The Ground-Image Vertical Antenna

BY JERRY SEVICK,* W2FMI

A RECENT JOB transfer and the subsequent move into a new neighborhood permitted me to review my antenna needs in a different light. I wanted to avoid, or at least minimize, the problems and difficulties involved in reinstalling my 40-foot tower and Yagi beam antenna at the new location. Even though a beam antenna supported at the modest height of 40 feet is a compromise (a 20-meter beam should be higher to be really effective), it still can be an obstacle to good neighborly relations, at least if your neighbors don't appreciate the ecological beauty of such an installation. Moreover, even that modest sort of an installation presents quite a number of engineering problems.

This report presents the results of the first phase of my investigation to find a less conspicuous but equally effective antenna for use at the new location. I hope it will provide suggestions for those faced with a similar problem. At the least, it may be of some value to those with a general interest in the subject of antennas.

* Technical Relations Manager, Bell Telephone Laboratories, 600 Mountain Ave., Murray Hill, NJ 07974.

The first part of this article deals briefly with theoretical considerations, the second with experimental results on quarter-wavelength and five-eighths-wavelength verticals, and the third on the test equipment. It should be pointed out at the outset that the information presented here is the work of a hobby and as such cannot be exhaustive. It is hoped that others will repeat some of the experiments, extend the work, and report the effect in practice of a ground-plane system above 3 MHz. To my knowledge such practical data has not been reported.

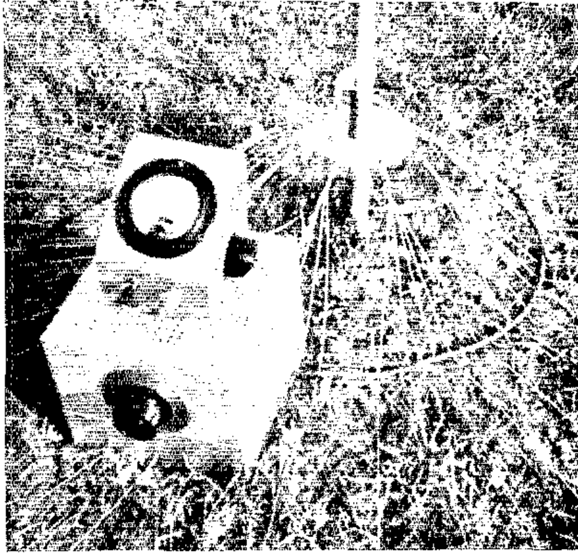
Theoretical Considerations

A beam antenna possesses the advantage of gain and directivity. Nevertheless, its DX capability is determined primarily by its vertical radiation pattern. A large portion of the radiated energy should be directed between 5 and 25 degrees from the horizon.[1,2] Horizontally polarized antennas yield lower angles of radiation with increase in height above the ground. This is a result of the interference pattern created by reradiation from the earth's surface. Since the earth is a somewhat conducting medium, the electric field tangential to the surface must be approximately zero. This "boundary" condition is brought about by the induced surface currents which create an electric field of opposite phase. This field then combines constructively and destructively with the initial radiation from the antenna. A model for this condition is an image antenna of opposite phase below the earth's surface at a depth equivalent to the height above the surface.[3] In order to get a lobe below 15 degrees, the antenna height must exceed a wavelength. This is greater than 60 feet on 20 meters.

On the other hand, a vertical antenna, in the ideal case, possesses an image which is in phase to produce a lobe tangential to the earth's surface. Only when the antenna length is increased to a wavelength, or multiple thereof, does the tangential lobe disappear. This is true whether the antenna is on the ground or suspended in space. Therefore, a vertical beam, i.e., an array of vertical antennas coupled together with an appropriate feed system, on the surface of the earth, seemed to me to be the logical choice for my new installation

1 Terman, *Radio Engineering*, McGraw-Hill, New York, 1947, p. 651.
2 Friis, Feldman, and Sharpless, "The Determination of the Direction of Arrival of Short Radio Waves," *Proceedings of the IRE*, Vol. 22, No. 1, January, 1934.
3 Williams, "Antenna Theory and Design," *The Electrical Design of Antennae*, Vol. 2, Second Edition, Sir Isaac Pitman and Sons Ltd., London, p. 126.

The 20-meter vertical antenna in the foreground, and the 26-foot test tower.



The base of the vertical element of the antenna and the impedance bridge. Forty radials, in bundles of 5, are fastened to the aluminum base plate, and are tied down with a ring made from copper tubing.

since it would appear to meet the following objectives: The system should

1) Exhibit a minimum profile.
2) Be easy to install and tune.
3) Offer a low angle of radiation.
4) Not require a large outlay of money.

I proceeded, therefore, to construct an array with four vertical elements. When my tests were begun, it immediately became apparent that the simple procedures I was using were inadequate to cope with such a complex system. I had to start anew to develop a test procedure and to build some suitable test equipment. The logical step was to backtrack to a single vertical antenna and use it as a standard on which to develop some basic test standards. As discussed subsequently, I found that relatively simple equipment, e.g., a simple impedance bridge, a field-strength meter, and a test oscillator, gave me all of the data about the system that I needed.

It is important to note that a true ground-image antenna differs substantially from a ground-plane antenna system which relies merely on a few $\lambda/4$ radials above the ground. A true ground-image system results when a sufficient number of radials are used and an image of only the vertical section is sufficient to describe it. Considerable information[4,5] is available on ground-image systems for verticals operating below 3 MHz. The results have shown that some 100 radials of $\lambda/2$ in length, buried just below the surface, provide an adequate ground system. At higher frequencies, the dielectric effect of the earth becomes important, resulting in severe discrimination of radiation or reception at very low angles.[6,7] At low angles, the waves not only suffer by absorption, but also by a change in phase which results in destructive interference. Since little specific information was available at higher frequencies, the objective of the present work was to measure the input impedance and vertical radiation pattern at low angles of a vertical antenna as a function of the number of radials, in order to determine the feasibility of a vertical-array system as a competitor to beams at high elevation. The results of my tests were most gratifying. I found that many of the "rules of thumb" which have developed and have been perpetuated to the point where they are practically taken for granted were more myth than truth.

[4] Brown, Lewis, and Epstein, "Ground Systems as a Factor in Antenna Efficiency," *Proceedings of the IRE*, Vol. 25, No. 6, June, 1937.

[5] Wait, "Input Resistance of L. F. Unipole Aerials," *Wireless Engineer*, May, 1955.

[6] Feldman, "The Optical Behavior of the Ground for Short Radio Waves," *Proceedings of the IRE*, Vol. 21, No. 6, June, 1933.

[7] Jager, "Effect of the Earth's Surface on Antenna Patterns in the Short Wave Range," *Internat Elekitron Rundschau 1970*, Nr. 4.

Experimental Results

The classical paper on radial systems, which reports experimental results at 1 and 3 MHz, indicates that a large number of radials 0.4λ long should be used.[8] This appeared to be a good starting point for a 20-meter vertical. Accordingly, to check the number of radials needed, I used eight bundles of wires, each 25 feet long, and each made up of five No. 18 copper wires. Each bundle was

[8] See footnote 4.

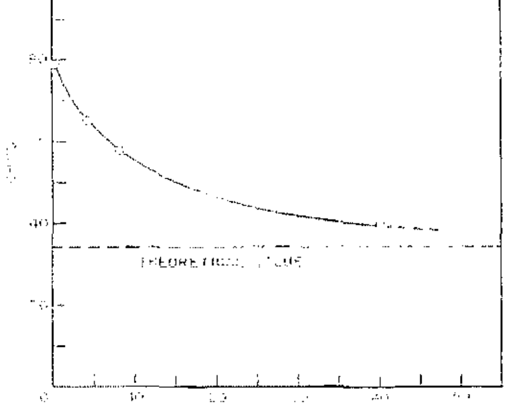


Fig. 1 — The input impedance of a 20-meter quarter-wave vertical antenna as a function of the number of radials 0.4-wavelength long. The 4 and 8 radials consisted of bundles of 5 wires of No. 18 gauge. The 40-radial point was obtained by fanning out the 8 bundles.

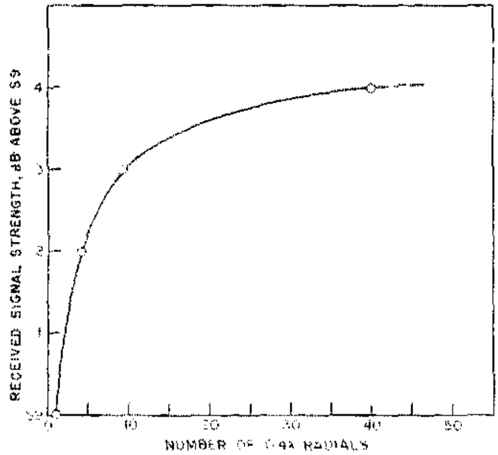


Fig. 2 – The improvement of low-angle radiation of a quarter-wavelength vertical antenna on 20 meters as a function of the number of added radials. A test oscillator was mounted on a wooden tower four wavelengths away at an elevation angle of 6 degrees from the base of the vertical.

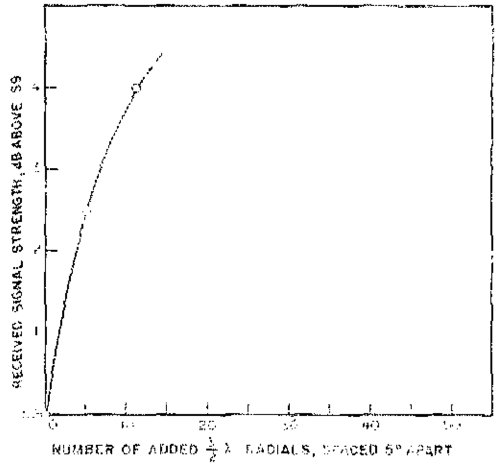


Fig. 3 – The result of interlacing 3/2-wavelength radials in a particular direction. Data were obtained by using a test oscillator on a wooden tower eight wavelengths away, at an elevation angle of 3 degrees from the base of the vertical. The results indicate the advantage of longer wires and the possibility of directional properties of a nonsymmetrical radial system.

bolted to a 5 x 1/4-inch aluminum plate as shown in the photograph. I was then able to use each bundle as a radial, measure the input impedance of the system, and then separate the bundles, wire by wire, to increase the number of radials in the system.

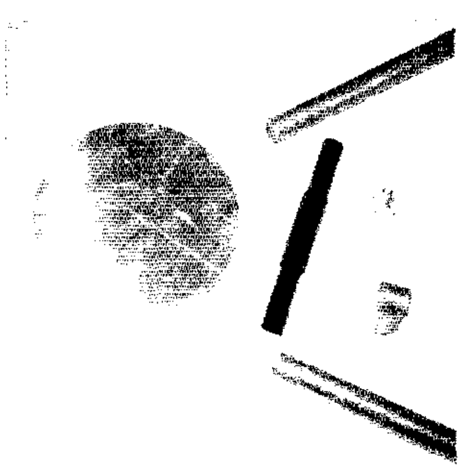
Fig. 1 shows the input impedance as a function of the number of radials used. Measurements were made with a simple impedance bridge. (Its construction is discussed later.) The antenna was resonated before each measurement was made, and the difference between the 40-radial system and the 8-radial system resulted only by fanning out the bundles of wires. This technique points out another important feature of ground systems and refutes one of the old myths: since the current carried by the radial system is equally divided among n radial elements, each radial is required to carry only $1/n$ of the total current. This means that relatively small diameter wire is perfectly adequate.

Moreover, it was found that at the higher frequencies it is best to keep the radials near the surface of the ground. Radials buried more than a few feet become less effective! Thus, you should not rely on the old admonition that radials should be six feet down to be effective. I found that burying the wires slightly below the surface is the best way of installing the system. Mechanically the radials can be nailed down, electrically they are most effective, and esthetically they provide little interference to a healthy stand of grass.

It will be seen from Fig. 1 that the input impedance for a vertical antenna is drastically affected by the number of radials. Many radial wires are necessary to prevent an excessive loss of power and to provide a convenient input impedance. Fig. 1 also shows the theoretical impedance limit for an antenna having an effective height-to-radius ratio of 300.[9]

Fig. 2 shows the effect on low-angle radiation as a function of the number of radials. These data were obtained by placing a test oscillator on a wooden tower, four wavelengths away. A photograph shows the 20-meter vertical and the 26-foot wooden test tower.

[9] King and Harrison, "The Impedance of Short, Long, and Capacitively Loaded Antennas with a Critical Discussion of the Antenna Problem," *Journal of Applied Physics*, Vol. 15, February, 1944.



Base hardware for the antennas being tested. The insulator was made from 1-inch maple dowel, turned down to accept the 7/8-inch inside diameter of the ground and antenna tubing.

The effect of using longer radials in a particular direction is shown in Fig. 3. Radials of No. 18 wire 3/2 wavelengths long, were put down between the existing 40 radials. The spacing between the longer wires was 5 degrees. The considerable improvement indicates the need for longer wires and the directional properties a ground plane could give.

A 5/8-wavelength vertical was also constructed *and tested. It consisted of a 40-ft telescoping* aluminum pole and a loading coil of 8 turns of No. 12 wire with a diameter of 2.5 inches. The comparison in low-angle radiation at a distance of 7.5 wavelengths is presented in Table I. A field-strength meter was mounted at different heights on the 26-foot tower. The ground plane for these data consisted of the forty 0.4λ radials plus the eleven 3/2λ ones. Measurements were taken in the direction of the added longer radials. The results show the improvement in low angle radiation offered by the 5/8λ vertical. The input impedance of this longer antenna was found to be 76 ohms.

On-The-Air Checks

From these experiments and measurements I decided to settle on a 1/4λ antenna with approximately 40 radials. My installation is shown in the photograph. I then proceeded to make on-the-air tests to compare its effectiveness with an inverted-V antenna having its apex at 0.4 wavelength, and with a 5/8λ vertical using the same ground system. Surprisingly, the 1/4λ vertical seemed to perform just as well as the much taller 5/8λ vertical. This could result from the fact that *most signals arrive after several hops and the* optimum lobe angle is probably as high as 15 to 20 degrees.[10] At that angle, the λ/4 antenna actually enjoys an advantage. With practically all DX contacts, the verticals had a 6- to 8-dB improvement over the inverted V! The only exceptions were at intermediate distances and for local contacts. At about 500 or 600 miles, the inverted V with its higher angle of radiation gave better results. Locally, the verticals gave far superior performance. Improvements of 10 to 15 dB were recorded. A triband trap vertical antenna was also tested on 20 meters and found to be practically the same in impedance and performance. This antenna had an overall height of only 12.5 feet!

Test Equipment

A most interesting aspect of antenna measurements is that the equipment can be rather simple and in many cases constructed from items most amateurs have in their junk boxes. All that is really needed is some standard to compare with, such as a wattmeter or an S meter that is known to have reasonable accuracy. I have used both – the wattmeter in my Drake L-4B linear amplifier and the S meter in my R-4B receiver.

The impedance bridge shown in the photograph was patterned after the one shown in the ARRL *Handbook*. Care was taken in shielding the input and output circuits. The meter was mounted externally in order to minimize stray pickup. A calibration curve was obtained at 14.25 MHz by using many carbon resistors of known values as the load.

The field-strength meter is a simple diode detector and dc amplifier. The instrument was constructed to cover the 10-, 15-, and 20-meter bands. Its meter was also mounted externally. The antenna length for the field-strength meter was determined by the strength of the available field. In addition to these pieces of test equipment, a 20-meter transistorized crystal oscillator was used for many of the tests.

(Continued on page 22)

[10] See footnote 2.

TABLE I

Comparison of responses of quarter-wavelength and 5/8-wavelength vertical antennas at low radiation angles. Data were taken by field-strength meter mounted on a wooden tower at a distance of 7.5 wavelengths at 14.25 MHz. Field strength (*E*) is normalized to maximum value obtained with 5/8-wavelength case.

θ	$E(\frac{\lambda}{4})$	$E(\frac{5}{8}\lambda)$	GAIN OF $\frac{5}{8}\lambda$ ANTENNA
0.1°	0	.58	∞
0.4°	0	.62	∞
0.75°	.62	.80	3.4 dB
1.1°	.69	1.0	3.2 dB
1.5°	.62	.92	3.4 dB
2.25°	.48	.80	4.3 dB
3°	.41	.69	4.5 dB

Shown here is the triband trap vertical antenna which has an overall height of only 12.5 feet. With the system of 40 radials, performance of this antenna on 20 meters was about the same as that of the quarter- and 5/8-wavelength vertical elements.

Low-voltage miniature capacitors and 1/2-watt resistors are used to keep the size of the blanker at a minimum. Connection in the author's homemade solid-state receiver was made inside the 1500-kHz shielded i-f compartment. The 1500-kHz second i-f is ahead of the highly selective 455-kHz third i-f; therefore, blanking action takes place prior to any crystal or mechanical filters, eliminating the pulse stretching that occurs in high-selectivity stages.

The only adjustment required to ready the blanker for operation after it is installed is to realign the i-f stages to which it is coupled and adjust L1 for maximum positive dc-voltage reading taken with a VTVM at point A in Fig. 1, with a signal centered in the i-f passband.

Operation

As a matter of curiosity, the noise blanker was connected to a number of points in the receiver i-f chain following the initial pick-up point. These connections produced varying degrees of successful blanking. As the blanker output connection was moved to the latter stages of the strip, it became less effective because considerable amplification of signal and noise pulses had taken place.

One of the severest noise tests that can be made is to attempt copying a signal through Loran interference around 1900 kHz. An image of a BBC station was purposely introduced at 1900 kHz and the blanker threshold carefully adjusted for heavy blanking action. As long as the desired signal was approximately the same strength as the Loran interference, the blanker made the difference between intelligible and unintelligible copy. When the desired signal was greater than the Loran interference, there was still a great amount of interference riding on it, but this was practically eliminated when the blanker was engaged.

Another realistic test was to tune the receiver to the 10-meter band while the author's Volkswagen pulse generator was set at a fast idle in the driveway under the antenna. What an eye-opener this test proved to be! With the receiver tuned to an unoccupied spot in the band where only atmospheric noise and the chain of noise pulses could be heard, the blanker was turned on. The ignition noise dropped right out of the picture. Weak signals, of the S1 to S3 variety, were tried next. Although they could be copied with considerable discomfort through the ignition noise, with the noise blanker on they were literally cleaned up so completely that it was hard to realize that there could have been a problem a moment before.

As the threshold control is advanced toward minimum reverse bias on the switching diode (maximum blanking), a point is reached where the last JFET conducts all of the time. From this point on, to the maximum position of the threshold control, the gain of the i-f stage to which the switching diode is connected is gradually reduced to almost zero – an effect similar to that produced by the action of an i-f gain control. By taking advantage of this feature, the gain of the i-f stage can be adjusted to provide a variable "window" through which only the strongest portion of the desired signal is allowed to pass. Thus, in a broad selectivity position, if the static level is S7 and the desired signal is S9, the gain can be reduced to lessen the QRN and signal. At the same time the heaviest pulses of QRN which ride through on top of the signal momentarily switch the i-f stage off. With the slow agc time constant selected, some fairly weak ssb stations on 75 meters have been copied comfortably in this manner. The optimum setting for the threshold control, with most types of pulse interference, seems to be at the position immediately before the i-f gain is affected, as observed on the S meter.

Conclusion

The solid-state noise blanker has performed remarkably well in the author's homemade solid-state receiver. The total retail cost of all parts, including semiconductors, is less than $20. The unit has not been tested in receivers using vacuum tubes or low-impedance bipolar transistor circuits. It is the author's opinion that is would work as well in a low-level i-f stage of a tube receiver as it works in the MOSFET receiver. Some modification of the output switching or gate circuit might be required for a receiver using bipolar transistors. QST

Vertical Antenna

(Continued from page 19)

Conclusion

The performance of a vertical antenna on the ground is highly dependent upon a good ground system, and, properly installed, the antenna can be a very good performer indeed for DX and local contacts. This is particularly true at the higher frequencies where the dielectric property of the earth plays a major role. Forty radials of No. 18 wire, 0.4λ long, will increase the total radiated power by about 3 dB. Radials can be thin if a sufficient number is used. The thought of using thick wires buried deeply, probably a carry-over from lightning grounds, is not valid at higher frequencies. The idea of using only four buried radials, as commonly recommended, is a serious error, and if this article does nothing more than eliminate that misconception, I will be satisfied. Since the electric field only penetrates the ground for a foot or two at the higher frequencies, the radial wires need be buried only as deep as necessary to escape children's feet and the lawn mower. Finally, these results from the single vertical antenna indicate that a vertical array could be a competitor to the more elaborate horizontal beams and warrants further investigation. QST