

Experimental Determination of Ground System Performance for HF Verticals

Part 4

How Many Radials Does My Vertical Really Need?

Experimental results to answer an often-asked question.

A frequently asked question is “How much of a ground system do I really need to make my vertical antenna work?” Usually, what’s wanted is an answer in the form of “This much ground system will improve your signal by X dB.” Another common question is “Does it matter if I lay the radials on the ground surface instead of burying them?” This is a practical consideration because it’s often much easier to lay out the radials on the surface and let them vanish into the grass.

These questions can be addressed analytically and with modeling, but for most of us that’s not very convincing. It’s much more satisfying to see actual field measurements on real antennas. In the past there has been professional work at MF broadcast frequencies and also the excellent work by Jerry Sevick, W2FMI, at HF.^{1,2} The problem with an experimental approach is the practical limit on the number of test examples: you can’t do all the possible variations! What’s needed are reliable field measurements that can be compared to calculations and/or modeling to see if there is reasonable correlation. If there is, we can use calculations or modeling for the wide variety of anten-

nas and soil characteristics we which we couldn’t test.

Some of the material that follows represents a redo of Sevick’s work with better instrumentation, but the material in this section, along with the other five parts of the series, goes well beyond Sevick’s work. The details of the test equipment and experimental setup were given in Part 1 of this series.³

Efficiency Limitations

The purpose of the ground system is to improve antenna efficiency so that less power is lost in the soil and more is radiated. Efficiency is the ratio of the power radiated to the total input power at the feed point. Of course what we want is to radiate all the input power (100% efficiency) and maximize our signal, but there are practical limits. We can represent the resistive part of the feed point impedance (R_s) by three series resistors as shown in Figure 1.

The input resistance at the feed point is $R_s = R_r + R_g + R_l$. We have to be a bit careful what we mean by “radiation resistance.” R_r is usually defined as the value of the resistance at a current maximum attributable to radiation. In a vertical antenna with a height of $\frac{1}{4} \lambda$ or less over perfect ground, this point is at the base of the antenna, which is the usual feed point. In real antennas with

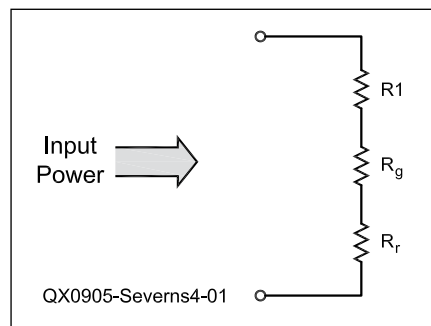


Figure 1 — An antenna input equivalent circuit. R_l represents the ohmic loss due to conductors, loading inductor series resistance, and so on. R_g represents the power dissipated in the soil by the near-field of the antenna. R_r is the radiation resistance, which accounts for the radiated power.

various numbers of ground surface radials, however, the height of the antenna may have to be modified to maintain resonance and the current maximum may actually be out on the radials or possibly even back up into the vertical. What this means in practice is that the fraction of the feed point impedance we attribute to R_r may not be converging to the ideal value from theory as we add radials or change radial lengths. For example,

¹Notes appear on page 42.

a resonant, very thin $\frac{1}{4} \lambda$ vertical over perfect ground will have $R_r = 36.2 \Omega$ but a real antenna may converge to a somewhat different value as we add radials and reduce ground loss.

With a $\frac{1}{4} \lambda$ vertical it is often assumed that if R_l is small, then R_g is simply $R_s - 36.2 \Omega$. This is not the case and should not be assumed. The radiation resistance varies as the ground system changes, and does not approach 36Ω until the ground system is relatively large. In a broadcast antenna with 120 radials 0.4λ long, this approximation is very good, but in the limited ground system typical of amateur antennas at HF, it is not. A detailed discussion of this point can be found in an article available on my Web site, "Radiation Resistance Variation with Radial System Design."⁴ (This may become a *QEX* article in the future.)

Because we are interested in the effect of efficiency on signal strength, it is handy to express efficiency (η) in terms of dB:

$$\eta = 10 \text{Log} \left(\frac{1}{1 + \frac{R_g}{R_r} + \frac{R_l}{R_r}} \right)$$

[Eq 1]

For 100% efficiency, $R_l = R_g = 0$ and $\eta = 0$ dB. If we increase R_l and/or R_g , η will decrease. For example 80% efficiency would be about -1 dB.

Experimental Tests

All of the measurements were made on 40 m, 7.2 MHz in most cases. I chose 40 m verticals for their manageable size. Even at that size, the ground system that had to be laid down and taken up numerous times, required over 2000 feet of wire.

I used five different antennas:

- A $\frac{1}{4} \lambda$, 1 inch aluminum tubing vertical, adjusted to resonate at 7.2 MHz.
- An $\frac{1}{8} \lambda$, 1 inch aluminum tubing vertical with three top loading wires sloping at roughly 45° , again, resonated at 7.2 MHz.
- An $\frac{1}{8} \lambda$, 1 inch aluminum tubing vertical with no top loading, but resonated to 7.2 MHz with a base inductor.
- A 40 m Hamstick mobile whip (about 7.5 feet high), the top section adjusted for resonance at 7.2 MHz.
- A Cushcraft R7000 vertical.

The minimum conceivable ground system for a vertical would be a single ground stake with a coaxial feed line back to the shack. In this case, the feed line acts as a

single random length radial. For these measurements I adopted this as the "zero radial" system, where the stake was a 4 foot copper-clad steel rod with $\frac{1}{2}$ inch Andrews Heliac, buried 6 inches below the ground surface, back to the shack. The ground system was improved progressively by adding 33 foot (no. 18 AWG) radials in the progression: 0, 4, 8, 16, 32 and 64. This was repeated for each antenna. A $\frac{1}{4} \lambda$ in free space is close to 33 feet at 7.2 MHz. As was shown in Part 2, however, the *electrical* length of the radials changes when the radials are placed close to the soil.⁵

The soil characteristics under the radial system were measured using the technique given in *QEX*.⁶ The average soil constants in the test field were: conductivity, $\sigma = 0.02$ S/m and relative dielectric constant, $\epsilon_r = 30$. I will refer to this as "N6LF soil."

For each number of radials and each antenna, two measurements were made: the input impedance and the relative signal strength at a point 1.8 wavelengths away from the test antenna, at an elevation angle of about 8 degrees. Because the number of radials affected the resonant frequency, each antenna was re-resonated by adjusting its height as the number of radials was changed.

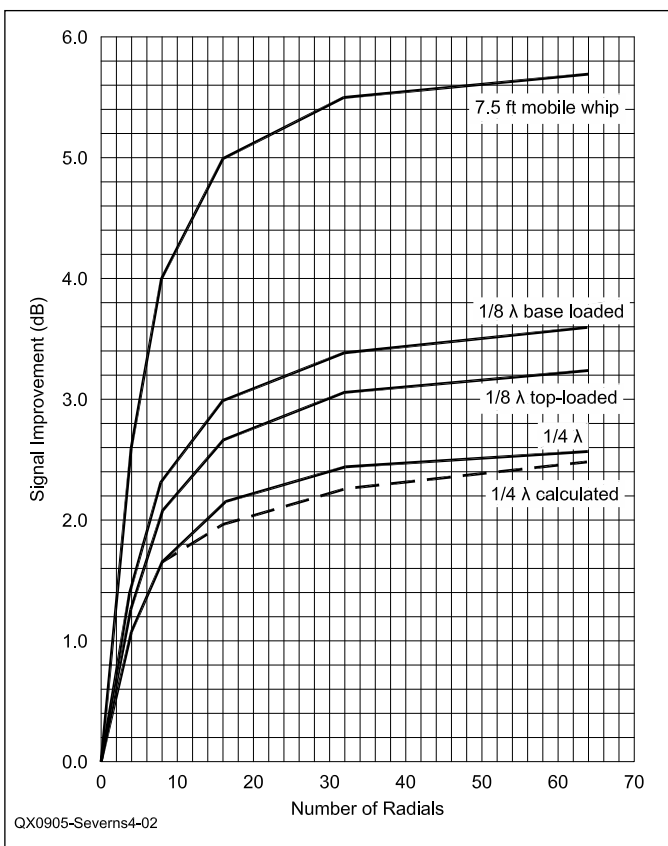


Figure 2 — Typical improvement in signal as $\frac{1}{4} \lambda$ radials are added to the basic ground system (a single ground stake).

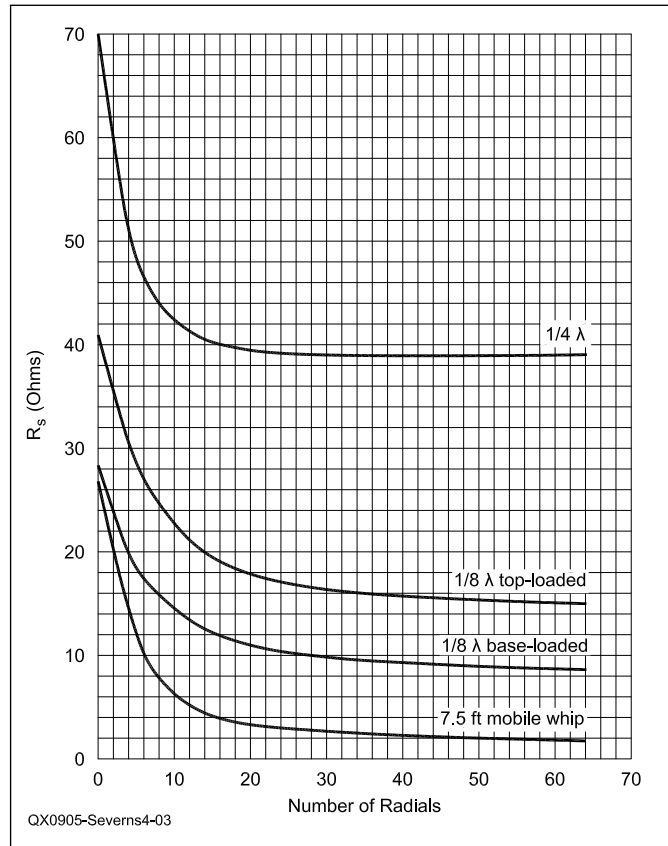


Figure 3 — Measured input resistance (R_s) at resonance as a function of the number of radials.

Experimental Results

When we compare the results for different numbers of radials on a given antenna, the change in relative signal strength directly answers the question of how much signal improvement we get by adding radials. Typical test results are shown in Figure 2.

Note that the graph is in terms of the *improvement* in signal over the single ground stake with no radials for *each* antenna. The graph does *not* compare the relative worth between each antenna. Obviously a short, lossy mobile whip will yield much less signal (-10 dB or worse!) than the $\frac{1}{4} \lambda$ vertical.

The effect of radial number on input resistance (R_s) is shown in Figure 3.

In the case of the Hamstick mobile whip, I have subtracted R_I from the measured input resistance because it has a fixed value independent of radial number. R_I is determined by the loading coil Q . We can see that as we add larger numbers of radials the values for R_s begin to level out and approximate, but not equal, values for ideal lossless antennas.

Interpreting the Data

One of the interesting things about Figure 2 is that it shows that *the shorter and more heavily loaded the antenna, the more you have to "gain" from an aggressive ground system*. For example, the improvement for the $\frac{1}{4} \lambda$ vertical, going from 0 to 64 radials, is about 2.6 dB, but for the $\frac{1}{8} \lambda$ base loaded vertical it's more like 3.4 dB, and for the mobile whip, nearly 6 dB.

What's going on here? As I pointed out in my July 2000 *QST* article on ground systems, when we shorten an antenna but keep the input power the same, both the magnetic and electric field intensities in the immediate vicinity of the antenna increase dramatically.⁷ This translates to much higher ground losses. What we see in Figure 2 is that adding the radial system reduces these losses, but since the losses are higher to start with for the shorter antennas, the improvement is greater. No mystery!

From Figure 2 we can see that for all the test antennas, most of the improvement comes with the first 16 radials. As we add more radials beyond 16, there is still improvement but it is proportionately smaller. You gain perhaps another fraction of a dB going to 32 radials but by the time you reach 64 radials there isn't much change. The broadcast standard of 120 radials 0.4λ long is hard to justify for amateur use, particularly given the present price of copper wire!

Figure 2 also has a dashed line very close to the curve for the $\frac{1}{4} \lambda$ vertical. This is a prediction using Abbott's calculation method.⁸ I could have also added calculated lines for the other antennas and would have seen the same

reasonable correlation, but that would have really cluttered the graph so I left them off.

We do have to be a little careful in using these graphs as general guides. They represent experimental results over my particular soil, at one frequency. Can we really draw any general conclusions? In lieu of running tests on all possible soils, we can get a feeling for this by calculating the signal improvement for different soils using Abbott's calculation method. (See Note 8.) Typical calculated results for different soils, at 7.2 MHz, are shown in Figure 4. This graph starts at 8 radials and goes to 64 radials. Smaller numbers of radials are omitted because the underlying calculation becomes inaccurate as the angle between the radials increases beyond 45° , the 8 radial case. From a practical point of view this is not a serious limitation. As I pointed out in Part 2 in the Jan/Feb 2009 issue of *QEX* (see Note 5), and as the data in Figure 2 shows, a four-radial ground system has very minimal performance; 8, or better yet 16 radials, should be the minimum, except perhaps in an emergency.

For the soil over which these tests were done (N6LF), the calculated 8 to 64 radial change is about 0.8 dB. Going back to Figure 2 we see that the measured change for the $\frac{1}{4} \lambda$ vertical is 0.9 dB (8 to 64 radials). The calculation agrees quite well with the measurements. Figure 4 tells us that when the soil is better, a given number of radials gives somewhat less improvement and with poorer soils there is more improvement. Again, no surprise. If you have better soil, you have lower losses to start with, so the improvement will be less. But even with very good soil it's

still worthwhile to use at least 16 radials.

What about frequencies other than 40 m? There are a couple of complications to extending the 40 m work to another band. First, the graph in Figure 4 does not scale directly with frequency because the field intensity at a given distance (feet or meters), for a given base current, does *not* scale linearly with frequency. Second, at a given site the ground characteristics will vary with frequency. (See Note 6) The result is that the ground loss is not the same for the scaled antennas at other frequencies, even though the input power may be similar.

As we go down in frequency, soil conductivity typically decreases, which tends to increase ground loss but the relative dielectric constant goes up, which tends to decrease ground loss. For N6LF soil at 7.2 MHz, $\sigma = 0.020$ S/m and $\epsilon_r = 30$, but at 1.8 MHz, $\sigma = 0.013$ S/m and $\epsilon_r = 68$. The net effect on signal improvement (8 to 64 radials) is shown in Figure 5.

If you examine Figures 2 and 3 closely and compare the curves for the $\frac{1}{4} \lambda$ vertical, you may see something funny going on. In Figure 2, even when we go from 32 to 64 radials, there is still some improvement in signal. But if you look at Figure 3, there appears to be no change in R_s , so how can the antenna be more efficient? This same paradox shows up in the Brown, Lewis and Epstein data (see Note 1) taken 70 years ago, and has been the subject of comment ever since. What's going on? Several things are going on simultaneously. First, the number of radials is increasing, which reduces R_g . Second, we are steadily increasing the height

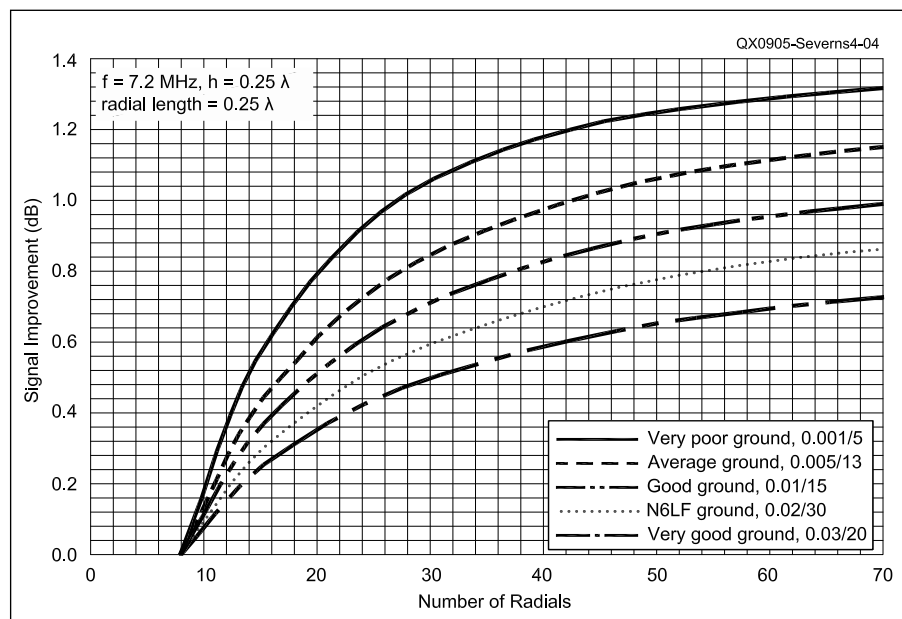


Figure 4 — Calculated signal improvement as we vary the number of radials over different soils with a $\frac{1}{4} \lambda$ vertical with $\frac{1}{4} \lambda$ radials at 7.2 MHz. Note: 0 dB is for the 8 radial case.

of the antenna to re-resonate it due to the effect of the radials on the ground, which we will look at shortly. This tends to raise R_s . In the case of the measurements for the $\frac{1}{4} \lambda$ antenna, the two effects cancel to some extent. Notice that for the other antennas, R_s is still trending down as signal strength goes up with number of radials. Altering the height as we add radials is not the full story, however, R_r is also affected by the radial system. (See Note 4.)

Additional Tests

In addition to the tests where antenna height and number of $\frac{1}{4} \lambda$ radials were the variables, I ran a few others. In one, I compared the performance of the $\frac{1}{8} \lambda$ top-loaded vertical with 64 radials, with and without, an $\frac{1}{8} \lambda$ circular ground screen (diameter = 36 feet) added over the radial fan. The addition of the ground screen made no detectable difference, which is in line with previous work. See Note 1. Obviously, if you have only a few radials, then a ground screen would help.

Modeling of gain versus radial number and radial length indicates that a larger number of shorter radials may be just as good or better than fewer longer radials, assuming both radial systems use the same amount of wire.⁹ To check this out I ran a test using the top-loaded $\frac{1}{8} \lambda$ vertical, comparing sixteen $\frac{1}{4} \lambda$ (33 ft) radials versus thirty two $\frac{1}{8} \lambda$ (17 ft) radials. In line with the modeling and also calculations, the signal strengths were almost the same. The feed point impedances were substantially different however. I had to lengthen the vertical to re-resonate it with the 32 short radials. This is a good example of the interaction between the feed point impedance and the radial system. If space is restricted, then more short radials in place of fewer long radials may work just fine, but to properly evaluate that option it would be best to do the modeling or calculation for a particular vertical and soil characteristics.

I made measurements on the R7000, with and without an external ground system, which showed that adding a 64 radial ground system had almost no effect on signal strength (+0.1 dB). This surprised me until I had an e-mail conversation with Joe Reisert, WIJR, the original designer. The antenna was designed to work without a ground system and although the antenna is physically less than $\frac{1}{4} \lambda$ on 40 m (25 ft), the loading is arranged so that it behaves more like a $\frac{3}{8} \lambda$. There are a set of 48 inch radials at the base, which are isolated from ground. The current maximum is well up into the antenna and the base is a high impedance point. The conventional wisdom, to which I have been a subscriber, is that even with a $\frac{1}{2} \lambda$ vertical, adding an extensive ground system

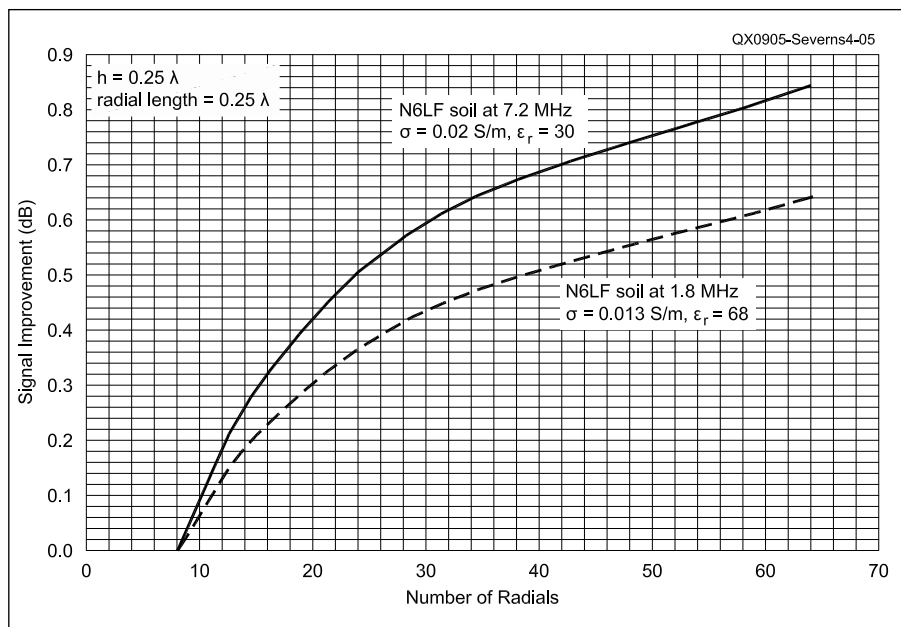


Figure 5 — Difference in signal improvement between 1.8 and 7.2 MHz over N6LF soil using the same vertical height and radial length in wavelengths (scaled with frequency). 0 dB is for the 8 radial case.

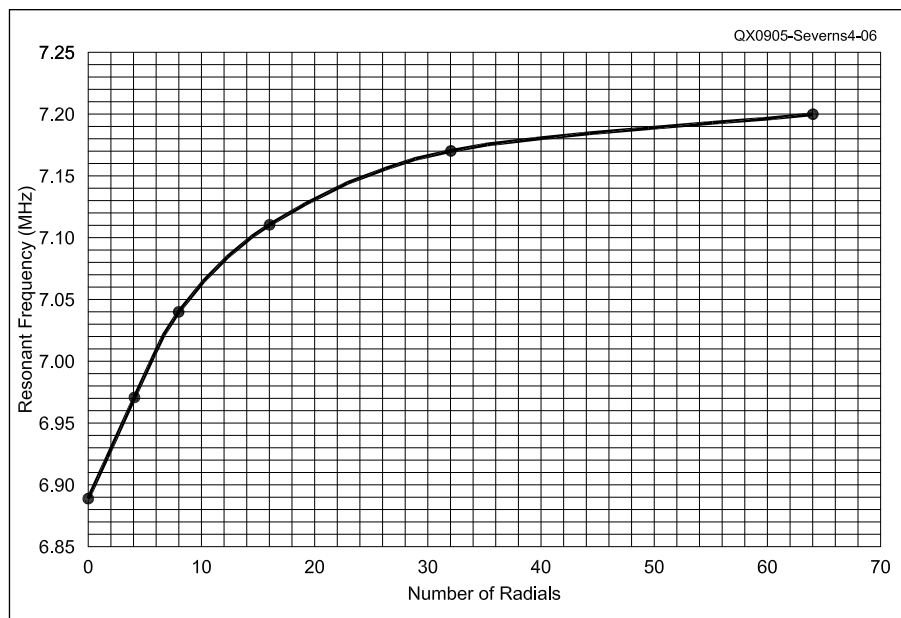


Figure 6 — Resonant frequency of a vertical antenna resonated at 7.2 MHz with sixty four 33 foot radials, as a function of the number of radials.

will improve performance. I did not see that here. This is a subject for more experiments, perhaps.

Measured Resonant Frequency

During the experiments, I found that changing the number of radials changed the resonant frequencies of all the antennas except the R7000. For example, using

the $\frac{1}{4} \lambda$ vertical, I laid down 64 radials and adjusted the height of the vertical so that it was resonant at 7.2 MHz. I then started removing radials (but not changing the height), measuring the resonant frequency as I went down to zero radials. The results are shown in Figure 6.

Obviously the resonant frequency is affected by the radials. You can of course re-

resonate the antenna by changing its height or loading. During the experiments for signal strength and input impedance, I adjusted the height to restore resonance at 7.2 MHz. With 64 radials resonance at 7.2 MHz was obtained with $h = 33$ feet 7 inches. With no radials, the 7.2 MHz resonant height was 32 feet 11 inches, 8 inches shorter.

What's going on? When there are no radials, only the ground stake and the random length of feed line, the resonant frequency is low primarily because the upper portion of the stake effectively adds to the antenna height. Even though the stake is driven into the soil, the top layer of soil, at least in summer when these measurements were made, is quite dry. The effective ground surface is actually somewhat below the physical surface. There was also some inductance in the lead connecting to the ground stake. As we add radials this effect is reduced but only slowly because, as shown in Part 2 (see Note 5), the radials are heavily loaded by their close proximity to the soil. They are resonant below 7.2 MHz so they are inductive at 7.2 MHz. This shunt inductance is across the

base of the antenna. As we add more radials we are adding more inductors in parallel, which reduces the effective reactance and increases the resonant frequency.

Conclusions

The answer to our original question, "Does laying the radials on the surface matter?" is a little clearer now. For the same number of radials of the same length, the efficiency will be pretty much the same whether buried or on the surface, but the effect on feed point impedance may be somewhat different. This can become a practical problem if the antenna tuning varies with the season (wet or dry or frozen ground). Radials lying on the ground surface really behave more like elevated radials even though they may be lying right in the dirt.

We can summarize all this with the following advice:

- Try to use at least sixteen $\frac{1}{4} \lambda$ radials.
- If you don't have the space for $\frac{1}{4} \lambda$ radials, lay down a larger number of shorter ones.
- More than 16 radials will help but give only a fraction of a dB over average or better soils.
- The shorter your antenna, the more you need a good ground system.
- The poorer your soil the more you need a good ground system.
- A surface-radial ground system will affect the resonant frequency and you may have to adjust the vertical height for that.
- Work hard at making the antenna itself more efficient. In other words, use high-Q loading coils, use top loading to minimize the size of loading coils, minimize conductor loss, and so on.
- Modeling and calculations seem to be in reasonable agreement with measurements and, with some caution, can usefully be used to estimate the magnitude of improvement when adding to a ground system.

Acknowledgments

This work was inspired by the classical articles by Jerry Sevick, W2FMI, which have served us so well.^{2, 10, 11, 12, 13} In many ways my experiments are just an update and reconfirmation of Sevick's work.

I want to thank Mark Perrin, N7MQ, for his help in making many of the measurements. Especially helping to drag the monstrously unwieldy chicken wire ground screen into position and out again.

In addition to the references already cited in this article, I have included several more related references, which the reader may find useful. See Notes 14 through 21.

Notes

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