A Novel Short AM Monopole Antenna with Low-Loss Matching System

James K. Breakall, Ph.D.
Department of Electrical Engineering,
The Pennsylvania State University,
University Park, PA, USA
jimb@psu.edu

Michael W. Jacobs
STAR-H Corporation,
State College, PA, USA
mike@star-h.com

Alfred E. Resnick, P.E.
Broadcast Consultant
Paoli, PA, USA
alresnick@ieee.org

G. Yale Eastman
STAR-H Corporation
Lancaster, PA, USA
yale@star-h.com

Milton D. Machalek, Ph.D.
STAR-H Corporation
Lancaster, PA, USA
milt@star-h.com

Thomas F. King
Kintronic Laboratories, Inc.
Bristol, TN, USA
tking@kintronic.com

Abstract

A number of reduced-size antennas for AM broadcasting have been presented over the years, but all have suffered from limitations inherent in presenting attractive impedances over the desired operating bandwidth to the transmitter. In this work, we present NEC-4.1 Method of Moments modeling results of a novel technique of using multiple independently fed short vertical elements in close proximity to increase the real impedance of an electrically short antenna while retaining the radiation pattern characteristics of a short monopole antenna. Atop each short vertical element is a horizontal loading structure to get the proper current distribution for radiation. The arrangement of elements provides a number of independent input impedances. By parallel combination of these independent input impedances, with the use of appropriate efficient matching techniques, the real part of the input impedance is effectively increased. This antenna exhibits a vertical height of approximately 0.05 wavelengths, resulting in a substantial height reduction from a quarterwave monopole radiator and the elimination of the need for lighted tower structures for AM antenna systems, resulting in reduced construction costs and increased community acceptance of new AM antenna systems. These antennas can also be used in arrays for directional AM patterns, and are fully compatible with the bandwidth requirements of AM stereo or IBOC transmission.

Keywords – low-profile antenna, cage monopole, monopole, short antenna, reduced size antenna, AM antenna, MF antenna

INTRODUCTION

The benefits and limitations of short monopole antennas for MF broadcasting are well known and have been covered thoroughly in the recent literature [1]. We have developed a method of combining the top-loaded monopole antenna over a ground plane with low-loss inexpensive impedance matching techniques to create an antenna with a vertically polarized omnidirectional radiation pattern with very good efficiency and impedance bandwidth performance. This antenna is expected to meet all FCC performance criteria and be capable of substitution for a standard quarterwave monopole for any power level, while having a height above ground of approximately 0.05 wavelengths. The unattenuated field strength generated by this antenna will be similar to that of a short monopole, on the order of 299.8 mV/m at 1km with 1kW of input power, only a slight penalty from the typical 313.6 mV/m value for the quarterwave antenna. With the reduced height, such an antenna can be situated much closer to the community being served, resulting in improved coverage, or it can be located on a wider range of available properties, with less community opposition, thus reducing site acquisition costs. The antenna itself can be constructed with standard overhead line construction techniques, and will not require obstruction lighting in most applications. STAR-H Corporation currently has a patent application for this antenna and its key concepts pending in both the US and international markets.

ANTENNA CONCEPT AND THEORY

It is well known that creating a cage monopole of vertical wires to increase the diameter of the radiator can increase the bandwidth of a short vertical antenna. If the vertical conductors of a short cage monopole are separated and excited individually in phase, then for a constant input power level the impedance of each monopole is increased. If there are n monopoles, then the impedance of each is now n times the original impedance of a single monopole, if the power is held constant, since the current is divided n ways. This configuration is shown in Figure 1. Providing that the monopoles are closely spaced and symmetrical, as when on even points on a circle with a radius that is small compared to a wavelength, all the radiated fields will add in phase and the far-field pattern will be essentially identical to that of a single monopole radiator.

This multiplication of the radiation resistance can be shown by considering that for a single radiating element:

$$P_{in} = I_{in} V_{in} = I_{in}^2 Z_{in} = \frac{V_{in}^2}{Z_{in}} \qquad (1)$$

If we hold the input power constant and neglect the losses, for the antenna system of Figure 1,

$$P_{in} = n \frac{I_{in}}{n} V_{in} = n \left(\frac{I_{in}}{n} \right)^2 Z_{in}' = n \frac{V_{in}^2}{Z_{in}'} \quad (2)$$

where $\frac{I_{in}}{n}$ is the input current for each individual radiator and Z_{in} ‘ is the impedance of each cage wire monopole.

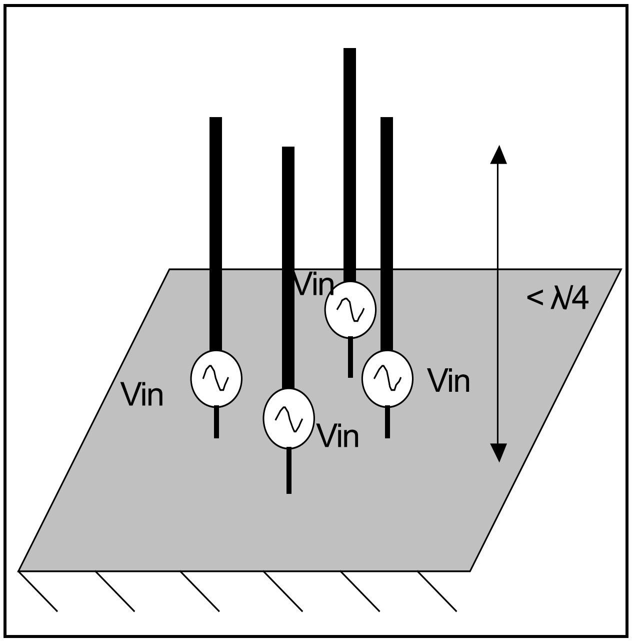


Figure 1. Cage monopole of vertical radiators closely spaced with independent voltage sources.

Solving for the input impedance of one individual monopole in the cage (Z_{in}’) gives:

$$Z_{in}' = n \frac{V_{in}}{I_{in}} \qquad (3)$$

If we use short monopoles for the cage, we also can use an analytical expression for the input resistance of a short monopole, neglecting the mutual impedance between the vertical elements, which will be small because of their reduced size (NEC modeling confirms this). For a 1/20th wavelength monopole (assuming we can achieve a constant current distribution on the short monopole), the radiation resistance is:

$$\begin{aligned} R_{\text{Radiation}} &= 160\pi^2 \left(\frac{l}{\lambda} \right)^2 \\ R_{\text{Radiation}} &= \frac{\pi^2}{2.5} = 3.95\,\Omega \end{aligned} \qquad (4)$$

where l is the length of the monopole and λ is the wavelength. This compares with a resistance of approximately 36 ohms for a quarterwave monopole. Of course, for the shortened monopole, a substantial reactive component will also be present. This ideal current distribution can be approximated by adding top loading, in the form of horizontal wires or other structures, to the short monopole elements, as shown in Figure 2. Adjustment of the dimensions of these antenna elements can be made to tune the antenna to resonance, so that the reactive components are zero. For other electrical heights, the input impedance can be calculated. Some values are shown in Table 1.

Table 1. Radiation resistance versus height for a monopole with constant current distribution.

Height (λ)	$R_{radiation}$ (Ohms)
0.01	0.16
0.04	2.52
0.08	10.1
0.1	15.8

We can see that by choosing the height and the number of radiators in our cage monopole, we can achieve substantial control of the input impedance. For example, a cage of four 0.08λ monopoles would result in each having a radiation resistance of approximately 40.4 ohms. This analysis is neglecting the mutual coupling effects, which computer modeling shows to be quite minimal if the element height is small.

The remaining task is to bring these independent input impedances together and to match them to a single 50-ohm source (or load, as the antenna is reciprocal), since we do not wish to use n separate transmitters. One attractive way of doing this is to use the quarterwave transmission line transformer and connect these in parallel.

This is shown in Figures 3 and 4. With the ability to control the input impedance of each radiator, we can select an impedance which can use commonly available 50 or 75 ohm semi-rigid transmission line to implement this with very low loss. A suitable impedance for this four-element example would be 200 ohms at the parallel connection, since four 200 ohm impedances in parallel gives us the desired 50 ohm input impedance at a single feedpoint.

$$Z_{in} = \frac{Z_0^2}{Z_{\text{parallel}}} \qquad (5)$$

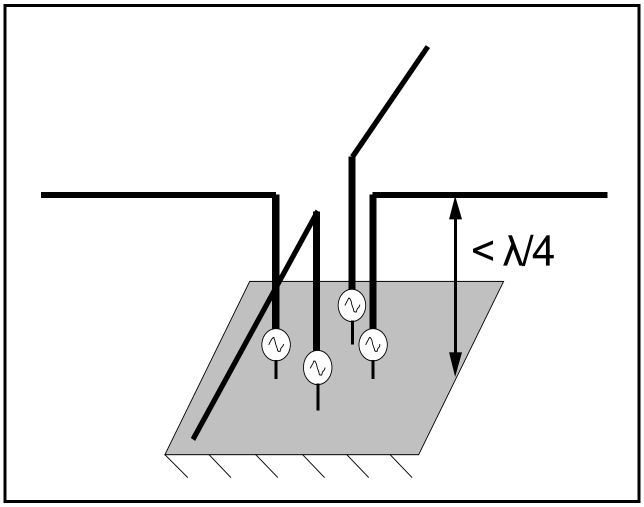


Figure 2. Short cage monopole antenna with independent feedpoints and top loading elements.

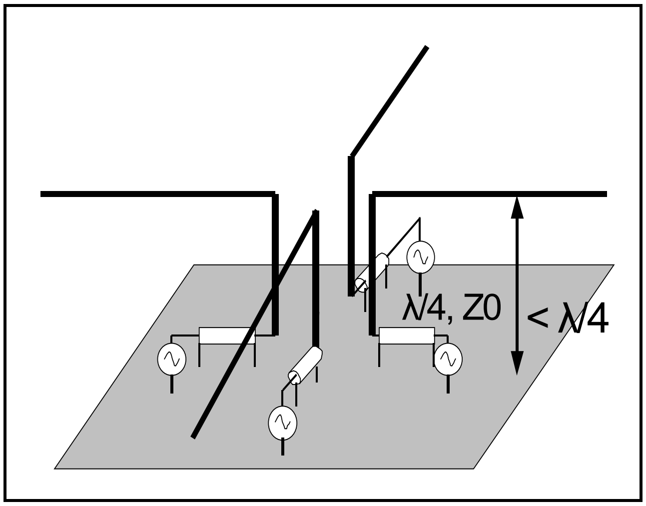


Figure 3. Short cage monopole antenna with addition of quarterwave transformer sections.

Calculating the transformer input impedance using a 50-ohm transmission line yields a value of 12.5 ohms. This 12.5 ohm impedance with n=4 for a 4-element antenna corresponds to a short monopole with an impedance of 3.125 ohms. This impedance can be obtained by using an antenna with a vertical height of about 0.044 wavelengths (obtained using Equation 4 or Table 1 above), which is 17.6% of the height of a quarterwave monopole.

For broadcast applications, common low-loss semi rigid coaxial cable can be used for this, and by suitably selecting the line size, the power handling requirements can be met and loss in the transformer section can be kept low for desirable antenna heights. For communications and WLAN applications, smaller sized coax can be used, as can microstrip or other transmission line types. Lumped element matching can also be used if desired, although transmission line transformers are usually less expensive and easier to construct. The antenna itself can be constructed from stranded aluminum wire conductors as are typically used in the power industry. At many frequencies in the US AM broadcast band, wooden utility poles can serve as the vertical supports.

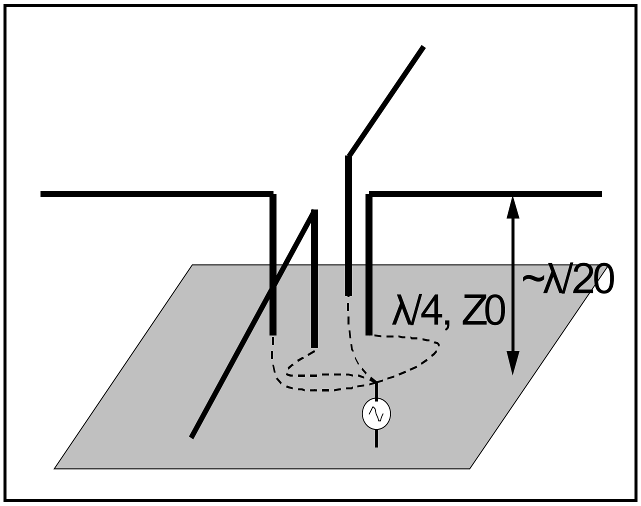
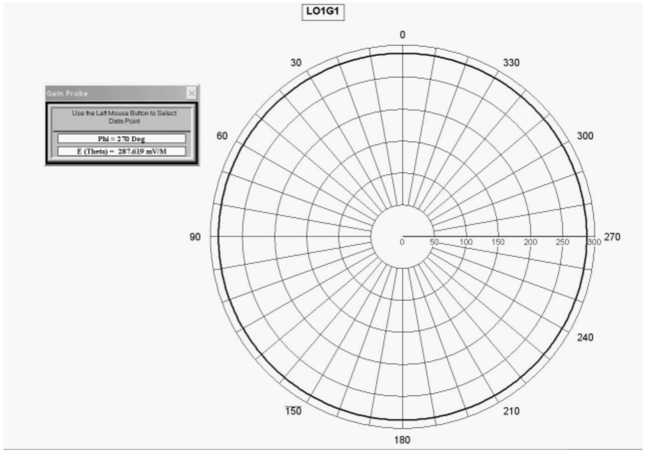


Figure 4. Resulting low-profile antenna with quarterwave matching lines to single feedpoint. Antenna has 50-ohm input impedance.

The radiation pattern from this antenna will be equivalent to that for any reduced size monopole antenna with a nearly constant current distribution, and will be vertically polarized. The fields due to the currents in the vertical radiating elements will add in-phase in the far field, while the currents in the horizontal components will be out of phase and will cancel. This antenna can be constructed with any number of radiating elements, in many different configurations. For broadcasting applications, a conventional 120-radial system is an anticipated requirement to minimize ground losses, although work is underway to develop an elevated radial version of the antenna [2].

NEC MODELING RESULTS

Much of the original development work for this antenna was done using the NEC-4.1 (Numerical Electromagnetics Code) Method of Moments code [3-4], with the GNEC GUI front end and the NECOPT numerical optimizer package for NEC developed at Penn State University [5]. The NECOPT program optimizes the performance of the antenna by automatically varying the parameters of the antenna, such as the height of the monopole, length of the horizontal elements, and radial distance of the monopoles to the center. NECOPT can thus be used to determine the complete antenna dimensions for a particular frequency and bandwidth requirement. Antenna designs consisting of 2, 4, and 8 element configurations have been modeled, using both slanted and level horizontal loading elements. The antenna bandwidth is determined by the number of elements in the antenna, the size of the wires used to make



Phi = 270 Deg

E (Theta) = 287.619 mV/M

Figure 5. NEC calculated field pattern of 4-element low-profile antenna over perfect ground excluding matching system losses, showing omnidirectional pattern.

those elements, and the radius of the circle on which the vertical radiators are located.

Additional work has been done to model the antenna performance over ground systems, including the analysis of radial systems and comparison with quarterwave monopole radiators. We have also modeled the antenna performance in a 3-element directional array with particular null requirements.

In anticipation of a full-scale test of this antenna in a configuration for AM broadcast applications, in partnership with Kintronic Laboratories, Inc., of Bristol, TN, we have designed and modeled with NEC an omnidirectional 4-wire version of the antenna at a frequency of 1680 kHz. The model included 120 ground radials and used the Sommerfeld-Norton method for calculating ground effects, and included conductor losses.

For the full-scale test, the antenna will be constructed using 3/8” diameter stranded aluminum conductors suspended between five 55’ telephone poles sunk into augured holes and guyed against the strain from the horizontal elements. Semi-rigid foam dielectric 50 ohm coaxial line 7/8” in diameter will be used for the matching transformers. The vertical wire elements will extend to 45 feet above the ground (0.072λ, compared to a quarterwave tower 145.48 feet high), and the horizontal loading wires will be 95 feet in length. The four vertical wires will be evenly spaced on a circle with a radius of five feet. Based on the bandwidth requirements for IBOC transmissions, NECOPT was used to also vary the length of the transmission lines with a goal of maximizing the bandwidth. This resulted in a line length of 38.42 feet with an 89% velocity factor.

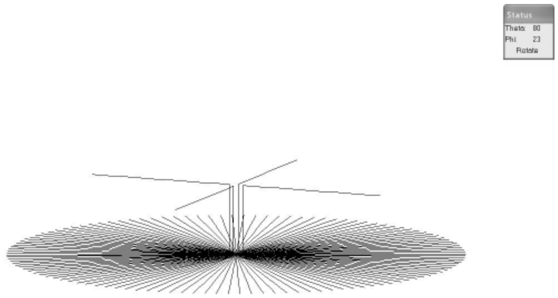


Figure 6. NEC model geometry of low profile antenna designed for 1680 kHz with 120 radial ground screen.

The impedance calculated by NEC at 1680 kHz at each vertical feedpoint is 38.3 + j63.3 ohms. The output impedance after passing through the transmission line transformer will be 194.9 – j8.06 ohms, which will yield a parallel combined impedance of 48.3 + j1.2 ohms. NEC’s calculated field value at 1 km for 1 kW input over 120 radials and lossy earth is 216.1 mV/m, exclusive of the loss in the matching system. Calculations show that line loss should be less than 0.02 dB, resulting in an attenuated field value of approximately 215 mV/m.

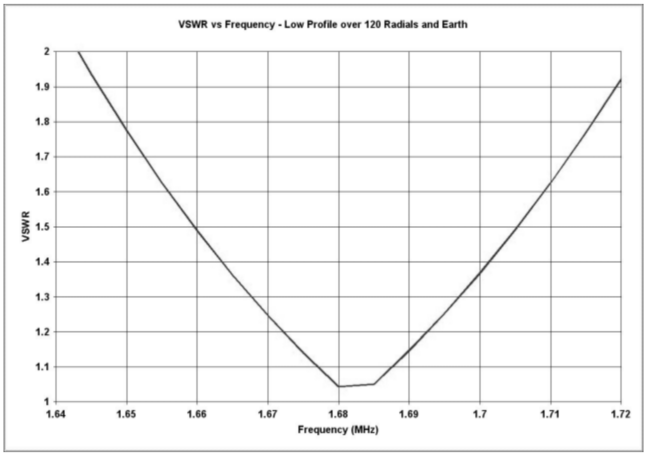


Figure 7. NEC predicted bandwidth for antenna model shown in Figure 5. 1.5:1 bandwidth obtained over 1660 – 1750 kHz.

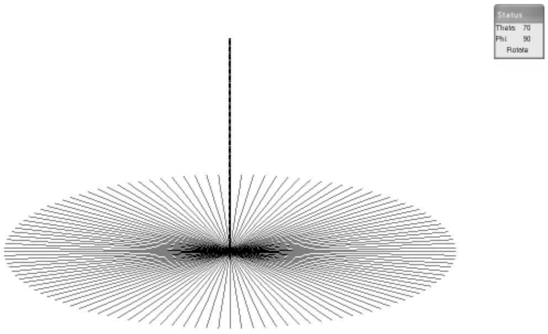


Figure 8. NEC model geometry for quarterwave tower monopole and 120 radial ground screen.

For comparison, NEC was used to model a quarterwave tower monopole at the same frequency and with the same ground system and conditions to yield a calculated value of 233.8 mV/m, without matching system losses. The performance of the low-profile antenna compared with the quarterwave monopole shows that this low-profile is 92.4% as efficient for field strength as the monopole, exclusive of matching system losses. The field values resulting from the low-profile antenna should be entirely sufficient to permit a broadcaster to cover the required service area almost as well as with the much higher quarterwave antenna.

In practice, the use of an optimizer will allow an antenna to be custom designed to meet the bandwidth requirements at any operating frequency. In addition to the transmission line matching system, Kintronic Laboratories is constructing a variable inductor/capacitor tuning unit to place at the parallel line connection for the test antenna to allow a small amount of adjustment for variations due to construction tolerances or other unforeseen effects.

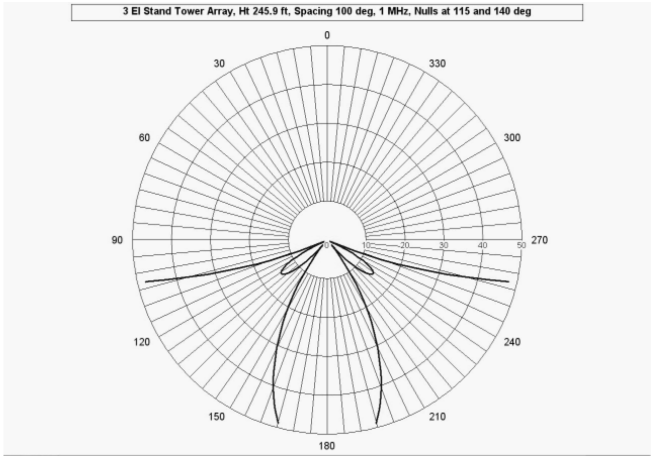


Figure 9. NEC model of directional pattern from 3-tower array.

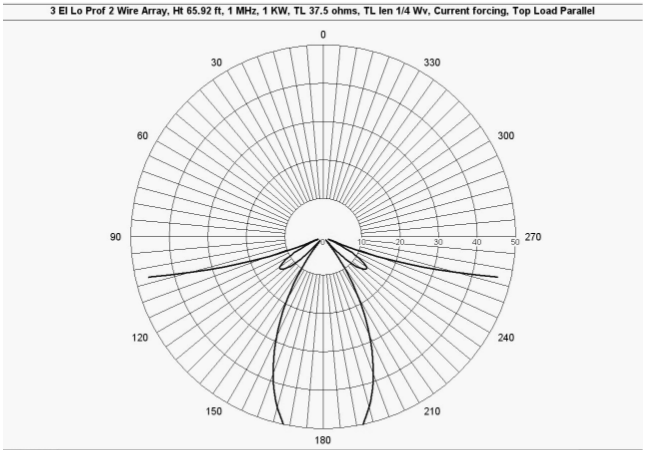


Figure 10. Example of directional pattern using three 2-wire element low-profile antennas to duplicate the pattern obtained with the three-tower array in Figure 9.

Because of the prevalence of directionality requirements on AM broadcast stations in the U.S., we decided to attempt a directional design using this antenna. For this example, nulls were required at 115 and 140 degrees. Comparison was made with a NEC model of an actual 3-tower array with this pattern. It is shown that for this pattern, the low-profile array can be designed to duplicate the directional pattern of the tower array. Figures 9 and 10 show the tower array and low-profile array patterns, respectively. We have used the 2-wire version of the antenna for directional arrays, as shown in Figure 11, to avoid a potential problem with coupling (or mechanical conflict) between horizontal elements of adjacent antennas. Further modeling shows that this may not be a significant problem, allowing the additional versatility and bandwidth of a four-wire version to be used in directional applications.

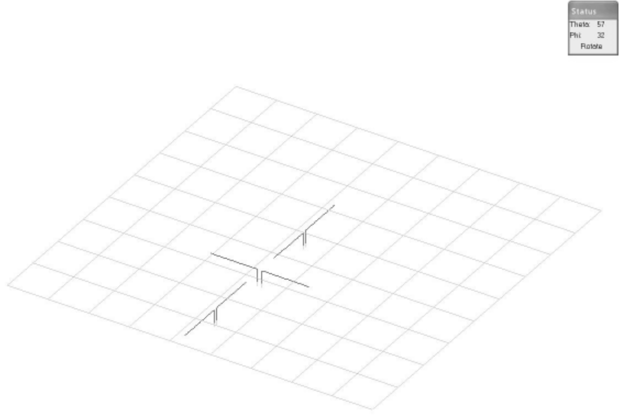


Figure 11 - Three-antenna array used to generate pattern in Figure 10. This array uses 2-element versions of low-profile antennas. Antennas are oriented to minimize mutual coupling between horizontal loading wires.

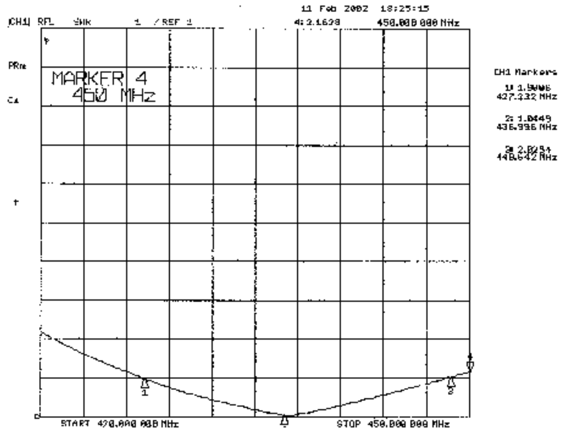


Figure 12. Measured VSWR of a 440 MHz low-profile antenna using 4 wire elements over copper ground plane.

PROTOTYPE TEST RESULTS

Several versions of this antenna have been constructed and tested by STAR-H Corporation, Lancaster and State College, PA. Prototypes have been built and tested at 1.3 GHz, 440 MHz, and 52 MHz using two and four-wire variants of the design. These antennas have served as both prototypes for communications antennas and as scale models for the broadcast version. All have performed as expected based on the computer modeling data. It is anticipated that this will also hold for the full-scale 1680 kHz prototype currently under construction in the Bristol, TN area. Figure 12 shows the VSWR versus frequency for a four-wire version of the low-profile antenna constructed over a circular quarter wavelength diameter copper ground plane, using 0.141” rigid coaxial line for the matching sections.

Comparison testing of the 52 MHz low-profile antenna, shown in Figure 13 on a radial wire ground screen, with a quarterwave monopole on the same ground screen in the same location showed no significant difference of the received signal power levels over path lengths of several miles of irregular terrain. Multipath signal variation adds uncertainty to any measurements in the VHF portion of the spectrum, but the observed data suggests that the performance of the low-profile at any test location was indistinguishable from that of the monopole, verifying the omnidirectional characteristic of the antenna. The VSWR versus frequency plot for this antenna is shown in Figure 14.

Full-scale prototype testing, consisting of comparison field measurements between a quarterwave monopole tower and a 4-wire low-profile antenna over a 120 radial ground screen is anticipated to begin in the September – October, 2002 time frame, with results anticipated shortly after. Ronald Rackley, of du Treil, Lundin, and Rackley, has been engaged to analyze the measurement data and prepare a report, which will be fully shared with the broadcasting and antenna engineering community upon completion. The report will also be filed with the US Federal Communications Commission in support of a request for review and approval of this antenna for use by AM broadcasters in the United States. Further experiments to implement the directional array concept will be considered in the near future. Parties interested in participating in future testing are urged to contact Mr. Jacobs of STAR-H Corporation.

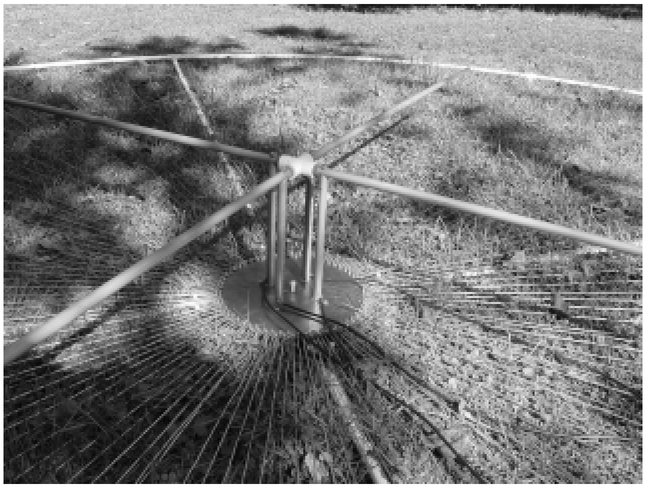


Figure 13. 52 MHz 4-wire low-profile antenna with 120 quarterwave radial ground wires. Antenna is approximately 8 inches high.

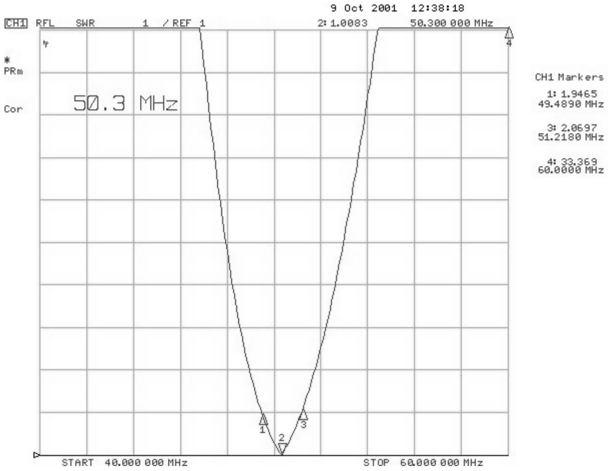


Figure 14. Measured VSWR of 52 MHz low-profile antenna shown in Figure 12. 2:1 bandwidth is from 49.48 to 51.21 MHz.

CONCLUSION

We have presented a novel concept for a practical low-profile antenna that has application at MF frequencies for the broadcasting community. This antenna trades a slight reduction of radiated field intensity for a large reduction of height. Given the expense of locating suitable real estate and meeting land-use regulations and community requirements, the advantage of an antenna that does not require an unsightly tower structure or the expense of aviation obstruction lighting is clear. Even at the low end of the U.S. AM broadcasting band, the antenna height is only approximately 140 feet, compared with 444 feet for a quarterwave antenna. At this height, the antenna in most cases will not require FAA lighting or marking. Since it is constructed using common utility company overhead transmission line methods, the materials and construction of the antenna are reliable, inexpensive, and easy to implement in almost any location using local contractors. Wooden or reinforced concrete poles, or lightweight tower sections or steel utility monopoles can be used as the vertical supports. Guying of the supports will provide a rugged antenna that can provide reliable service during storms and icing conditions. The antenna can be constructed rapidly, simplifying installation in remote areas, or as an expedient replacement for a fallen tower. It can also be operated in an array to create a directional pattern as required by FCC or other license conditions.

REFERENCES

[1] V. Trainotti, “Short Medium Frequency AM Antennas”, *IEEE Trans. on Broadcasting*, vol 47, no. 3, pp 263-284, September, 2001

[2] A. Christman, R. Radcliff, R. Adler, J. K. Breakall, A. Resnick, ”AM broadcast antennas with elevated radial ground systems”, *IEEE Transactions on Broadcasting*, vol 34 no 1, pp 75-77, March 1988

[3] J. K. Breakall, “Computer modeling of antennas using NEC and MININEC”, Proceedings of the 32nd Midwest Symposium on Circuits and Systems,1990 Page(s): 724 -726 vol.2.

[4] J. K. Breakall, G. J. Burke, and E. K. Miller, "The Numerical Electromagnetics Code (NEC)," EMC Symposium and Exhibition, Zurich, Switzerland, 1985.

[5] J. K. Breakall, J. S. Young, R. J. Bauerle, A. I. McDowell and T. A. Erdley, "Numerical Electromagnetics Code Optimization Design Software (NECOPT*)," 10th Annual Review of Progress in Applied Computational Electromagnetics*, Naval Postgraduate School, Monterey, CA, 1994.