

Vertical antenna ground system experiment No. 4

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In the Winter 1998 Communications Quarterly (pp. 29-40) 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 1/4-wave vertical. One of the observations in that article was that the use of a small number of 1/4-wave (free space) radials, lying on the ground surface, could lead to much higher losses than expected and that shortening the radials could reduce ground loss.

This seems counter to the classical analyses which show that making radials too long may be a waste of wire but does no harm. But then the classic analysis does not take into account the possibility of resonances in the radial screen which 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 from April 26th to May 15th, 2008:

1) The antenna for part 1 was a telescoping aluminum tube vertical, averaging 1" in diameter, with a fixed height of 34'. The test frequency was 7.2 MHz. Four #18 insulated wire radials lying on the ground surface were employed. All four radials were of equal length, which was varied from 33' down to 18'. 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 feedline 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 made without any radials, just 1, 2 or three ground stakes connected to the base plate.

3) 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' 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. S21 and the feed-point impedance were measured at each point.

5) After completing the first four parts of the experiment it was clear that shortening the radials from the standard free space 1/4-wave value did indeed improve the signal, at least in the case of 4 and 8 radials, I wanted to see what the effect was for 16 and 32 radials. However, trimming that many radials to gradually shorten them 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 1/4-wave (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.

Experimental results

Part 1

Figure 1 shows the variation in $|S_{21}|$ (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', which is approximately a 1/4-wave in free space at 7.2 MHz. The Y-axis shows the improvement in dB as the radials are shortened.

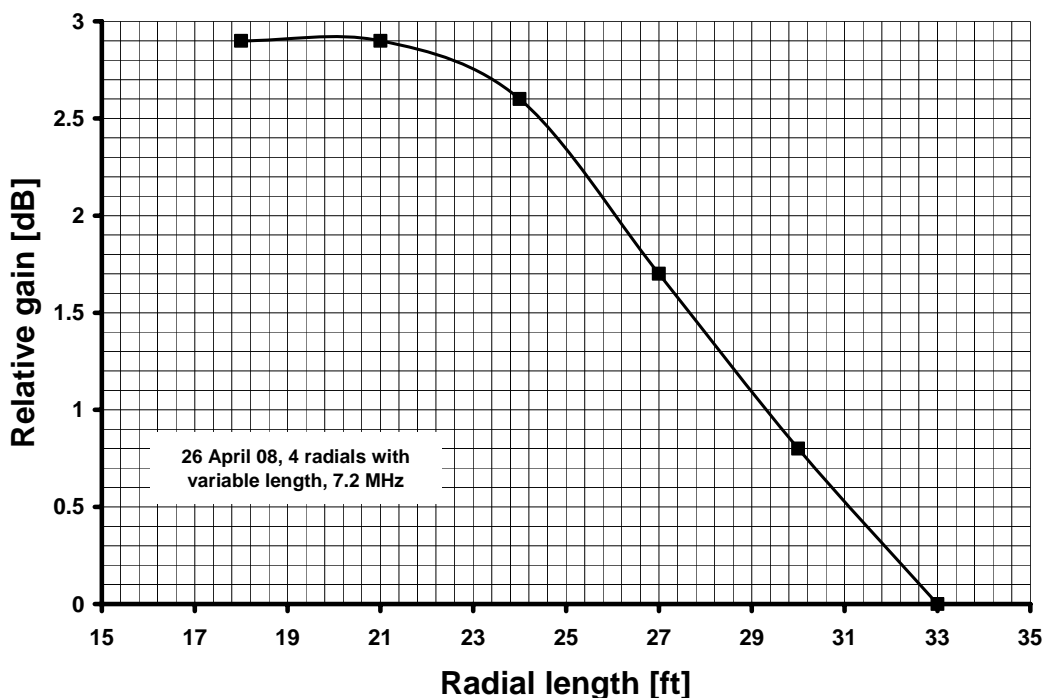


Figure 1, improvement in $|S_{21}|$ as the radials were shortened. 4 radials lying on the ground surface.

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 $\epsilon_r = 30$, which is quite a bit better than average ground. These values were derived from ground probe measurements. One would expect more improvement for poorer soil.

An earlier experiment in which the current distribution on a 33' radial, at 7.2 MHz, was measured gave the result shown in figure 2.

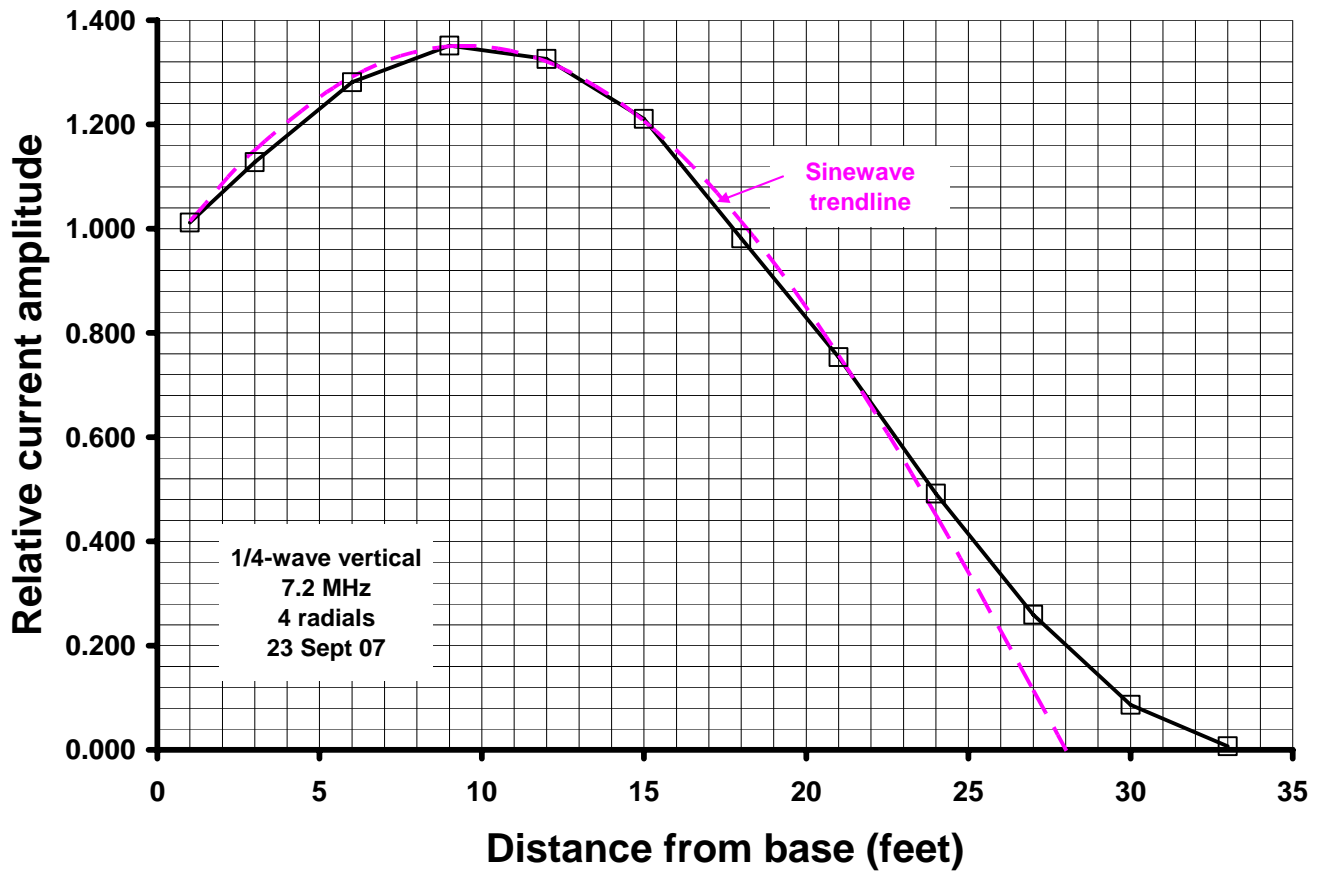


Figure 2, relative current amplitude along a radial.

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'. Looking back at figure 1 we see that we are very close to the maximum $|S_{21}|$ when the length has been reduced by 10' to 23'. 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' and 33' 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 1A of total base current.

radial number	In, 33' radials	In, 18' radials
1	0.24	0.26
2	0.24	0.25
3	0.25	0.25
4	0.27	0.24

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

Table 2, measured feed-point impedances

radial length [ft]	feed-point impedance [Ohm]
33	135 + j 28
30	108 + j 55
27	83 + j 51
24	67 + j 37
21	60 + j 22
18	57 + j 8

Parts 2 and 3

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. Part 1 was done during a week of heavy rain.

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' 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'). The results are shown in figure 3.

At all lengths, 8 radials are a 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 it would be in poorer soil.

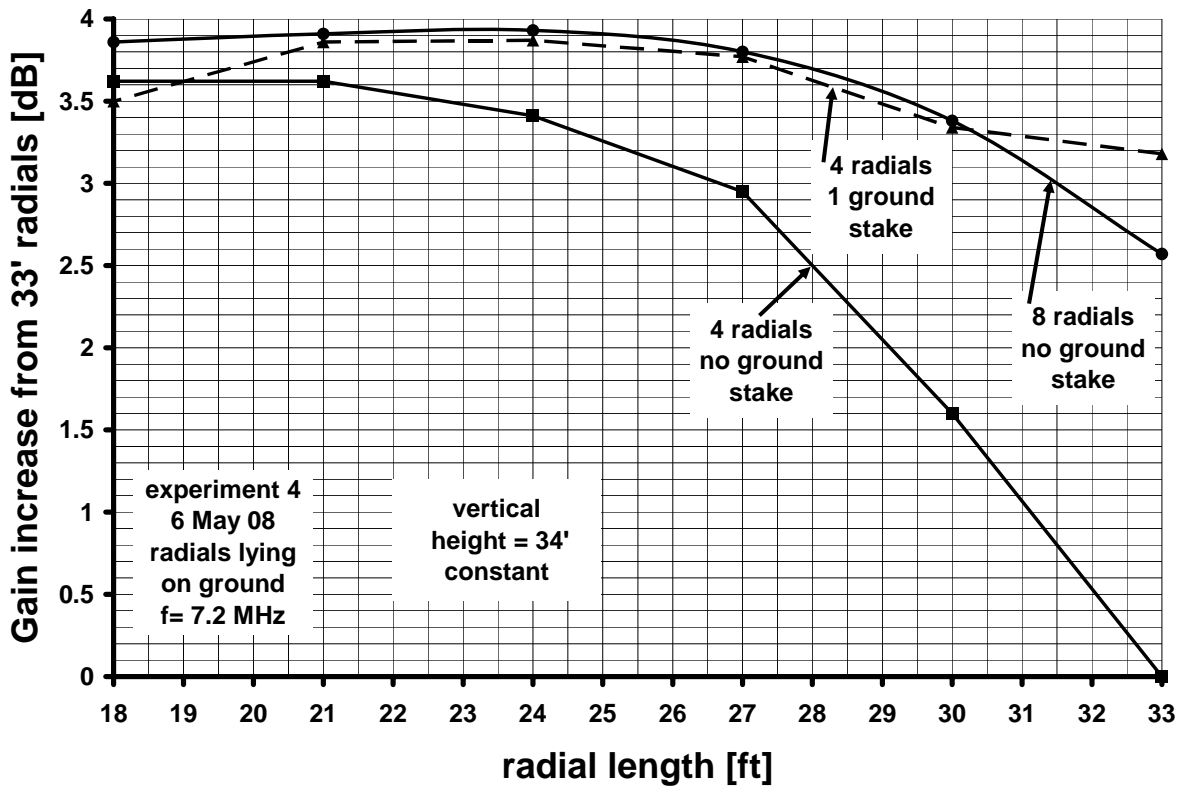


Figure 3, |S21| change with radial length. Vertical height constant at 34'.

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

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 [Ohm]	compared to four 33' radials, no ground stakes [dB]	compared to four 21'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

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.

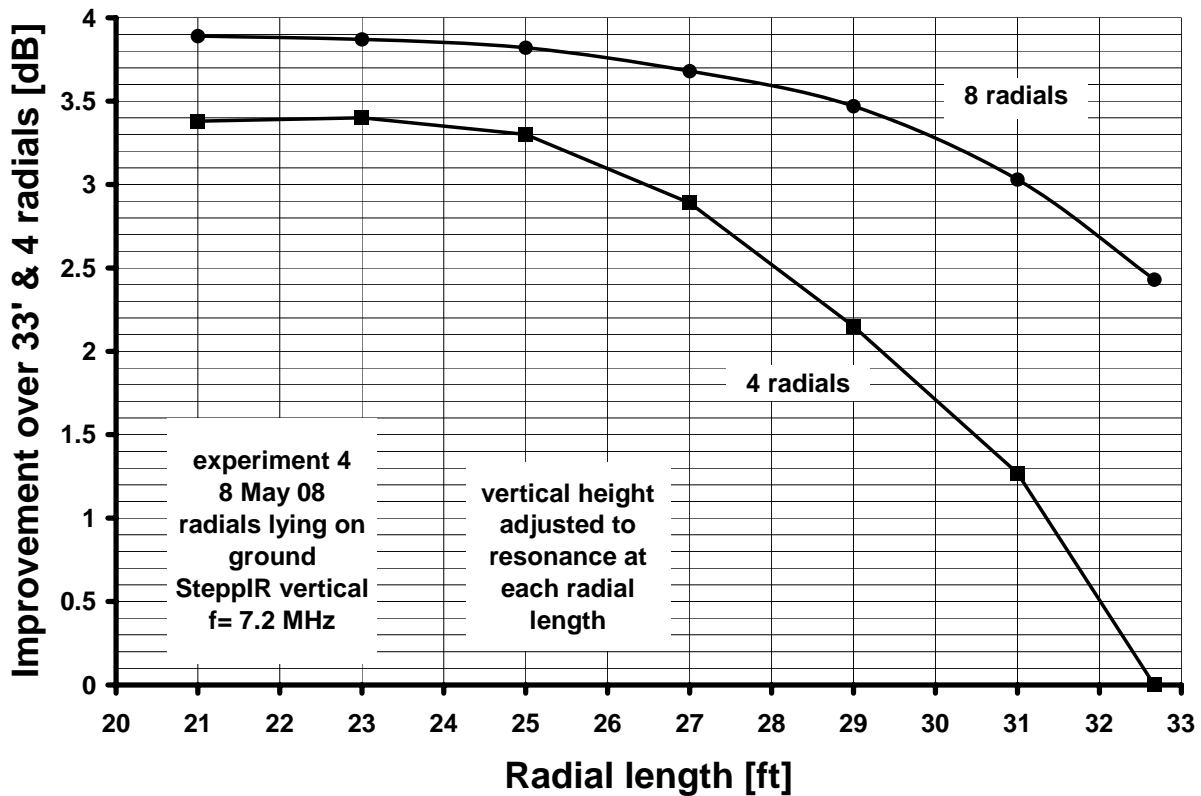


Figure 4, $|S_{21}|$ change with radial length. Height adjusted to resonance for each radial length.

Part 5

From the earlier test results it could be seen that the improvement due to radial shortening decreased as the number of radials increased. 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, 33' radials and then repeated with the same numbers of 21' radials. The SteppIR antenna was used and its height 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 reflecting small changes in ground characteristics, radial layout, etc. 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, etc, etc. Shortening the radials does seem to reduce this sensitivity but even still 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. However, over poorer

soils radial shortening with 16 radials might be worth doing. The lower value for feed-point impedance (Z_i) with 33' radials is at least in part due to the shorter height needed to resonate. For 21' radials the height had to be increased to re-resonate the antenna.

Table 4, Results for 4, 8, 16 and 32 radials, with lengths of 33' and 21'.

	33' radials	21' radials	33' radials	21' radials	
number of radials	feed-point impedance [ohm]	feed-point impedance [Ohm]	S21 relative to 4, 33' radials [dB]	S21 relative to 4, 33' 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

It is interesting to note that with 32 radials, the 33' radials were actually slightly better (0.12 dB) than 21' 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 over average or better soil.

Table 5, indicated height of the vertical.

	33' radials	21' radials
number of radials	h [in]	h [in]
4	357	381
8	366	382
16	374	382
32	377	382

Table 5 shows the antenna height (h) in inches. This is the reading from the control box. The actual height is about 12" longer due to the height above ground of the 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' radials the change is quite large (20") between 4 and 32 radials. On the other hand with 21' radials the change in h with radial number is very small, fractions 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 1/4-wave (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 1/4-wave lengths would have been, 24.3', 17.3' and 11.6' respectively. The results are shown in tables 6, 7 and 8. The value for |S21| is the actual measurement.

Table 6, 30 m, 1/4-wave free space = 24.3'.

Radial length [ft]	Zi [Ohm]	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

Table 7, 20 m, 1/4-wave free space = 17.3'.

Radial length [ft]	Zi [Ohm]	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, 1/4-wave free space = 11.6'.

Radial length [ft]	Zi [Ohm]	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

One oddity in this data was that the best radial length on both 30 and 20 m was the same, about 15'. 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 1/4-wave length. 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

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 6.4m (21') to 10m (33'). 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.

Table 9, model wire table

End 1			End 2			Diameter	Segs	Show lengths in <input checked="" type="radio"/> m <input type="radio"/> wl		
X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)	(mm or #)	(359)	Wire	Length	Seg Len
40m gp 4rad 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, Zi and peak gain

Freq (MHz)	L	M	R at Src1	X at Src1	SWR(50)	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.

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

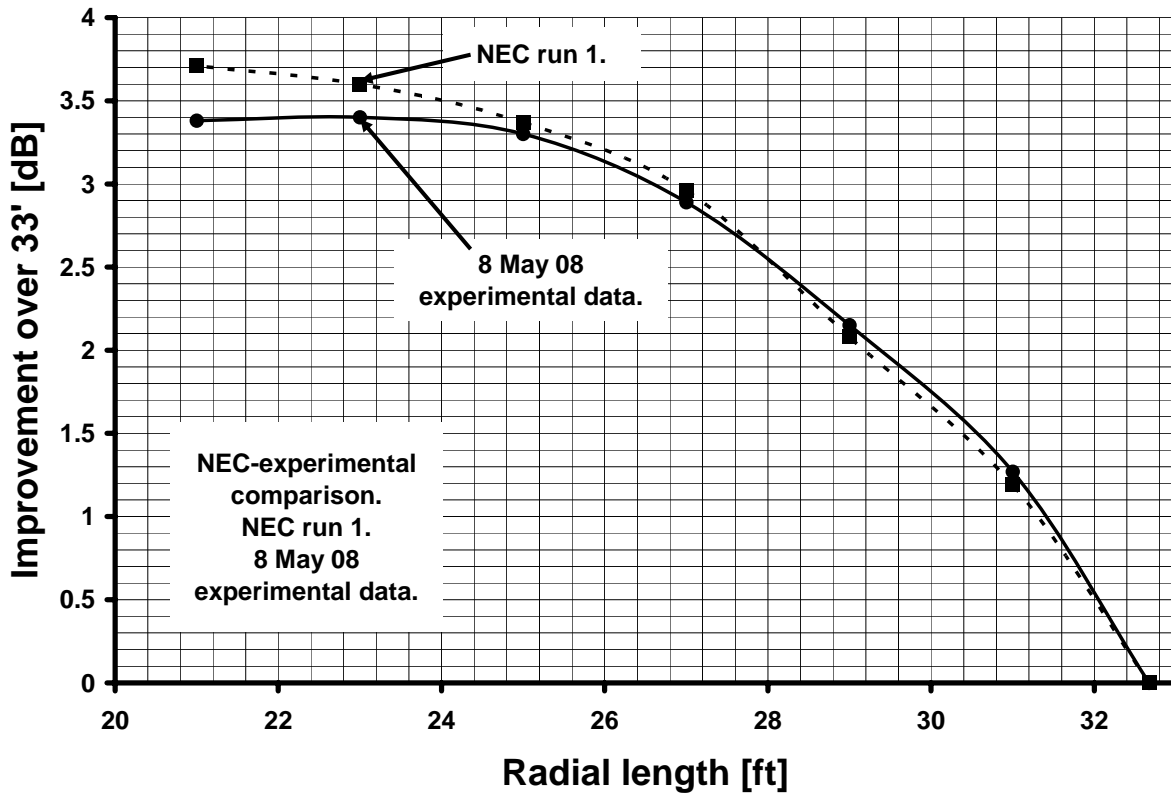


Figure 5, comparison between NEC modeling run 1 and 8 May 08 experimental data using 4 radials.

The match in gain data is very good, as was the current distribution on the radials and the impedance data was close also. 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' radial for NEC model 1.

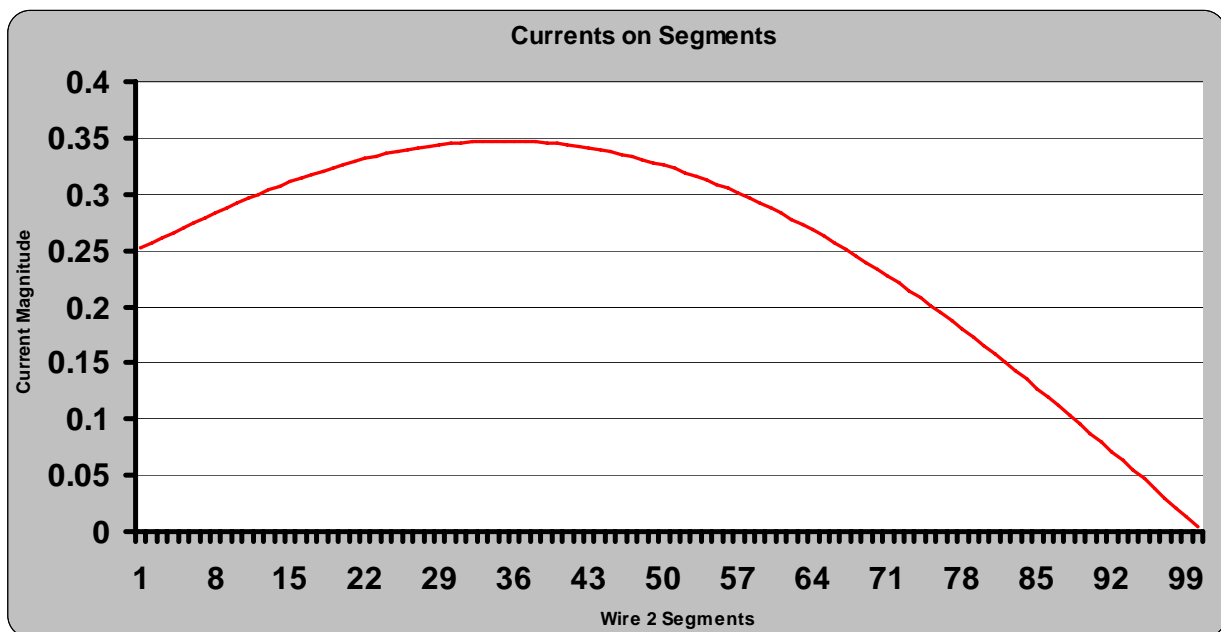


figure 6, current distribution on a 33' radial (NEC model)

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

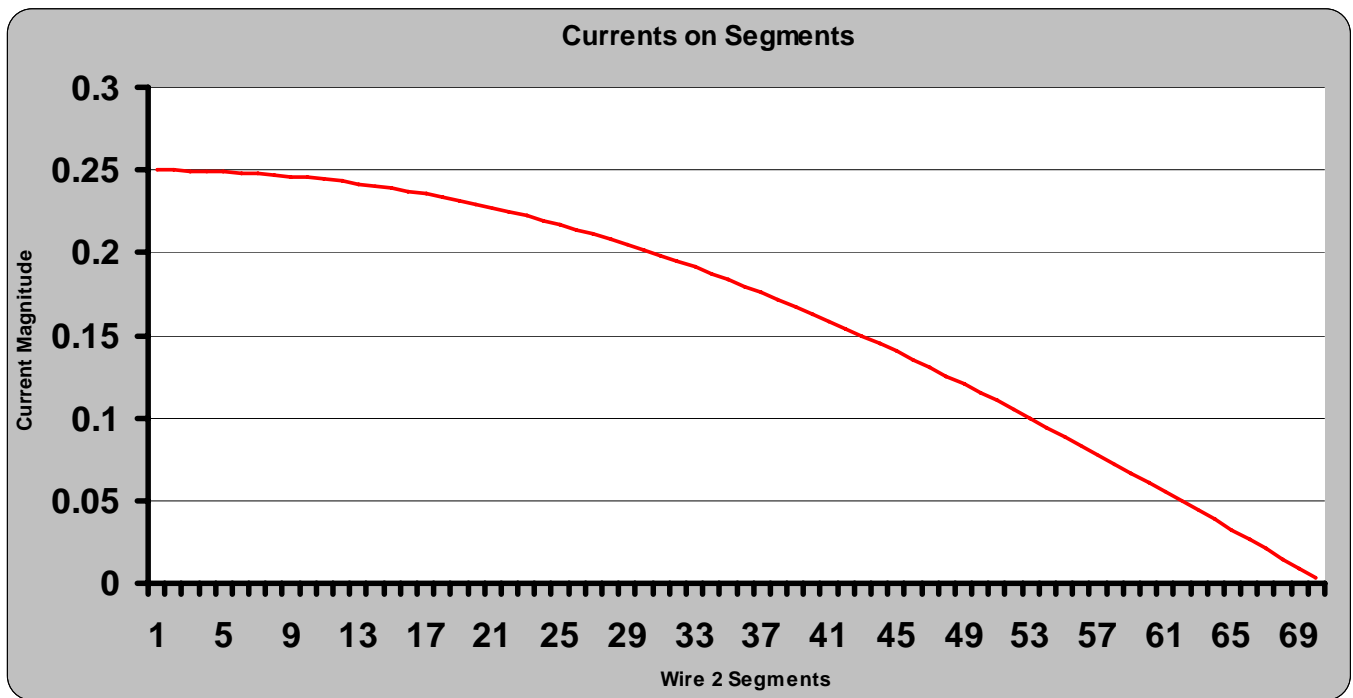


Figure 7, current distribution on a 21' radial (NEC model).

However, the match in gain and current distribution is really too good to be believed. First of all this is not an exact model of the real antenna which for the vertical uses a strip Beryllium-copper not a #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 surface 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 can be way off. When it comes to wires very close to ground 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, who knows what the effective height really is.

Final comments

I think it's clear that for a sparse radial system lying directly on the ground surface, it is possible to incur substantial additional ground losses over what we would expect from calculations valid for more dense radial systems using free space 1/4-wave radial lengths. The prediction from NEC modeling of this effect appears to be confirmed, at least quantitatively. I have been able to reproduce it 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 two ways to attack the problem of radial resonance and excess ground loss: one, cut the radials to be near resonance while lying on the ground or, two, use at least 16 or better yet, 32 radials. As pointed out earlier, ground systems using only four radials are a poor idea.