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Short Ground-Radial Systems for Short Verticals

When is a ground not a ground? Should my radials be buried? How deep? How many? Will my vertical work without a ground? Let W2FMI give you the answers.

By Jerry Sevick, W2FMI

How do you engineer the performance of ground-radial systems under vertical antennas? There isn't much engineering design information available, particularly for conditions where space is limited and cost is an important consideration.

The often-asked questions which need answering are (a) Do four quarter-wavelength radials constitute an adequate ground system? (b) Must radials be buried deeply in the earth? (c) Must the thickest copper conductor available be used? And while we are at it, how about the mistaken notion that short verticals can never compete in performance with a full-sized quarter-wavelength antenna?

This paper presents experimental evidence which answers these questions in a clear and concise way. Investigation shows that short verticals over very small radial systems of almost any kind of thin wire on the ground's surface can perform surprisingly well. On-the-air comparisons with much larger verticals over extensive ground systems show performance reduced by only a few decibels.

Introduction

Vertical antennas have enjoyed considerable popularity on the 80- and 160-meter amateur bands because of the difficulty of erecting horizontal antennas at heights sufficient for low-angle radiation. Optimum heights, which are in excess of a half wavelength (λ) on these bands, are impractical for most amateurs. In many cases short verticals are used since they have been shown to compete favorably with 1/4-λ vertical antennas.[1] This is true if losses in the ground system, matching networks and loading elements are small compared to the reduced radiation resistances of the short antennas.[2] Considerable information is available describing the effects of buried radials on the efficiency of 1/4-λ verticals in the mf and lf bands as a function of length and number of radials, and conductivity of the soil.[3-19] But little is available on radials lying on the ground's surface, particularly in connection with short verticals.

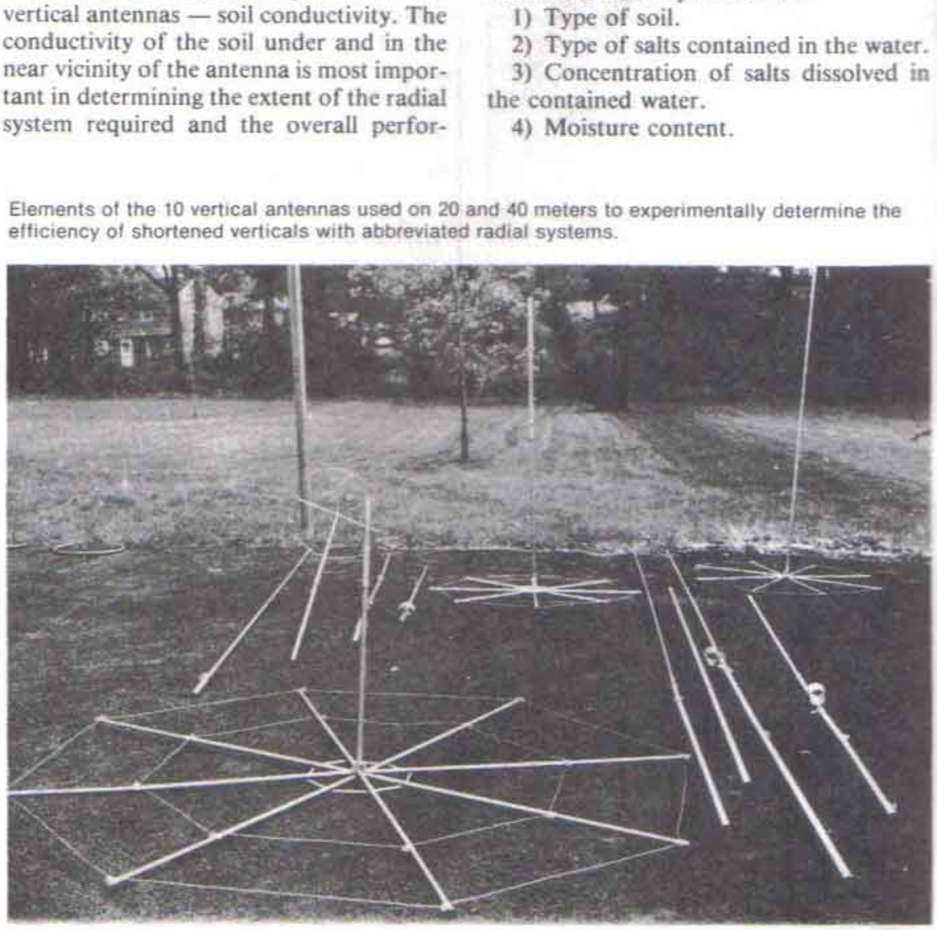
During the author's experiments, various antenna heights from $1/4\,\lambda$ to $1/8\,\lambda$ were included. Also developed and described here is a simple method for measuring an important parameter for vertical antennas — soil conductivity. The conductivity of the soil under and in the near vicinity of the antenna is most important in determining the extent of the radial system required and the overall performance. As will be seen, short verticals with very small radial systems can be surprisingly effective.

Soil Conductivity

Most soils are nonconductors of electricity when completely dry. Conduction through the soil results from conduction through the water held in the soil. Thus, conduction is electrolytic. Dc techniques for measuring conductivity are impractical because they tend to deplete the carriers of electricity in the vicinity of the electrodes. The main factors contributing to the conductivity of soil are

1) Type of soil.
2) Type of salts contained in the water.
3) Concentration of salts dissolved in the contained water.
4) Moisture content.

Elements of the 10 vertical antennas used on 20 and 40 meters to experimentally determine the efficiency of shortened verticals with abbreviated radial systems.



5) Grain size and distribution of material.

6) Temperature.

7) Packing density and pressure.

Although the type of soil is an important factor in determining its conductivity, rather large variations can take place between locations because of the other factors involved. Generally, loams and garden soils have the highest conductivities. These are followed in order by clays, sand and gravel. Soils have been classified according to conductivity, as shown in Table 1. Although some differences are noted in the reporting [20,21] of this mode of classification because of the many variables involved, the classification generally follows the values shown in the table.

Table 1
General Classification in Conductivity

Material	*Conductivity (millimhos/meter)*
Poor Soil	1-5
Average Soil	10-15
Very Good Soil	100
Salt Water	5000
Fresh Water	10-15

Since conduction through the soil is almost entirely electrolytic, ac measurement techniques are preferred. Many commercial instruments employing ac techniques are available and described in the literature.[22] But rather simple ac measurement techniques can be used which provide accuracies on the order of 25 percent and are quite adequate for the radio amateur. Such a setup was developed by a colleague and neighbor, M. C. Waltz,[23] W2FNQ and is shown schematically in Fig. 1. Fig. 2 shows the conductivity readings taken over the last three months in 1976. It is interesting to note the general drop in conductivity over the three months as well as the short-term changes due to periods of rain. The results presented in the following sections on antenna efficiencies were obtained in the period October 10 to November 10, 1976, when the conductivity varied between 22 and 25 millimhos/meter.

Antenna Efficiency Considerations

The antenna efficiencies to be discussed are based upon the losses which appear in series with the radiation resistance of resonant verticals. Although this approach does not give a comparison between the very low angles of radiation (i.e., less than 15 degrees) of various radial systems, it does allow for comparisons in the 15- to 30-degree range which is important for sky-wave transmission on the 40-, 80- and 160-meter bands. Mathematically this definition for antenna efficiency can be written as

$$\text{Antenna efficiency} = \frac{R_{rad}}{R_{rad} + R_g + R_A}$$

where R_{rad} = radiation resistance

R_g = ground loss

R_A = ohmic losses due to loading and the antenna itself.

With high-Q loading coils and practically any size of aluminum tubing for the antenna, R_A can be minimized and therefore eliminated from the relationship above.

An example of this technique for determining antenna efficiency uses the results shown in Fig. 3. The input impedance of a resonant quarter-wavelength vertical is plotted as a function of the number of radials. Two lengths of radials (0.2 λ and 0.4 λ) were considered. Since the radiation resistance is 35 ohms for the thickness of the verticals used in this experiment, it can be seen that with 50 radials, losses were about 2 ohms and with 100 radials, 1 ohm. This amounts to efficiencies of 94 and 97 percent, respectively. Also, it can be seen that the efficiency with only four radials is less than 60 percent. This poor efficiency exists even for a location with a soil conductivity that can be considered average.

Further, the efficiency of a radial system employing small numbers of radials is quite dependent on the moisture content of the soil. Fig. 4 shows this result with a resonant quarter-wavelength vertical on 20 meters while the number of radials varies from one to eight. As can be seen, the difference in efficiency between wet and dry conditions becomes less pronounced as the number of radials is increased. The antenna system also becomes more independent of soil conductivity as the number of radials is increased.

In order to determine the efficiencies of shortened verticals over abbreviated radial systems, input impedances were compared with similar antennas over a near-ideal radial system. Fig. 5 shows the experimental results[24] obtained by the author on a near-ideal image plane (100 radials on the ground, about 50 feet long, and terminated in 10- to 12-inch nails). The top-hat loading consisted of an eight-spoked wheel with several rings of aluminum wire to improve its effect. This family of curves has been very useful to the author in designing verticals since it predicts the value of the input impedance of shortened verticals using various loading methods. In particular, it was noted that a simple rule of thumb existed for top-hat loading. That is, a top hat with a diameter D is equivalent to an electrical height of 2D. Further, top-hat loading yielded the highest impedance and bandwidth for a particular height.

Since the investigations reported here involved short radials on the surface of the ground, a study of the effect of the length of a spike terminating the radials was necessary. The efficiency for resonant 1/4-λ verticals with small numbers of

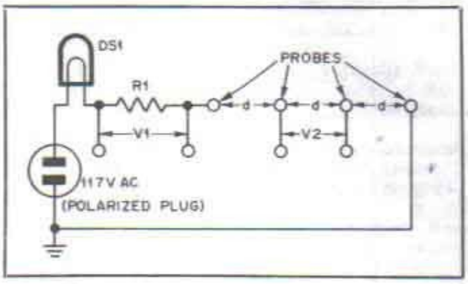


Fig. 1 — Schematic diagram of four-point probe method for measuring earth conductivity.

DS1 — 100-watt light bulb.
R1 — 14.6 ohms (5 watt).
Probes — 5/8-inch dia (iron or copper); spacing, d = 18 inches; penetration depth, D = 12 inches.

Earth conductivity = (21) × $\frac{V1}{V2}$ (millimhos/meter).

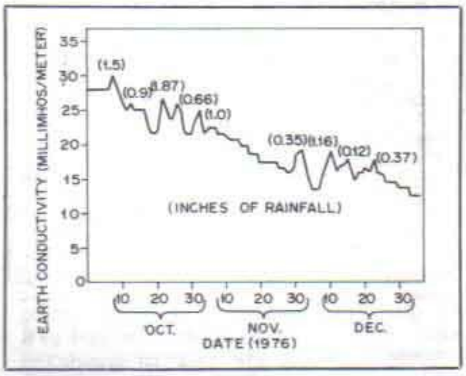


Fig. 2 — Earth conductivity at author's location during last three months in 1976.

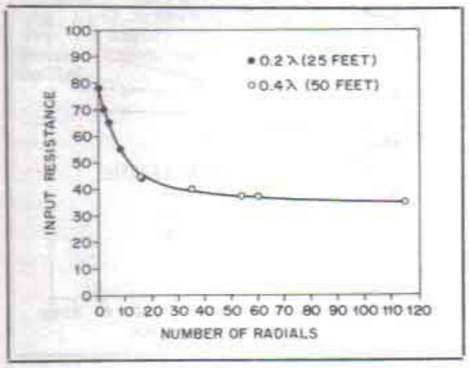


Fig. 3 — Input impedance of resonant quarter-wavelength vertical as a function of the number of radials.

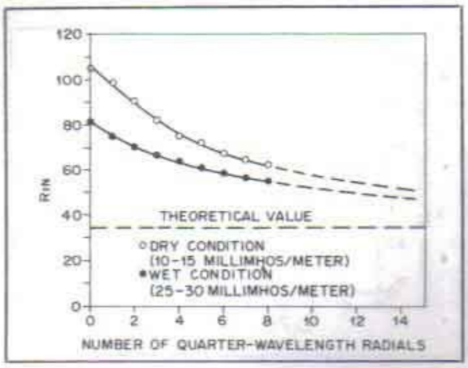


Fig. 4 — Input impedance of resonant quarter-wavelength vertical as a function of the number of radials and the condition of the soil.

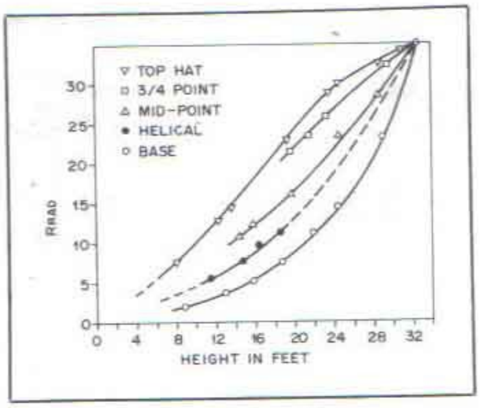


Fig. 5 — Experimental results of radiation resistance as a function of height of antenna for various methods of loading.

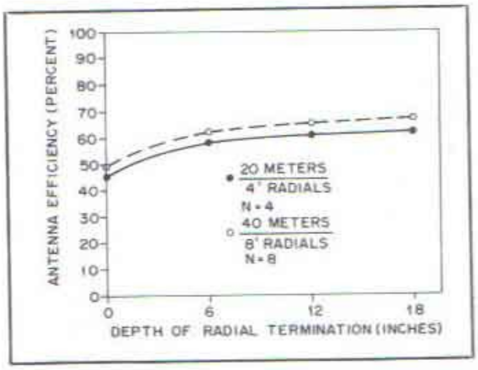


Fig. 6 — Efficiency of resonant quarter-wavelength verticals on 20 and 40 meters as a function of the length of spike terminating the radials.

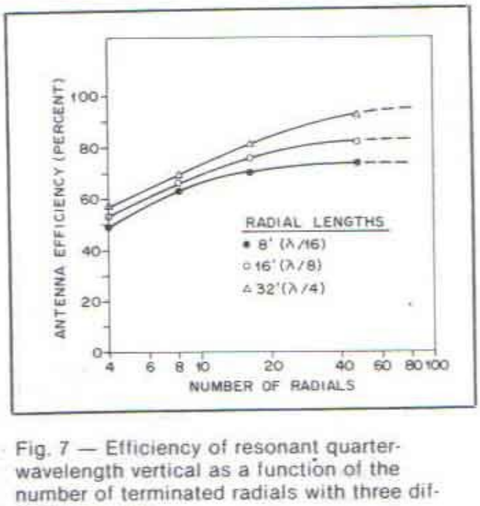


Fig. 7 — Efficiency of resonant quarter-wavelength vertical as a function of the number of terminated radials with three different lengths.

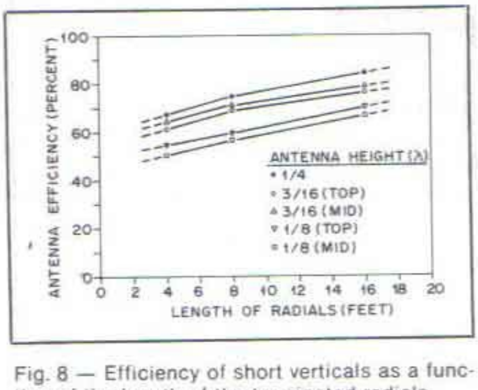


Fig. 8 — Efficiency of short verticals as a function of the length of the terminated radials, with the number kept constant at 48.

shortened radials was measured on the 20-and 40-meter bands. The radials were four and eight feet long (1/16 λ) respectively. Fig. 6 shows the results for four different depths of termination. As can be seen, depths of 10 to 12 inches should be sufficient for the soil conductivity at the author's location for 20 and 40 meters, and most likely for 80 and 160 meters as well. Incidentally, the effectiveness of radials of a 1/4 λ or longer did not change appreciably as a function of the depth of the termination. Therefore, terminations for long radials are primarily used for mechanical reasons.

Abbreviated Radial Systems

In order to determine experimentally the efficiency of shortened verticals with abbreviated radials on the surface of the ground, five verticals of different heights and loading schemes were used on the 20-and 40-meter bands. The results were then compared with similar antennas on a near-ideal image plane as shown in Fig. 5. The five resonant verticals selected were

1) 1/4 wavelength.
2) 3/16 wavelength, top-hat loaded.
3) 3/16 wavelength, midpoint loaded.
4) 1/8 wavelength, top-hat loaded.
5) 1/8 wavelength, midpoint loaded.

One of the photographs shows the elements for these 10 antennas.

A radial system with various lengths of 17-gauge steel electric fence wire, terminated with 10- to 12-inch nails, was employed. A picture shows the 12-inch aluminum base and the input connection arrangement. The antenna system was erected in the front yard about 50 feet from the house, and it offered an opportunity for on-the-air comparisons with verticals mounted on the near-ideal system in the backyard.

The results are shown in Figs. 7 and 8. Only the 40-meter data is presented since little difference was noted on 20 meters. Fig. 7 shows the effect on the efficiency of a resonant 1/4-λ vertical on 40 meters as a function of the number of radials using three different lengths of terminated radials. Although these curves were taken on a 40-meter system, the relationships are generally valid for all other frequencies in the hf range if the same fractional wavelengths are used for the radials. As can be seen the longer radials (1/4 λ) yielded the highest efficiency. But it is interesting to note that this improvement in efficiency with length decreases as the number of radials becomes smaller. At four radials, the efficiency with eight-foot radials is not much poorer than that with 32-foot radials, i.e., 50 percent compared to 56. Further, other interesting trade-offs exist with various lengths and numbers of radials. Fig. 8 shows that 16 1/4-λ radials are equivalent to about 35 1/8-λ radials, and 8 1/4-λ radials are equivalent to only 12 1/16-λ radials. Obviously other equivalences can be obtained from the figure.

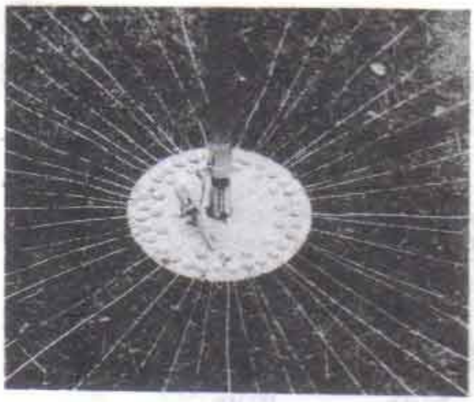
Fig. 8 shows the results of antenna efficiency for short verticals as a function of the length of radials, with the number of radials kept constant at 48. As expected, 1/4-λ verticals, with their higher radiation resistance, have the highest efficiencies. Surprisingly, the efficiency of the 1/8-λ verticals does not suffer proportionally. That is, the 1/8-λ vertical with midpoint loading still has a 67-percent efficiency compared to the 84-percent efficiency of the 1/4-λ vertical, even though its radiation resistance is only about one-third as large (12.5 ohms compared to 35 ohms). A further comparison with a 1/4-λ vertical over an ideal image plane predicts that this 1/8-λ vertical with 48 1/8-λ radials (terminated) should show a reduced performance of only 1.7 dB.

On-the-Air Comparisons

As was shown in the previous section, short verticals with a sufficient number of abbreviated radials that are terminated should yield performances only a decibel or two poorer than 1/4-λ verticals over extensive ground systems. Several on-the-air comparisons were made to confirm this prediction, which was based upon efficiency considerations.

The first comparison involved a 40-meter, 1/8-λ, top-hat-loaded vertical with 48 1/8-λ radials (17-gauge steel wire on the ground and terminated with 10- to 12-inch nails). The input impedance of this vertical was about 25 ohms and it was matched to the 50-ohm transmission line with a highly efficient 2:1 step-down transmission-line transformer. This antenna system was compared with a 29-foot vertical using a 13-1/2-foot-diameter top hat in the backyard. The ground system for this larger antenna consisted of 100 radials of no. 15 aluminum wire, each about 50 feet long. Each radial was on the surface of the ground and terminated with 10- to 12-inch nails. This larger antenna was resonated by a small variable capacitor in series at the base. Over 100 contacts on 40 meters plus about 200 observations on reception showed that the differences between the two systems were generally negligible. A few reports showed a 1- to 2-dB difference in favor of the larger system but these were in the minority.

An even more interesting comparison was made on 80 meters. A 20-foot vertical with an 8-foot top hat was erected over the same image plane of 48 16-foot radials in the front yard. It required a base-loading coil of about 20 turns of 12-gauge wire, 2-1/2-inch diameter, 6 tpi to resonate it. The input impedance was about 12 ohms and a 4:1 transmission line transformer was used for matching. This antenna configuration represents a radiation resistance of about 5 ohms and a loss in the ground system and loading coil of about 7 ohms. The 29-foot vertical with the 13-1/2-foot diameter top hat needed



The 12-inch aluminum base and input-connection arrangement. Shown are 48 radials of 17-gauge steel electric-fence wire.

about eight turns on a powder-iron core (T200) at the base to resonate it on 80 meters. Its input impedance was 15 ohms (showing negligible loss in the ground system and base loading coil), and matching was accomplished with an efficient transmission-line transformer having a 3.33:1 step-down impedance ratio. Again about 100 contacts were made on the air and another 200 observations were made on reception. The average difference between these two systems amounted to only about 5 dB in favor of the much larger system in the backyard. This is quite noteworthy since many previous contacts with the larger antenna established it as a very competitive antenna system.

Concluding Remarks

Quarter-wavelength vertical antennas over an extensive radial ground system have been known to be efficient, low-angle radiators. Even short verticals over the same large ground system have been shown to lose little in the way of performance. With low-loss matching and loading techniques, short verticals over a large ground system suffer only in bandwidth. But full-sized verticals and radial ground systems are beyond the reach of most radio amateurs on the 80- and 160-meter bands. This investigation was undertaken because little information was available on limited radial systems, particularly for short verticals.

As was shown, short radials over soil of average conductivity can perform quite acceptably for verticals of all heights. The results of this investigation now allow one to predict quite accurately the operation of verticals with heights less than a quarter-wavelength and with radials as short as 1/16 λ in length. The simple soil-conductivity measurement scheme described also gives one a tool for comparing a given location with others, as well as predicting the performance of a vertical antenna system.

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