New Results on Antenna Impedance Models and Matching

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Electromagnetic Cloaking

- Idea introduced in the *Star Trek* television series, episode 9, on December 15, 1966, which featured a Romulan Bird Of Prey
- Practical technique presented at Pacificon Antenna Seminar, October 13, 2006
- Laboratory proof announced by Duke University on October 17, 2006
Outline

- Antenna impedance models
- SWR basics
- Why not conjugate match?
- Impedance matching networks
  - Multi-band match networks
  - Networks that give extremely broad match bandwidths
- Interesting antennas
- Terrain effects by computational electromagnetics
  - Meshing Silicon Valley
Antenna Impedance Models
Sidney Darlington, 1906-1997
Darlington Forms (1939)

- Every immittance function can be realized as a lossless two-port terminated by a resistor.
- Every antenna impedance function has an equivalent circuit in Darlington form.

- The Darlington form is the starting point for interesting results in network and matching theory:
  - The Fano (1947) and Carlin-LaRosa (1952) bounds on impedance matching.
  - Constant resistance reflectionless impedance matching networks.
  - Non-Foster active impedance matching networks.
Impedance Models for Electrically-Small Dipoles & Monopoles

K6OIK 3-Element

Tang, Tieng, Gunn 4-Element

Series RLC

K6OIK 4-Element

K6OIK 5-Element
Broadband Models of Dipole Impedance

That Span Multiple Resonances
Schelkunoff’s Universal Antenna Impedance Models

- Schelkunoff (1941) gave universal impedance models for a two broad classes of antennas
- Cascaded transmission lines terminated by a $TE_{10}$ or $TM_{10}$ mode impedance (e.g. loops or dipoles)
Foster’s 1st Canonical Form with Small Losses Added

- Fits dipole impedance best near antiresonances

\[
\begin{align*}
C_0 &= 43.9 \text{ pF} & C_1 &= 22.9 \text{ pF} & C_2 &= 30.3 \text{ pF} & C_3 &= 57.1 \text{ pF} \\
L_\infty &= 4.49 \text{ mH} & L_1 &= 12.5 \text{ } \mu\text{H} & L_2 &= 2.26 \text{ } \mu\text{H} & L_3 &= 522 \text{ nH} \\
R_1 &= 4,970 \Omega & R_2 &= 3,338 \Omega & R_3 &= 2,702 \Omega
\end{align*}
\]
Accuracy of Hamid & Hamid’s Equivalent Circuit
Accuracy of Hamid & Hamid’s Equivalent Circuit

Resonant resistances are wrong!
Foster’s 2nd Canonical Form with Small Losses Added

- Fits dipole impedance best near resonances

Example Dipole

- \( C_{\infty} = 5.44 \text{ pF} \)
- \( C_1 = 42.9 \text{ pF} \)
- \( C_2 = 5.05 \text{ pF} \)
- \( C_3 = 1.92 \text{ pF} \)
- \( L_0 = \infty \)
- \( L_1 = 24.9 \mu\text{H} \)
- \( L_2 = 22.8 \mu\text{H} \)
- \( L_3 = 21.4 \mu\text{H} \)
- \( R_1 = 72.2 \Omega \)
- \( R_2 = 106 \Omega \)
- \( R_3 = 122 \Omega \)
Accuracy of Foster’s 2\textsuperscript{nd} Form With Small Losses
Accuracy of Foster’s 2nd Form With Small Losses
Long, Werner, & Werner’s Broadband Model (2000)
Frequency Scaled to $f_0 = 5$ MHz, $\Omega' = 7.8$

Cs = 150 pF  
C11 = -975 pF  
Z1 = 215 $\Omega$  
C12 = 24.0 pF  
C13 = 8.33 pF  

R11 = 13.1 $\Omega$  
E1 = 44.9 deg  
R12 = 3,600 $\Omega$  
R13 = 500 $\Omega$

C21 = 17.6 pF  
Z2 = 195 $\Omega$  
E2 = 46.9 deg  
C22 = -3.00 pF  
R21 = 700 $\Omega$  
R22 = 295 $\Omega$
Accuracy of Long, Werner, & Werner’s Model

Resonant frequency 5.3 MHz is too high!
Accuracy of Long, Werner, & Werner’s Model

Resonant resistance 96 Ω is too high!
Streable & Pearson’s Broadband Equivalent Circuit
Frequency Scaled to $f_0 = 5$ MHz, $\Omega' = 10.6$

C11 = 86.6 pF  C31 = 15.0 pF  C51 = 7.17 pF  C71 = 4.51 pF
L11 = 13.8 $\mu$H  C32 = 33.8 pF  C52 = 8.87 pF  C72 = 3.98 pF
R11 = 0.663 $\Omega$  L31 = 11.7 $\mu$H  L51 = 10.9 $\mu$H  L71 = 10.3 $\mu$H
R12 = 2,201 $\Omega$  R31 = 4,959 $\Omega$  R51 = 6,514 $\Omega$  R71 = 7,542 $\Omega$
Accuracy of Streable & Pearson’s Equivalent Circuit

3rd Antiresonant frequency is too high

Resistance should decrease to zero
Accuracy of Streable & Pearson’s Equivalent Circuit

\( \frac{\lambda}{2} \) impedance

88\( +j47 \, \Omega \)
is a bit off
Antennas Ring at Many Frequencies (Like Bells)

- Tesche (1973) derived antenna TM modes by SEM
- Distributed and electromagnetic systems are infinite-dimensional linear systems
Equivalent Circuits for Transcendental Immittances

- Schelkunoff (1944), Zinn (1952): Transcendental immittances of continuous electromagnetic structures can be represented by ladder networks made of one of four subcircuits
K6OIK’s Broadband Equivalent Circuit

\[ R_{11} = 5.06 \, \Omega \quad R_{21} = 0 \, \Omega \quad R_{31} = 25.5 \, \Omega \quad R_{41} = 0 \, \Omega \]
\[ C_{1} = 39.9 \, \text{pF} \quad C_{2} = 4.64 \, \text{pF} \quad C_{3} = 4.69 \, \text{pF} \quad C_{4} = 1.68 \, \text{pF} \]
\[ L_{1} = 27.1 \, \mu\text{H} \quad L_{2} = 24.9 \, \mu\text{H} \quad L_{3} = 2.26 \, \mu\text{H} \quad L_{4} = 24.5 \, \mu\text{H} \]
\[ R_{12} = 10.1 \, \text{k}\Omega \quad R_{22} = 50.1 \, \text{k}\Omega \quad R_{32} = 2.68 \, \text{k}\Omega \quad R_{42} = 116 \, \text{k}\Omega \]
Accuracy of K6OIK’s Broadband Equivalent Circuit
Accuracy of K6OIK’s Broadband Equivalent Circuit
## Comparison of Antenna Impedance Models

<table>
<thead>
<tr>
<th>Antenna Impedance Model</th>
<th>Approximation</th>
<th>Realizable Equivalent Circuit</th>
<th>Darlington Form</th>
<th>Element Types</th>
<th>Maximum Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series RLC</td>
<td>fair</td>
<td>yes</td>
<td>yes</td>
<td>R, L, C</td>
<td>0.94 $f_0$ to 1.05 $f_0$</td>
</tr>
<tr>
<td>Witt model</td>
<td>good</td>
<td>no</td>
<td>yes</td>
<td>R($f$) and TL stub</td>
<td>0.6 $f_0$ to 1.2 $f_0$</td>
</tr>
<tr>
<td>K6OIK 3-Element</td>
<td>good</td>
<td>yes</td>
<td>yes</td>
<td>R, L, C</td>
<td>0.90 $f_0$ to 1.08 $f_0$</td>
</tr>
<tr>
<td>Tang-Tien-Gunn 4-Element</td>
<td>excellent</td>
<td>yes</td>
<td>yes</td>
<td>R, L, C</td>
<td>DC to 1.4 $f_0$</td>
</tr>
<tr>
<td>K6OIK 4-Element</td>
<td>excellent</td>
<td>yes</td>
<td>yes</td>
<td>R,L,C,TL</td>
<td>DC to 1.4 $f_0$</td>
</tr>
<tr>
<td>K6OIK 5-Element</td>
<td>excellent</td>
<td>yes</td>
<td>yes</td>
<td>R, L, C</td>
<td>DC to 1.4 $f_0$</td>
</tr>
<tr>
<td>Fosters 1&lt;sup&gt;st&lt;/sup&gt; Form with small losses</td>
<td>poor, best near antiresonances</td>
<td>yes</td>
<td>no</td>
<td>R, L, C</td>
<td>no limit</td>
</tr>
<tr>
<td>Fosters 2&lt;sup&gt;nd&lt;/sup&gt; Form with small losses</td>
<td>poor, best near resonances</td>
<td>yes</td>
<td>no</td>
<td>R, L, C</td>
<td>no limit</td>
</tr>
<tr>
<td>Long-Werner-Werner</td>
<td>fair</td>
<td>no</td>
<td>no</td>
<td>R, C, TL</td>
<td>5 octaves</td>
</tr>
<tr>
<td>Streable-Pearson</td>
<td>good</td>
<td>yes</td>
<td>no</td>
<td>R, L, C</td>
<td>no limit</td>
</tr>
<tr>
<td>K6OIK Broadband</td>
<td>excellent</td>
<td>yes</td>
<td>no</td>
<td>R, L, C</td>
<td>no limit</td>
</tr>
</tbody>
</table>
Standing Wave Ratio Basics
Question – Do the Meters Read the Same SWR?
Answer

- **For lossless lines:**
  - Forward and reverse wave amplitudes are the same everywhere along the line
  - SWR is the same everywhere along the line
  - SWR is the ratio of max to min voltage (or current)

- **For lossy lines**
  - Forward and reverse wave amplitudes vary along the line
  - SWR is maximum at the load and decreases gradually to a minimum at the source
  - The “max / min” definition of the lossless case doesn’t work
  - Best definition is
    \[
    SWR = \frac{1 + \sqrt{\frac{P_R}{P_F}}}{1 - \sqrt{\frac{P_R}{P_F}}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}
    \]
Voltage and Current Standing Waves
Impedance and SWR Along a Line
A Nomogram Relating Input and Output SWR

Reference Data for Engineers, 9th ed., p. 29-9, Newnes, 2002
Standing Wave Ratio at a Resistive Load

\[ SWR = \max \left\{ \frac{Z_0}{R_L} \quad \text{or} \quad \frac{R_L}{Z_0} \right\} \]
Losses Are Due to Reflection and Dissipation

\[ IL_{dB} = ML_{dB} + DL_{dB} \]

**Lossless networks**

\[ DL_{dB} = 0 \]
\[ IL_{dB} = ML_{dB} \]

**Reflectionless networks**

\[ ML_{dB} = 0 \]
\[ IL_{dB} = DL_{dB} \]
Reflection Loss of a Terminated Line vs Input SWR
Dissipation Loss of a Terminated Transmission Line

\[
\text{Dissipation Loss} = 10 \log \left( \frac{1 - A|\Gamma_{\text{Load}}|^2}{A \left( 1 - |\Gamma_{\text{Load}}|^2 \right)} \right) \text{ dB}
\]

where

\[
A = 10^{-\alpha l/1000} < 1 = \text{power attenuation ratio}
\]

\[
\alpha = \text{line attenuation rate in dB/100 ft}
\]

\[
l = \text{line length in feet}
\]

\[
|\Gamma_{\text{Load}}| = \frac{\text{SWR}_{\text{Load}} - 1}{\text{SWR}_{\text{Load}} + 1}
\]

- Reference: *ARRL Antenna Book, 21st ed.*, p. 24-10, eq. 16 with \( A = 1/a \)
A More Useful Form in Terms of SWR at Transmitter

\[
\text{Dissipation Loss} = 10 \log_{10} \left( \frac{1 - |\Gamma_{Tx}|^2}{A - \frac{1}{A} |\Gamma_{Tx}|^2} \right) \text{ dB}
\]

where

\[
A = 10^{-\alpha l/1000} < 1 = \text{power attenuation ratio}
\]

\[
\alpha = \text{line attenuation rate in dB/100 ft}
\]

\[
l = \text{line length in feet}
\]

\[
|\Gamma_{Tx}| = \frac{SWR_{Tx} - 1}{SWR_{Tx} + 1}
\]

- **Reference:** *ARRL Antenna Book, 22\textsuperscript{nd} ed.?*
A Nomogram for Finding Additional Loss Due to SWR

Reference Data for Engineers, 9th ed., p. 29-11, Newnes, 2002
Myths and Bloopers

- **Impedance formula for open wire line**
  - $Z_0 = 276 \log_{10}(2s/d) = 120 \log_e(2s/d) \text{ versus } 120 \cosh^{-1}(s/d)$
  - “$Z_0$ approaches 83 ohms as $s/d$ approaches unity.”
    George Murphy, VE3ERP, CQ, Nov. 2000

- **Return loss**
  - “Return Loss is 20 times the reflection coefficient.”
    Kurt N. Sterba, World Radio, Jan, 2007
  - “Return Loss is not a commonly used quantity.”
  - “Return Loss is 20 times the reciprocal of the reflection coefficient.”
    Kurt N. Sterba, World Radio, June 2007

- **Conjugate match**
  - Numerous theorems of circuit theory incorrectly stated
  - Poor reasoning and incorrect conclusions at every turn
Impedance Formulas for Open-Wire Line

Approximate Formula
\[ 276 \log_{10}(2s/d) = 120 \ln(2s/d) \]

Exact Formula
\[ 119.917 \cosh^{-1}(s/d) \]
Why Not Conjugate Match?

- A conjugate match at the input does not imply a conjugate match at the output (load) and vice versa unless the 2-port is lossless.
- Conjugate matching in long transmission line systems leads to reduced system bandwidth – not good for communication except for narrowband signals, and poor for digital modulations.
- The goal of communication is information transmission, not power transmission. Digital modulations hate distortion caused by echoes, multipath, and reflections.
- Solid state amplifiers are designed for stability by various methods, e.g. unilateralization, load-pull, source-push – to prevent oscillation!
- Conjugate matching plays no particular role in output impedance selection.
Transducer Power Gain

- Maximum power delivery from a given source through a general 2-port to a load is achieved by maximizing “Transducer Power Gain,” not by conjugate matching at input or output.

\[
G_T = \frac{\text{Power delivered to load}}{\text{Power available from source}} = \frac{|S_{21}|^2 (1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)}{|(1 - S_{11}\Gamma_S)(1 - S_{22}\Gamma_L) - S_{12}S_{21}\Gamma_L\Gamma_S|^2}
\]

- Don’t use this fact to match a solid state amplifier to a load, unless you want an oscillator!
Multi-Band Match Networks
Three-Band Match Network

- Ward Silver (N0AX) proposed to design an antenna for the 75, 60, and 40 meter bands
- K6OIK’s easy solution: Take an existing antenna and design a feedpoint match network for the three bands
- Antenna: 98.4-foot wire dipole antenna resonant at 4.868 MHz – nothing special
- Frequencies: 3.9 MHz; 5.35 MHz; and 7.2 MHz
- Design goal: SWR = 1 at these three frequencies
Dipole Impedance
Dipole Impedance on the Smith Chart

Frequency sweep
3.8 to 7.3 MHz
Dipole SWR Before Matching
Dipole SWR Before Matching

![Graph showing SWR vs Frequency](image)
Circuit of Three-Band Match Network

Parts list
C1 = 64.8 pF
L1 = 11.8 μH
Z1 = 171 Ω
E1 = 24º @ 1 MHz
L2 = 3.93 μH
C2 = 83.8 pF
Impedance After Matching

Frequency sweep 3.8 to 7.3 MHz

Perfect match at design frequencies
SWR After Matching

Before matching

After matching

FREQ [MHz]

SWR
Question

- Can a fixed (non-tunable) impedance-matching network provide unity SWR at all frequencies?
Reflectionless Broadband Impedance Matching

Constant-Resistance Networks
Non-Foster Active Networks
The Idea

- Traditional impedance-matching networks are “reflection” filters that create reflected waves
  - Subject to the Fano bound
- Constant-resistance reflectionless networks
  - Developed by E.L. Norton (1937)
  - Have unity SWR over a wide band
  - Are “diplexers” that divide power between two loads
  - Rated by insertion-loss bandwidth instead of SWR bandwidth
  - Side-step the Fano bound but are subject to the Carlin-LaRosa bound
How to Do It

- **Step 1:** Shorten “half-wave” dipoles or lengthen “quarter-wave” monopoles so that $R_A = 50$ ohms
  - Dipoles: Use $K \approx 0.86$, or $L \approx 0.43\lambda$
  - Monopoles: Use $K \approx 1.07$, or $L \approx 0.27\lambda$

- **Step 2:** Insert a series reactance to cancel feedpoint reactance
  - Dipoles: Add a series inductor
  - Monopoles: Add a series capacitor

- **Step 3:** Insert a shunt network to yield a 50-ohm constant-resistance network
Antenna Impedance on the Smith Chart

Monopole Length

\[ R_A = 50 \implies L = 0.27\lambda \]

Dipole Length

\[ R_A = 50 \implies L = 0.43\lambda \]
Example 1: Reflectionless Match to 0.43λ Dipole

Matching Network

Antenna Model

\[ L_S = 7 \, \mu H \]

\[ L_M = C_A R_A^2 = 111 \, nH \]

\[ C_M = \frac{L_S + L_A}{R_A^2} = 12,300 \, pF \]

\[ R = R_A = 50 \, \Omega \]
Network Performance on Dipole Impedance Data

- Frequency sweep 1 to 8 MHz
- Maximum SWR = 1.04
- Input resistance: 48.8 to 51.2 ohms
- Input reactance: -2.1 to 0 ohms
Power Delivered to the 0.43λ Dipole

- Pattern gain = -0.11 dBi
- Minimum insertion loss = 0 dB
- 100% power delivery at 4.3 MHz
- 3-dB Bandwidth = 259 kHz (6.0%)
- 0.51-dB Bandwidth = 91 kHz (2.1%)

<table>
<thead>
<tr>
<th>Bandwidths to Compare</th>
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</thead>
<tbody>
<tr>
<td><strong>Lossless Networks</strong></td>
</tr>
<tr>
<td>$BW_{\text{VSWR 5.83:1}}$</td>
</tr>
<tr>
<td>$BW_{\text{VSWR 2:1}}$</td>
</tr>
<tr>
<td><strong>Reflectionless Networks</strong></td>
</tr>
<tr>
<td>$BW_{\text{IL 3-dB}}$</td>
</tr>
<tr>
<td>$BW_{\text{IL 0.51-dB}}$</td>
</tr>
</tbody>
</table>
Interesting Antennas
John Daniel Kraus, 1910-2004
Chen-To Tai, 1915-2004
Ronold Wyeth Percival King, 1905-2006

Sergei Alexander Schelkunoff, 1897-1992
Amateur Antenna Paradigms

- Antennas made of straight elements (wires, rods, and tubes)
- Antennas made of conductors (metals)
- Resonant antennas
- Narrowband antennas
- But ... many interesting and novel antennas break these rules!
- And some strange antennas don’t ...
Landstorfer Antenna (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)

- Helix: 4 arms, 1 turn
- Height (radius): $\lambda/16.5$
- Frequency: 300 MHz
- Polarization: vertical
- Z: 50 ohms real
- SWR: < 1.16
- Efficiency: > 94%
- Bandwidth: 22.8 MHz (7.6%)
- $Q_A$: 32 ($Q_{Chu} = 22.8$)
Polyrod Antenna (1947)

- Material: Polystyrene
- Frequency: 11.6 GHz
- Gain: 20 dBi
- Bandwidth: 40%

Dielectric rods made of ceramic or fused quartz can handle high power.
Stealth Antennas
Saguaro Cactus (Carnegia gigantea)?
Evergreen Trees?
Deciduous Tree?
Non-Stealth Antennas
90-Foot Drive-Up Discone, Green Valley, Arizona
Why Little Transmitters Get Heard

K0DK in Boulder, Colorado
K4JA at Callao, Virginia
The W5UN Mighty Big Antenna. 32 - 17 element yagis used for 2 meter EME operation.
W6AM’s Antennas As Seen from Space

W6AM at Rancho Palos Verdes, California
Broadband Antennas
Vivaldi Antenna (1974)

- Exponentially tapered slot antenna
- Gain: 8 to 9 dBi
- Bandwidth: no limit
- Arbitrary polarizations obtained by feeding two crossed antennas
- Construction: PC board

Bandwidths of one octave to one decade can be achieved
Four-Sector Vivaldi Antenna

- Antenna mounts horizontally
- Polarization: horizontal
- Four directional beams
- Beam selected by PIN diodes
- Gain: 8 to 9 dBi per sector

Dual use! Could be mounted as a horizontal capacity hat on a short HF monopole to span all UHF bands

Or mount two vertically and crossed for vertical polarization in four sectors
Computer Evolved Antennas via Genetic Optimization

- Crooked Wire Genetic Antennas (CWGA)
- Types: 1 and 4 arms
- Frequencies: 2 to 18 GHz
- Pattern: Omni 10° above horizon

Courtesy of JEM Engineering
NASA ST5 Satellite Antenna

- **Frequencies:**
  - Tx: 8.470 GHz
  - Rx: 7.209 GHz

- **Polarization:** RHCP

- **Gain:**
  - -5 dBi, 0° to 40°
  - 0 dBi, 40° to 90°
  - No null at zenith

- **SWR:**
  - Tx: 1.19
  - Rx: 1.22

- **Wire:** 20 gauge

Courtesy of JEM Engineering
Loaded UWB Antenna for 1 to 15 GHz

SWR < 3 from 1 to 15 GHz

Courtesy of JEM Engineering
Air Force 10-Segment Resonant Antenna (0.03 $\lambda$)

Courtesy of JEM Engineering
Inexpensive Curtain Quad Arrays

Courtesy of Ross Anderson, W1HBQ
Ross Anderson W1HBQ’s Curtain Quad for WiFi

- Frequency 2.4 GHz IEEE 802.11
- Gain: 17 dBi
- Polarization: V (as shown)
- Material: 3 × 2 inch welded wire fence
- Wire: #16 steel wire, 0.031 in
- Backing: 1 inch foam board, backed with aluminum foil
- Feedpoint Z: 600 Ω
- Match device: ~1 in of 125 Ω speaker wire
W1HBQ’s 221-Element Curtain Quad for 1296 MHz

- Gain: 26 dBi
- Polarization: H (as shown)
- Feedpoint Z: 99 Ω
Metamaterial Radomes
Transmitter Inside Cow
Performance of Cow Radome – Longitudinal Plane
Cow Radome – Transverse Plane
Bell Laboratories Monopole in Metamaterial Shell

- Shell type: ENG
- Stub length: $\lambda/50$
- Shell radius: $\lambda/18.5$
- Frequency: 2.025 GHz
- $Z$: 50 ohms real
- VSWR: < 1.02
- Bandwidth: 4.76%
- $Q_A$: 42 ($Q_{Chu} = 28.9$)
- Polarization: vertical
- Efficiency: > 61%
Two-Port Equivalent Circuit of Monopole Antenna

Antenna Reactance

Free-Space Load

376.73 Ω
Monopole Space-Matched by Thin DNG Shell

Antenna Reactance

DNG Shell

Free-Space Load

376.73 Ω
K6OIK’s Electrically-Small 2-Meter Antenna
Close Up View of the Radiator
Metamaterial Radome for Impedance Matching
Radome for Impedance Matching on 2 Meters
Analyzing Terrain Effects
by Computational Electromagnetics

Meshing Silicon Valley
Courtesy of Keith Snyder, KI6BDR
Antenna Modeling Software for Radio Amateurs

- EZNEC and EZNEC+ by Roy Lewallen, W7EL
  - 500 and 1,500 segments respectively, $89 and $139

- EZNEC-ARRL
  - Included on ARRL Antenna Book CD, $45

- MultiNEC by Dan Maguire, AC6LA, http://www.ac6la.com
  - Low cost but currently unavailable
  - Puts EZNEC on autopilot for making a series of many runs
  - Doesn’t work with EZNEC-ARRL

- 4nec2 by Arie Voors, http://home.ict.nl/~arivoors
  - Free download
  - Runs under Windows 2000 and XP
  - Handles up to 11,000 segments
  - Optimizer included

- Professional evaluation software
  - FEKO LITE http://www.feko.info
  - WIPL-D Lite http://www.wipl-d.com
Earth Currents and Hills Looking South West
Computer Used For Antenna Design and Electromagnetic Systems Analysis

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

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Triangles</th>
<th>Hours</th>
<th>Memory (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,900</td>
<td>3,928</td>
<td>0.125</td>
<td>0.53</td>
</tr>
<tr>
<td>3,750</td>
<td>12,834</td>
<td>1.54</td>
<td>5.48</td>
</tr>
<tr>
<td>7,150</td>
<td>38,717</td>
<td>52.1</td>
<td>9.38</td>
</tr>
</tbody>
</table>
Ground Currents

7.15 MHz  Antenna Height = 50 m, Polarization = Horizontal

Earth’s Contribution

Surface current [dBµA/m]

-95.0
-103.3
-110.8
-118.3
-125.8
-133.3
-140.8
-148.3
-155.9
-163.3
-170.8

North

South
3D Antenna Pattern

7.15 MHz
Antenna Height = 50 m
Polarization = Horizontal
Fields = Total V+H

South

North
New Antenna Books for 2007

Amateur Reference

Engineering Reference
Favorite Antenna Books

- **Books for antenna engineers and students**

- **Antenna research papers**
Favorite Antenna Books continued

- **Books for radio amateurs**

- **ARRL Antenna Compendium series – Volumes 1 through 7**

- **ARRL Antenna Classics series – five titles**
The End

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