

An Experimental Look at Ground Systems for HF Verticals

In this groundbreaking work we obtain definitive results on ground system effectiveness.

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It's been over 100 years since Marconi used vertical antennas. With such a long history it would seem unlikely that anything new could be said about them. The way Amateur Radio operators use and implement vertical antennas often differs from commercial or military practice leaving amateurs with unanswered questions.

These questions can be addressed analytically or through the use of modeling and simulation, but for most of us neither is quite convincing. Actual measurements on real antennas are a lot more satisfying, at least to verify the modeling.

Some years ago, Jerry Sevick, W2FMI, (SK) published exactly this kind of information in *QST*.¹⁻⁵ Reading his articles inspired me to take another experimental look at HF ground systems. The result was an 18 month effort, partly replicating Jerry's work, but also addressing other questions such as the comparison between ground

surface and elevated radial systems. These experiments have been covered in detail in a series of seven *QEX* articles. Since not everyone wants all the gory details, this article is a summary of the more interesting results.⁶

Near and Far

It is important to keep in mind the role of the ground system associated with the radiation from a vertically polarized antenna. The radiation pattern for a vertical is strongly influenced by the characteristics of the soil in the neighborhood of the antenna. This is particularly true at lower angles for which the pattern is determined by soil characteristics out to a great distance (many wavelengths), often referred to as the *far-field* region.⁷ As a practical matter we can't usually do much about conditions beyond perhaps $\frac{1}{2}$ wavelength from the base of the vertical, other than select our location — we simply have to accept what's out there. We can, however, do a lot to reduce the losses in the immediate vicinity

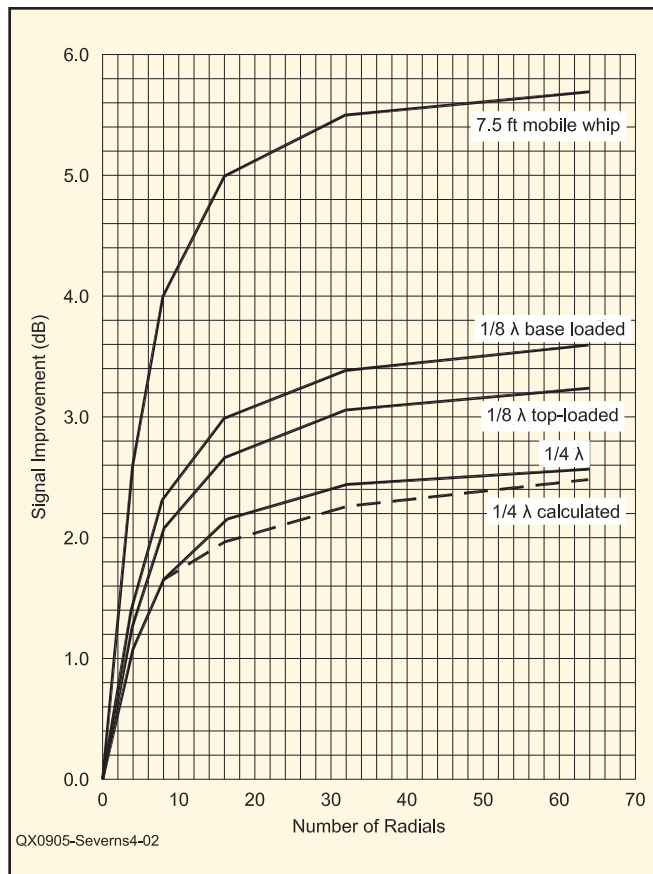


Figure 1 — Typical improvement in signal as $\frac{1}{4}$ wave radials are added to the basic ground system of a single ground stake.

¹Notes appear on page 33.

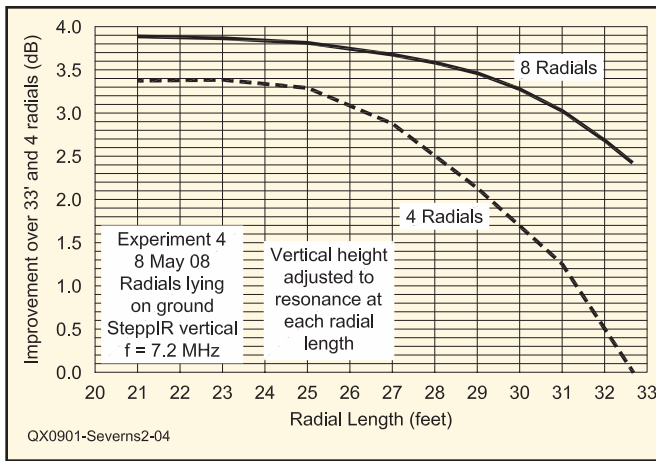


Figure 2 — Effect on signal strength of shortening radial lengths. The 0 dB reference is four 33 foot radials.

of the antenna (the *near-field* region), where the losses can be very high.⁸ The purpose of the ground system is to reduce these near-field losses, increasing efficiency and allowing us to radiate as much of the antenna input power as possible, which ultimately improves our signal.

Overview of the Experiments

This work started with a 160 meter vertical with which I varied the number of $\frac{1}{4}$ wave radials and measured the change in signal strength for a fixed input power. This was interesting and educational but I realized that repeatedly laying down and picking up some 8000 feet of #12 AWG wire was not practical for more extensive investigations. I thus changed the test frequency to 7.2 MHz initially, and later added experiments for multiband ground systems (40 through 10 meters). This initial experiment also stimulated me to use the much more accurate measurement procedure that is outlined in the sidebar on the QST In Depth Web site.⁹

I went through several rounds of experiments, each one answering some questions but, of course, always generating more. In the following three sections we'll consider radials for vertical monopoles — on and above the ground and finally, radial systems for multiband verticals.

Round One — Radials on the Ground

This set of experiments used four different antennas: a $\frac{1}{4}$ wave vertical, an $\frac{1}{8}$ wave vertical with base loading, an $\frac{1}{2}$ wave vertical with sufficient top loading to be resonant at 7.2 MHz and a 40 meter mobile whip. I started with a single 4 foot ground stake (zero radials) and then progressively added $\frac{1}{4}$ wave radials, measuring the changes in signal strength with each increase in radial num-

ber. The results are shown in Figure 1. Note that the graph is in terms of the *improvement* in signal for a given input power for *each* antenna over the single ground stake with no radials. The graph does *not* compare the relative merit of each antenna. Obviously a short, lossy mobile whip will yield less signal, typically 10 dB less, than a full size $\frac{1}{4}$ wave vertical. The signal improvement metric gives us a direct idea of how much is gained for a given improvement in the ground system.

How Many Radials?

This graph shows several things. First it makes clear just how important a radial system is. It can make a difference of many dB in our signal strength. Keep in mind that the soil over which the experiments were done would be classified as good to very good. Over average or poor soils the signal improvements could be many dB greater than shown here. The second thing the graph shows is the point of diminishing returns. Laying down a system with at least 16 radials will give you most of the obtainable improvement. As we go to 32 and then 64 radials the improvement gets progressively smaller. It's arguable that the improvement from going from 32 to 64 radials is worth the cost and clearly the standard 120 radial BC ground system would be overkill.

A final point the graph makes is that *the shorter and more heavily loaded your vertical, the more you have to gain from improving the ground system.* The shorter the vertical, the higher will be the field intensity (for a given input power) in the near field of the antenna and the lower will be the radiation resistance. This leads to much higher ground losses, which translates to more improvement when you reduce these losses by improving the ground system.

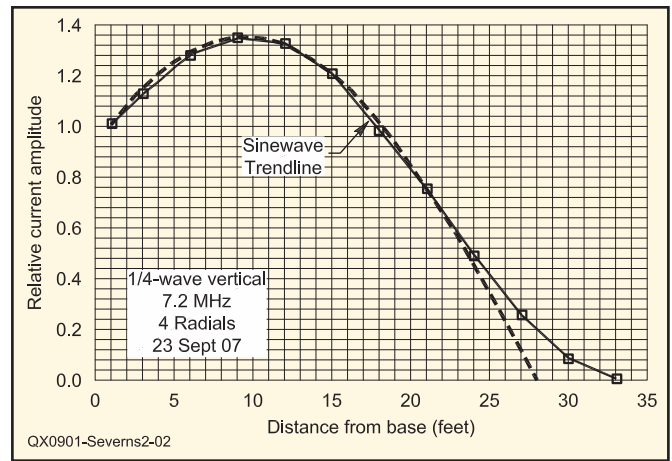


Figure 3 — Measured current distribution on a radial.

How Long Should They Be?

Radials $\frac{1}{4}$ wave in length are known to be effective in ground systems, but I wondered what the penalty would be from using shorter radials. I was expecting to see a fairly uniform decrease in signal strength (due to an increase in ground loss) as the radials were shortened. That is *not* what I found. Figure 2 shows the results of an experiment in which I measured the signal strength while progressively shortening the radials in four and eight radial systems.

Surprisingly, shortening the radial lengths *increased* the signal strength — not by just a little bit, but by more than 3 dB. This is certainly counterintuitive, but I was seeing clues that helped explain what was happening. I noticed that with only the ground stake the resonant frequency of the vertical was much lower than expected and, as I added more radials, the resonant frequency increased slowly. Most of the change occurred between 4 and 16 radials and had pretty much leveled out by the time I had 64 radials. This suggested to me that the radials might be self-resonant below 7.2 MHz. To check this out I measured the current distribution on a radial and found it to be sinusoidal. The results are shown in Figure 3.

The maximum current point has been moved from the base of the antenna out onto the radials and this substantially increases the ground loss. The radials are resonant below the band and this affects the antenna. A wire, close to ground, can be heavily loaded by the ground, decreasing its resonant frequency. The extent of the loading will depend on the characteristics of the soil. Figure 3 shows that the maximum current point is 10 to 11 feet away from the base. Looking at Figure 2 we see that the maximum signal occurs when we have shortened the radial by this amount.

Figure 3 also illustrates a difference

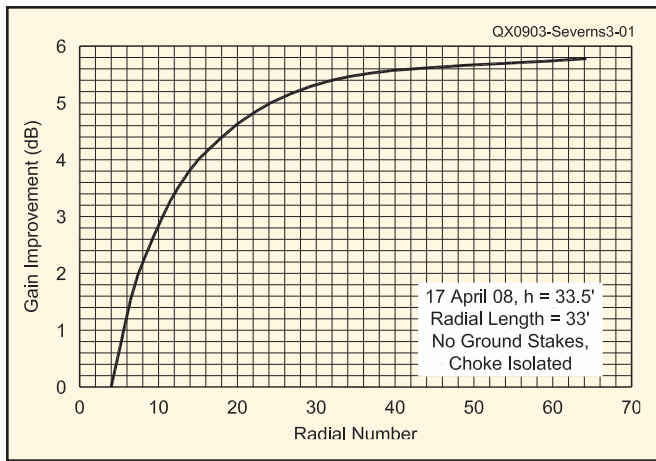


Figure 4 — Signal improvement as a function of radial number. All radials lying on the ground surface, F = 7.2 MHz.

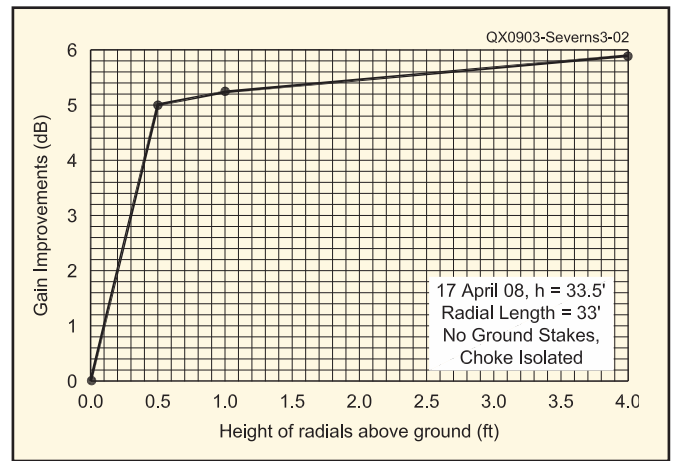


Figure 5 — Signal improvement with four radials and the antenna base at different heights. F = 7.2 MHz.

Table 1 — Relative Signal Strengths for 4, 8, 16 and 32 Radials, Comparing Lengths of 33' and 21'

Number of Radials	Normalized to Four 33' Radials (dB)	Normalized to Four 33' Radials (dB)	Gain Change (dB)
	33' Radials	21' Radials	
4	0	3.08	+3.08
8	2.26	3.68	+1.42
16	3.76	3.95	+0.19
32	4.16	4.04	-0.12

between buried bare wire radials and radials lying on or very near the surface of the soil. The current distribution on a buried bare radial will usually decrease exponentially from the base regardless of its length.¹⁰ You will not see the standing wave shown in Figure 3 except in very poor soils. The insulated radial lying on the ground surface behaves much more like a radial in an elevated radial system in that it has a sine wave-like current distribution. A buried insulated wire will be somewhere in between these two cases depending on the burial depth and soil characteristics.

You can also see in Figure 2 that the signal increases as the radial numbers increase. To check this out I extended the experiment to 32 radials, comparing 33 to 21 foot radials. The results are given in Table 1.

The results in Table 1 indicate that the excess loss due to radial resonance has pretty much disappeared by the time you reach 16 radials. This leads to some advice — rather than trying to determine the optimum radial length, which will vary with every installation due to soil differences, just use at least 16 radials. If you are limited by the total amount of wire available, you're better off to use a larger number of shorter radials rather than a few long ones.

I didn't have time to run an extensive set

of experiments comparing different radial length and radial number combinations (each with the same total length of wire), but I did model that situation with *EZNEC*.¹¹ The modeling predicted, particularly with short verticals, that it was often advantageous to reduce the length of the radials and increase their number. The modeling showed that there is a correlation between vertical height and optimum radial lengths. More details can be found in the modeling report and in the work of others.¹²⁻¹⁵

Round Two — Elevated Radials

Over the past few years there has been a lot of discussion about the relative merits of ground systems using a large number of surface or buried radials versus only a few elevated radials. This stems from *NEC* modeling that indicated that four radials elevated 8 feet or so above ground could be just as effective as 120 buried radials. Many of us, including me, simply could not believe that.

I decided the best way to address this question would be to directly compare two antennas, one with a large number of ground radials and the other with only a few elevated radials. The same antenna was used in both cases, a simple ¼ wave vertical. For the surface tests I used ¼ wave radials and varied the number from 4 to 64. For the

elevated tests I used four ¼ wave radials. The elevated radials were placed at 0, 6, 12 and 48 inches above ground. The results are shown in Figures 4 and 5. The 0 dB point in the graphs is normalized to the signal strength for the case of four ¼ wave radials lying on the surface (0 dB). What you see in the graphs is the improvement as you either add more surface radials or elevate the antenna and the four radials above ground.

The most striking thing shown by the graphs is that four elevated radials at a height of 48 inches are within 0.2 dB of 64 radials lying on the ground. This would seem to support the predictions from *NEC* modeling. A detailed view of the results with different elevated configurations is provided on the QST In Depth Web site.

Round Three — Multiband Ground Systems

While single band verticals are frequently used, multiband verticals are even more popular but I'd not seen any experimental work related to multiband ground systems. So I did some. The experiments were performed in two phases. The first was for radials lying on the ground and the second was for elevated radials. These represent two typical scenarios for amateurs, helping to answer a related question: "Do I put the antenna in the backyard or up on the roof?" For this series of tests I used a SteppIR III vertical.¹⁶ The motor driven SteppIR can be adjusted to be resonant anywhere between 40 and 6 meters.

For these experiments I made up four sets of thirty-two ¼ wave radials, one set for each band (40, 20, 15 and 10 meters). I then tried several different configurations starting with sets of 32 single band radials, *one set at a time*. In this way I had a ¼ wave vertical over a ground system of thirty-two ¼ wave radials on each band. These antennas were

then measured individually on each band. I then tried groups of four and eight (32 total) ¼ radials for each band, connected all at the same time. Next I tried 32 radials each 32 feet long, followed by 16, 8 and 4 at 32 feet each.

Obviously with a multiband antenna you would not run out to the antenna and change the radials whenever you changed bands! But this data can give us a feeling for any compromises resulting from the shift from monoband to multiband ground systems.

Four radials per band (16 radials in a four band system) probably represents the most common multiband ground system in general use both for elevated and ground surface radial systems, and we will use this as one measurement standard. I could have chosen many other possible combinations but those I did choose are at least reasonable. In particular I wanted to show that a few long radials don't work very well whether on the ground or elevated.

Radials Lying on the Ground

A comparison of the relative signal strength of each configuration with radials lying on the ground was made in comparison to the four radials per band case. The detailed results of this and following cases are shown on the QST In Depth Web page. In summary, however, there was little to choose among the cases (1 dB or less) until we came to the four 33 foot case that was down 2 to 4 dB from the standard four radials per band. The best performer is found with the 32 radials of 33 feet each, which is 0.4 to 1 dB better than our standard depending on the band. This case does require almost four times as much wire, however.

In the final analysis it appears that the standard ground system works just fine, but you can add more wire and get some improvement.

Vertical and Radials Elevated 48 inches

Once again the standard multiband radial system of four elevated radials appears to work well, nearly as well as the 32 radials of 33 feet each, although it has an edge of about 1.1 dB on 10 meters. As we move to fewer long radials, however, we found a problem on 20 meters in which the gain starts to fall quickly. This is related to the fact that the 33 foot, ¼ wave, radials on 40 meters are close to ½ wave radials on 20 meters, presenting a high impedance. At eight 33 foot radials the 20 meter response is down 4 dB, and at four 33 foot radials the performance was so poor I wouldn't consider it a multiband ground system. The four long radials didn't even work well on 15 meters, on which they were close to ¾ wave long.

Elevated Versus Ground Surface Radials

How do elevated multiband and ground surface radial systems compare to each other and to a large number of radials on the ground on each band? While the details are tabulated in the In Depth Web page, some conclusions can be summarized.

The differences between a 32 radial monoband system on the ground and a four radial elevated monoband system on each band are small, as we would expect from our earlier results.

If we compare a 16 radial multiband system on the ground with the same configuration elevated, the elevated system has about a 1 dB advantage on all bands. Doubling the number of radials on the ground will reduce the differences by 0.2 to 0.3 dB. The standard multiband system works just fine if elevated, but when the radials are lying on the ground it's not quite as good. If a radial system lies on the ground, the rule is you should use more radials to achieve comparable performance.

Acknowledgments

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In addition to creating the design for the VNA used in these experiments, Paul Kiciak, N2PK, originally suggested to me the use of a VNA for these experiments when I was moaning and groaning about more conventional techniques. Paul also provide important criticism at several points to keep me on the straight and narrow

Notes

- ¹J. Sevick, W2FMI, "The Ground-Image Vertical Antenna," *QST*, Jul 1971, pp 16-19.
- ²J. Sevick, "The W2FMI 20 Meter Vertical Beam," *QST*, Jun 1972, pp 14-18.
- ³J. Sevick, "The W2FMI Ground-Mounted Short Vertical," *QST*, Mar 1973, pp 13-19.
- ⁴J. Sevick, "A High Performance 20, 40 and 80 Meter Vertical System," *QST*, Dec 1973, pp 30-33.
- ⁵J. Sevick, *The Short Vertical Antenna and Ground Radial*, CQ Communications Inc, 2003, ISBN 0-943016-22-3. This is a compendium of Sevick's earlier work.
- ⁶R. Severns, N6LF, "Experimental Determination of Ground System Performance — Part 1," *QEX*, Jan/Feb 2009, pp 21-25; Part 2, Jan/Feb 2009, pp 48-52; Part 3, Mar/Apr 2009, pp 29-32; Part 4, May/June 2009, pp 38-42; Part 5, Jul/Aug 2009, pp 15-17; Part 6, Nov/Dec 2009, pp 19-24, and Part 7, Jan/Feb 2010, pp 18-19.
- ⁷R. D. Straw, Editor, *The ARRL Antenna Book*, 21st Edition, pp 3-11 to 3-32. Available from your ARRL dealer or the ARRL Bookstore, ARRL order no. 9876. Telephone 860-594-0355, or toll-free in the US 888-277-5289; www.arrl.org/shop; pubsales@arrl.org.

- ⁸R. Severns, N6LF, "Verticals, Ground Systems and Some History," *QST*, Jul 2000, pp 38-44. www.arrl.org/qst/qstdepth.
- ⁹A. Doty, K8CFU, "Improving Vertical Antenna Efficiency," *CQ*, Apr 1984, pp 24-31.
- ¹⁰Several versions of EZNEC antenna modeling software are available from developer Roy Lewallen, W7EL, at www.eznec.com.
- ¹¹Rudy Severns, N6LF, "Vertical Height Versus Radial Length," 2008. Available at www.antennasbyn6lf.com.
- ¹²J. Stanley, K4ERO, "Optimum Ground Systems for Vertical Antennas," *QST*, Dec 1976, pp 13-15.
- ¹³R. Sommer, N4UU, "Optimum Radial Ground Systems," *QST*, Aug 2003, pp 39-43.
- ¹⁴A. Christman, K3LC, "Maximum Gain Radial Ground Systems for Vertical Antennas," *NCJ*, Mar/Apr 2004, pp 5-10.
- ¹⁵www.steppir.com.

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