Modeling the Long Wavelength Array Crossed-Dipole Antenna

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1. Introduction

This paper describes an electromagnetic model developed for the Long Wavelength Array (LWA) crossed-dipole antenna using the free antenna modeling and simulation tool 4NEC2 {4NEC2}. Note: Links in braces { } and references in brackets [ ] are provided in **section 9**. This model is used to explore far-field radiation patterns and other antenna characteristics. No attempt has been made so far to verify this model with field measurements. Additional background information and ordering details can be found in **section 7**. The original design documents for the entire LWA antenna system are available online at {LWA}. The antenna is being used in both government and privately funded observatories.

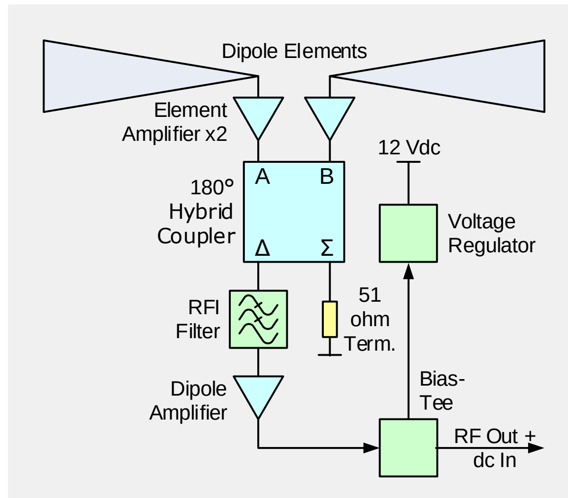
2. Antenna description

The LWA antenna is a receive-only, inverted-V, "tied fork" design with elements consisting of triangular sloping wings or blades (figure 1-1). The design frequency range is 5 to 90 MHz. An active balun assembly, called front end electronics (FEE) in the LWA, converts the balanced dipoles to unbalanced 50 ohm impedance for connection to coaxial cable transmission lines and also provides approximately 35 dB gain (figure 1-2). Each active balun provides a 100 ohm termination for its associated dipole and is powered through the coaxial cable feedline by a bias-tee arrangement. The active balun is a dual assembly with two identical printed circuit boards, one for each crossed-dipole. Each dipole feeds a separate receiver or signal processor. Applications are briefly discussed in **section 5**.

Figure 1-1 ~ Crossed-dipole antenna installed by radio astronomer Stan Nelson at Roswell, New Mexico in January 2014. Each of the two dipoles consists of two triangular aluminum frame elements sloping down 45° and supported from the steel center post by non-conductive horizontal fiberglass rod braces. Each element is 1.5 m long x 0.8 m wide. At the base of the antenna is a 3 m x 3 m galvanized wire mesh ground screen. The peak (apex) of the two dipoles is 1.5 m above ground level with the dual active balun assembly in the gray enclosure at the top. Two coaxial cables can be seen leading away from the antenna, one for each dipole (Image © 2014 S. Nelson, used with permission)

A nice feature of 4NEC2 compared to similar software tools is a drag-and-drop geometry editor that enables easy construction of the NEC wire model and avoidance of the spreadsheet style entry method. This feature is not yet flawlessly implemented but it can help speed up the model building process. The 4NEC2 model described here is based on public domain version 2 of the Numerical Electromagnetics Code (NEC-2). The Numerical Electromagnetic Codes simulate the electromagnetic response of antennas and arbitrary metal structures by finding a numerical solution to the mathematical equations that describe the induced currents. Additional information can be found at {NEC2}. 4NEC2 is claimed to work with NEC-4 but I have not yet tried anything but NEC-2 (note: NEC-4 requires a license from Lawrence Livermore National Laboratory, {LLNL}).

Figure 1-2 ~ Active balun block diagram shows one balun and associated dipole. A crossed-dipole antenna uses two identical dipoles and two identical baluns. The currents produced in each dipole element by incoming radio waves have opposite polarity and are coupled directly to an amplifier with about 25 dB gain. This arranagement provides 100 ohms balanced dipole termination impedance. The amplified outputs from the two elements are connected to a 180° hybrid coupler. The Δ output of the coupler combines the opposite polarities. Any common mode interference currents on the dipole elements are directed to the Σ output where they are dissipated in the 50 ohm termination resistor. The Δ output from the hybrid coupler is filtered and then amplified by about 12 dB. The total gain from the elements to output is about 35 dB, and the reported noise temperature is 250 K (2.7 dB noise figure). The active balun itself has a usable frequency range of 500 kHz to 115 MHz. (Image © 2013 W. Reeve)



3. NEC Model

This section describes how the model was developed. A complete model description (the .nec file itself) is available on request.

Structure: All dimensions are taken from the OEM (original equipment manufacturer) drawings shown on the last three pages of [LWA0020]. The 4NEC2 model wireframe layout is identical to the actual antenna (figure 3-1).The antenna uses 0.75 in (19 mm) welded square aluminum tubes for all structural components. I used 20 mm equivalent diameter round wire elements in the model because 4NEC2 does not accept square wires. These wires were configured with the conductivity of 6061-T6 aluminum (using copper or even a material with infinite conductivity has insignificant effect on model results).

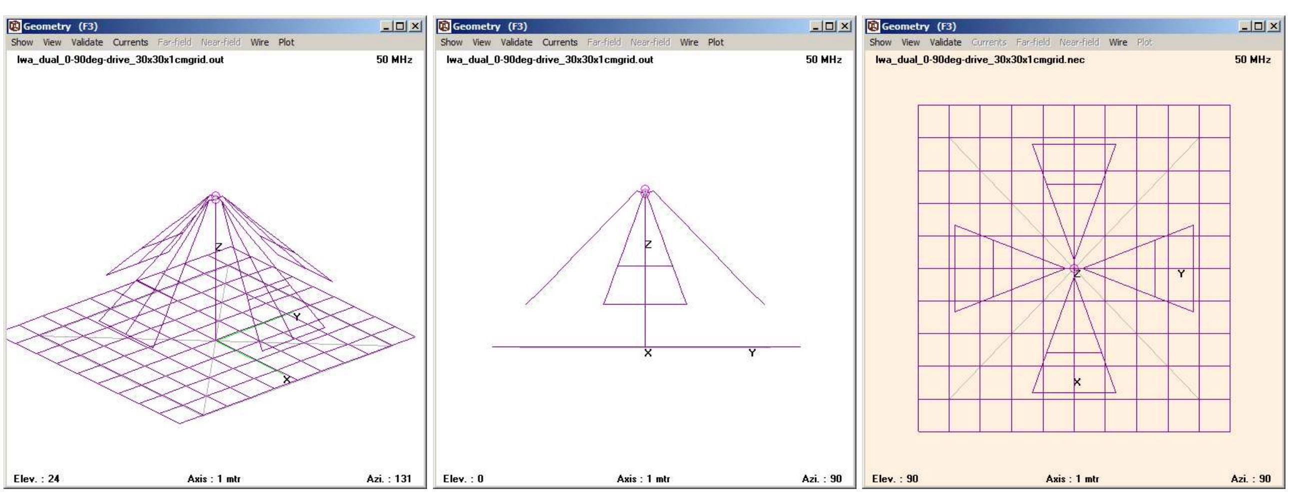


Figure 3-1 ~ Left-to-right: Isometric, side and top views of the crossed-dipole antenna including vertical support mast and 3 x 3 m ground screen. (Images © 2014 W. Reeve)

Software settings: Modeling any physical structure involves compromises such as using round wires instead of square. In addition to dimensional and geometry inputs, it is necessary to specify excitation sources, segmentation, frequencies, and earth ground environment. 4NEC2's main window is shown for reference (figure 3-2).

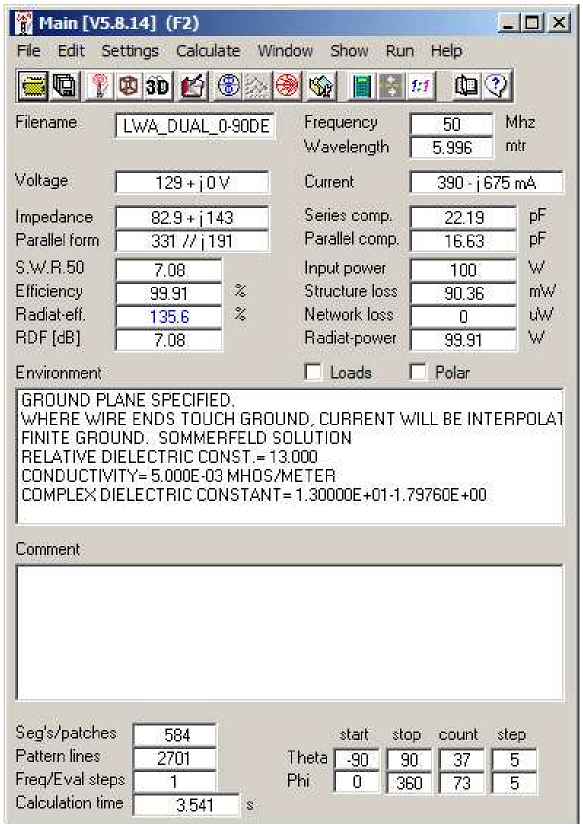


Figure 3-2 ~ 4NEC2 main window shows calculation results and other details such as number of segments and calculation times. (Images © 2014 W. Reeve)

The frequency range investigated is 14 to 100 MHz, slightly higher than the design. It should be noted that Earth's ionosphere cuts off space radiations below about 15 MHz except in rare circumstances. The actual cutoff frequency varies with solar activity, but it is unlikely this antenna will be used much below 15 MHz. When modeling a crossed-dipole for circular polarizations, the excitation sources for the two dipoles are specified with equal amplitude but ±90° phase difference.

Programs that use numerical electromagnetic codes require wires to be divided into short straight segments. These segments are required to comply with certain dimensional rules in relation to the wavelength. 4NEC2 can automatically segment the antenna wires but only at one frequency (wavelength). I investigated the LWA crossed-dipole over almost three octaves in frequency, so I manually adjusted the segmentation for compliance over the full frequency range. This resulted in a total of 584 segments for the model with a 3 x 3 m ground screen.

Ground screen: A ground screen is used with the LWA antenna to stabilize its environment [LWA007B]. Without a ground screen the peak gains vary significantly (several dB) with the type of earth ground used in the simulation (see **section 4** for simulation results). Unless noted otherwise, all patterns and gains in this paper are based on a ground screen and "average" earth ground derived from the Sommerfeld-Norton (so called "real") earth ground model. In all cases, the electrical characteristics of the earth ground used in the simulations are consistent with [P.527-3].

The LWA antenna uses a 3 m x 3 m galvanized steel, 4 in (100 mm) mesh screen installed directly below the antenna on the ground surface. Rather than a 100 mm mesh, I used 300 mm in the model (wire diameter 1 mm) to ease model construction. NEC-2 cannot handle wires that are on the surface or embedded in earth (unlike NEC-4). To work around this limitation, I modeled the ground screen 1 cm above the surface. There are slight changes in the peak gains (about 0.1 dB and of no practical significance) with changes in screen height from 0.5 to 10 cm. I also modeled a larger 4.2 x 4.2 m screen (almost 100% increased area over the 3 x 3 m screen).

4. Model results

The following plots show circular polarizations denoted *RHCP* for right-hand circular polarization, *LHCP* for left-hand circular polarization and *Total* for the combined response. The polarization was produced by setting the dipole voltage sources with quadrature relative phase. Although RHCP is seen as the dominating polarization in these plots, simply changing one voltage source from leading to lagging quadrature phase changes the polarization to LHCP. Changing the polarization does not change the plot shapes. All results are with the 3 x 3 m ground screen except the results reported at the end of this section include comparisons with a 4.2 x 4.2 m ground screen.

Average gain test: A basic integrity check for NEC models is the *average gain test*, and I used this to check the model at 14, 50 and 100 MHz. The average gain is the ratio of total power in the far field to the power delivered to the antenna by the sources. A perfect antenna model over perfect ground yields a value of 2.0, and a very good model should be 2.0 ± 0.10. For the model described here, the average gain test results are 1.899 at 14 MHz, 1.994 at 50 MHz, and 2.019 at 100 MHz. It should be noted that adequate results from the average gain test do not always mean the model is adequate. However, inadequacies in the model usually show up as anomalies in the results and none were noticed.

Antenna gain: The antenna gains are relative to an isotropic antenna (an isotropic antenna has equal response in all directions and often is used as a reference). The total peak antenna gain is comparatively low at 14 MHz but rises rapidly until 25 MHz and is flat within approximately 1.5 dB to 104 MHz (figure 4-1). The peak gains of the crossed-dipole described occur at an elevation angle of 90°.

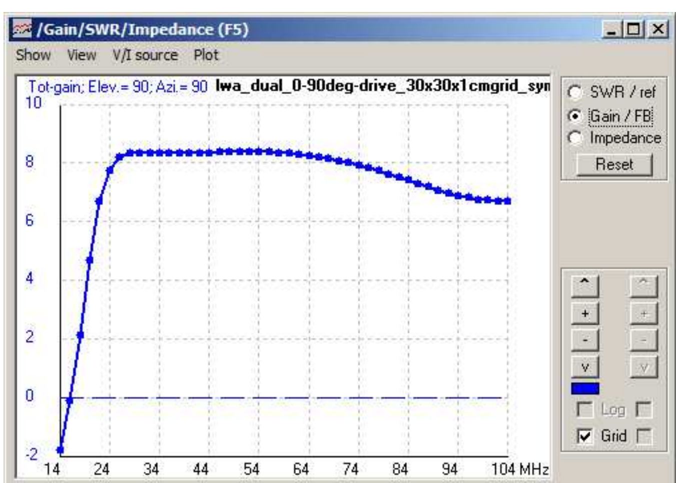


Figure 4-1 ~ Total peak antenna gain in dBi for the frequency range 14 to 104 MHz (2 MHz resolution) and 90° elevation and 90° azimuth angle. When receiving circular polarization, the antenna is omnidirectional (equal response at all azimuths for a given elevation angle). (Images © 2014 W. Reeve)

Patterns: 4NEC2 can display the far field antenna patterns in various formats including familiar 2-dimensional elevation plots (figure 4-2) and azimuth plots (figure 4-3) and an informative 3-dimensional view that shows the antenna, ground and radiation pattern (figure 4-4). 4NEC2 also can display surface wave and near field plots (not shown).

The elevation (vertical plane) pattern plots indicate that discrimination between right-hand and left-hand circular polarizations is at least 20 dB to 90 MHz and the azimuth (horizontal plane) pattern plots show the omnidirectional characteristics. The half-power beamwidths in elevation are 98° at 14 MHz, 100° at 50 MHz and 80° at 100 MHz and have very little variation at intermediate frequencies.

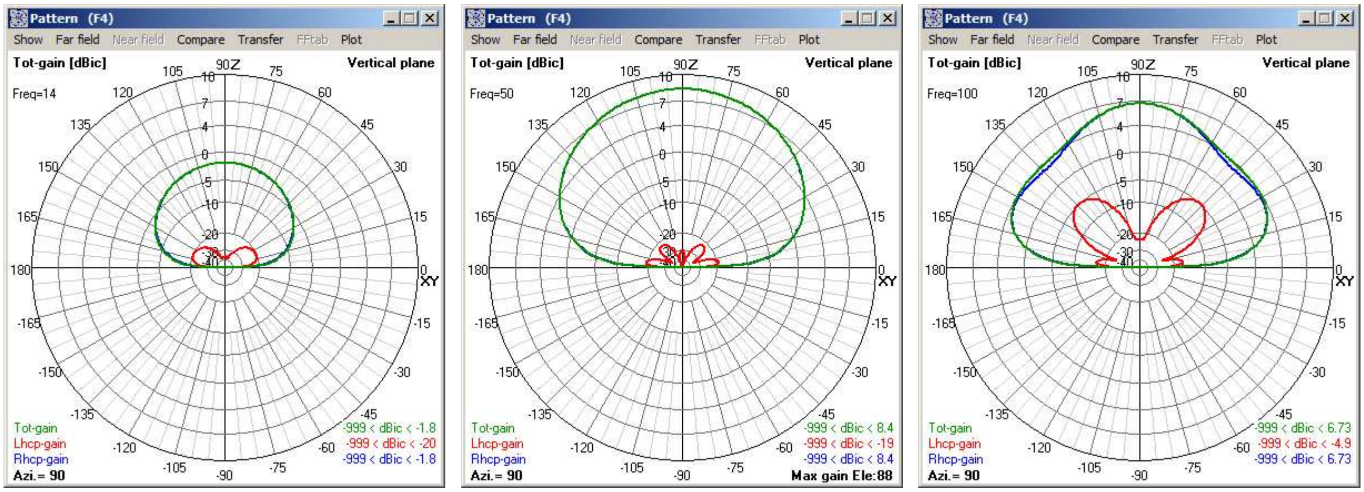


Figure 4-2 ~ 2-dimensional vertical plane antenna patterns for (left-to-right) 14, 50 and 100 MHz. The total gain (green trace) is indistinguishable from the RHCP gain (hidden blue trace). The LHCP gains (red trace) typically are 21 to 29 dB lower than RHCP up to 90 MHz, decreasing to about 11 dB at 100 MHz. Plots for intermediate frequencies are very similar to 50 MHz with no flattening at intermediate elevation angles until 100 MHz. (Images © 2014 W. Reeve)

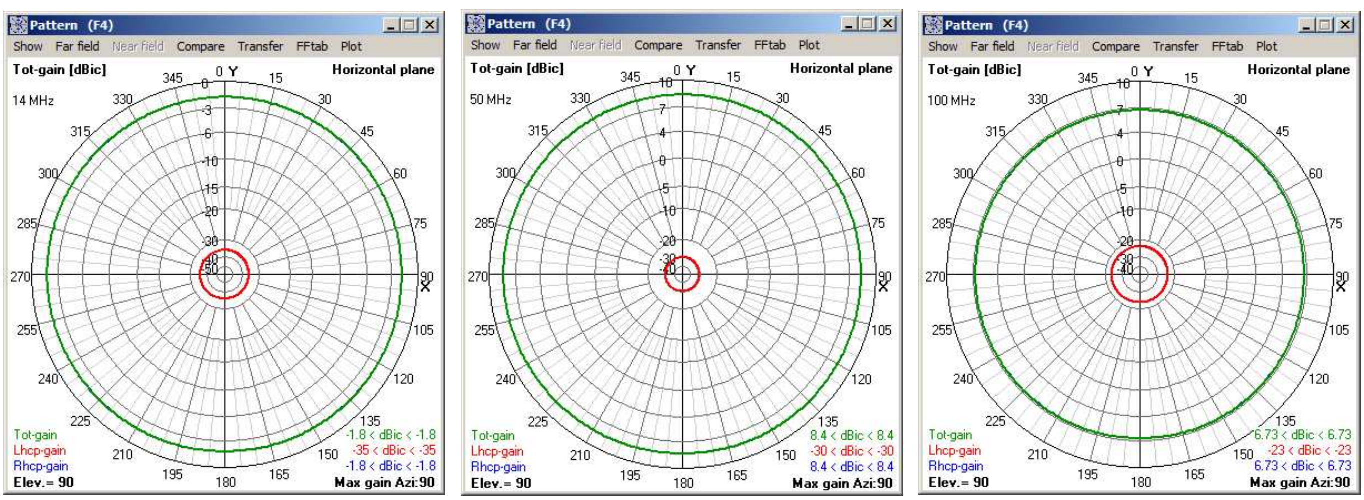


Figure 4-3 ~ 2-dimensional horizontal plane antenna patterns for (left-to-right) 14, 50 and 100 MHz illustrating the omnidirectional response of the antenna in azimuth. The plots for intermediate frequencies are very similar. As with the elevation patterns, the total gain (green trace) is indistinguishable from the RHCP gain (hidden blue trace). The LHCP gains also are shown (red trace). (Images © 2014 W. Reeve)

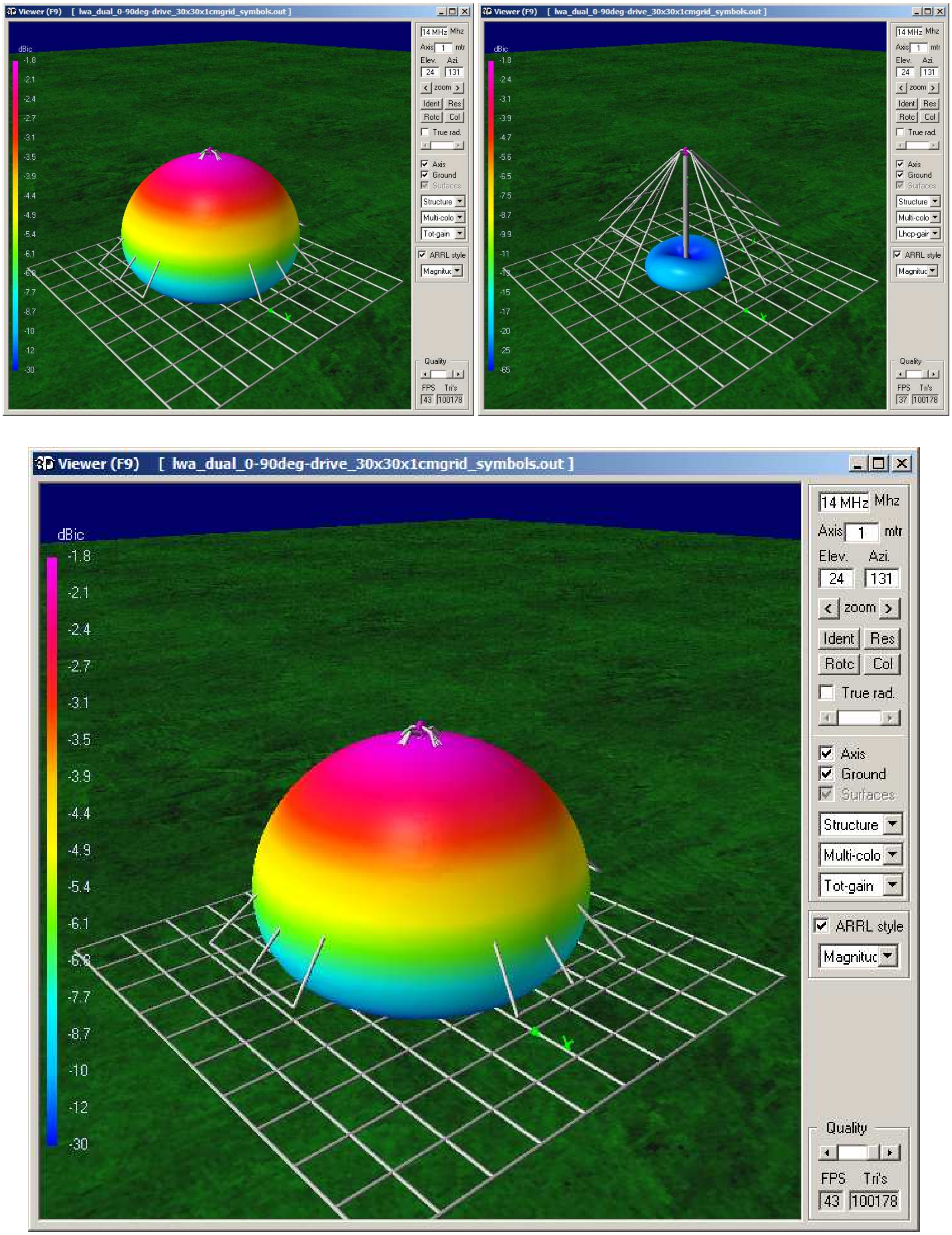


Figure 4-4a ~ 3-dimensional response patterns at 14 MHz where color indicates gain according to the scale on the left of each image. Clockwise from upper-left: RHCP, LHCP and Total gain. The antenna structure is shown embedded in the radiation pattern image over the ground screen and earth ground. (Images © 2014 W. Reeve)

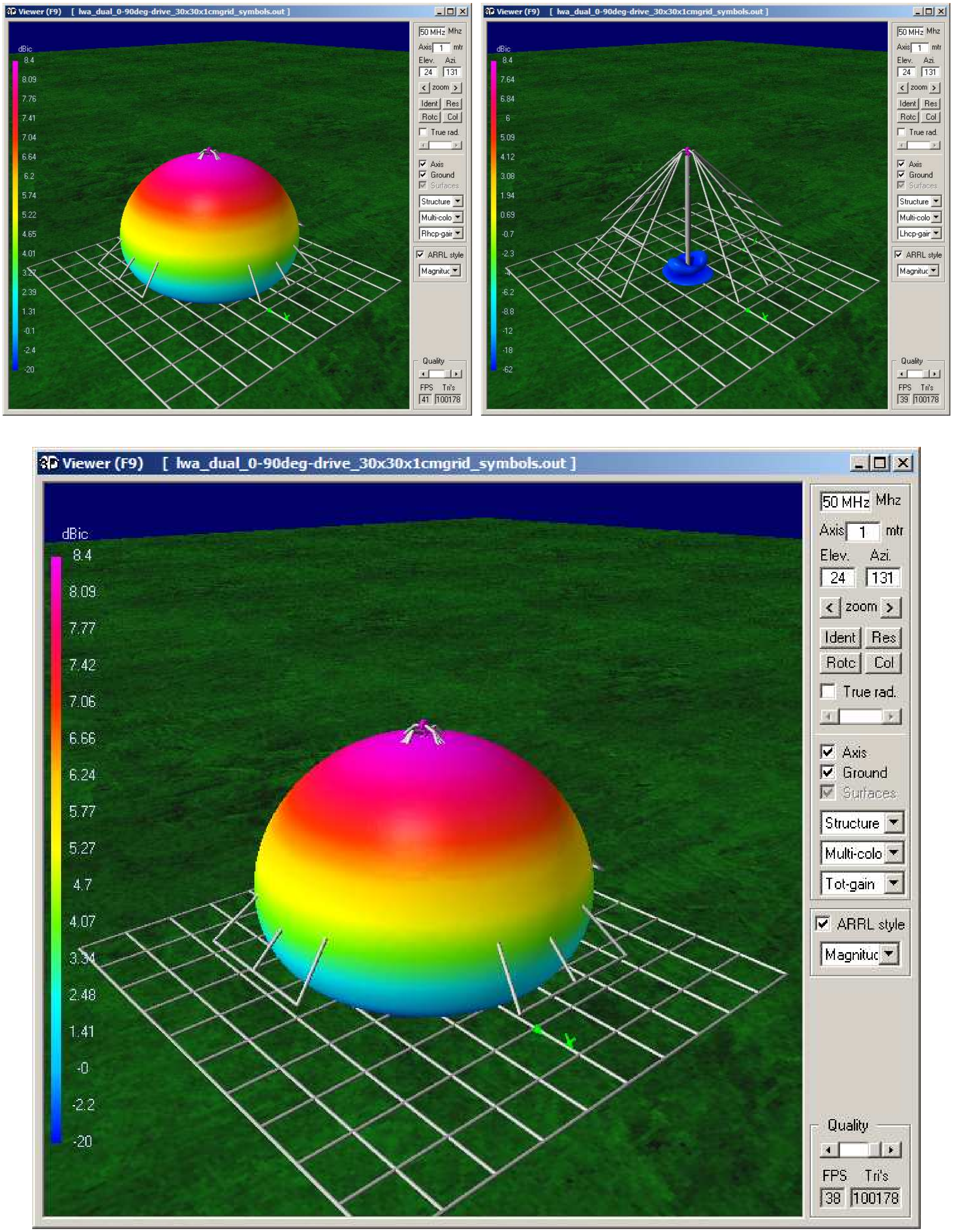


Figure 4-4b ~ 3-dimensional response patterns at 50 MHz. Clockwise from upper-left: RHCP, LHCP and Total gain. (Images © 2014 W. Reeve)

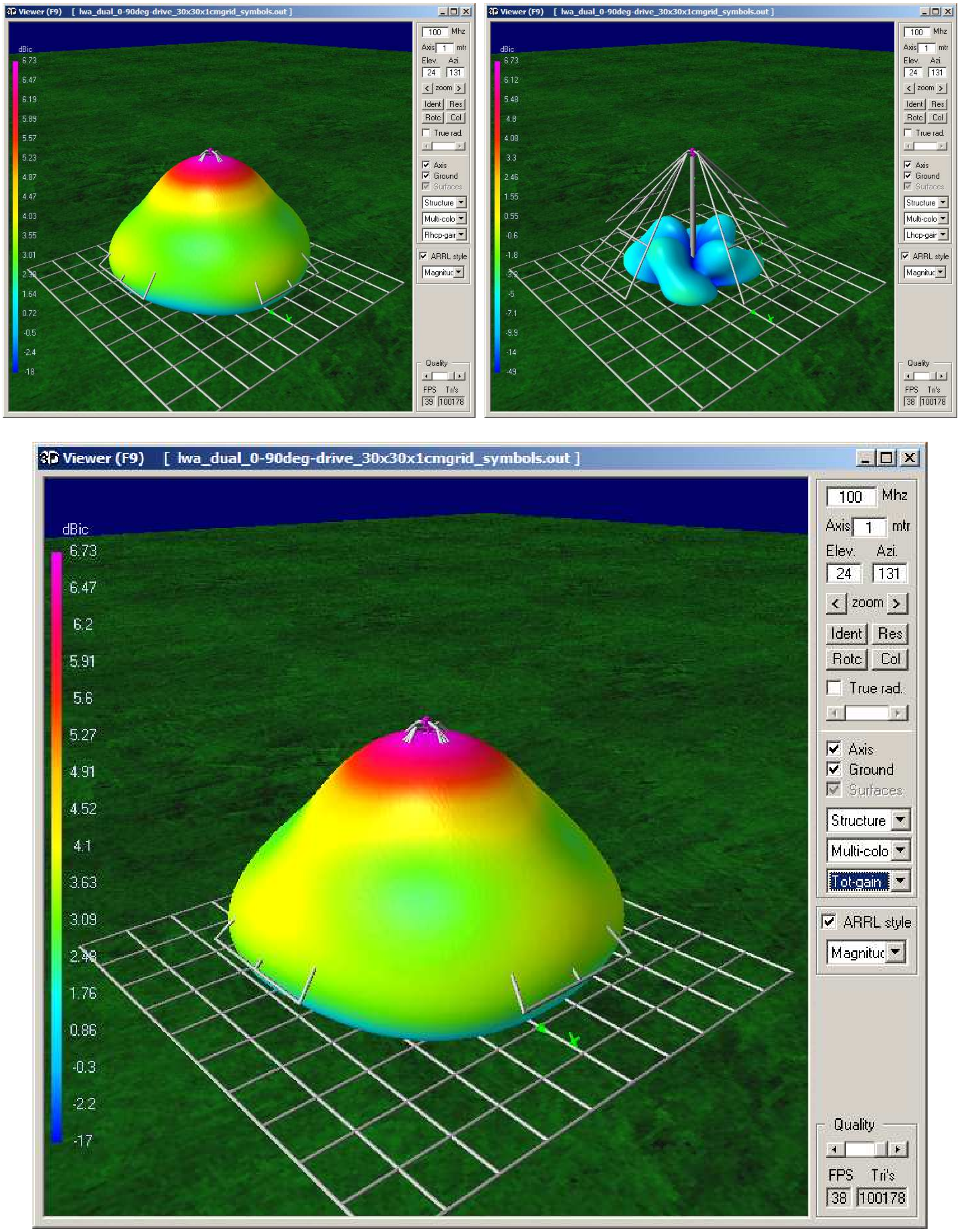


Figure 4-4c ~ 3-dimensional response patterns at 100 MHz. Clockwise from upper-left: RHCP, LHCP and Total gain. (Images © 2014 W. Reeve)

Impedances: Each dipole is connected to a pair of MMIC (monolithic microwave integrated circuit) amplifiers, which provide a balanced 100 ohm resistive termination. I produced impedance plots over the 14 to 100 MHz frequency range largely out of curiosity (figure 4-5). As expected, the antenna impedance varies with frequency and the 100 ohm termination is a compromise.

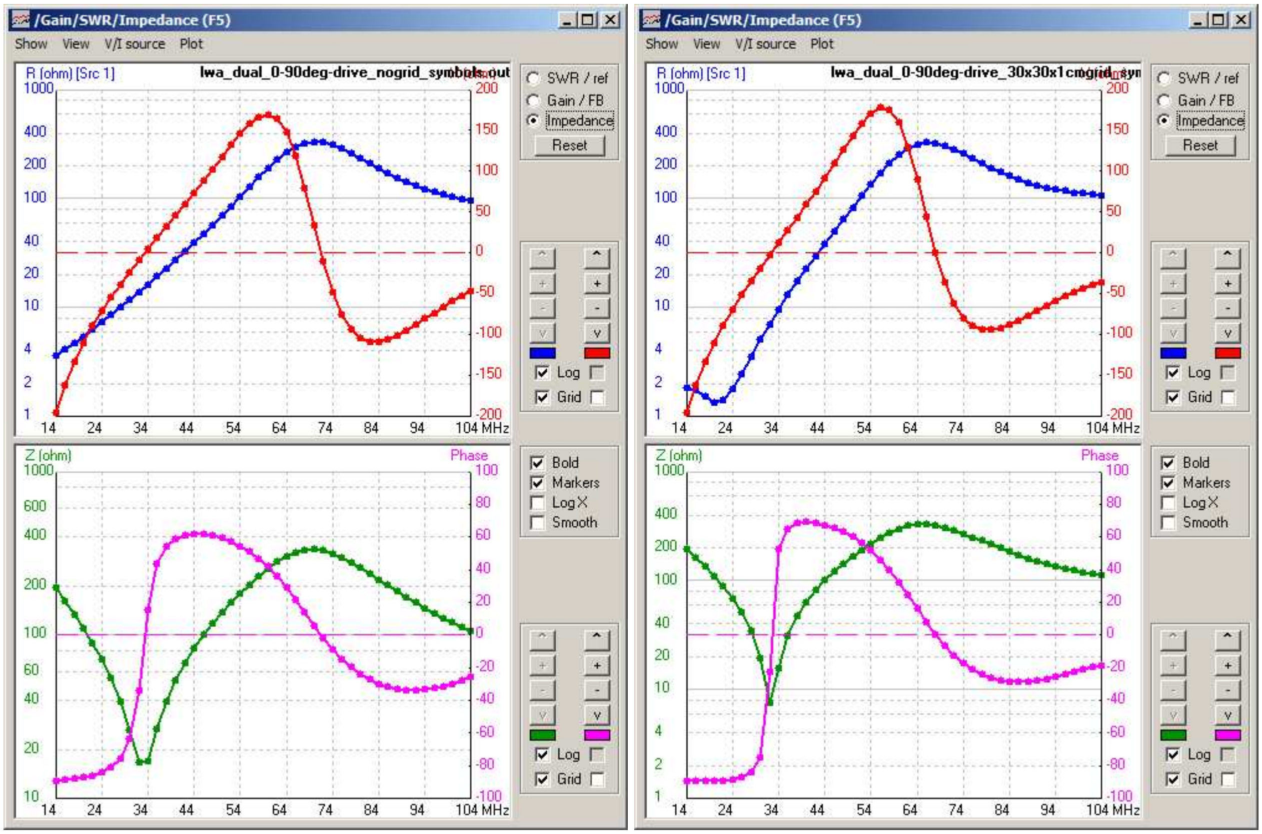


Figure 4-5 ~ Calculated impedances of the crossed-dipole antenna from 14 to 100 MHZ (2 MHz resolution) for no ground screen (left) and 3 x 3 m ground screen (right). There is little difference except at the lower frequencies, and the plots for the 4.2 x 4.2 m ground screen described below are substantially the same. (Images © 2014 W. Reeve)

Ground screen: The above characteristics are determined with a 3 x 3 m ground screen. I then modified the model for a 4.2 x 4.2 m ground screen (same 30 cm mesh size) and prepared patterns for comparison (figure 4-6). The basic pattern shapes do not change but the peak gains increase 0.6 to 0.8 dB and beamwidths narrow slightly with the larger screen size (table 4-1).

5. Applications

The crossed-dipole antenna can be connected in a number of different configurations (figure 5-1). If setup for circular polarization, it discriminates between circular polarized radio waves with different rotation directions – RHCP and LHCP. It can be made to discriminate a certain direction of rotation by simply changing the phase relationship of the two dipoles. This antenna also responds equally to linearly polarized radio waves with any (or random) orientation.

One setup that may be used to observe circular polarization involves connecting a quadrature (90° hybrid) coupler and two receivers, one each for RHCP and LHCP. The two antennas also may be tied together with a 90° phasing cable after the baluns; however, this would be a narrowband configuration and would not take advantage of the LWA antenna's bandwidth (the phasing will be correct only for a narrow frequency range corresponding to the cable's electrical length).

Table 4-1 ~ Peak gain and beamwidth at 50 MHz with various earth ground types and ground screen configurations. Peak gains are at 90° elevation angle. The Perfect ground type (infinite conductivity) is shown for comparison.

Ground type	**Conductivity (S/m)**	**Relative permittivity**	**Total peak gain (dBi)**	**3 dB Beamwidth (°)**
Perfect + no ground screen	Infinite		9.48	102
Poor + no ground screen			5.34	108
Poor + 3 x 3 m ground screen	0.001	5	8.38	98
Poor + 4.2 x 4.2 m ground screen			9.19	90
Moderate + no ground screen			5.24	110
Moderate + 3 x 3 m ground screen	0.003	4	8.38	98
Moderate + 4.2 x 4.2 m ground screen			9.17	90
Average + no ground screen			6.47	104
Average + 3 x 3 m ground screen	0.005	3	8.40	100
Average + 4.2 x 4.2 m ground screen			8.90	94
Good + no ground screen			5.72	110
Good + 3 x 3 m ground screen	0.01	4	8.26	102
Good + 4.2 x 4.2 m ground screen			9.03	92
Arctic land + no ground screen			4.80	112
Arctic land + 3 x 3 m ground screen	0.0005	3	8.47	98
Arctic land + 4.2 x 4.2 m ground screen			9.21	90

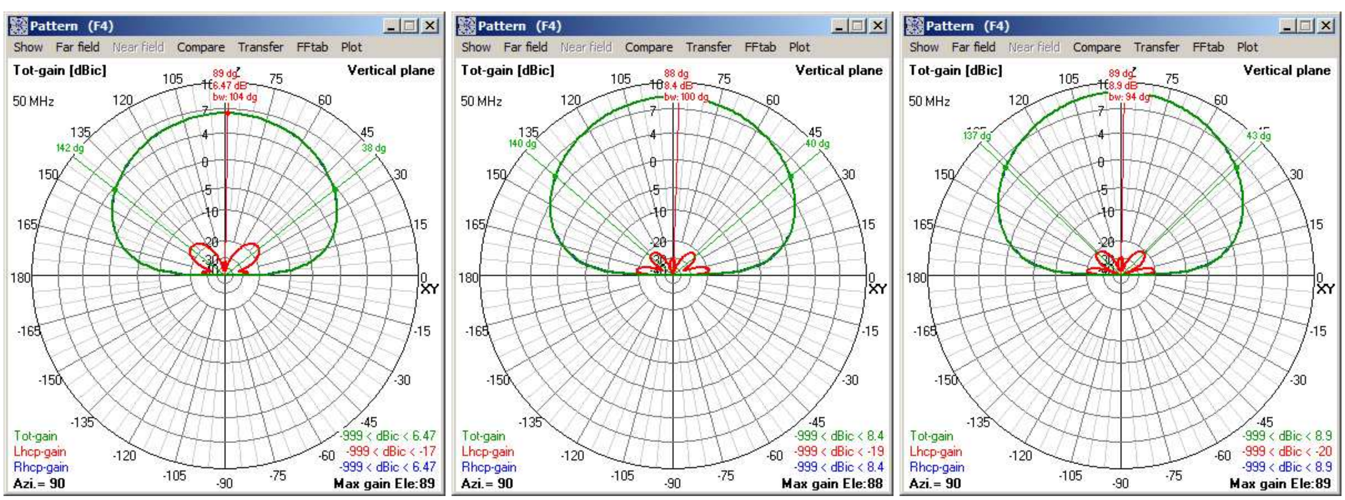


Figure 4-6 ~ RHCP (green trace) and LHCP (red trace) pattern plots for average earth ground and no ground screen (left), 3 x 3 m ground screen (middle) and 4.2 x 4.2 m ground screen (right). The patterns indicate a slight change in the response to LHCP and an overall slight increase in gain for higher conductivity earth ground. (Images © 2014 W. Reeve)

It also is possible to provide the quadrature phase shift after the receivers or by signal processing – the method would depend on the receiver front-end and back-end configurations. This setup could use two receivers, one connected directly to each dipole, or a single receiver connected to the two dipoles through an alternating switch. Perhaps the simplest configuration involves connecting one receiver to the two dipoles through a combiner. This configuration does not allow discrimination of circular polarization but does provide equal response to random polarizations.

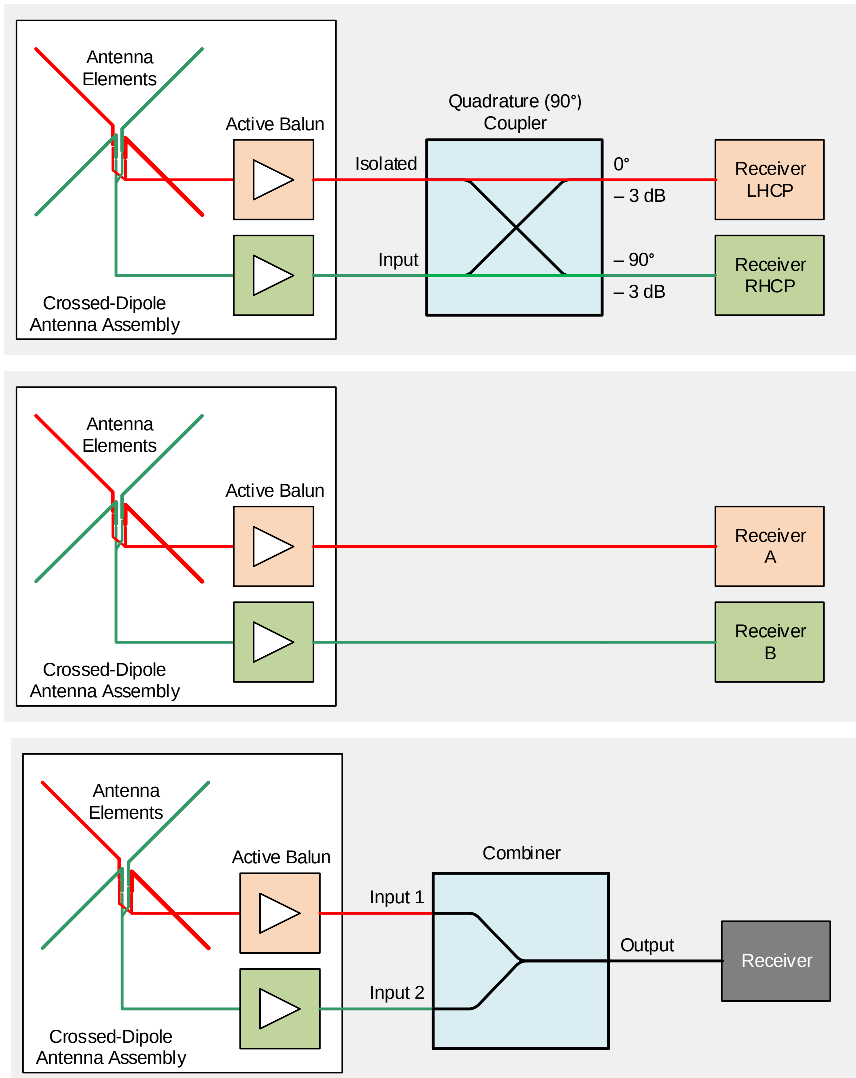


Figure 5-1 ~ Examples of crossed-dipole connections to receivers. The upper configuration allows discriminating between RHCP and LHCP using two receivers and a quadrature coupler. It also has equal response to random polarizations. The middle configuration can discriminate circular polarizations if 90° phase shift is provided after the receivers or it can be used to discriminate two linear but orthogonal polarizations. The lower configuration with the combiner cannot discriminate between circular polarizations but simply combines the two dipole outputs and provides equal response to random polarizations. (Images © 2014 W. Reeve)

6. Conclusions

The LWA antenna was modeled with 4NEC2, a free software tool that uses NEC-2, to produce antenna radiation patterns and impedances in the 14 to 100 MHz frequency range. The original LWA antenna uses a 3 x 3 m ground screen and results are presented for that as well as no ground screen and a larger 4.2 x 4.2 m ground screen. The larger ground screen provided a marginal increase in peak gain. The antenna patterns show symmetrical response characteristics in azimuth and elevation and moderate gain over the antenna's 90° (±) beamwidth. These results have academic utility but are not supported by measurements.

7. LWA antenna ordering information

The entire crossed-dipole antenna system may be ordered at {Order} and additional information may be found at {Info} and [Reeve]. Available components are the pre-welded dipole antenna assemblies, center post and ground stake (post) for supporting the antenna, and ready-built and tested front-end electronics (active balun). These components are identical to the components used in the Long Wavelength Arrays located at the Very Large Array site in New Mexico (LWA1) and at Owens Valley Radio Observatory in California.

8. Acknowledgements

I would like to acknowledge and thank Kurt Poulsen for introducing me to 4NEC2 and for his considerable help developing the LWA antenna wire models described here.

9. References [ ] and internet links { }

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[P.527-3] Recommendation ITU-R P.527-3, Electrical Characteristics of the Surface of the Earth, International Telecommunications Union – Radio Communication Sector, 1992

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{4NEC2} http://www.qsl.net/4nec2/
{Info} http://www.reeve.com/RadioScience/Antennas/ActiveCrossed-Dipole/Active_Crossed-Dipole_antenna.htm
{LLNL} https://ipo.llnl.gov/data/assets/docs/nec.pdf
{LWA} http://www.ece.vt.edu/swe/lwa/
{NEC2} http://www.nec2.org/
{Order} http://www.reeve.com/RadioScience/Antennas/ActiveCrossed-Dipole/ActiveBalunOrderInfo.htm
{Polar} http://www.youtube.com/watch?feature=player_detailpage&v=Q0qrU4nprB0

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