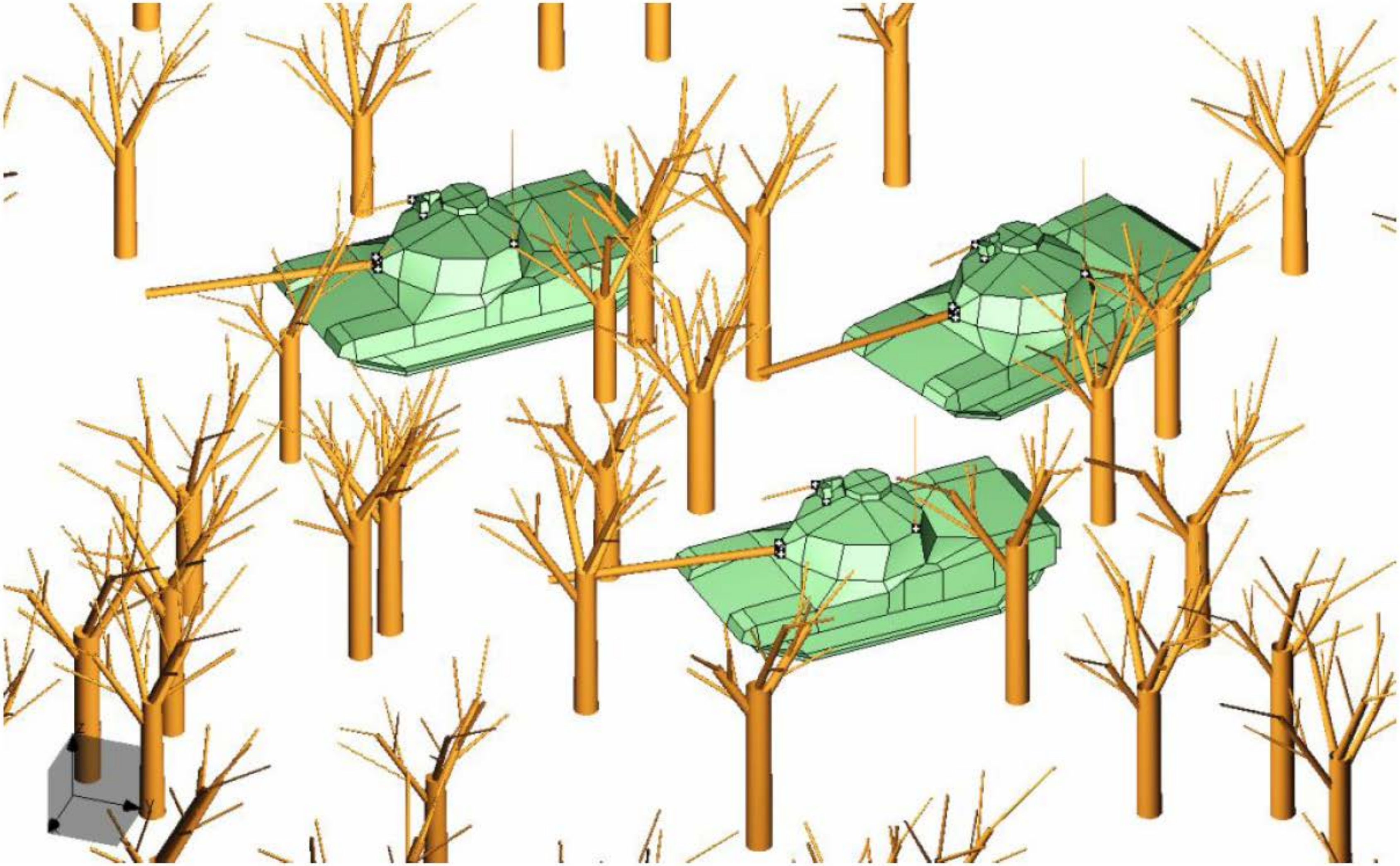
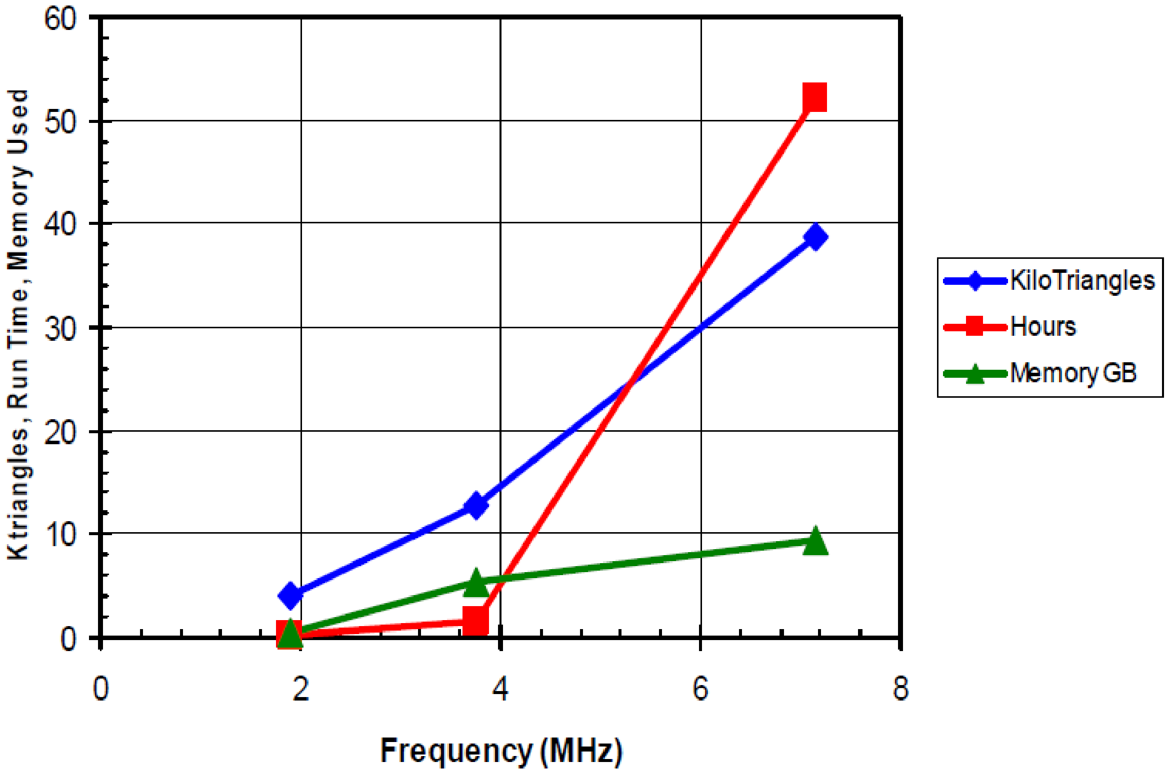


***Figure 8. Pod location, performance of horn array at 90 deg***

# The Next Step – Modeling the Landscape



# Required Computation



| Frequency (kHz) | Triangles | Hours | Memory (GB) |
|---|---|---|---|
| 1,900 | 3,928 | 0.125 | 0.53 |
| 3,750 | 12,834 | 1.54 | 5.48 |
| 7,150 | 38,717 | 52.1 | 9.38 |

# Other Useful Antenna Software

- **winSMITH 2.0 by Agilent (formerly Eagleware)**
  - ISBN 1884932908
  - $127 from SciTech Publishing http://www.scitechpublishing.com/
  - $149 from Amazon.com
  - For interactive design of ladder networks for impedance matching
  - Excellent tool for learning to use the Smith chart
  - Grossly overpriced
- **MultiNEC by Dan Maguire, AC6LA, http://www.ac6la.com**
  - Excel/Visual Basic program; low cost but currently unavailable
  - Puts NEC, EZNEC, and 4nec2 on autopilot for making a series of runs
  - Inexpensive alternative to a real optimizer
  - Doesn’t work with EZNEC-ARRL
  - Temporarily unavailable

# Finite Difference Time Domain

# FDTD

# Reason for interest in FDTD

In the time domain, Maxwell’s equations give rise to PDEs involving time and spatial derivatives.
Some good reasons for dealing with PDE’s are:

- Complex-value materials easily accommodated.
- Computer resources are adequate.
- PDE solutions are robust.
- Time domain PDE methods usually have no matrices.
- Geometries to be solved can be more varied.

# Some big advantages

- Broadband response with a single excitation.
- 3D models easily.
- Memory requirement scales linearly with problem size
- Frequency dependent materials accommodated.
- Most parameters can be generated e.g.

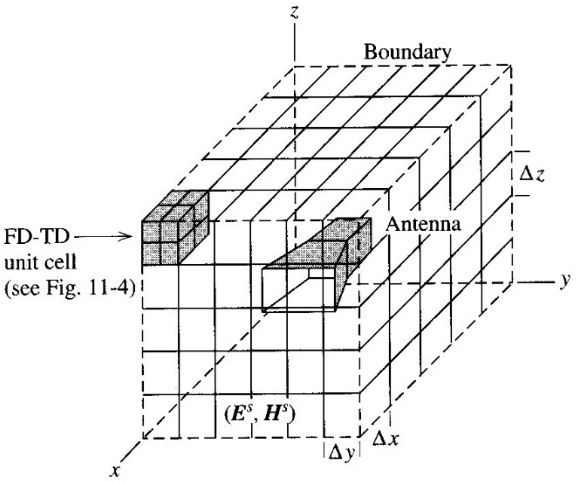
  Scattered fields
  antenna patters
  RCS
  S-parameters
  etc…..

# How does it work?

Based on the two Maxwell curl equations in derivative form. These are linearized by central finite differencing. We only consider nearest neighbor interactions because all the fields are advanced temporally in discrete time steps over spatial cells.

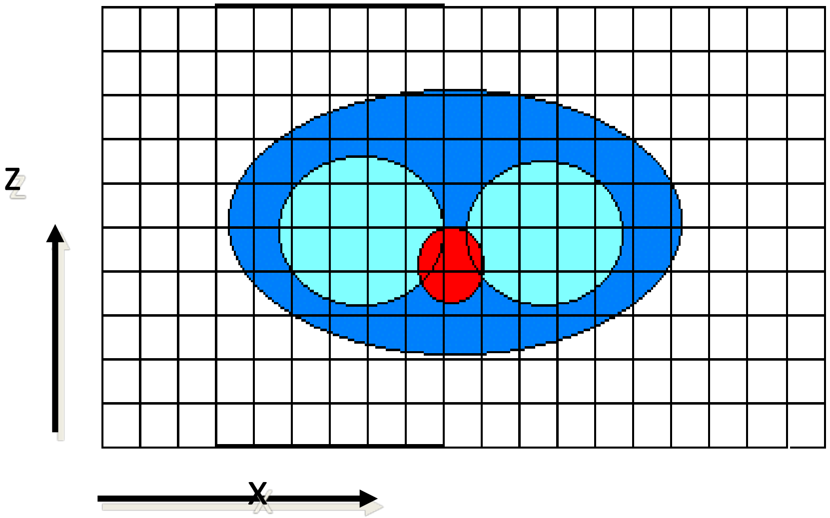
ie we sample in space & time

embedding of an antenna
in a FDTD space lattice
(note that the whole volume
is meshed!)

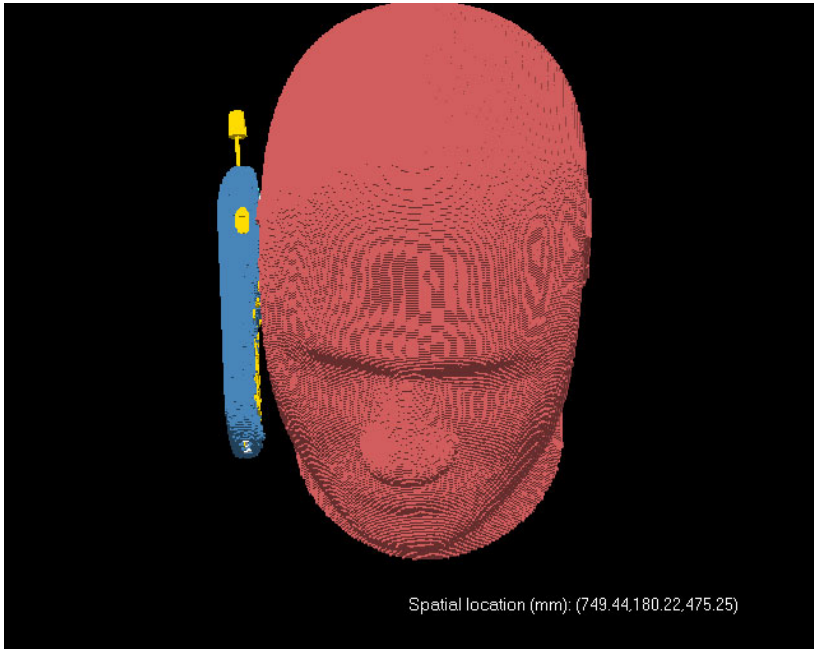


# Discretize Objects in Space using Cartesian Grid

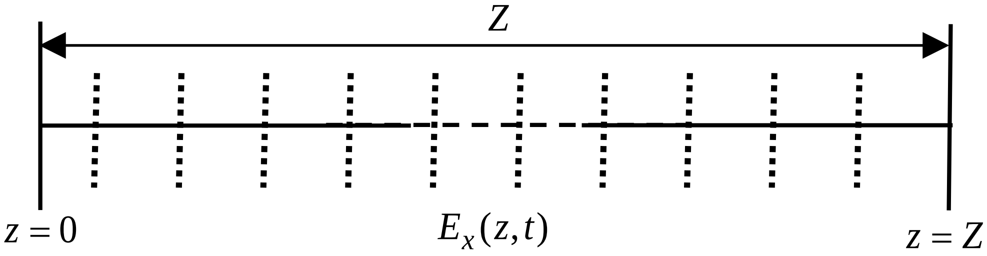
## 2D Discretization



## 3D Discretization



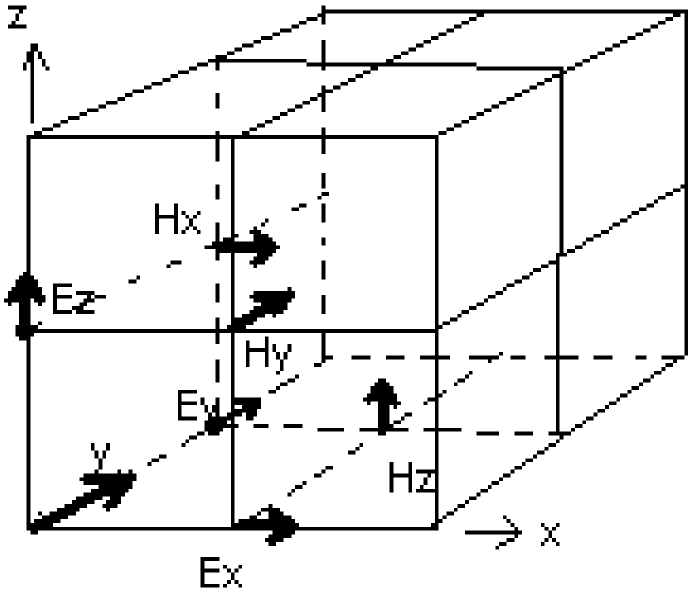
## 1D Discretization



# Define Locations of Field Components: FDTD Cell called Yee Cell

- Finite-Difference
  - Space is divided into small cells

    One Cell: (dx)(dy)(dz)
  - E and H components are distributed in space around the Yee cell (note: field components are not collocated)



**FDTD:** Yee, K. S.: Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. *IEEE Transactions on Antennas Propagation*, Vol. AP-14, pp. 302-307, 1966.

# 3D formulation

$$\frac{\partial H_x}{\partial t}=\frac{1}{\mu}\left(\frac{\partial E_y}{\partial z}-\frac{\partial E_z}{\partial y}-\rho' H_x\right)$$

$$\frac{\partial H_y}{\partial t}=\frac{1}{\mu}\left(\frac{\partial E_z}{\partial x}-\frac{\partial E_x}{\partial z}-\rho' H_y\right)$$

$$\frac{\partial H_z}{\partial t}=\frac{1}{\mu}\left(\frac{\partial E_x}{\partial y}-\frac{\partial E_y}{\partial x}-\rho' H_z\right)$$

**Convert equations like these**

$$\frac{\partial E_x}{\partial t}=\frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y}-\frac{\partial H_y}{\partial z}-\sigma E_x\right)$$

$$\frac{\partial E_y}{\partial t}=\frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z}-\frac{\partial H_z}{\partial x}-\sigma E_y\right)$$

$$\frac{\partial E_z}{\partial t}=\frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}-\sigma E_z\right)$$

**To ones like these**

$$H_x^{n+\frac12}\left(i,j+\tfrac12,k+\tfrac12\right)-H_x^{n-\frac12}\left(i,j+\tfrac12,k+\tfrac12\right)=\frac{1}{\mu_0\mu_r\left(i,j+\tfrac12,k+\tfrac12\right)}\cdot\left[\frac{E_y^n\left(i,j+\tfrac12,k+\tfrac12\right)-E_y^n\left(i,j+\tfrac12,k\right)}{\Delta z}-\frac{E_z^n\left(i,j+\tfrac12,k+\tfrac12\right)-E_z^n\left(i,j,k+\tfrac12\right)}{\Delta y}\right]$$

$$H_x^{n+\frac12}\left(i+\tfrac12,j,k+\tfrac12\right)-H_x^{n-\frac12}\left(i+\tfrac12,j+\tfrac12,k\right)=\frac{1}{\mu_0\mu_r\left(i+\tfrac12,j,k+\tfrac12\right)}\cdot\left[\frac{E_z^n\left(i+1,j,k+\tfrac12\right)-E_z^n\left(i,j,k+\tfrac12\right)}{\Delta x}-\frac{E_x^n\left(i+\tfrac12,j,k+1\right)-E_x^n\left(i+\tfrac12,j,k\right)}{\Delta z}\right]$$

$$\frac{H_z^{n+\frac12}\left(i+\tfrac12,j+\tfrac12,k\right)-H_z^{n-\frac12}\left(i+\tfrac12,j+\tfrac12,k\right)}{\Delta t}=\frac{1}{\mu_0\mu_r\left(i+\tfrac12,j+\tfrac12,k\right)}\cdot\left[\frac{E_x^n\left(i+\tfrac12,j+1,k\right)-E_x^n\left(i+\tfrac12,j,k\right)}{\Delta y}-\frac{E_y^n\left(i+1,j+\tfrac12,k\right)-E_y^n\left(i,j+\tfrac12,k\right)}{\Delta x}\right]$$

$$\frac{E_x^{n+1}\left(i+\tfrac12,j,k\right)-E_x^n\left(i+\tfrac12,j,k\right)}{\Delta t}=\frac{1}{\varepsilon_0\varepsilon_r\left(i+\tfrac12,j,k\right)}\cdot\left[\frac{H_z^{n+\frac12}\left(i+\tfrac12,j+\tfrac12,k\right)-H_z^{n+\frac12}\left(i+\tfrac12,j-\tfrac12,k\right)}{\Delta y}-\frac{H_y^{n+\frac12}\left(i+\tfrac12,j,k+\tfrac12\right)-H_y^{n+\frac12}\left(i+\tfrac12,j,k-\tfrac12\right)}{\Delta z}\right]-$$
$$\sigma\left(i+\tfrac12,j,k\right)\left[\frac{E_x^{n+1}\left(i+\tfrac12,j,k\right)+E_x^n\left(i+\tfrac12,j,k\right)}{2}\right]$$

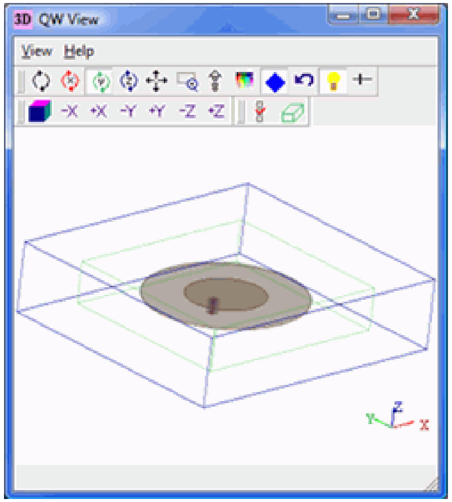
# QuickWave (http://www.qwed.eu/)

- Commercial FDTD package with CAD interface
- Uses conformal FDTD mesh
- Many special features for antenna problems
- Written and supported by QWED, Poland
- Runs under 32/x64 bit Windows platforms and Linux

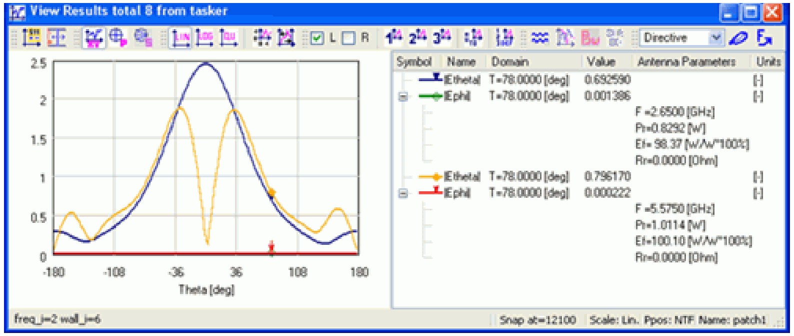
# QuickWave  (http://www.qwed.eu/)

## Examples:

Circular Patch Antenna - a circular patch fed by a thin vertical coax line

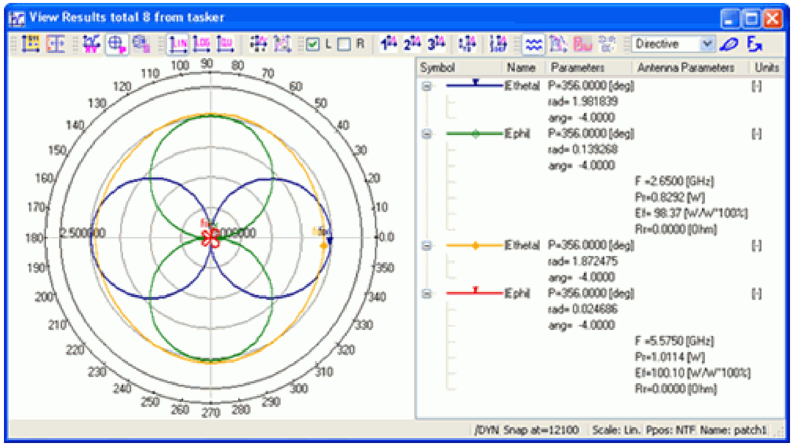


Circular patch antenna model



```
Symbol  Name     Domain              Value     Antenna Parameters        Units
        |Etheta|  T=78.0000 [deg]    0.692590                            [-]
        |Ephi|    T=78.0000 [deg]    0.001386                            [-]
                                               F =2.6500 [GHz]
                                               Pr=0.8292 [W]
                                               Ef= 98.37 [W/W*100%]
                                               Rr=0.0000 [Ohm]
        |Etheta|  T=78.0000 [deg]    0.796170                            [-]
        |Ephi|    T=78.0000 [deg]    0.000222                            [-]
                                               F =5.5750 [GHz]
                                               Pr=1.0114 [W]
                                               Ef=100.10 [W/W*100%]
                                               Rr=0.0000 [Ohm]
freq_i=2 wall_i=6                     Snap at=12100   Scale: Lin.  Ppos: NTF  Name: patch1
```

Radiation patterns versus elevation angle *Theta* with azimuthal angle *Phi=0*, calculated for two frequencies: 2.65 and 5.575 GHz.



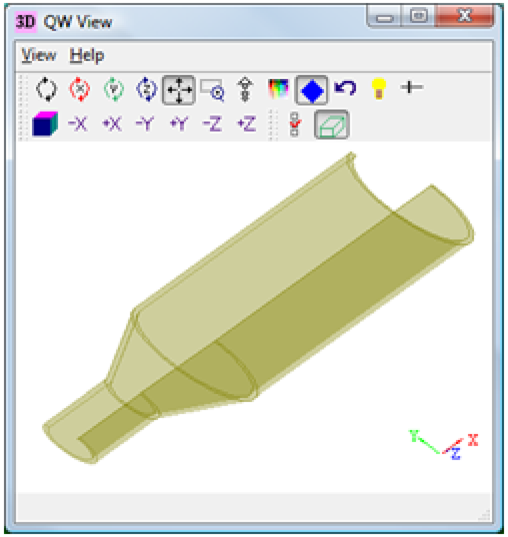
```
Symbol  Name     Parameters          Antenna Parameters        Units
        Etheta|  P=356.0000 [deg]                               [-]
                 rad= 1.981839
                 ang= -4.0000
        Ephi|    P=356.0000 [deg]                               [-]
                 rad= 0.139268
                 ang= -4.0000
                                     F =2.6500 [GHz]
                                     Pr=0.8292 [W]
                                     Ef= 98.37 [W/W*100%]
                                     Rr=0.0000 [Ohm]
        Etheta|  P=356.0000 [deg]                               [-]
                 rad= 1.872475
                 ang= -4.0000
        Ephi|    P=356.0000 [deg]                               [-]
                 rad= 0.024686
                 ang= -4.0000
                                     F =5.5750 [GHz]
                                     Pr=1.0114 [W]
                                     Ef=100.10 [W/W*100%]
                                     Rr=0.0000 [Ohm]
/DYN Snap at=12100   Scale: Lin.  Ppos: NTF  Name: patch1
```

Radiation patterns versus azimuthal angle *Phi* with elevation angle *Theta=30°*, calculated for two frequencies: 2.65 and 5.575 GHz

# QuickWave (http://www.qwed.eu/)

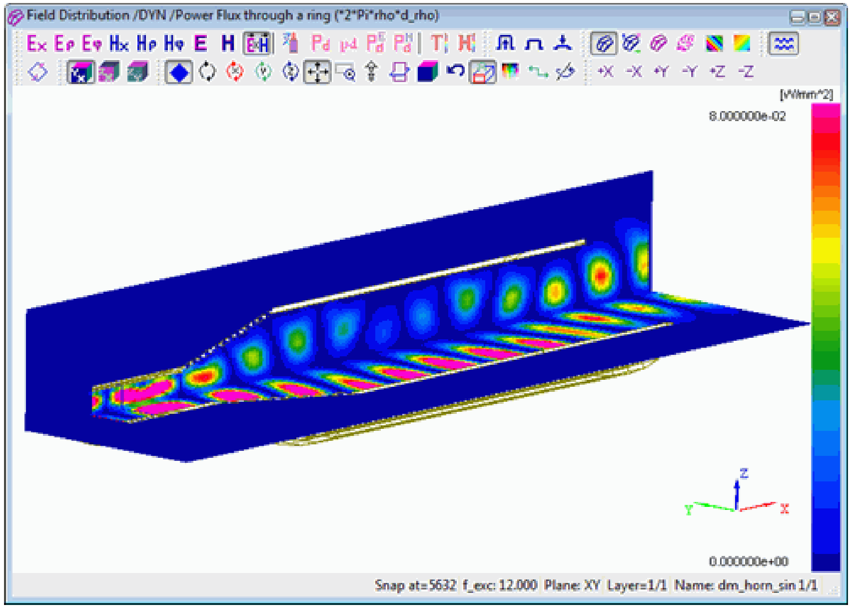
**Examples:**

Dual mode horn antenna (V2D example)



Consider *Standard/Dmhorn/dm_horn.pro*, which is an example of dual-mode axisymmetrical horn antenna [43]. Input of the antenna is excited with the fundamental mode TE11 of 10..14 GHz spectrum range. However, as the wave propagates through the tapered section, some of its energy is transformed into TM11 mode. Thus, an appropriate design allows us to equalise polarisation in E and H planes. It makes this horn a good feed for reflector antennas. Additionally, proper choices of flare angle and length of the horn's tube help suppress the side lobes in the radiation pattern. Changing *Gain Reference* in the *Radiation pattern* window from *Relative* to *Directive* we see that the gain of this antenna is about 14.5 dB for both E and H planes. The 3 dB beamwidth is $35.4^0$ and $37^0$ for the E and H plane, respectively.

Dual mode horn antenna model



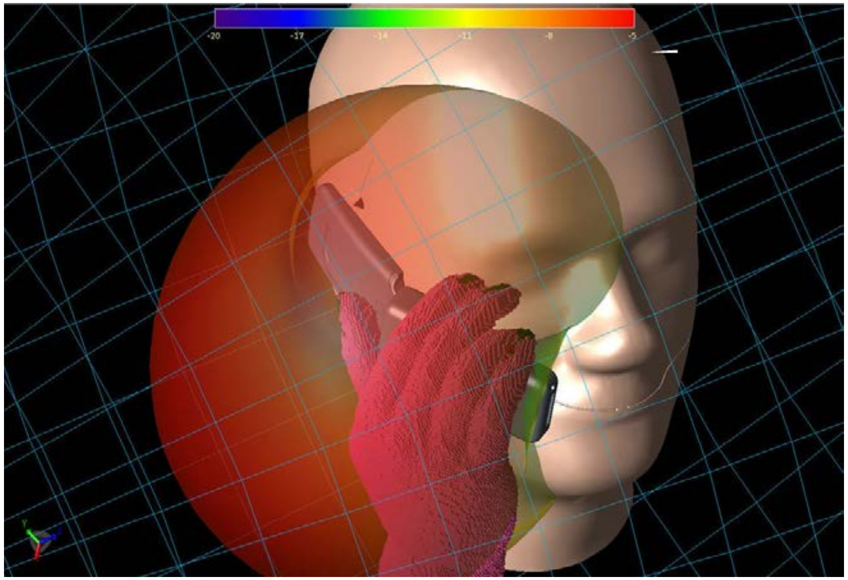
Sinusoidal excitation of the model at the central frequency ($f$ = 12 GHz) confirms that the same radiation levels at both E and H planes are obtained at the end of the antenna.

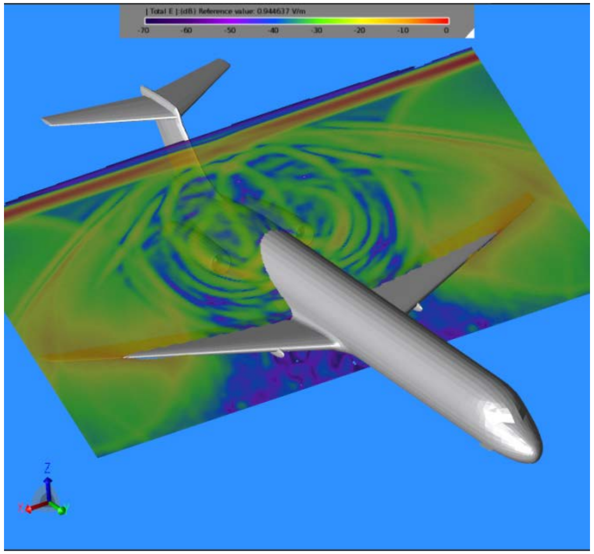
Poynting vector for example with sinusoidal excitation.

# XFdtd (http://www.remcom.com /)

- Commercial FDTD package with CAD interface
- Probably the most popular FDTD package for antenna problems
- Many special features for antenna problems including full human body mesh
- Written and supported by Remcom, USA
- Runs under 32/x64 bit Windows, Mac OS X and Linux

# XFdtd (http://www.remcom.edu /)





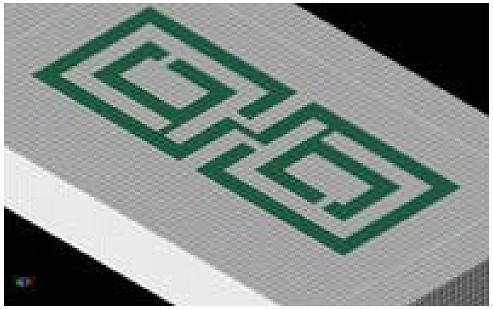


Figure 1
A CAD representation of the cavity-backed antenna. The white material represents the metal layers while the green color is the dielectric substrate under the slots.

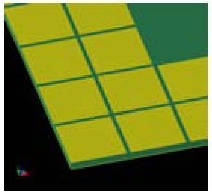


Figure 5
Mesh representation of EBG reflector.

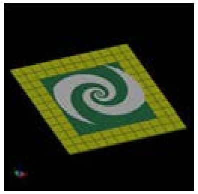


Figure 6
Full model with spiral antenna and EBG reflector.

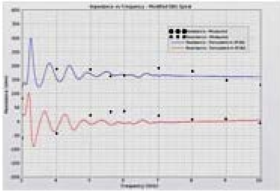


Figure 7
Comparison of impedance of antenna over EBG reflector.

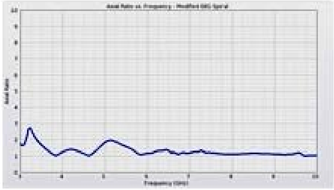


Figure 8
Axial ratio of antenna over EBG reflector.

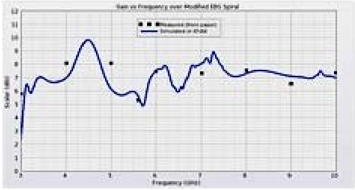
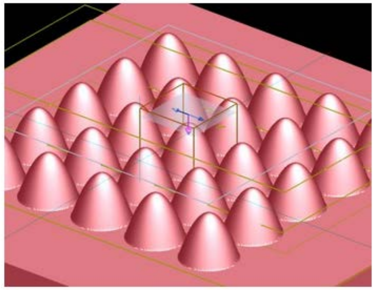
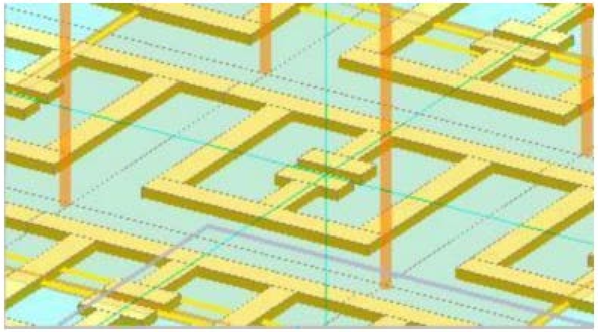
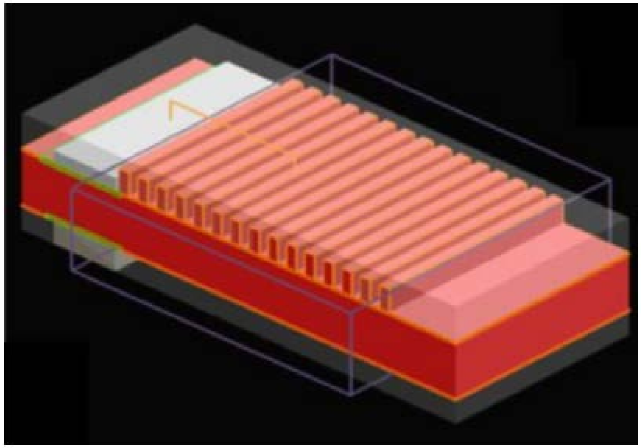
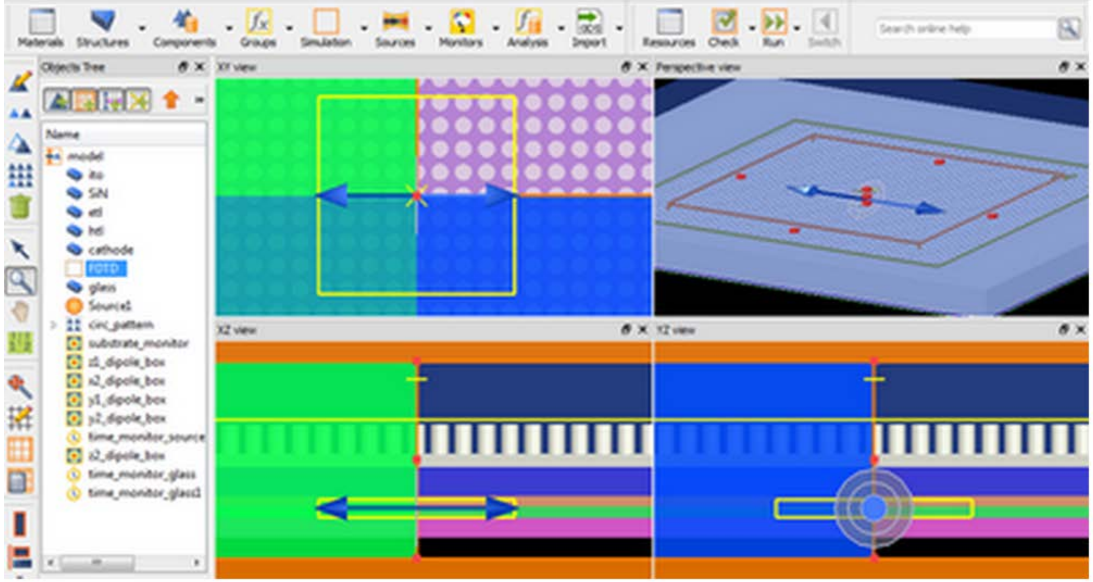


Figure 9
Comparison of peak gain of antenna over EBG reflector.

# Lumerical (http://www.lumerical.com /)

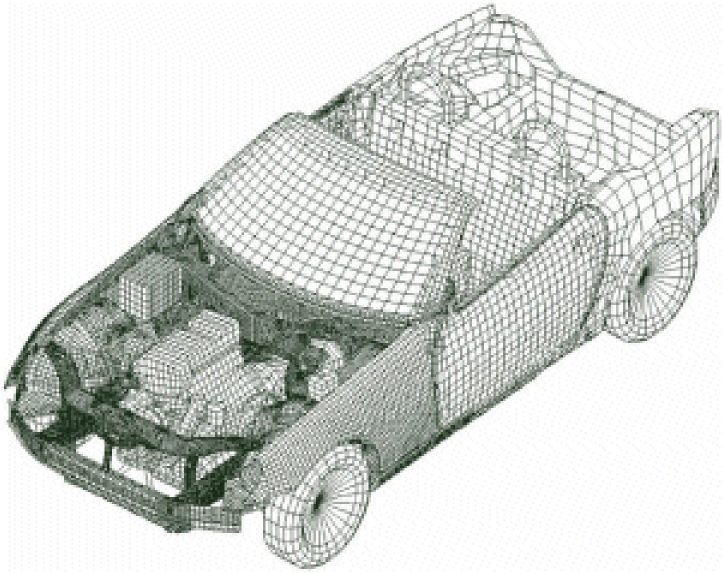
- Commercial FDTD package with CAD interface
- Popular FDTD package for the optics folks (i.e. integrated optics, light scattering, plasmonics)
- Large library of materials at optical wavelengths
- Has very nice scripting language for defining large complicated problems.
- Has nice built in optimization
- Runs under 32/x64 bit Windows, Mac OS X and Linux

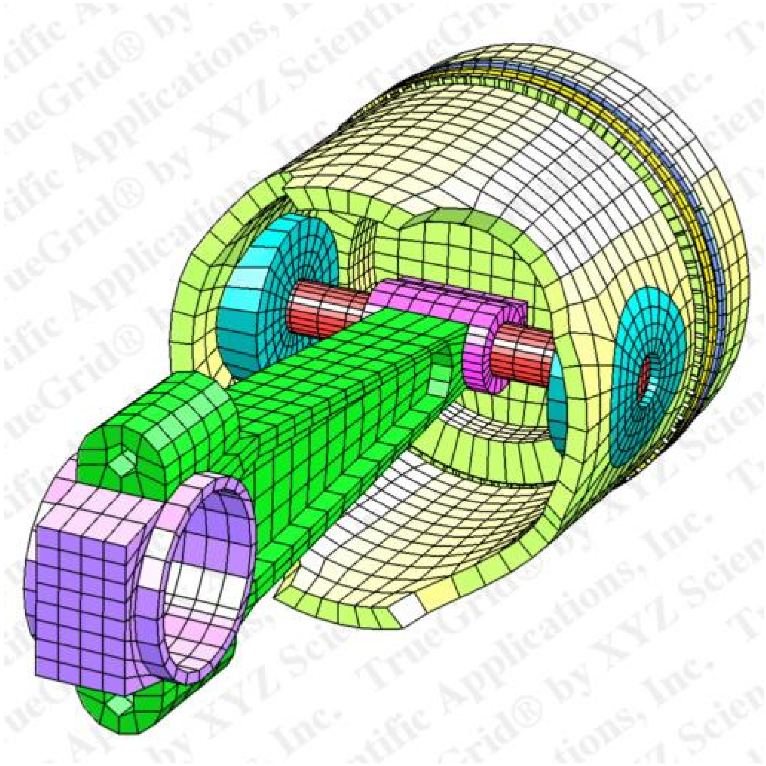
# Lumerical (http://www.lumerical.com /)

# Finite Element Method

# Finite Element Method





# Variational Approach

In solving problems arising in physics and engineering it is often possible to replace the problem of integrating a differential equation by the equivalent problem of seeking a function that gives a minimum value of some integral. Problems of this type are called *variational problems*.

The methods that allow us to reduce the problem of integrating a differential equation to the equivalent variational problem are usually called *variational methods*.

# Variational Approach

| **Name of equations** | **PDE** | **Variational principle** |
|---|---|---|
| Homogeneous wave equation with sources | $\nabla^2\Phi + k^2\Phi = g$ | $I(\Phi) = \frac{1}{2}\int_v \left[\lvert\nabla\Phi\rvert^2 - k^2\Phi^2 + 2g\Phi\right] dv$ |
| Homogeneous wave equation without sources | $\nabla^2\Phi + k^2\Phi = 0$ | $I(\Phi) = \frac{1}{2}\int_v \left[\lvert\nabla\Phi\rvert^2 - k^2\Phi^2\right] dv$ |
| Diffusion equation | $\nabla^2\Phi - k\frac{\partial\Phi}{\partial t} = 0$ | $I(\Phi) = \frac{1}{2}\int_t\int_v \left[\lvert\nabla\Phi\rvert^2 - k^2\Phi\frac{\partial\Phi}{\partial t}\right] dv\,dt$ |
| Poisson's equation | $\nabla^2\Phi = g$ | $I(\Phi) = \frac{1}{2}\int_v \left[\lvert\nabla\Phi\rvert^2 + 2g\Phi\right] dv$ |
| Homogenous Laplace's equation | $\nabla^2\Phi = 0$ | $I(\Phi) = \frac{1}{2}\int_v \left[\lvert\nabla\Phi\rvert^2\right] dv$ |

# Finite Element Method

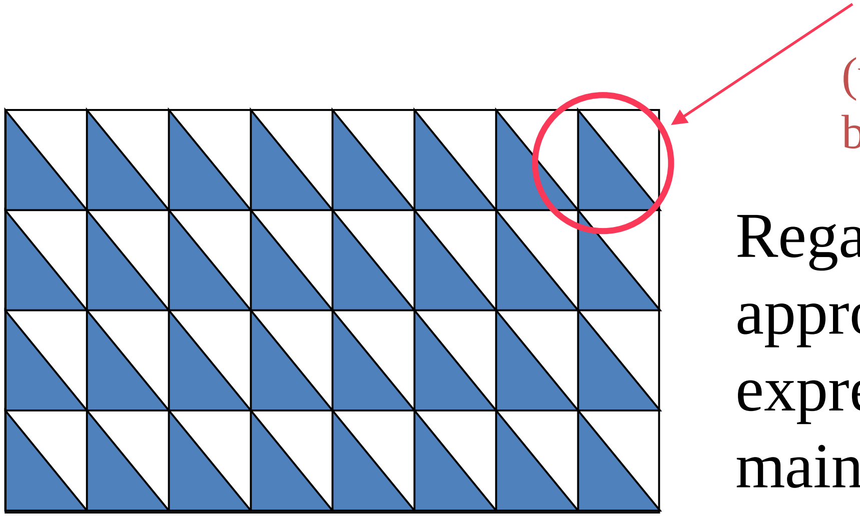
The finite element method (FEM) has its origin in the field of structural analysis. However, since then the method has been employed in nearly all areas of computational physics and engineering.

The FEM method, while more difficult to program than either the finite difference (FD) or method of moments (MOM), is a more powerful and versatile numerical technique for handling problems involving complex geometries and inhomogeneous media.

# Basic concept

Although the behaviour may be complex when viewed over a large region, a simple approximation may suffice over a small subregion.

The region is divided up into finite elements.



(usually, triangles or squares, but can be more complicated)

Regardless of the shape the field is approximated by a different expression over each element, maintaining continuity at adjoining elements.

# Solution Strategy: Variational Approach

The equations to be solved are usually stated not in terms of field the variables but in terms of an integral-type functional such as energy.

The functional is chosen such that the field solution makes the functional stationary

The total functional is the sum of the integral over each element

# Finite Element Method

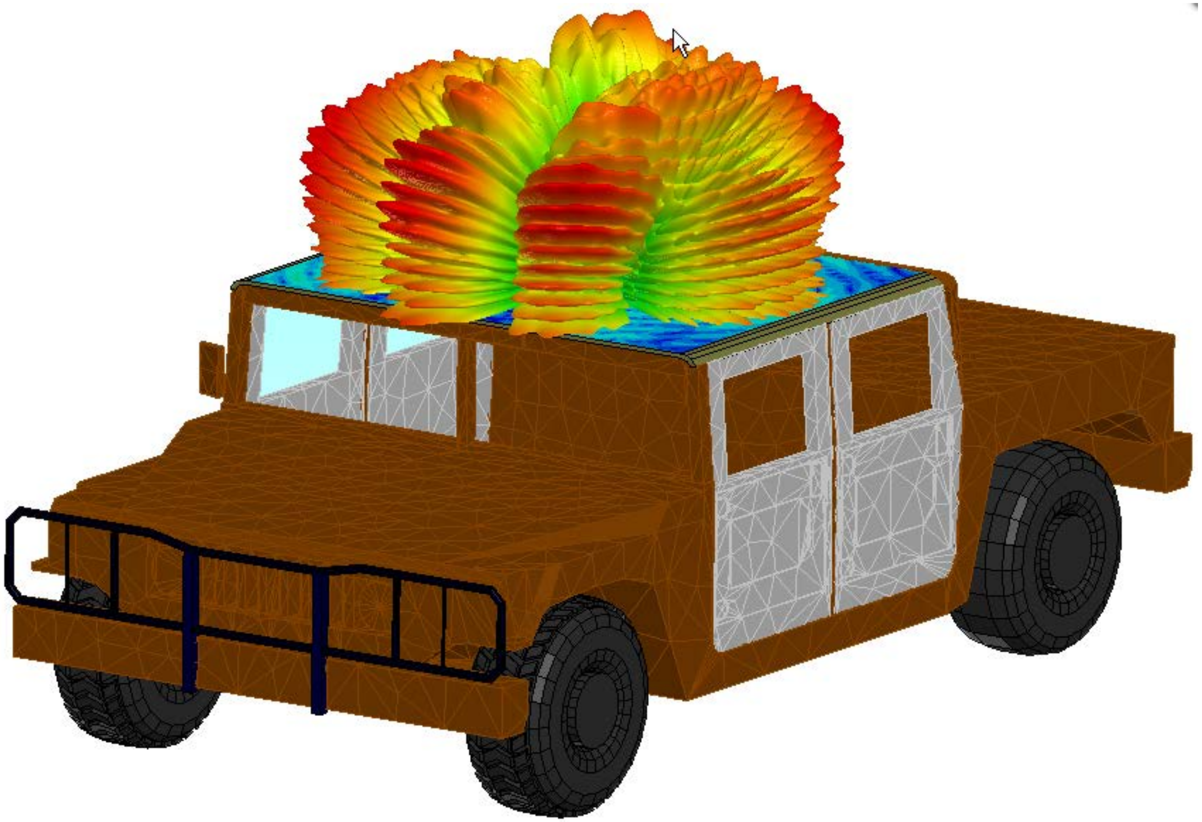
The finite element method (FEM) involves basically four steps:

1. Discretize the solution region into a finite number of subregions or elements
2. Derive the governing equations for each element based on either a variational approach or Galerkin's method
3. Assemble all the elements together in the solution space.
4. Solve the resulting system of equations

# HFSS (http://www.ansoft.com/)

- Commercial FEM package with CAD interface
- Uses adaptive meshing
- Probably the most popular commercial package for antenna applications.
- Written and supported by Ansoft, USA
- Runs under 32/x64 bit Windows platforms, Redhat Linux, Solaris (Sun workstations).
- Has integrated hybrid finite element / boundary integral methods (MoM)
- Kind of expensive!
- Optional optimization package (optimetrics)

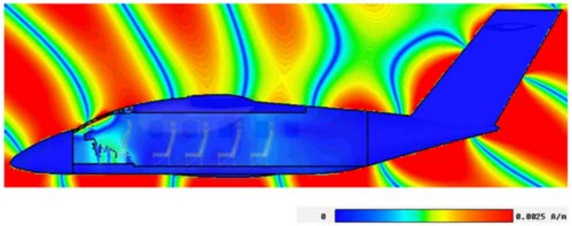
# HFSS (http://www.ansoft.com/)

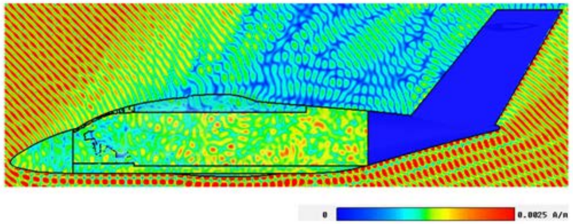


# CST Microwave Studio (http://www.cst.com/)

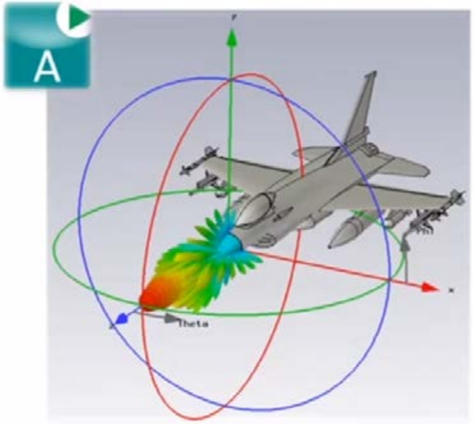
- Commercial FEM, MoM and TLM package with CAD interface
- Mature and easy to use interface
- Popular program for microwave circuit applications but also very useful for antennas.
- Written and supported by CST, International
- Runs under 32/x64 bit Windows platforms and Redhat Linux,
- Kind of expensive!
- Has a specific antenna design option called Magus

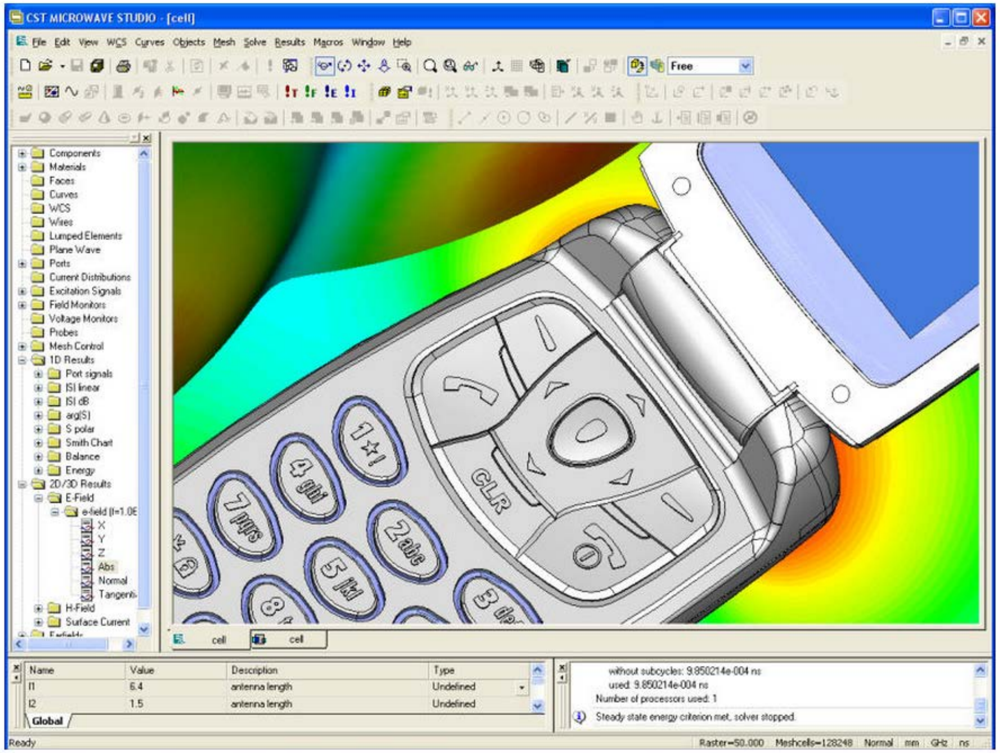
# CST Microwave Studio (http://www.cst.com/)





## Installed Antenna Performance





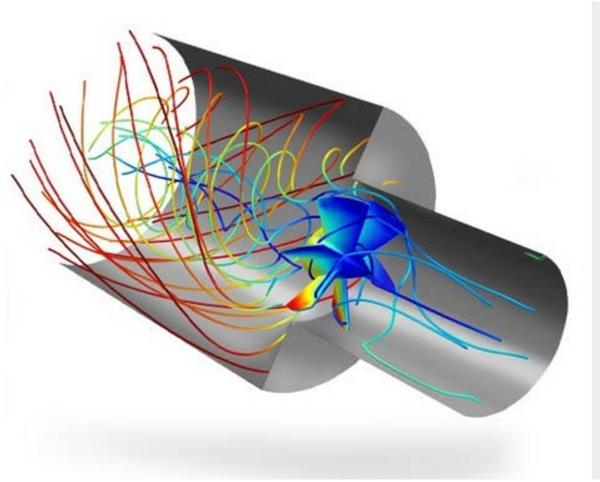
| Name | Value | Description | Type |
|---|---|---|---|
| l1 | 6.4 | antenna length | Undefined |
| l2 | 1.5 | antenna length | Undefined |

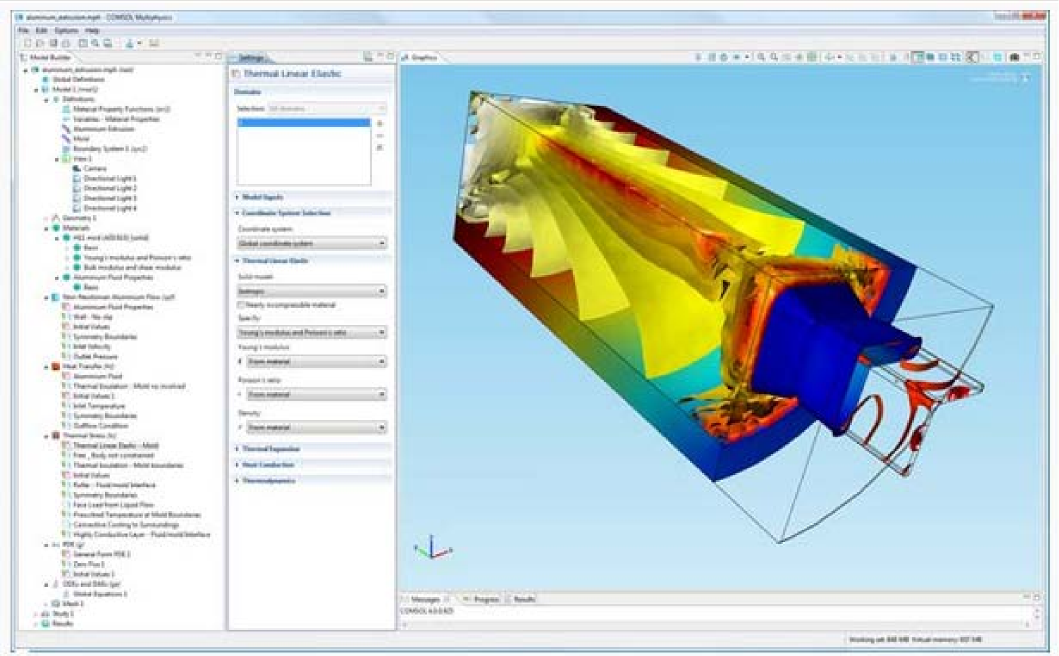
```
    without subcycles: 9.850214e-004 ns
    used: 9.850214e-004 ns
  Number of processors used: 1
  Steady state energy criterion met, solver stopped.
```

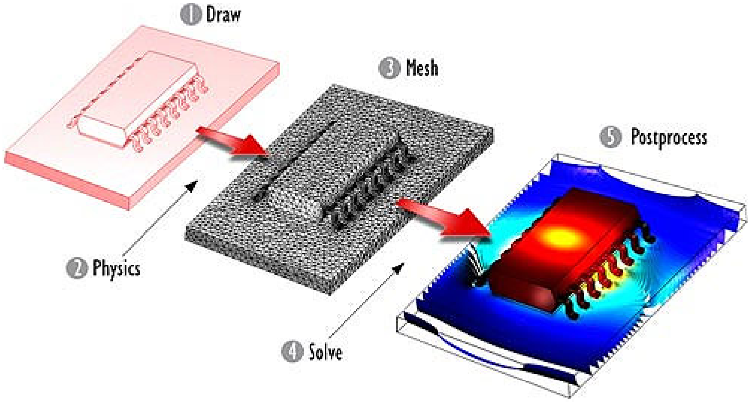
# Comsol Multiphysics(http://www.comsol.com/)

- Commercial FEM package with CAD interface
- Is best known for its ability to solve multiphysics problems
- Becoming a very popular program.
- Links nicely with Matlab
- Easy to learn interface
- Runs under 32/x64 bit Windows platforms
- Moderately prices

# Comsol Multiphysics(http://www.comsol.com/)







# References:

1. Clemson site lists all the free EM modeling tools

   http://www.clemson.edu/ces/cvel/modeling/EMAG/free-codes.html

2. Clemson site lists all the commerical EM modeling tools

   http://www.clemson.edu/ces/cvel/modeling/EMAG/csoft.html