Antenna Modeling for Radio Amateurs
Revised and Expanded

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Abstract

Where do antenna modeling programs come from, how do they work, what are their limitations, what is the state of the art? These questions and others will be answered by Steve Stearns, K6OIK, in this tutorial introduction to antenna modeling. Steve will review the historical timeline of events that led to modern computational electromagnetics.

Steve will tell which antenna modeling programs are free or inexpensive, the capabilities of different software to handle various shapes and materials, and which show results as graphs, 3D depictions, or movies of full-wave simulations. Also covered is meshing by 1D segments, 2D surface patches, and 3D voxels needed to compute fields inside inhomogeneous dielectric objects such as people.

This presentation will show the power of modern computational electromagnetics to solve practical problems in antenna engineering and Amateur Radio.
Speaker’s Biography

- Stephen D. Stearns
- Technical Fellow, ret., Northrop Grumman Corp.
- 40 years experience in electronic systems
  - Northrop Grumman, TRW, GTE Sylvania, Hughes Aircraft
  - Electromagnetic and signal processing systems for communications and radar surveillance, cochannel signal separation, measurement, identification, characterization, polarimetric array signal processing of ionospheric skywave signals for precision geolocating HF emitters, sensor fusion
  - Recent work: Antenna and scattering theory; Non-Foster circuits for antennas and metamaterials; antennas to radiate OAM Bessel-Vortex beams; double-reflectionless harmonic reject filters

- FCC licenses
  - Amateur Radio Extra Class
  - 1st-Class Radiotelephone
  - General Radio Operator License (GROL)
  - Ship Radar Endorsement

- Education
  - Stanford – under Prof. T.M. Cover
  - CSUF – under Profs. J.E. Kemmerly and G.I. Cohn

- More than 100 publications and presentations, both professional (IEEE) and hobbyist (Amateur Radio)
ARRL Pacificon Presentations by K6OIK

1999  Mysteries of the Smith Chart
2000  Jam-Resistant Repeater Technology
2001  Mysteries of the Smith Chart
2002  How-to-Make Better RFI Filters Using Stubs
2003  Twin-Lead J-Pole Design
2004  Antenna Impedance Models – Old and New
2005  Novel and Strange Ideas in Antennas and Impedance Matching
2006  Novel and Strange Ideas in Antennas and Impedance Matching II
2007  New Results on Antenna Impedance Models and Matching
2008  Antenna Modeling for Radio Amateurs
2010  Facts About SWR, Reflected Power, and Power Transfer on Real Transmission Lines with Loss
2011  Conjugate Match Myths
2012  Transmission Line Filters Beyond Stubs and Traps
2013  Bode, Chu, Fano, Wheeler – Antenna Q and Match Bandwidth
2014  A Transmission Line Power Paradox and Its Resolution
2015  Weird Waves: Exotic Electromagnetic Phenomena
2015  The Joy of Matching: How to Design Multi-Band Match Networks
2016  The Joy of Matching 2: Multi-Band and Reflectionless Match Networks
2016-7 Antenna Modeling for Radio Amateurs – Revised and Expanded
2017  VHF-UHF Propagation Planning for Amateur Radio Repeaters

Archived at http://www.fars.k6ya.org
8.3 REFERENCES AND BIBLIOGRAPHY

Professional Literature


Outline

- History of electromagnetics
- History of computational electromagnetics (CEM)
  - Method of Moments (MoM)
- Antenna modeling programs for Radio Amateurs
  - EZNEC
  - 4nec2
  - MININEC
  - MMANA-GAL Basic
  - FEKO
  - WiPL-D
  - HOBBIES
  - openEMS
- Advanced applications
  - Terrain Modeling as Alternative to HFTA
  - Monopole on Planet Cubo
  - Field Strength Inside Car for 2-meter Mobileers
  - Baking a Potato
  - And more…
- References and resources
  - Software for antenna modeling
  - Antenna books
Question

- Is the current the same everywhere along a wire?

\[ I_{in} = I_{out} \]
Answer: It Depends

- “Yes” for steady-state d-c current
- “Almost yes” for low-frequency a-c current or short wires
- But “no” for high-frequency a-c current because electrons can bunch up
- James Clerk Maxwell found a way to turn “no” into “yes”

\[ \nabla \times H = J + \frac{\partial D}{\partial t} \]

\[ 0 = \oint_{S} \left( J + \frac{\partial D}{\partial t} \right) \cdot dS \]

\[ I_{in} = I_{out} + \frac{\partial}{\partial t} \oint_{S} D_{n} \ dS \]

Total current, conduction plus displacement current, entering is the same as that leaving every part of a wire!
History
Who Does Not Belong in this Picture?
Answer: Leonardo Da Vinci and Isaac Newton

Leonardo Da Vinci 1452-1519

Isaac Newton 1642-1727

André-Marie Ampère 1775-1836

Michael Faraday 1791-1867

James Clerk Maxwell 1831-1879

Carl Friedrich Gauss 1777-1855

Georg Simon Ohm 1789-1854
Maxwell 1865 and the Equations in His 1873 Treatise

VIII. A Dynamical Theory of the Electromagnetic Field. By James Clerk Maxwell, F.R.S.

Received October 27,—Read December 8, 1864.

PART I.—INTRODUCTORY.

(1) The most obvious mechanical phenomenon in electrical and magnetical experiments is the mutual action by which bodies in certain states set each other in motion while still at a sensible distance from each other. The first step, therefore, in reducing these phenomena into scientific form, is to ascertain the magnitude and direction of the force acting between the bodies, and when it is found that this force depends in a certain way upon the relative position of the bodies and on their electric or magnetic conditions, it seems at first sight natural to explain the facts by assuming the existence of something either at rest or in motion in each body, constituting its electric or magnetic state, and capable of acting at a distance according to mathematical laws.

In this way mathematical theories of statical electricity, of magnetism, of the mechanical action between conductors carrying currents, and of the induction of currents, have been formed. In these theories the force acting between the two bodies is treated with reference only to the condition of the bodies and their relative position, and without any express consideration of the surrounding medium.

These theories assume, more or less explicitly, the existence of substances the particles of which have the property of acting on one another at a distance by attraction or repulsion. The most complete development of a theory of this kind is that of M. W. Weber, who has made the same theory include electrostatic and electromagnetic phenomena.

In doing so, however, he has found it necessary to assume that the force between two electric particles depends on their relative velocity, as well as on their distance.

This theory, as developed by M. W. Weber and C. Neumann, is exceedingly ingenious, and wonderfully comprehensive in its application to the phenomena of statical electricity, electromagnetic attractions, induction of currents and diamagnetic phenomena; and it comes to us with the more authority, as it has served to guide the speculations of one who has made so great an advance in the practical part of electrical science, both by introducing a consistent system of units in electrical measurement, and by actually determining electrical quantities with an accuracy hitherto unknown.

† "Explicatio tentativa quomodo fiat ut lucis planae polarizantur per vives electricas vel magneticas declinatur."—Halles Saxonum, 1858.

\[ z \]

\[
\begin{align*}
\alpha &= \frac{dU}{dy} - \frac{d\Phi}{dz} \\
\beta &= \frac{d\Phi}{dx} - \frac{dU}{dy} \\
\gamma &= \frac{d\Phi}{dx} - \frac{dU}{dy} \\
\mathbf{P} &= c \frac{d\mathbf{u}}{dt} - b \frac{d\mathbf{v}}{dt} - d \frac{d\mathbf{v}}{dt} + a \frac{d\mathbf{u}}{dt} \\
\mathbf{Q} &= \mathbf{a} \frac{d\mathbf{v}}{dt} + \mathbf{c} \frac{d\mathbf{u}}{dt} - b \frac{d\mathbf{v}}{dt} - \frac{d\mathbf{v}}{dt} \\
\mathbf{R} &= \mathbf{b} \frac{d\mathbf{v}}{dt} + \mathbf{a} \frac{d\mathbf{u}}{dt} - \frac{d\mathbf{v}}{dt} - \frac{d\mathbf{v}}{dt} \\
X &= vy - wb \\
Y &= wa - uc \\
Z &= ub - va \\
\mathbf{a} &= \alpha + 4\pi \mathbf{A} \\
\mathbf{b} &= \beta + 4\pi \mathbf{B} \\
\mathbf{c} &= \gamma + 4\pi \mathbf{C} \\
\mathbf{4\pi u} &= \frac{d\mathbf{u}}{dy} - \frac{d\mathbf{u}}{dz} \\
\mathbf{4\pi v} &= \frac{d\mathbf{v}}{dx} - \frac{d\mathbf{v}}{dz} \\
\mathbf{4\pi w} &= \frac{d\mathbf{w}}{dx} - \frac{d\mathbf{w}}{dy} \\
\mathbf{D} &= \frac{1}{4\pi} K \mathbf{E} \\
\mathbf{\mathbf{R}} &= \mathbf{C} \mathbf{E} \\
\mathbf{\mathbf{E}} &= \mathbf{\mathbf{R}} + \mathbf{D} \\
\mathbf{u} &= \mathbf{p} + \frac{d\mathbf{p}}{dt} \\
\mathbf{v} &= \mathbf{q} + \frac{d\mathbf{q}}{dt} \\
\mathbf{w} &= \mathbf{r} + \frac{d\mathbf{r}}{dt} \\
\mathbf{\mathbf{E}} &= (\mathbf{C} + \frac{1}{4\pi} K \frac{d\mathbf{p}}{dt}) \mathbf{E} \\
\mathbf{u} &= \mathbf{CP} + \frac{1}{4\pi} K \frac{d\mathbf{p}}{dt} \\
\mathbf{v} &= \mathbf{CQ} + \frac{1}{4\pi} K \frac{d\mathbf{Q}}{dt} \\
\mathbf{w} &= \mathbf{CR} + \frac{1}{4\pi} K \frac{d\mathbf{R}}{dt} \\
\rho &= \frac{\mathbf{d\rho}}{dt} + \frac{d\mathbf{p}}{dt} + \frac{d\mathbf{q}}{dt} \\
\mathbf{s} &= l f + mg + nh + l f' + m' g' + n' h' \\
\mathbf{\mathbf{B}} &= \mathbf{\mu s} \\
\end{align*}
\]
The Maxwellians

George Francis FitzGerald
1851-1901

Oliver Heaviside
1850-1925

Oliver Joseph Lodge
1851-1940

Heinrich Rudolph Hertz
1857-1894

John Henry Poynting
1851-1914
Heaviside’s “Duplex” Equations for Maxwell’s Theory

\[ \nabla \times \mathbf{E} = -\mathbf{M} - \frac{\partial \mathbf{B}}{\partial t} \]

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]

\[ \nabla \cdot \mathbf{D} = \rho_e \]

\[ \nabla \cdot \mathbf{B} = \rho_m \]

\[ \mathbf{D} = \varepsilon \mathbf{E} \]

\[ \mathbf{J} = \sigma_e \mathbf{E} \]

\[ \mathbf{B} = \mu \mathbf{H} \]

\[ \mathbf{M} = \sigma_m \mathbf{H} \]

“And God said, Let there be light; and there was light.” *Genesis* 1:3
Pre-History of Antennas

1785  Coulomb’s Law is published – C-A. de Coulomb
1812  Poisson’s Equation is published – S.D. Poisson
1813  Gauss’s Divergence Theorem – C.F. Gauss or M.V. Ostrogradskii
1820  Discovery that electric current makes magnetic effects (field concept not yet articulated) – H.C. Øersted
1820  Discovery that electricity and magnetism are linked phenomena – André-Marie Ampère
1820  Biot-Savart Law discovered – J-B. Biot & P. Savart
1826  Ampère’s Law is published – André-Marie Ampère
1831  Faraday’s Law is published – M. Faraday
1842  Discovery of radiation – J. Henry
1856  “On Faraday’s Lines of Force” – J.C. Maxwell
1861  “On Physical Lines of Force” – J.C. Maxwell
1865  “A Dynamical Theory of the Electromagnetic Field” – J.C. Maxwell
1873  A Treatise on Electricity and Magnetism – J.C. Maxwell
1879-94 The “Maxwellians” period – O. Heaviside, G.F. FitzGerald, O.J. Lodge
## Key Dates in Antennas

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1875-87</td>
<td>Early radiation demonstrations: T.A. Edison 1875; A.E. Dolbear 1882; H. Hertz 1887</td>
</tr>
<tr>
<td>1889-06</td>
<td>Phased arrays – A. Artom, S.G. Brown, J.E. Murray</td>
</tr>
<tr>
<td>1895-01</td>
<td>Radio communication, fan dipole, polar plots – G. Marconi</td>
</tr>
<tr>
<td>1897</td>
<td>Biconical dipole, loading coil, tunable $LC$ matching network, counterpoise, “impedance” – O.J. Lodge</td>
</tr>
<tr>
<td>1907</td>
<td>Goniometer, electrical steerable array, radio direction-finding – E. Bellini and A. Tosi</td>
</tr>
<tr>
<td>1907</td>
<td>Ground losses, ground waves – J. Zenneck</td>
</tr>
<tr>
<td>1909-26</td>
<td>Infinite half-space problem – A.N. Sommerfeld</td>
</tr>
<tr>
<td>1919</td>
<td>Trees as antennas – G.O. Squier</td>
</tr>
<tr>
<td>1923</td>
<td>Wave-tilt antenna – H.H. Beverage</td>
</tr>
<tr>
<td>1928</td>
<td>Endfire array with parasitic elements – H. Yagi and S. Uda</td>
</tr>
<tr>
<td>1934-37</td>
<td>Radials, ground currents and losses – G.H. Brown</td>
</tr>
<tr>
<td>1940</td>
<td>Albert Einstein popularizes the name “Maxwell’s Equations”</td>
</tr>
<tr>
<td>1947</td>
<td>Polyrod antenna – G.E. Mueller and W.L. Tyrell</td>
</tr>
<tr>
<td>1947-75</td>
<td>Small antennas – H. Wheeler</td>
</tr>
</tbody>
</table>
### Key Dates in Antennas continued

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948</td>
<td>Fundamental limit on antenna bandwidth – L.J. Chu</td>
</tr>
<tr>
<td>1950</td>
<td><em>Antennas</em> – J.D. Kraus</td>
</tr>
<tr>
<td>1952</td>
<td><em>Antennas: Theory and Practice</em> – S.A. Schelkunoff and H.T. Friis</td>
</tr>
<tr>
<td>1952</td>
<td><em>Advanced Antenna Theory</em> – S.A. Schelkunoff</td>
</tr>
<tr>
<td>1956</td>
<td><em>Theory of Linear Cylindrical Antennas</em> – R.W.P. King</td>
</tr>
<tr>
<td>1959</td>
<td>“Method of moments” – A.V. Kantorovich, G.P. Akilov</td>
</tr>
<tr>
<td>1961</td>
<td><em>Antenna Engineering Handbook</em> – H. Jasik</td>
</tr>
<tr>
<td>1966</td>
<td>Finite difference method for fields problems – K.S. Yee</td>
</tr>
<tr>
<td>1976</td>
<td>Landstorfer antenna – F.M. Landstorfer</td>
</tr>
<tr>
<td>2006</td>
<td><em>Electrically Small, Superdirective, and Superconducting Antennas</em> – R.C. Hansen</td>
</tr>
<tr>
<td>2016</td>
<td><em>Antenna Theory, 4th edition</em> – C.A. Balanis</td>
</tr>
</tbody>
</table>
Antenna Analysis

- **Methods for finding impedance without solving for the current distribution**
  - Assume sinusoidal – induced EMF method (Brillouin, 1922)
  - Assume thin bicone – radial transmission line (Schelkunoff, 1941)
  - Far field radiation pattern integration (Rhodes, 1964; Hill, 1967)

- **Methods for finding current distribution and impedance**
  - Solve Pocklington’s (1897) integral equation
  - Solve Hallen’s (1938) integral equation
  - Mathematical methods (asymptotic or variational)
    - King-Harrison (Proc. IRE, 1943)
    - Middleton-King (J. Appl. Phys., 1946)
    - Storer (Cruft Lab., Harvard, 1950)

- **Limitations and complications**
  - Not all antennas shapes are simple
  - Not all antennas are made of metal; dielectrics affect radiation too
  - Math is hard
Induced EMF Method

- L. Brillouin, *Radioélectricité*, April 1922
- A.A. Pistolkors, *Proc. IRE*, March 1929
- P.S. Carter, *Proc. IRE*, June 1932

- Assume sinusoidal current distribution
- Obtain pattern, radiation resistance and reactance
- Accurate for pattern and impedance of dipoles up to half-wavelength and verticals up to quarter-wavelength
- Inaccurate for impedance of dipoles longer than half-wavelength and verticals longer than quarter-wavelength
- Widely used for the design of AM broadcast towers
- Obsoleted by numerical methods
Dipole Impedance via Induced EMF Method

- **Resistance**

\[
R_{in} = \frac{\eta}{4\pi \sin^2(kl)} \left\{ 2\gamma + 2 \ln(2k l) - 2\text{Ci}(2k l) + \sin(2k l) \left[ \text{Si}(4k l) - 2\text{Si}(2k l) \right] + \cos(2k l) \left[ \text{Ci}(4k l) - 2\text{Ci}(2k l) + \gamma + \ln(k l) \right] \right\}
\]

Terms vanish when \( l / \lambda \) is a half integer; impedance is independent of wire diameter for such lengths

- **Reactance**

\[
X_{in} = \frac{\eta}{4\pi \sin^2(kl)} \left\{ 2\text{Si}(2k l) - \cos(2k l) \left[ \text{Si}(4k l) - 2\text{Si}(2k l) \right] + \sin(2k l) \left[ \text{Ci}(4k l) - 2\text{Ci}(2k l) + \gamma + \ln \left( \frac{ka^2}{l} \right) \right] \right\}
\]

- **Accurate for dipoles in free space of length less than \( \lambda/2 \); not accurate for longer dipoles**

\( l = 2l \) = dipole total length
\( l = \text{dipole half length} \)
\( a = \text{wire radius} \)

Wire radius affects only reactance
Dipole Impedance by Tai-Elliott Equation

- **Resistance**

\[ R_{in} = -0.4787 + 7.3246kl + 0.3963(kl)^2 + 15.6131(kl)^3 \]

- **Reactance**

\[ X_{in} = -\frac{\eta}{\pi} \left( \ln \left( \frac{l}{a} \right) - 1 \right) \cot kl + \left( -0.4456 + 17.0082kl - 8.6793(kl)^2 + 9.6031(kl)^3 \right) \]

Wire radius affects only reactance

- **Accuracy** is ±0.5 ohm for a dipole in free space shorter than \( \lambda/2 \)
- Not accurate for longer dipoles

\[ L = 2l = \text{dipole total length} \]
\[ l = \text{dipole half length} \]
\[ a = \text{wire radius} \]
Integral Equations for the Current Along a Wire

- Pocklington’s equation (1897)

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

- Hallen’s equation (1938)

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

- General form

\[
L(f) = g \]

Linear operator \hspace{1cm} Driving function

Unknown function
Ronold Wyeth Percival King, 1905-2006

R.W.P. King, Harvard University authority on linear cylindrical antennas, speaking at his 100th birthday party, Oct. 2005
Resistance of Dipole, $L = 98.4$ ft., $L/d = 11,013$
Reactance of Dipole, $L = 98.4$ ft., $L / d = 11,013$

Tai-Elliott 3$^{rd}$-degree polynomial (black)
Induced EMF Method (blue)
NEC4 (red)
King-Wu (black dashed)

IEMF and NEC4

Tai-Elliott polynomial
Electric and Magnetic Fields of an Infinitesimal Dipole

- Fields of dipole source in free space, or monopole over perfect electrical conductor (PEC) plane

\[ H_r = H_\theta = 0 \]

\[ H_\phi = j \frac{k I_0 l \sin \theta}{4\pi r} \left[ 1 + \frac{1}{j kr} \right] e^{-j kr} \]

\[ E_r = \eta \frac{k I_0 l \cos \theta \left( \frac{2}{kr} \right)}{4\pi r} \left( 1 + \frac{1}{j kr} \right) e^{-j kr} \]

\[ E_\theta = j\eta \frac{k I_0 l \sin \theta}{4\pi r} \left[ 1 + \frac{1}{j kr} - \frac{1}{(kr)^2} \right] e^{-j kr} \]

\[ E_\phi = 0 \]

Near field terms assuming

- Uniform current distribution with
  - Current \( I_0 \)
  - Dipole length \( l \)

- Triangular current distribution with
  - Peak current \( I_0 \)
  - Dipole length \( 2l \)

One radian length defined as \( r = 1/k = \lambda/2\pi \) is the distance at which far field and near field terms are equal.
Heinrich Hertz’s Drawings of Electric Fields of a Dipole circa 1888
Inside sphere, E field lines terminate on charges

Outside sphere, E field lines form closed loops

Radius ~ 3 radian lengths
Diameter ~ 0.94 wavelengths
Dipole Fields Animations

View PowerPoint in Slide Show mode (Shift F5) to see field animations.
Poynting Vector of Infinitesimal Dipole

\[ S = \frac{1}{2} \mathbf{E} \times \mathbf{H}^* = a_r S_r + a_\theta S_\theta + a_\phi 0 \]

\[ S_r = \frac{1}{2} \left( E_\theta H_\phi^* - E_\phi H_\theta^* \right) \]

Real power

\[ = \frac{\eta \sin^2 \theta}{2} \left( \frac{k I_0 l}{4\pi r} \right)^2 \left( 1 - \frac{j}{(k r)^3} \right) \]

\[ S_\theta = \frac{1}{2} \left( E_r H_\phi^* - E_\phi H_r^* \right) \]

Reactive power

\[ = -j \frac{\eta \sin 2\theta}{4} \left( \frac{k I_0 l}{4\pi r} \right)^2 \left( 1 + \frac{1}{(k r)^2} \right) \]

\[ S_\phi = \frac{1}{2} \left( E_r H_\theta^* - E_\theta H_r^* \right) = 0 \]

- Power flow has real and reactive parts
- Real power flows radially outward from the origin
- Reactive power circulates in the near field
- But the power in the far field is not just real
- The theta component of the power flow survives into the far field and is reactive
- Does the far field have stored energy, like the near field?
Computational Electromagnetics
Evolution of Tools and Methods for Antennas

- **Old style antenna analysis (1880 to 1970)**
  - Used mathematics, slide rules, nomographs, desk top calculators, lab measurements and field testing
  - Limited to simple geometries, and few antenna properties
    - Impedance
    - Far fields

- **Modern antenna analysis (1970 to present)**
  - Uses sophisticated computational electromagnetics (CEM) computer codes, aka antenna modeling software, and less dependence on measurement
  - Results validated by agreement among different algorithms
  - Allows for evaluation of complicated geometries, materials, and more antenna properties
    - Radiation pattern for each field or polarization
    - Polarization
    - Efficiency
    - Near fields
    - Specific absorption rate (SAR)
    - Mutual coupling between antennas in an array
    - Scattering and radar cross-section
The Universe of Antenna Modeling Methods

- **UTD**
- **GO**
- **PO**
- **MLFMM**
- **MOM**
- **FEM-MOM**

**FDTD**
- Ultra Wideband antennas
- Impulse Radiating antennas
- Transient response
- Inhomogeneous materials

Complexity of Materials vs. Electrical Size

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 frequency
  - Earliest and longest legacy of software codes for antenna modeling
  - BRAC, WIRA, AMP, NEC, NEC2, NEC3, NEC4, MININEC, ELNEC, EZNEC, winNECPlus, 4nec2, Mentor Graphics (Zeland) IE3D, Altair (EMSS) FEKO, WiPL-D, HOBBIES

- **Finite element method (FEM)**
  - Best for design of small antennas of complex structure
  - ANSYS (Ansoft) HFSS

- **Finite difference time-domain method (FDTD)**
  - Pioneered by K.S. Yee 1966 and A. Taflove 1980
  - Best for design of small antennas for wide bandwidth applications
  - Dassault Systèmes (CST) Microwave Studio, Remcom XFdtd, Faustus MEFiSTo, openEMS

- **Geometric, physical, and uniform theories of diffraction**
  - Best for electrically-large antennas and radiating structures
  - ANSYS (Delcross) Savant
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
Steve Stearns, K6OIK

Gleb Pavlovich Akilov
1924-1964
ARRL Pacificon Antenna Seminar, San Ramon, CA

Roger F. Harrington
1925-
October 20-22, 2017
Method of Moments

- Published by Kantorovich and Akilov in 1959 as a general method for solving linear integro-differential equations
- Introduced into electromagnetics by Roger Harrington in 1967
  - Currents are weighted sum of basis functions
  - Solve for the coefficients of the basis functions for all segments
  - Calculate radiation pattern and feedpoint impedance from currents
- Uses two classes of functions, which may be the same or different
  - Basis functions and Test functions
  - Can be global or local (subsectional)
  - Global basis functions expand the current on a wire in an infinite series, e.g. Fourier series
  - Local basis functions divide an antenna into line segments, surface patches, or volume elements
- Subsectional basis functions appear to give better results solving Hallen’s equation rather than Pocklington’s
- Test functions are used to create “projections”
Integro-Differential Equations Made Simple

- Start with an equation. The 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
  \[ \sum_n a_n L(f_n \cdot \phi_m) = g \cdot \phi_m \]

- Write as a matrix equation of simultaneous linear equations
  \[
  \begin{bmatrix}
  L(f_1 \cdot \phi_1) & \cdots & L(f_N \cdot \phi_1) \\
  \vdots & \ddots & \vdots \\
  L(f_1 \cdot \phi_M) & \cdots & L(f_N \cdot \phi_M)
  \end{bmatrix}
  \begin{bmatrix}
  a_1 \\
  \vdots \\
  a_N
  \end{bmatrix}
  = 
  \begin{bmatrix}
  g \cdot \phi_1 \\
  \vdots \\
  g \cdot \phi_M
  \end{bmatrix}
  \]
The Solution

- Solve for the vector of expansion coefficients

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

- Obtain \( f \)

\[
f = \sum_{n} a_n f_n = [f_1 \ \cdots \ f_N]
\begin{bmatrix}
L(f_1 \cdot \phi_1) & \cdots & L(f_N \cdot \phi_1) \\
\vdots & \ddots & \vdots \\
L(f_1 \cdot \phi_M) & \cdots & L(f_N \cdot \phi_M)
\end{bmatrix}^{-1}
\begin{bmatrix}
g \cdot \phi_1 \\
\vdots \\
g \cdot \phi_M \\
\end{bmatrix}
\]
Meshing

- 1D segments
- 2D patches
  - Flat rectangles
  - Flat quadrilaterals
  - Flat triangles
  - Curved (bilinear) quadrilaterals
- 3D voxels
  - Cubic or hexahedral
  - Tetrahedral
- Manually specified meshing
- Automatic meshing
- Adaptive (smart) meshing
Principal MoM Computer Codes

- **WIRA** – Developed late 1960s by M. Andreasen, F. Harris and R. Tanner at Technology for Communications International (TCI)
- **BRACT & ANTBRACT** – Developed late 1960s at MBAssociates, San Ramon, CA
- **AMP/AMP2** – Developed mid 1970s by G.J. Burke at MBAssociates, San Ramon
- **NEC (1979)** – Added more accurate current expansions; multiple wire junctions; thick wires
- **NEC-BSC (1980)** – Added Basic Scattering Code of J. Richmond at Ohio State
- **MiniNEC (1980)** – Developed by J. Rockway and J. Logan. Different algorithms from NEC. Basis of MMANA-GAL.
- **NEC2 (1981)** – Sommerfield-Norton ground interaction for wire structures above lossy ground; numerical Green's function allows modifying without repeating whole calculation
- **NEC3 (1985)** – Buried wires
- **NEC4 (1992)** – Improved accuracy for stepped-radius wires and electrically-small segments, end caps and insulated wires, catenary-shaped wires, improved error detection
- **WiPL-D (ca 2000)** – Advanced MoM for wires, plates, and dielectrics based on work of A.R. Djordjevic, B.M. Kolundzija, University of Belgrade, Serbia
The History 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

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

NEC4.2 2012

- Improved Sommerfeld ground model
- Automatic memory scaling
- Current sources

R. Mainhardt and A.T. Biehl
Founded MBAssociates 1960
Acquired by Tracor 1980

Albertson et al.
Tech. U. of Denmark

NEC-BSC 1979

Gerald J. Burke

Courtesy of Applied Computational Electromagnetics Society
A More Accurate “Thin-Wire” Code

- Multiradius Bridge Current (MBC) method
- Developed by M.A. Tilston 1983-89 while at Univ. of Toronto
- Better accuracy than NEC4 when wires are very close to other wires or ground or join at acute angles, e.g. wire grid models of surfaces
- Used commercially by Phoenix Antenna Systems in Perth, Ontario, Canada
- Fortran source code

The wire structure to be modeled consists of straight wire segments all of the same radius, and usually shorter than a quarter-wavelength. Conceptually, a current expansion function is a tubular dipole current spanning the surface of two adjoining wire segments that are not necessarily collinear. Each expansion function has a corresponding identical tubular testing function, in a coincident location. The current on each segment is axially directed, sinusoidally distributed, continuous at the segment junction, and zero at the other end of each segment. The total current at the junction is unity. The mutual impedance between a tubular expansion dipole and a tubular testing dipole is composed of four tubular-monopole-to-tubular-monopole mutual impedances. The mutual impedance between a tubular expansion monopole and a tubular testing monopole is approximated by the mutual impedance between two filamentary monopoles that are placed on their respective segment axes unless the axes intersect or coincide. If the axes coincide, the expansion monopole is offset by a wire radius in a direction orthogonal to the coincident axes. If the two axes intersect, the expansion monopole is offset by a wire radius in a direction orthogonal to the plane containing both axes.

Now consider one testing monopole and two expansion monopoles that form an expansion dipole. With certain geometries, the filamentary expansion monopoles may be offset from their segment axes in different directions, thus forming a dipole that is broken at its vertex. This would occur, for example, if the segment axis of one, and only one, of the two expansion monopoles was coplanar with (but not parallel to) that of the testing monopole. In such a case, the break is bridged by a straight, uniformly distributed “bridge current.” With this geometry, the bridge current is orthogonal to the testing monopole. Because of this orthogonality, and because of its uniform current distribution, the bridge current does not contribute to the following symmetric integral form for the mutual impedance $Z_{ab}$ between a filamentary testing monopole $a$ and a bridged filamentary expansion dipole $b$:

$$Z_{ab} = \frac{1}{j\omega} \int \int \left[ \frac{\rho_a(r) \rho_b(r)}{R} \left( e^{-\frac{r}{R}} \right) \right] \frac{d\sigma}{d\Omega} \frac{d\Omega}{d\Omega}$$

where

$$R = \sqrt{r - r'},$$

This implementation of the moment method for electromagnetic analysis of multiradius thin-wire structures, including multires, multiradius junctions and grounded, is called the multiradius bridge-current (MBC) moment method. It is an extension of the authors’ multiradius bridge-current formulation of Richmond’s multiradius thin-wire theory. The method features an exact symmetric mutual impedance matrix inverting reciprocity between sources, it is unconstrained with respect to both the length ratio and the radius ratio of adjoining segments provided the wires are electrically thin, and it permits the self-consistent inclusion of coaxial cable sections in the configuration under analysis. The method is validated through comparison with transmission-line theory for a two-wire line and a coax cable, and through analysis of a simple monopole antennas and a log-periodic dipole array. Finally, the MBC moment method program is shown to surpass the Numerical Electromagnetics Code (NEC) in terms of reciprocity and convergence for both an AM broadcast tower detailed wind problem and a bent two-wire transmission problem.

I. Introduction

A well-known moment method computer program for the electromagnetic analysis of infinitesimal thin-wire structures is that of Richmond [1]. It has been shown by Butler and Wilton [2] that the particular method of expansion and testing, which they term “Pocklington piecewise-analytical Galerkin,” is one of the best methods for obtaining rapid convergence in the solution. Although very useful, Richmond’s program can display asymmetric artifacts when used to analyze certain symmetric structures, a problem that was observed by Vainberg and Balmain [3], explained and corrected approximately by Hiltbert, Tilston, and Balmain [4], and finally corrected more completely by the authors in their “bridge-current” formulation [5]. In this work, the bridge-current formulation is extended to allow solution of the multiradius problem.

II. Description of Bridge-CURRENT MOMENT METHOD

A. Uniradius Bridge-CURRENT Version

The uniradius bridge-current version forms the starting point for the multiradius bridge-current version. The uniradius version is described in detail in [5], and is described here briefly because it is necessary in order to explain the multiradius version.
Le Roy Bruce (L.B.) Cebik, W4RNL, 1939-2008

Popularized computational antenna modeling in Amateur Radio in the decade 1998-2008
EZNEC
EZNEC [http://www.eznec.com](http://www.eznec.com)

- Developed by Roy Lewallen, W7EL
- Now in version 6.0
- Five products available
  - EZNEC v.6 Demo Free (20 segments, also runs ARRL models)
  - EZNEC v.6 $100 (500 segments)
  - EZNEC+ v.6 $150 (2,000 segments)
  - EZNEC Pro/2 v.6 $525 (45,000 segments)
  - EZNEC Pro/4 v.6 $675 (sold only to NEC4 licensees)
- EZNEC includes either the NEC2 or NEC4 engines
- A NEC4 noncommercial user license can be obtained from Lawrence Livermore National Laboratory for $300
  - See [https://ipo.llnl.gov/technologies/nec](https://ipo.llnl.gov/technologies/nec)
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 crosssection 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
EZNEC v3 Main Screen and Control Panel

“Model contains loss” notice
Wires and Segments

- Each wire in an antenna is defined by
  - Location (coordinates) of both ends
  - Diameter or gauge of wire
  - Number of segments (all equal in length)
  - Metal type or conductivity

\[(x_1, y_1, z_1)\] \hspace{1cm} \[(x_2, y_2, z_2)\]

Diameter = AWG #12
No. segments = 7
Copper \(\sigma = 58\) MS/m
# Wire Table for UHF Discone Antenna

Steve Stearns, K6OIK, “All About the Discone Antenna,” *QEX*, Jan/Feb 2007

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<th>Y (mm)</th>
<th>Z (mm)</th>
<th>Conn</th>
<th>X (mm)</th>
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Discone Model

Steve Stearns, K6OIK, “All About the Discone Antenna,” QEX, Jan/Feb 2007
Discone SWR and Impedance Referenced to 75 Ω

1. Perform a frequency sweep from 100 MHz to 1 GHz
2. Write impedance data to MicroSmith .gam output file
3. Reformat the .gam file to Touchstone .s1p file format
4. Import file into Smith chart or circuit simulation program
5. Design matching network

UHF TV band 470 to 710 MHz
Blue highlight
Result After Matching

Steve Stearns, K6OIK, “All About the Discone Antenna,” QEX, Jan/Feb 2007
EZNEC Gain Patterns of Discone at 470 MHz

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<th>Parameter</th>
<th>Value</th>
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<td>Elevation Plot</td>
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<td>Outer Ring</td>
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<td>Slice Max Gain</td>
<td>3.49 dBi @ Elev Angle = 12.0 deg.</td>
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<td>Front/Back</td>
<td>0.75 dB</td>
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<td>Beamwidth</td>
<td>87.2 deg.; -3dB @ 325.1, 52.3 deg.</td>
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<td>Sidelobe Gain</td>
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<td>Front/Sidelobe</td>
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<td>Cursor Elev Gain</td>
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<td>3.49 dBi</td>
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<tr>
<td></td>
<td>0.0 dBmax</td>
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Tips for Getting Better Accuracy from NEC2

- **Segment length to wavelength rule**
  - Segment length < λ/20

- **Segment length to diameter rule**
  - Segment length > 2 × diameter is preferred
  - Segment length > 1.0 × diameter is required (no tuna cans or hockey pucks)

- **Equal segment length rule**
  - Segments that join should have approximately equal lengths
  - Never connect long segments to short segments

- **Acute angle junction rule**
  - Junction angles or segment lengths large enough that middle 1/3 of joined segments don’t interpenetrate

- **Segment alignment rule for parallel wires**
  - Closely spaced parallel wires should have their segments aligned (paired)

- **Wires near ground**
  - All wires should be least two diameters above ground
  - Wires cannot touch ground
Excitation Sources

- NEC2 and NEC4 provide 6 excitation source types: 3 for transmit and 3 for receive or scattering analysis
  - Multiple feedpoints are allowed and useful for phased arrays
  - Rules determining whether loads, network connections, and transmission lines are in series or parallel with source vary by source type

- Type 0 voltage source (applied field source)
  - Located mid segment; cannot be located in a NEC symmetry plane
  - Adjacent segments should have same length
  - A good general purpose source; not finicky

- Type 4 current source (magnetic frill)
  - Located mid segment; cannot be located in a NEC symmetry plane; should not be placed near ground or nearby metal
  - A good general purpose source; not finicky

- Type 5 voltage source (bicone source)
  - Is located at a segment end or at a junction between adjacent segments; can be located in a NEC symmetry plane
  - Junction must be of two segment that are parallel, equal lengths and radii; no 3-way junctions; no loads, network connections, or transmission lines
  - Two Type 5 sources can make a “split-feed” by putting two half-voltage sources on adjacent segment ends
Wire Loads

- Ideal, non-radiating point loads can be inserted in any segment
- If a segment contains both source and load, they are in series
- Loads are used to model coils, traps, wire conductivity and plastic insulation
- Load types available in NEC2 are series loads of the following types
  - Constant impedance $R + jX$
  - Series RLC network
  - Parallel RLC network
- Load types not native to NEC2
  - Loads in parallel, not series
  - Trap networks
  - Laplace impedances positive-real rational function up to 5th degree

\[
Z(f) = \frac{P(j\omega)}{Q(j\omega)} = \frac{a_5(j\omega)^5 + a_4(j\omega)^4 + a_3(j\omega)^3 + a_2(j\omega)^2 + a_1(j\omega) + a_0}{b_5(j\omega)^5 + b_4(j\omega)^4 + b_3(j\omega)^3 + b_2(j\omega)^2 + b_1(j\omega) + b_0}
\]
Dielectrics and Wire Insulation

- Dielectrics occur in antennas in bulk form or insulated wires, e.g. polyrod antennas, twin-lead folded dipoles, twin-lead J-poles, Butternut radials, buried radials
- NEC2 has no capability for dielectrics
- NEC3 and NEC4 handle dielectrics by accurate methods
  - NEC3 handles wires in semi-infinite dielectric media, e.g. buried radials
  - NEC4 handles insulated wires by accurate methods
  - Modern CEM codes such as FEKO, WiPL-D, and HOBBIES handle dielectrics accurately by surface or volume equivalence principles
- L.B. Cebik in Note 83 attempted to reverse engineer insulated wire corrections from NEC4 but did not discover the full answer
- EZNEC v.4 and up claim to do insulated wires but use NEC2, which has no capability to model dielectric coated wires
- EZNEC Pro/4 uses NEC4, which has accurate dielectric capability
**Insulated Wires Done Right!**

- **Rigorous theory**

- **Best approximation**
  - B.D. Popović and A. Nešić, “Generalisation of the Concept of Equivalent Radius of Thin Cylindrical Antennas,” *IEE Proc.*, June 1984
  - Replace each insulated wire with an uninsulated wire of larger diameter
  - Add distributed inductance to correct smaller inductance of larger wires

\[
a' = a \times \left( \frac{b}{a} \right)^{\left( \frac{\varepsilon_r - 1}{\varepsilon_r} \right)} \quad \text{and} \quad L = \frac{\mu_0}{2\pi} \ln \left( \frac{a'}{a} \right) = 2 \times 10^{-7} \left( \frac{\varepsilon_r - 1}{\varepsilon_r} \right) \ln \left( \frac{b}{a} \right)
\]

- Other methods
  - A. Yurkov RA9MB (similar method)
  - L.B. Cebik W4RLN (Note 83, less accurate)
  - D. Federov UA3AVR
Pop Quiz

**Question:**

- To model dielectric coated wire, the goal is to increase distributed capacitance $C$ while keeping distributed inductance $L$ constant. Sure, one can increase wire diameter to achieve desired $C$ and then add inductive loading to achieve desired $L$.

- But instead, why not keep the wire diameter constant to fix $L$ at its desired value and add capacitive loading to increase $C$ to achieve desired value?
Pop Quiz

- **Question:**
  - To model dielectric coated wire, the goal is to increase distributed capacitance $C$ while keeping distributed inductance $L$ constant. Sure, one can increase wire diameter to achieve desired $C$ and then add inductive loading to achieve desired $L$.
  - But instead, why not keep the wire diameter constant to fix $L$ at its desired value and add capacitive loading to increase $C$ to achieve desired value?

- **Answer:**
  - A wire’s distributed inductance $L$ is series inductance and distributed capacitance $C$ is shunt capacitance
  - Reactance loading is in series with the wire
  - Capacitive loading inserts series not shunt $C$. Hence the proposed approach does not work
## Insulated Wire Equivalents

\[ a' = a \times \left( \frac{b}{a} \right)^{\frac{\varepsilon_r - 1}{\varepsilon_r}} \quad \text{and} \quad L = \frac{\mu_0}{2\pi} \ln \left( \frac{a'}{a} \right) = 2 \times 10^{-7} \left( \frac{\varepsilon_r - 1}{\varepsilon_r} \right) \ln \left( \frac{b}{a} \right) \]

<table>
<thead>
<tr>
<th>AWG wire gauge</th>
<th>Wire diameter ( d = 2a ) (mm)</th>
<th>Insulation diameter ( D = 2b ) (mm)</th>
<th>Insulation material &amp; dielectric constant ( \varepsilon_r )</th>
<th>Equivalent diameter ( d' = 2a' ) (mm)</th>
<th>Loading inductance ( L ) (nH/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 stranded</td>
<td>2.9</td>
<td>3.4</td>
<td>2.1 (PTFE)</td>
<td>3.15</td>
<td>16.7</td>
</tr>
<tr>
<td>10 solid</td>
<td>2.6</td>
<td>4.5</td>
<td>3.6 (PVC)</td>
<td>3.86</td>
<td>79.2</td>
</tr>
<tr>
<td>12 stranded</td>
<td>2.4</td>
<td>2.9</td>
<td>2.1 (PTFE)</td>
<td>2.65</td>
<td>19.8</td>
</tr>
<tr>
<td>12 solid</td>
<td>2.1</td>
<td>3.9</td>
<td>3.6 (PVC)</td>
<td>3.28</td>
<td>89.4</td>
</tr>
<tr>
<td>14 stranded</td>
<td>1.9</td>
<td>2.4</td>
<td>2.1 (PTFE)</td>
<td>2.15</td>
<td>24.5</td>
</tr>
<tr>
<td>14 solid</td>
<td>1.6</td>
<td>3.4</td>
<td>3.6 (PVC)</td>
<td>2.76</td>
<td>108.9</td>
</tr>
</tbody>
</table>
Five Ground Types and Their Restrictions

- **Perfect PEC ground**
  - A lossless perfect electrically conducting (PEC) ground plane, i.e. a flat mirror
  - Wires may touch ground
  - Good for distinguishing ground loss from antenna ohmic loss

- **Real grounds**
  - High-accuracy ground (Sommerfeld-Norton)
    - Wires may not touch ground
    - Horizontal wires should be at least $\frac{\lambda}{200}$ above ground
  - Fast ground (Fresnel Reflection Coefficient Analysis (RCA))
    - Wires may not touch ground
    - Horizontal wires should be at least $\frac{\lambda}{10}$ above ground
  - MININEC ground
    - Uses PEC ground for calculating currents and impedance; uses Fresnel reflection coefficient for far-field pattern
    - Method of images used to calculate currents and impedance
    - Vertical and slanted wires may touch ground
    - But for accurate far field patterns, horizontal wires should be at least $\frac{\lambda}{10}$ above ground (same as for Fast ground)
### Ground Parameters (Typical)

<table>
<thead>
<tr>
<th>Ground Characteristics</th>
<th>$\sigma$</th>
<th>$\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely poor: cities, high buildings</td>
<td>0.001</td>
<td>3</td>
</tr>
<tr>
<td>Very poor: cities, industrial</td>
<td>0.001</td>
<td>4 – 5</td>
</tr>
<tr>
<td>Sandy, dry</td>
<td>0.002</td>
<td>10</td>
</tr>
<tr>
<td>Poor: rocky, mountainous</td>
<td>0.002</td>
<td>13</td>
</tr>
<tr>
<td>Average: pastoral, heavy clay</td>
<td>0.005</td>
<td>13</td>
</tr>
<tr>
<td>Pastoral: medium hills and forest</td>
<td>0.006</td>
<td>13</td>
</tr>
<tr>
<td>Flat, marshy, densely wooded</td>
<td>0.0075</td>
<td>12</td>
</tr>
<tr>
<td>Pastoral, rich soil, US midwest</td>
<td>0.010</td>
<td>14</td>
</tr>
<tr>
<td>Very good: pastoral, rich, central US</td>
<td>0.030</td>
<td>20</td>
</tr>
<tr>
<td>Fresh water</td>
<td>0.001 – 0.01</td>
<td>80 – 81</td>
</tr>
<tr>
<td>Salt water</td>
<td>3 – 5</td>
<td>80 – 81</td>
</tr>
<tr>
<td>Polar water</td>
<td>0.001</td>
<td>4</td>
</tr>
<tr>
<td>Polar ice</td>
<td>0.00025</td>
<td>3</td>
</tr>
<tr>
<td>Arctic land: frozen, permafrost</td>
<td>0.0005</td>
<td>3 – 5</td>
</tr>
</tbody>
</table>
Ground conductivity $\sigma$ and dielectric constant $\varepsilon_r$ vary with frequency and are not independent – Kramers-Kronig.
Ground conductivity $\sigma$ and dielectric constant $\varepsilon_r$ vary with frequency and are not independent – Kramers-Kronig.
4nec2
4nec2 http://www.qsl.net/4nec2

- A *free* full-featured Windows GUI for NEC2 and NEC4
- Written and supported by Arie Voors, Netherlands
- Developed in Visual Basic for Windows XP and C++
- Includes standard EZNEC models as .nec files
- Comes with NEC2 executables, and can use NEC4 executables
- Comes configured for 11,000 segments but can be increased by recompiling the NEC2 or NEC4 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 gives access to all NEC2 and NEC4 commands
4nec2 Wire-Grid Models of Boeing 747 and Automobile
4nec2 Screen Displays

Main screen

Geometry screen

Edit screen

Wire table
4nec2 3D Pattern of Antenna on 747 – Vert Pol
The Equal Area Rule for Wire Grid Models of Surfaces

- Grid spacing determines best diameter for wires
- Wire circumference should equal center-to-center grid spacing in the direction perpendicular to wires
Comments and Cautions on Antenna Modeling with NEC

- **NEC computes current on a wire**
  - Cannot resolve common and differential current modes
  - Cannot determine characteristic modes

- **When changing the design frequency of an antenna model, not all phenomena scale with frequency**
  - Ohmic loss increases with frequency due to skin effect
  - Insulation on wires affects common and differential current modes differently and can cause such modes to frequency scale differently

- **When modeling antennas made of insulated wire, use NEC4. With NEC2, use the method given here**
  - For circular wires with uniform circular insulation

- **Run the geometry check and average gain test to check that results (impedance, pattern, SWR) are insensitive to**
  - Small changes in source position or type
  - Small changes in segmentation density

- **Determine ground losses by comparing absolute average gain for Sommerfeld-Norton ground versus for PEC ground**

- **Always compare results against a different, independent method – measurements or a different computational technique**
Field Calculations for Bodies with Arbitrary Surface
FEKO [http://www.feko.info](http://www.feko.info)

- The most popular code in professional antenna engineering
- Developed by EM Software & Systems (EMSS), South Africa; acquired by Altair in 2014
- Has multiple “engines”
  - Main method is MoM/SIE, but has MoM/VIE, FEM, FMM, and several optics approximations
- Many features and capabilities
  - Lossy conductors; dielectric and magnetic materials; far field, near field, and scattering calculations; optimizers including genetic algorithm; Sommerfeld-Norton ground; characteristic mode analysis; …
- Curved surfaces are approximated by many flat triangles
  - Rao-Wilton-Glisson (RWG) basis functions
- “Student Edition” is of interest to Radio Amateurs
  - Part of HyperWorks 2017 Student Edition
Meshed Model of Global Hawk (RQ-4A)

FEKO Pattern of Horn Antenna in Wing Pod

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

WiPL-D

Wires, Plates, and Dielectrics
WiPL-D [http://www.wipl-d.com]

- Competes with FEKO in professional antenna engineering
- Originated at University of Belgrade, Serbia (former Yugoslavia)
- Now in version 14.0
- Handles 3D antennas and planar microwave circuits
- Main method is MoM/SIE, using surface equivalence principle; has fast multipole method (FMM)
- Capabilities include lossy conductors; dielectric and magnetic materials; far field, near field, and scattering calculations; optimization
- Polynomial basis functions
  - High accuracy with small computational burden
- Curved, bilinear quadrilateral surface meshing
  - Meshed surfaces appear faceted but are really bilinear curved surfaces
- Lacks Sommerfeld-Norton ground
- Versions of interest to Radio Amateurs
  - WiPL-D Pro – Free 30-day “Demo” trial includes training
  - WiPL-D Microwave Lite – Free 2006 version 6.0
WiPL-D Models of Single and 4x4 Array of Polyrods

Steve Stearns, K6OIK
ARRL Pacificon Antenna Seminar, San Ramon, CA
October 20-22, 2017
WiPL-D Model of Fighter Plane
HOBIES

Higher Order Basis Based Integral Equation Solver
HOBBIES

- Developed at Syracuse University funded by U.S. government
- Similar to WiPL-D – quadrilateral meshing, bilinear surface
- Current version Academic v10.5.1
  - Download [http://www.em-hobbies.com](http://www.em-hobbies.com); need registration key to run
  - Unknowns: 15,000
  - Nodes in mesh: 3,000
  - Sample points: 5,000 (number of points in post processing display)
- Online tutorial videos (9)
  - Dipole antenna
  - Linear phased array of dipoles
  - Square plate scatterer
  - Cube scatterer
  - Bowtie antenna
  - Inhomogeneous dielectric cube scatterer
  - Dielectric spherical radome
  - Optimizer demo: optimizing the forward gain of a horn antenna
  - Surface meshing
Meshed Car
Near Field Scattering of 1-meter PEC Cube at 100 MHz
A Comparison of Programs

Broadband Dipole Impedance
Comparison of Calculated Dipole Impedance

- **Antenna**
  - 1-meter dipole, diameter 20 mm, $L/d = 50$, segments = 51

- **Frequency range**
  - 1 MHz to 1,500 MHz

- **Methods compared**
  - Induced EMF Method (sine and cosine integrals)
  - NEC2
  - NEC4
  - FEKO
  - WiPL-D
  - HOBBIES

- **Excitation**
  - Delta-gap source
Resistance

Resistances computed by different programs do not agree.
Reactances computed by different programs do not agree.
Smith Chart – Yikes!

IEMF - black
NEC2 – red
NEC4 – blue
FEKO – pink
WiPL-D – Lt green
HOBBIES – thin black
Conductances computed by different programs agree.
Susceptance computed by different programs differ in linear tilt.
Explanation

- HOBBIES and WiPL-D curves are identical in resistance, reactance, conductance, and susceptance
- Conclude that HOBBIES and WiPL-D have identical thin-wire algorithms
- NEC2 and NEC4 curves are highly similar
- All methods except IEMF have near identical conductance curves
- Hence differences among methods can be attributed to shunt susceptance alone
- Susceptance curves are the same except for linear tilts
- Conclude that different susceptances are due to different shunt capacitances of the delta-gap source models
- FEKO’s delta-gap source has the smallest shunt capacitance
- HOBBIES and WiPL-D’s delta-gap sources have the most shunt capacitance
- NEC2 and NEC4’s delta-gap sources have intermediate shunt capacitance
Advanced Applications

Terrain Modeling
Monopole on a Cube Planet
Field Strength inside Car for 2-meter Mobileers
Baking a Potato
And more …
Terrain Modeling as Alternative to HFTA

Surface meshed terrain of Saratoga, CA
Color indicates computed earth currents
Zoom to see current direction arrows

Earth terrain looking down Saratoga-Sunnyvale Road
Ground Currents

Frequency = 7.15 MHz
Antenna type = 3 element Yagi
Antenna height = 164 ft. (50 m)
Antenna polarization = horizontal
**3D Antenna Pattern**

Frequency = 7.15 MHz
Antenna type = 3 element Yagi
Antenna height = 164 ft. (50 m)
Antenna polarization = horizontal
|E| field pattern shown

Courtesy of Keith Snyder, KI6BDR
Computation Statistics

<table>
<thead>
<tr>
<th>Computer</th>
<th>6 Xi NetRAIDer network servers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processors</td>
<td>12 AMD Opteron 64-bit</td>
</tr>
<tr>
<td>Memory</td>
<td>96 Gbytes</td>
</tr>
<tr>
<td>Disk storage</td>
<td>12 Tbytes</td>
</tr>
<tr>
<td>Compute speed</td>
<td>&gt; 53 GFLOPs/sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Triangles</th>
<th>Hours</th>
<th>Memory (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.900</td>
<td>3,928</td>
<td>0.125</td>
<td>0.53</td>
</tr>
<tr>
<td>3.750</td>
<td>12,834</td>
<td>1.54</td>
<td>5.48</td>
</tr>
<tr>
<td>7.150</td>
<td>38,717</td>
<td>52.1</td>
<td>9.38</td>
</tr>
</tbody>
</table>
The Next Step – Modeling the Landscape
Landscaping Details

Details of leaves and branches

Models of trees

Courtesy of WiPL-D
Monopole on Planet Cubo

HOBBIES
0.5-m Dipole Half in 0.6-m Dielectric Cube or 0.25-m Monopole Fed Against a 0.25-m Ground Rod

Ground rod driven to center of planet
Return Loss

-10 dB - S(1,1)
Antenna Pattern at 200 MHz
Antenna Pattern at 335 MHz
Impedance versus Frequency
## How to Extract Impedance Data from HOBBIES

**HOBBIES Postprocessor .ad1 File Format:** 9 data columns

| Frequency | G[mS]   | S[mS]   | R[ohms] | X[ohms] | |S₁₁| | ∠S₁₁ |
|-----------|---------|---------|---------|---------|-------|------|-------|
| > MHz     |         |         |         |         |       |      |       |
| 0.1000E+01 1  1 | 0.2452E-03 | 0.3621E+00 | 0.1870E+01 | -0.2762E+04 | 0.9993E+00 | -0.3620E-01 |
| 0.1050E+01 1  1 | 0.3008E-03 | 0.3816E+00 | 0.2066E+01 | -0.2621E+04 | 0.9992E+00 | -0.3815E-01 |
| 0.1100E+01 1  1 | 0.3659E-03 | 0.4013E+00 | 0.2272E+01 | -0.2492E+04 | 0.9992E+00 | -0.4012E-01 |

- Open .ad1 file in Microsoft Word
- Remove all extra spaces
- Convert text to table
- Delete unnecessary columns
- Copy/paste to Excel
- Change number format
- Copy/paste back to Word table
- Convert table to text
- Add comment and header lines
- Save as text file
- Change file extension to .s1p

### HP/EEsotf Touchstone® .s1p File Format

- Dipole computed 9/25/2016
- Len=98.357 ft., Dia=0.10717 in.

<table>
<thead>
<tr>
<th># MHz</th>
<th>Z</th>
<th>RI</th>
<th>R 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>1.8700195E+00</td>
<td>-2.7616719E+03</td>
<td></td>
</tr>
<tr>
<td>1.050</td>
<td>2.0657369E+00</td>
<td>-2.6205186E+03</td>
<td></td>
</tr>
<tr>
<td>1.100</td>
<td>2.2718233E+00</td>
<td>-2.4917314E+03</td>
<td></td>
</tr>
</tbody>
</table>

...
Field Strength Inside Car for 2-meters Mobileers

FEKO
Near Fields of a Mobile Mounted 2 Meter Antenna

The author uses FEKO, a patch-based computational software package, to reveal EM fields around a vehicle.

Keith Snyder, K6BDR

FEKO is a computational electromagnetic (CEM) tool that I used to calculate the antenna pattern of a 2 meter antenna located on the center of the roof of a sedan-type automobile. FEKO computer code can calculate the electromagnetic fields both inside and outside the vehicle. I show images of the near fields around the vehicle.

Many radio amateurs are familiar with modern NEC-based computer software like EZNESC and 4ne2 used to calculate the fields of wire antennas and wire structures in the presence of a ground.5,8 These computer software codes facilitate antenna analysis as a function of frequency, antenna height above ground, along with antenna patterns in presence of wire models of structures. The FEKO computer code is similar in that, like the NEC codes, it uses the method of moments (MOM) and the Sommerfeld ground capabilities.

FEKO Software

FEKO uses triangular patches in the models so that we can represent arbitrary shapes such as the metal skin of an automobile or aircraft. FEKO stands for “feldberechnung für körper mit beliebiger Oberfläche,” which translates from German to “field calculations for arbitrarily shaped structures.”6

I first encountered FEKO at the Applied Computational Electromagnetics Society meeting in Monterey, California in 2003. I met Dr. C. J. Reddy, who helped me model a rolled-edge discone antenna. Later, I met Dr. Ulrich Jakobs, who wrote the code as part of his research activities at the University of Stuttgart in 1991. Capabilities of FEKO software include the Finite Element Method (FEM), Method of Moments (MOM), Multi-Level Fast Multipole Method (MLFMM), Physical Optics/Geometrical Optics (PO/GO), and UTD (Uniform Theory of Diffraction).7

Steve Stearns, K6OIK, in a presentation to the Foothill Amateur Radio Society, has compared several CEM tools including a few of the NEC software packages, along with FEKO.8

The Vehicle Model

I found a generic car model on the FEKO software web page that is already meshed with simple triangular patches. I modeled a quarter-wave monopole antenna on the roof to see the near and far fields at 147 MHz. The 19-inch tall monopole is located near the center of the roof. Figure 1 shows the patch model of a car with the monopole on the roof.

The car model is composed of 21,600 triangles. There are also 31 wire segments used to model the 2 meter monopole and a short antenna on the back of the roof that is treated as a scatterer. The ground constants are a relative permittivity of 30, and conductivity of 0.005 S/m. The green plane under the car in Figure 1 indicates in FEKO that the Sommerfeld ground has been implemented.

The output of the computer code indicates that the antenna is near resonance with an
Car with 2-Meter Monopole on Roof

Courtesy of Keith Snyder, KI6BDR
Skin Currents

Courtesy of Keith Snyder, KI6BDR
Electric Field Strength in Longitudinal Plane

Transmit power 75 watts
Electric Field Strength in Transverse Plane

Transmit power 75 watts
Generic Car in HOBBIES

- Import .STL mesh file
- Convert .STL mesh to NURBS geometry
- Remesh using HOBBIES unstructured mesher
  - 2,903 nodes
- Add monopole in center of roof
  - Frequency 146 MHz
  - Length = 48.8 cm
  - Diameter = 4 mm
- Run HOBBIES
  - 5,664 unknowns
  - 92.3 seconds (pattern only)
  - 128.3 seconds (currents, pattern, near fields)
- Differences from FEKO model – minor stuff
  - Ground model turned off
  - Input power
  - Scaling of far field pattern shapes
  - Color sequence of pseudocolor scale
Quadrilateral Bilinear Surface Mesh

Ground model is off. Car is in free space.
Pattern – Max Gain 2.713 dBi
| E | Field in Central Plane (y = 0)

Source 1 V into 26.6 mS
Power is 2.6 mW
Field Strength is V/m

View PowerPoint in Slide Show mode (Shift F5) to see field animation.
Summary

- A car is not a Faraday cage
  - Many Amateurs use 2-meter HTs from inside their cars
- A car’s cabin is an irregularly shaped cavity resonator with apertures (windows)
- Windows couple exterior and interior fields at 2 meters
- Currents around apertures couple exterior and interior fields
- Electric and magnetic fields inside a car can be measured and computed by modern CEM software
- Measurement and computation have good agreement if
  - Measurements are made carefully
  - Computer model has good detail
- Modern CEM tools give radio amateurs new capabilities
  - Model surfaces more accurately than wire grid models
  - Include dielectric objects and surfaces in models
  - Compute fields in and around objects with high accuracy
Baking a Potato

MEFiSTo
Potato In Microwave Oven

Courtesy of Faustus Scientific Corporation
**Dimensions**

**Potato**
Uniform lossy sphere  
Diameter = 63 mm (2.5 in)  
Volume = 131 cm³  
(tennis ball size)  
\( \varepsilon_r = 65 - j \, 20 \)  
Density = 1 g/cm³  
Mass = 131 g (4.6 oz)

Turntable: dielectric  
\( \varepsilon_r = 2.55 - j \, 0 \)

Oven walls: PEC

Courtesy of Faustus Scientific Corporation
Electric Field $|E_z|$ inside Oven and Potato

Courtesy of Faustus Scientific Corporation
Magnitude of Electric Field | $E$ | inside Oven and Potato
Electric Field Strength in Potato

Courtesy of Faustus Scientific Corporation
Specific Absorption Rate (SAR) of Potato

Potato cooks unevenly
Bottom cooks faster than top
Center hot spot due to focusing
Return loss is properly a positive number.
Potato’s SAR

- RF parameters at 2.45 GHz (12.2 cm)
  - Return Loss = +4.83 dB
  - SWR = 3.69
  - $P_{\text{incident}} = 1000$ W
  - $P_{\text{reflected}} = 329$ W (32.9%)
  - $P_{\text{absorbed}} = 671$ W (67.1%)

- Specific Absorption Rate (SAR) of potato

  $$SAR_{avg} = \frac{P_{\text{absorbed}}}{V_{\text{potato}} \times \rho_{\text{potato}}} = \frac{671 \text{ W}}{0.131 \text{ kg}} = 5125 \text{ W/kg}$$

- Potato SAR is $3200 \times$ the uncontrolled MPE limit! (but only for 6-8 minutes)
  - FCC uncontrolled MPE limit is 1.6 W/kg
Questions for lawyers and philosophers: Is the RF exposure controlled or uncontrolled? Does it depend on whether the potato knows it is in the oven?

Courtesy of Hasbro
Fields in People

FEKO, WiPL-D and XFdtd
No – Fields *in* People! Not a Field of People
No – Fields in **People**!

Transmitter Inside a Cow
### People Can Be Simple

![Human anatomy diagram](image)

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ S/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>43</td>
<td>1.5</td>
</tr>
<tr>
<td>Skull</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td>Stuff</td>
<td>54</td>
<td>1.8</td>
</tr>
</tbody>
</table>
People Can Be Complex

- **Male body phantom**
  - 1 MHz to 20 GHz
  - Tetrahedral size 12.3 mm
  - 12 tissue types

- **Head phantom**
  - Tetrahedral size 8.3 mm
  - 8 tissue types

Courtesy of EMSS/Altair
People Can Be Very Complex

• **Male body phantom**
  • 1 MHz to 20 GHz
  • 4 million voxels
    (EM not biological)
  • 23 tissue types

• **Head phantom**
  • 8 million voxels
  • 17 tissue types

Courtesy of Remcom
## Tissue Parameters for Simple People

Frequency = 2,450 MHz

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ S/m</th>
<th>Density kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Brain</td>
<td>42.538925</td>
<td>1.511336</td>
<td>1030.0</td>
</tr>
<tr>
<td>Average Skull</td>
<td>14.965101</td>
<td>0.599694</td>
<td>1850.0</td>
</tr>
<tr>
<td>Average Muscle</td>
<td>53.573540</td>
<td>1.810395</td>
<td>1040.0</td>
</tr>
</tbody>
</table>

Source: FCC, Body Tissue Dielectric Parameters
[https://www.fcc.gov/general/body-tissue-dielectric-parameters](https://www.fcc.gov/general/body-tissue-dielectric-parameters)
## Tissue Parameters for Very Complex People

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladder</td>
<td>18.000759</td>
<td>0.685294</td>
</tr>
<tr>
<td>Blood</td>
<td>58.263756</td>
<td>2.544997</td>
</tr>
<tr>
<td>Bone Cancellous</td>
<td>18.548979</td>
<td>0.805112</td>
</tr>
<tr>
<td>Bone Cortical</td>
<td>11.381223</td>
<td>0.394277</td>
</tr>
<tr>
<td>Bone Marrow Infiltrated</td>
<td>10.308158</td>
<td>0.458822</td>
</tr>
<tr>
<td>Bone Marrow Not Infiltr</td>
<td>5.296872</td>
<td>0.095031</td>
</tr>
<tr>
<td>Breast Fat</td>
<td>5.146670</td>
<td>0.137039</td>
</tr>
<tr>
<td>Cartilage</td>
<td>38.771160</td>
<td>1.755682</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>44.803696</td>
<td>2.101270</td>
</tr>
<tr>
<td>Cerebro Spinal Fluid</td>
<td>66.243279</td>
<td>3.457850</td>
</tr>
<tr>
<td>Colon (Large Intestate)</td>
<td>53.878193</td>
<td>2.038204</td>
</tr>
<tr>
<td>Cornea</td>
<td>51.614494</td>
<td>2.295194</td>
</tr>
<tr>
<td>Dura</td>
<td>42.035004</td>
<td>1.668706</td>
</tr>
<tr>
<td>Eye Tissue (Sclera)</td>
<td>52.627628</td>
<td>2.033048</td>
</tr>
<tr>
<td>Fat</td>
<td>5.280096</td>
<td>0.104517</td>
</tr>
<tr>
<td>Fat (Mean)</td>
<td>10.820482</td>
<td>0.267954</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>57.633728</td>
<td>2.059032</td>
</tr>
<tr>
<td>Gall Blad Bile</td>
<td>68.360931</td>
<td>2.800733</td>
</tr>
<tr>
<td>Grey Matter</td>
<td>48.911255</td>
<td>1.807664</td>
</tr>
<tr>
<td>Heart</td>
<td>54.814018</td>
<td>2.256186</td>
</tr>
<tr>
<td>Kidney</td>
<td>52.742668</td>
<td>2.429709</td>
</tr>
<tr>
<td>Lens Cortex</td>
<td>44.625317</td>
<td>1.504036</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens Nucleus</td>
<td>33.973507</td>
<td>1.086901</td>
</tr>
<tr>
<td>Liver</td>
<td>43.034443</td>
<td>1.686411</td>
</tr>
<tr>
<td>Lung (Inflated)</td>
<td>20.476801</td>
<td>0.804128</td>
</tr>
<tr>
<td>Lung (Deflated)</td>
<td>48.380974</td>
<td>1.682395</td>
</tr>
<tr>
<td>Muscle (Parallel Fiber)</td>
<td>54.417614</td>
<td>1.882011</td>
</tr>
<tr>
<td>Muscle (Transverse Fiber)</td>
<td>52.729469</td>
<td>1.738781</td>
</tr>
<tr>
<td>Nerve (Spinal chord)</td>
<td>30.145145</td>
<td>1.088474</td>
</tr>
<tr>
<td>Ovary</td>
<td>44.699692</td>
<td>2.263874</td>
</tr>
<tr>
<td>Skin (Dry)</td>
<td>38.006660</td>
<td>1.464073</td>
</tr>
<tr>
<td>Skin (Wet)</td>
<td>42.852562</td>
<td>1.591928</td>
</tr>
<tr>
<td>Small Intestine</td>
<td>54.424351</td>
<td>3.172779</td>
</tr>
<tr>
<td>Spleen</td>
<td>52.449310</td>
<td>2.238070</td>
</tr>
<tr>
<td>Stomach Esop Duodenum</td>
<td>62.158325</td>
<td>2.210518</td>
</tr>
<tr>
<td>Tendon</td>
<td>43.121975</td>
<td>1.684531</td>
</tr>
<tr>
<td>Testis Prostate</td>
<td>57.550518</td>
<td>2.167421</td>
</tr>
<tr>
<td>Thyroid Thymus</td>
<td>57.200367</td>
<td>1.967798</td>
</tr>
<tr>
<td>Tongue</td>
<td>52.627628</td>
<td>1.802514</td>
</tr>
<tr>
<td>Trachea</td>
<td>39.732574</td>
<td>1.448737</td>
</tr>
<tr>
<td>Uterus</td>
<td>57.813835</td>
<td>2.246464</td>
</tr>
<tr>
<td>Vitreous Humour</td>
<td>68.208023</td>
<td>2.478094</td>
</tr>
<tr>
<td>White Matter</td>
<td>36.166599</td>
<td>1.215008</td>
</tr>
</tbody>
</table>

Frequency = 2,450 MHz  Source: FCC
### Free People!

**Download Free From [www.FEKO.info](http://www.FEKO.info)**

<table>
<thead>
<tr>
<th>Articulated (parametric) Human (SEP)</th>
<th>Standing Human (FEM)</th>
<th>Articulated Hand (SEP)</th>
<th>IEEE Head (SEP)</th>
<th>Visible Human Full Model (Inhomogeneous FEM)</th>
<th>Visible Human Head and Shoulders (Inhomogeneous FEM)</th>
<th>IEEE SAM (Homogeneous FEM)</th>
<th>Hugo (4 Organs FEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using geometry cards in EDITFEKO.</td>
<td>Model is based on</td>
<td>Using geometry cards in</td>
<td>This CADFEKO</td>
<td>The model contains 2.2 mil tetrahedrals</td>
<td>The model contains 900,000 tetrahedrals (4mm size)</td>
<td>The model contains 5mm tetrahedral mesh air box</td>
<td>The model has 5 different media: brain, lungs, eyes, muscle and an outer air shell. The model contains 749,507 tetrahedrals (8mm size) and can be used up to 1GHz. Requires more than 2 GByte of RAM.</td>
</tr>
<tr>
<td>Parametric i.e. change positions, sit, stand, raise arms, bend legs etc. The mesh size will change with frequency and has been tested up to 900 MHz.</td>
<td>the Articulated Human. The model consists of 334,733 tetrahedrals (8mm size) and can be used for runs up to 1GHz. Requires more than 2 GByte of RAM.</td>
<td>EDITFEKO. Change position of fingers, 16 degrees of freedom. (Tested up to 1800 MHz)</td>
<td>a triangle mesh of the inner layer of the IEEE SAM phantom. The minimum triangle length is 10mm. The model is set up for 1800 MHz. + 2 GByte of RAM required.</td>
<td>and is suitable up to 1GHz. Requires a 64bit machine and will use + 10 GByte of RAM.</td>
<td>and can be used up to 1GHz. Can be solved on a 32bit machine with 2 GByte of RAM.</td>
<td>mesh air box around the head. The model is set up for 1800 MHz. Requires 1.4 GByte of RAM (with hertzian dipole as antenna (MoM)).</td>
<td></td>
</tr>
</tbody>
</table>

![Images of human models](image)

Courtesy of Altair
Quadrilateral Surface Meshed Homogeneous Phantom

Courtesy of WiPL-D
Introducing SAM
Specific Anthropomorphic Mannequin
Field Strength and SAR in Phantom Head

- **Specific Absorption Rate (SAR)**
  - Units: watts/kilogram (W/kg)
- **Peak SAR (averaged over a gram) must not exceed**
  - Controlled exposure: 8.0 W/kg
  - Uncontrolled exposure: 1.6 W/kg
References and Resources
References

- **Current distribution on a wire**

- **Bubnov and Galerkin methods**

- **Method of Moments**
References

- **Antenna modeling theory – early years**
References

- **Wire grid models**

- **Rectangular patch models (flat)**

- **Triangular patch models**

- **Quadrilateral models (curved)**
References

- **NEC**
  - Official NEC license page [https://ipo.llnl.gov/technologies/nec](https://ipo.llnl.gov/technologies/nec)
  - Unofficial NEC Archives [http://nec-archives.pa3kj.com](http://nec-archives.pa3kj.com)
References

- **EZNEC** [http://www.eznec.com](http://www.eznec.com)

- **4nec2** [http://www.qsl.net/4nec2](http://www.qsl.net/4nec2)
References

- **MININEC**  [http://www.w8io.com/mininec.htm](http://www.w8io.com/mininec.htm)
  - R. Lewallen, W7EL, “MININEC: The Other Edge of The Sword,” QST, February 1991; correction May 1991

  - S. Nichols, G0KYA, *An Introduction to Antenna Modelling*, RSGB, 2014
References

- **MBC (Multiradius Bridge Current)**
References

- **FEKO** [https://www.feko.info](https://www.feko.info)
- **WiPL-D** [http://www.wipl-d.com](http://www.wipl-d.com)
- **HOBBIES** [http://em-hobbies.com](http://em-hobbies.com)
References

- **Finite Difference Time Domain Method**
  - Remcom XFdtd [http://www.remcom.com](http://www.remcom.com)
  - Faustus Scientific Corp MEFiSTo [http://www.faustcorp.com](http://www.faustcorp.com)
References

Phantoms and Dielectric Properties of Biological Tissues

- IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communication Devices: Measurement Techniques, IEEE Standard 1528-2013, June 14, 2013
Commercial CEM Software Industry

- **Recent consolidations**
  - **2008** ANSYS bought Ansoft for $832M (HFSS)
  - **2010** Mentor Graphics bought Zeland Software (IE3D and Fidelity)
  - **2011** National Instruments bought Applied Wave Research for $58M (Analyst, Axiem, EM Socket, Microwave Office)
  - **2014** Keysight spun off from Agilent (ADS, EMPro)
  - **2014** Altair bought EM Software and Systems (FEKO)
  - **2015** ANSYS bought Delcross Technologies (Savant)
  - **2016** Dassault Systèmes bought CST for €220M Euros (Studio Suite)

- **Others**
  - Cadence (Allegro Sigrity)
  - COMSOL (Multiphysics)
  - Faustus Scientific (MEFiSTo)
  - IMST (Empire XCcel 3D)
  - Mician (μWave Wizard)
  - MiG (WASP-NET)
  - Remcom (XFdtd)
  - Sonnet (Blink)
  - Tech-X (VSim, Vorpal)
  - WiPL-D

The CEM software business is evolving as fast as CEM software.
Antenna Modeling Programs for Radio Amateurs

- **EZNEC** [http://www.eznec.com](http://www.eznec.com)
  - EZNEC v.6 Demo program: Free (20 segments, also runs ARRL models)
  - EZNEC v.6: $100 (500 segments)
  - EZNEC+ v.6: $150 (2,000 segments)
  - EZNEC Pro/2 v.6: $525 (45,000 segments)
  - EZNEC Pro/4 v.6: $675 (sold only to NEC4 licensees)

- **4nec2** [http://www.qsl.net/4nec2](http://www.qsl.net/4nec2)
  - Free, 11,000 segments, two optimizers, all NEC commands supported

- **MININEC** [http://www.w8io.com/mininec.htm](http://www.w8io.com/mininec.htm) or [http://www.blackcatsystems.com/software](http://www.blackcatsystems.com/software)
  - Black Cat Systems offers MiniNEC Pro version 1.4.0, $29

  - Free Basic version 8,192 segments. Pro version 32,000 segments, $130

- **NEC4** [https://ipo.llnl.gov/technologies/nec](https://ipo.llnl.gov/technologies/nec)
  - Noncommercial user license $300

  - Free to students. Part of HyperWorks 2017 Student Edition

- **WiPL-D** [http://www.wipl-d.com](http://www.wipl-d.com)
  - Free “Microwave Lite” v6.0 (665 unknowns) and free 30-day trial of professional v13.0

- **HOBBIES** [http://em-hobbies.com](http://em-hobbies.com)
  - Book includes software registration code, online price varies from $125 to $231 MSRP

  - Free 3D basic version, 10,000 tet voxels, 9 example modeling files and tutorial videos

- **MEFiSTo** [http://www.faustcorp.com](http://www.faustcorp.com)
  - Free FDTD modeling code 2D basic version and free trial of 3D professional version

- **openEMS** [http://openems.de](http://openems.de)
  - Free open-source FDTD modeling code that uses Matlab or Octave
Accessory Software for EZNEC

- AutoEZ 2.0.18 by Dan Maguire, AC6LA, [http://www.ac6la.com](http://www.ac6la.com)
  - Excel/Visual Basic program
    - Demo version, free (30 segment limit)
    - Regular version, $79
  - Requires Excel and EZNEC installed on computer
  - Controls EZNEC to make multiple runs
    - It’s a GUI for a GUI for NEC
  - Has optimizer – Nelder-Mead algorithm
  - Reads NEC, AO, and MMANA-GAL files
  - Doesn’t work with EZNEC-ARRL or EZNEC Demo
  - Replaces MultiNEC, which is no longer available
  - Highly recommended for EZNEC users
HOBBIES

- [HOBBIES]

- [http://em-hobbies.com](http://em-hobbies.com)


- Make sure to buy a new copy with software license registration code intact and unused
Favorite Antenna Books

- **Books for antenna engineers and students**

- **Antenna research papers**
  - IEEE AP-S Digital Archive, 2001-2009 (1 DVD), JD0307
  - IEEE AP-S Digital Archive, 2001-2006 (1 DVD), JD0304
  - IEEE AP-S Digital Archive, 2001-2003 (1 DVD), JD0301
  - IEEE AP-S Digital Archive, 1952-2000 (2 DVDs), JD0351

- **ACES Journal Archives**
Free Downloadable Books

  - [http://www.ece.rutgers.edu/~orfanidi/ewa](http://www.ece.rutgers.edu/~orfanidi/ewa)
- C.A. Balanis, *Antenna Theory: Analysis and Design*, 3e, Wiley, 2005
  - [https://archive.org/details/antennatheorypr00sche](https://archive.org/details/antennatheorypr00sche)
  - [http://www.dtic.mil/docs/citations/AD0706545](http://www.dtic.mil/docs/citations/AD0706545)
  - [https://archive.org/details/antennastheorypr00sche](https://archive.org/details/antennastheorypr00sche)
  - [http://snulbug.mtview.ca.us/books/RadioAntennaEngineering](http://snulbug.mtview.ca.us/books/RadioAntennaEngineering)
  - [https://archive.org/details/radioengineering00henn](https://archive.org/details/radioengineering00henn)
  - [https://archive.org/details/radiotrondesigne00lang](https://archive.org/details/radiotrondesigne00lang)
  - [https://archive.org/details/principlesofradi00henn](https://archive.org/details/principlesofradi00henn)
Favorite Antenna Books continued

**Books for Radio Amateurs**

- A. Krischke, DJ0TR, ed., *Rothammel’s Antennenbuch*, 13e, DARC Verlag, 2013
- J. Devoldere, ON4UN, *ON4UN’s Low-Band Dxing*, 5e, American Radio Relay League, 2011
- L. Moxon, G6XN, *HF Antennas for All Locations*, 2e, RSGB, 1983

**ARRL Antenna Compendium series – eight volumes**

**ARRL Antenna Classics series – eight titles**
Recent Antenna Books of Interest


Y. Zhang et al., *Higher Order Basis Based Integral Equation Solver (HOBBIES)*, Wiley, 2012


S. Nichols G0KYA, *An Introduction to Antenna Modelling*, RSGB, 2014

Four Good History Reads


The End

This presentation will be archived at
http://www.fars.k6ya.org/others