The Best Shape for a Wire Antenna

Revised and Expanded

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A Conundrum

A ham wants to make a wire antenna for 20-meter DX. It needs to have a lot of gain. More gain is better. He is blessed with an infinite spool of antenna wire but cursed with rusty, old wire cutters. He can make but two cuts. He cuts off two pieces of wire to drive one against the other. How much gain can his antenna have? In answering this simple question, Steve will lead us beyond dipoles into a world of 2D paths in 3D space. You will throw away your wire cutters after Steve shows how Texas longhorns and cowboy hats can beat beams.

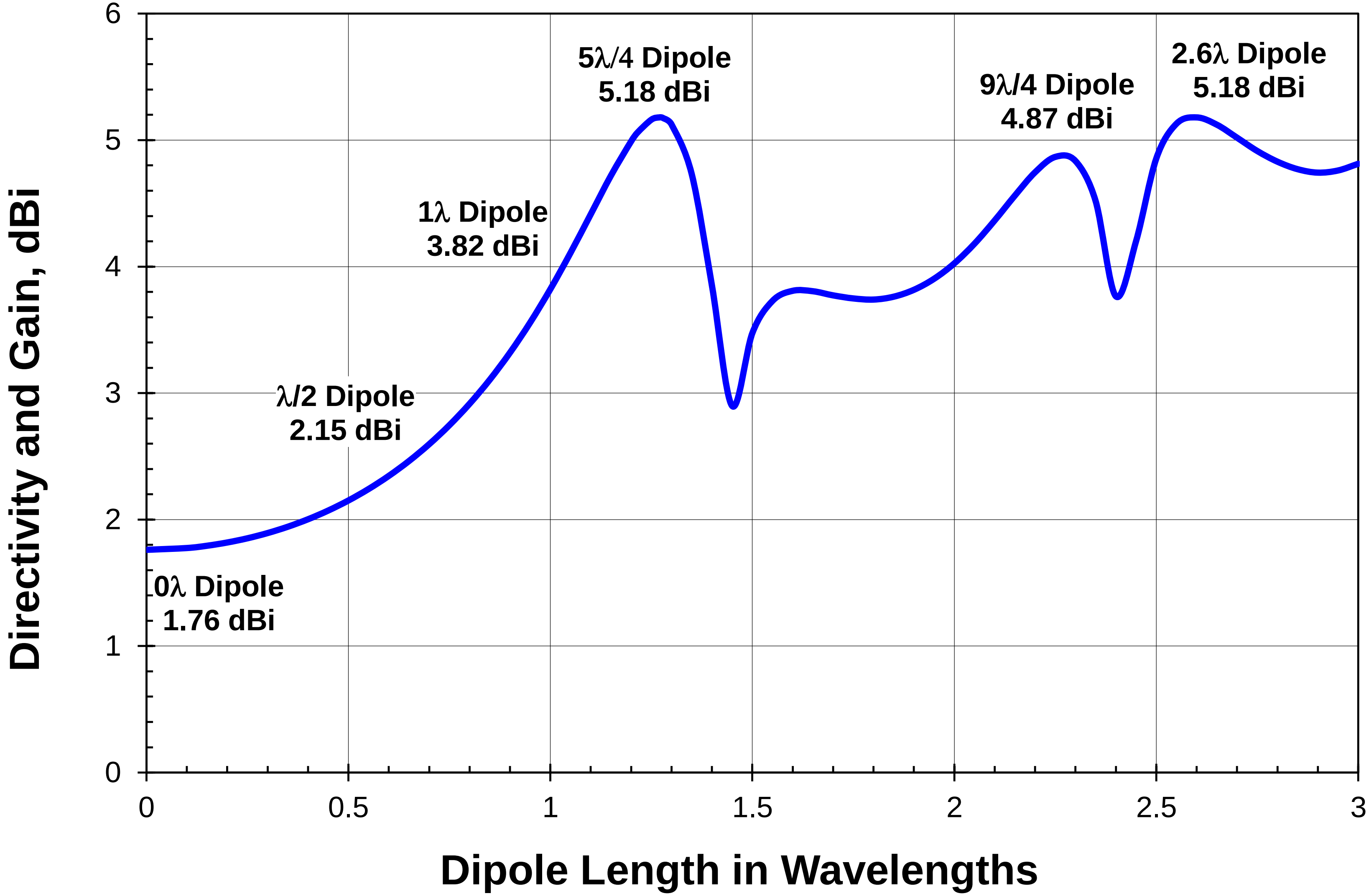
Speaker's Biography

- **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
  - 1st-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	✓
2023	Grow an Antenna … from Seeds	✓
2024	The Best Shape for a Wire Antenna	

Antenna Question for 2024
A Dipole's Gain versus Its Length?



Topics

- **Wire antenna design choices**
- **What antenna optimizers can do**
- **Genetic evolved antennas**
- **Planar symmetric wire antennas**
  - Plane contains main lobe, max gain direction
  - Plane perpendicular to main lobe, max gain direction
- **The Landstorfer family**
  - Cowboy hats
  - Texas longhorns
- **Tensile structures and tensegrity**
- **Optimized NVIS antennas: how to "beat a vertical Yagi"**
- **Summary and surprising conclusions**

Amateur Antenna Paradigms

- Antennas made of straight elements (wires, rods, and tubes)
- Antennas made of conductors (metals)
- Resonant antennas
- Narrowband antennas
- But … many interesting antennas break these rules!

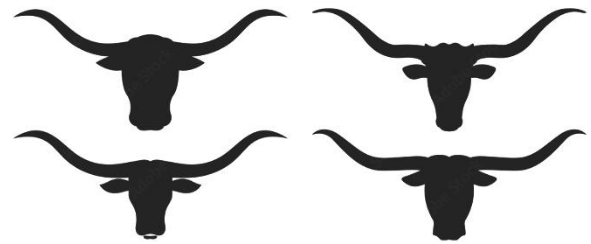
Wire Antenna Design Considerations

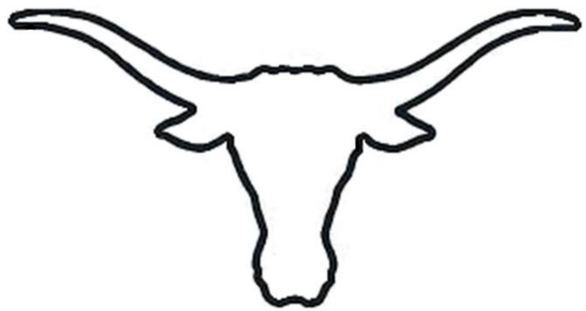
- **Traditional wire antenna variables**
  - Wire length
  - Wire diameter
- **Often unconsidered wire antenna variables**
  - Topology
    - Connectedness: continuous or disconnected
    - Joints or junctions (To solder or not to solder, that is the question!)
  - Geometry: antenna size and shape
- **Design objective**
  - Narrowband, broadband, multi-band
  - Feedpoint impedance, SWR
  - Losses and radiation efficiency
  - Pattern: shape and directional gain

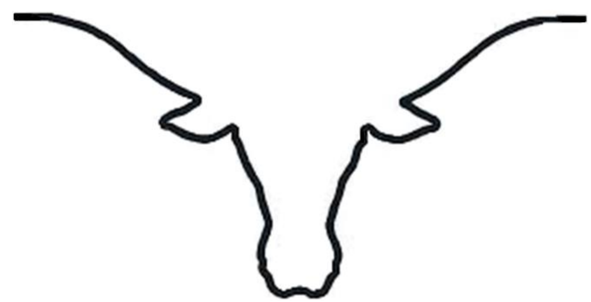
Today's goal: maximum directional gain!

Some Interesting Shapes

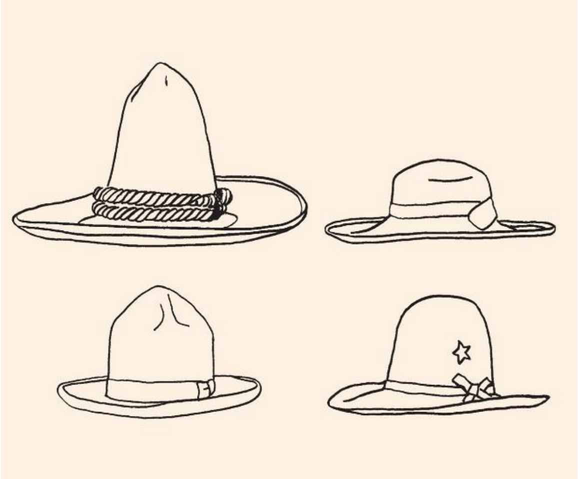
Texas Long Horn Steers

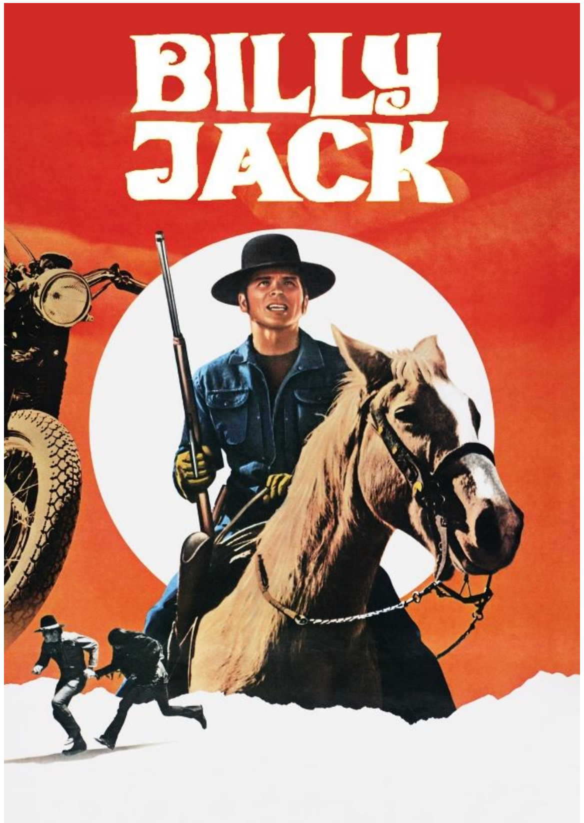






Cowboy Hats





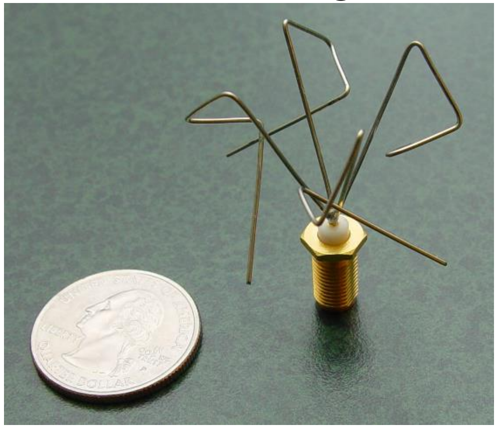
Tom Laughlin, *Billy Jack* (1971)

Charles Bronson, *Chato's Land* (1972)

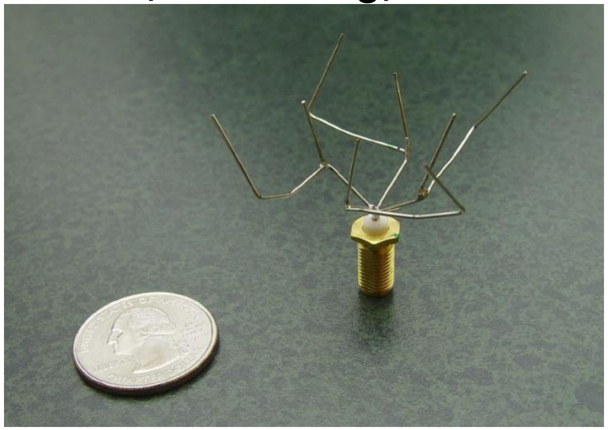
Father Guido Sarducci
Saturday Night Live (1978)

Genetic Evolved Antennas – "Crooked" Wires

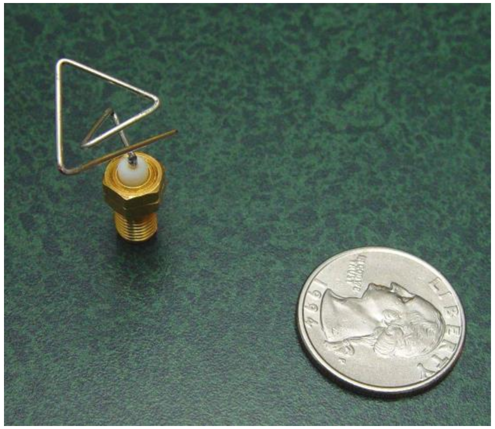
Gen-1, Non-Branching, ST5-4W-03



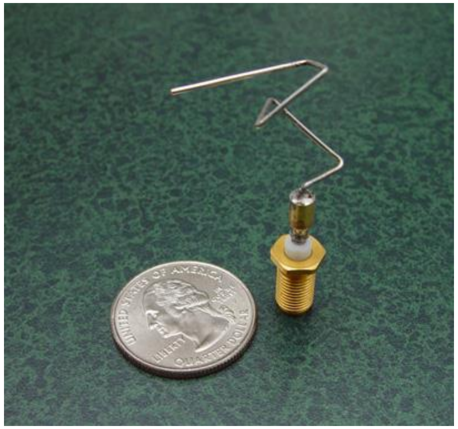
Gen-1, Branching, ST5-3-10



Gen-2, EA 1

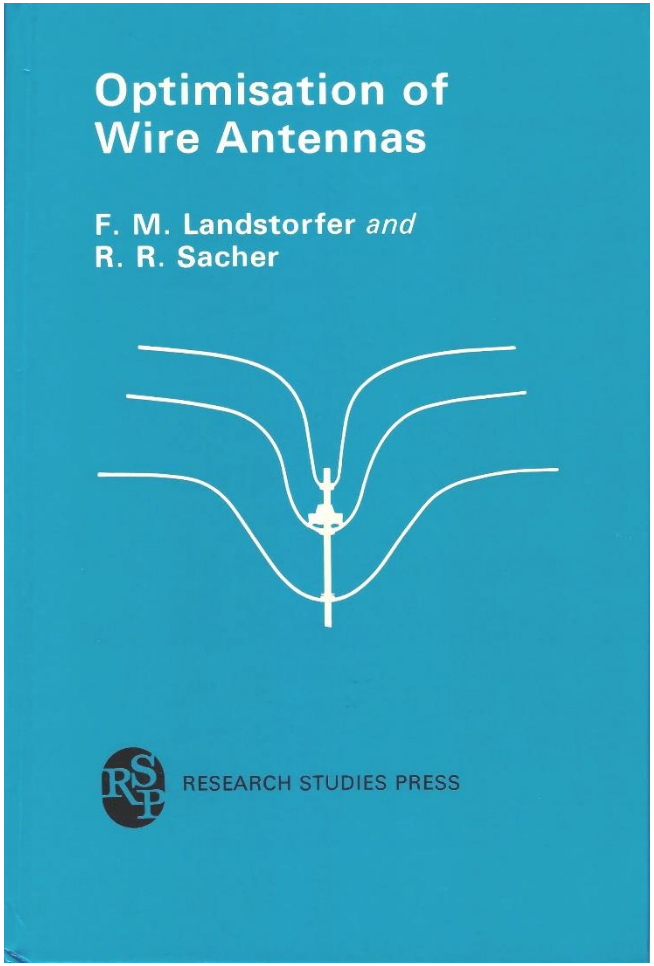


Gen-2, EA 2



Dr. Jason D. Lohn, "Automated Antenna Design and Optimization," Foothills Amateur Radio Society, June 17, 2011.

An Old Book Inspired Me



F.M. Landstorfer and R.R. Sacher, *Optimisation of Wire Antennas*, Research Studies Press/Wiley, 1985.

Modeling Programs with Optimizers

- **AutoEZ and NEC-5**
  - Sommerfeld ground
  - NEC-5 is better suited to junctions at arbitrary angles than NEC-2 or NEC-4
  - Allows constants, variables, and formulas
  - Optimizer: Nelder-Mead
  - Optimizer is slow due to serial processing and software structure
    - AutoEZ invokes EZNEC which invokes NEC-5
  - Suitable for a small number of variables
- **HOBBIES**
  - Meshed dielectric surface ground
  - Allows constants, symbols, and formulas
  - Optimizers: Powell, Nelder-Mead, Particle Swarm
  - Optimizer is fast due to parallel multi-core hyperthreaded processing (Windows MPI), direct access to engine, and memory management
  - Handles large number of variables

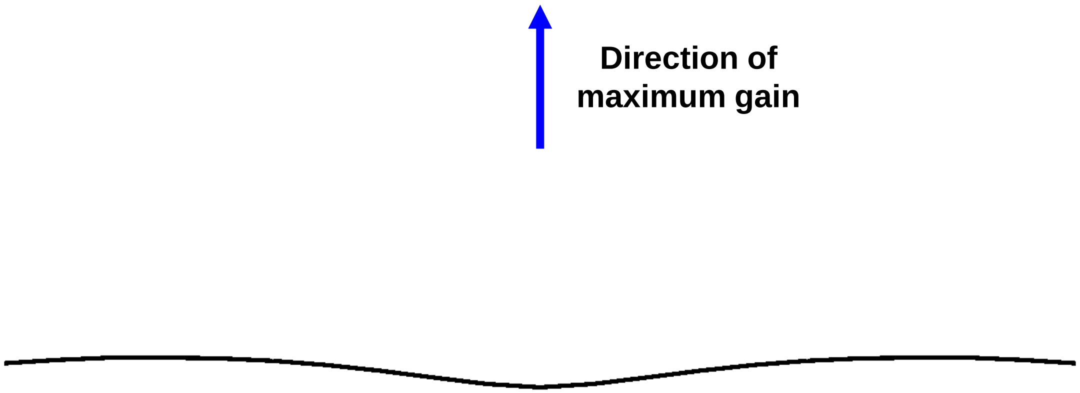
The Four-Part Optimization Specification

- **Antenna model (class of antennas)**
  - Planar wire antenna
  - Max gain direction lies in the plane
  - Topologically connected
    - Excludes Yagi-Uda arrays
  - No branching
    - Excludes fan dipoles
  - Single wire of specified length, arbitrary shape, and symmetric about a center feedpoint
- **Optimization variables and constraints**
  - Wire junction angles
  - Single segment wires
  - Wire lengths fixed at $\lambda/20$
  - Total wire length (sum of wire lengths) is an even multiple of $\lambda/20$
- **Single, simple goal**
  - Unidirectional with direction of maximum gain in the plane of the antenna
- **Optimizer algorithm**
  - Nelder-Mead (slow but reliable)

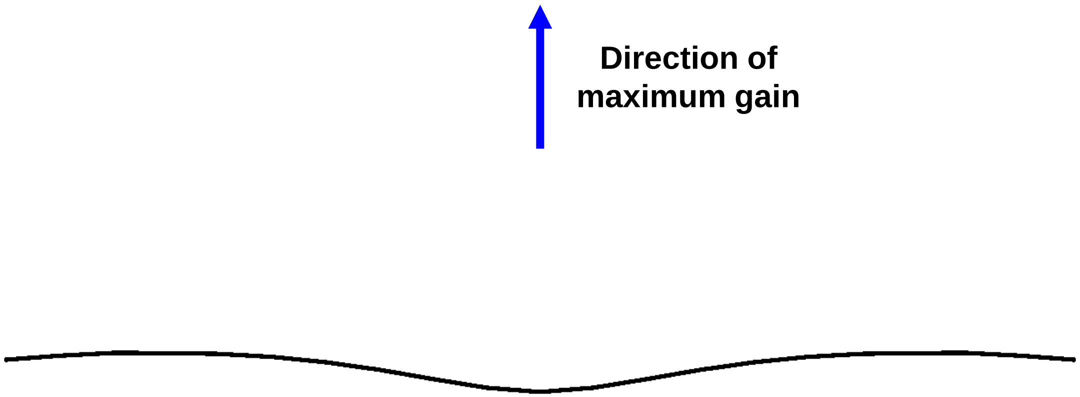
Optimal Free Space Shapes and Gains

Shapes and gains for 30 lengths that transition
from straight dipole
to cowboy hats
to Texas longhorn steers
to wavy vees

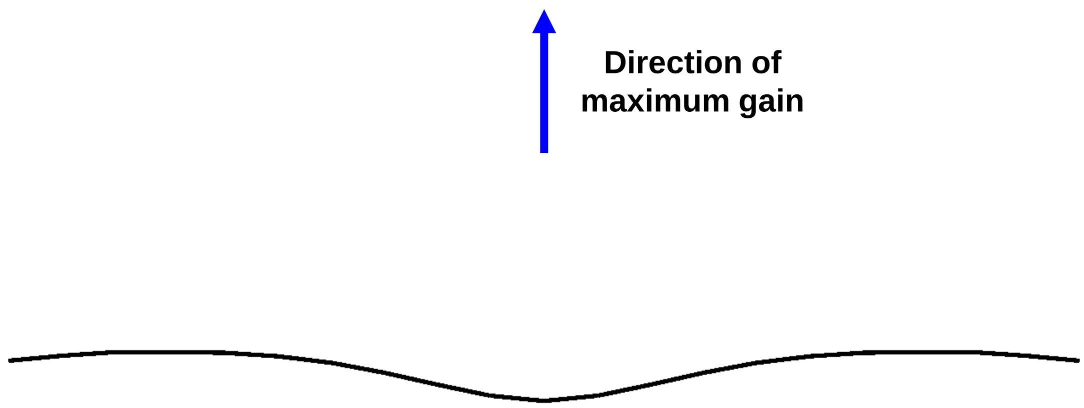
Length 0.5 Wavelength, Gain = 2.19 dBi



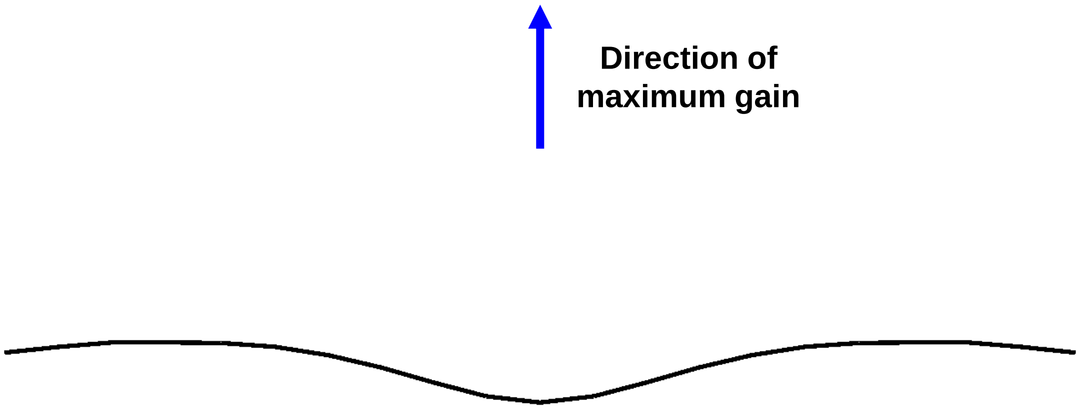
Length 0.6 Wavelength, Gain = 2.42 dBi



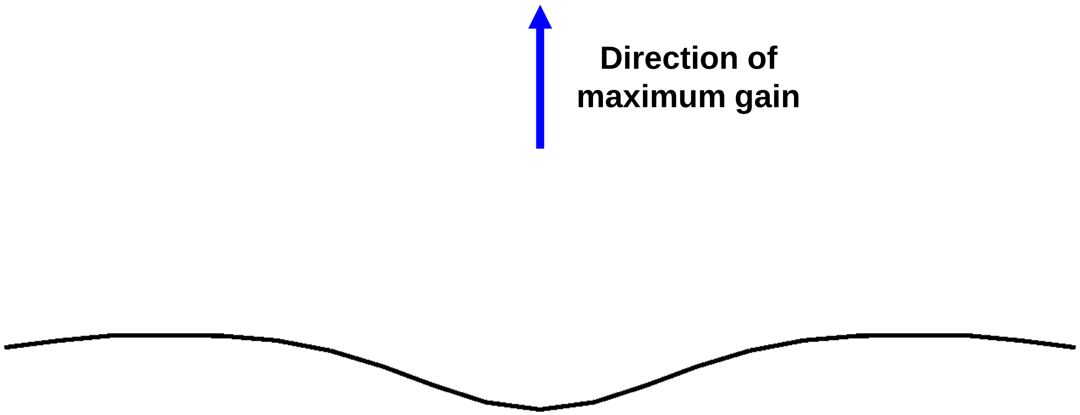
Length 0.7 Wavelength, Gain = 2.72 dBi



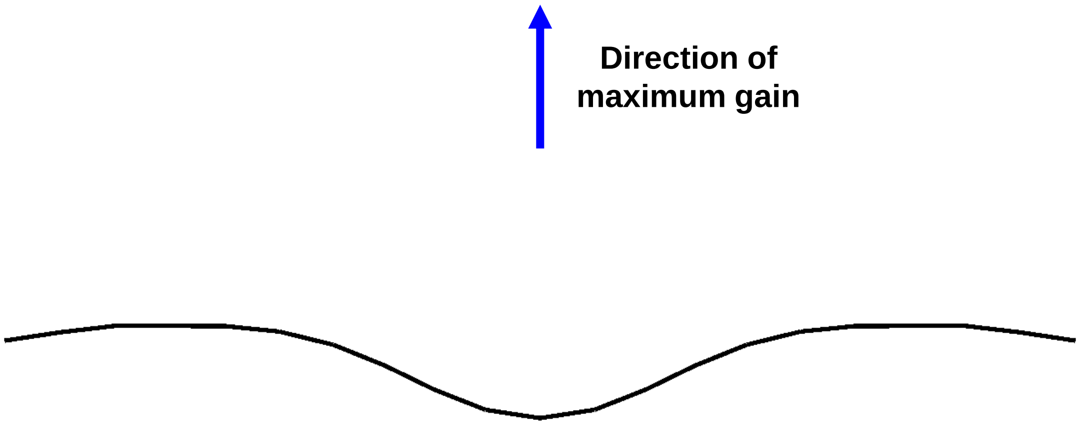
Length 0.8 Wavelength, Gain = 3.10 dBi



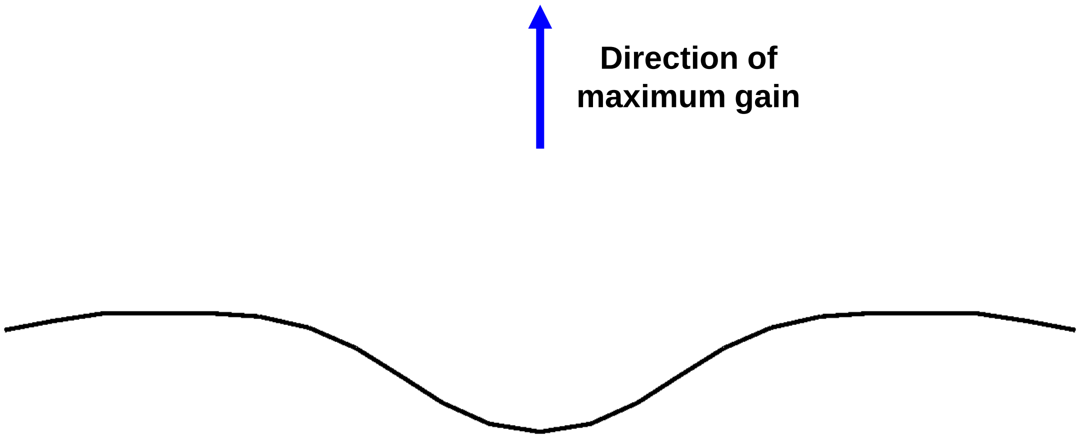
Length 0.9 Wavelength, Gain = 3.59 dB



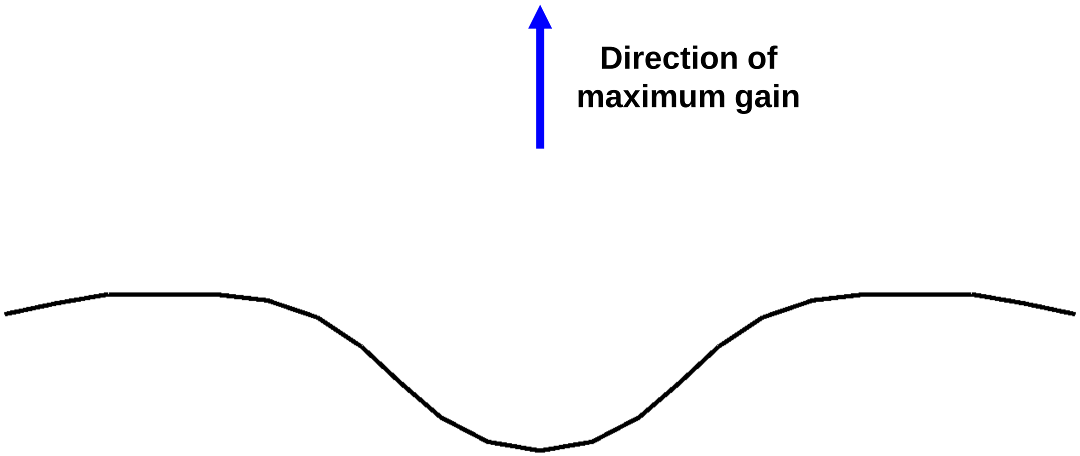
Length 1.0 Wavelength, Gain = 4.20 dBi



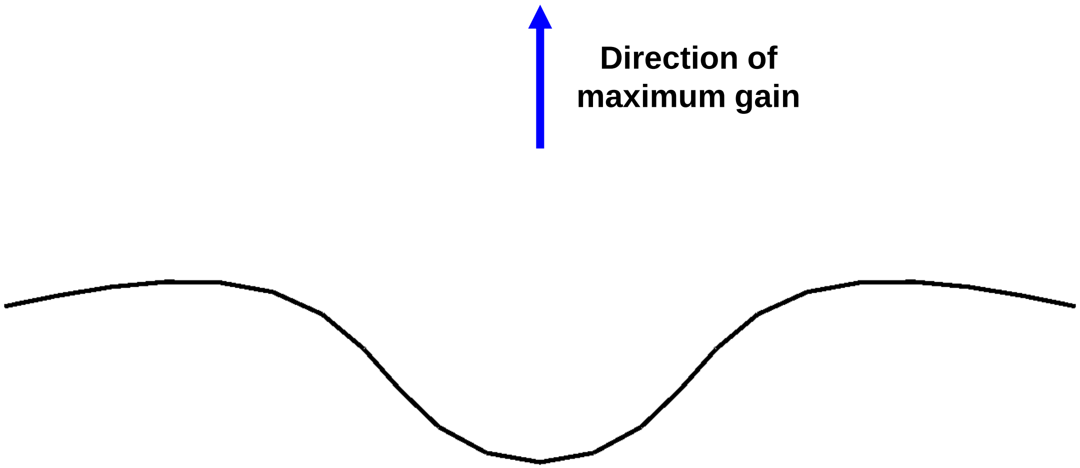
Length 1.1 Wavelengths, Gain = 4.95 dBi



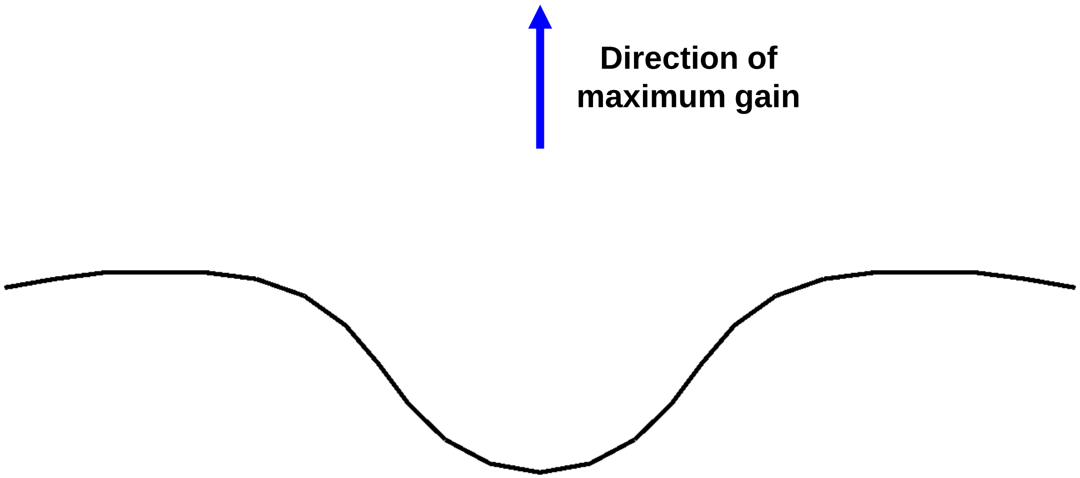
Length 1.2 Wavelengths, Gain = 5.81 dBi



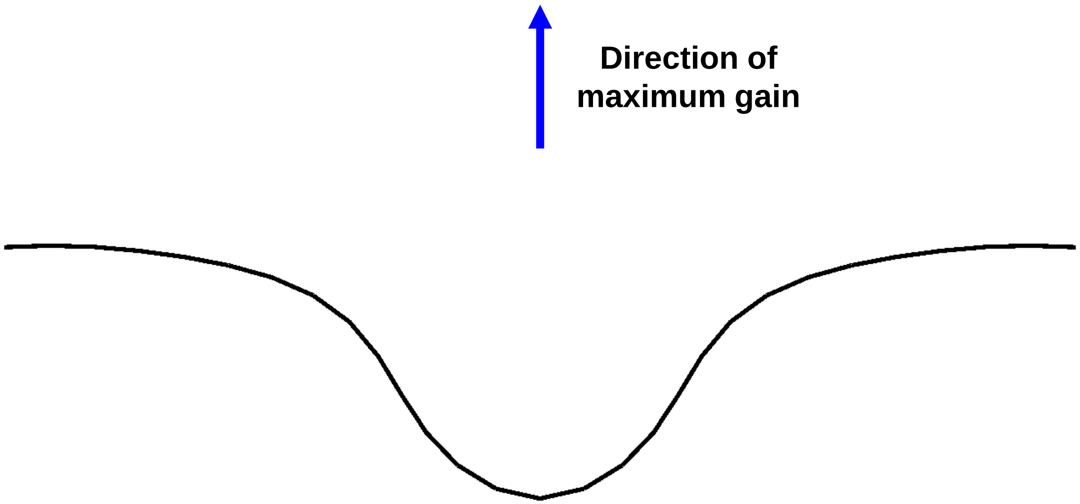
Length 1.25 Wavelengths, Gain = 6.22 dBi



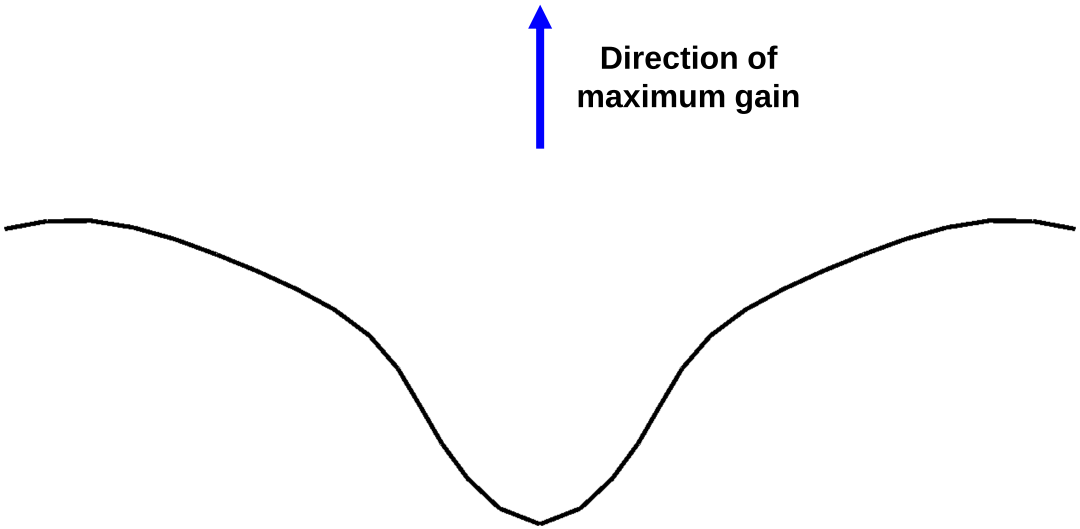
Length 1.3 Wavelengths, Gain = 6.57 dBi



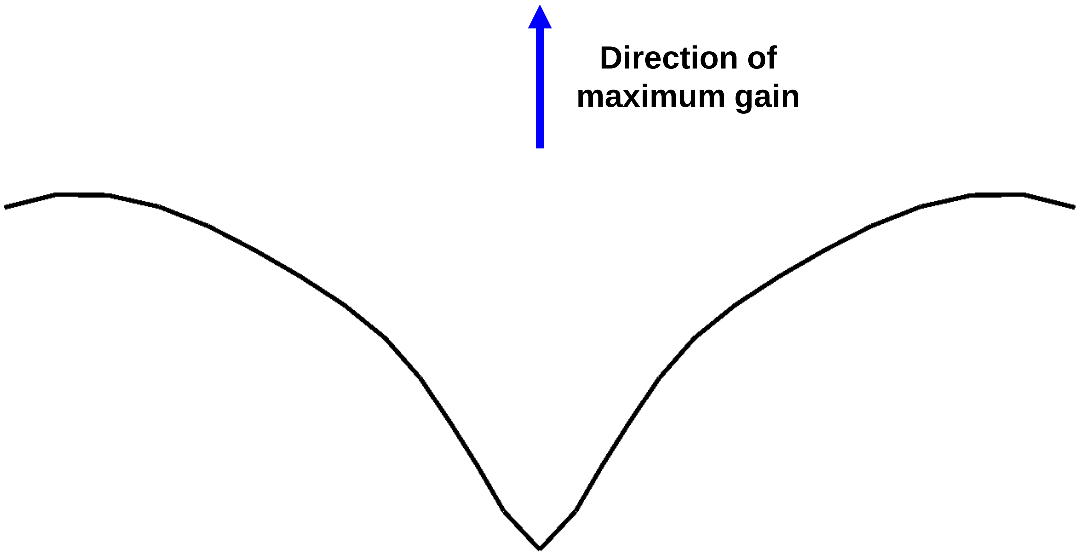
Length 1.4 Wavelengths, Gain = 7.00 dBi



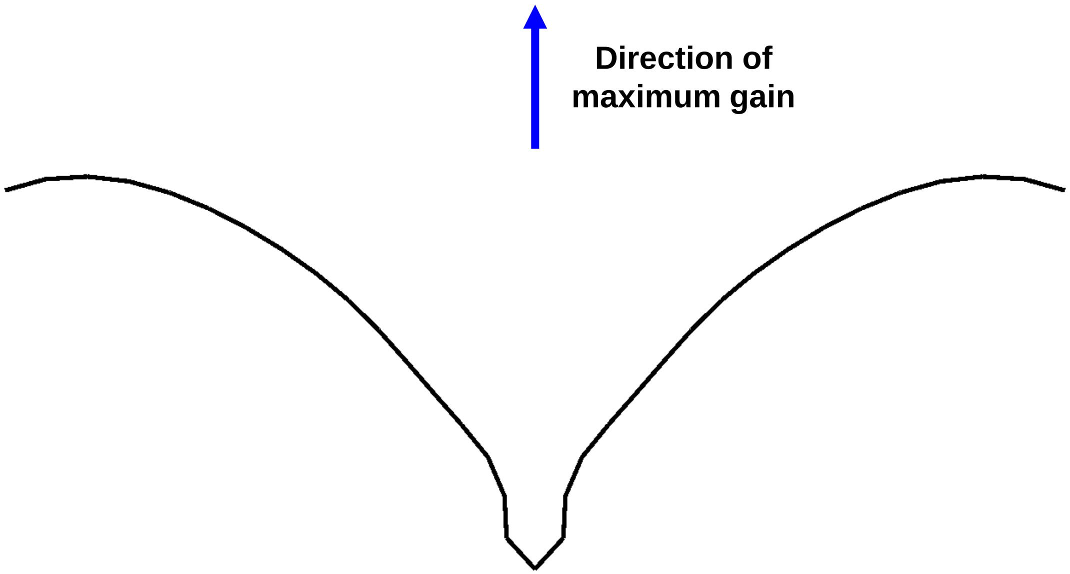
Length 1.5 Wavelengths, Gain = 7.13 dBi



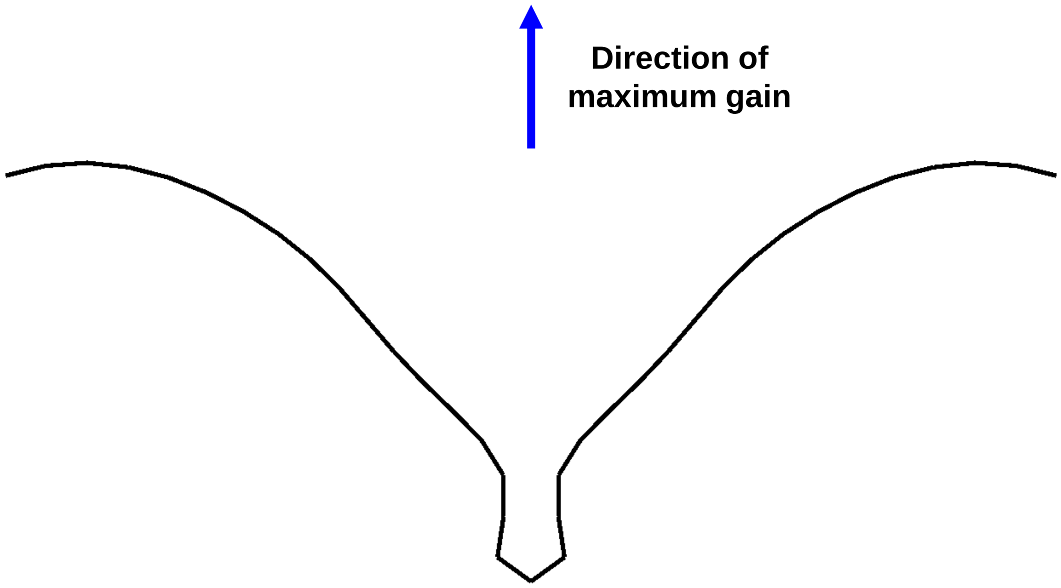
Length 1.6 Wavelengths, Gain = 7.16 dBi



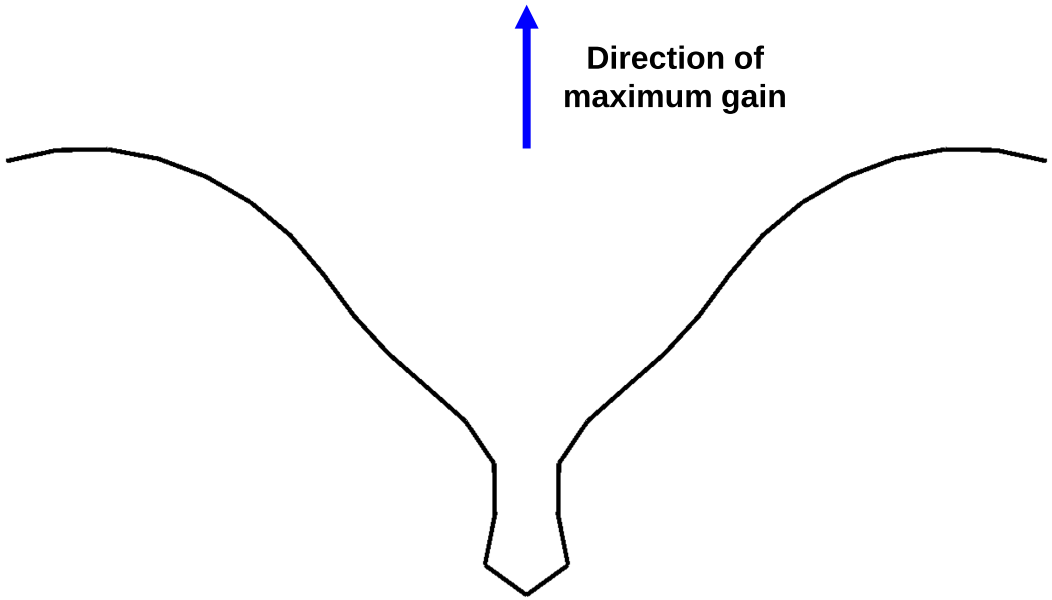
Length 1.7 Wavelengths, Gain = 7.18 dBi



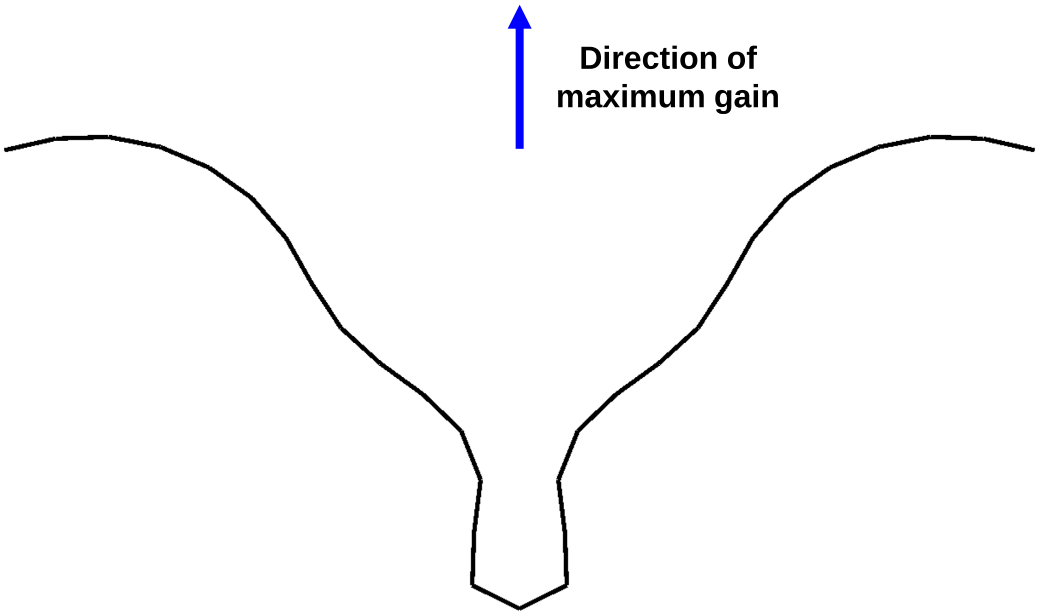
Length 1.8 Wavelengths, Gain = 7.22 dBi



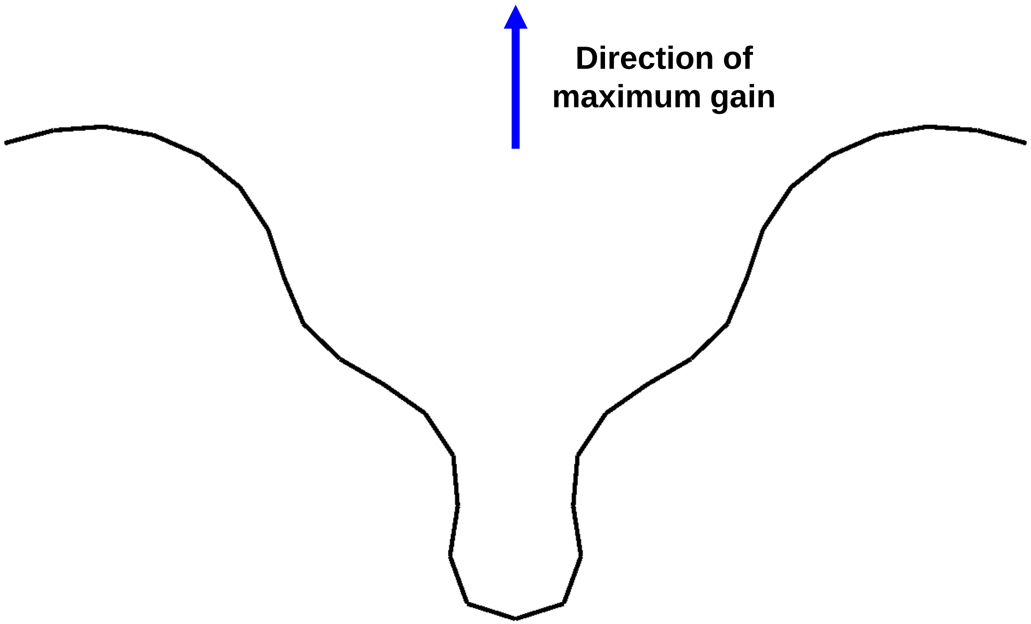
Length 1.9 Wavelengths, Gain = 7.30 dBi



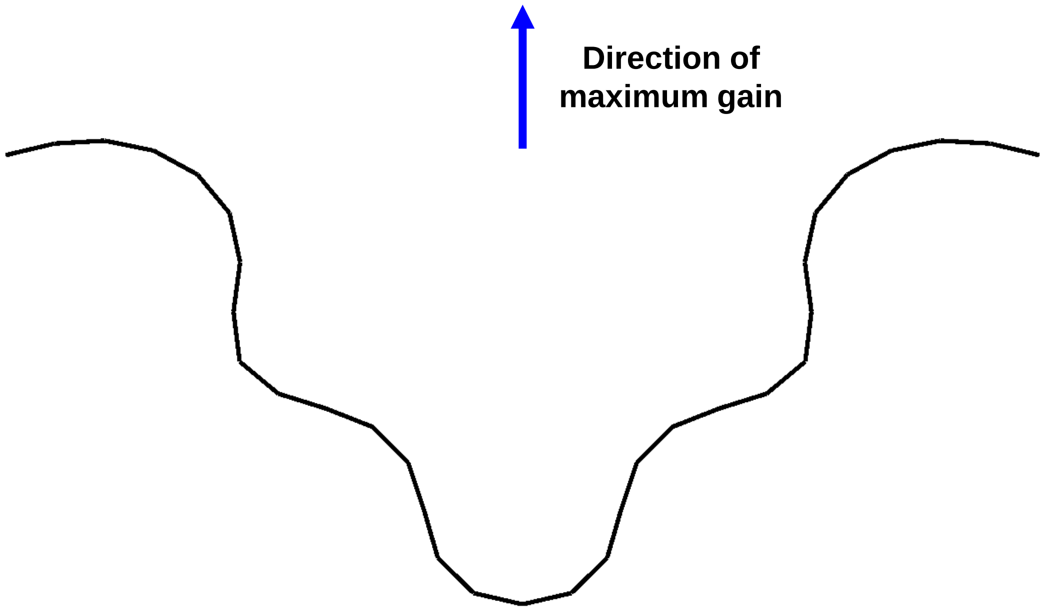
Length 2.0 Wavelengths, Gain = 7.46 dBi



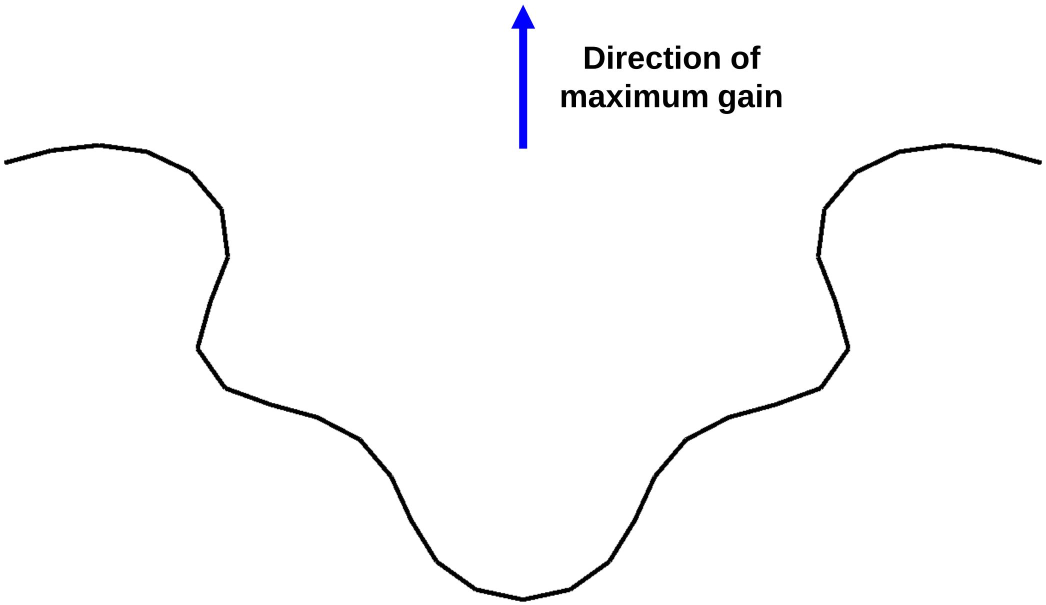
Length 2.1 Wavelengths, Gain = 7.73 dBi



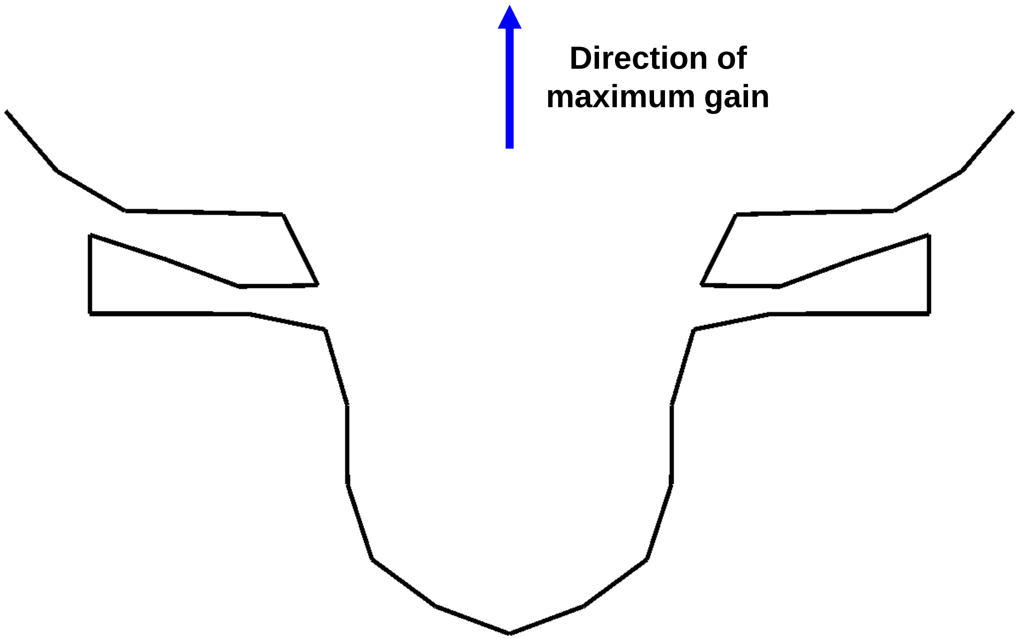
Length 2.2 Wavelengths, Gain = 8.12 dBi



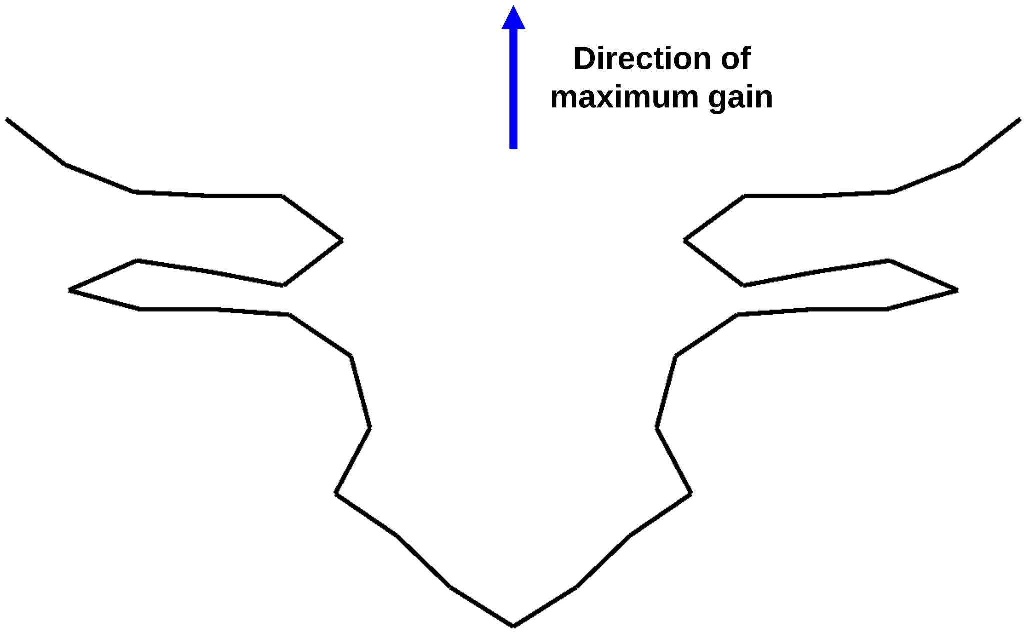
Length 2.3 Wavelengths, Gain = 8.62 dBi



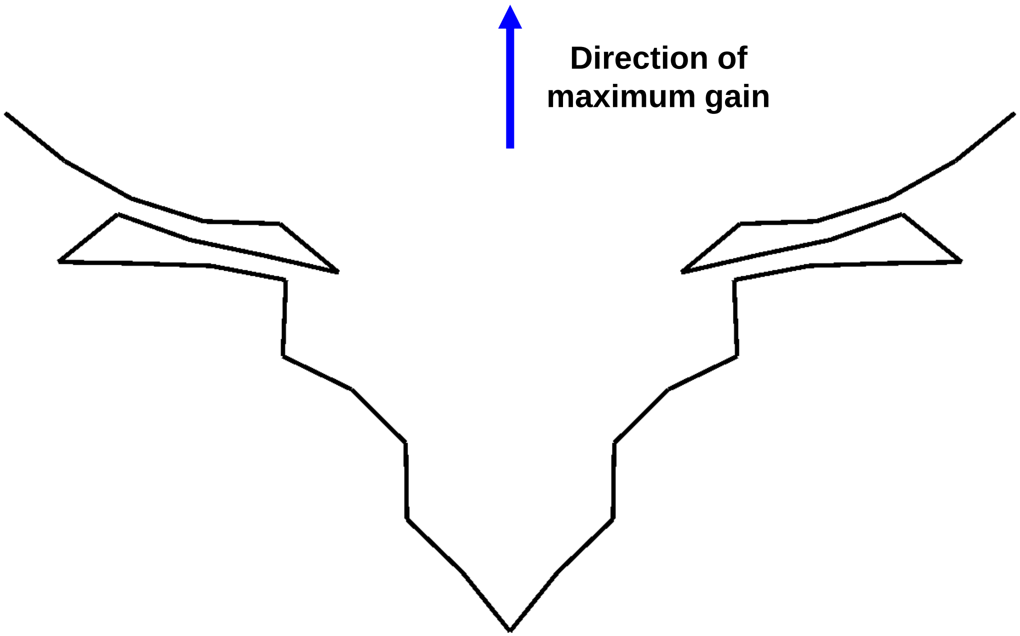
Length 2.4 Wavelengths, Gain = 9.38 dBi



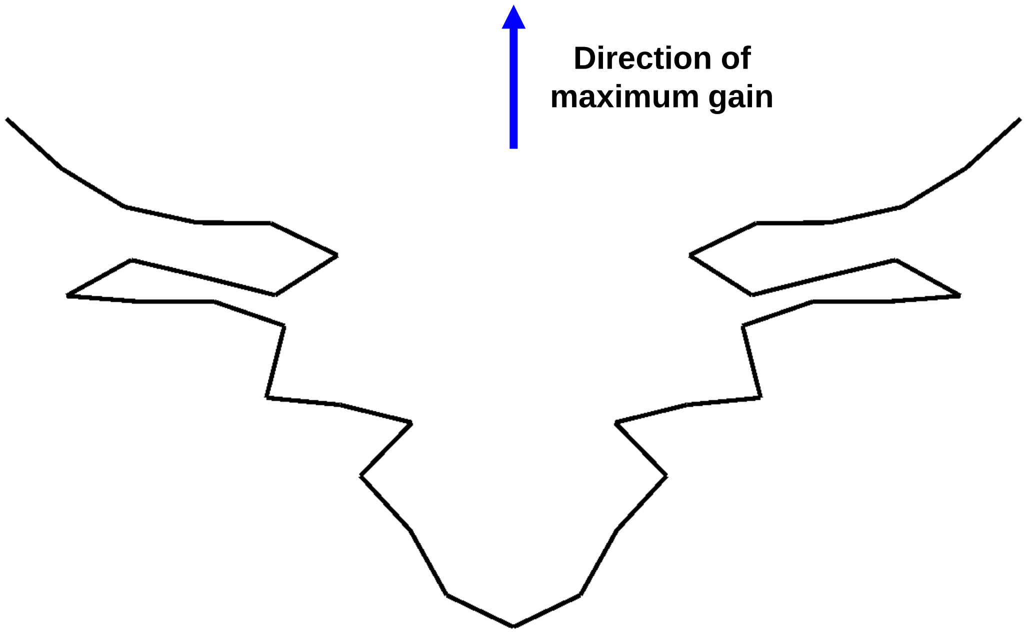
Length 2.5 Wavelengths, Gain = 9.51 dBi



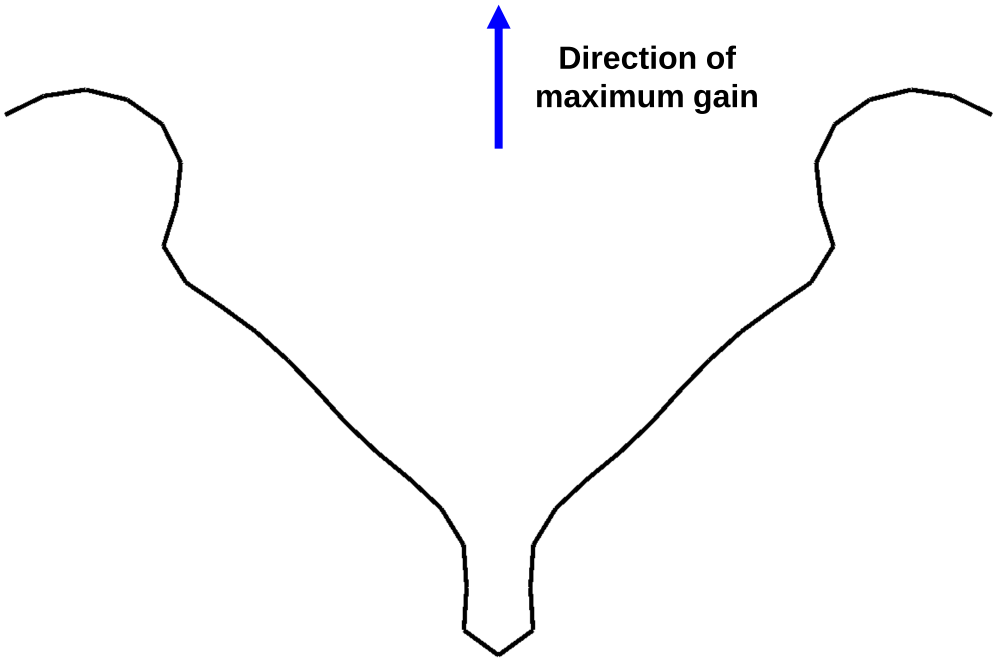
Length 2.6 Wavelengths, Gain = 9.66 dBi



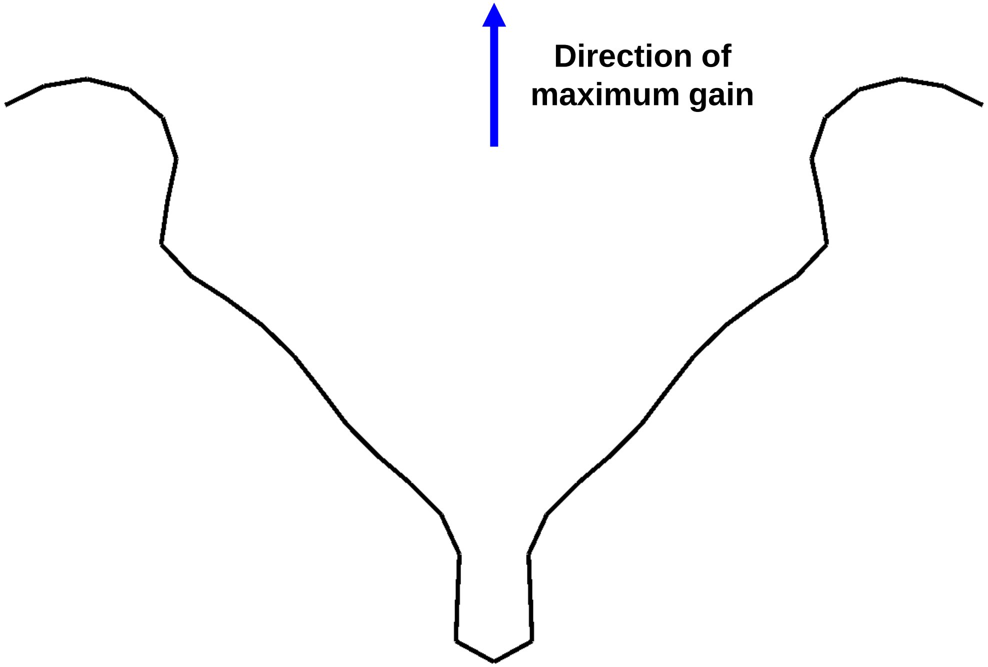
Length 2.7 Wavelengths, Gain = 9.59 dBi



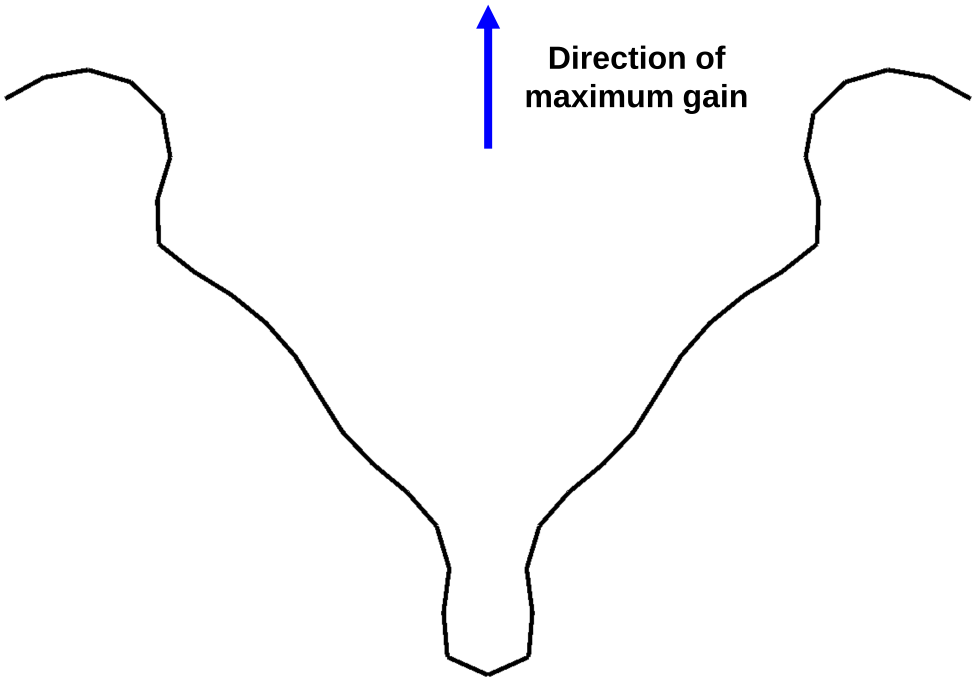
Length 2.9 Wavelengths, Gain = 9.21 dBi



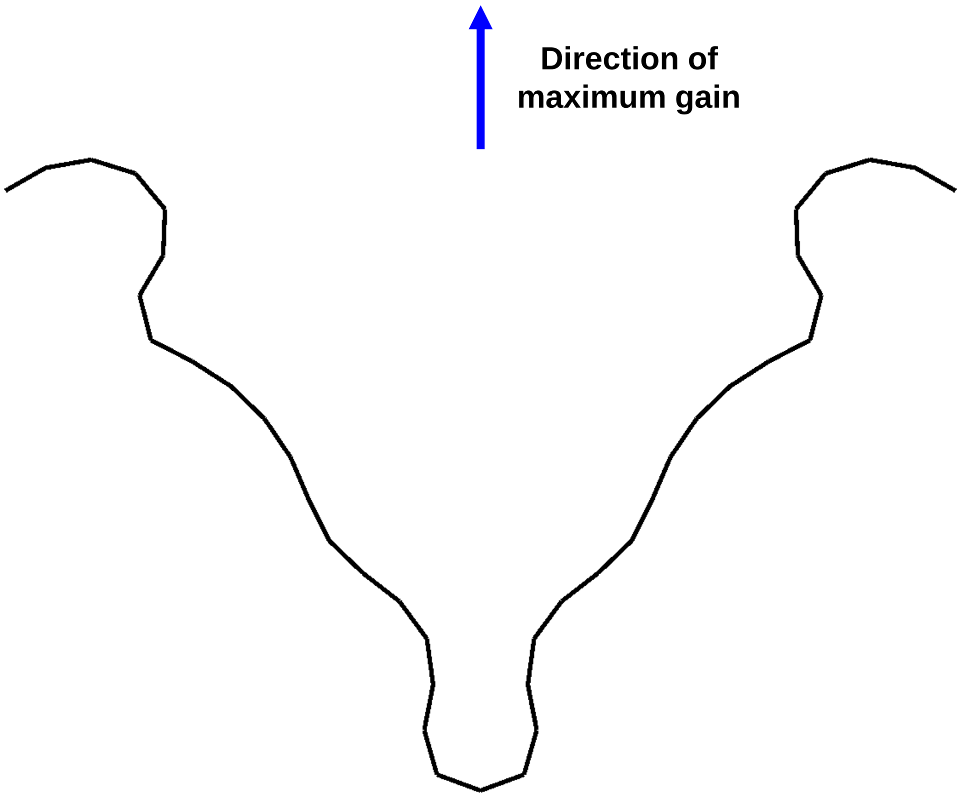
Length 3.0 Wavelengths, Gain = 9.34 dBi



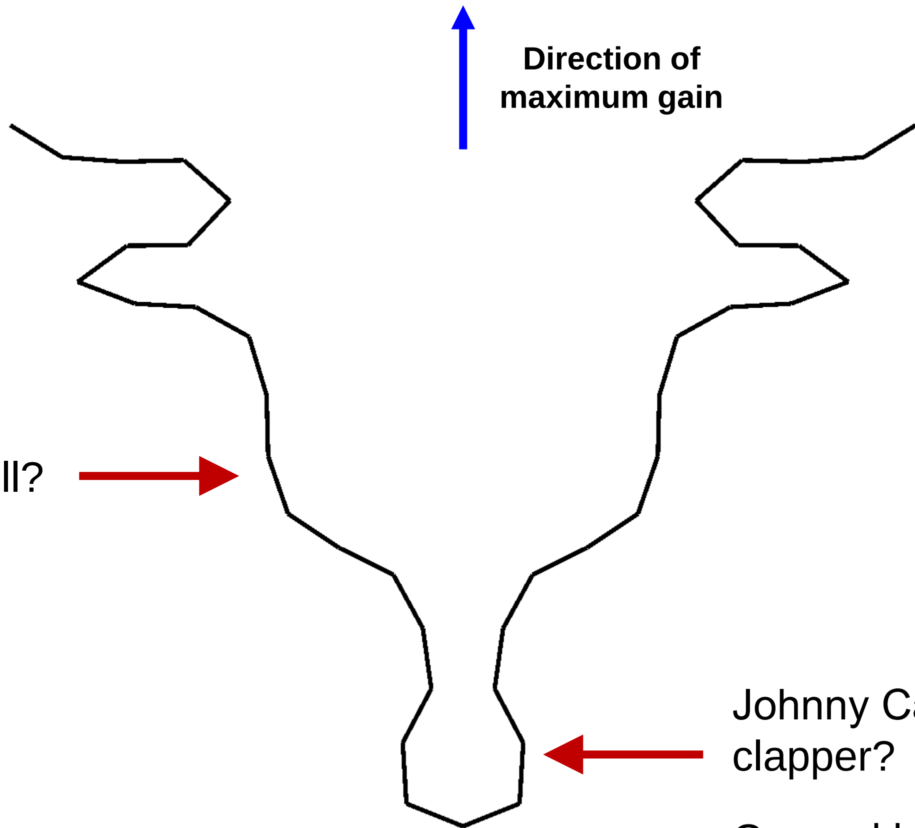
Length 3.1 Wavelengths, Gain = 9.53 dBi



Length 3.2 Wavelengths, Gain = 9.76 dBi



Length 3.3 Wavelengths, Gain = 10.14 dBi



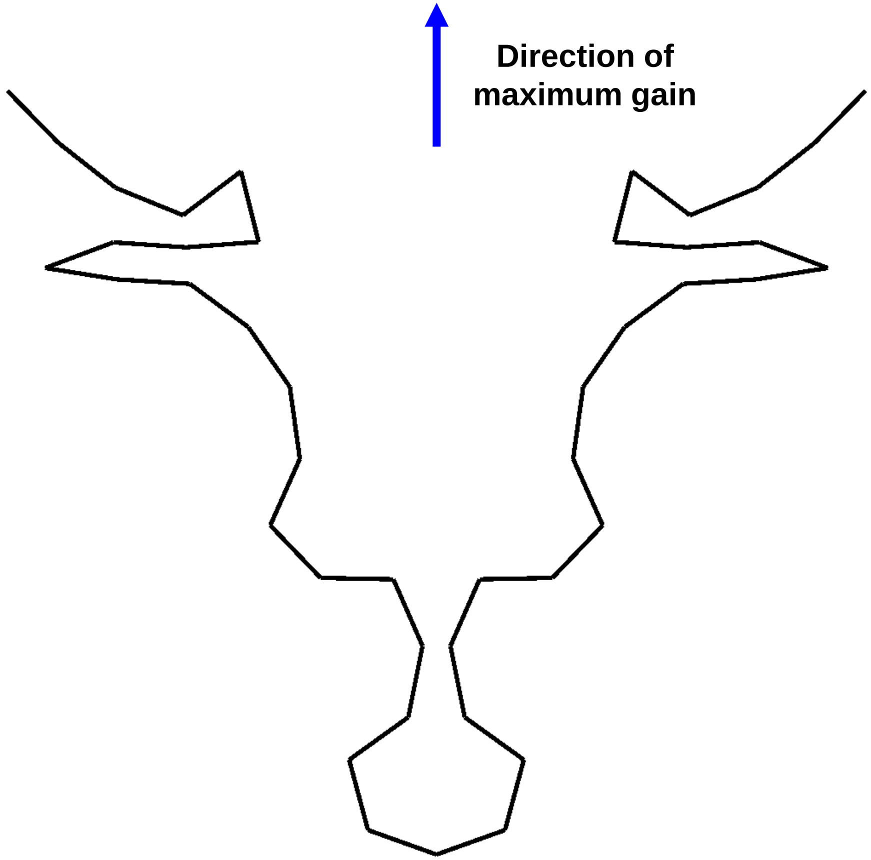
An upside down bell?

Johnny Carson's missing copper clapper?

Copped by kleptomaniac Claude Cooper of Cleveland on February 19, 1968.

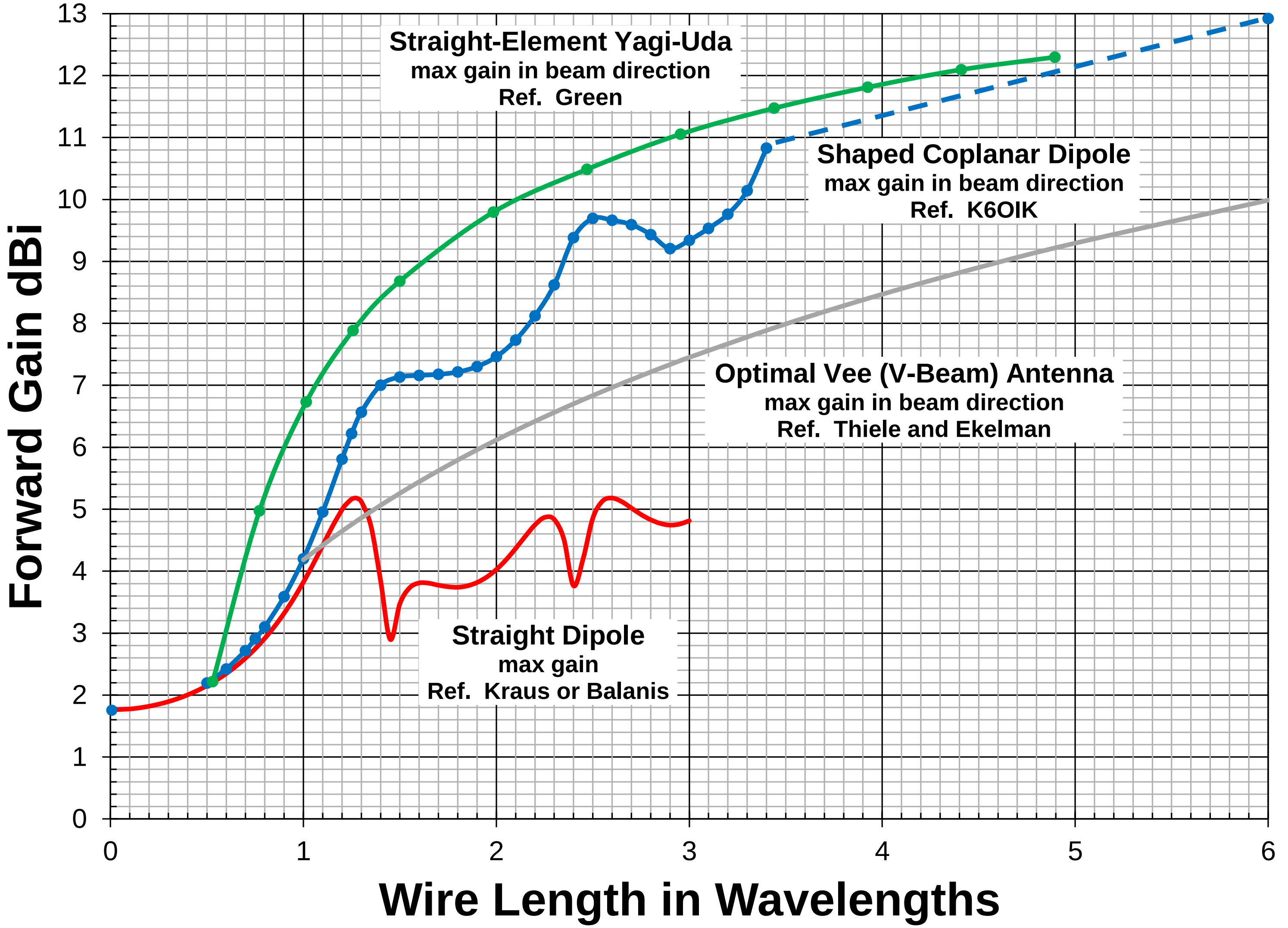
Discovered by K6OIK 60 years later outside the bell.

Length 3.4 Wavelengths, Gain = 10.83 dBi

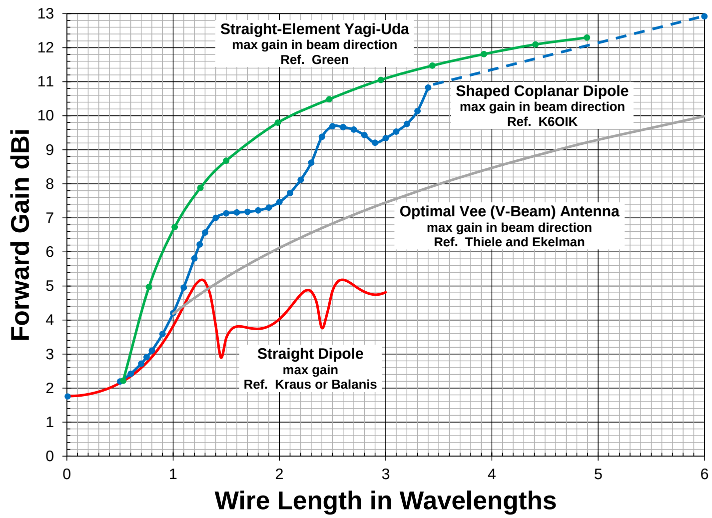


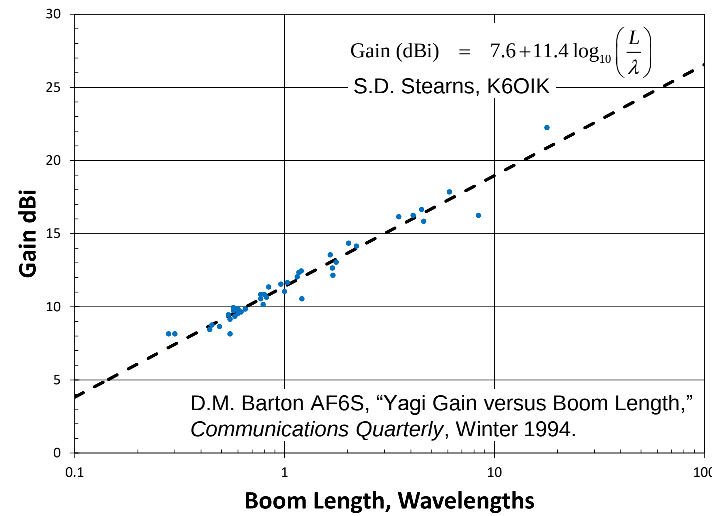
The Rudolph Antenna?

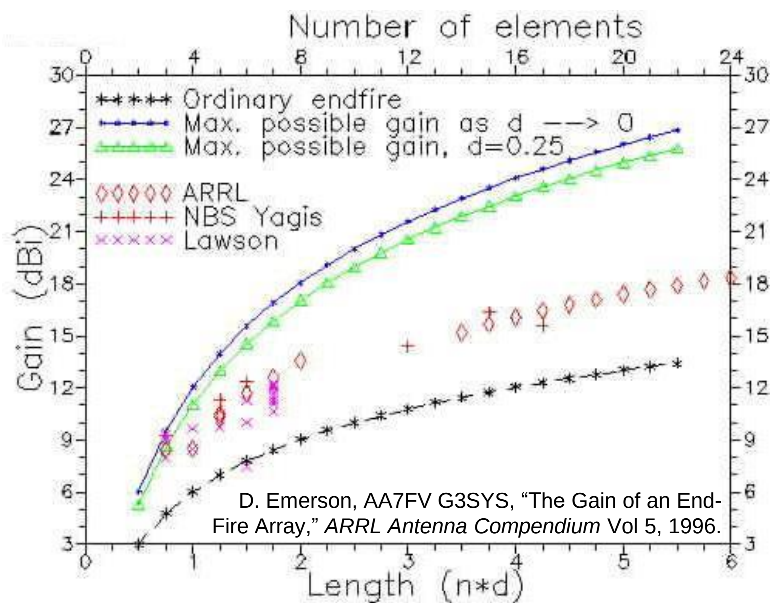
Gain Comparison

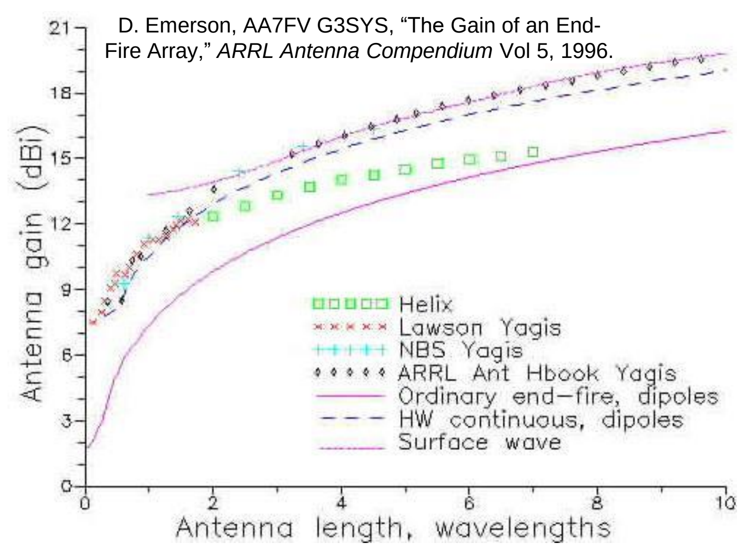


Gain Behavior of Traveling Wave Antennas





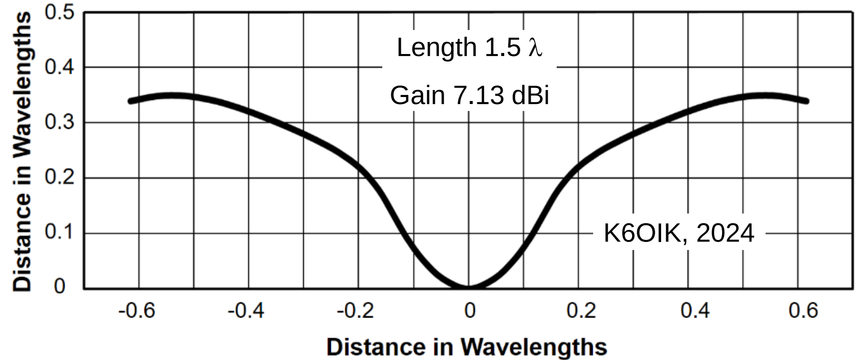


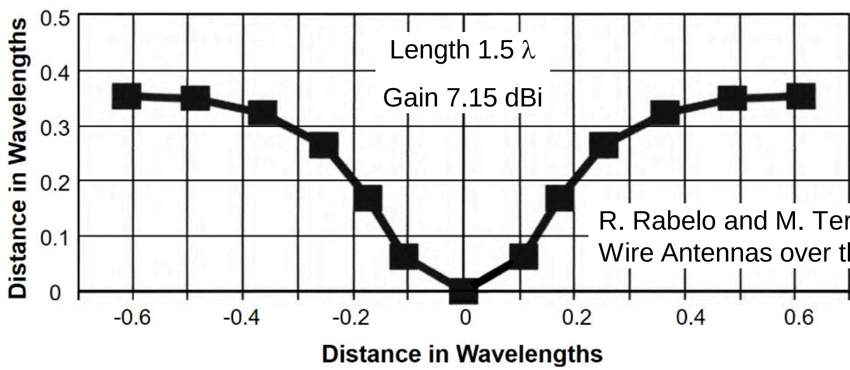


Shape Modeling Techniques

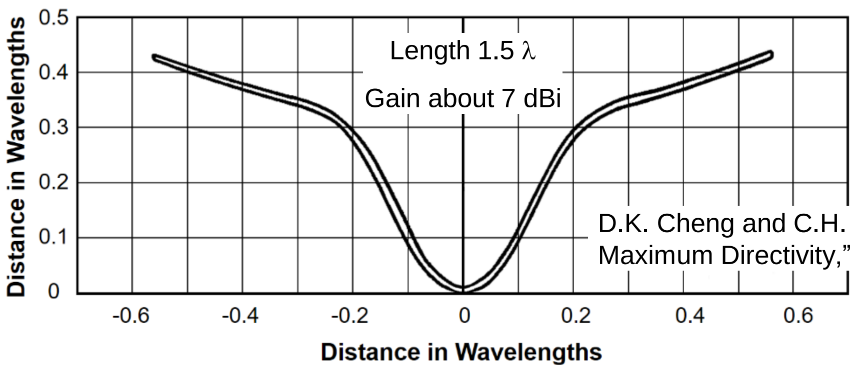
- **Cheng and Liang (1982) defined shapes parametrically**
  - Shape defined globally by equations having parameters
    - Rational: Cauchy, Lorentzian, Witch of Agnesi
    - Polynomial
    - Piecewise parabolic
  - Optimization variables are the parameters of the equation
- **Rabelo and Terada (2010) defined shapes nonparametrically by subsectional models**
  - Shape is defined by short straight wires joined at arbitrary angles
  - Optimization variables are the angles at wire junctions
  - Goal is max directional gain
- **Crooked wire antennas developed using Rabelo-Terada method**
  - Goal is usually max bandwidth or max beamwidth
  - Genetic evolution optimizer
- **K6OIK (2024) also used Rabelo-Terada nonparametric method**
  - Greater wire density – short $\lambda/10$ wires
  - Nelder-Mead optimizer

Best Shapes from Independent Research Works





R. Rabelo and M. Terada, “Analysis and Optimization of Wire Antennas over the Internet,” *IEEE AP Mag.*, Feb. 2010



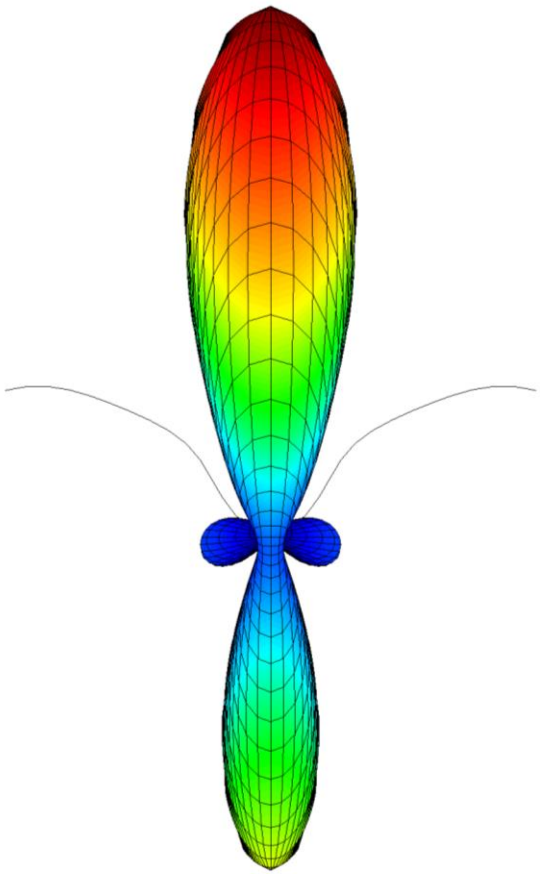
D.K. Cheng and C.H. Liang, “Shaped Wire Antennas with Maximum Directivity,” *Electronics Letters*, Sept. 1982

Length 1.5 Wavelengths – Optimal Shape Coordinates

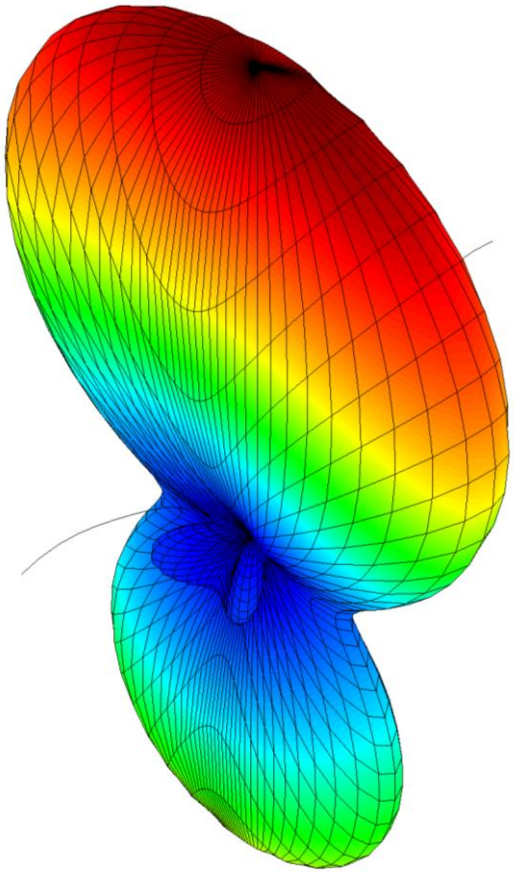
X (λ)	*Z* (λ)
-0.615442490	0.339302950
-0.566275980	0.348394410
-0.516277800	0.348820940
-0.466895860	0.340983580
-0.418801630	0.327310780
-0.371868390	0.310069240
-0.325579130	0.291166750
-0.280104290	0.270381200
-0.236139900	0.246566650
-0.195984980	0.216774330
-0.163338450	0.178903440
-0.137766250	0.135937610
-0.112693880	0.092678202
-0.083024610	0.052432278
-0.046562198	0.018219817
0.000000000	0.000000000
0.046562198	0.018219817
0.083024610	0.052432278
0.112693880	0.092678202
0.137766250	0.135937610
0.163338450	0.178903440
0.195984980	0.216774330
0.236139900	0.246566650
0.280104290	0.270381200
0.325579130	0.291166750
0.371868390	0.310069240
0.418801630	0.327310780
0.466895860	0.340983580
0.516277800	0.348820940
0.566275980	0.348394410
0.615442490	0.339302950

Typical Pattern – Large Backlobe, Small Sidelobes

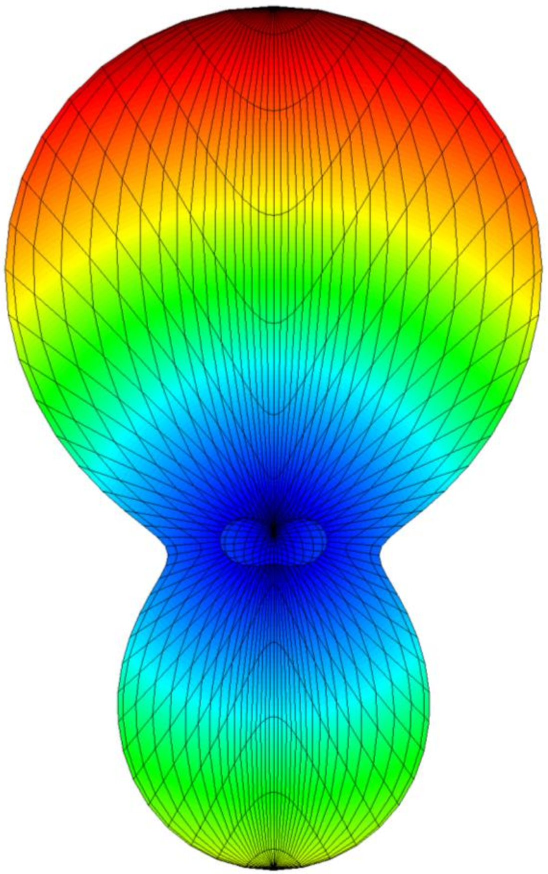
Side View
E-Plane



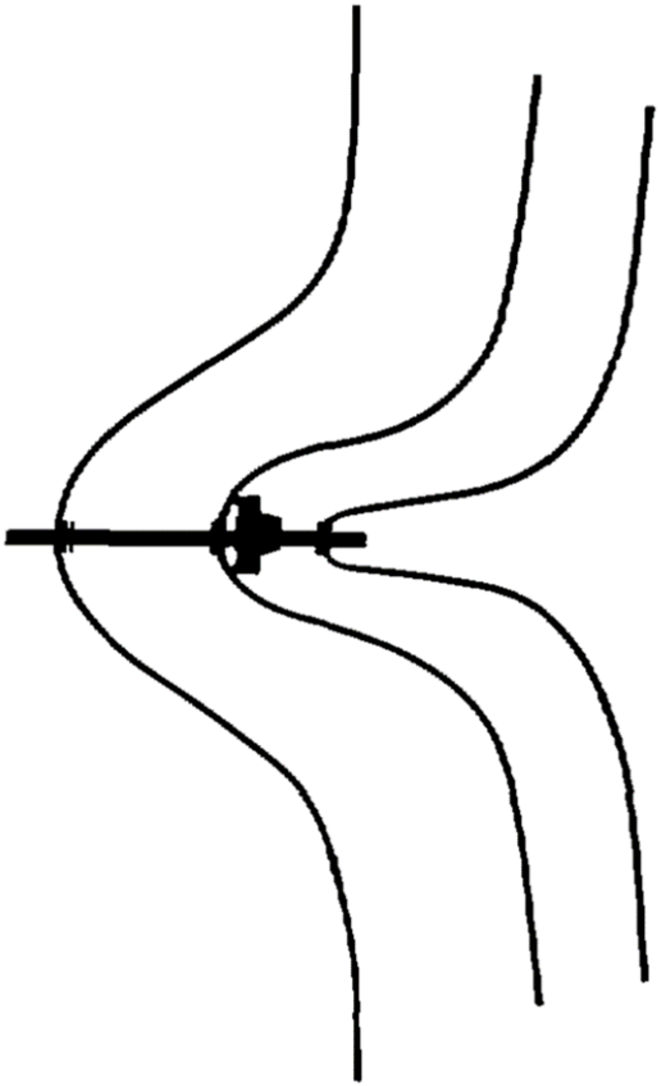
Isometric View



End View
H-Plane



Eliminate the Backlobe



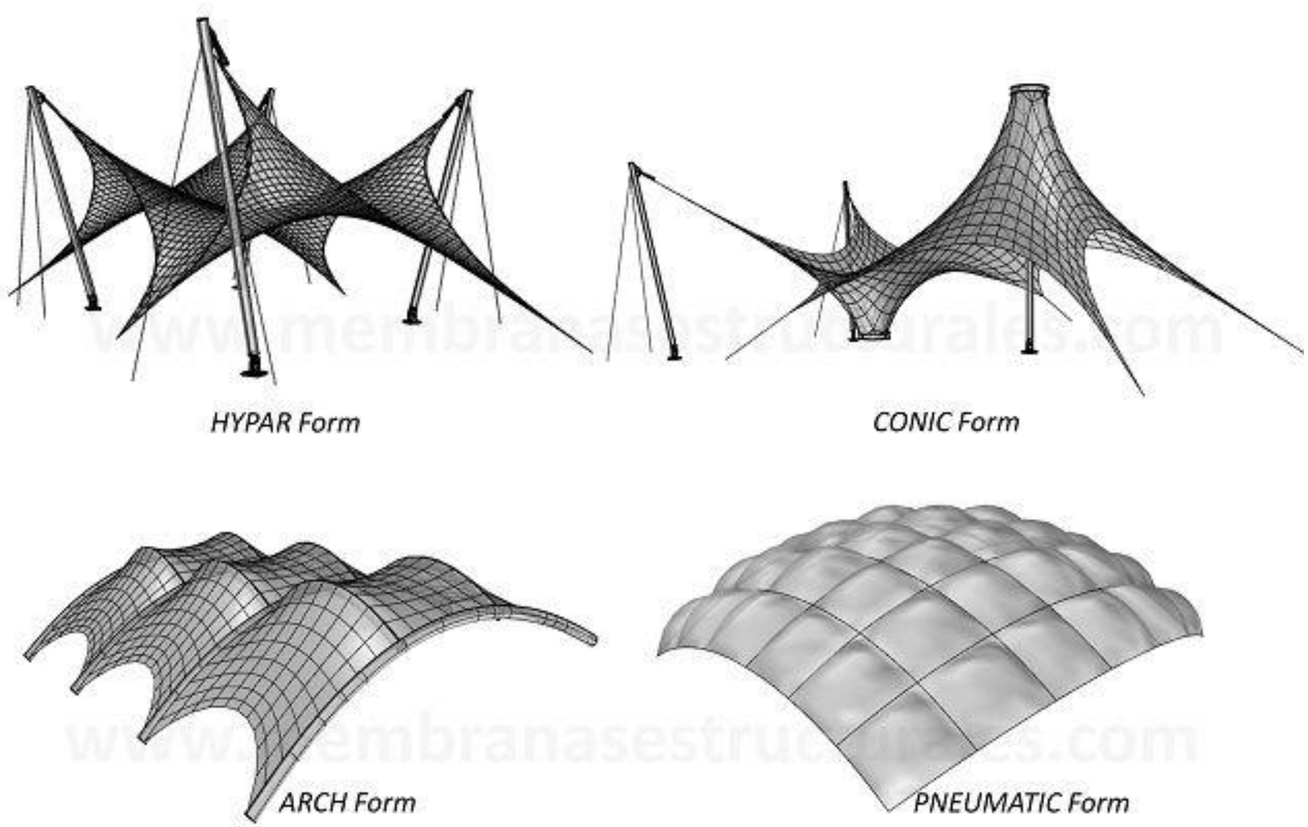
- Landstorfer array (1976)
- Elements: 3
- Element shape: Optimized (approximately Gaussian)
- Gain: 11.5 dBi
- Sidelobes: < -20 dB
- F/B ratio: 26 dB
- Performance similar to 10-element Yagi – except…
- Bandwidth: > 3% (W4RNL)
- Introduced at Pacificon 2005 by K6OIK

But Curved Wire Antennas Are Hard to Make, Right?

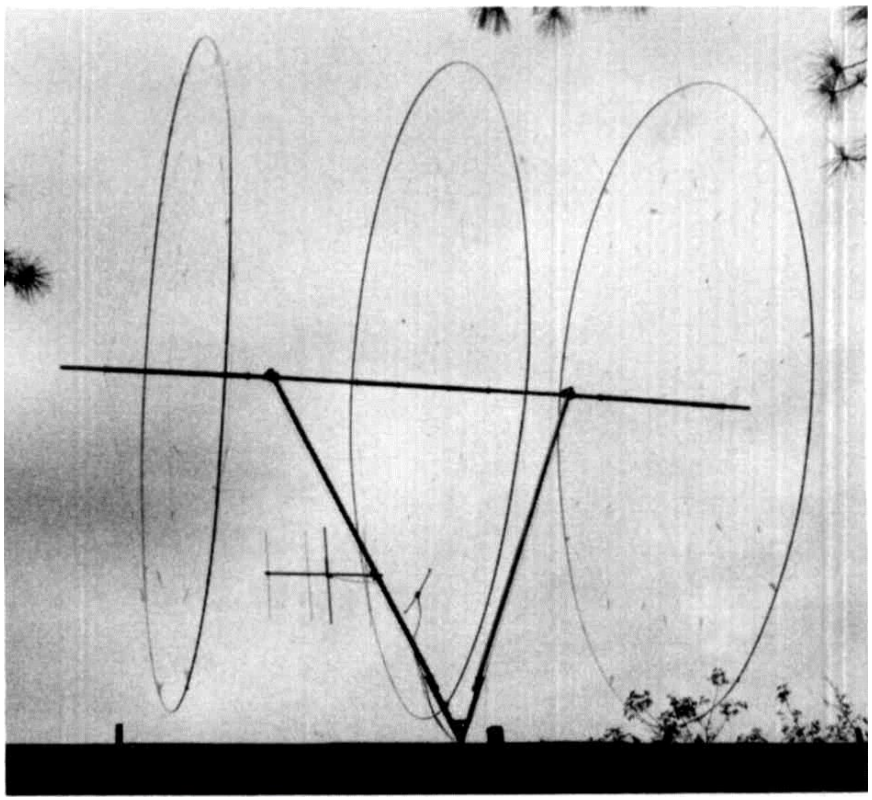
Wrong!

Tensile Structures and Tensegrity

Tensile Structures



Amateur Ingenuity – Tensegrity



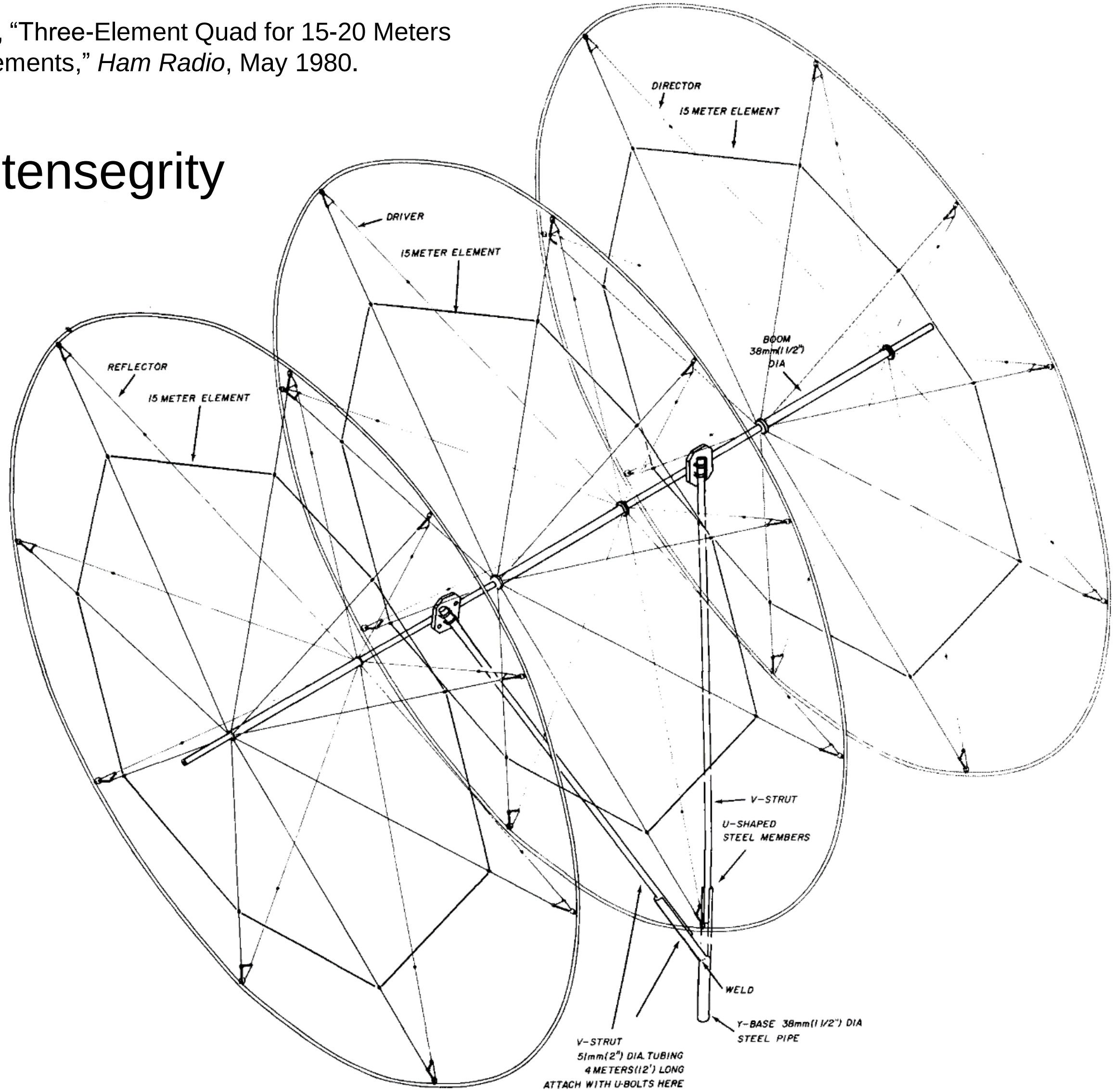
J.W. Kennicott W4OVO, "Three-Element Quad for 15-20 Meters Which Uses Circular Elements," *Ham Radio*, May 1980.

- **W4OVO 3-element HF loop array**
- **Circular loop arrays have more gain than Yagi-Uda arrays for a given boom length**
- **W4OVO's 3-element array has 2 dB more gain**

W4OVO's Solution – Three Jumbo Bicycle Wheels

J.W. Kennicott W4OVO, "Three-Element Quad for 15-20 Meters Which Uses Circular Elements," *Ham Radio*, May 1980.

Example of tensegrity



The Big Picture

- **We presented optimal shapes for planar wire antennas whose max gain direction lies in the plane of the wire**
  - Examples: dipoles, inverted v's, loops, many endfire and traveling wave antennas but not Yagi-Uda's

Property	Dipoles	Vees & Inverted V's	Loops	Yagi-Uda's
Thin-wire type (metal wires, rods, or tubes)	✓	✓	✓	✓
Planar (shape lies in a plane)	✓	✓	✓	✓
Connected (contiguous wire without cuts)	✓	✓	✓	
No junctions (a single wire with no branching)	✓	✓	✓	✓
Left-right symmetric about a central feedpoint	✓	✓	✓	✓
Max gain is along symmetry axis in antenna's plane	✓	✓	✓	✓

- **However the direction of max gain can also be perpendicular to the antenna's plane**
  - Examples: dipoles and loops but not endfire and traveling wave antennas
- **Such antenna shapes can have even greater gain for a given length of wire**
  - Stacks can have greater gain than endfire and traveling wave antennas for a given wire length
- **Such antennas will be the subject of a future discussion**

Resources

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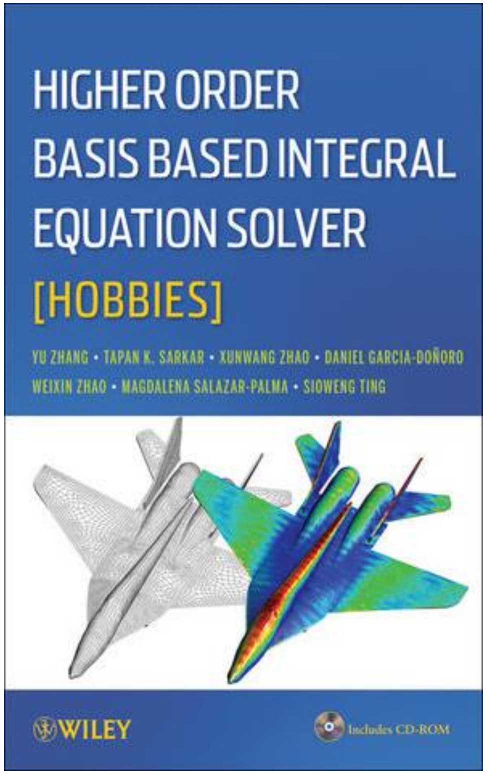
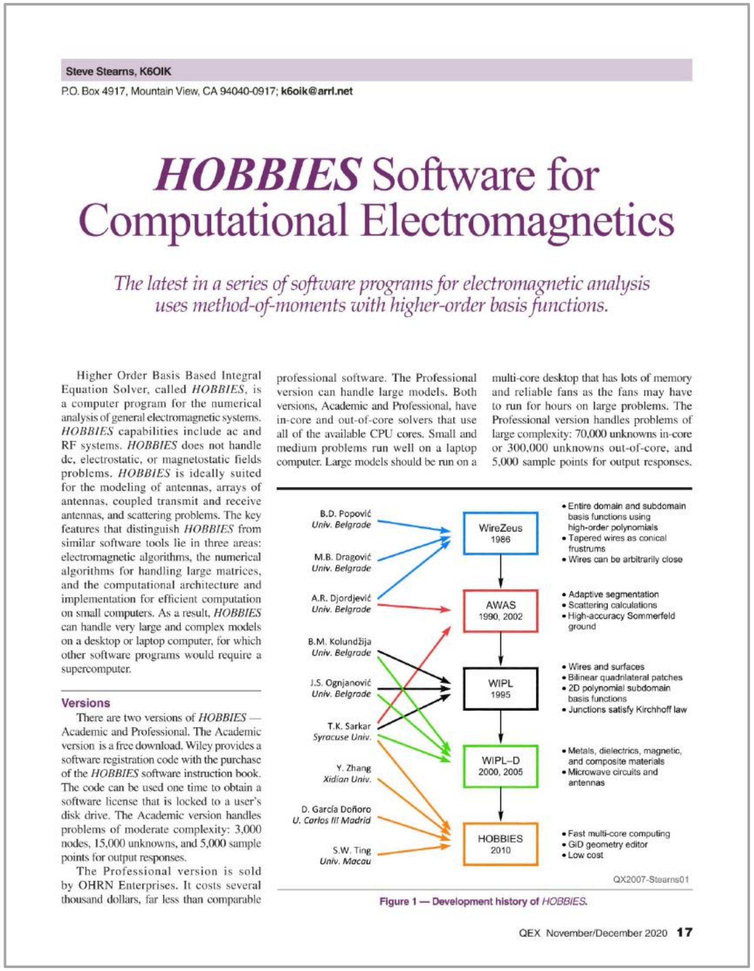
Free or Low Cost Antenna Modeling Software Links at https://www.fars.k6ya.org/others

- **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

HOBBIES – No Longer Supported



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



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P.O. Box 4917, Mountain View, CA 94040-0917; **k6oik@arrl.net**

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.

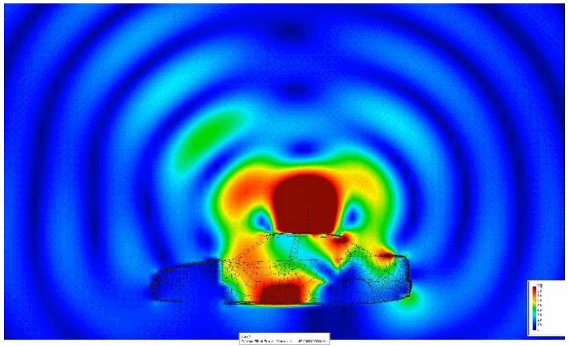
Higher Order Basis Based Integral Equation Solver, called *HOBBIES*, is a computer program for the numerical analysis of general electromagnetic systems. *HOBBIES* capabilities include ac and RF systems. *HOBBIES* does not handle dc, electrostatic, or magnetostatic fields problems. *HOBBIES* is ideally 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.

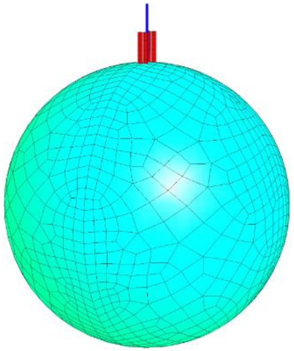
Versions

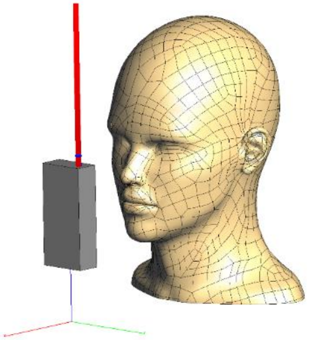
There are two versions of *HOBBIES* — Academic and Professional. The Academic version is a free download. Wiley provides a software registration code with the purchase of the *HOBBIES* software instruction book. The code can be used one time to obtain a software license that is locked to a user's disk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

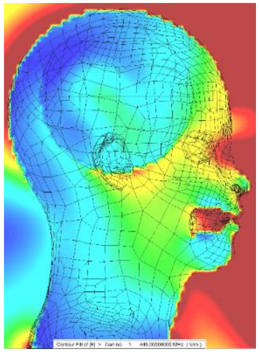
The Professional version is sold by OHRN Enterprises. It costs several thousand dollars, far less than comparable professional software. The Professional version can handle large models. Both versions, Academic and Professional, have in-core and out-of-core solvers that use all of the available CPU cores. 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.

Figure 1 — Development history of *HOBBIES*.

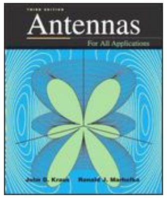


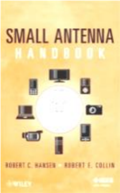


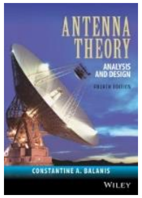




Good Antenna Books







- **Books for antenna engineers and students**
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  - IEEE Xplore subscription online archive, https://ieeexplore.ieee.org/Xplore/home.jsp
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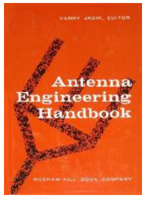
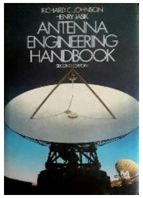
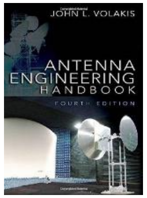
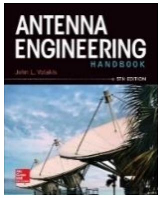
  - Progress in Electromagnetics Research https://www.jpier.org
- **Antenna Engineering Handbooks – 5 editions**



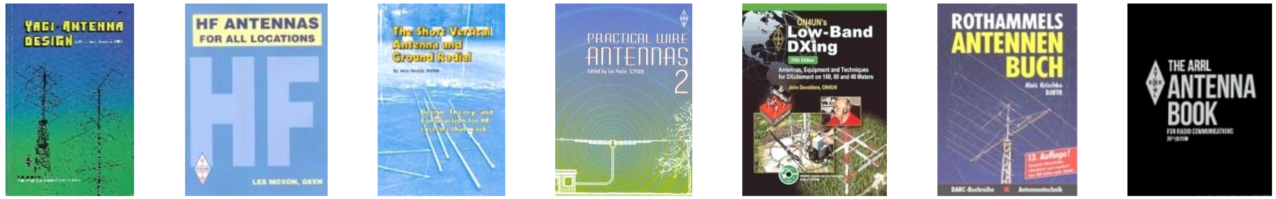






1961 **1984** **1993** **2007** **2019**

Good Antenna Books continued



- **Books for Radio Amateurs**
  - H.W. Silver, N0AX, ed., *ARRL Antenna Book*, 25e, ARRL, 2023
  - A. Krischke, DJ0TR, ed., *Rothammel's Antenna Book*, 13e, English, DARC, 2019
  - J. Devoldere, ON4UN, *ON4UN's Low-Band Dxing*, 5e, ARRL, 2011
  - I. Poole, G3YWX, ed., *Practical Wire Antennas 2*, RSGB, 2005
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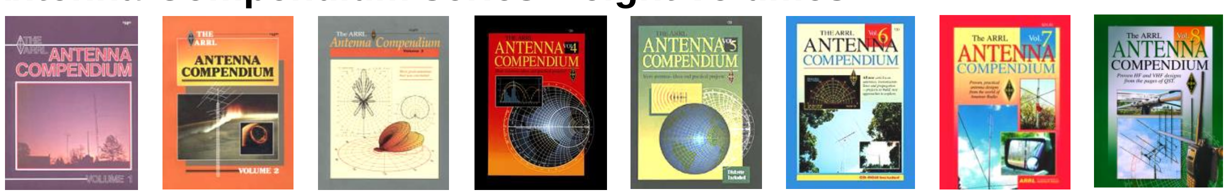
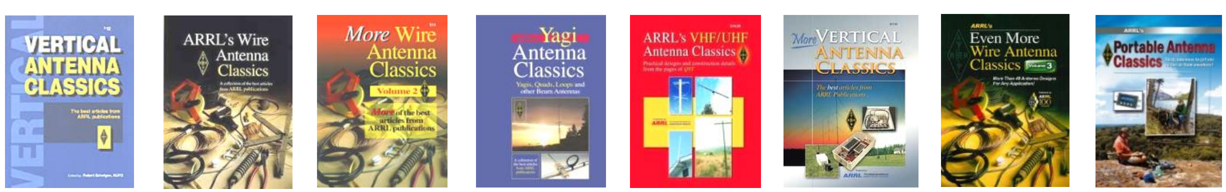
  - L. Moxon, G6XN, *HF Antennas for All Locations*, 2e, RSGB, 1983
  - J.L. Lawson, W2PV, *Yagi Antenna Design*, ARRL, 1986
- **ARRL Antenna Compendium series – eight volumes**

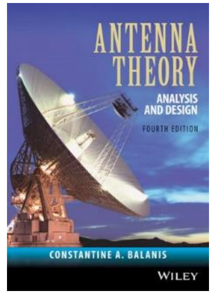


- **ARRL Antenna Classics series – eight titles**



Recent Antenna Books of Interest

B.M. Kolundžija and A.R. Djordjević, *Electromagnetic Modeling*, Artech, 2002



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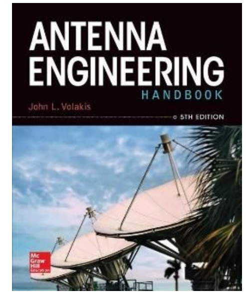

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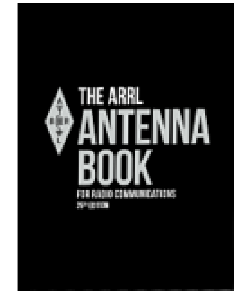

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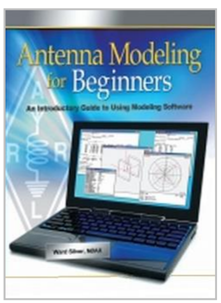
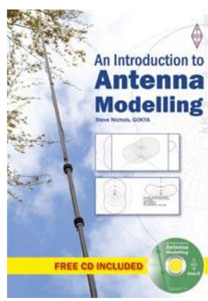


H.W. Silver, N0AX, *Antenna Modeling for Beginners*, ARRL, 2012



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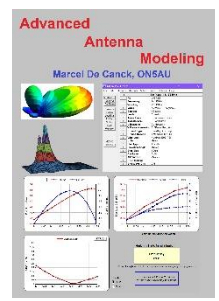

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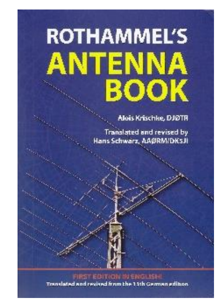
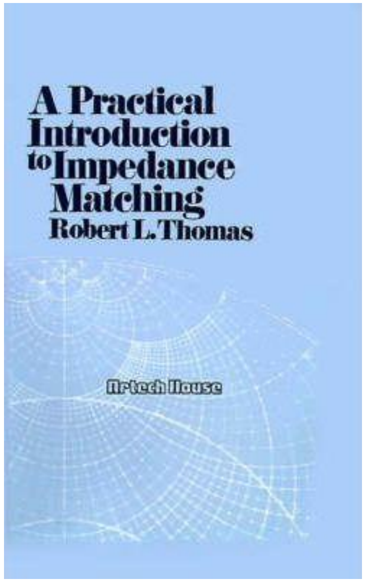
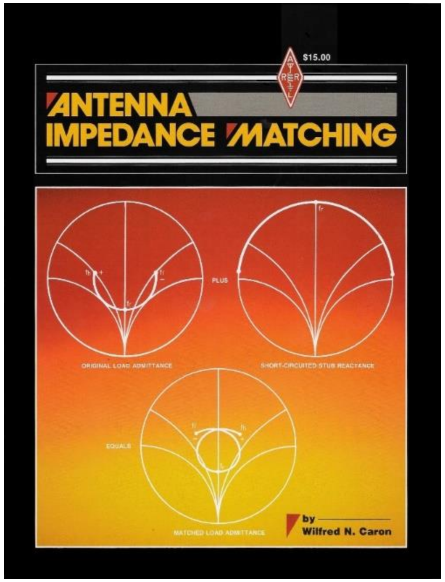


A. Krischke, DJ0TR, ed., *Rothammel's Antenna Book*, English transl., 13e, DARC, 2019

Impedance Matching for Beginner and Professional



R.L. Thomas, *A Practical Introduction to Impedance Matching*, Artech House, 1976



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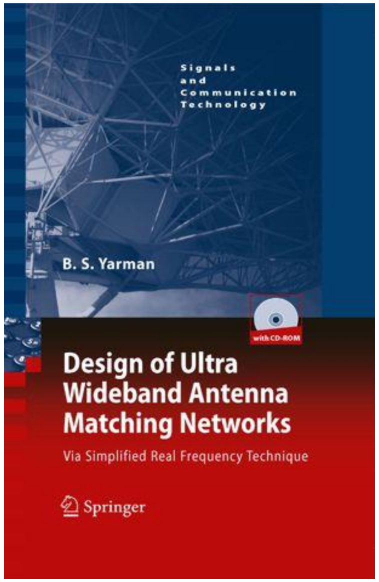

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The End