Maximum-Gain Radial Ground Systems for Vertical Antennas

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Abstract

This article compares the peak gain generated by quarter-wave vertical-monopole antennas when they are installed over a variety of ground systems. All of these ground systems utilize symmetrically-placed radials that are buried to a shallow depth in the soil. Computer analysis indicates that, for a given total length of wire, some configurations yield more gain than others.

Overview

Vertically-polarized antennas are widely used on the lower amateur bands, and the question often arises concerning how to achieve the best performance when a specific amount of wire is available for use as ground radials. Recently, N4UU published a fascinating article[1] that addressed this question from the perspective of minimizing the amount of antenna input power that is dissipated in the soil. I decided to tackle the same issue, but chose instead to maximize the gain of the antenna, since most amateurs are accustomed to comparing antenna performance based upon this parameter. Presumably, both of these methods should yield similar results, as will be discussed later. All three of the low bands (40, 80, and 160 meters) will be investigated, using three different types of soil on each band.

I have access to *EZNEC4*[2], which enables me to analyze ground systems using buried radials. For simplicity, all computer simulations were performed using #12 AWG copper wire for the vertical element, and #16 AWG copper wire (which is available from several sources at a reasonable price) for the radials. The lower end of the vertical element touches the surface of the earth (at z = 0), and its total height is exactly 0.25 wavelengths. No attempt was made to shorten the element in order to achieve resonance. The buried radials all begin at the base of the vertical element (zero height) and the inner segment of each radial slopes downward so that its outer end is at the "final" burial depth of three inches. The wire segment-lengths for the vertical element and the radials are all tapered in accordance with the most conservative *EZNEC* guidelines. The shortest segments, such as the one containing the feed-point at the base of the vertical element, and the inner segment of each radial, have a length of about six inches.

[1]Notes appear at end of article.

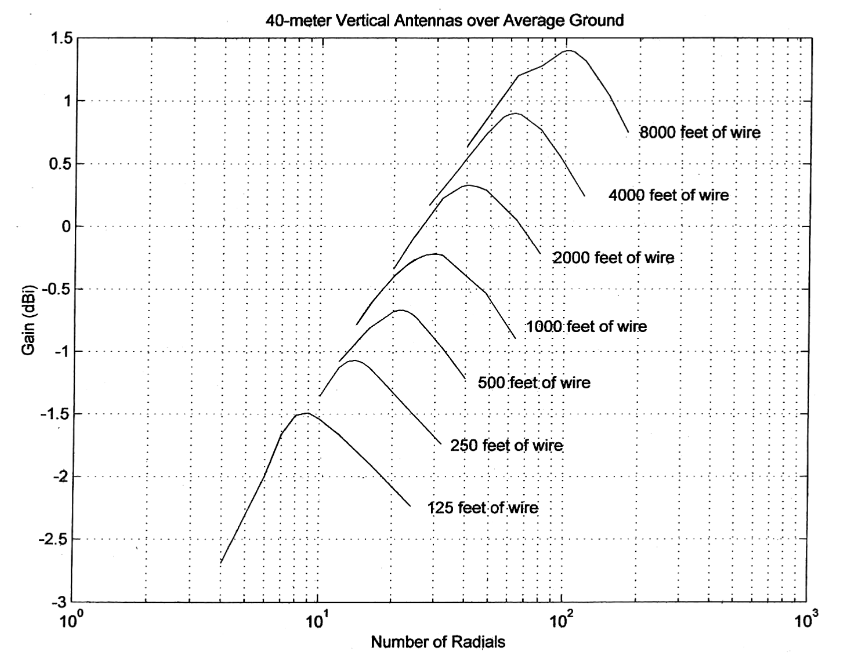

Figure 1—Gain of a quarter-wave 40 meter vertical antenna over average soil, as the number of buried radials is varied, for seven different total lengths of wire.

Table I

Optimum number and length of radials for a vertical antenna on 40 meters (7.15 MHz) operating over average soil (conductivity = 0.005 Siemens/meter and relative permittivity = 13).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
125	9	13.89	-1.49
250	14	17.86	-1.07
500	21 – 22	23.81 – 22.73	-0.67
1000	28 – 31	35.71 – 32.26	-0.22
2000	39 – 43	51.28 – 46.51	0.33
4000	62 – 63	64.52 – 63.49	0.90
8000	100 – 104	80.00 – 76.92	1.40

Table II

Optimum number and length of radials for a vertical antenna on 40 meters (7.15 MHz) operating over very poor soil (conductivity = 0.001 Siemens/meter and relative permittivity = 5).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
125	6	20.83	-2.93
250	10	25.00	-2.21
500	16	31.25	-1.48
1000	25	40.00	-0.74
2000	34 – 36	58.82 – 55.56	0.11
4000	56 – 58	71.43 – 68.97	1.02
8000	96 – 100	83.33 – 80.00	1.68

Results on 40 Meters

A frequency of 7.15 MHz was selected for the analysis on 40 meters, leading to a height of about 34.39 feet for the vertical element. Seven different total wire-lengths were utilized, ranging from 125 feet (just less than one wavelength of wire) to 8000 feet (more than 58 WL). In each case, the number of radials was varied in an effort to maximize the gain of the antenna. Figure 1 displays the results graphically, for the situation where the radials are buried in "average soil" with a conductivity of 0.005 Siemens/meter and a dielectric constant of 13. Notice that the optimum number of radials climbs steadily as the total length of available wire increases. A logarithmic scale was utilized for N (the number of radials) on the x-axis, because this parameter ranges over several orders of magnitude. Unfortunately, the log scale makes it difficult to discern the exact value of N that yields maximum gain.

Table I presents the same information in a different format, and only the optimal values of N are listed. EZNEC supplies the gain data to the nearest 0.01 dBi, so it's possible that two (or more) radial configurations will sometimes yield exactly the same peak gain. For example, with a total of 8000 feet of wire in the ground system, the "best" number of radials is anywhere from 100 (each 80 feet long) to 104 (each 76.92 feet long). In this case there are five different "best" combinations of radial length and number of radials, all of which will generate a peak gain of 1.40 dBi. The ham with plenty of land could install 100 of the 80-foot radials, while the operator who is more cramped for space might prefer to use 104 of the shorter 76.92-foot radials. For the sake of simplicity, N = 102 (which is the average value) could be selected.

Table II shows the results for the same quarter-wave 40-meter vertical when the soil is "very poor," with a conductivity of 0.001 Siemens/meter and a dielectric constant of 5. If the soil is "very good," (conductivity = 0.0303 Siemens/meter and dielectric constant = 20), then the outcome will be as listed in Table III. Typically, for a given total length of wire, fewer (but longer) radials are needed in poor soil, while more (but shorter) radials provide the highest gain in good soil. This agrees with N4UU's findings. As he stated, "more closely spaced radials are needed to coax the ground current out of more highly conductive soil and into the radial system[3]."

Results for 80 Meters

On 80 meters a frequency of 3.75 MHz was utilized, so the height of the vertical element is about 65.57 feet. Again, seven different total wire-lengths were utilized, this time ranging from 250 feet (just less than one wavelength of wire) to 16,000 feet (more than 61 WL). As before, the number of radials was varied in an effort to maximize the gain of the antenna. When the radials are buried in average soil, the results are as shown in Figure 2.

Table IV summarizes this data in numerical form, listing only the "best" values for N. Again we see that in many instances it is possible to achieve maximum gain (for a particular total wire length) from several different combinations of radial length and number of radials. Tables V and VI list the outcomes for very poor soil and very good soil, respectively.

Results on 160 Meters

A frequency of 1.835 MHz was selected for the computer simulation on top band, requiring a height of 134 feet for the quarter-wave vertical element. Here the seven different total wire-lengths spanned the range from 500 feet (just less than one wavelength of wire) to 32,000 feet (almost 60 WL). As usual,

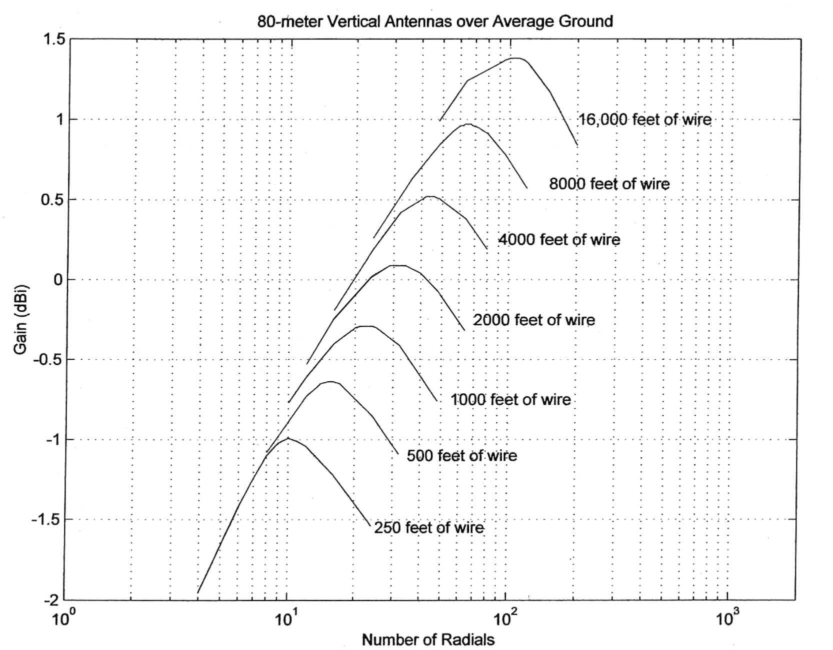

Figure 2 —Gain of a quarter-wave 80 meter vertical antenna over average soil, as the number of buried radials is varied, for seven different total lengths of wire.

Table III

Optimum number and length of radials for a vertical antenna on 40 meters (7.15 MHz) operating over very good soil (conductivity = 0.0303 Siemens/meter and relative permittivity = 20).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
125	12	10.42	0.85
250	17 – 20	14.71 – 12.50	1.04
500	24 – 28	20.83 – 17.86	1.24
1000	37	27.03	1.45
2000	48 – 58	41.67 – 34.48	1.66
4000	68 – 85	58.82 – 47.06	1.88
8000	102 – 127	78.43 – 62.99	2.10

Table IV

Optimum number and length of radials for a vertical antenna on 80 meters (3.75 MHz) operating over average soil (conductivity = 0.005 Siemens/meter and relative permittivity = 13).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
250	10	25.00	-0.99
500	15 – 16	33.33 – 31.25	-0.64
1000	21 – 24	47.62 – 41.67	-0.29
2000	29 - 34	68.97 – 58.82	0.09
4000	42 – 46	95.24 – 86.96	0.52
8000	63 – 67	126.98 – 119.40	0.97
16,000	99 – 111	161.62 – 144.14	1.38

Table V

Optimum number and length of radials for a vertical antenna on 80 meters (3.75 MHz) operating over very poor soil (conductivity = 0.001 Siemens/meter and relative permittivity = 5).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
250	7	35.71	-3.48
500	11	45.45	-2.72
1000	17	58.82	-2.00
2000	24 – 26	83.33 – 76.92	-1.23
4000	35 – 36	114.29 – 111.11	-0.30
8000	57 – 59	140.35 – 135.59	0.59
16,000	98 – 104	163.26 – 153.85	1.29

Table VI

Optimum number and length of radials for a vertical antenna on 80 meters (3.75 MHz) operating over very good soil (conductivity = 0.0303 Siemens/meter and relative permittivity = 20).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
250	14 – 16	17.86 – 15.62	1.70
500	19 – 25	26.32 – 20.00	1.84
1000	29 – 32	34.48 – 31.25	1.99
2000	39 – 50	51.28 – 40.00	2.13
4000	56 – 70	71.43 – 57.14	2.28
8000	80 - 103	100.00 – 77.67	2.43
16,000	119 – 152	134.45 – 105.26	2.58

Table VII

Optimum number and length of radials for a vertical antenna on 160 meters (1.835 MHz) operating over average soil (conductivity = 0.005 Siemens/meter and relative permittivity = 13).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
500	11 – 12	45.45 – 41.67	0.11
1000	17 – 18	58.82 – 55.56	0.38
2000	23 – 28	86.96 – 71.43	0.63
4000	32 – 40	125.00 – 100.00	0.89
8000	45 – 55	177.78 – 145.45	1.17
16,000	76	210.53	1.48
32,000	99 – 122	323.23 – 262.30	1.75

Table VIII

Optimum number and length of radials for a vertical antenna on 160 meters (1.835 MHz) operating over very poor soil (conductivity = 0.001 Siemens/meter and relative permittivity = 5).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
500	7 – 8	71.43 – 62.50	-3.13
1000	12	83.33	-2.47
2000	18	111.11	-1.87
4000	25 – 26	160.00 – 153.85	-1.24
8000	35 – 36	228.57 – 222.22	-0.49
16,000	55 – 59	290.91 – 271.19	0.27
32,000	96 – 100	333.33 – 320.00	0.93

the number of radials was varied in an effort to maximize the gain of the antenna. Figure 3 displays the results when the radials are buried in average soil.

Table VII summarizes the same information. As we have come to expect, there is often more than one "best" number of radials to achieve maximum gain, when the total length of wire is fixed. Interestingly, when the total length of wire is 16,000 feet, N = 76, so there is only one "optimum" number of radials in this case. Tables VIII and IX give the results for top-band verticals used in environments with very poor soil and very good soil, respectively.

Comparing All Three Bands

Table X lists the "best" number of radials to maximize the gain, for each specific total wire length, on all three bands, in average soil. For a given total length of wire, fewer (but longer) radials are needed as we go lower in frequency. Since the wavelength is greater at lower frequencies, the physical height of the quarter-wave vertical-monopole (radiator) also increases as we switch from 40 to 80 to 160 meters. As a result, the displacement currents leaving the vertical element intersect the earth farther from the base of the antenna, and longer radials are needed in order to collect this current. Figure 4 displays the same data in graphical form. Whenever the computer analysis showed that several different values of N would provide the same peak gain, I calculated the average value and used that number for the plot.

The results for very poor soil are displayed in Table XI and Figure 5, while Table XII and Figure 6 illustrate the outcome for very good soil. Figures 4 to 6 may be helpful for those who want to determine the best number of radials to install in those

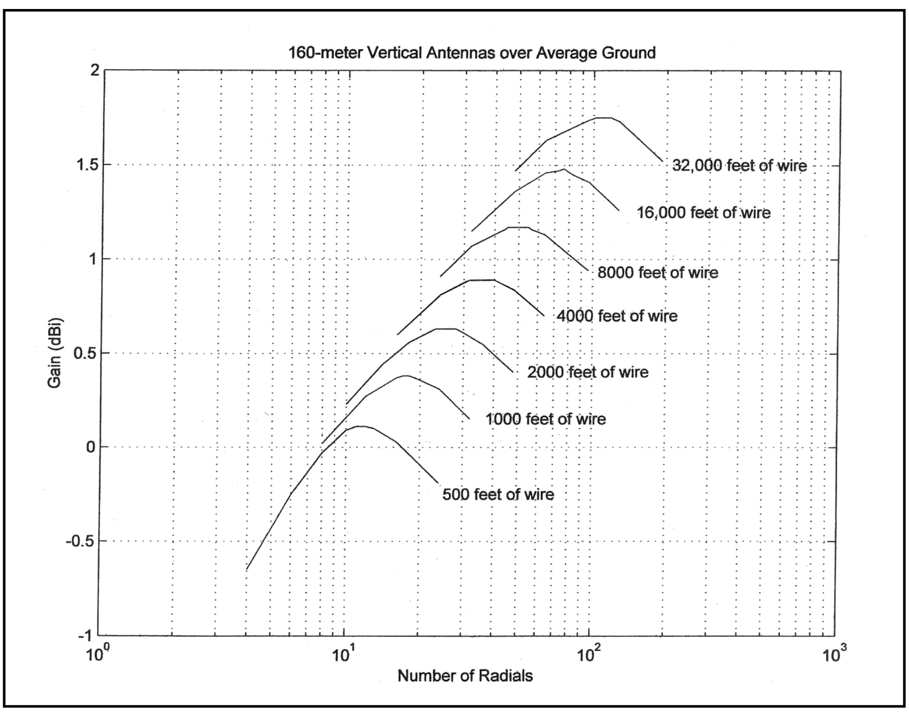

Figure 3—Gain of a quarter-wave 160 meter vertical antenna over average soil, as the number of buried radials is varied, for seven different total lengths of wire.

Table IX

Optimum number and length of radials for a vertical antenna on 160 meters (1.835 MHz) operating over very good soil (conductivity = 0.0303 Siemens/meter and relative permittivity = 20).

Total Wire Length (ft)	*Optimum Number of Radials*	*Optimum Length of Radials (ft)*	*Peak Gain (dBi)*
500	17 – 21	29.41 – 23.81	2.53
1000	23 – 30	43.48 – 33.33	2.63
2000	33 – 42	60.61 – 47.62	2.73
4000	47 – 59	85.11 – 67.80	2.83
8000	67 – 83	119.40 – 96.39	2.93
16,000	93 – 122	172.04 – 131.15	3.03
32,000	136 – 181	235.29 – 176.80	3.13

Table X

Optimum number of radials versus total wire length, for all three bands, in average soil.

Total Wire Length (ft)	*Optimum number of radials for each band 40 meters*	*80 meters*	*160 meters*
125	9		
250	14	10	
500	21 – 22	15 – 16	11 - 12
1000	28 – 31	21 – 24	17 - 18
2000	39 - 43	29 – 34	23 - 28
4000	62 – 63	42 – 46	32 - 40
8000	100 - 104	63 – 67	45 - 55
16,000		99 – 111	76
32,000			99 - 122

Table XI

Optimum number of radials versus total wire length, for all three bands, in very poor soil.

Total Wire Length (ft)	*Optimum number of radials for each band 40 meters*	*80 meters*	*160 meters*
125	6		
250	10	7	
500	16	11	7 - 8
1000	25	17	12
2000	34 – 36	24 – 26	18
4000	56 – 58	35 – 36	25 – 26
8000	96 – 100	57 – 59	35 – 36
16,000		98 – 104	55 – 59
32,000			96 – 100

Table XII

Optimum number of radials versus total wire length, for all three bands, in very good soil.

Total Wire Length (ft)	*Optimum number of radials for each band 40 meters*	*80 meters*	*160 meters*
125	12		
250	17 – 20	14 – 16	
500	24 – 28	19 – 25	17 – 21
1000	37	29 – 32	23 – 30
2000	48 – 58	39 – 50	33 – 42
4000	68 – 85	56 – 70	47 – 59
8000	102 – 127	80 – 103	67 – 83
16,000		119 – 152	93 – 122
32,000			136 – 181

cases where the total length of available wire is different from the seven choices I selected. A cubic spline interpolation was used when plotting these three figures, to make the curves as smooth as possible, and to improve their accuracy between the calculated data points.

A Surprise

An AM-broadcast station typically utilizes a ground-system composed of 120 quarter-wave radials per tower, or a total wire length of 30 WL for a single element. In other words, we assume that N = 120 is optimum when the total wire length is 30 WL. Let's examine our results and see if this same strategy is effective on the amateur bands. On 40 meters (7.15 MHz), 30 WL is about 4100 feet of wire, so we can use the 4000-foot data in Tables I through III, with only a small amount of error. For a total wire length of 30 WL, computer analysis indicates that the optimum number of radials is about 63 for average soil, 57 for very poor soil, and 76 for very good soil. Thus, on the 7-MHz band, the best number of radials is far less than 120, when 30 wavelengths of wire are available.

On 80 meters (3.75 MHz), 30 WL is nearly 7900 feet of wire, allowing us to safely utilize the 8000-foot data from Tables IV, V, and VI with good accuracy. On this band, we find that the best number of ra-

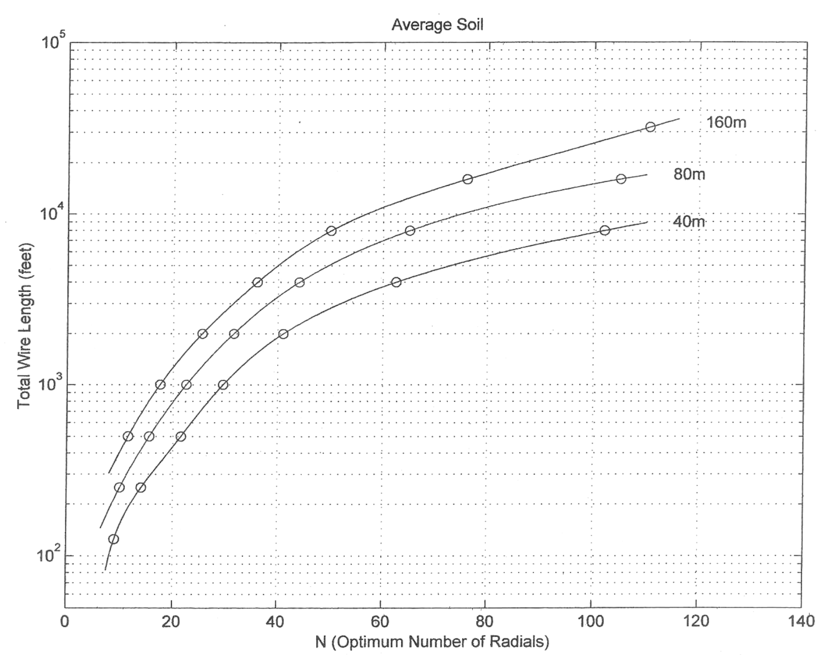

Figure 4—Optimum number of buried radials for quarter-wave vertical antennas over average soil, as the total wire length is varied, for the three "low bands" 40, 80, and 160 meters.

Table XIII

Optimum number of radials versus total wire length, for all three bands, in average soil with a conductivity of 0.005 siemens/meter. [Results using the N4UU formula are shown in brackets.]

Total Wire Length (ft)	*Optimum number of radials for each band* 7.15 MHz	*3.75 MHz*	*1.835 MHz*
125	9 [11]		
250	14 [15]	0 [13]	
500	21-22 [22]	15-16 [19]	11-12 [16]
1000	28-31 [31]	21-24 [26]	17-18 [22]
2000	39-43 [44]	29-34 [37]	23-28 [31]
4000	62-63 [62]	42-46 [53]	32-40 [44]
8000	100-104 [88]	63-67 [74]	45-55 [62]
16,000		99-111 [105]	76 [88]
32,000			99-122 [125]

Table XIV

Optimum number of radials versus total wire length, for all three bands, in very poor soil with a conductivity of 0.001 siemens/meter. [Results using the N4UU formula are shown in brackets.]

Total Wire Length (ft)	*Optimum Number of Radials for Each Band* 7.15 MHz	*3.75 MHz*	*1.835 MHz*
125	6 [7]		
250	10 [10]	7 [9]	
500	16 [15]	11 [12]	7-8 [10]
1000	25 [21]	17 [18]	12 [15]
2000	34-36 [29]	24-26 [25]	18 [21]
4000	56-58 [41]	35-36 [35]	25-26 [29]
8000	96-100 [59]	57-59 [50]	35-36 [42]
16,000		98-104 [70]	55-59 [59]
32,000			96-100 [83]

dials to install is 65 for average soil, 58 for very poor soil, and 92 for very good soil, if 30 wavelengths of wire are available.

Finally, on top band (1.835 MHz), 30 WL amounts to slightly less than 16,100 feet of wire, so the 16,000-foot data from Tables VII through IX will work nicely. Now we discover that the optimal number of radials is 76 for average soil, 57 for very poor soil, and 108 for very good soil, when 30 WL of wire are available.

We can see that, for most ham-radio applications, a ground system composed of 120 0.25-WL radials is not optimum, unless you want to operate on 160 meters and your soil conductivity is very good. If you have 30 WL of radial wire at your disposal, computer simulation reveals that, in many situations, fewer than 90 radials should be installed, with each one having a length greater than 0.25 WL, in order to maximize the gain of the antenna.

Comparison with N4UU

In his article, N4UU gives a formula that enables one to calculate the optimum number of radials for a vertical-antenna ground system, when the frequency, soil conductivity, and total length of wire are specified[4]. Tables XIII through XV compare the results obtained from this formula with those predicted by the "maximum gain" computer analysis that I performed using *EZNEC*. For average and very good soils, N4UU's formula generally yields a somewhat higher value for the optimum number of radials, while the results for very poor soil are mixed. However, the graphs show that relatively large variations in the number of radials produce changes in antenna gain of only a few tenths of a decibel, so the exact number of radials used is not critical.

Conclusions

For a single-element vertical antenna with a buried-radial ground system, the number and length of the radials can be

Table XV

Optimum number of radials versus total wire length, for all three bands, in very good soil with a conductivity of 0.0303 siemens/meter. [Results using the N4UU formula are shown in brackets.]

Total Wire Length (ft)	*Optimum Number of Radials for Each Band* 7.15 MHz	*3.75 MHz*	*1.835 MHz*
125	12 [17]		
250	17-20 [24]	14-16 [21]	
500	24-28 [34]	19-25 [29]	17-21 [24]
1000	37 [49]	29-32 [41]	23-30 [35]
2000	48-58 [69]	39-50 [58]	33-42 [49]
4000	68-85 [97]	56-70 [83]	47-59 [69]
8000	102-127 [137]	80-103 [117]	67-83 [98]
16,000		119-152 [165]	93-122 [138]
32,000			136-181 [195]

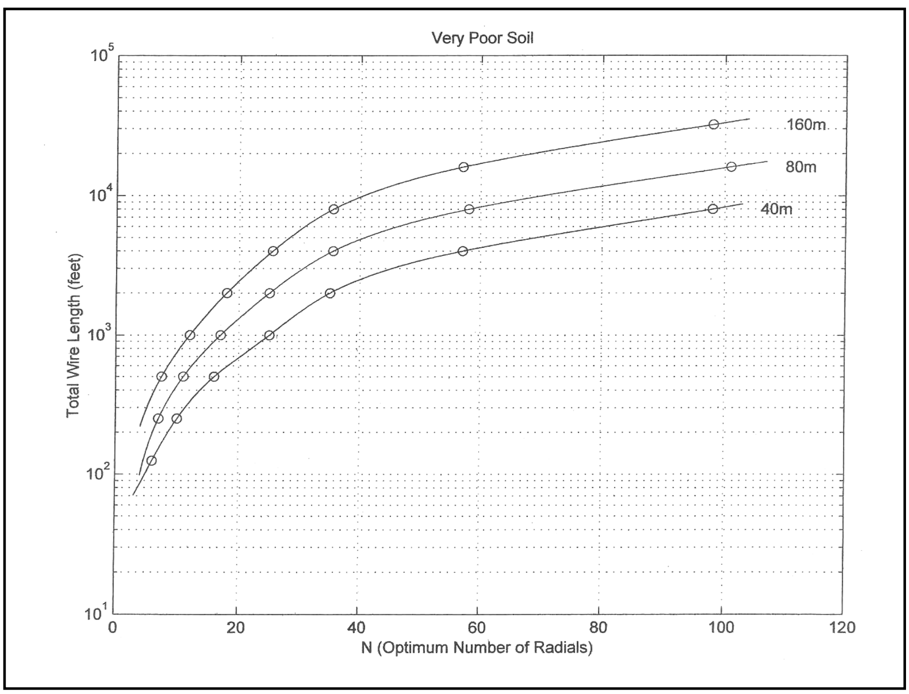

Figure 5—Optimum number of buried radials for quarter-wave vertical antennas over very poor soil, as the total wire length is varied, for the three "low bands" 40, 80, and 160 meters.

adjusted so the antenna will have the highest possible gain. The "best" number of radials depends upon the total amount of wire which can be dedicated to the ground system, and the electrical characteristics of the soil in which the radials are immersed. Contrary to what is generally used for AM-broadcast verticals, a ground system of 120 quarter-wave radials may represent a sub-optimal utilization of wire on the amateur bands from 40 through 160 meters. This article supplies tables and graphs which allow the active low-band operator to achieve maximum performance from the radial wire at his or her disposal.

Notes

[1]Robert C. Sommer, N4UU, "Optimum Radial Ground Systems," *QST*, August 2003, pages 39 - 43.

[2]Several versions of *EZNEC* antenna-modeling software are available from Roy Lewallen, W7EL, PO Box 6658, Beaverton, OR 97007.

[3]Robert C. Sommer, N4UU, "Optimum Radial Ground Systems," *QST*, August 2003, page 40.

[4]Robert C. Sommer, N4UU, "Optimum Radial Ground Systems," *QST*, August 2003, page 39.

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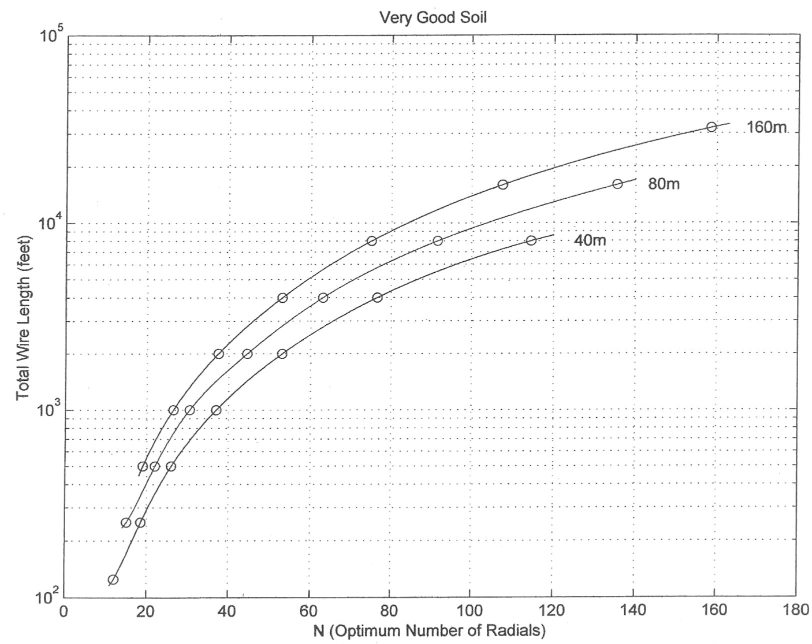

Figure 6—Optimum number of buried radials for quarter-wave vertical antennas over very good soil, as the total wire length is varied, for the three "low bands" 40, 80, and 160 meters.