

Directive, electrically-small UWB antennas

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Abstract—This paper presents a variety of directive, electrically-small ultra-wideband (UWB) antenna designs. Employing a multipole-synthesis design methodology yields stable patterns with directivity of +4.7dBi or more across multiple decade bandwidths. The antenna may be thought of as an electrically-short, resistively-terminated transmission line. Open field testing of a 3m prototype antenna yields confirmation of NEC-derived performance predictions. The proposed antenna design is particularly well-suited for use as a receive antenna at HF frequencies or lower, where antenna loss cancels out high levels of atmospheric noise without impacting received signal-to-noise ratio (SNR).

Keywords: UWB antennas, small antennas.

I. INTRODUCTION

An “electrically-small” antenna (ESA) is one that completely fits within the “radiansphere:” the surface of radius $\lambda/2\pi$ (0.159λ) centered on the antenna. The radiansphere marks the transition between the near field and far field regions of a small element antenna [1]. As antenna size reduces past the natural resonant frequency, antenna bandwidth becomes narrower and antenna efficiency degrades. An ESA has increasing difficulty coupling energy into and out of a radiation field. In other words the radiation resistance of the antenna diminishes, and is swamped by Ohmic losses. Classical ESA practice aims to optimize a small-element with an omnidirectional pattern, trading bandwidth for performance.

This paper explores a virtually forgotten aspect of ESA design: ESAs that are directive and operate over an ultra-wideband (UWB) range of frequencies. The approach described in this paper yields cardioid patterns with a nominal directivity around +4.7 dBi or higher. These directive UWB ESAs are lossy. However they are well-suited for use as receive antennas at HF or lower frequencies where antenna loss cancels out atmospheric noise without impacting the received signal-to-noise ratio (SNR).

This paper begins by tracing the historical roots of directional UWB ESAs back to Harold Beverage and an electrically short version of his travelling wave antenna concept. Then this paper presents a multipole synthesis process by which arbitrarily high directionality ESAs might be implemented, albeit at the price of reduced efficiency. Several examples are well-suited for reception in the HF band and lower. Finally, this paper presents results from validation of a prototype quadrupole antenna in an open field setting.

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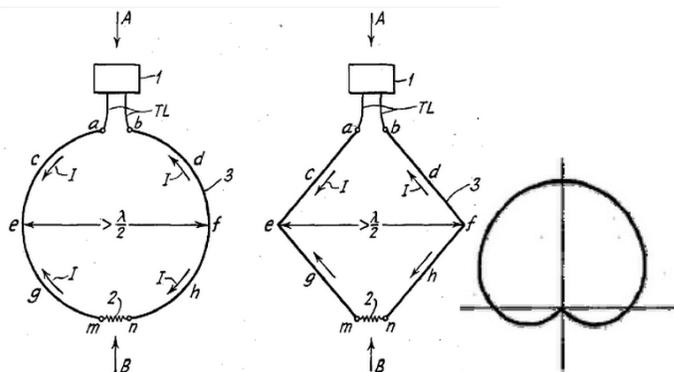


Fig. 1. Beverage's 1938 resistively loaded loop achieved octave bandwidth directional performance. Intended as a television receive element, Beverage proposed a circular loop (left), and a diamond loop (center). He also confirmed they exhibit a cardioid response (right) [5].

II. THE BEVERAGE LOOP

Harold Beverage developed the travelling wave antenna concept in 1920 [2]. Beverage collaborated with Chester Rice and Edward Kellogg to describe his antenna research at length a few years later in 1923 [3]. That same year, Charles Manneback developed the theory of radiation from twin lead transmission lines [4]. In 1938, Beverage invented the earliest-identified broadband directive ESA: a loop, resistively loaded to achieve octave bandwidth performance [5].

The aim of Beverage's design was to provide for directional, broadband, horizontally-polarized reception of television signals. Beverage implemented a self-supporting prototype antenna of one-half inch diameter copper tubing in a circle of diameter 0.966m. He found a damping resistor of 700ohms opposite the feed point yielded good performance. Beverage also found the directionality “was practically constant over a frequency range from 45 megacycles to 100 megacycles.” A NEC analysis confirmed a VSWR 1.85:1 or better, referenced to 700ohms across the 45MHz - 100MHz band [6]. The NEC analysis found gain as low as -12dBi at 40MHz, increasing to about -4dBi at 100MHz. Gain rolls off at about 40dB/decade for decreasing frequency. Directivity is enhanced on the feed point or source side of the loop: about 4.2dBi at 41MHz, decreasing to 1.4dBi around 100MHz. The resistive termination causes a null in the opposing direction. The pattern exhibits exact cardioid-like behavior when the antenna is perfectly matched. A front-to-back ratio across the band on the order of 10-20dB is typical because 700ohms does not yield an exact match. Figure 2 presents gain and directivity.

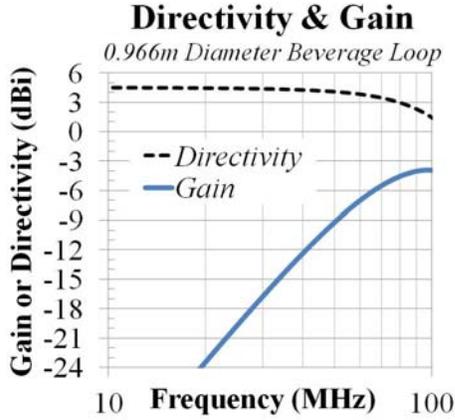


Fig. 2. A NEC analysis confirms that Beverage’s 0.966m diameter resistively-loaded loop yields a broadband directional response.

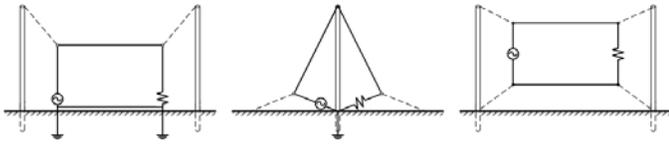


Fig. 3. A variety of electrically small resistively loaded loops are employed in amateur radio practice, including “Ewe” antennas (top left) with or without optional ground wires, K9AY antennas (top right), and a “flag” antenna (bottom).

III. EWES, FLAGS, AND K9AYS

A variety of resistively loaded loops remain popular in amateur radio practice for low-band receive applications. Floyd Koontz described a “Ewe” antenna – an antenna shaped like the letter “U” [7]. A four element array of Ewe antennas can provide directivity [8]. Gary Breed (K9AY) devised a variant co-locating source and load to enable a more compact configuration [9]. And, an elevated “Ewe” antenna or “flag” antenna Fig. 3 shows these electrically-small resistively loaded loop antennas.

IV. MULTIPOLE SYNTHESIS

This section will present a multipole-synthesis design procedure that encompasses the Beverage and other resistively loaded electrically small loops while extending the concept to higher-order multipoles. Then, this section presents a variety of designs resulting from the synthesis process.

A. Multipole Synthesis Procedure

There is a straightforward design process to synthesize directive multipole patterns:

- Start with a linear or planar arrangement of dipole sources arranged so as to create a multipole distribution.
- Phase the dipole sources so as to exactly cancel out signals in a particular null direction.
- Evaluate the resulting directive pattern.
- Implement the design to employ a single feed point with negligible unintentional radiation.

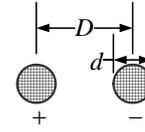


Fig. 4. A twin-lead transmission line provides a balanced, low-radiation conduit for signal propagation. Characteristic impedance depends upon conductor diameter d and separation D .

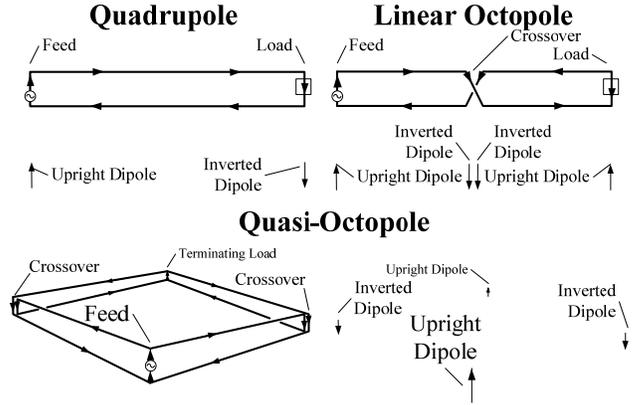


Fig. 5. A quadrupole (upper left) approximates displaced opposing dipoles. A linear octopole (upper right) and a “quasi-octopole” (bottom) approximate a superposition of two quadrupoles.

A key challenge in multipole antenna synthesis is to create an antenna structure that radiates at the desired source points and not along the interconnecting feed lines. Twin-lead transmission lines as shown in cross-section in Fig. 4 are one solution to the problem. At any given instant, at any location along the transmission line, equal and opposite currents (+ and -) flow along the paired symmetric conductors. This configuration is thus a “balanced” line. If the conductor diameter is d and the distance between conductors is D , then the characteristic impedance of the twin-lead transmission line is:

$$Z = \frac{Z_0}{\pi\sqrt{\epsilon_r}} \cosh^{-1} \frac{D}{d} \quad (1)$$

where $Z_0 = 376.7\Omega$ is the impedance of free space and ϵ_r is the relative permeability of the line ($\epsilon_r = 1$ for free space). Practical twin lead transmission lines tend to have relatively high impedance, on the order of 150-600 Ω . By using copper pipe as the conductors, self-supporting structures capable of very high power levels are possible.

B. Multipole Designs

Fig. 5 shows a variety of quadrupole and octopole designs. An upright and an inverted dipole may be superimposed to yield a quadrupole. In practice, one may implement a quadrupole as an electrically-short, terminated twin-lead transmission line: the feed point and the terminating load yield an opposing dipole pair, connected by a twin-lead transmission line. The upright feed point current is exactly

cancelled out by the inverted termination current along the axis of the antenna. Signal propagation on the twin-lead line is at the speed of light, so the phasing of the cancellation is both exact and frequency independent. The balanced currents in the twin-lead transmission line contribute negligible radiation broadside, and precisely no radiation along the axis of the antenna. If the antenna is exactly matched, the result is a deep null in the direction of the termination. The residual, almost-cancelled fields yield a cardioid pattern.

A linear octopole works similarly. A crossover in the twin-lead transmission line yields a double-inverted current with respect to the feed. The termination current is aligned with the feed current. The double quadrupole or linear octopole configuration results in additional cancellation but an even more directive pattern.

A “quasi-octopole” also approximates a superposition of two quadrupoles, however the path delay and cancellation are not exact, due to longer signal paths through the diagonal transmission lines. The following section considers the behavior of these designs in detail.

V. PERFORMANCE OF MULTIPOLE DESIGNS

This section presents NEC results for seven archetypical electrically small directive antennas, as shown in Figure 6. “EZ-NEC,” with a NEC4 engine, and “4NEC2,” with a NEC2 engine, generated the results [11, 12].

A. Matching

These electrically small directive antennas may be thought of as short, terminated twin-lead transmission lines. Fig. 7 shows their excellent matching at low frequencies. The pure twin-lead quadrupoles exhibit the best matching with the relatively extreme width-to-length of the 600ohm quadrupole not quite as well-matched as the more conservative 450 ohm design. The Beverage designs with their variable width twin-lead structure are not quite as well-matched as the twin-lead designs, but still deliver respectable performance. The octopole designs include crossover structures that tend to impair matching particularly above 25MHz where the 3m antenna dimensions exceed quarter-wavelength scale.

B. Noise and Receive Antenna Gain

Fig. 8 presents noise by source. Unlike microwave links that may be thermal noise limited, high frequency (HF: 3-30MHz) links must operate in the presence of substantial noise. At 10MHz, for instance, 30dB of RF noise over thermal is the minimum to be expected. Atmospheric noise may rise to 40dB and in an urban area RF noise of 50dB or over thermal may be experienced. The five classes of noise plotted in Fig. 8 are as follows:

- A:** Atmospheric Noise (exceeded 0.5% of the time).
- B:** Atmospheric Noise (exceeded 99.5% of the time).
- C:** Man-made Noise, Quiet Receiving Site
- D:** Galactic Noise
- E:** Median Business Area, Man-made Noise

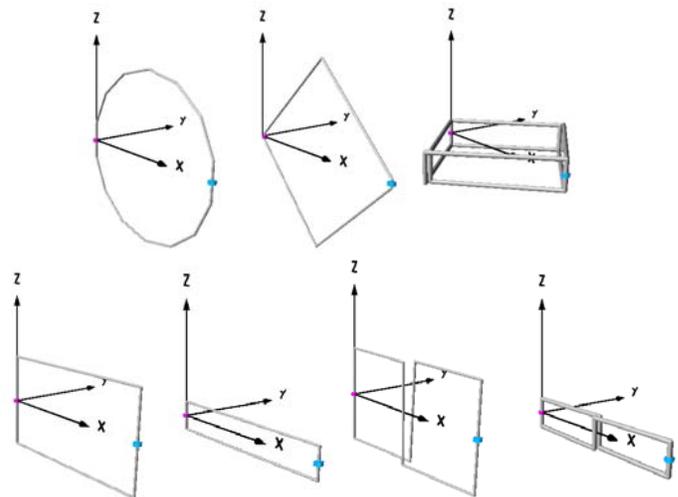


Fig. 6. From upper left: 600ohm Beverage loop (BevL600), 300ohm Beverage diamond (BevD300), 150 ohm Quasi-octopole (QuasiOct), 600ohm Quadrupole (Quad600), 450ohm Quadrupole (Quad450), 600ohm Linear Octopole (LinOct600), and 300ohm Linear Octopole (LinOct300). Antenna maximum dimension ~3m. Axes scale to 2m in each figure.

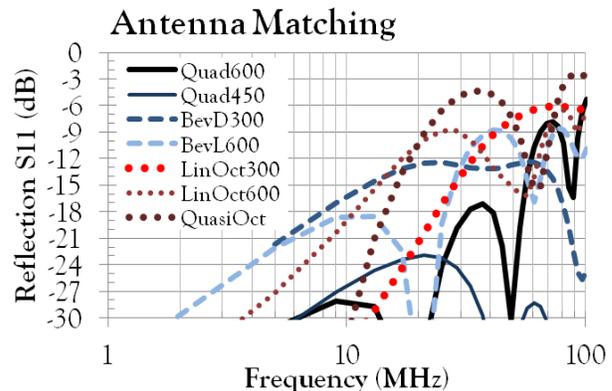


Fig. 7. Matching of typical 3m directive electrically small antennas.

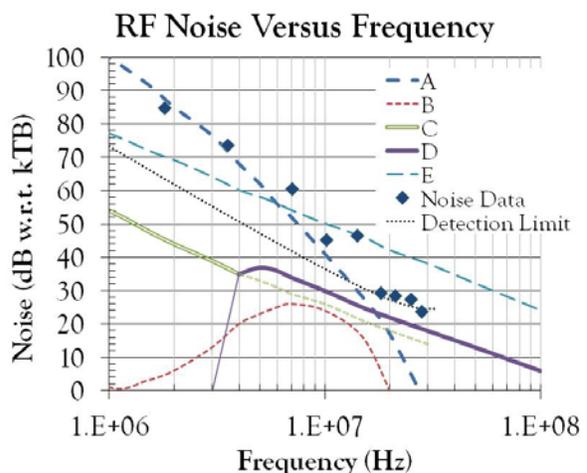


Fig. 8. The various sources of ambient RF noise set a specification for receive antenna gain below 100MHz. The graph also plots detection limit and noise data from the experimental validation of Section 6.

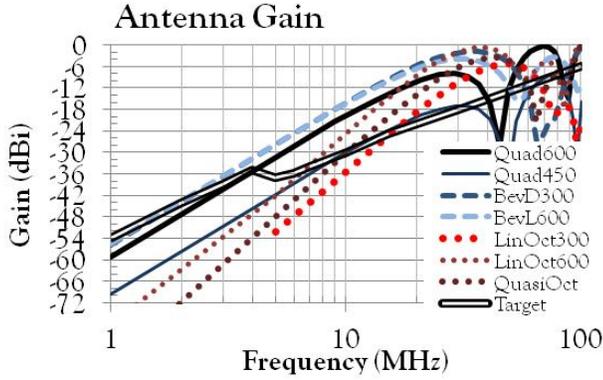


Fig. 9. Gain of typical 3m directive electrically small antennas.

The C and D curves set the specification for minimum expected noise which in turn sets the specification for receive antenna gain. Where ambient noise lies 20dB above thermal, for instance, an isotropic antenna with -20dBi gain (i.e. 20dB loss) drops the ambient noise to thermal and still enables recovery of an optimal Signal-to-Noise Ratio (SNR) signal. The minimum expected ambient noise from Fig. 8 sets a receive antenna target, as shown in the gain results of Fig. 9. The target may be adjusted to account for RF front end noise figure, directivity, or the spatial distribution of the noise.

C. Antenna Gain and Directivity

Unlike the gain of an electrically small dipole which varies as 20dB per decade, quadrupole and octopole gain roll off as 40dB and 60dB per decade with decreasing frequency, respectively. The noise-derived gain target also rolls off with frequency. In fact, several antennas including the Beverage loop and diamond, and the 600ohm quadrupole exceed the gain target above 4MHz. Fig. 9 shows these gain results.

For very small beamwidths, the directivity is:

$$D \cong \frac{BW_\phi BW_\theta}{4\pi} \quad (2)$$

where BW_ϕ and BW_θ are the azimuthal and elevation radian -3dB beamwidths, respectively. For somewhat larger beamwidths, directivity may be estimated:

$$D \cong \frac{BW_\phi}{2\pi} \sin \frac{BW_\theta}{2} \quad (3)$$

The quadrupole antennas and the Beverage loop converge to a directivity of about +4.7dBi at low frequencies. Typical patterns have -3dB beamwidths of about 130deg. Octopole elements yield +6dBi or more. Fig. 10 shows directivity results from NEC-derived patterns:

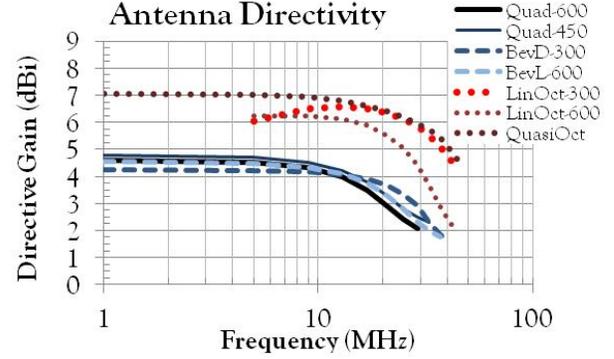


Fig. 10. Directivity of typical 3m directive electrically small antennas.



Fig. 11. Testing a 3m 450ohm quadrupole antenna (Trials #1 and #2).

VI. EXPERIMENTAL RESULTS

This section describes measurements of a 450 ohm prototype 3m quadrupole antenna for use in the HF band. The measured gain was consistent with NEC predictions. Background noise was elevated, despite making measurements in a rural setting several miles away from an urban area.

A. Experimental Design

In each of three trials, we compared the received signal strength from the prototype to the received signal strength from a calibrated loop antenna (an EMCO 6509 passive loop, see figure, following page). When the two antennas are exposed to common signals, the difference in the received signal strength yields the difference in the antenna gain. We used a Mini-Circuits ZFL-500 preamp with an HP 8593E spectrum analyzer to measure the received power. An EMCO 6509 passive loop antenna served as the reference antenna. Set to Band 4, the EMCO 6509 covered the 1-30MHz range of the test. Fig. 11 shows the reference antenna and the prototype antenna.

In the first two trials (#1 and #2) we used ambient signals of opportunity. Uncertainties included the angle of elevation of the incident signals and variation of the ambient signals during the time involved to switch between the two antennas. These uncertainties make Trials #1 and #2 difficult to interpret. In the third trial (#3), we used amateur radio beacon signals in the 160m, 80m, 40m, 30m, 20m, 15m, 12m, and 10m bands. By controlling the transmission at a fixed (10W) transmit power, we obtained improved stability and repeatability as well as a fixed and known angle-of-arrival. This data was all consistent with the 4-8deg elevation angle we estimated for the distant antennas. Two outliers (at 3.5MHz and 7MHz) correspond to the higher elevation angle due to the closer delta loop antenna.

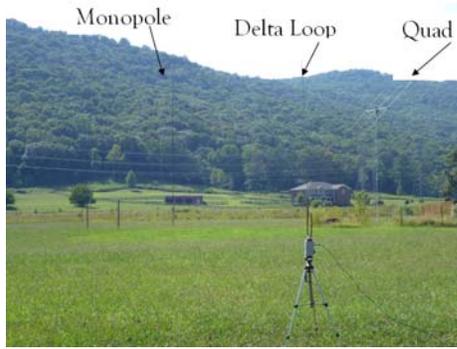


Fig. 12. Amateur radio reference beacons (Trial #3).

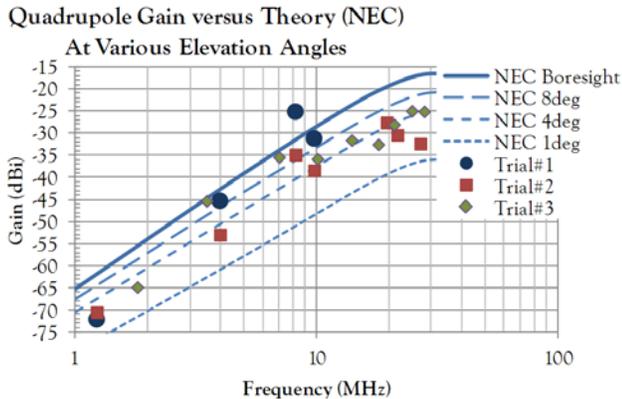


Fig. 13. Gain measurements for a 3m 450 ohm quadrupole.

B. Gain Results

Fig. 13 shows the gain results for the three trails compared against NEC model predictions. The inferred gain from the received power comparison was consistent with the NEC model predictions. These results give us high confidence that NEC modeling of quadrupole antennas yields reasonable numbers for gain.

C. Pattern Results

We performed a simple pattern test, measuring prototype received power on boresight, each broadside, and on the null. Pattern measurements were confounded by the transmission line which tended to act as an antenna at certain wavelengths. Measurements at 7MHz and 10MHz yielded results consistent with theory. All other measurements had various levels of distortion. More accurate pattern measurements would require a better feed line arrangement than we used in this trial.

D. Noise Results

Fig. 8 superimposes our estimated detection limit and measured noise levels on the ITU noise graph. Although we made our measurements several miles from an urban area, the noise level was consistent with urban noise. This is another of the principal difficulties in making accurate HF pattern and gain measurements.

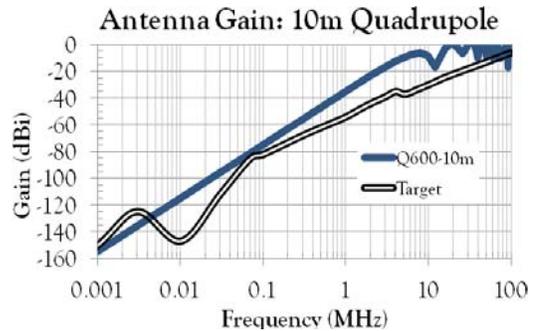


Fig. 14. A 10m quadrupole provides excellent directional UWB receive response from a few kHz up to about 10MHz.

VII. CONCLUSIONS

This paper reintroduces a largely forgotten class of UWB antennas: ones that are both directional and electrically small. Multipole antenna design applies electromagnetic jujitsu to make antenna fields almost, but not exactly, cancel each other out, leaving in their wake the desired directional pattern. These antennas are well-suited for receive applications in high noise environments where antenna loss may be tolerated as part of the system design. For instance, a 10m quadrupole may provide excellent directional behavior in receive applications spanning a few kilohertz to about 10MHz, as shown in Fig. 14. Other applications include UWB detectors or probes for strong signals.

REFERENCES

- [1] Harold A. Wheeler, "Fundamental limitations of small antennas," Proc. IRE, **35**, Dec. 1947, pp. 1479-1484.
- [2] Harold H. Beverage, "Radio receiving system," U.S. Patent 1,381,089, June 7, 1921.
- [3] Harold H. Beverage, Chester W. Rice, and Edward W. Kellogg, "The wave antenna: a new type of highly directive antenna," Transactions of the American Institute of Electrical Engineers, Vol. 42, Feb. 1923, pp. 215-266. [Link](#)
- [4] Charles Manneback, "Radiation from transmission lines," Transactions of the American Institute of Electrical Engineers, Vol. 42, Feb. 1923, pp. 289-301. [Link](#)
- [5] Harold H. Beverage, "Antenna," U.S. Patent 2,247,743, July 1, 1941.
- [6] G. J. Burke and A. J. Poggio, Numerical Electromagnetics Code. (NEC)—Method of Moments. Livermore, CA: Lawrence Livermore National Lab., 1981.
- [7] Floyd Koontz, "Is this Ewe for You?," QST, February 1995, pp. 31-33.
- [8] Floyd Koontz, "More EWES for You," QST, January 1996, pp. 32-34.
- [9] Gary Breed, "The K9AY Terminated Loop - A Compact, Directional Receiving Antenna," QST, September 1997, pp. 43-46.
- [10] Earl W. Cunningham, "Flags, Pennants and Other Ground-Independent Low-Band Receiving Antennas," QST, July 2000, pp. 34-37.
- [11] Roy Lewallen, EZNEC Pro/4 v. 5.0.20, 2008. See: <http://www.ez nec.com/>
- [12] Arie Voors, 4nec2, Version: 5.7.6, November 2009. See: <http://home.ict.nl/~arivoors/>
- [13] International Telecommunication Union, Recommendation ITU-R P.372-8: Radio noise, 2003, as cited in NATO RTO Technical Report, "HF Interference, Procedures, and Tools," RTO-TR-IST-050, June 2007, pp. 2-11 to 2-12. See: [http://ftp.rta.nato.int/public/PubFullText/RTO/TR/RTO-TR-IST-050/\\$STR-IST-050-ALL.pdf](http://ftp.rta.nato.int/public/PubFullText/RTO/TR/RTO-TR-IST-050/$STR-IST-050-ALL.pdf)