**Rudy Severns, N6LF**

PO Box 589, Cottage Grove, OR 97424; n6lf@arrl.net

# Experimental Determination of Ground System Performance for HF Verticals

## Part 2

## Excessive Loss in Sparse Radial Screens

*These experimental results may surprise you, and might turn "conventional wisdom" upside down.*

In 1998, Jack Belrose, VE2CV, used *NEC* modeling to show the effect of resonant and non-resonant radials placed very close to the ground surface on the behavior of a ¼ wavelength vertical.[1] One of the observations in that article was that the use of a small number of ¼ wavelength (free space) radials, lying on the ground surface, could lead to much higher losses than expected, and that shortening the radials could actually reduce ground loss. This seems counter to more classical analyses which show that making radials too long may be a waste of wire but does no harm. The classic analysis, however, does not take into account the possibility of resonances in the radial screen that might amplify the radial current, increasing ground loss.

The purpose of this experiment was to see if a real antenna would actually demonstrate the predicted behavior, and validate the *NEC* predictions experimentally.

### Description of the Experiment

The experiment was done in six parts spread over a three week period:

1) The antenna for part 1 was a telescoping aluminum-tubing vertical, averaging 1 inch in diameter, with a fixed height of 34 feet. The test frequency was 7.2 MHz. I used four no. 18 insulated wire radials lying on the ground surface. All four radials were of equal length, which was varied from 33 feet down to 18 feet. The impedance at the feed point, the transmission gain (S21) and the current division ratios between the radials were measured and recorded. The antenna and radials were isolated from ground and the feed line with a common mode choke.

2) For part 2, part 1 was repeated, first isolated from ground and then with one or more ground stakes connected, to evaluate the effect of using ground stakes at the base of the antenna. Tests were also done without any radials, and with just 1, 2 or 3 ground stakes connected to the base plate.

3) Part 3 of the experiment was the same as part 1 except with 8 radials (no ground stakes).

4) For part 4, the antenna was changed from the fixed tubing vertical to a remotely adjustable SteppIR vertical. In parts 1, 2 and 3, the antenna height was kept constant at 34 feet, but in this part of the experiment the height was changed to re-resonate the antenna as the radial number and radial lengths were changed. The test frequency was 7.2 MHz.

5) After completing the first four parts of the experiment it was clear that shortening the radials from the standard free space ¼ wavelength value did indeed improve the signal, at least in the case of 4 and 8 radials, so I wanted to see what the effect was for 16 and 32 radials. Trimming that many radials to gradually shorten them, however, was a bit more work and wasted wire than I was prepared for. Instead, I ran this part of the experiment first with 4, 8, 16 and 32, thirty-three foot radials, which I had on hand, and then with 4 ,8, 16 and 32, twenty-one foot radials, which were also on hand. This gave me two data points for each number of radials. Again, the test frequency was 7.2 MHz, with measurements of S21 and feed-point impedance.

6) Part 6 of the experiment was a check to see if the same kind of improvement would be seen at 30, 20 and 15 m by shortening the radials from ¼ wavelength (free space). This part of the experiment was not nearly as thorough as the first five parts but did confirm that the same basic behavior was present at the higher frequencies as that seen on 40 m. The test frequencies were 10.120 MHz, 14.200 MHz and 21.200 MHz.

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[1] Notes appear on page 52.

## Experimental Results

### Part 1

Figure 1 shows the variation in |S21| (magnitude of the transmission gain) as a function of radial length. The amplitude scale is normalized to 0 dB for a radial length of 33 feet, which is approximately a ¼ wavelength in free space at 7.2 MHz. The Y-axis shows the improvement in dB as the radials are shortened.

The improvement is quite large, about 2.8 dB, which would have a noticeable effect on signal strength. In Belrose's paper the improvement was about 3.5 dB but that was for average soil. My average ground characteristics are *approximately* $\sigma = 0.015$ S/m and $\varepsilon_r = 30$, which is quite a bit better than average ground. These values were derived from ground probe measurements.[2] One would expect more improvement for poorer soil.

An earlier experiment in which the current distribution on a 33 foot radial, at 7.2 MHz, was measured, gave the results shown in Figure 2.

A quick check was made during the present experiment, and the current distribution appeared to be essentially the same. From the current distribution we can see that the radial in Figure 2 is resonant well below 7.2 MHz. To move the current maxima back to the base of the vertical we would have to reduce the radial length by about 10 feet. Looking back at Figure 1, we see that we are very close to the maximum |S21| when the length has been reduced by 10 feet to 23 feet. What appears to be happening is that we are tuning the radials to resonance (or at least close to it) at 7.2 MHz to compensate for the loading effect of the soil in close proximity to the radial wire.

The division of current between the radials was measured for 18 foot and 33 foot lengths. Table 1 shows the results. The current division was quite uniform and the differences too small to have significant effect on the observed gain changes.

**Table 1**
**Current Division Between Radials Normalized to 1 A of Total Base Current.**

| *Radial Number* | *$I_n$, 33-Foot Radials (A)* | *$I_n$, 18-Foot Radials (A)* |
|---|---|---|
| 1 | 0.24 | 0.26 |
| 2 | 0.24 | 0.25 |
| 3 | 0.25 | 0.25 |
| 4 | 0.27 | 0.24 |

**Table 2**
**Measured Feed Point Impedances**

| *Radial length (ft)* | *Feed Point Impedance (Ω)* |
|---|---|
| 33 | 135 + *j* 28 |
| 30 | 108 + *j* 55 |
| 27 | 83 + *j* 51 |
| 24 | 67 + *j* 37 |
| 21 | 60 + *j* 22 |
| 18 | 57 + *j* 8 |

The variation of feed-point impedance as the radial lengths were shortened (with the vertical height constant at 34 feet) is shown in Table 2.

### Parts 2 and 3

Part 1 was done during a week of heavy rain. Parts 2 and 3 were performed 8 days after part 1, when the soil had drained and dried out significantly so the ground characteristics may have changed somewhat.

The next step in the experiment was to expand the radial count from 4 to 8 radials and also to investigate the effect of using grounding stakes (4 foot copper clad steel rods) connected at the base of the antenna. Measurements with 4 and 8 radials were repeated in each run. This run was with a fixed height for the vertical (34 feet). The results are shown in Figure 3.

At all lengths, 8 radials are an improvement over 4. With 8 radials, the amount of improvement with radial shortening is smaller but still useful. We can also see that adding a ground stake in the case of 4 radials also makes a substantial improvement but we should keep in mind that my soil would be classified as "very good" so we would expect ground stakes to be more effective than they would be in poorer soil.

The results for the case of no radials and 1, 2 or 3 ground stakes, normalized to the cases of four 33 foot radials and four 21 foot radials, with no ground stakes, are given in Table 3. Vertical height was constant at 34 feet.

### Part 4

In part 4 I changed to the SteppIR vertical and adjusted the height to re-resonate the vertical for each radial length. The results are shown in Figure 4, which are very similar to the results for constant height given in Figure 3. No ground stakes were employed.

### Part 5

From the earlier test results, I could see that the improvement due to radial shortening decreased as the number of radials increased.

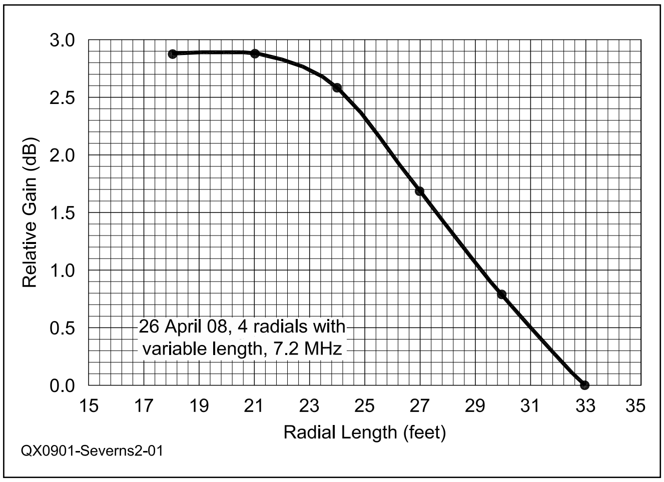

**Figure 1 — This graph shows the improvement in |S21| as the radials were shortened. There were four radials lying on the ground surface.**

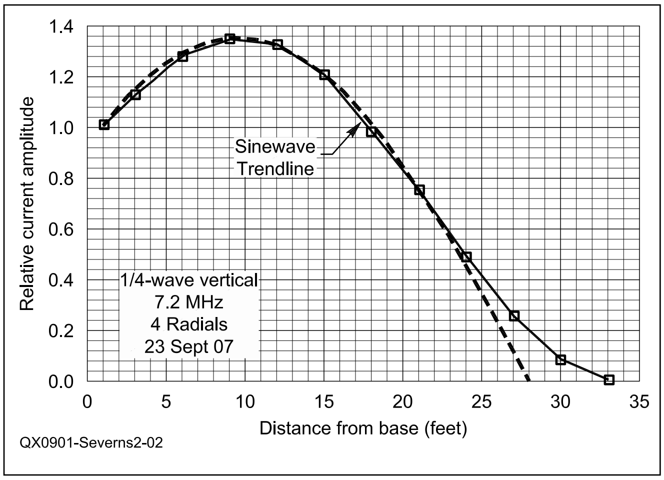

**Figure 2 — This graph shows the relative current amplitude along a radial.**

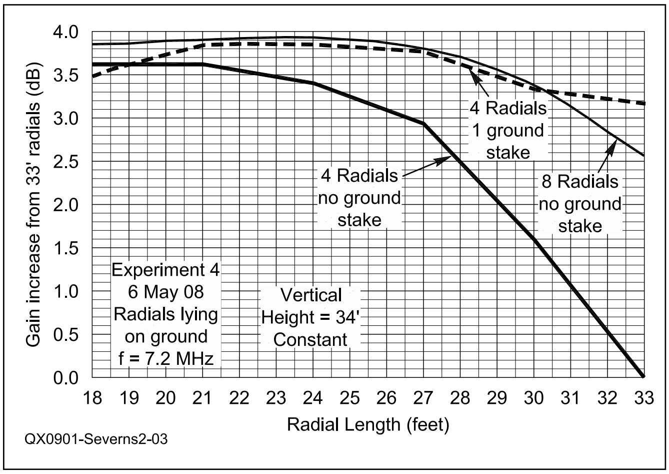

**Figure 3 — This graph shows the change in |S21| with radial length. The vertical antenna height was a constant 34 feet.**

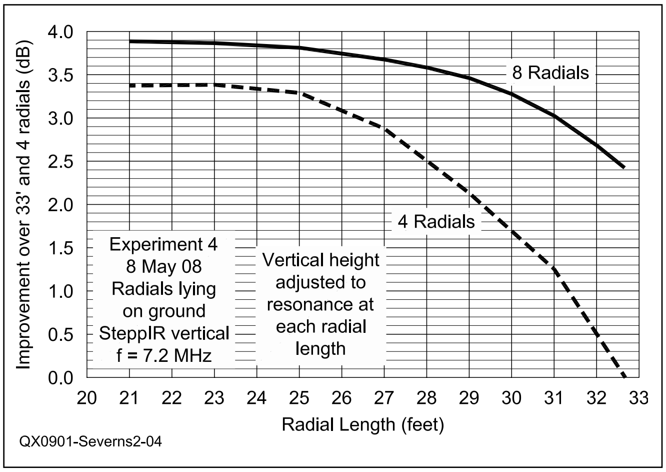

**Figure 4 — This graph shows the change in |S21| with radial length. I adjusted the SteppIR antenna height to resonance for each radial length.**

**Table 3**
**Test Results for no Radials and 1, 2 or 3 Stakes, Compared to 4 Radials with no Ground Stakes.**

| *Number of Stakes* | *Feed Point Z (Ω)* | *Compared to Four 33-Foot Radials, No Ground Stakes (dB)* | *Compared to Four 21-Foot Radials No Ground Stakes (dB)* |
|---|---|---|---|
| 1 | 77 + *j* 40 | 2.67 | –0.95 |
| 2 | 69 + *j* 30 | 3.09 | –0.53 |
| 3 | 66 + *j* 26 | 3.25 | –0.37 |

**Table 4**
**Results for 4, 8, 16 and 32 Radials, with Lengths of 33 Feet and 21 feet.**

| *Number* | *33-Foot Radials Feed Point Impedance (Ω)* | *21-Foot Radials Feed Point Impedance (Ω)* | *33-Foot Radials \|S21\| Relative to Four 33-Foot Radials (dB)* | *21-Foot Radials \|S21\| Relative to Four 33-Foot Radials (dB)* | *Delta Gain Change (dB)* |
|---|---|---|---|---|---|
| 4 | 89.8 | 52.5 | 0 | 3.08 | +3.08 |
| 8 | 51.8 | 45.6 | 2.26 | 3.68 | +1.42 |
| 16 | 40.5 | 42.8 | 3.76 | 3.95 | +0.19 |
| 32 | 37.7 | 41.6 | 4.16 | 4.04 | –0.12 |

In this part of the experiment the number of radials was extended to include 16 and 32 radials to quantify that difference. The test was conducted with sets of 4, 8, 16 and 32 thirty-three foot radials, and then repeated with the same numbers of 21-foot radials. The StepIR antenna was used, and its height was adjusted to re-resonate as the radials were altered. The results are tabulated in Table 4. These measurements were made several days after those used in Figure 4, so there are some differences because of small changes in the ground characteristics, radial layout, and other conditions. These day-to-day variations are a major reason for repeating some parts of earlier experiments multiple times and trying to do a complete experiment in a short period of time (a couple of hours).

It should be noted that a ground system consisting of only four radials is really flaky. Measurements vary significantly with small variations in radial layout, changes in soil moisture, placement of the feed line relative to the radials, and so on. Shortening the radials does seem to reduce this sensitivity, but even so, a four radial system should only be an emergency measure.

As expected, as the number of radials is increased the change due to radial shortening gets much smaller. Over the very good ground on which these measurements were made, shortening the radials gave only a modest advantage when more than 8 radials were used. Over poorer soils, however, radial shortening with 16 radials might be worth doing. The lower value for feed point impedance ($Z_i$) with 33-foot radials is at least in part due to the shorter height needed to resonate. For 21-foot radials the height had to be increased to re-resonate the antenna.

It is interesting to note that with 32 radials, the 33-foot radials were actually slightly better (0.12 dB) than 21-foot radials. Quite probably there was some optimum length in-between that may have been slightly higher than either, but that is not likely to be very large and I decided it wasn't worth the trouble to cut up a set of 32 radials to find out. The important point is that the changes in gain, input impedance and height variation to re-resonate all get much smaller when more radials are used. I would think that with 32 or more radials you wouldn't worry about resonances in the radial screen. The problem is only important when fewer than 16 radials are deployed.

Table 5 shows the antenna height (h) in inches. This is the reading from the control box. The actual height is about 12 inches longer due to the height above ground of the

**Table 5**
**Indicated Height of the Vertical.**

| *Number of Radials* | *33-Foot Radials h (inches)* | *21-Foot Radials h (inches)* |
|---|---|---|
| 4 | 357 | 381 |
| 8 | 366 | 382 |
| 16 | 374 | 382 |
| 32 | 377 | 382 |

reel and the lengths of connecting wires, plus the length of radials from the reel box to ground surface. The columns for h do, however, give an idea of the change in height. In the case of 33-foot radials the change is quite large (20 inches) between 4 and 32 radials. On the other hand with 21-foot radials the change in h with radial number is very small, factions of an inch. The values in the Table are rounded off to the nearest inch.

### Part 6

In the final part of this experiment the effect of radial shortening on 30, 20 and 15 m was examined. This was really just a quick look using radials left over from the earlier parts of the experiment, cut down from them rather than making up a new set of ¼ wavelength (free space) radials for each band. *In all three cases 8 radials were used*. The test frequencies were: 10.120 MHz, 14.200 MHz and 21.200 MHz. The corresponding free space ¼ wavelengths would have been, 24.3 feet, 17. 3 feet and 11.6 feet respectively. The results are shown in Tables 6, 7 and 8. The value for |S21| is the actual measurement.

One oddity in this data was that the best radial length on both 30 and 20 m was the same, about 15 feet. There is some dispersion (variation with frequency) in the soil characteristics but I don't think that's a full explanation. In all cases the optimum length was well short of the free space ¼ wavelength. I think this part of the experiment needs to be rerun cutting down from full length radials. This will be done at some future time.

## *NEC* Modeling

At this point it was clear that Belrose's original work was basically confirmed experimentally, but I was curious to see how closely this data could be replicated using *NEC4-D* modeling software (*EZNEC Pro + MultiNEC*). The first trial model employed 4 radials with lengths from 6.4 m (21 feet) to 10 m (33 feet). The wire table for this model is given in Table 9. The radials were placed 5 mm above 0.01/14 soil. The test frequency was 7.2 MHz and the vertical height was adjusted to maintain resonance as the radial number was changed.

We can compare the maximum gain data against the experimental data for 4 radials (from Figure 4) as shown in Figure 5.

The match in gain data is very good, as was the current distribution on the radials. The impedance data was also close. We can also see what *NEC* predicts about the current distribution on a radial as we change the length. Figure 6 shows the current distribution on a 33-foot radial for *NEC* model 1.

Figure 6 looks very similar to the experimental measurement shown in Figure 2. When we shorten the radials to 21 feet, we get the current distribution shown in Figure 7. This is very close to resonance.

The match in gain and current distribution, however, is really too good to be believed. First of all, this is not an exact model of the real antenna. The vertical uses a strip of beryllium-copper, not a no. 12 wire, and I believe my ground characteristic is better than the 0.01/14 used in the model. Models with wires very close to the ground sur-

**Table 6**
**30 m, ¼ Wavelength Free Space = 24.3 Feet.**

| *Radial Length (ft)* | *$Z_i$ (Ω)* | *\|S21\| (dB)* | *h (in)* |
|---|---|---|---|
| 21 | 44.4 | –62.31 | 260 |
| 20 | 41.6 | –61.12 | 261 |
| 18 | 41.0 | –61.84 | 264 |
| 16 | 42.6 | –61.78 | 267 |

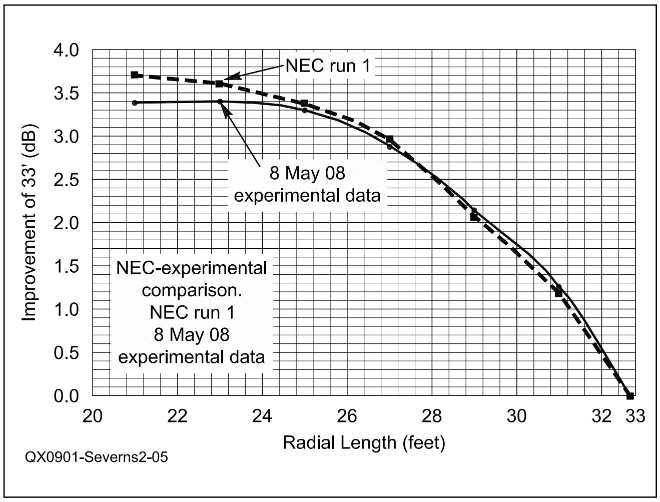

**Figure 5 — Here is a comparison between *NEC* modeling run 1 and the experimental data using 4 radials taken on May 8, 2008.**

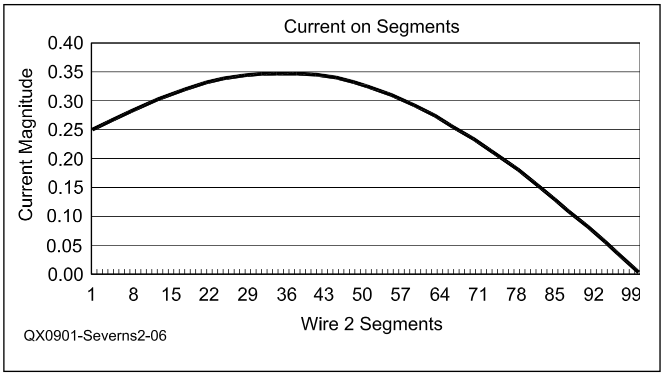

**Figure 6 —This graph shows the current distribution on a 33 foot radial (*NEC* model).**

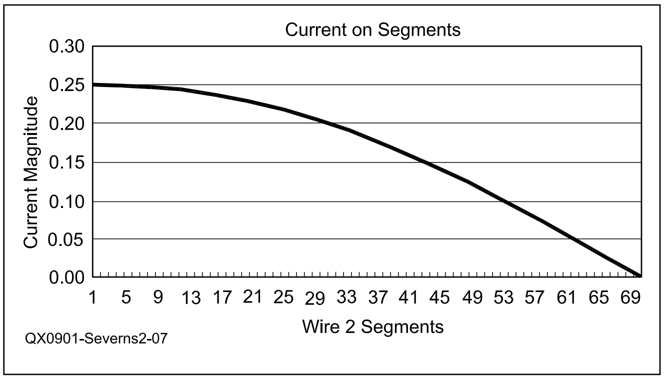

**Figure 7 — Here is the current distribution on a 21 foot radial (*NEC* model).**

**Table 7**
**20 m, ¼ Wavelength Free Space = 17.3 Feet.**

| *Radial Length [ft]* | *$Z_i$ (Ω)* | *\|S21\| (dB)* | *h (in)* |
|---|---|---|---|
| 16 | 37.8 | –62.03 | 178 |
| 15 | 36.0 | –61.84 | 179 |
| 14 | 35.0 | –61.91 | 181 |

**Table 8**
**15 m, ¼ Wavelength Free Space = 11.6 Feet.**

| *Radial Length [ft]* | *$Z_i$ (Ω)* | *\|S21\| (dB)* | *h (in)* |
|---|---|---|---|
| 9 | 27.3 | –60.34 | 60 |
| 8 | 30.0 | –60.29 | 60 |
| 7 | 34.3 | –60.11 | 60 |
| 6 | 41.0 | –60.46 | 60 |

**Table 9**
**Model Wire Table**

| ***End 1*** | | | ***End 2*** | | | ***Diameter*** | ***Segs*** | *Show Lengths in ● m ○ wl* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *X (m)* | *Y (m)* | *Z (m)* | *X (m)* | *Y (m)* | *Z (m)* | *(mm or #)* | *(359)* | *Wire* | *Length* | *Seg Len* |
| *40 m gp 4 rad A* | | | | | | | | | | |
| 0.000 | 0.000 | 0.005 | 0.000 | 0.000 | 10.306 | #12 | 103 | W1 | 10.301 | 0.100 |
| 0.000 | 0.000 | 0.005 | 6.400 | 0.000 | 0.005 | #12 | 64 | W2 | 6.400 | 0.100 |
| 0.000 | 0.000 | 0.005 | 0.000 | 6.400 | 0.005 | #12 | 64 | W3 | 6.400 | 0.100 |
| 0.000 | 0.000 | 0.005 | -6.400 | 0.000 | 0.005 | #12 | 64 | | | |
| 0.000 | 0.000 | 0.005 | 0.000 | –6.400 | 0.005 | #12 | 64 | | | |

**Table 10**
**$Z_i$ and Peak Gain**

| *Freq (MHz)* | *L* | *M* | *R at Src1* | *X at Src1* | *SWR(50 Ω)* | *Max Gain* |
|---|---|---|---|---|---|---|
| 7.200 | 9.056 | 10 | 83.15 | 0.03 | 1.663 | –4.41 |
| 7.200 | 9.275 | 9.45 | 65.72 | 0.01 | 1.314 | –3.22 |
| 7.200 | 9.535 | 8.84 | 54.59 | 0.00 | 1.092 | –2.12 |
| 7.200 | 9.757 | 8.23 | 49.83 | –0.01 | 1.003 | –1.45 |
| 7.200 | 9.955 | 7.62 | 48.23 | –0.02 | 1.037 | –1.04 |
| 7.200 | 10.136 | 7.01 | 48.48 | 0.01 | 1.031 | –0.81 |
| 7.200 | 10.306 | 6.4 | 49.91 | –0.02 | 1.002 | –0.70 |

Where L is the height of the vertical in meters and M is the length of the radials in meters.

face are very sensitive to small changes in the model and wire segmentation. A change in height as small as 1 mm when the wires are at 5 mm above ground, makes a very substantial change in the results. By diddling the model, I can get the kind of match shown in Figure 5, but when I go the other way and attempt to use the model to predict the behavior of the real antenna, the results could be way off. When it comes to wires very close to ground — distances comparable to the wire diameter — *NEC* replicates the general behavior but you do not know enough of the details of the real antenna and it's immediate environment to expect exact quantitative results from the model.

In addition, the characteristics of real soil vary widely even at a fixed location: vertically, horizontally and over time. The soil will very likely have grass (weeds?) over it, which varies in length and water content during the year. We will seldom have more than a general idea what our ground characteristics are even with ground probe measurements. We will also not really know the height above ground to a fraction of mm! The radials will be buried somewhere in the grass, so who knows what the effective height really is.

## Final comments

The effect that showed up initially in Belrose's article and in later *NEC* modeling appears to be real. I think it is clear that in a sparse radial system lying directly on the ground surface, it is possible to incur substantial additional ground losses over what we might expect. The prediction from *NEC* modeling of this effect appears to be confirmed, at least qualitatively. I have been able to reproduce it experimentally multiple times, on multiple bands, with different antennas.

While *NEC* predicts the effect, you can't rely on *NEC* modeling for exact predictions. You will have to do final adjustment in the field. This is not a general indictment of *NEC*. When the antenna has not been right down next to the ground surface, I have found *NEC* predictions to be very good when I went out and built the actual antenna.

We have a couple of ways to attack the problem of radial resonance and excess ground loss: first, cut the radials to be near resonance while lying on the ground. That works if you have the instrumentation, but is hardly a practical approach in general. The second and much more practical approach is to use at least 16, or better yet, 32 radials. As I pointed out earlier, ground systems using only a few radials are a poor idea for many reasons.

## Notes

[1] J. Belrose, VE2CV, "Elevated Radial Wire Systems For Vertically Polarized Ground-Plane Type Antennas, part 1 — Monopoles," *Communications Quarterly*, Winter 1998, pp 29-40.

[2] R. Severns, N6LF, "Measurement of Soil Electrical Parameters at HF," ARRL, *QEX*, Nov/Dec 2006, pp 3-9.