Grow an Antenna …
from Seeds

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Abstract

Amateur antennas are universally made of metal conductors, often made by "bending metal." Trees, shrubs, buildings and other objects near an antenna, are regarded as nuisances that reduce an antenna's performance by distorting its pattern or adding unknown losses. Antenna modeling software is commonly thought to be incapable of modeling such effects. In this presentation K6OIK will reveal how popular antenna modeling programs EZNEC, 4nec2, and MMANA-GAL, which use thin-wire engines like NEC or MiniNEC, can be used to model dielectric objects. He first shows three different methods to model insulated wires. He then shows how general dielectric objects may be modeled with thin-wire codes. Finally he shows that trees can do more than just support an antenna. They can be an effective part of an antenna. In fact, metal is unnecessary. Antennas can be organic and renewable. K6OIK shows how to landscape an antenna farm for improved performance – what seeds to plant and where to plant them!

Speaker's Biography

- **Stephen D. Stearns**
- **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 for radiating OAM Bessel-Vortex beams; reflectionless filters
- **FCC licenses**
  - Amateur Radio Extra Class
  - 1^{st}-Class Radiotelephone
  - General Radio Operator License (GROL)
  - Ship Radar Endorsement
- **Education**
  - PhD Stanford – under Prof. T.M. Cover
  - MSEE USC – under Profs. H.H. Kuehl and C.L. Weber
  - BSEE CSUF – under Profs. J.E. Kemmerly and G.I. Cohn
- **10 patents**
- **More than 100 publications and presentations, both professional (IEEE) and hobbyist (Amateur Radio)**

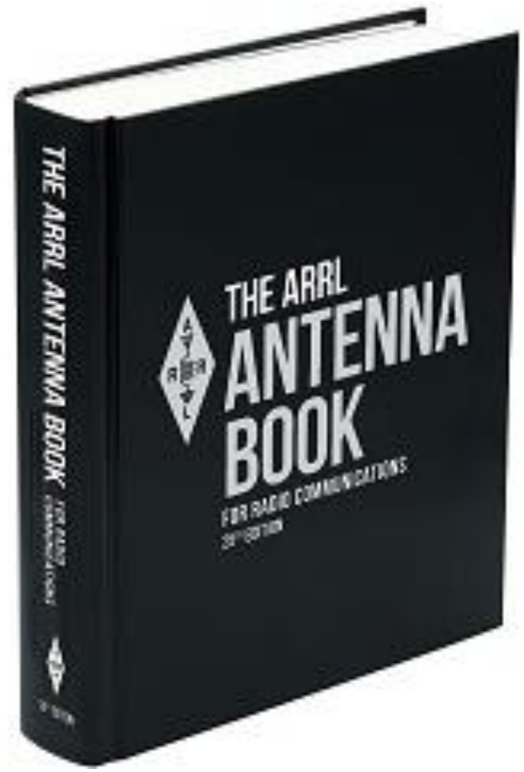
ARRL Pacificon Presentations by K6OIK

Year	Title	Archived at http://www.fars.k6ya.org
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	✓
2018	Antennas: The Story from Physics to Computational Electromagnetics	✓
2018	Novel Antennas, The Mysterious Factor *K*, Impromptu Antenna Modeling	
2019	Dipole Basics	✓
2019	Antenna Modeling Half-day Seminar	
2021	Universal Equivalent Circuits for All Antennas	✓

“Universal Equivalent Circuits for All Antennas”

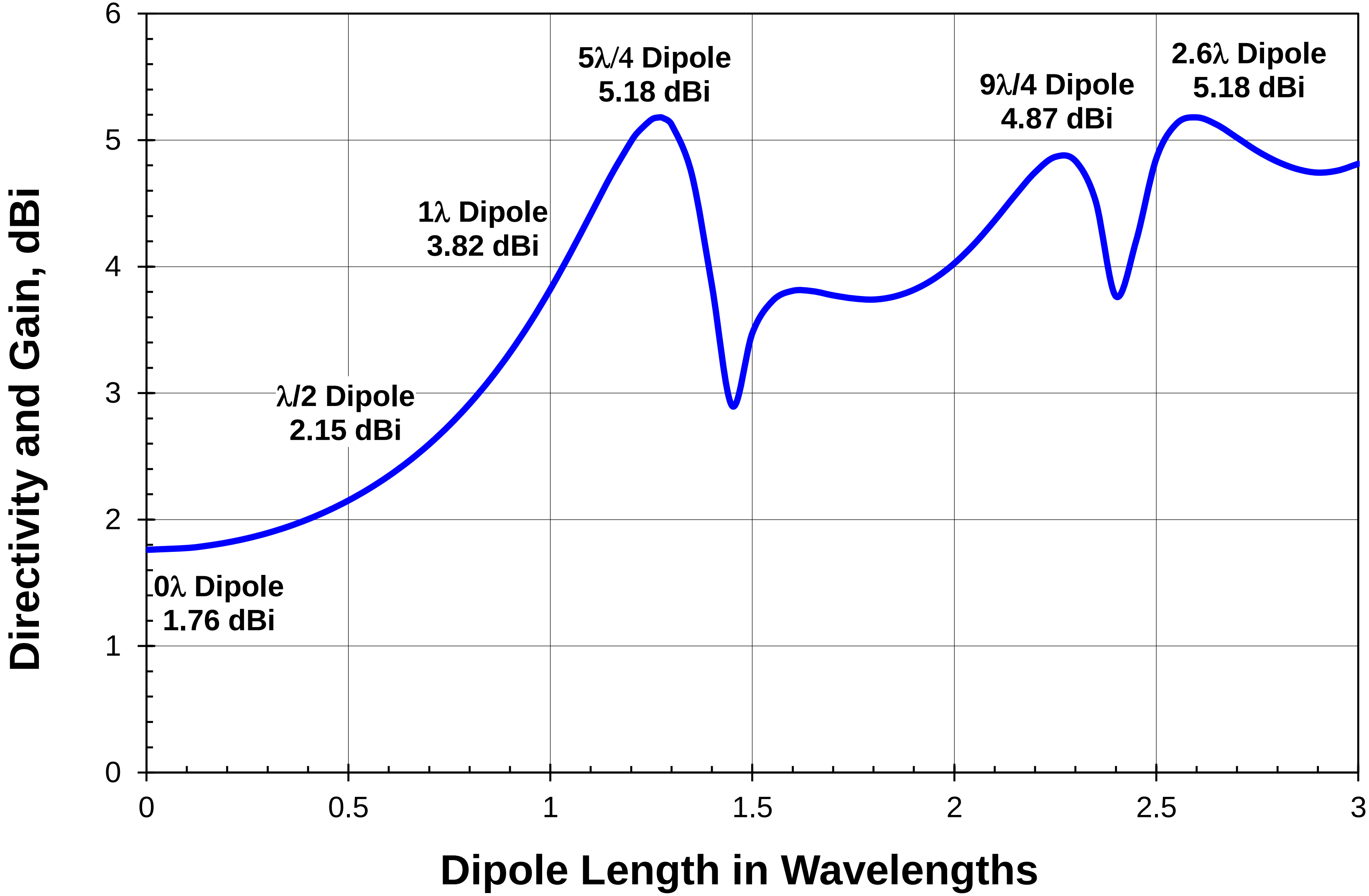
- **Presented at Pacificon Antenna Seminar 2021**
- **Invited talk at joint meeting IEEE Antennas and Propagation and Microwave Theory and Techniques Societies**
- **IEEE recorded lecture**
  - https://www.youtube.com/watch?v=vQ9BFdmFHCM
- **Slides**
  - https://www.fars.k6ya.org/docs/k6oik

Hot Off the Press!



H. Ward Silver, N0AX, ed.
***ARRL Antenna Book*, 25th Edition**
ARRL, 2023

Antenna Trivia for 2023 – Dipole Gain



Topics

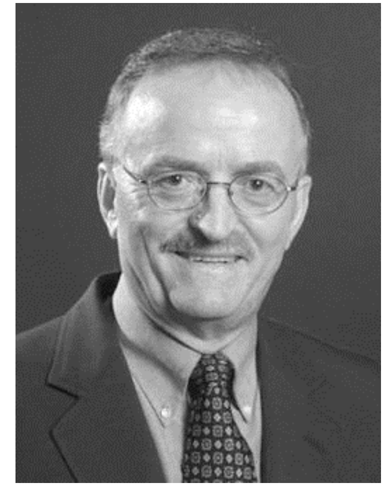
- **A bit of history – pioneers of antenna theory**
- **Antenna modeling software – thin-wire and surface codes**
  - Capabilities, accuracy, and limitations
- **Surface impedance**
  - Wideband equivalent circuits for surface impedance
- **Dielectric objects**
  - How to model insulated wire
  - How to model ground
  - How to model general dielectric objects
- **Antenna analysis**
  - How to model trees and shrubs accurately
- **Antenna design**
  - Antennas that have some dielectric parts
  - Antennas that have only dielectric parts
- **Summary and conclusions**
- **Resources**
  - References
  - Software
  - Books

Notable Men of Antennas

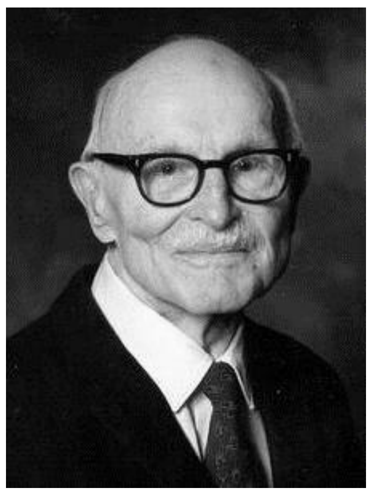

Shintaro Uda
1896-1976


John Daniel Kraus
1910-2004


Robert Clinton Hansen
1926-2018


Constantine Apostle Balanis
1938-

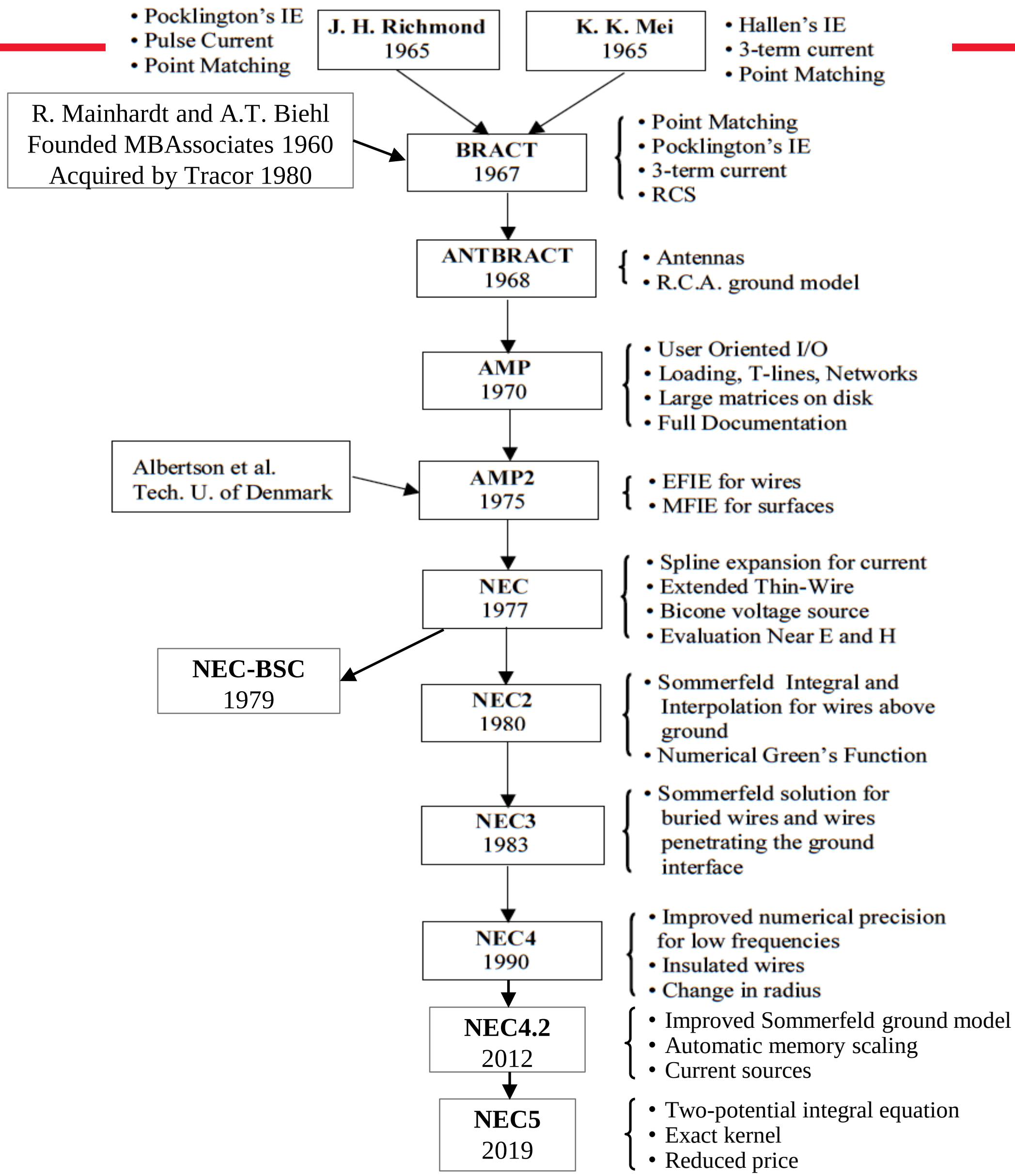

Sergei Alexander Schelkunoff
1897-1992

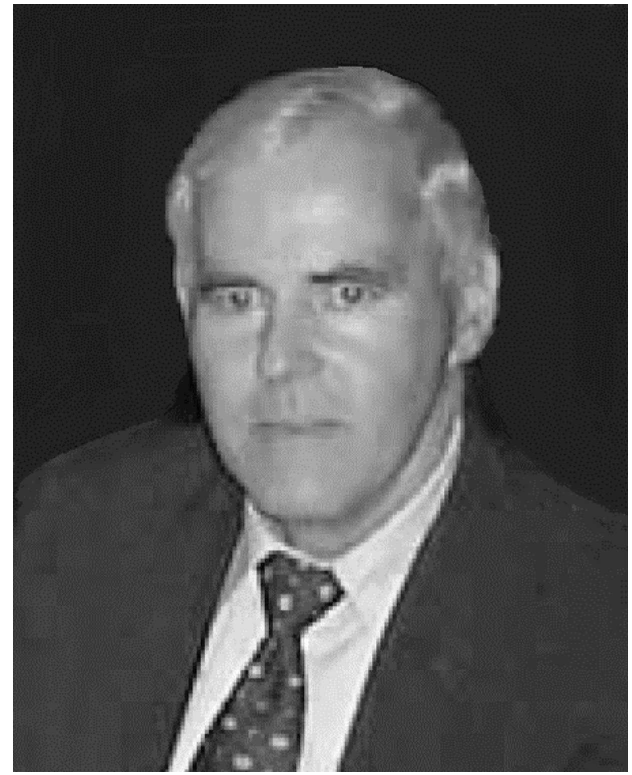

Ronold W. P. King
1905-2006


Chen-To Tai
1915-2004


Roger Fuller Harrington
1925-

The History of NEC





Gerald James Burke, 1943-2021

Courtesy of Applied Computational Electromagnetics Society

The History of HOBBIES

B.D. Popović
Univ. Belgrade

M.B. Dragović
Univ. Belgrade

A.R. Djordjević
Univ. Belgrade

B.M. Kolundžija
Univ. Belgrade

J.S. Ognjanović
Univ. Belgrade

T.K. Sarkar
Syracuse Univ.

Y. Zhang
Xidian Univ.

D. García Doñoro
U. Carlos III Madrid

S.W. Ting
Univ. Macau

WireZeus
1986

- Entire domain and subdomain basis functions using high-order polynomials
- Tapered wires as conical frustums
- Wires can be arbitrarily close

AWAS
1990, 2002

- Adaptive segmentation
- Scattering calculations
- High-accuracy Sommerfeld ground

WIPL
1995

- Wires and surfaces
- Bilinear quadrilateral patches
- 2D polynomial subdomain basis functions
- Junctions satisfy Kirchhoff law

WIPL-D
2000, 2005

- Metals, dielectrics, magnetic, and composite materials
- Microwave circuits and antennas

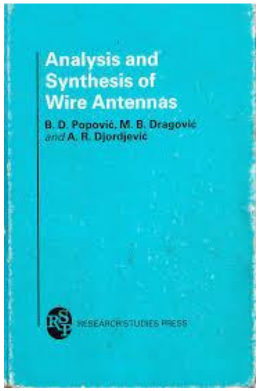
HOBBIES
2010

- Fast multi-core computing
- GiD geometry editor
- Low cost

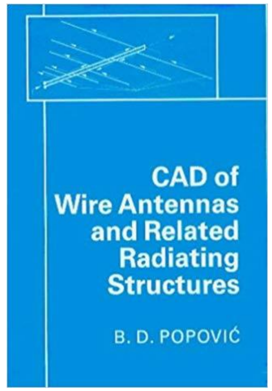
Branko D. Popović
1934-2002

The University of Belgrade "Popović" Lineage

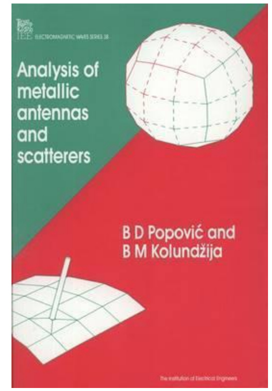
- **Theory**



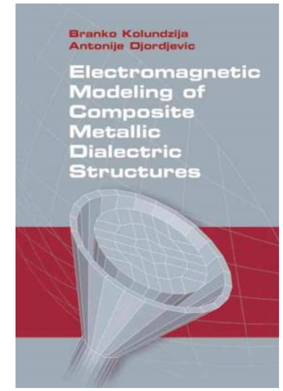
Popović et al.,1986



Popović,1991



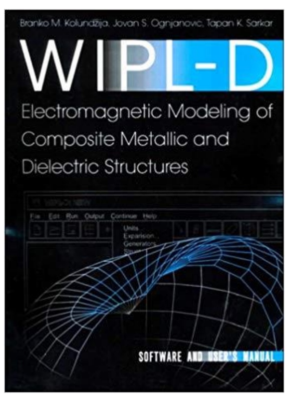
Popović et al.,1994



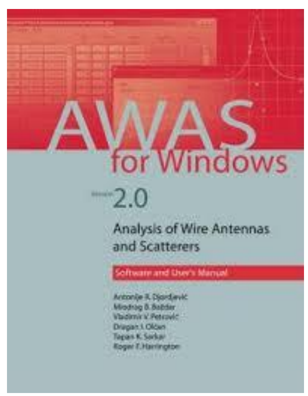
Kolundžija et al., 2002

- **Software**

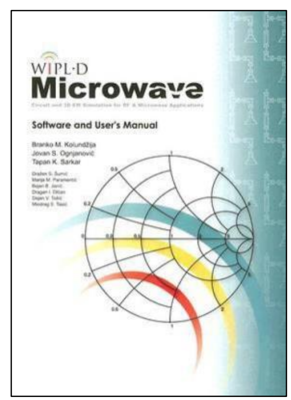
Djordjević et al.,1995



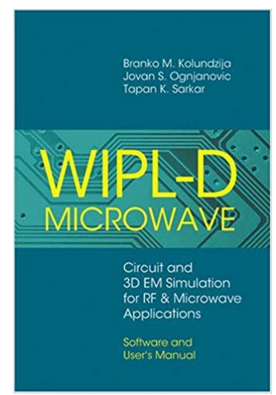
Kolundžija et al., 2000



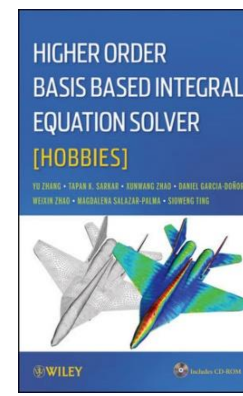
Djordjević et al., 2002



Kolundžija et al., 2005



Kolundžija et al., 2006



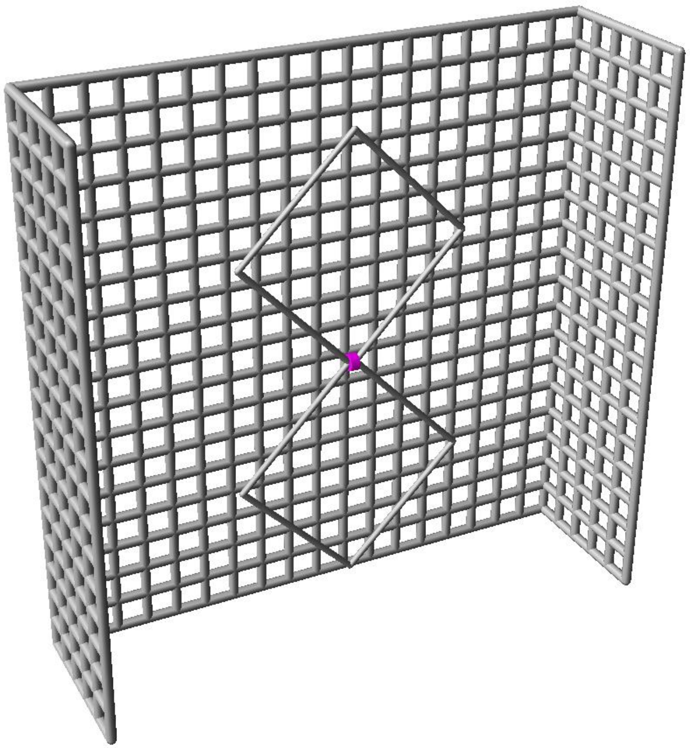
Zhang et al., 2012

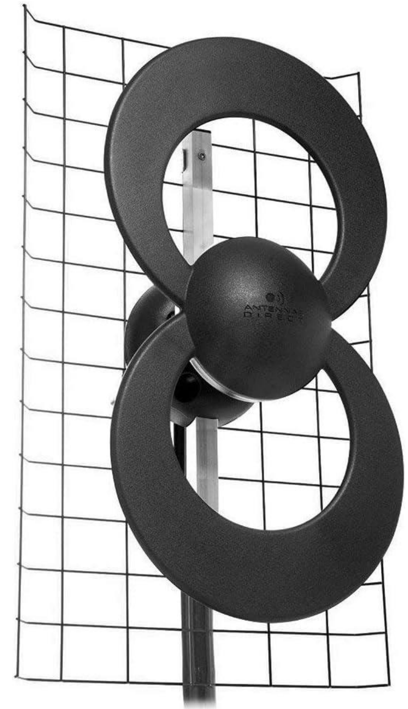
Modeling Surfaces

Wire Grids

Surface Patches

Wire Grid Models of Reflector Antennas

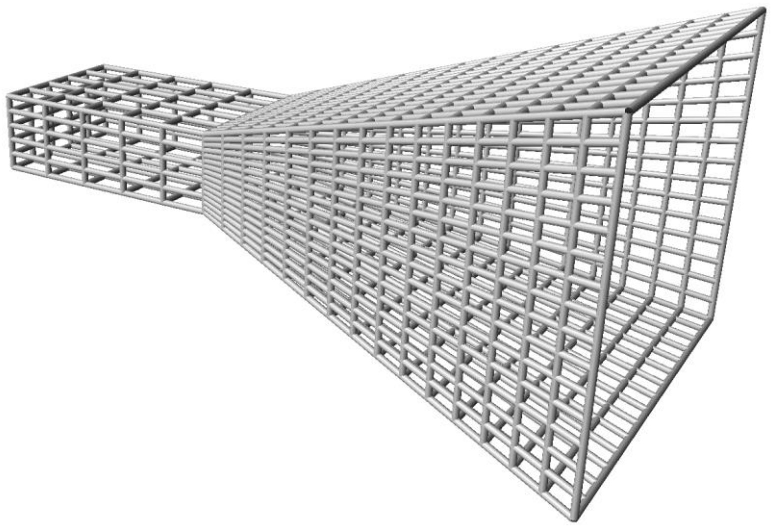


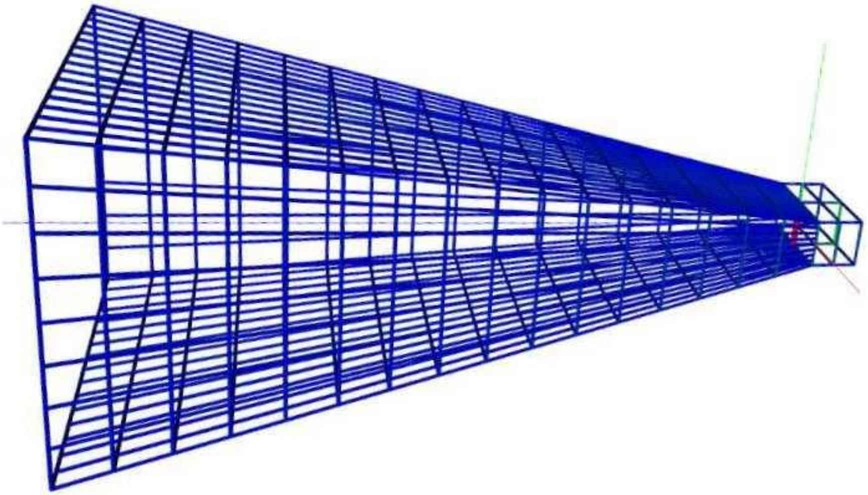


- Biquad with wire-grid reflector
- Two quad loops driven in parallel
- Popular DTV and Wi-Fi antenna
- 1,143 wire segments

- ClearStream DTV antennas use circular loops

Wire Grid Models of Horn Antennas

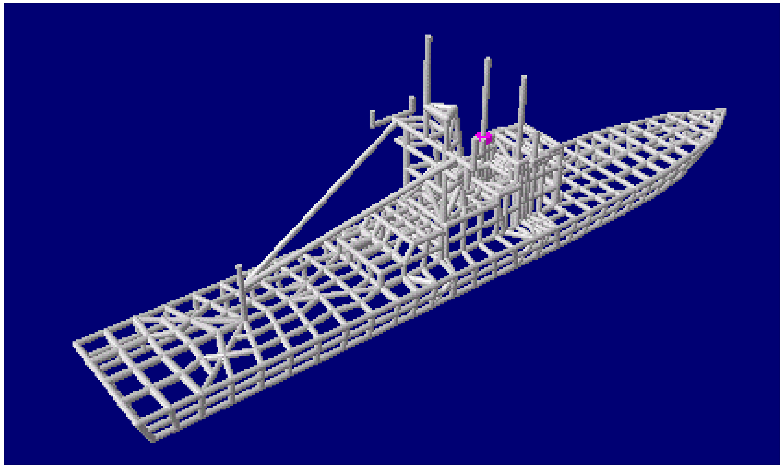


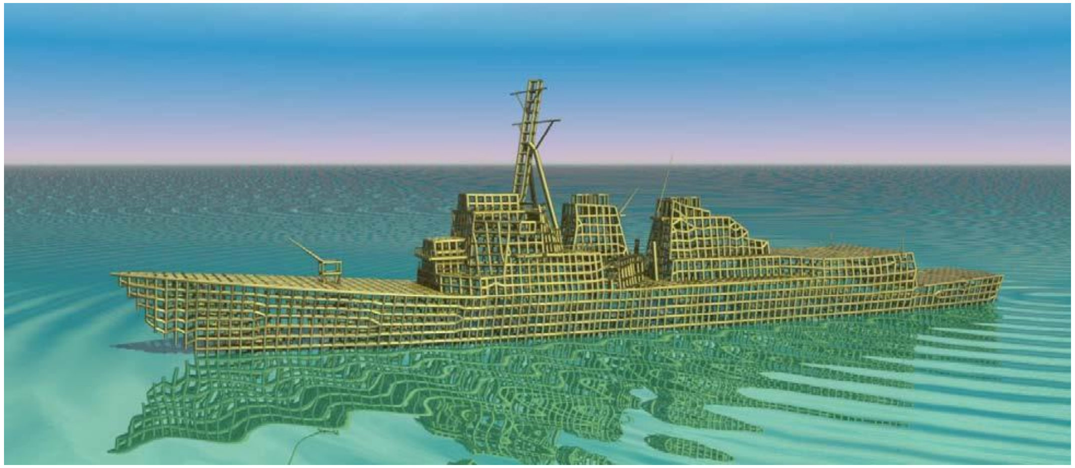


- Square horn antenna
- 4nec2
- UHF and microwave antenna
- 300 MHz
- 2,100 wire segments

- Rectangular horn antenna

Wire Grid Models of Ships

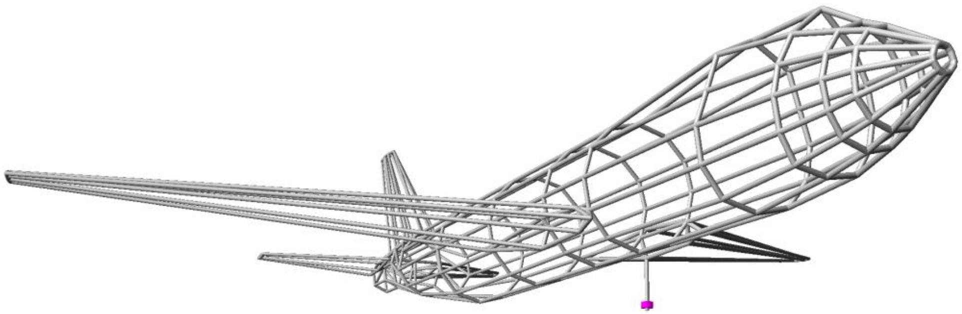




- Generic ship
- 4nec2
- 1,205 wire segments
- PEC ground plane
- 12.5 MHz

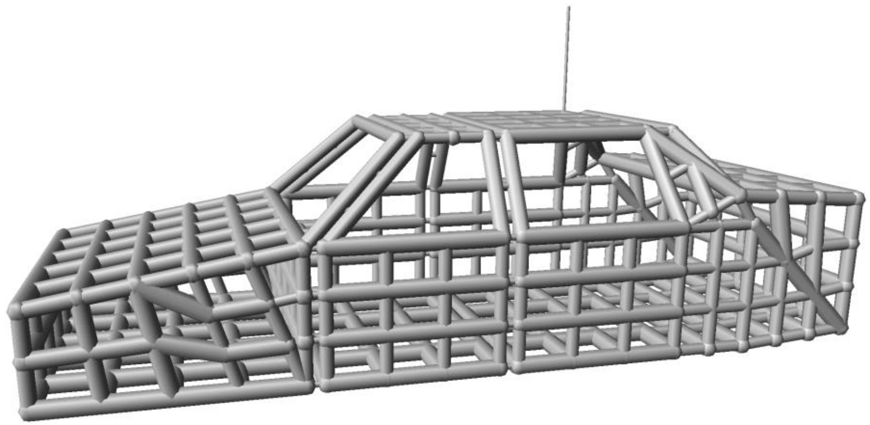
- USS Mitscher DDG-57 Destroyer
- NEC-4
- 8,031 wire segments
- 16 antennas
- PEC ground plane
- 20 MHz

Wire Grid Models of Airplane and Automobile

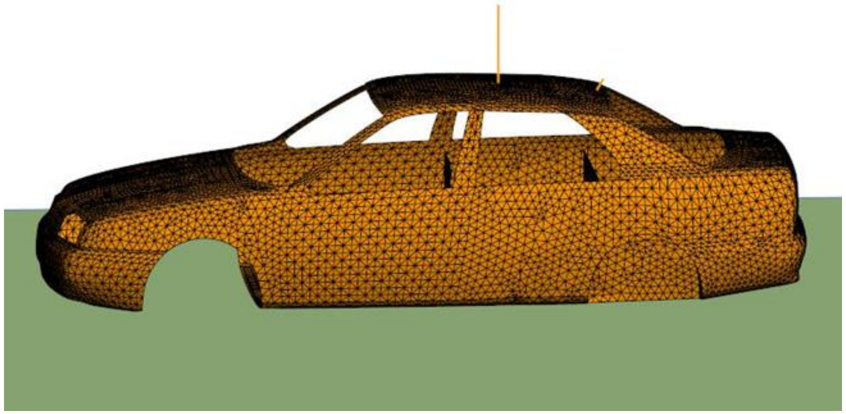


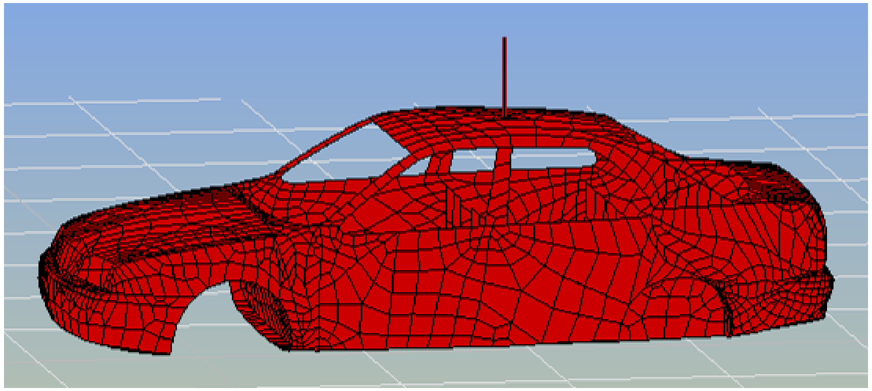
- Boeing 747
- 4nec2
- 2 MHz
- 1,603 wire segments

- Generic car
- 4nec2
- 300 MHz
- 694 wire segments



Surface Models of an Automobile

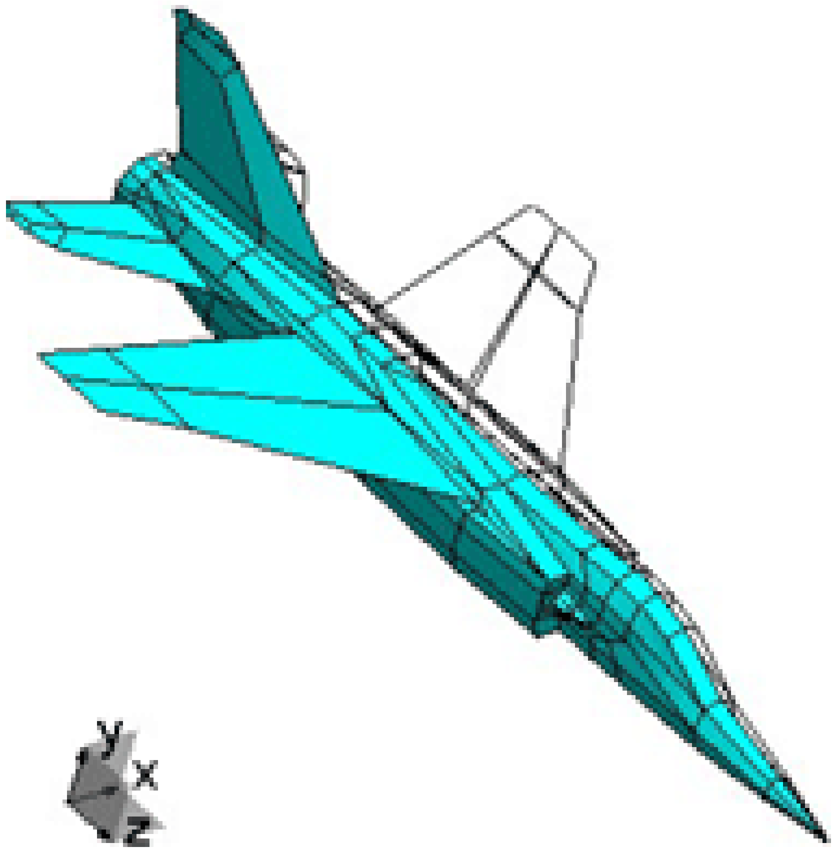


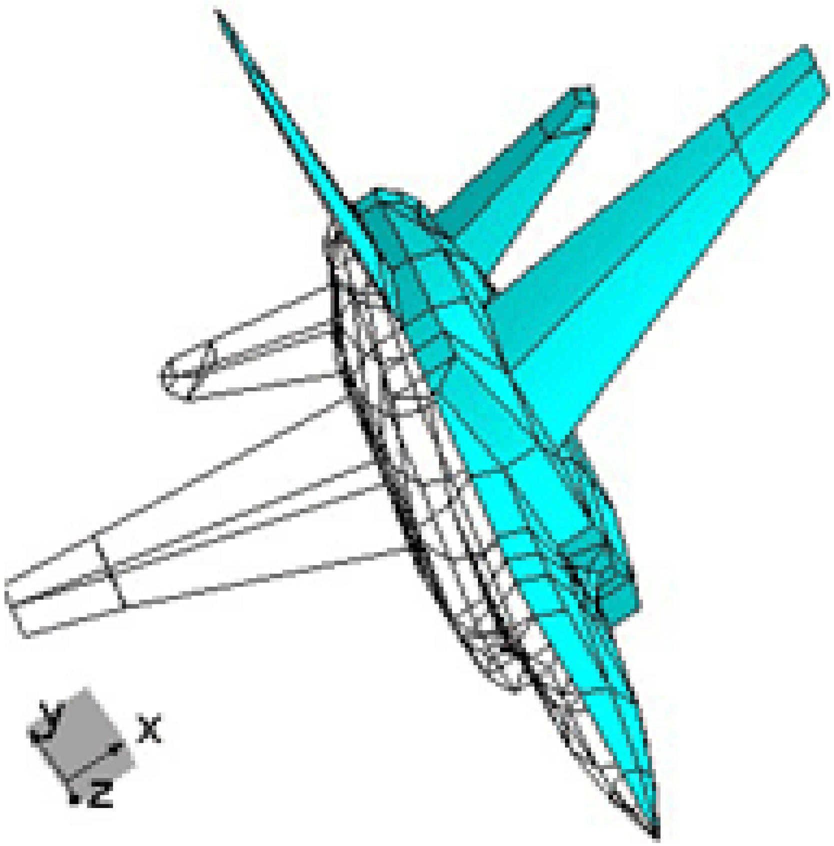


- **FEKO**
- **KI6BDR, *QST*, October 2016**
- **Triangle mesh**
- **RWG basis functions**
- **Sommerfeld ground**
- **21,602 triangles**
- **147 MHz**

- **HOBBIES**
- **K6OIK at Pacificon 2017**
- **Quadrilateral mesh**
- **Higher order basis functions**
- **Dielectric surface ground plane**
- **147 MHz**

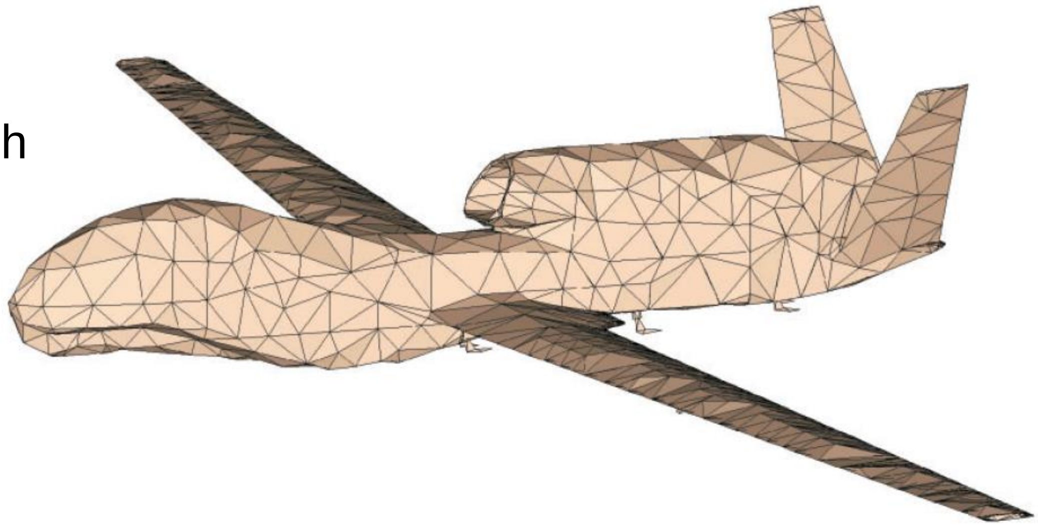
Fighter Plane Meshed in WIPL-D



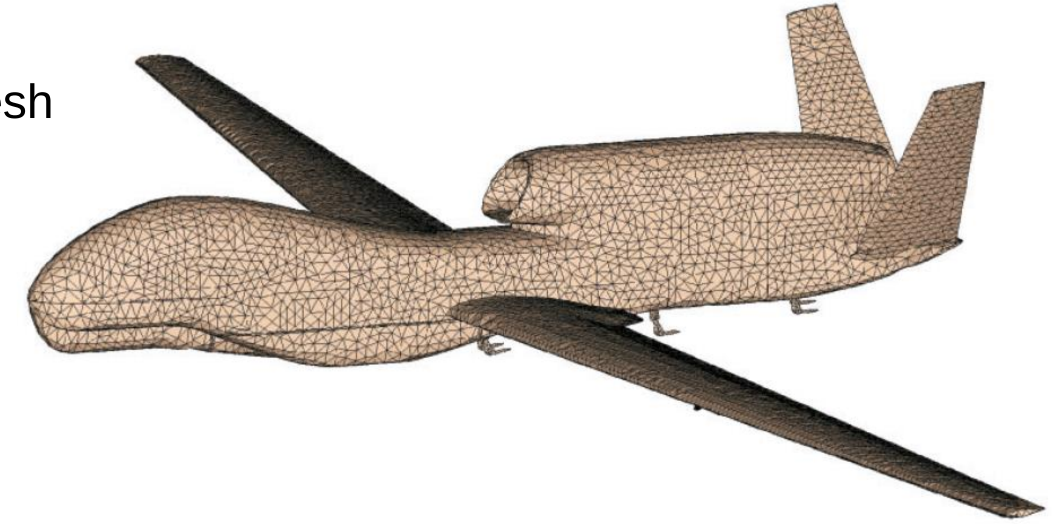


Global Hawk (RQ-4A) Meshed in FEKO

Coarse mesh



Refined mesh



Wire Grids and Meshes

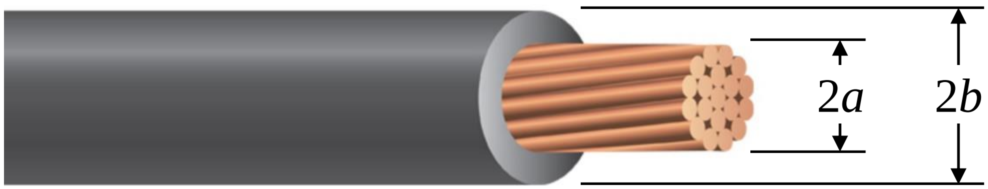
- **Wire grid rules**
  - Grid spacing and wire diameter are important
  - Equal Area Rule: Wire circumference should equal center-to-center grid spacing in the direction perpendicular to wires
- **A mesh is a database of vertices, edges, and faces**
  - Surface programs use the faces of a mesh
    - FEKO, HOBBIES, WIPL-D
- **A wire grid can be made from a mesh**
  - The vertices and edges of a mesh can be used to make a wire table for a wire grid
  - The wire grid can then be used by any thin-wire program
    - ANSim, AN-SOF, AWAS, MiniNEC, NEC

Modeling Non-Metallic Materials

Modeling Dielectric Objects

- **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**
- **NEC-2 has no native capability for dielectrics**
- **NEC-3, NEC-4, and NEC-5 handle dielectrics by accurate methods**
  - Insulated wires
  - Wires in dielectric ground, e.g. buried radials
- **Modern CEM codes (FEKO, WIPL-D, HOBBIES, HFSS) model dielectrics accurately by surface or volume equivalence principles**

Modeling Insulated Wires



- **NEC-2 and MiniNEC have no native ability to model insulated wires**
- **So how can EZNEC and 4nec2 using NEC-2, and MMANA-GAL using MiniNEC handle insulated wires??**
- **L.B. Cebik, W4RNL, (Note 83) gave formulas to model insulated wire, but the formulas are not rigorous; wire loading is *ad hoc***
  - Used in 4nec2
- **Alexander Yurkov, RA9MB, gave better formulas based partly on EM theory**
  - Used in MMANA-GAL
- **The author, K6OIK, gave still better, rigorous formulas based on EM theory**
  - Presented at Pacificon 2008; to appear in *ARRL Antenna Book* 25
- **NEC-3, NEC-4, and NEC-5 handle insulated wire by accurate methods**

Methods to Define Wires Equivalent to Insulated Ones

Method	W4RNL	RA9MB	K6OIK
Length	No change	No change	No change
Radius	a	b	$a\left(\frac{b}{a}\right)^{\left(1-\frac{1}{\varepsilon_r}\right)}$
Distributed inductance load	$\frac{\mu_0}{2\pi}\left(\frac{b}{a}\varepsilon_r\right)^{\frac{1}{12}}\left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right)$	$\frac{\mu_0}{2\pi}\left(1-\frac{1}{\varepsilon_r k_{abs}^2}\right)\ln\left(\frac{b}{a}\right)$	$\frac{\mu_0}{2\pi}\left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right)$
Conductivity load	σ	σ	$\sigma\left(\frac{a}{b}\right)^{2\left(1-\frac{1}{\varepsilon_r}\right)}$
Accuracy	Good	Better	Best
Insulation	Dielectric	Dielectric	Can be generalized to magneto-dielectrics
Found in	4nec2	MMANA-GAL	*ARRL Antenna Book* 25

Examples of Insulated Wire Equivalents, K6OIK Method

AWG gauge and Insulation	Wire diameter (mm)	Insulation diameter (mm)	Insulation dielectric constant ε_r	Equivalent diameter (mm)	Distributed inductance *L* (nH/m)	Equivalent conductivity (MS/m)
10 stranded PTFE	2.9	3.4	2.1	3.15	16.7	49.1
10 solid PVC	2.6	4.5	3.6	3.86	79.2	26.3
12 stranded PTFE	2.4	2.9	2.1	2.65	19.8	47.6
12 solid PVC	2.1	3.9	3.6	3.28	89.4	23.7
14 stranded PTFE	1.9	2.4	2.1	2.15	24.5	45.4
14 solid PVC	1.6	3.4	3.6	2.76	109	19.5

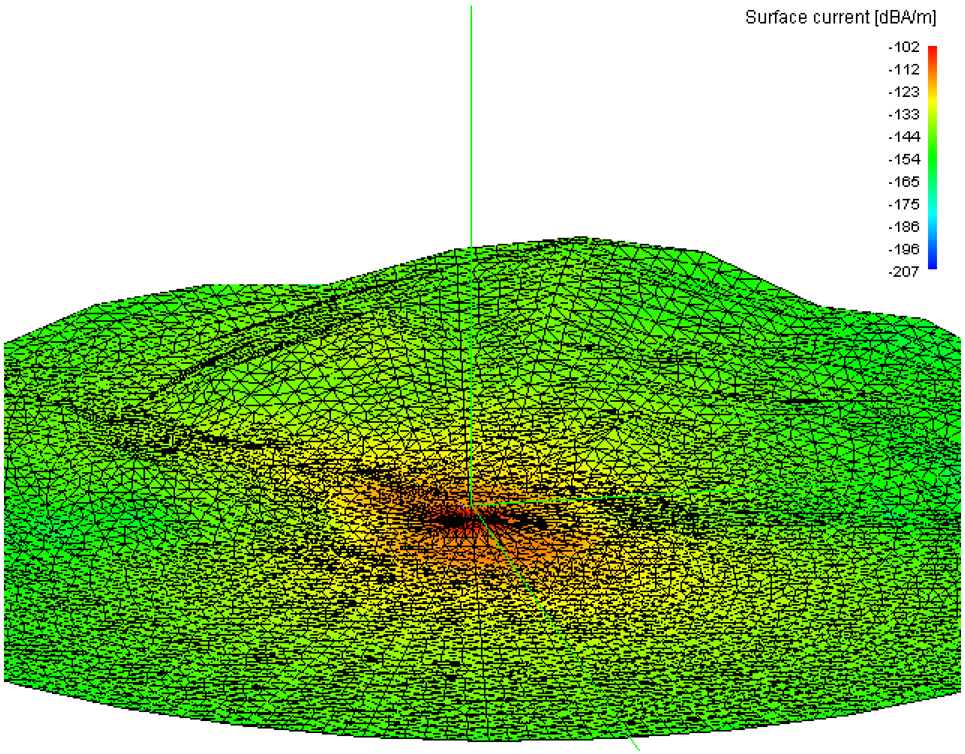
Assuming copper, conductivity 58 MS/m

Modeling Ground

- **Flat mirror models**
  - For ideal PEC or PMC ground, the ground acts like a perfect mirror
  - The method of images allows ground to be replaced by an image antenna in the lower half space
  - For general dielectric ground, there is not one but an infinite series of images – J.E. Wait
  - The flat "mirror" and surface impedance leads to V and H Fresnel complex reflection coefficients
- **Surface models**
  - An approach opposite to that of the method of images is taken by
    - Surface impedance models
    - Surface Equivalence Principle models
  - Sources (and images of sources) in the lower half space are replaced by surface currents
  - Irregular terrain is modeled by meshing the terrain's geometry

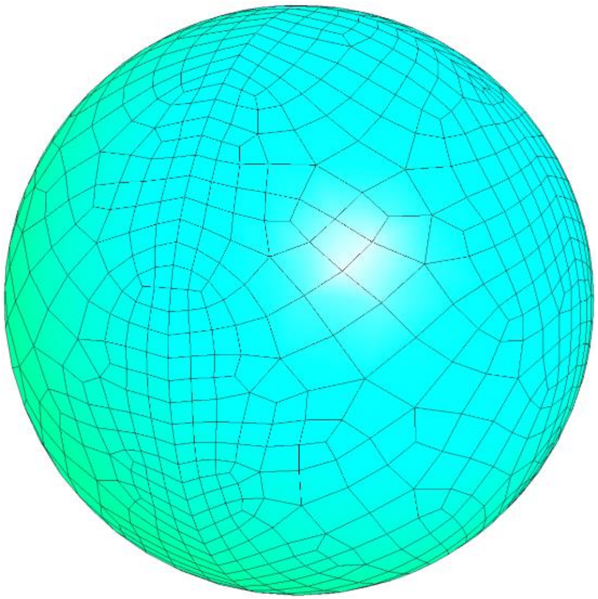
**Mirror models only work for flat ground.
Surface models aren't so restricted.**

Ground That is Not Flat – Irregular Terrain



Real ground is not flat!

Ground That is Not Infinite – A Planet



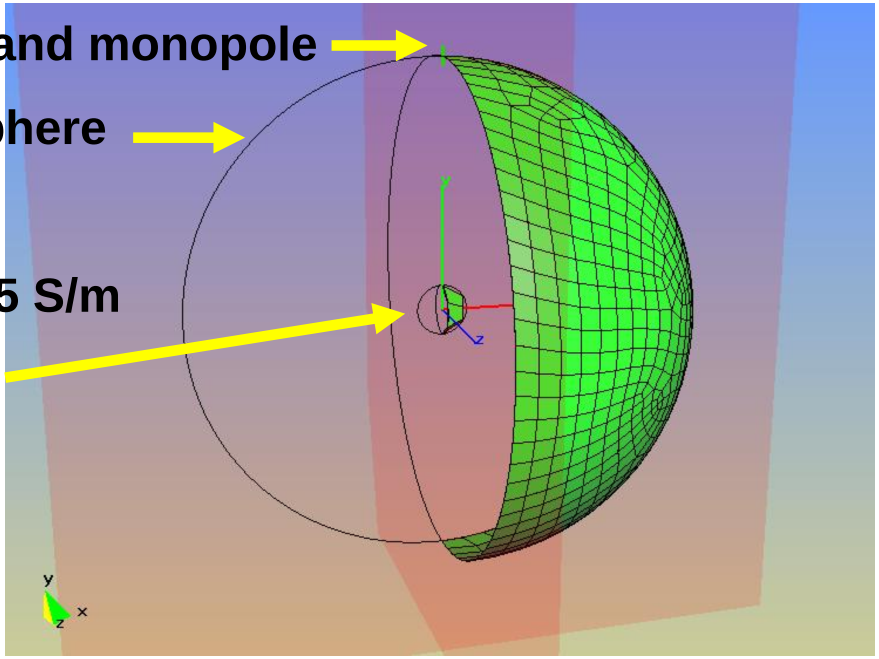
160-meter band monopole

Dielectric sphere

ε_r = 15

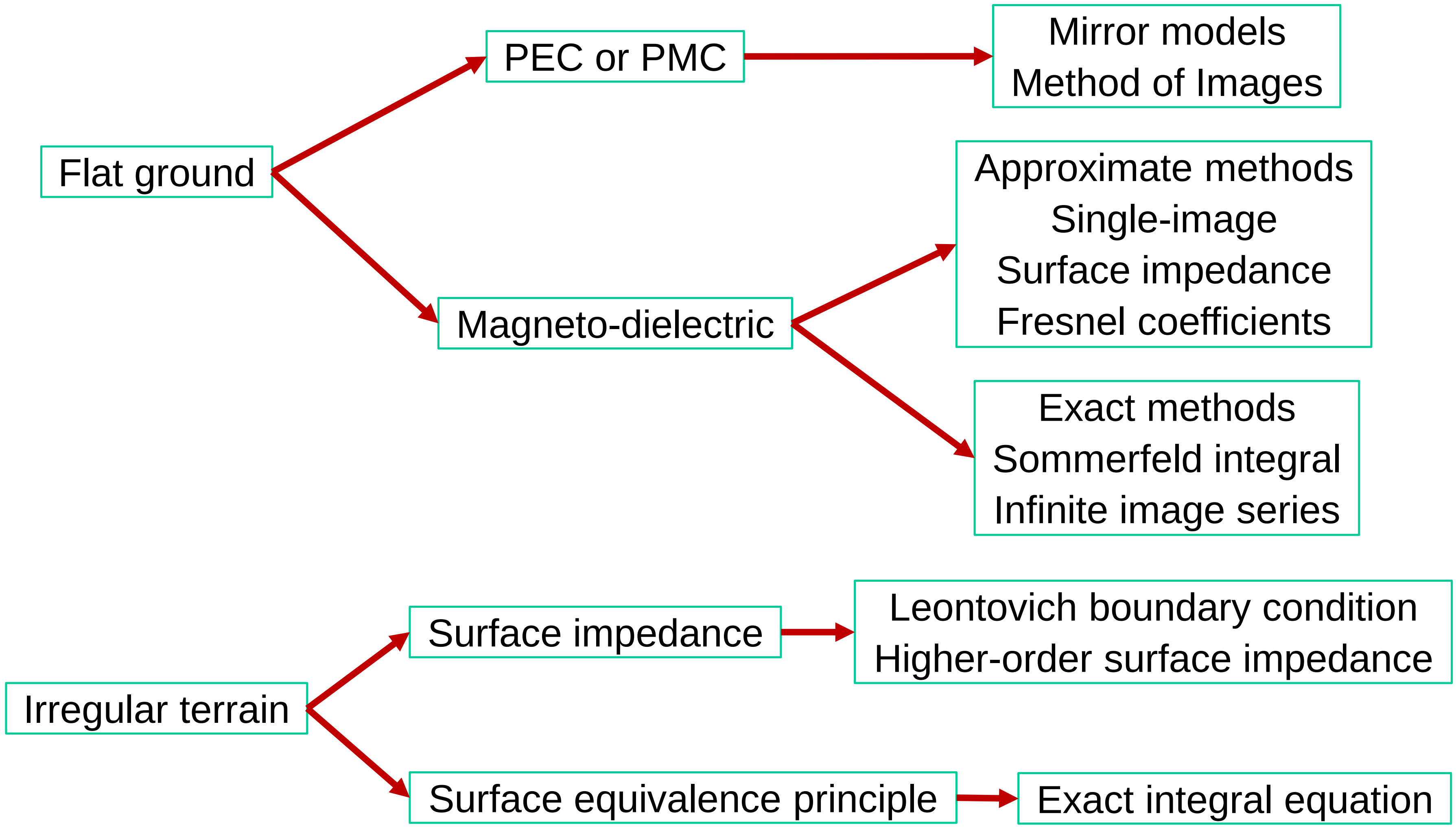
σ = 0.005 S/m

Metal core



Real ground is not infinite!

Choices of Ground Models



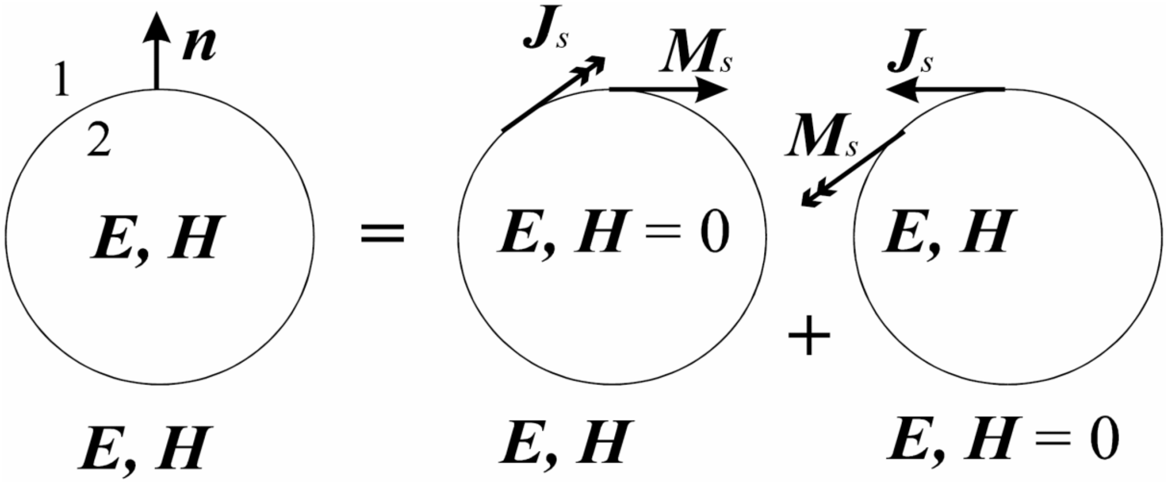
Surfaces

Uniqueness Theorem
Surface Equivalence Principle/Theorem
Surface Impedance Boundary Conditions

Electromagnetic Uniqueness Theorem

- **Sources determine the fields in a region**
- **But the converse is not true**
  - The fields do not determine the sources
  - The same fields may result from different source configurations
- **The uniqueness theorem states a boundary condition that guarantees there is only one solution to Maxwell's equations**
- **Surface(s) can divide space into regions**
  - Region(s) that are source free
  - Region(s) that have sources
- **The fields in the source-free regions are uniquely determined by either tangential E or tangential H on each region's boundary surface**
  - Analogous to Thévenin's and Norton's theorems of circuit theory
    - Substitute "region" for "sub-circuit" or "black box"
    - Substitute "tangential E" for "voltage"
    - Substitute "tangential H" for "current"

Surface Equivalence Principle

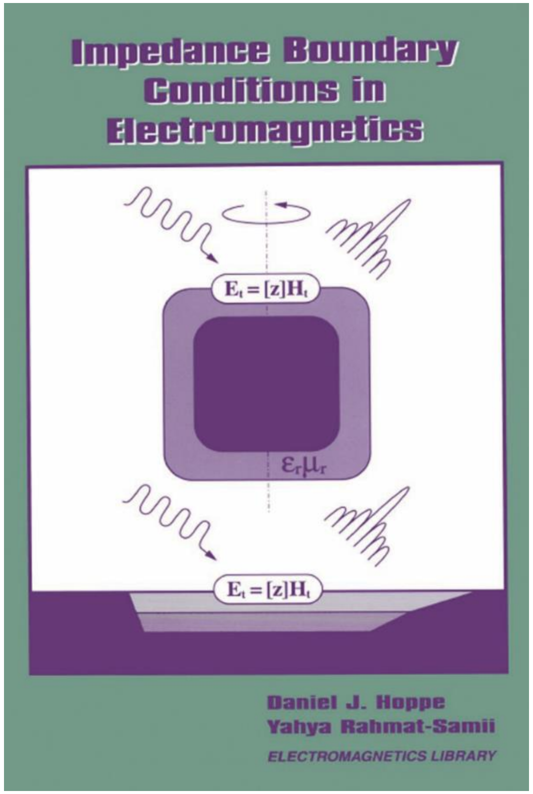


- **Simplifies electromagnetic calculations**
- **Idea evolved over 4 centuries by physicists and mathematicians**
  - Huygens, Babinet, Helmholtz, Kirchhoff, Love, Schelkunoff
- **Allows sources inside or outside of homogeneous objects to be replaced by fictitious currents on the surface of the object**
- **Analogous to Thévenin and Norton equivalent sources**
- **Exact currents are found from surface integral equations (SIEs)**
- **Currents approximately given by surface impedance boundary conditions (SIBCs)**

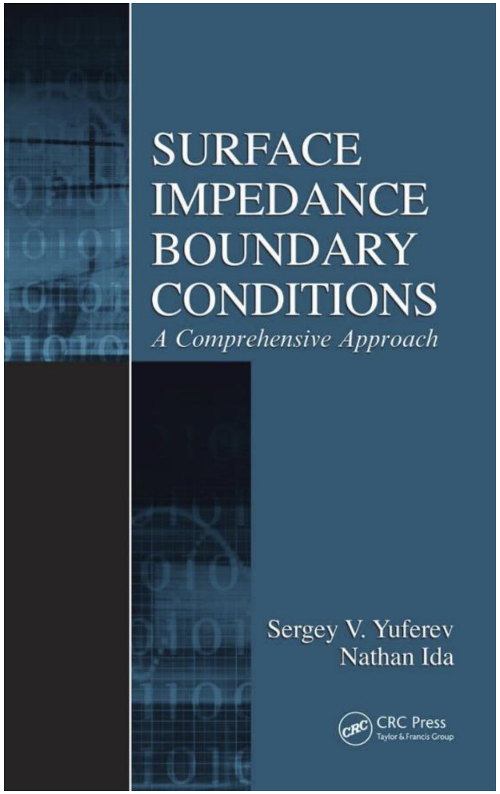
C. A. Balanis, *Advanced Engineering Electromagnetics*, 2nd edition, Wiley, 2012

Surface Impedance Boundary Conditions (SIBCs)

Mikhail Alexandrovič Leontovič
1903-1981



D. J. Hoppe and Y. Rahmat-Samii, *Impedance Boundary Conditions in Electromagnetics*, CRC Press, 1995



S. V. Yuferev and N. Ida, *Surface Impedance Boundary Conditions*, CRC Press, 2010

Surface Impedance

- **Leontovich boundary condition surface impedance (1944)**

$$Z_S = \sqrt{\frac{j\,2\pi f\,\mu_r \mu_0}{\sigma + j\,2\pi f\,\varepsilon_r \varepsilon_0}}$$

- **where**

Z_S	=	Surface impedance in ohms per square
j	=	$\sqrt{-1}$
f	=	Frequency in hertz
μ_r	=	Relative permeability of material
μ_0	=	Magnetic permeability of vacuum in henries per meter
ε_r	=	Relative permittivity of material (dielectric constant)
ε_0	=	Electric permittivity of vacuum in farads per meter
σ	=	Conductivity of material in siemens per meter

- **Accurate if**
  - Dielectric material is thick and/or lossy
  - Skin depth << surface curvature

The Nature of Surface Impedance

$$Z_S = \sqrt{\frac{j\,\omega\,\mu}{\sigma + j\,\omega\,\varepsilon}} \;\rightarrow\; \begin{cases} \sqrt{\dfrac{j\,\omega\,\mu}{\sigma}} & \text{as } f \rightarrow 0 \\[2ex] \eta_0 \sqrt{\dfrac{\mu_r}{\varepsilon_r}} & \text{as } f \rightarrow \infty \end{cases}$$

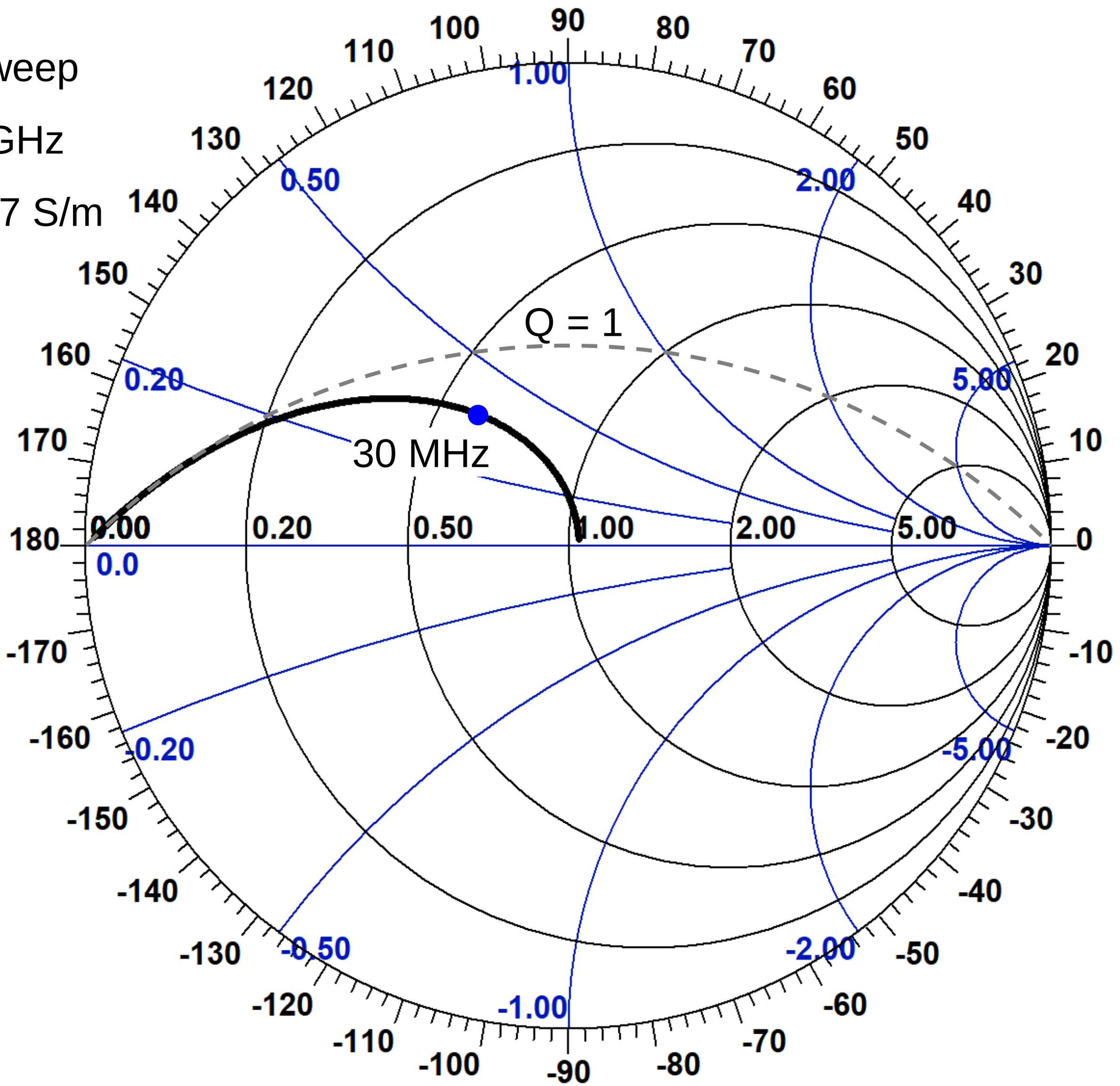
- **For constant parameter materials**
  - Z_S is zero at zero frequency
  - Z_S has no poles or zeros at other frequencies
  - Z_S is a positive resistance at infinite frequency
  - X_S (the imaginary part of Z_S) is positive, i.e. inductive, at all real frequencies
  - Z_S phase angle decreases from +45 degrees to zero as frequency varies from zero to infinity
  - Surface impedance on the Smith chart follows the Q = 1 arc at low frequencies but bends below it at high frequencies, ending on the real axis

Surface Impedance on Smith Chart

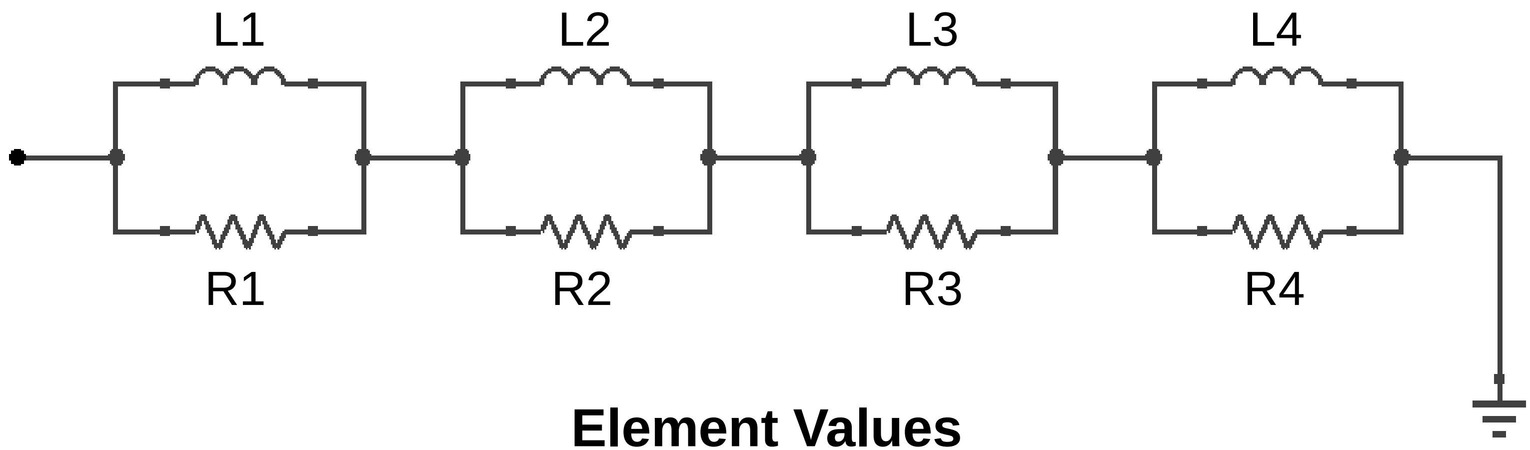
Frequency Sweep

10 kHz to 1 GHz

$\varepsilon_r = 52 \quad \sigma = 0.17$ S/m



Universal Equivalent Circuit for Surface Impedance DC to 100 MHz

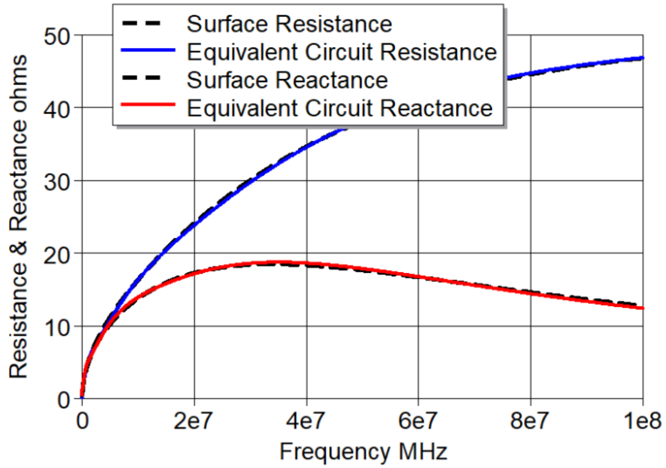


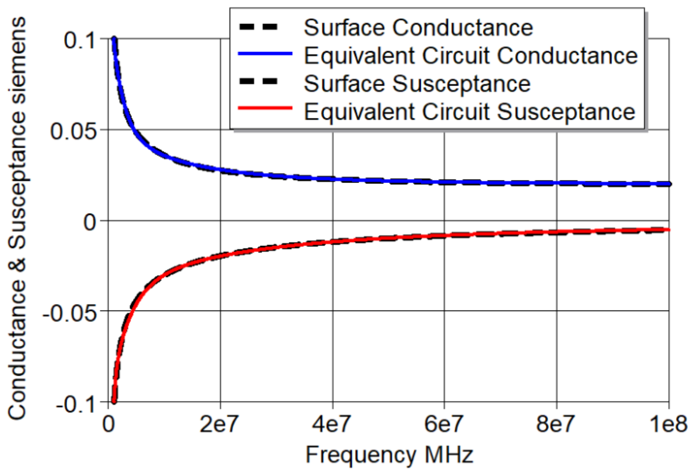
Element Values

	Tree A $\varepsilon_r = 5 \quad \sigma = 0.017$	Tree B $\varepsilon_r = 52 \quad \sigma = 0.17$	Tree C $\varepsilon_r = 32 \quad \sigma = 0.28$
L1 nH	31,520	6,345	3,082
L2 nH	4,125	895.1	495.2
L3 nH	1,160	253.8	145.6
L4 nH	523.6	124.5	79.98
R1 ohms	3.922	1.770	1.852
R2 ohms	11.74	5.097	5.125
R3 ohms	31.95	12.49	12.33
R4 ohms	112.2	32.22	41.33

S. D. Stearns, K6OIK, “Universal Equivalent Circuits for All Antennas,” Pacificon Antenna Seminar, Oct. 15-17, 2021

Accuracy of Equivalent Circuit for Surface Impedance DC to 100 MHz

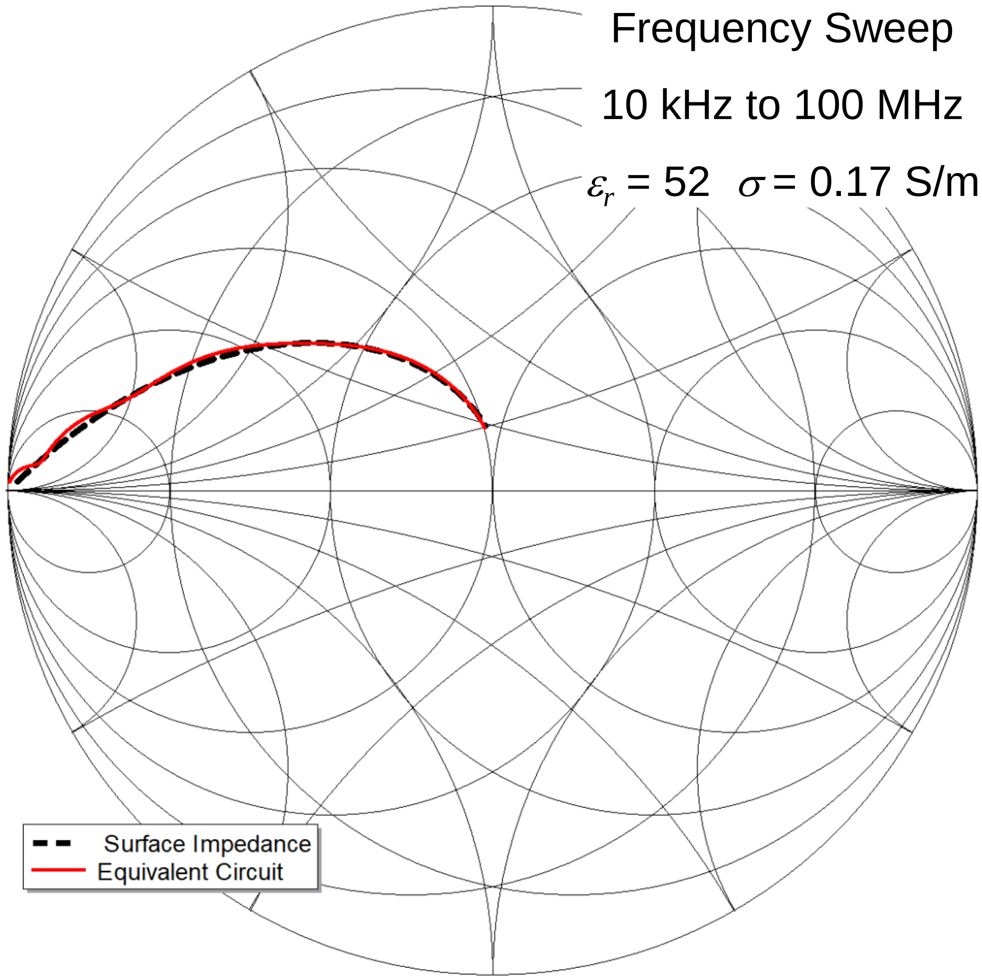




Frequency Sweep

10 kHz to 100 MHz

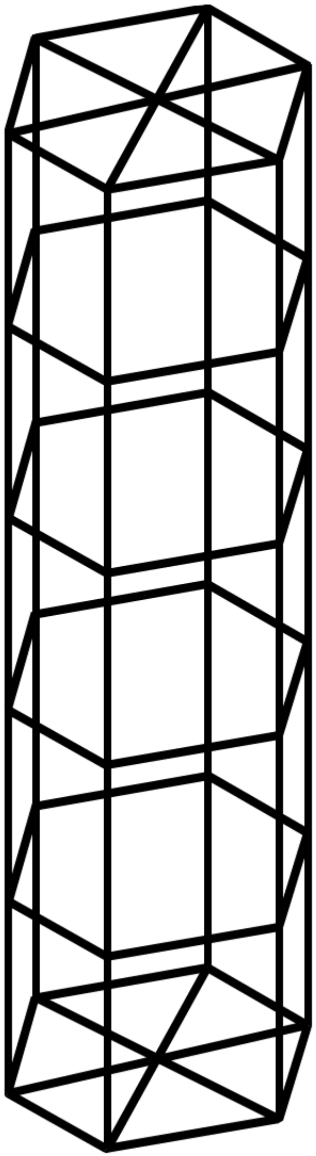
$\varepsilon_r = 52$ $\sigma = 0.17$ S/m



Using Thin-Wire Programs to Model Dielectric Objects

- **When using NEC or MiniNEC dielectric objects can be modeled similarly to conducting objects**
  - Make a wire grid of the surface of the object
  - Load the wires
    - Exact method: load wires to achieve correct electric and magnetic currents (obtained by solving integral equations)
    - Approximate method: load wires to obtain desired surface impedance
- **For good accuracy**
  - Wire grid should satisfy the Equal Area Rule (EAR)
  - Skin depth should be small compared to object's thickness
    - Object should be lossy or thick or both
  - Skin depth should be small compared to surface curvature
  - Frequencies should not be near the object's cavity resonances
- **Advanced tricks**
  - Use a CAD program to construct a surface mesh
  - Construct a wire table from the mesh's node and edge data

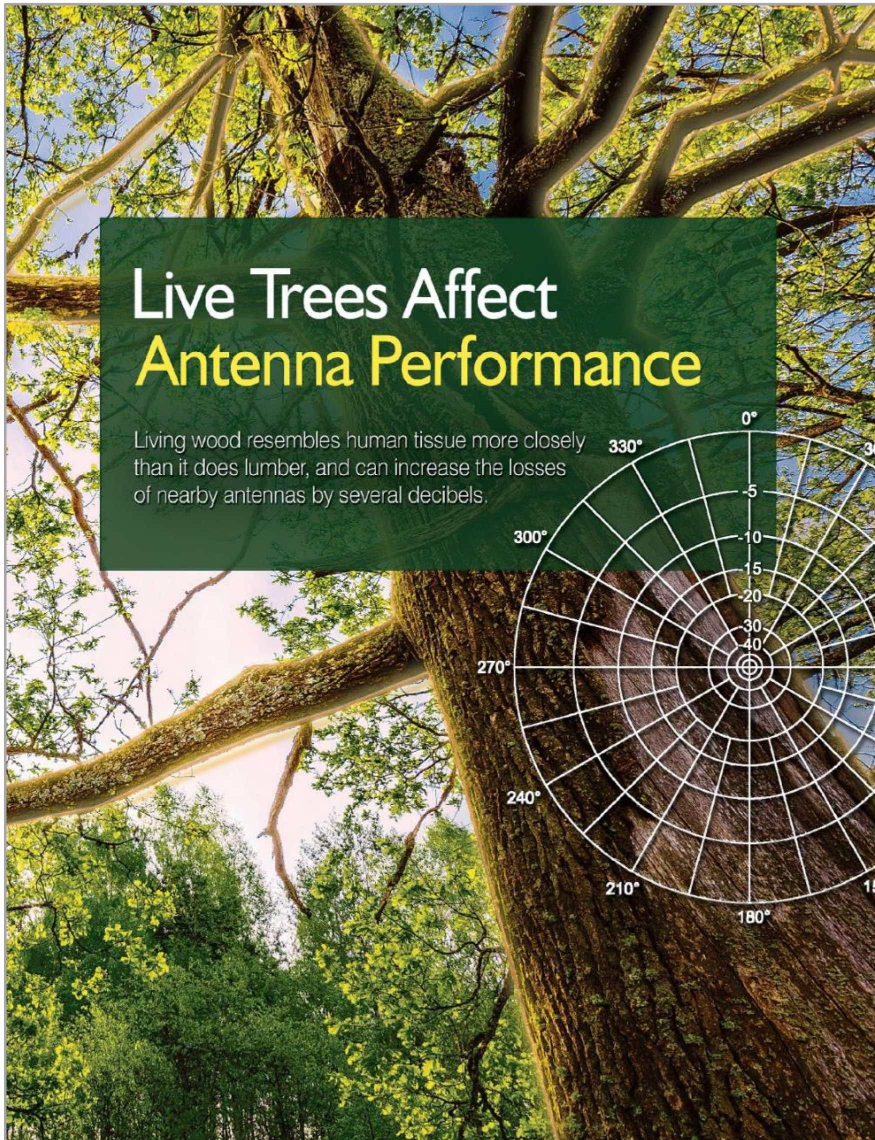
Modeling Dielectric Cylinders of Finite Length



- Hexagonal model
- 6 vertical wires on perimeter
- Faces are square
- Segment lengths equal tree radius
- Wire diameter is length ÷ π
- Satisfies EAR
- Wires loaded to set surface impedance

Trees in Antenna Models

Modeling a Single Tree: *QST*, February 2018



Kai Siwiak, KE4PT, and Richard Quick, W4RQ

Placing HF antennas amid towering trees[1] raises questions about their impact on antenna effectiveness, and how far away the antenna should be from trees. We simulated the effects of a vertical antenna near lossy cylinder models of live tree trunks to help answer such questions. The electrical parameters of live trees are dramatically different than those for dead wood or lumber and vary with tree type, so we carried out our simulations over a range of dielectric parameters. We'll also comment on the effect of a forest of trees.

Live Trees

Dielectric properties of live trees for frequencies below 1 GHz span the range of values[2] shown in Table 1. We chose an average value of 52 for relative permittivity and 0.17 S/m for conductivity for polarization aligned with the tree axis, then varied those nominal values over a range. The tree parameters include summer and winter variations, and tree trunk thickness.[3]

The Models and Simulations

We used two independent methods to find the effect of a vertical antenna next to a live tree trunk. In one method, we used *NEC* to simulate a tree trunk next to a half-wave dipole in free space. In the second method, we applied a purely analytical solution to wave scattering of a line source near an infinitely long two-layered lossy dielectric cylinder.

The *NEC* Simulation

Figure 1 shows a lossy cylinder representing a live tree modeled by a single fat wire loaded by a parallel *RC* impedance. A dipole 10.3 meters in length, nominally resonant at 14.11 MHz, is near the lossy wire. To reduce computational artifacts, we maintained strict symmetry in the tree and dipole axis dimensions, with the dipole source centered. We also used identical segment lengths *s* for the dipole and the tree. Using the live tree permittivity ε_r and conductivity σ values, and noting that $\varepsilon_0 = 8.8542\times10^{12}$ F/m, the equivalent

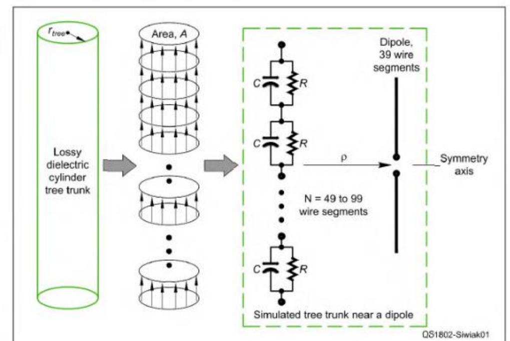


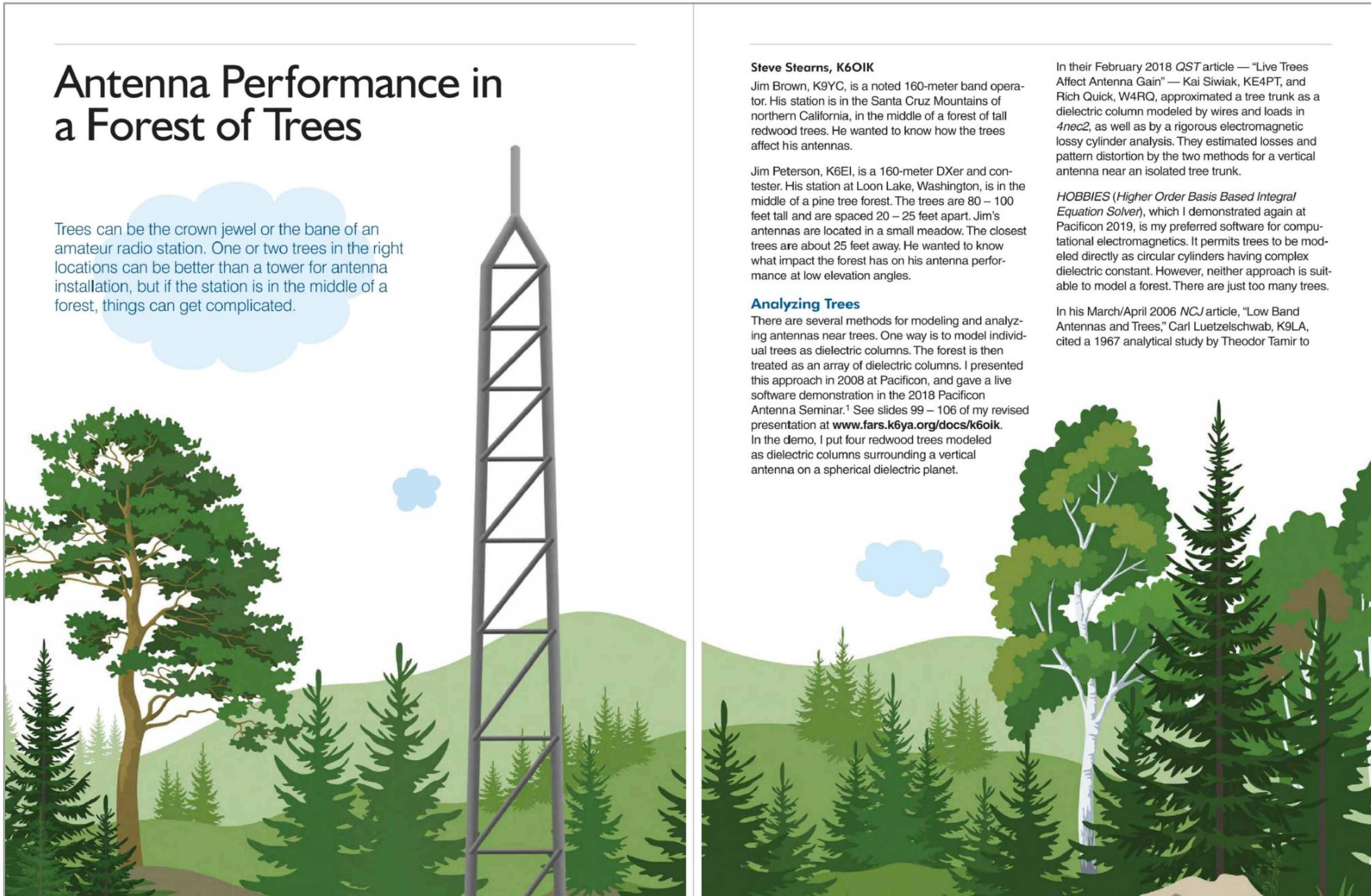
Figure 1 — An impedance-loaded wire simulates a tree trunk near a dipole. Tree and dipole segment lengths were identical, and symmetry was maintained on the vertical axis.

Table 1

Dielectric properties of live softwood and live hardwood trees for frequencies below 1 GHz. We used average values of 52 for relative permittivity and 0.17 S/m for conductivity in vertical polarization. The tree parameters include summer and winter variations. Dry, dead wood is dramatically different than living wood, while human muscle tissue and saline water are in the same order of magnitude as living wood.

Tree Type	Permittivity Range	Conductivity, S/m	Comments
Softwood, parallel to wood grain, or random polarization	46 – 72	0.17	below 1 GHz
Hardwood, parallel to wood grain, or random polarization	32 – 59	0.17	below 1 GHz
Softwood, perpendicular to wood grain	38 – 56	0.012	below 1 GHz
Hardwood, perpendicular to wood grain	12 – 31	0.012	below 1 GHz
Nonliving wood	2 – 9	<0.008	3 – 30 MHz, <65% moisture
Human muscle tissue	200 – 92	0.60 – 0.66	3 – 30 MHz
Saline water at 4 gm/L NaCl	79	0.63 – 0.69	below 500 MHz

Modeling a Forest of Trees: *QST*, August 2020



Antenna Performance in a Forest of Trees

Trees can be the crown jewel or the bane of an amateur radio station. One or two trees in the right locations can be better than a tower for antenna installation, but if the station is in the middle of a forest, things can get complicated.

Steve Stearns, K6OIK

Jim Brown, K9YC, is a noted 160-meter band operator. His station is in the Santa Cruz Mountains of northern California, in the middle of a forest of tall redwood trees. He wanted to know how the trees affect his antennas.

Jim Peterson, K6EI, is a 160-meter DXer and contester. His station at Loon Lake, Washington, is in the middle of a pine tree forest. The trees are 80 – 100 feet tall and are spaced 20 – 25 feet apart. Jim's antennas are located in a small meadow. The closest trees are about 25 feet away. He wanted to know what impact the forest has on his antenna performance at low elevation angles.

Analyzing Trees

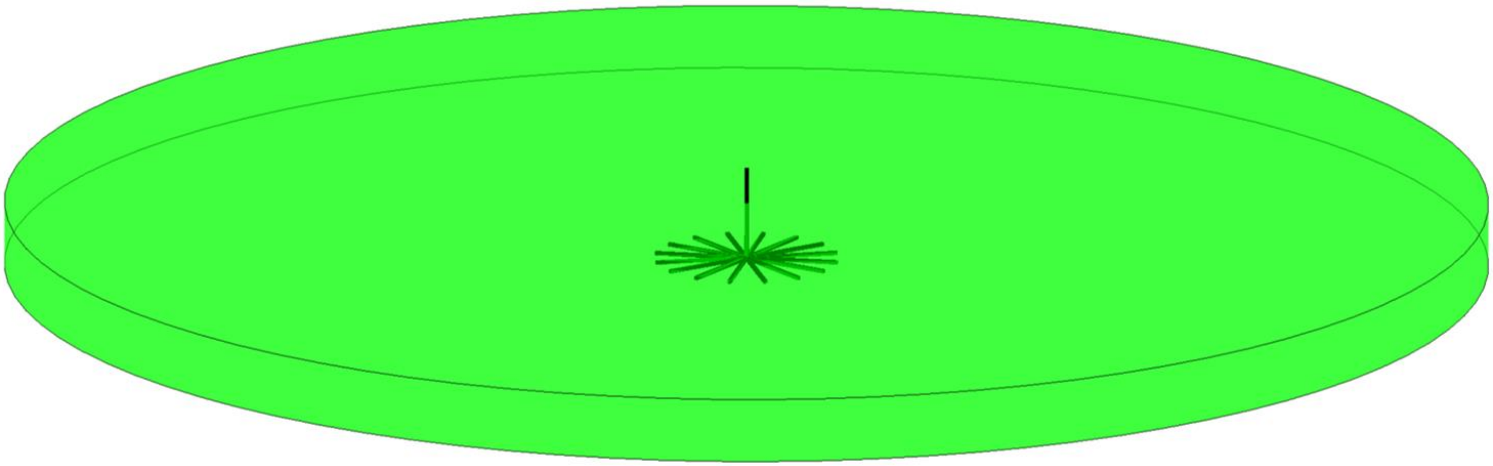
There are several methods for modeling and analyzing antennas near trees. One way is to model individual trees as dielectric columns. The forest is then treated as an array of dielectric columns. I presented this approach in 2008 at Pacificon, and gave a live software demonstration in the 2018 Pacificon Antenna Seminar.[1] See slides 99 – 106 of my revised presentation at **www.fars.k6ya.org/docs/k6oik**. In the demo, I put four redwood trees modeled as dielectric columns surrounding a vertical antenna on a spherical dielectric planet.

In their February 2018 *QST* article — "Live Trees Affect Antenna Gain" — Kai Siwiak, KE4PT, and Rich Quick, W4RQ, approximated a tree trunk as a dielectric column modeled by wires and loads in *4nec2*, as well as by a rigorous electromagnetic lossy cylinder analysis. They estimated losses and pattern distortion by the two methods for a vertical antenna near an isolated tree trunk.

HOBBIES (*Higher Order Basis Based Integral Equation Solver*), which I demonstrated again at Pacificon 2019, is my preferred software for computational electromagnetics. It permits trees to be modeled directly as circular cylinders having complex dielectric constant. However, neither approach is suitable to model a forest. There are just too many trees.

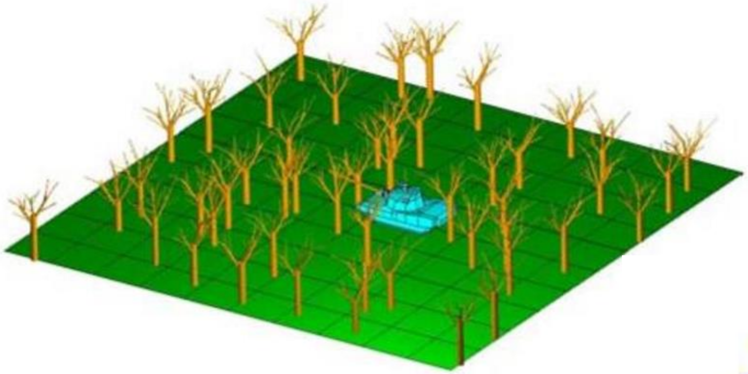
In his March/April 2006 *NCJ* article, "Low Band Antennas and Trees," Carl Luetzelschwab, K9LA, cited a 1967 analytical study by Theodor Tamir to

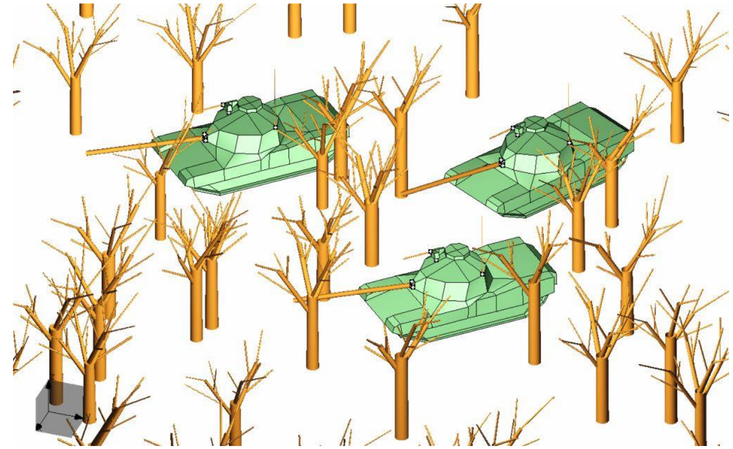
K6OIK Forest Model

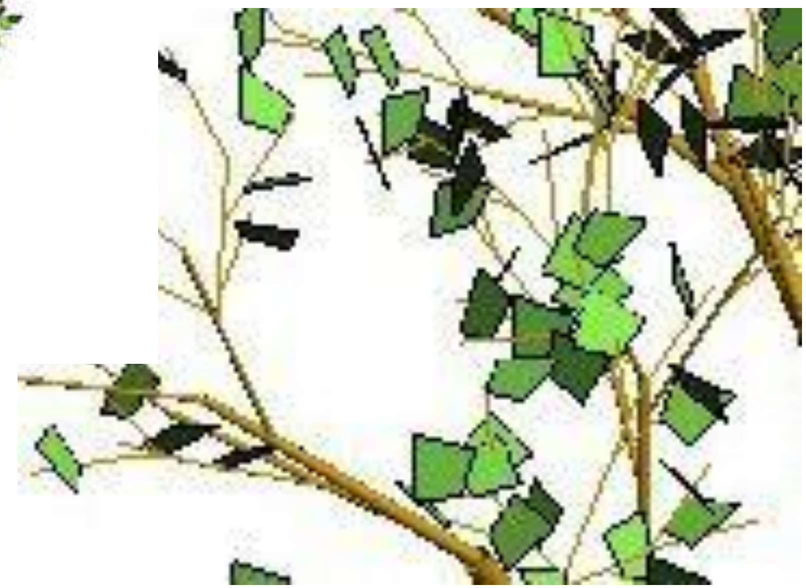


- Forest assumed to be dense, homogeneous, isotropic – modeled as a uniform dielectric “hockey puck” – a macro-model
- Dielectric parameters determined from “effective media theory”
- Model was created in HOBBIES, a surface MoM program
- Antenna: a 160 meter vertical monopole with elevated radials
- Forest 90 feet high and 2 wavelengths in diameter
- Antenna is 140 feet and sticks out above the forest top

Simulated Forests of Many Individual Trees

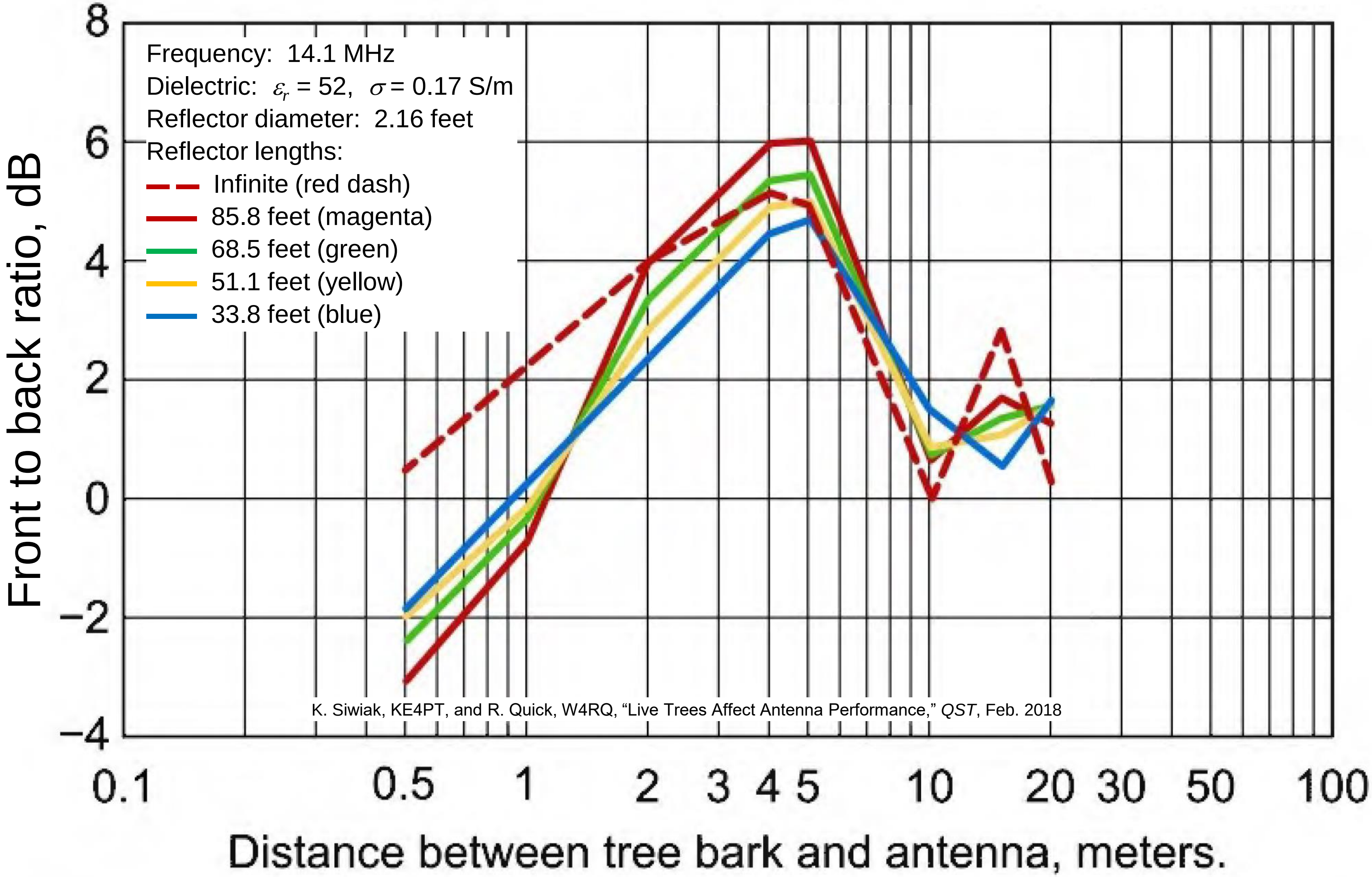




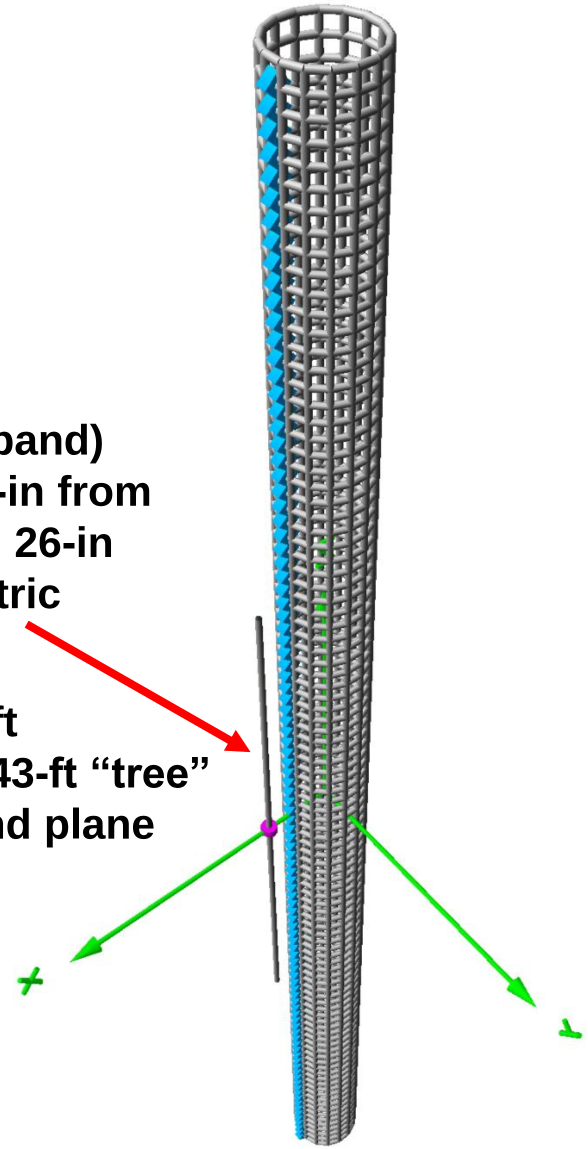


D.I. Olcan and B.M. Kolundzija, “On the Simulation of RCS from Trees and Forests Above Real Finite Ground,” *EuCAP*, Nov 2006
D.I. Olcan and B.M. Kolundzija, “Precise and Efficient EM Modeling of Trees with WIPL-D Code,” *ACES Conf*, April 2004

Effect of a Tree as a Reflector Near a Vertical



Hexadecagon Tree Model for 14 MHz



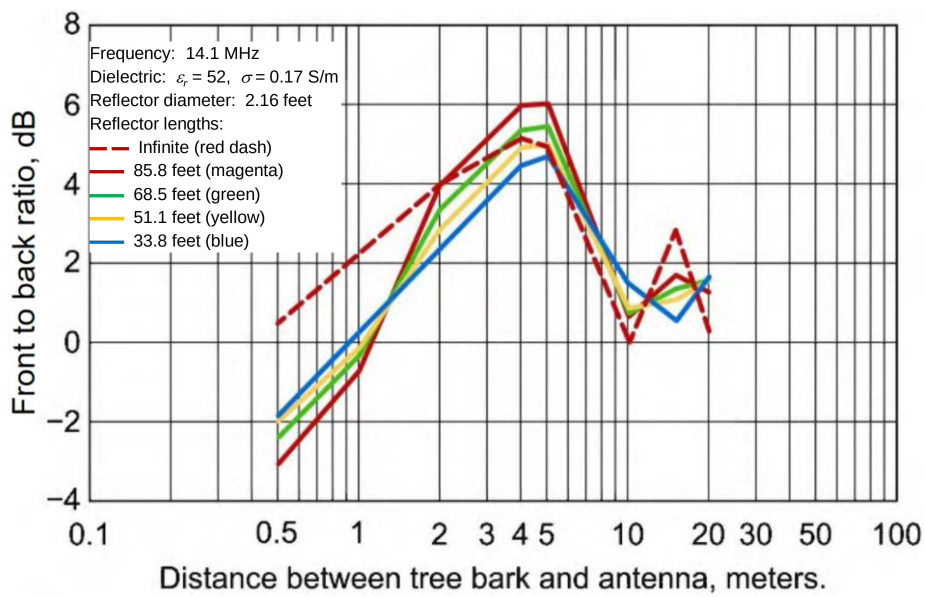
34-ft (20 meter band) metal dipole 20-in from surface of 86-ft, 26-in diameter dielectric cylinder

Represents 17-ft monopole and 43-ft “tree” over PEC ground plane

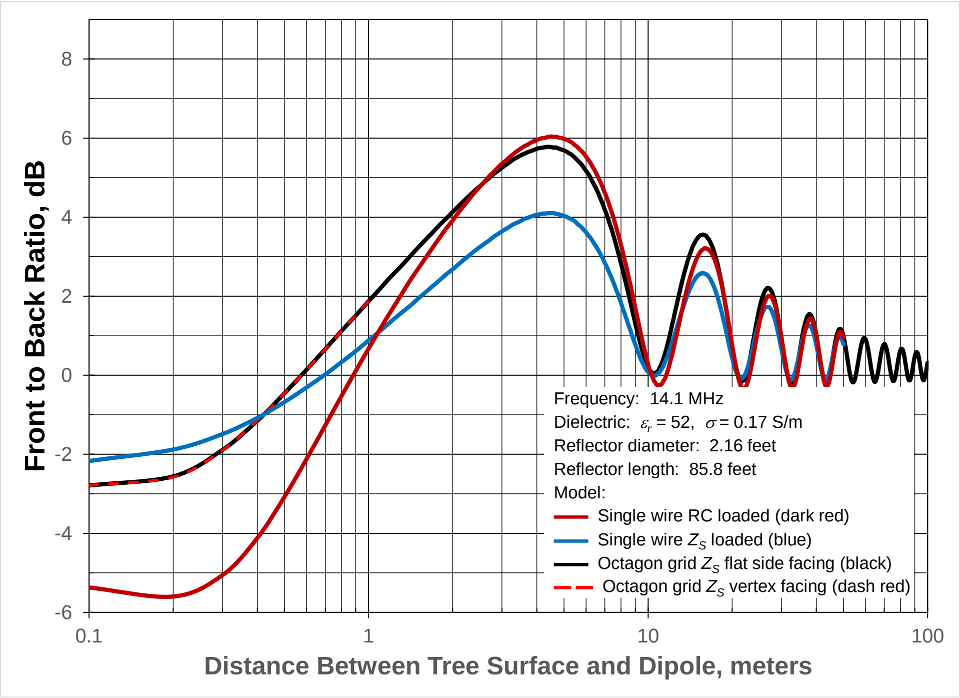
- 16-sided tree model
- 16 vertical wires on tree perimeter
- Grid facets are square
- Segment lengths equal $R \times 2 \sin(11.25°)$
- Segment len ÷ diameter = π
- Satisfies EAR
- Wires are loaded to match surface impedance
- Dipole and tree segments equal and aligned
- Model runs in 4nec2 in minutes, not hours

Predicted Front-to-Back Ratio vs Distance to Reflector

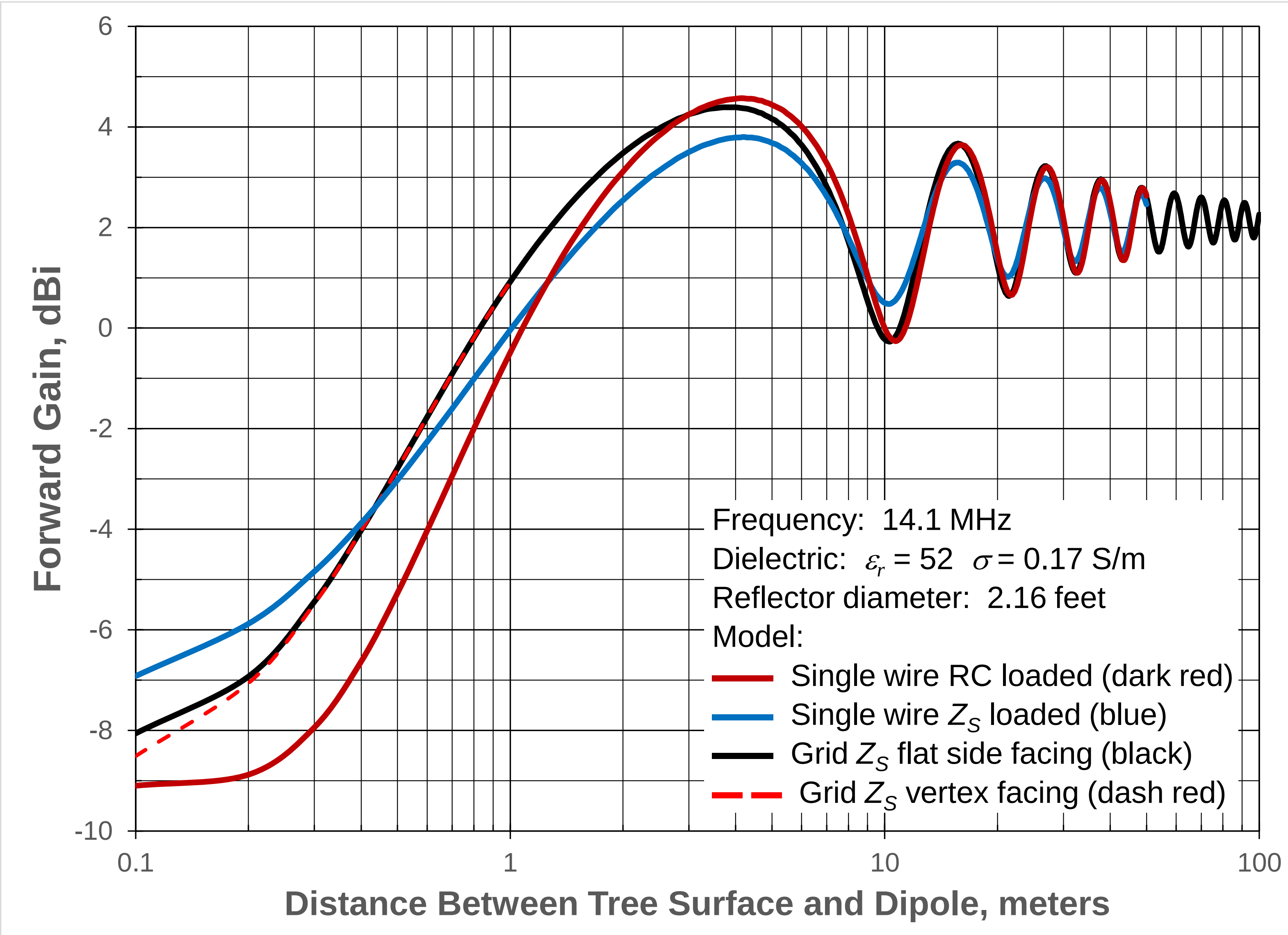
Fat RC loaded wires



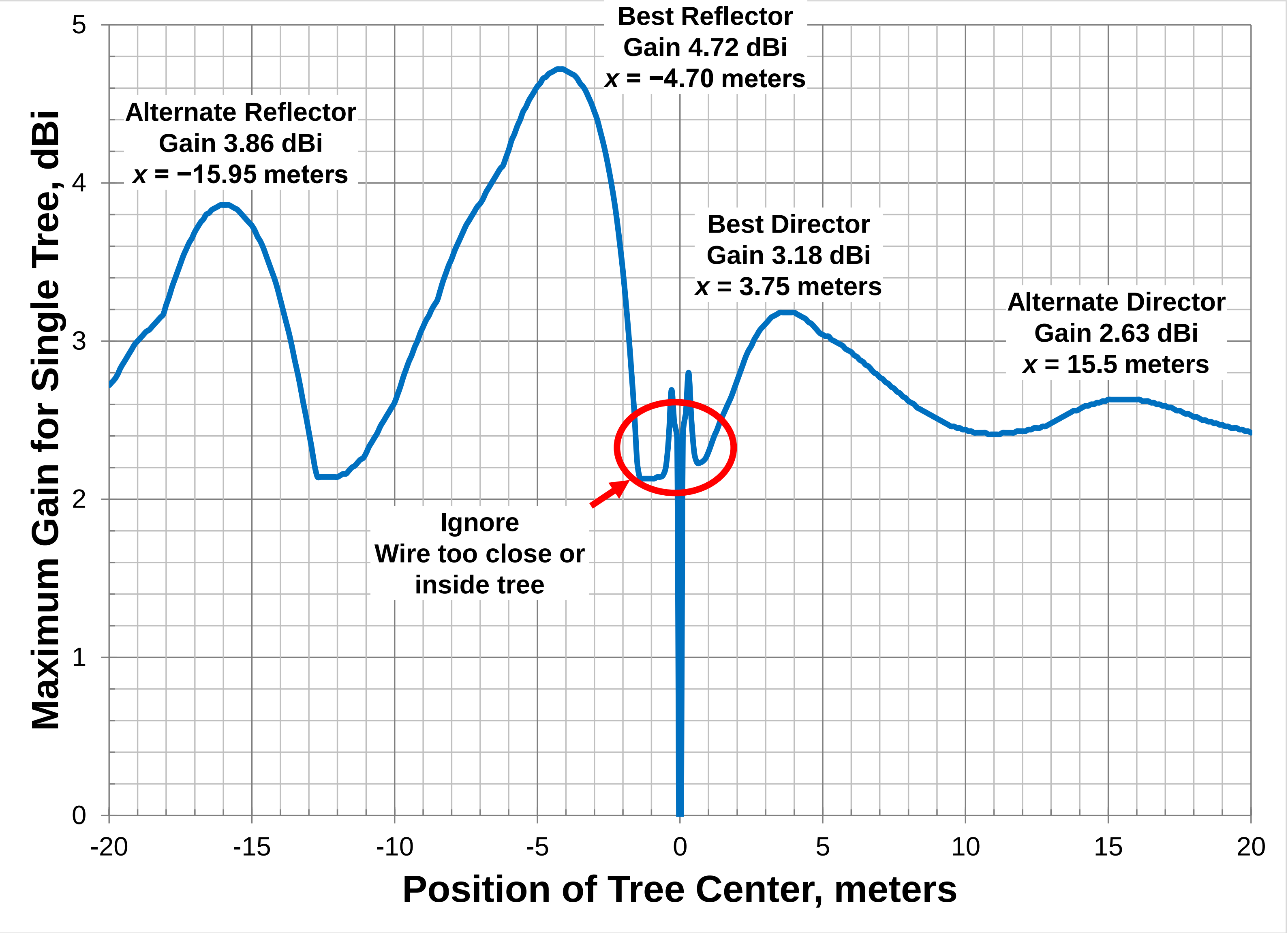
Fat loaded wires versus Wire grids with Z_S loading



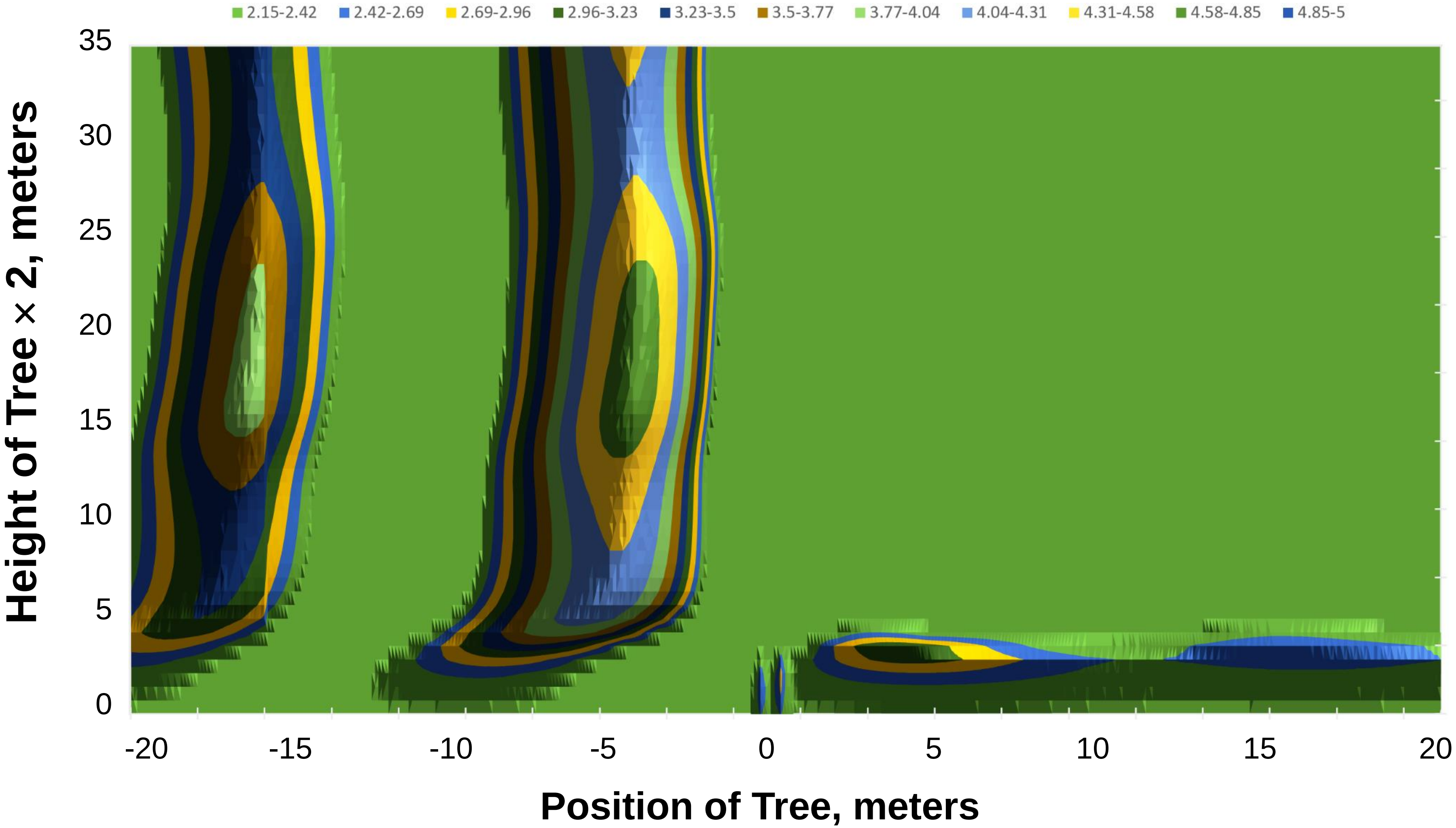
Gain vs Distance to Reflector



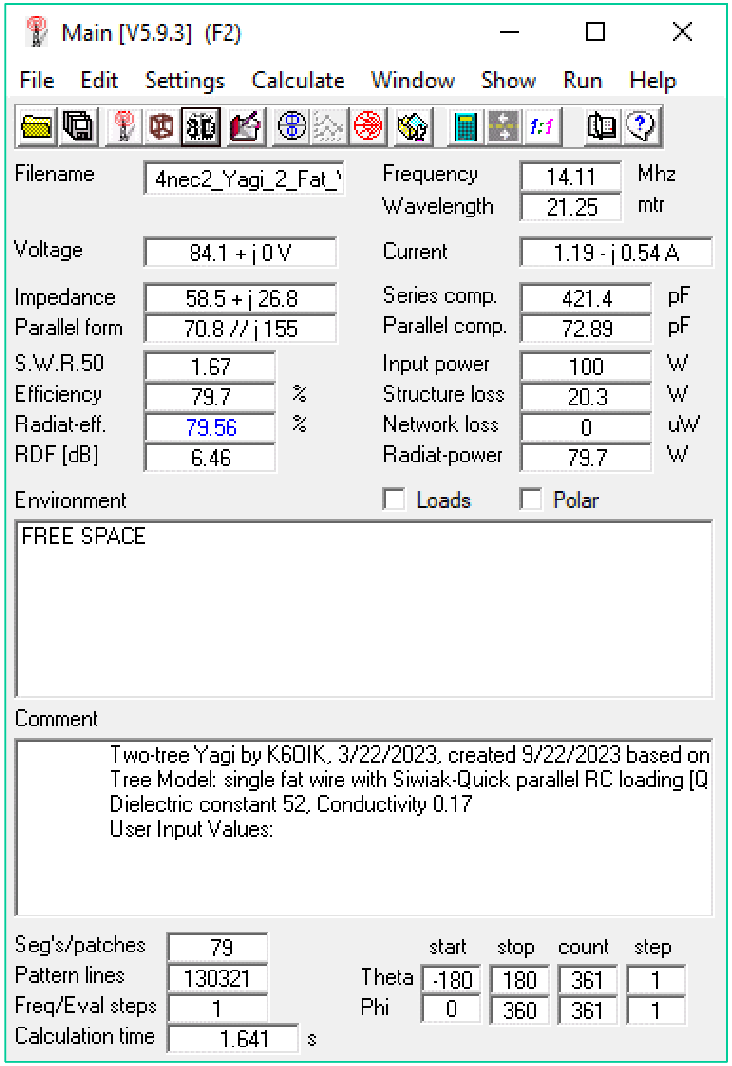
Forward Gain vs Tree Position on *X*-Axis

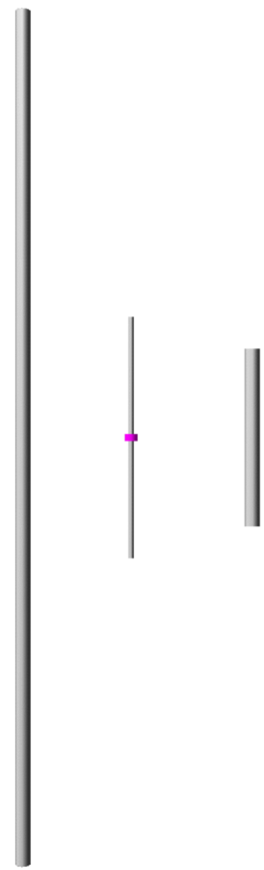


Gain with Single Parasitic Tree vs Position and Height



3-Element Yagi Using Fat-Wire Trees





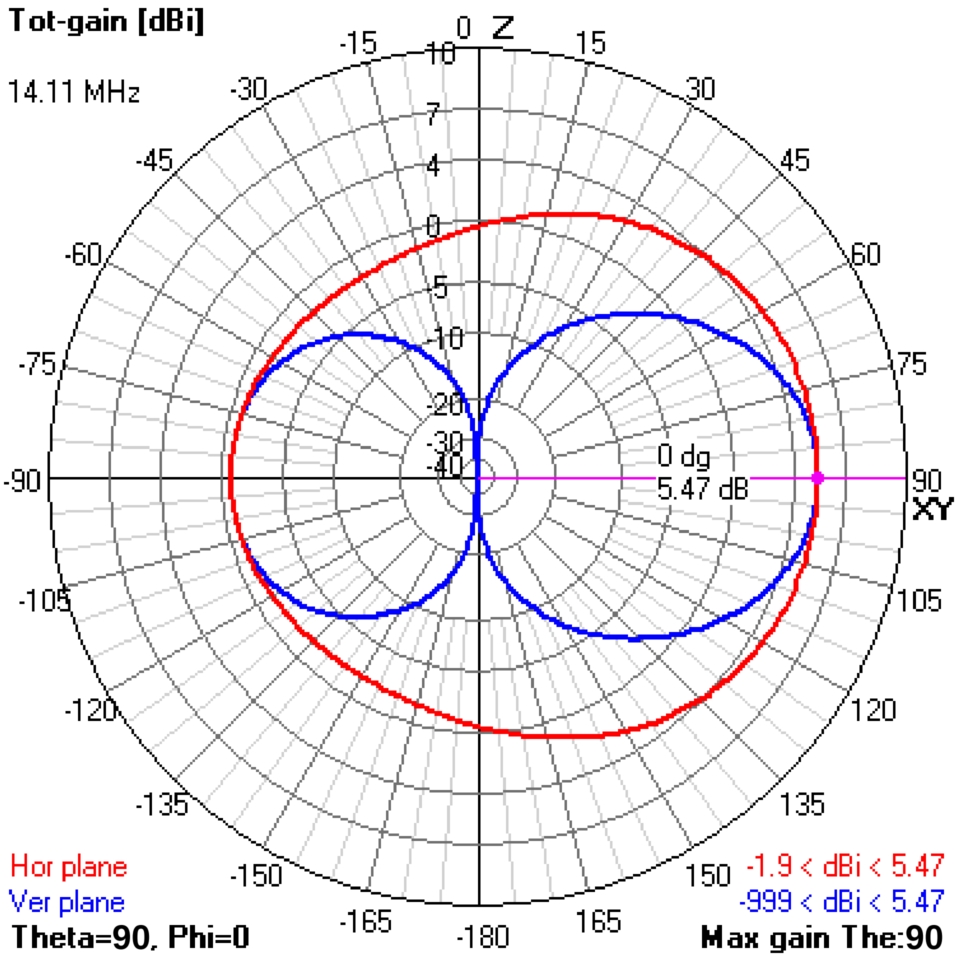
Free space (dipole) model

For monopole, use upper half and ground plane

Two trees (fat RC loaded wires)

$\varepsilon_r = 52$, $\sigma = 0.17$ S/m	
Tree diam	2.15 ft
Seg length	2.25 ft
Seg len/diam ratio	1.04
Segments per λ	30.9
Model segments	79
Optimum dimensions	
Refl-driver	15.16 ft
Refl-director	32.07 ft
Refl half length	59.71 ft
Driver half len	16.90 ft
Dir half length	12.39 ft

Tree Yagi Gain: 5.47 dBi



Frequency: 14.1 MHz

Dielectric: $\varepsilon_r = 52$, $\sigma = 0.17$ S/m

Tree diameters: 2.15 feet

Trees: Fat-wire RC loaded wires

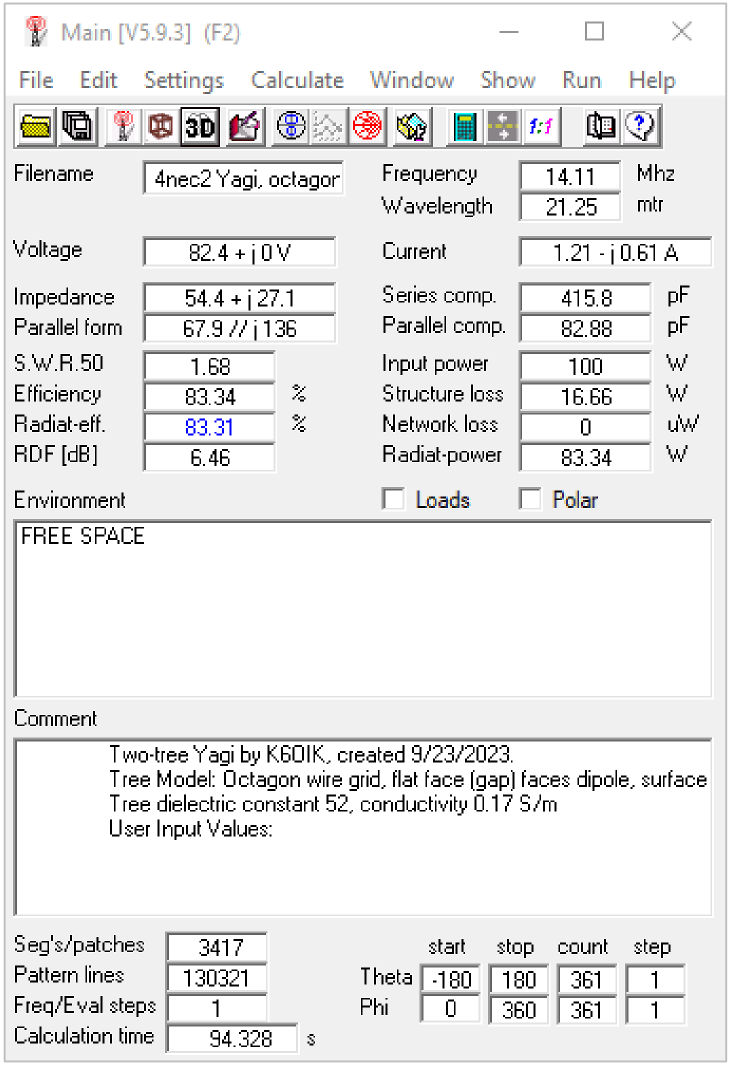
V plane (blue)

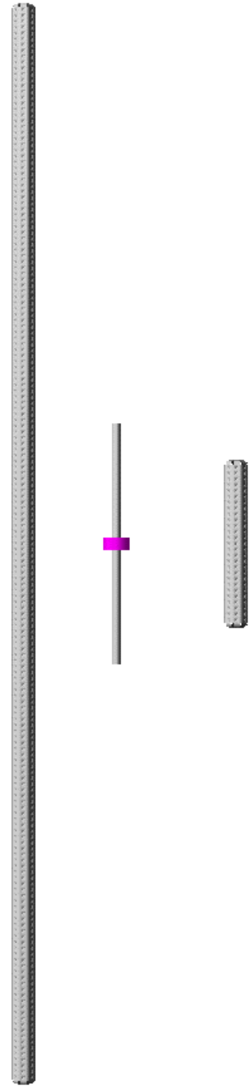
H plane (red)

Gain: 5.47 dBi

Efficiency: 79.6%

3-Element Yagi Using Octagonal Grid Trees

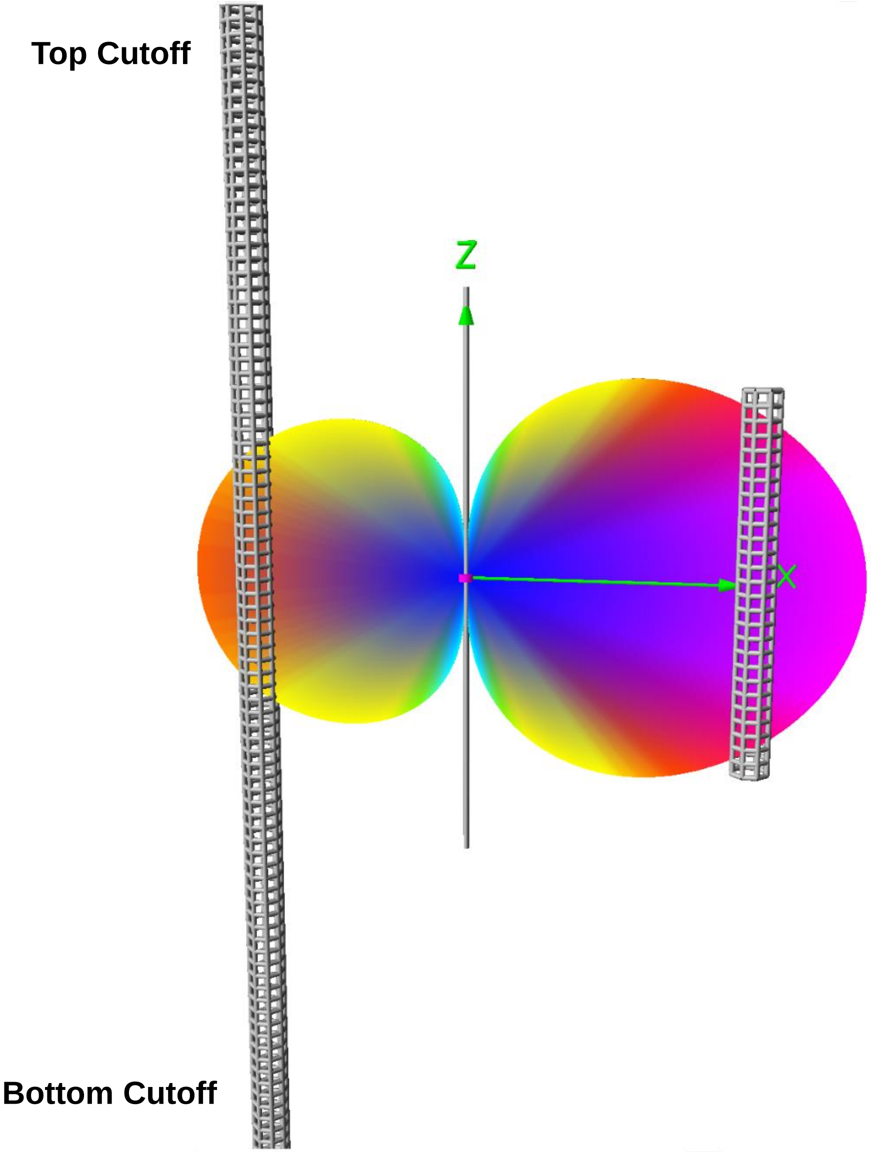




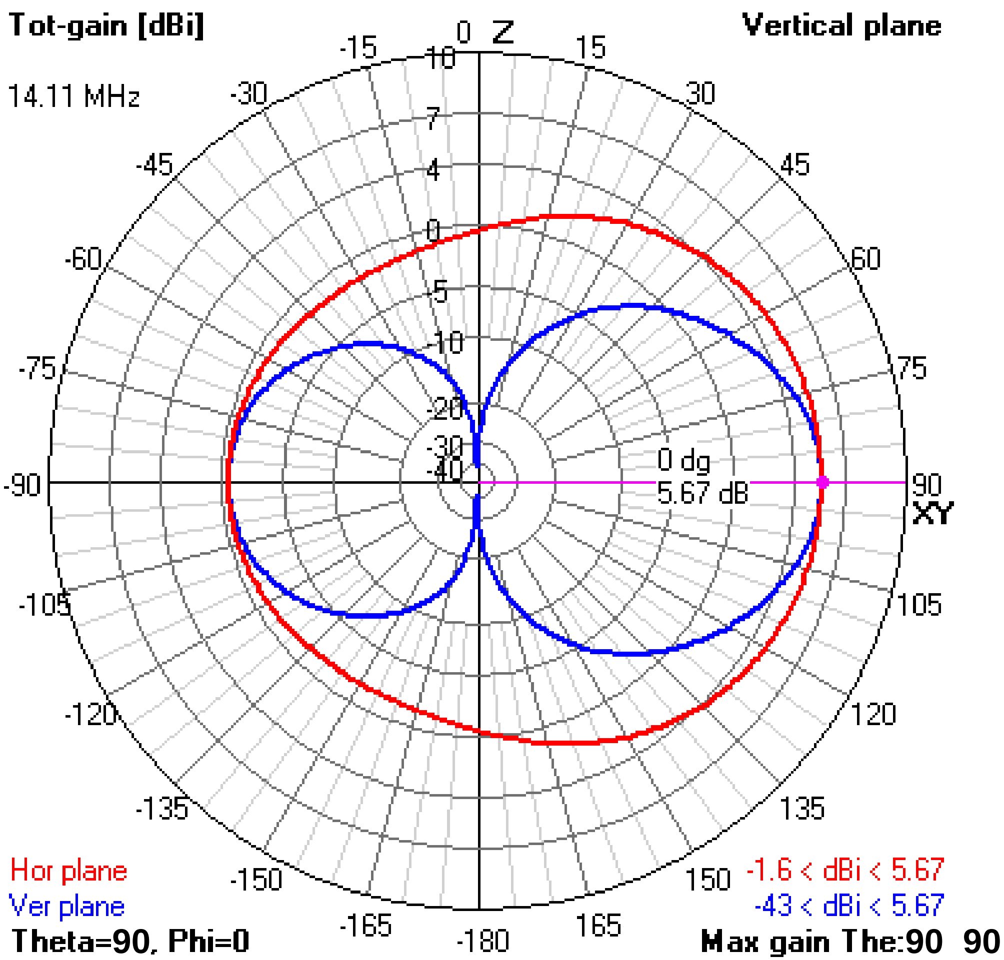
Free space (dipole) model
For monopole, use upper half and ground plane
Two trees (loaded wire grids)

$\varepsilon_r = 52$, $\sigma = 0.17$ S/m	
Tree diam	2.15 ft
Seg length	0.824 ft
Grid wire diam	0.262 ft
Seg len/grid w diam	3.14
Segments per λ	84.6
Model segments	3,417
Optimum dimensions	
Refl-driver	13.02 ft
Refl-director	29.87 ft
Refl half length	75.43 ft
Driver half len	16.90 ft
Dir half length	11.13 ft

Zoomed Structure and V-Plane Pattern



Tree Yagi Gain: 5.67 dBi (Octagonal Wire Grid)



Frequency: 14.1 MHz

Dielectric: $\varepsilon_r = 52$, $\sigma = 0.17$ S/m

Tree diameters: 2.15 feet

Trees: Octagonal wire grid

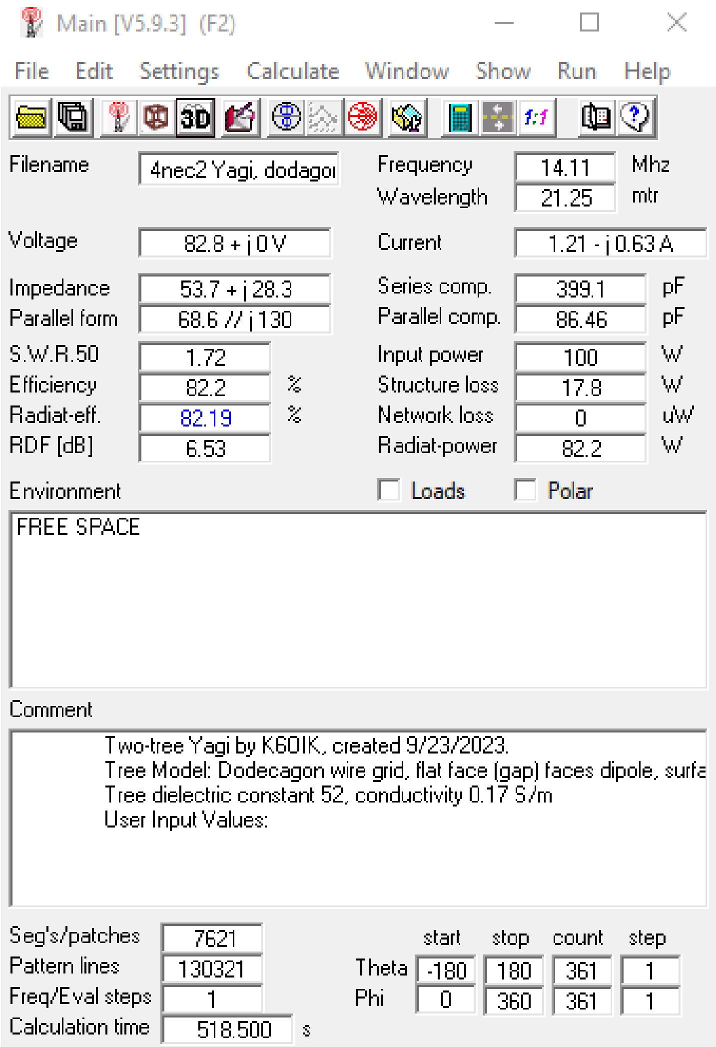
V plane (blue)

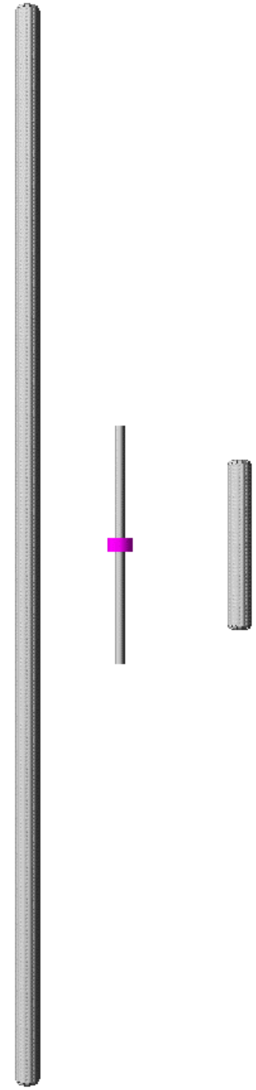
H plane (red)

Gain: 5.67 dBi

Efficiency: 83.3%

3-Element Yagi Using Dodecagonal Grid Trees

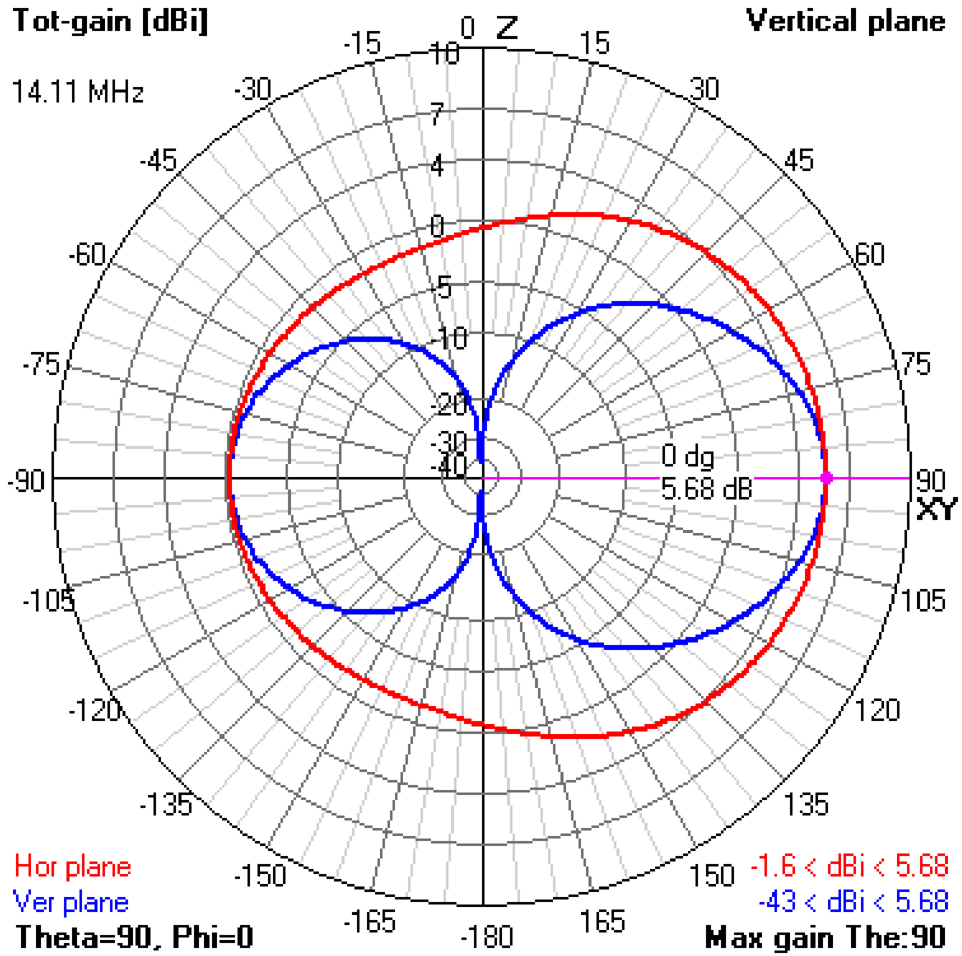




Free space (dipole) model
For monopole, use upper half and ground plane
Two trees (loaded wire grids)

$\varepsilon_r = 52$, $\sigma = 0.17$ S/m	
Tree diam	2.14 ft
Seg length	0.554 ft
Grid wire diam	0.176 ft
Seg len/grid w diam	3.14
Segments per λ	126
Model segments	7,621
Optimum dimensions	
Refl-driver	13.02 ft
Refl-director	29.66 ft
Refl half length	75.63 ft
Driver half len	16.90 ft
Dir half length	11.36 ft

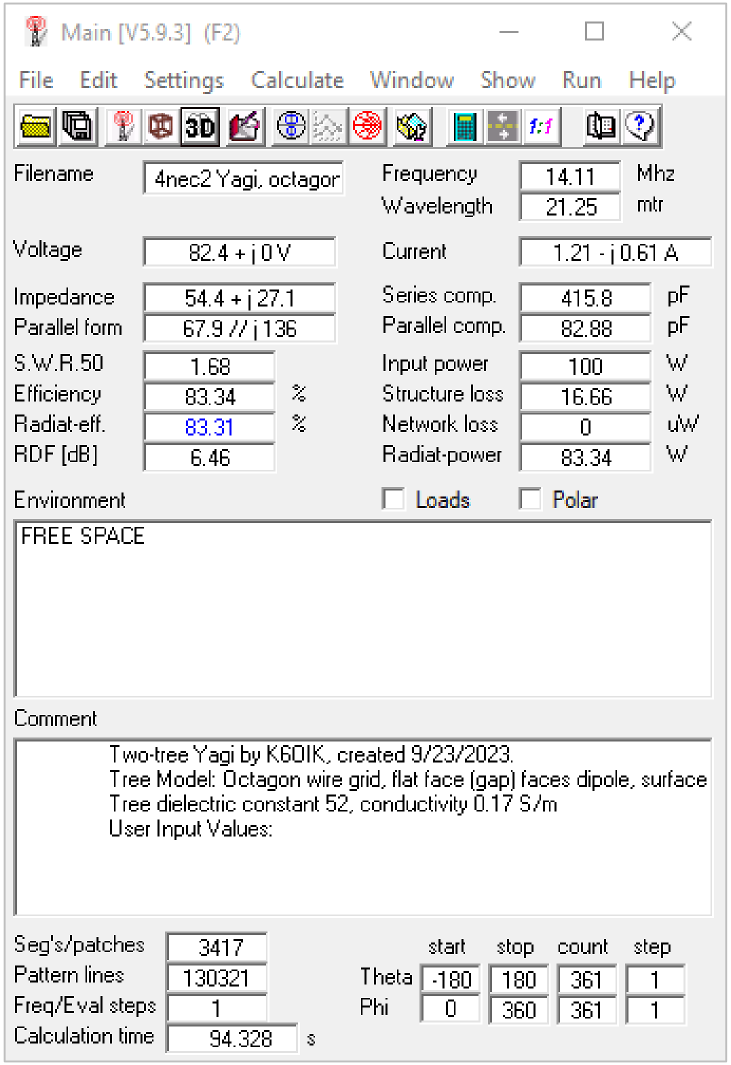
Tree Yagi Gain: 5.68 dBi (Dodegonal Wire Grid)

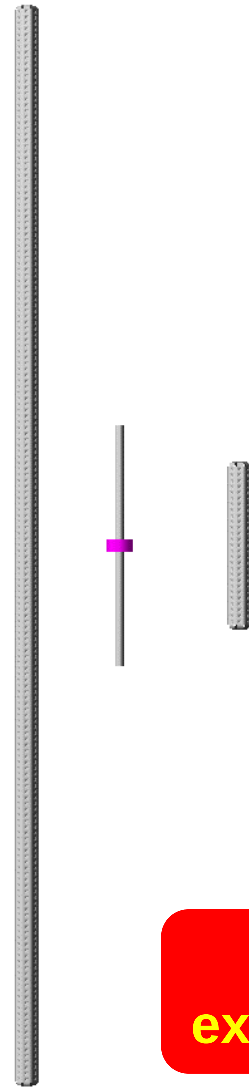


90

Frequency: 14.1 MHz
Dielectric: $\varepsilon_r = 52$, $\sigma = 0.17$ S/m
Tree diameters: 2.14 feet
Trees: Dodecagonal wire grid
V plane (blue)
H plane (red)
Gain: 5.68 dBi
Efficiency: 82.2%

3-Element Yagi Using Hexadecagonal Grid Trees





Free space (dipole) model

For monopole, use upper half and ground plane

Two trees (loaded wire grids)

- $\varepsilon_r = 52$, $\sigma = 0.17$ S/m
- Tree diam 2.14 ft
- Seg length 0.417 ft
- Grid wire diam 0.133 ft
- Seg len/grid w diam 3.14
- Segments per λ 167

Model segments 13,489

Optimum dimensions undetermined

Number of segments exceeds 4nec2 limit of 11,000

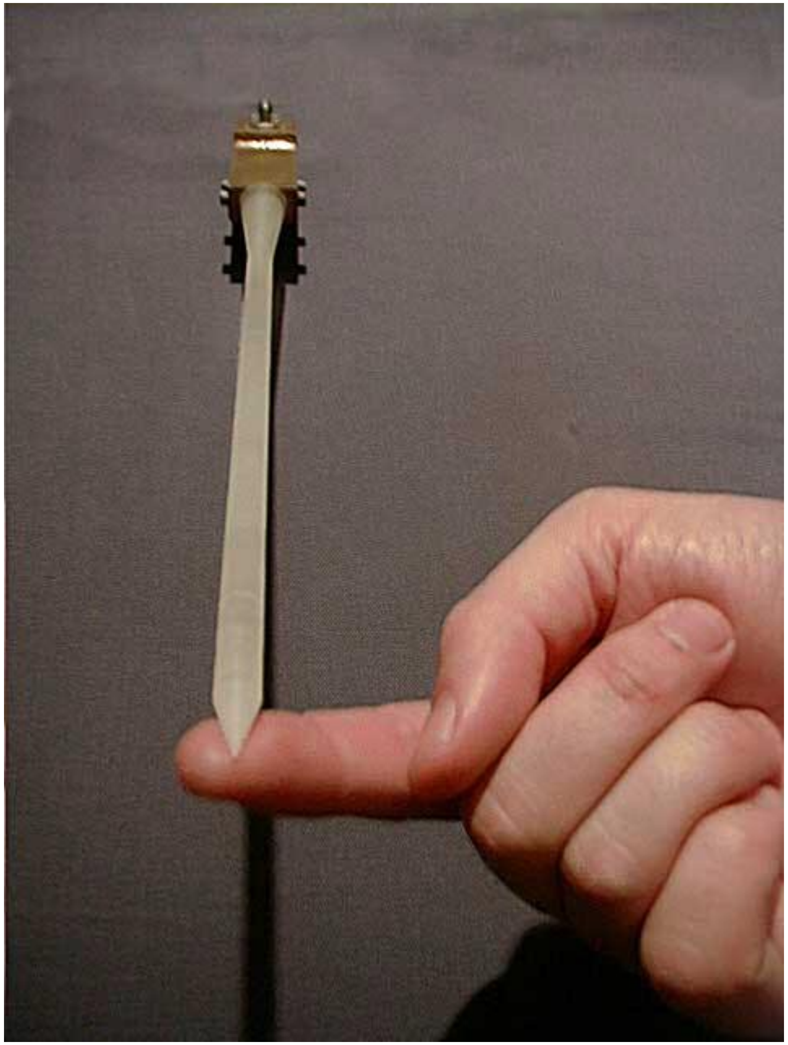
Eliminate (Almost All) Metal

Organic driven elements

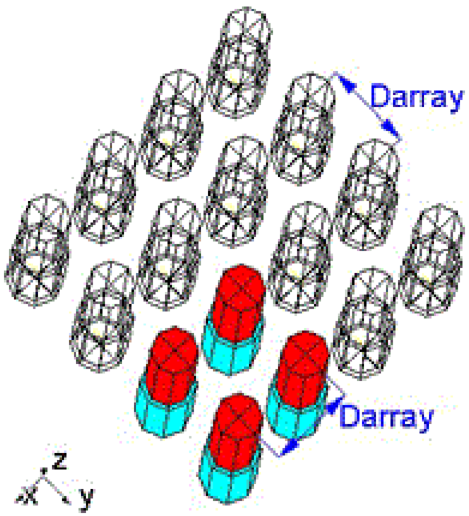
Cylindrical Dielectric Resonator Antennas (DRAs)

- **The internal fields in a dielectric resonator antenna are cavity modes**
- **The cavity modes drive (couple to) the external fields**
- **Radiation from a cylindrical resonator is generally either**
  - Axial
    - Radiation is "end-fire," in the direction of the axis
    - Cylinder acts like a waveguide or traveling wave structure
    - Examples: Polyrod antennas, helical antennas
  - Normal
    - Radiation is sideways, normal (perpendicular) to the axis
    - Cylinder acts like a dipole
    - Examples: Rubber ducks, tall trees

Dielectric Rod (Polyrod) Antennas and Arrays



- Material: Polystyrene
- Frequency: 11.6 GHz
- Gain: 20 dBi
- Bandwidth: 40%
- Ceramic or fused quartz rods can handle high power
- Polyrod arrays are used in high-power radar systems

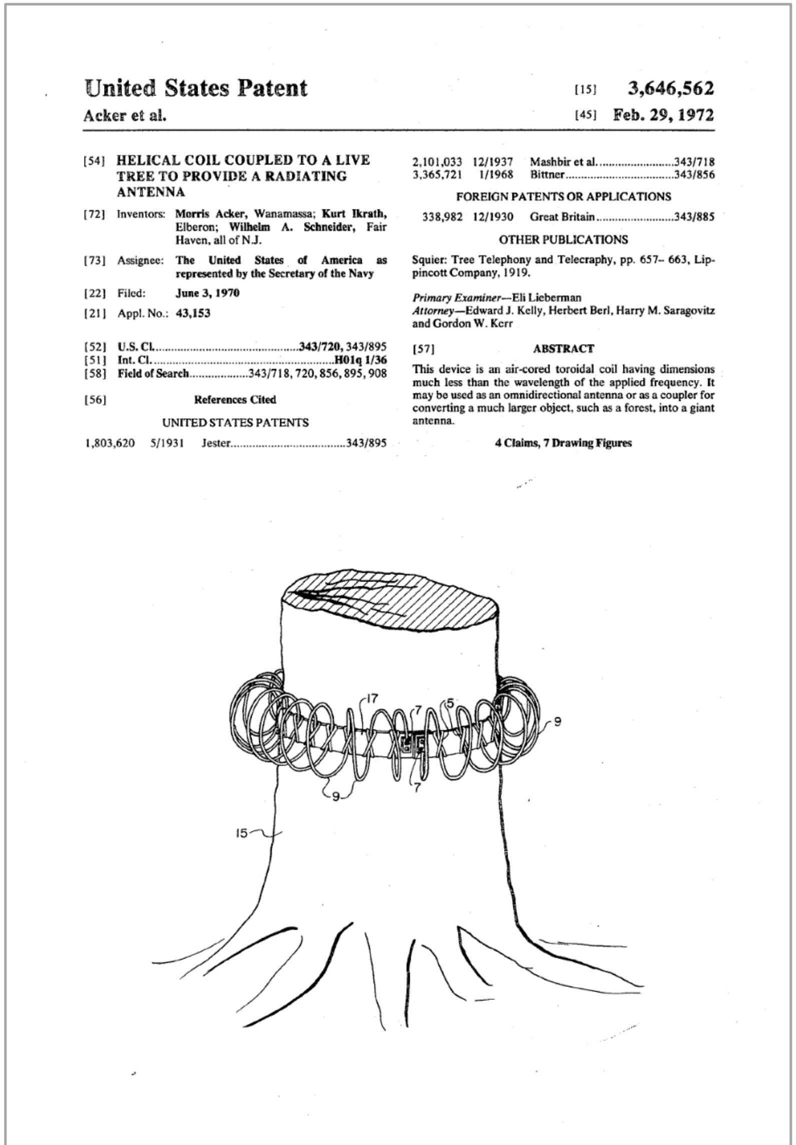


An Organic Antenna Farm?

Ralph Hartwell, W5JGV

https://w5jgv.com/tree_antenna

Hybrid Electromagnetic Antenna Couplers (HEMAC)



United States Patent [15] **3,646,562**

Acker et al. [45] **Feb. 29, 1972**

[54] **HELICAL COIL COUPLED TO A LIVE TREE TO PROVIDE A RADIATING ANTENNA**

[72] Inventors: **Morris Acker**, Wanamassa; **Kurt Ikrath**, Elberon; **Wilhelm A. Schneider**, Fair Haven, all of N.J.

[73] Assignee: **The United States of America as represented by the Secretary of the Navy**

[22] Filed: **June 3, 1970**

[21] Appl. No.: **43,153**

[52] **U.S. Cl.** **343/720**, 343/895
[51] **Int. Cl.** **H01q 1/36**
[58] **Field of Search** 343/718, 720, 856, 895, 908

[56] **References Cited**

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2,101,033 12/1937 Mashbir et al. 343/718
3,365,721 1/1968 Bittner 343/856

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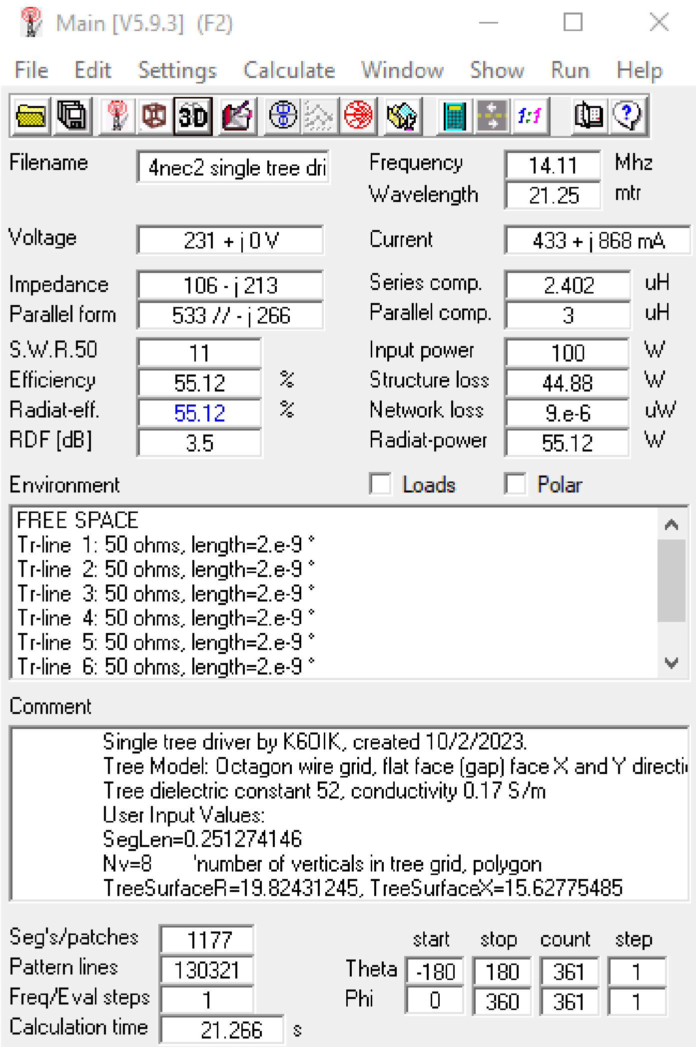
Primary Examiner—Eli Lieberman
Attorney—Edward J. Kelly, Herbert Berl, Harry M. Saragovitz and Gordon W. Kerr

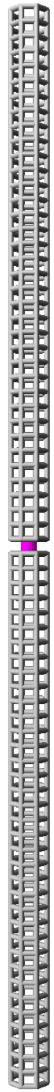
[57] **ABSTRACT**

This device is an air-cored toroidal coil having dimensions much less than the wavelength of the applied frequency. It may be used as an omnidirectional antenna or as a coupler for converting a much larger object, such as a forest, into a giant antenna.

4 Claims, 7 Drawing Figures

A Single Driven Tree – Octagonal Grid Model





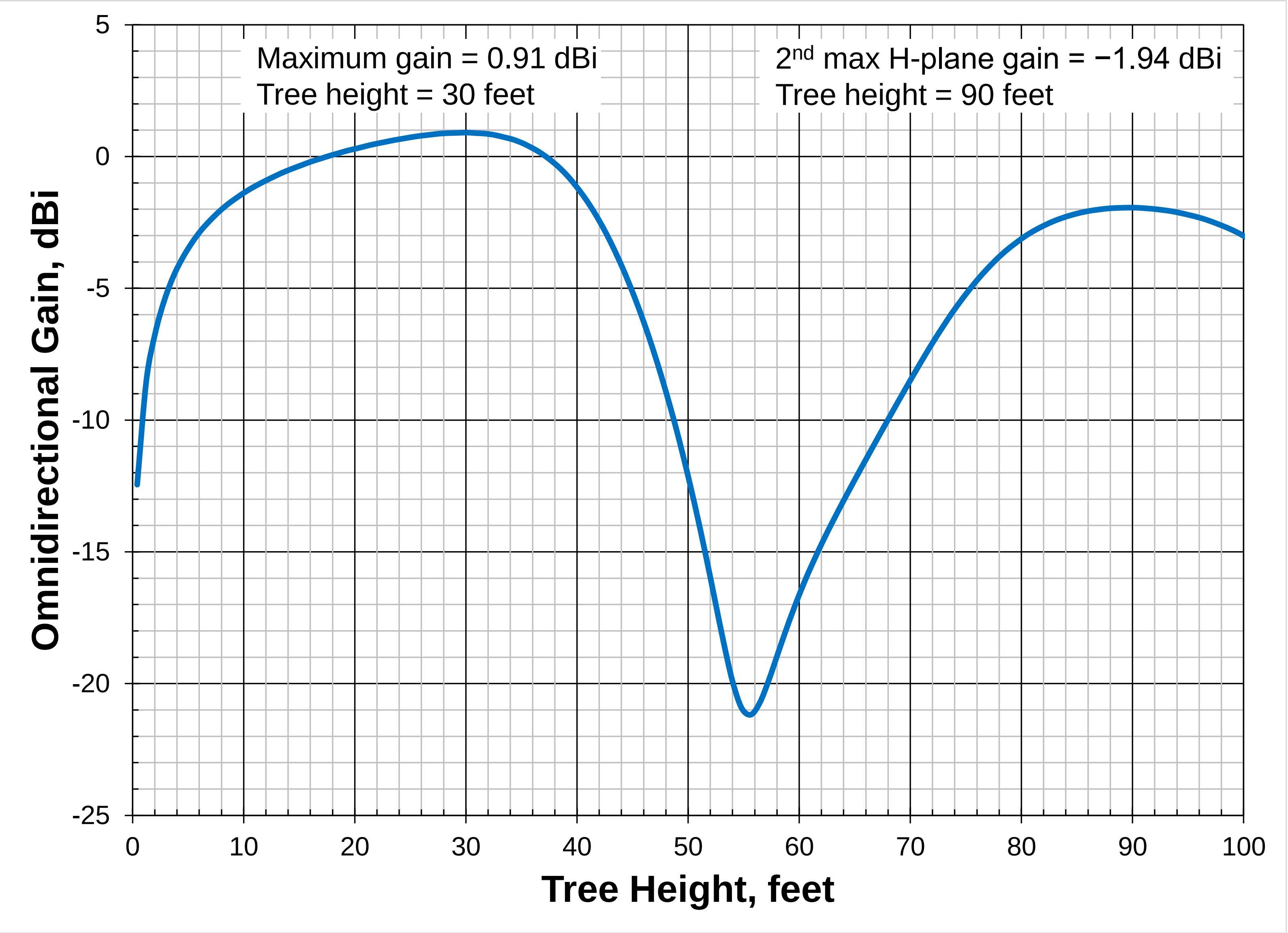
Free space (dipole) model
For monopole, use upper half and ground plane
Tree (loaded wire grid)

ε_r = 52, σ = 0.17 S/m	
Tree diam	2.15 ft
Seg length	0.824 ft
Grid wire diam	0.262 ft
Seg len/grid w diam	3.14
Segments per λ	84.6
Model segments	1,177
Optimum dimensions	
Tree height	30.1 ft
(driver half-length	0.43 λ)

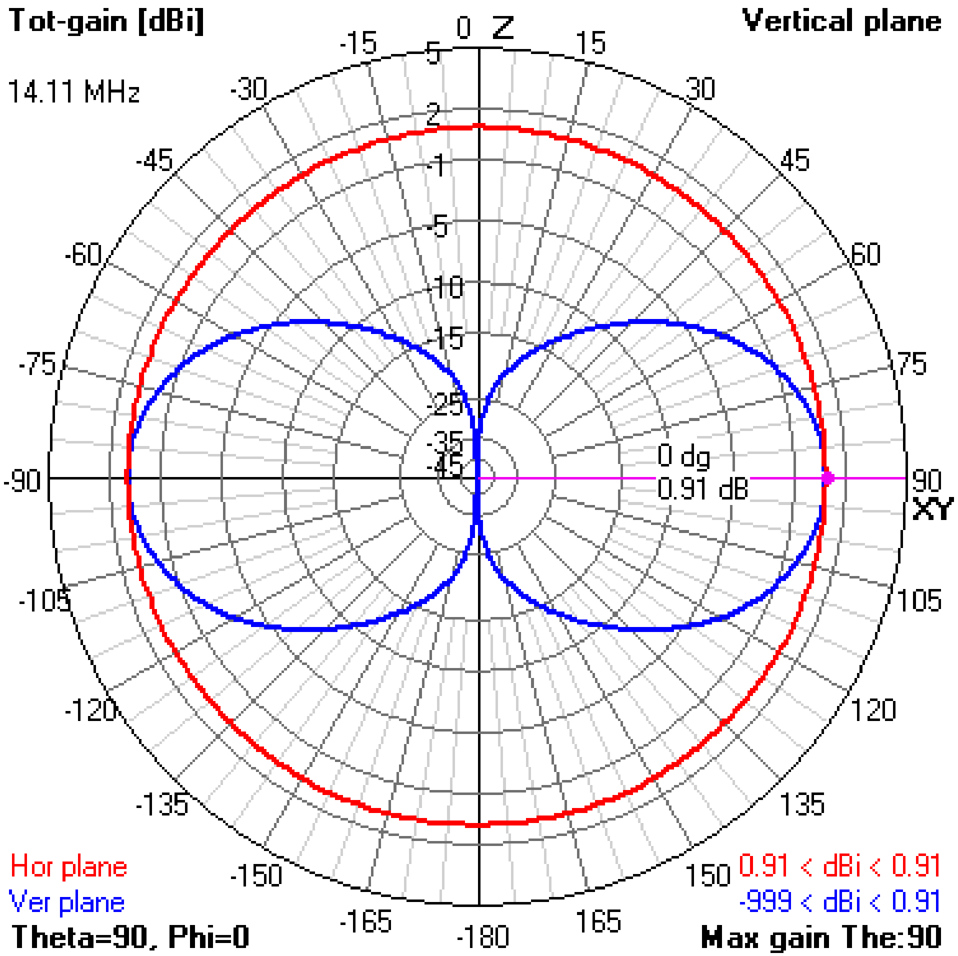
<u>Driven Element Feed</u>

NEC-2 cannot model HEMAC feed directly
NEC-2 lacks magnetic frill for this structure
Tree vertical wires fed by distribution network
8 infinitesimal transmission lines
Source on short segment on central axis

Gain of Driven Tree vs Tree Height



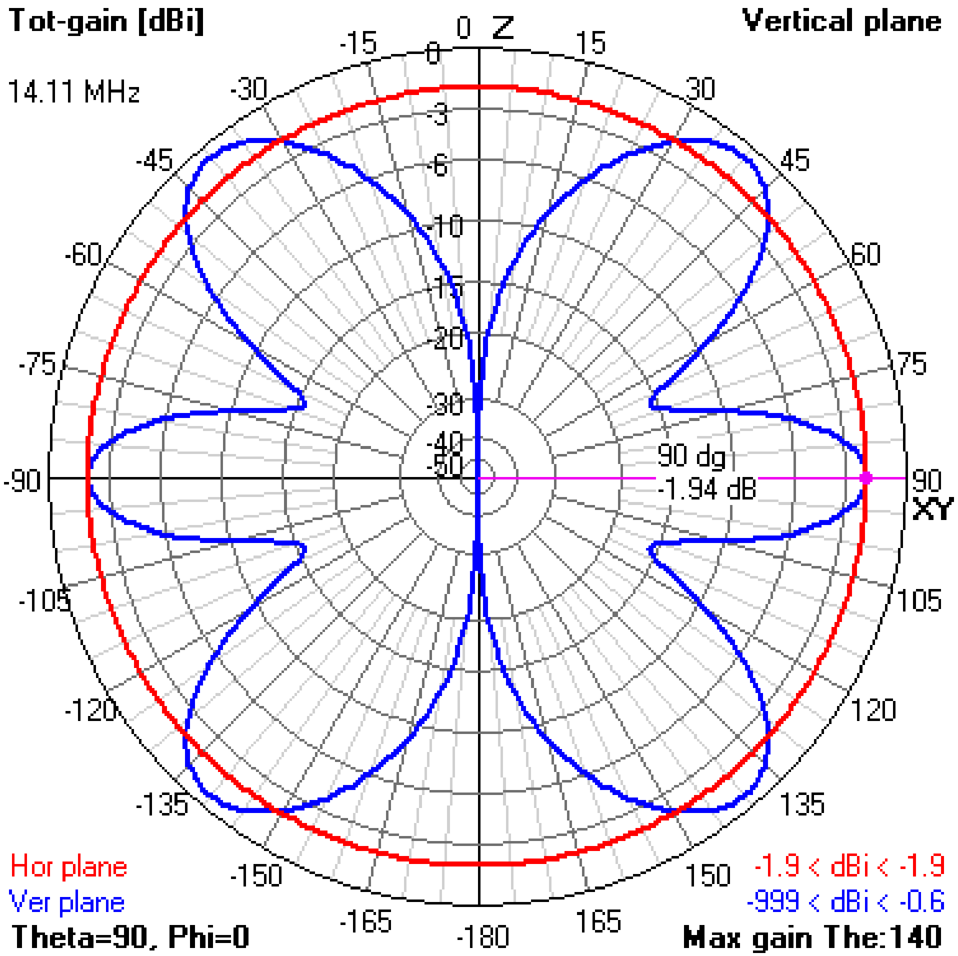
Driven Tree Max Gain: 0.91 dBi



Frequency: 14.1 MHz
Dielectric: $\varepsilon_r = 52$, $\sigma = 0.17$ S/m
Tree diameter: 2.15 feet
Trees: Octagonal wire grid
V plane (blue)
H plane (red)
Tree height: 30.1 feet (0.43 λ)
Gain: 0.91 dBi
Efficiency: 55.1%
Model segments: 1,177

Note: Tree height optimized for maximum H-plane gain

Driven Tree 2nd Max Gain: −1.94 dBi



Frequency: 14.1 MHz

Dielectric: $\varepsilon_r = 52$, $\sigma = 0.17$ S/m

Tree diameter: 2.15 feet

Trees: Octagonal wire grid

V plane (blue)

H plane (red)

Tree height: 89.9 feet (1.29 λ)

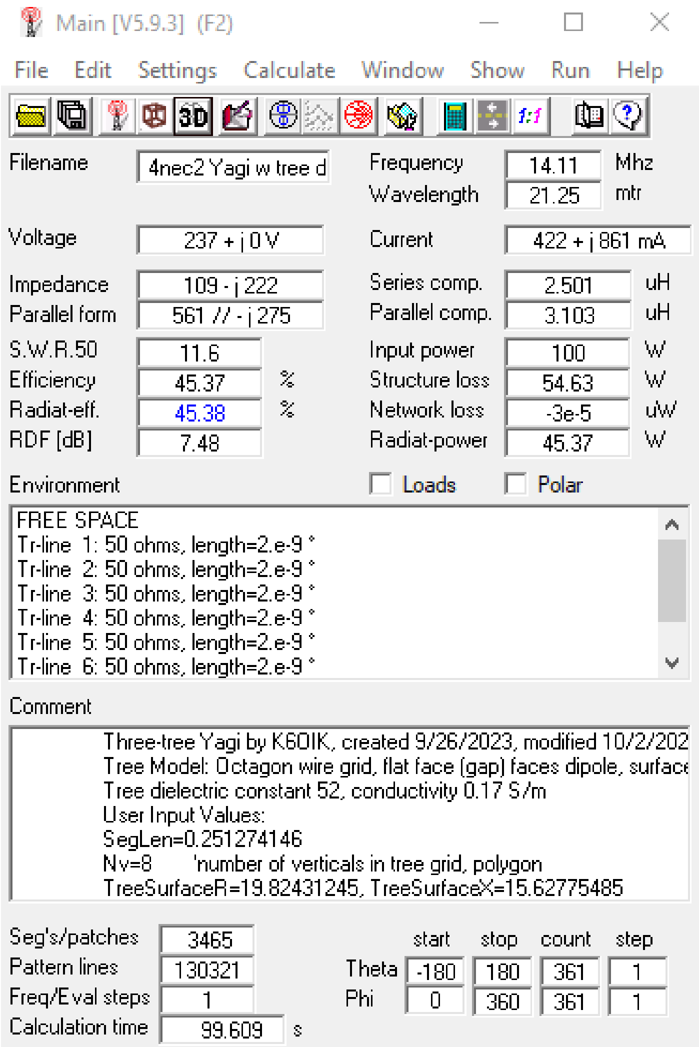
H-plane Gain: −1.94 dBi

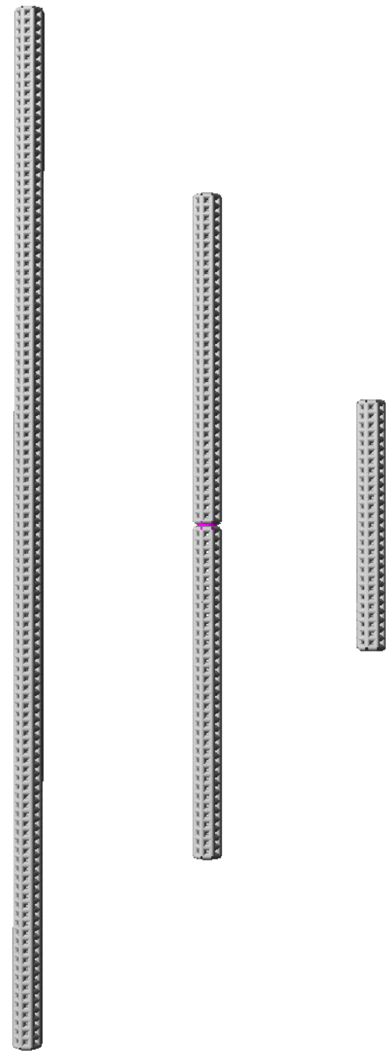
Efficiency: 36.7%

Model segments: 3,513

Note: Tree height optimized for 2nd maximum H-plane gain

100% Organic Yagi-Uda Using Octagonal Grid Trees



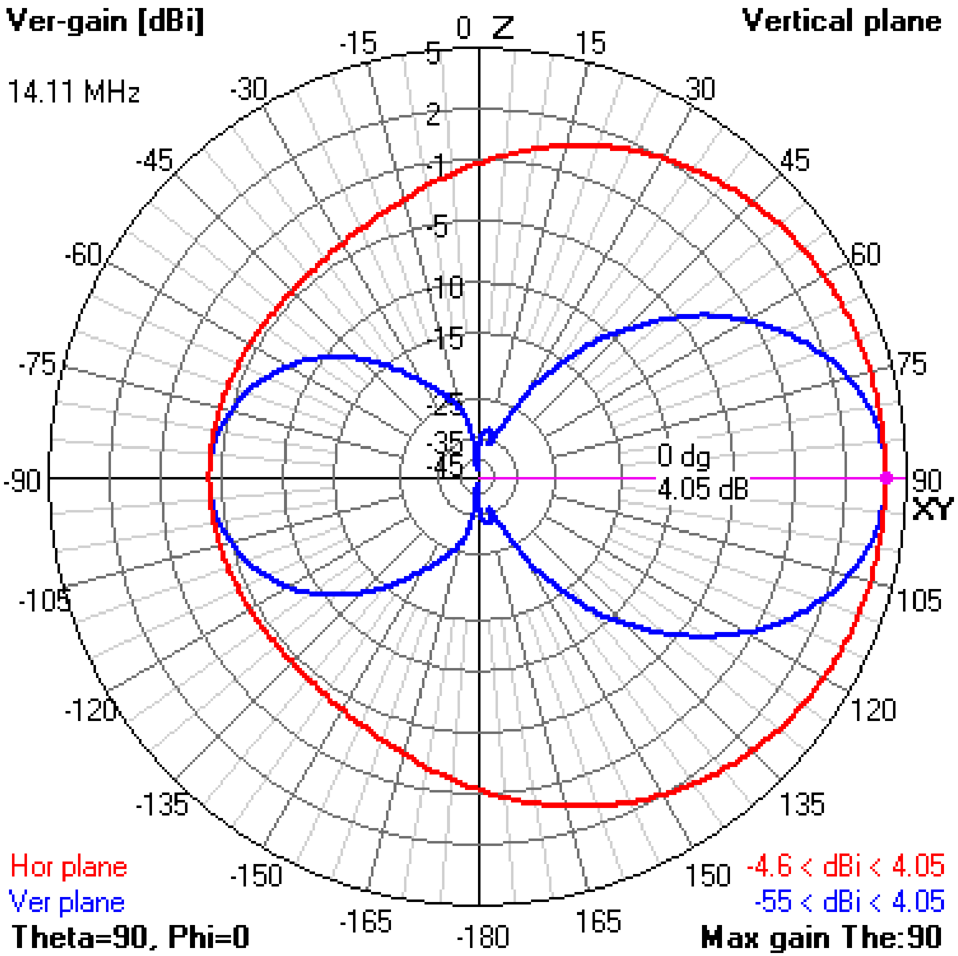


Free space (dipole) model
For monopole, use upper half and ground plane
Three trees (loaded wire grids)

$\varepsilon_r = 52$, $\sigma = 0.17$ S/m

Tree diam	2.15 ft
Seg length	0.824 ft
Grid wire diam	0.262 ft
Seg len/grid w diam	3.14
Segments per λ	84.6
Model segments	3,465
Optimum dimensions	
Refl-driver	16.39 ft
Refl-director	31.35 ft
Refl half length	47.40 ft
Driver half len	30.09 ft
Dir half length	11.13 ft

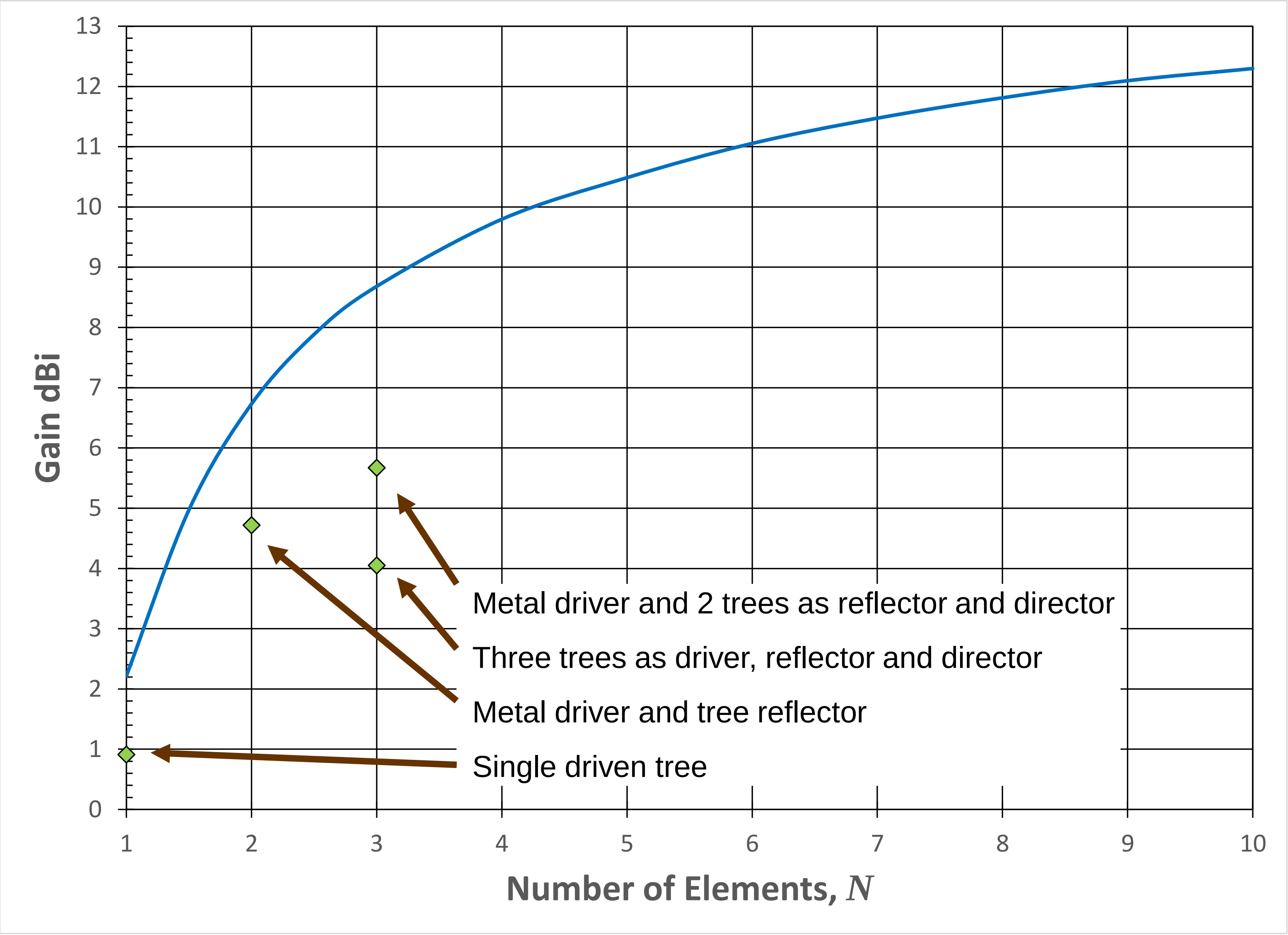
100% Organic Yagi-Uda Gain: 4.05 dBi



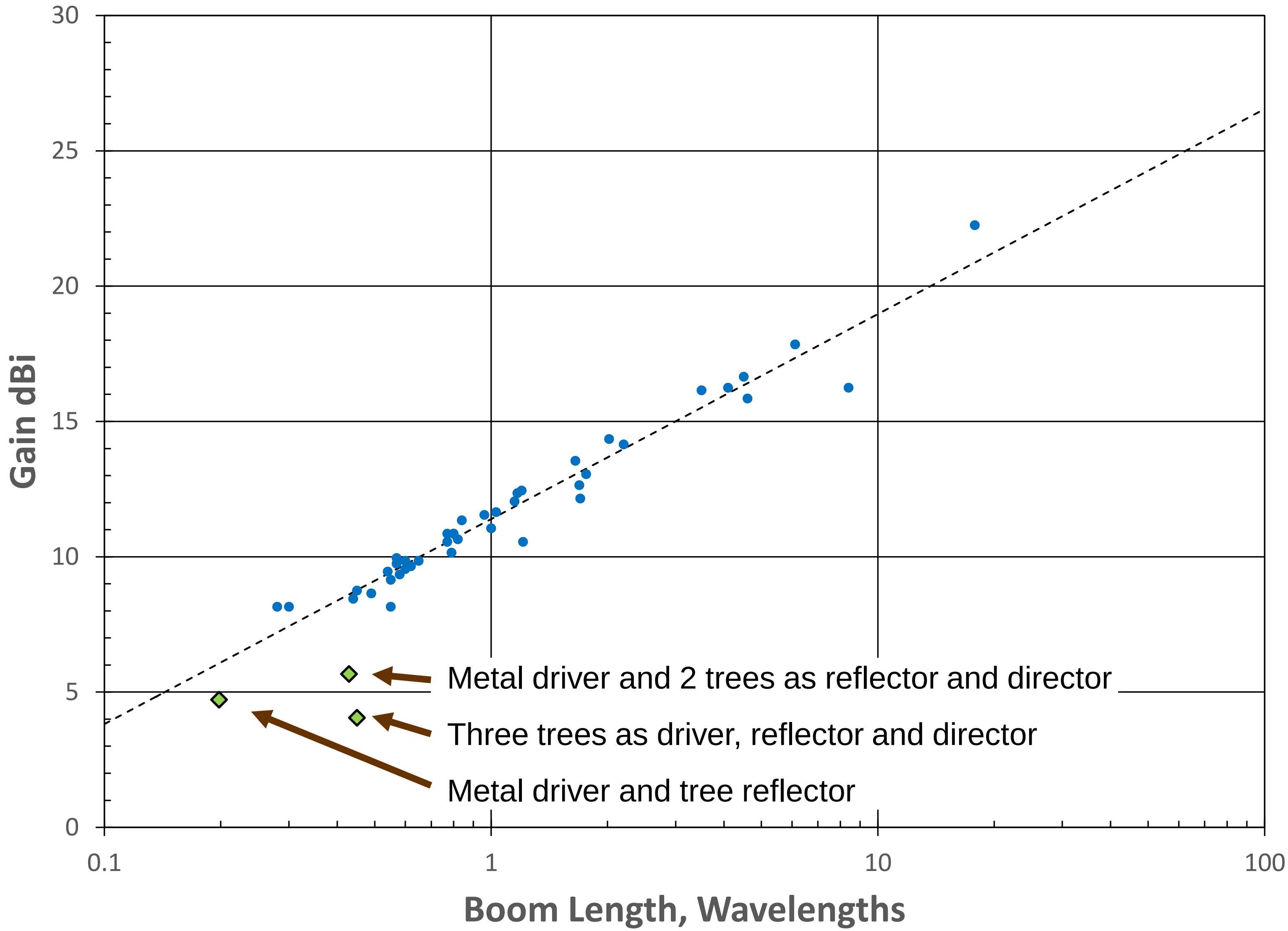
Frequency: 14.1 MHz
Dielectric: $\varepsilon_r = 52$, $\sigma = 0.17$ S/m
Tree diameters: 2.15 feet
Trees: Octagonal wire grid
V plane (blue)
H plane (red)
Gain: 4.05 dBi
Efficiency: 45.4%
Model Segments: 3,465
Refl-driver: 16.39 ft (0.235 λ)
Refl-director: 31.35 ft (0.450 λ)
Refl half length: 47.40 ft (0.680 λ)
Driver half len: 30.09 ft (0.432 λ)
Dir half length: 11.13 ft (0.160 λ)

Summary

Yagi-Uda Antennas – Organic Trees vs Lossless Metal



Yagi-Uda Antennas – Organic Trees vs Lossless Metal



Summary and Conclusions

- Trees and shrubs can increase antenna performance
- Antenna modeling software can model dielectric objects
- Dielectric surfaces can be modeled by wire grids of loaded wires
- Surface impedance is always inductive, never capacitive
- At HF, trees act like dielectric columns which can be modeled by hexagonal or octagonal loaded wire grids
- Computer modeling is faster than building (growing) and testing experimental prototypes – hours vs decades
- Putting a vertical beside an existing tree can boost gain by 2.5 dB
- A single driven tree can have omnidirectional gain of -1.25 dB relative to half-wave dipole or quarter-wave vertical monopole
- Trees make good elements for Yagi-Uda vertical arrays
- Our modeling method can be used to quantify the effect of trees on supported wire antennas such as dipoles, slopers and vees
- Organic arrays are not easy to rotate!

Rotate? … If It's Impossible, Someone Will Do It!

The Frontier – Loop Antennas ... To Be Continued

Resources

References, Software, Books

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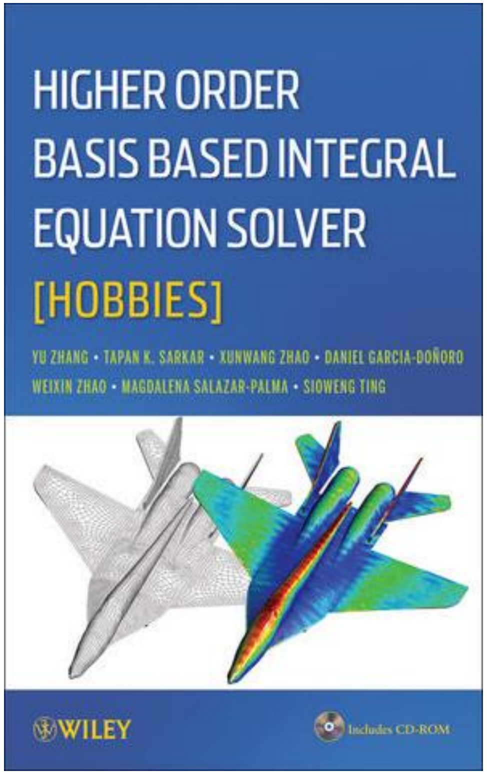
Free or Low Cost Antenna Modeling Software Links at https://www.fars.k6ya.org/others

- **Thin Wire MoM Codes**
  - ANSim – by Mark Tilson, Multiradius Bridge Current method is more accurate than NEC-4
  - AN-SOF – by Tony Golden, similar accuracy to NEC-5, uses exact kernel and integral equation
  - NEC-5 (2019) – Improved accuracy, replaced kernels with exact kernel and integral equation, fewer artifacts, improved numerical stability, less strict geometry rules, similar accuracy to AN-SOF
  - NEC-4 (1992) – Improved accuracy for stepped-radius wires and electrically-small segments, end caps and insulated wires, catenary-shaped wires, improved error detection
  - NEC-2 (1981) – Sommerfield-Norton ground interaction for wire structures above lossy ground; numerical Green's function allows modifying without repeating whole calculation
  - MiniNEC (1980) – by Jay Rockway and Jim Logan, N6BRF, different algorithms from NEC, used inside MMANA-GAL
  - AWAS 2.0 (2001) – by Tony Djordjević, predecessor thin-wire formulation to that in WIPL-D and HOBBIES, has exact kernel, higher-order polynomial basis functions, minimal geometry restrictions, high numerical efficiency
- **User Interface Programs**
  - AutoEZ – by Dan Maguire, AC6LA. GUI for EZNEC that adds useful features
  - EZNEC Pro+ v7.0 – by Roy Lewallen, W7EL. Free GUI for NEC-2, NEC-4, and NEC-5
  - 4nec2 – by Arie Voors. Free GUI for NEC-2 and NEC-4
  - MMANA-GAL – GUI for MiniNEC (popular in the UK)
- **Yagi Design**
  - QY4 (Quick Yagi) – by Sidney Smith, WA7RAI, a calculator for Yagi-Uda design
  - Yagi Calculator – by John Drew, VK5DJ, a calculator for DL6WU VHF/UHF Yagi-Uda design
  - YagiCAD – by Paul McMahon, VK3DIP, a calculator for VHF/UHF Yagi-Uda design
  - YO (Yagi Optimizer) – by Brian Beezley, K6STI, a MiniNEC based DOS program for Yagi-Uda antenna design, v6.5.1 archived by IW5EDI
  - YW 2.0 (Yagi for Windows) – by Dean Straw, N6BV, for monoband Yagi-Uda design, included with the *ARRL Antenna Book*
- **Surface MoM Code**
  - HOBBIES (2010) – Similar to WIPL-D except has out-of-core solver. Development led by T.K. Sarkar, Syracuse University, based on algorithms developed at University of Belgrade. No longer available
- **Finite Difference Time Domain (FDTD) Codes**
  - GprMax
  - Meep
  - OpenEMS

Accessory Software

- **AutoEZ by Dan Maguire, AC6LA, https://www.ac6la.com**
  - Recommended accessory software for EZNEC
  - Excel/Visual Basic program
    - Free demo version (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
  - Optimizer – Nelder-Mead algorithm
  - Reads NEC, AO, and MMANA-GAL files
- OPTENNI **https://optenni.com**
  - Automated match network synthesis. Free trial on request
- **Ampsa Impedance Matching Wizard https://www.ampsa.com/c/imw-technical-overview**
  - Automated match network synthesis. Free trial on request

HOBBIES – No Longer Available



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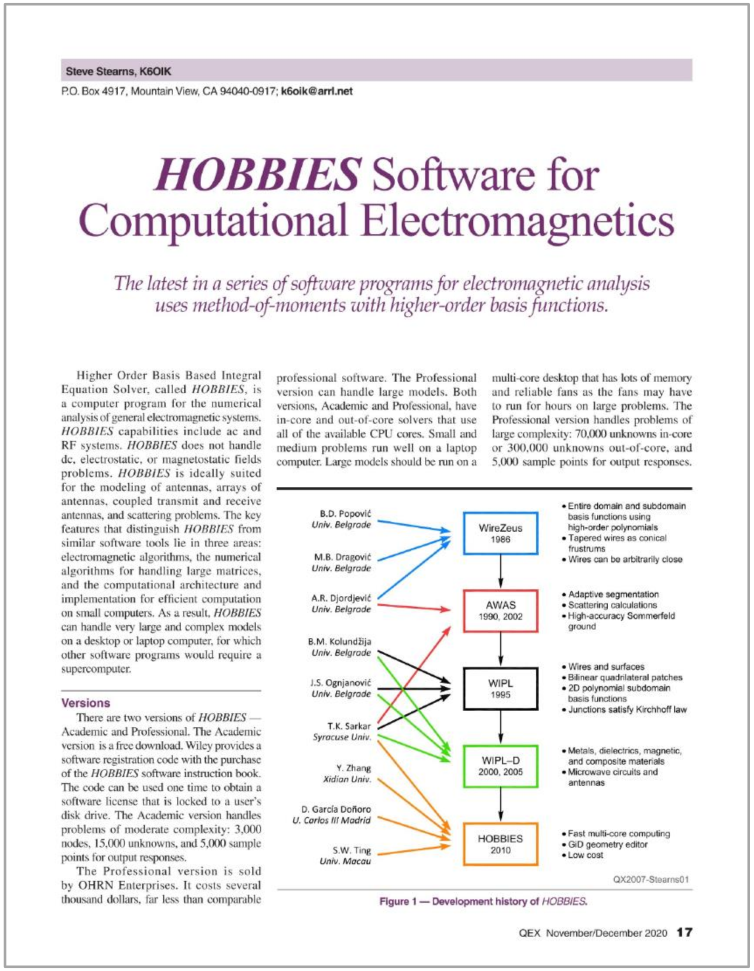

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HOBBIES Software for Computational Electromagnetics

The latest in a series of software programs for electromagnetic analysis uses method-of-moments with higher-order basis functions.

Higher Order Basis Based Integral Equation Solver, called *HOBBIES*, is a computer program for the numerical analysis of general electromagnetic systems. *HOBBIES* capabilities include ac and RF systems. *HOBBIES* does not handle dc, electrostatic, or magnetostatic fields problems. *HOBBIES* is ideally suited for the modeling of antennas, arrays of antennas, coupled transmit and receive antennas, and scattering problems. The key features that distinguish *HOBBIES* from similar software tools lie in three areas: electromagnetic algorithms, the numerical algorithms for handling large matrices, and the computational architecture and implementation for efficient computation on small computers. As a result, *HOBBIES* can handle very large and complex models on a desktop or laptop computer, for which other software programs would require a supercomputer.

Versions

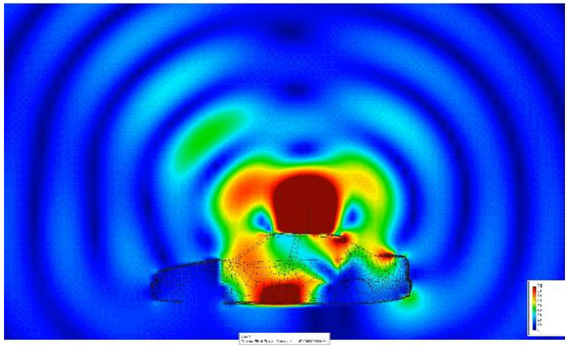
There are two versions of *HOBBIES* — Academic and Professional. The Academic version is a free download. Wiley provides a software registration code with the purchase of the *HOBBIES* software instruction book. The code can be used one time to obtain a software license that is locked to a user's disk drive. The Academic version handles problems of moderate complexity: 3,000 nodes, 15,000 unknowns, and 5,000 sample points for output responses.

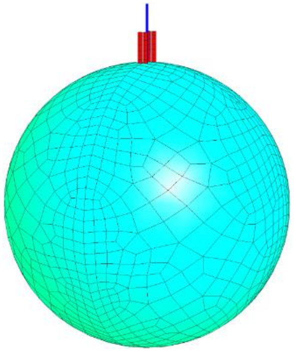
The Professional version is sold by OHRN Enterprises. It costs several thousand dollars, far less than comparable professional software. The Professional version can handle large models. Both versions, Academic and Professional, have in-core and out-of-core solvers that use all of the available CPU cores. Small and medium problems run well on a laptop computer. Large models should be run on a multi-core desktop that has lots of memory and reliable fans as the fans may have to run for hours on large problems. The Professional version handles problems of large complexity: 70,000 unknowns in-core or 300,000 unknowns out-of-core, and 5,000 sample points for output responses.

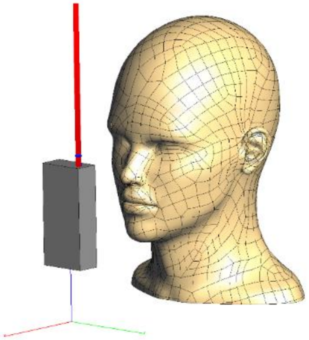
B.D. Popović
Univ. Belgrade
M.B. Dragović
Univ. Belgrade
A.R. Djordjević
Univ. Belgrade
B.M. Kolundžija
Univ. Belgrade
J.S. Ognjanović
Univ. Belgrade
T.K. Sarkar
Syracuse Univ.
Y. Zhang
Xidian Univ.
D. García Doñoro
U. Carlos III Madrid
S.W. Ting
Univ. Macau
WireZeus
1986
AWAS
1990, 2002
WIPL
1995
WIPL–D
2000, 2005
HOBBIES
2010
• Entire domain and subdomain basis functions using high-order polynomials
• Tapered wires as conical frustrums
• Wires can be arbitrarily close
• Adaptive segmentation
• Scattering calculations
• High-accuracy Sommerfeld ground
• Wires and surfaces
• Bilinear quadrilateral patches
• 2D polynomial subdomain basis functions
• Junctions satisfy Kirchhoff law
• Metals, dielectrics, magnetic, and composite materials
• Microwave circuits and antennas
• Fast multi-core computing
• GiD geometry editor
• Low cost
QX2007-Stearns01

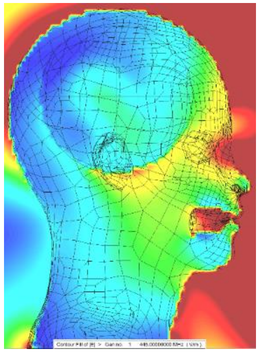
Figure 1 — Development history of *HOBBIES*.

QEX November/December 2020 **17**

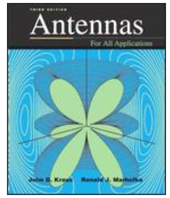


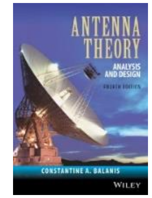




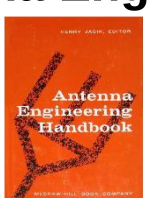


Good Antenna Books

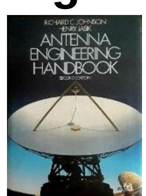




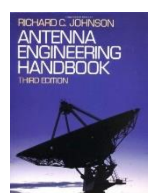
- **Books for antenna engineers and students**
  - C.A. Balanis, *Antenna Theory: Analysis and Design*, 4e, Wiley, 2016
  - R.C. Hansen and R.E. Collin, *Small Antenna Handbook*, Wiley, 2011
  - J.D. Kraus and R.J. Marhefka, *Antennas*, 3e, McGraw-Hill, 2001
- **Antenna research papers**
  - IEEE Xplore subscription online archive, https://ieeexplore.ieee.org/Xplore/home.jsp
  - Allerton Antenna Applications Symposium DVD archive 1952-2018
  - ACES Journal Archives http://www.aces-society.org/journal.php
  - Progress in Electromagnetics Research https://www.jpier.org
- **Antenna Engineering Handbooks – 5 editions**



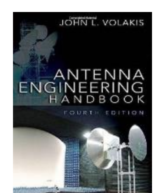
1961



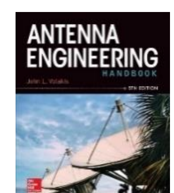
1984



1993

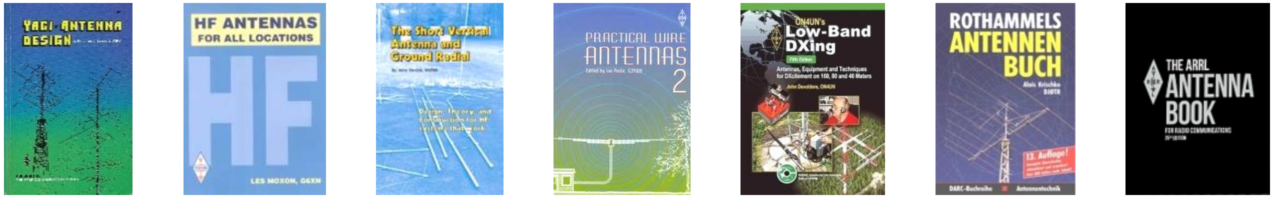


2007



2019

Good Antenna Books continued



- **Books for Radio Amateurs**
  - H.W. Silver, N0AX, ed., *ARRL Antenna Book*, 25e, ARRL, 2023
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  - J. Devoldere, ON4UN, *ON4UN's Low-Band Dxing*, 5e, ARRL, 2011
  - I. Poole, G3YWX, ed., *Practical Wire Antennas 2*, RSGB, 2005
  - J. Sevick, W2FMI, *The Short Vertical Antenna and Ground Radial*, CQ, 2003
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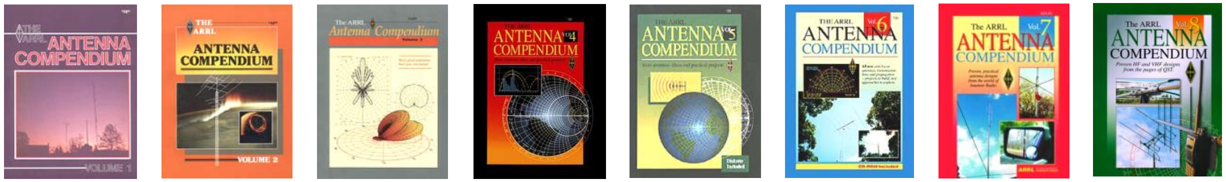
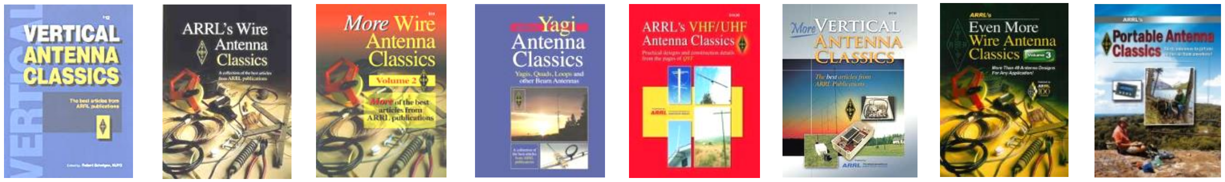
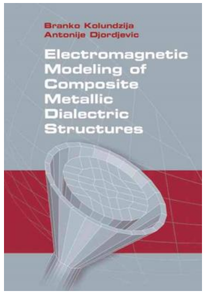
- **ARRL Antenna Compendium series – eight volumes**



- **ARRL Antenna Classics series – eight titles**



Recent Antenna Books of Interest



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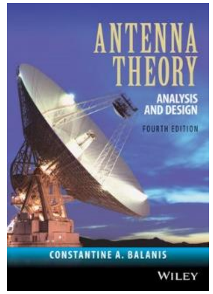

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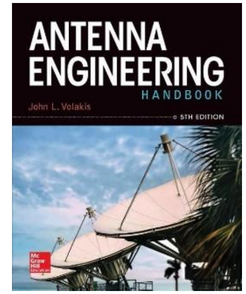

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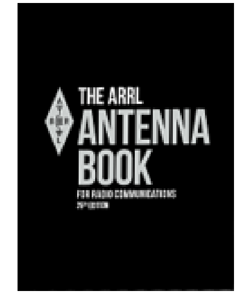

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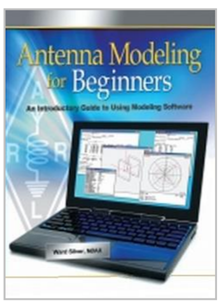

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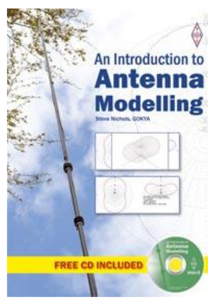

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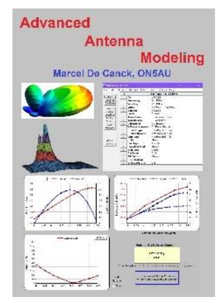

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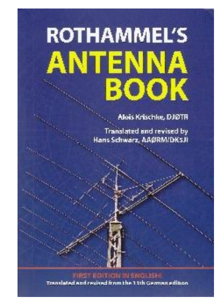
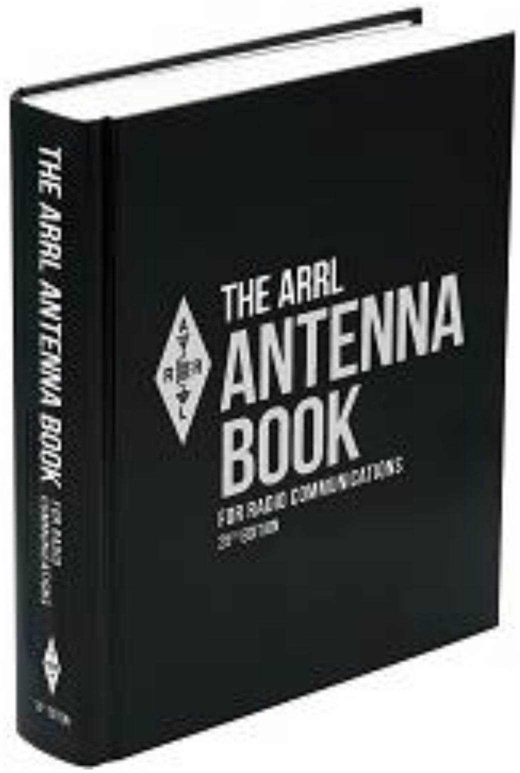


A. Krischke, DJ0TR, ed., *Rothammel's Antenna Book*, English transl., 13e, DARC, 2019

Hot Off the Press!



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***ARRL Antenna Book*, 25th Edition**
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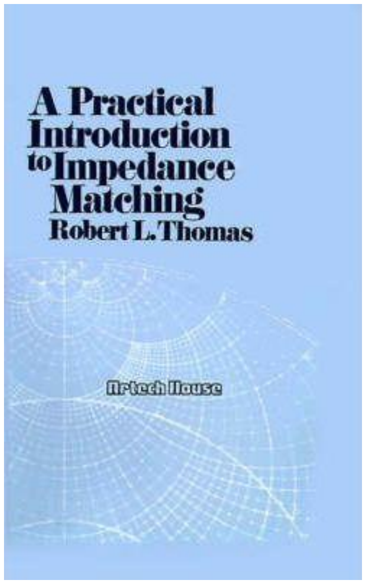
Impedance Matching for Beginner and Professional



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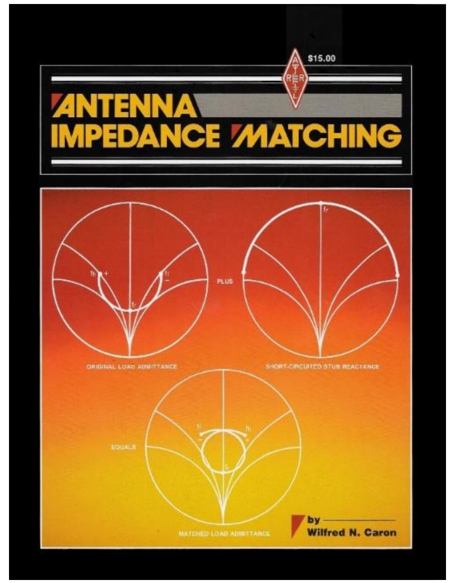

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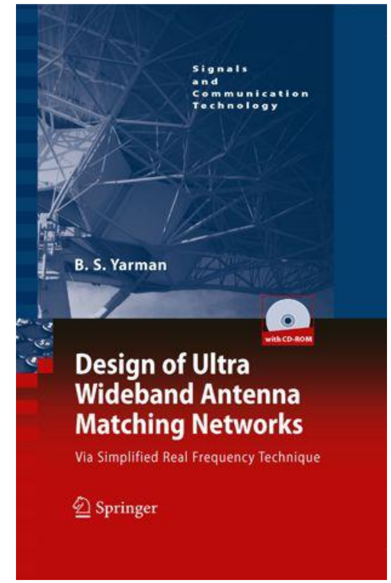

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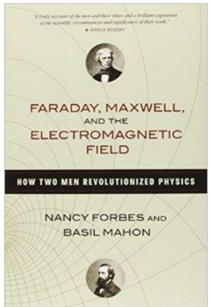

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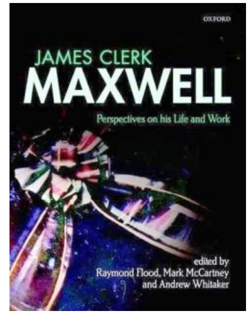

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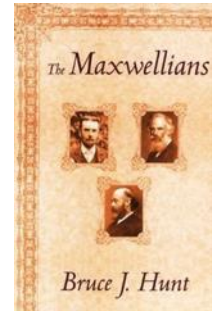

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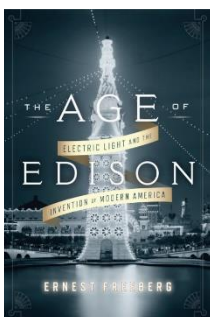

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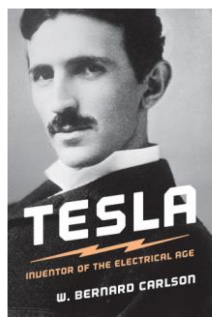

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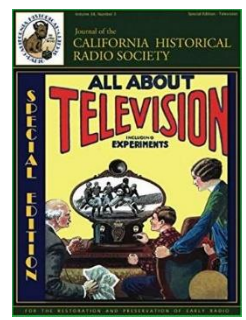

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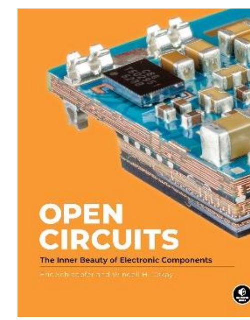

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Fear Not the Tree!

This presentation will be archived at
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Except for U.C. Berkeley bears who shall forever fear Stanford University's tree.