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A Closer Look at Vertical Antennas With Elevated Ground Systems—Part 2

N6LF shares his results from further HF vertical antenna experiments.

[Part 2 concludes this article, which began in the Mar/Apr 2012 issue of *QEX*. — Ed.]

Multiband Verticals

For a single band antenna we can avoid the problems of long radials by simply using radials that are short enough or by increasing the number of radials, but what about the case of multiband antennas where you typically have four $\lambda/4$ radials for each band? For example, if you have 40 m $\lambda/4$ radials, these will be $\lambda/2$ on 20 m, ¾ λ on 15 m, and so on. In light of the information we found for G_a as a function of L in Part 1, is that a problem? I don't have the space here to explore it in detail with modeling, but I have looked at multiband elevated verticals experimentally. The information was in Part 5 of my *QEX* series, "Experimental Determination of Ground System Performance for HF Verticals." Part 5 was in the July/August 2009 issue of *QEX*, pp 15-17. That series of articles is available for viewing on my website: (**www.antennasbyn6lf.com**). The experimental work indicated that as long as there are a large number of radials (whether they are the same length or of different lengths) you don't have a problem but if you try to use only a few long radials you will have problems. Read the article for the details.

Potentials on the Radials

As Laport stated, elevated ground systems can have very high voltages between the wires and ground. Figure 27 shows examples of the voltage from a radial wire to ground for ideal 4, 12 and 32 $\lambda_0/4$ radial systems.

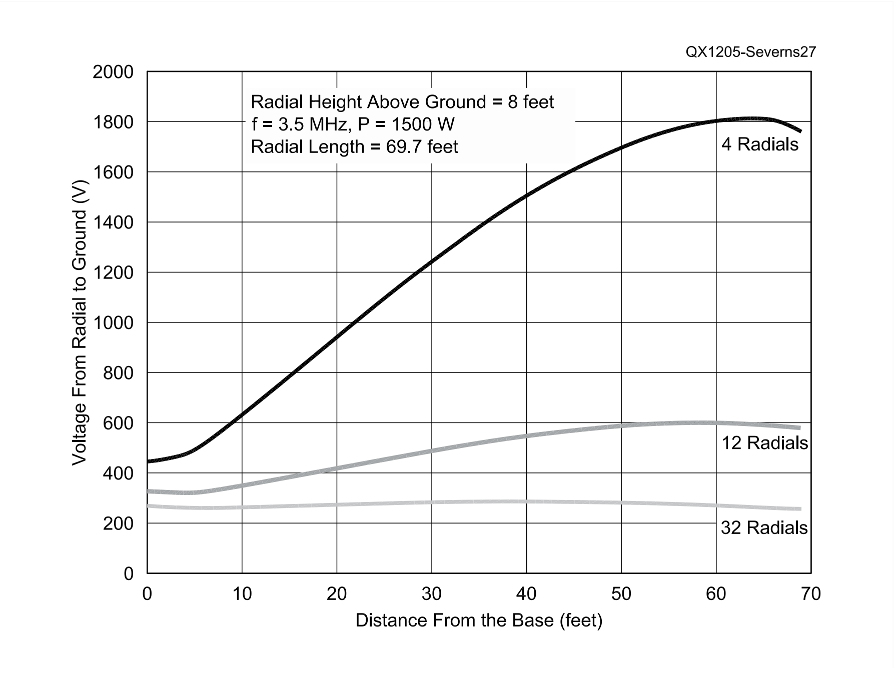

Figure 27 — Examples of the voltage from a radial wire to ground with different numbers of radials. The input power to the vertical is 1500 W, the operating frequency is 3.5 MHz and the radial system is elevated 8 feet above ground.

I think this Figure makes it clear why you want to keep the radials out of reach! Note that as more radials are added the potential difference between the radials and ground drops significantly and becomes more uniform as we go away from the base of the antenna. This is a reflection of the reduction in E-field amplitude with more numerous radials, as was shown in Figures 24, 25 and 26 in Part 1 of this article (Mar/Apr 2012 *QEX*). Even with a large number of radials that voltage is still high. This voltage will vary with the square root of the power level so that going down from 1500 W to 100 W, a change of 15:1 (0.067), the voltage only drops by 0.26! Be careful!

Feed Point Impedances

The behavior of the feed point impedance over the band (3.5 to 3.8 MHz for these examples) as we vary H, L, J, N and soil characteristics is an important factor. The point I want to make in this section is how widely the input impedance of ground-plane antenna can vary as we change one or more of the variables. There is no one number for Z_{in}! We will also look at variations in SWR bandwidth.

A graph of the feed point impedance ($Z_{in} = R_{in} + j\, X_{in}$) from 3.5 to 3.8 MHz for different numbers of radials is shown in Figure 28. Note that in Figures 28 to 31, H = L and is adjusted so that the model is resonant at 3.65 MHz for each variation of parameters. As the parameters N, J and soil characteristics are changed, the values for H and L vary somewhat. From Figure 28 we can see that N has a strong effect on the feed point impedance (Z_{in}) although that effect diminishes as N increases. As shown in Figure 29, we can convert the information in Figure 28 to SWR. In this case the Z_0 impedance for the SWR calculation is taken to be R_{in} at resonance (3.65 MHz) for *each* value of N.

Figure 29 shows that the 2:1 SWR bandwidth increases somewhat as N is increased but by N = 16 we are approaching the point of vanishing returns for bandwidth.

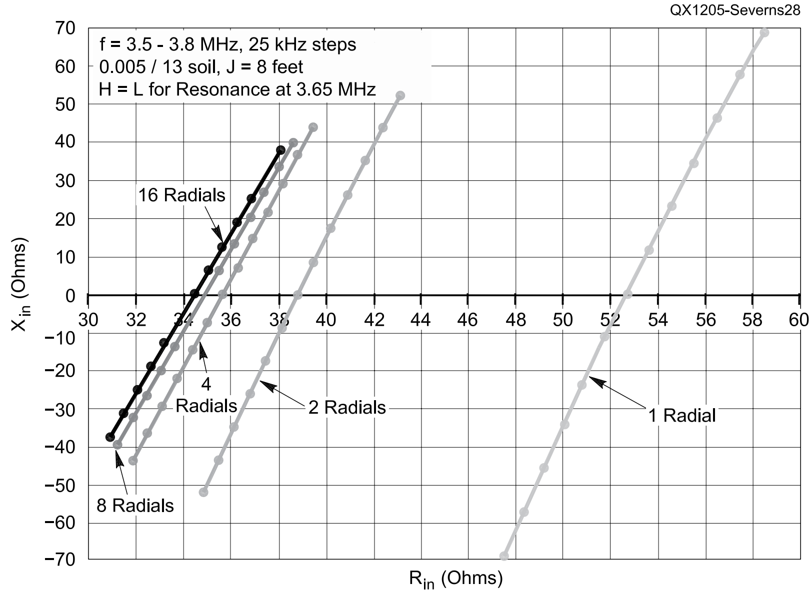

Figure 28 — X_{in} versus R_{in} ($Z_{in} = R_{in} + j\, X_{in}$) where frequency varies from 3.5 MHz (lower left ends of the curves) to 3.8 MHz (upper right ends of the curves) for different values of N. Frequency is stepped in 25 kHz intervals.

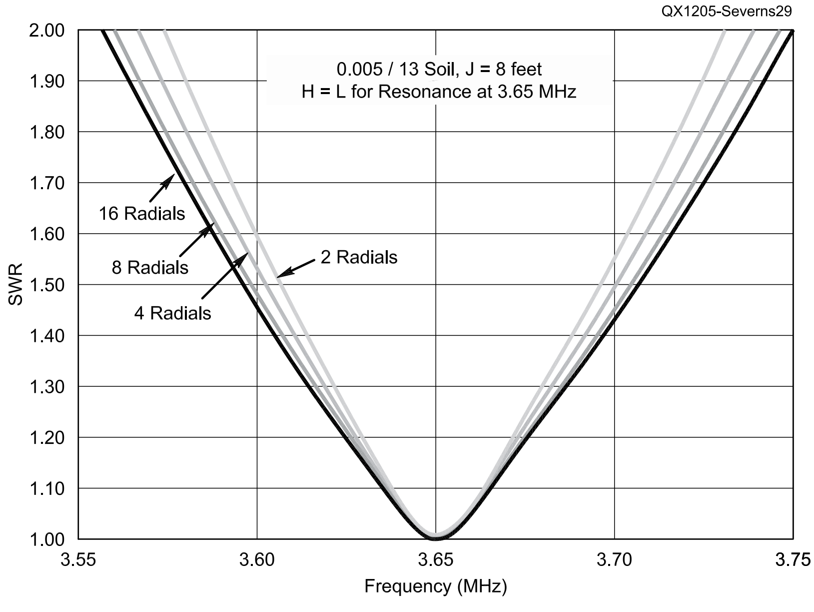

Figure 29 — Feed point SWR as a function of N.

Figure 30 shows the effect of height above ground of the radial fan (J) on Z_{in} for N = 4. It's pretty clear that the value for J has a strong effect on Z_{in}. The effect of different soil characteristics for a given value of J (8 feet in this example) is shown in Figure 31.

The information in Figures 28 to 31 represents only a few possible combinations, but the graphs make the point that the feed point impedance of an elevated radial vertical is a strong function of all the variables, so that each installation is unique.

We can also see the behavior of Z_{in} over the band for different combinations of H and L that are resonant at 3.65 MHz. Some examples are given in Figure 32 and the associated graphs for SWR, are given in Figures 33 and 34. N = 4 and the H&L combinations are shown on the graphs.

The combination H = 73.25 feet and L = 43.11 feet has the very nice property that $Z_{in} = 50\ \Omega$ at 3.65 MHz. As shown in Figure 33, this results in a relatively wide 2:1 SWR bandwidth compared to the other combinations.

The greater match bandwidth is not just because $Z_{in} = 50\ \Omega$ at resonance. The combination also has intrinsically more bandwidth as shown in Figure 33, where the Z_0 at resonance is set to R_{in} at resonance for *each* combination of H and L separately.

The idea of increasing the feed point impedance at resonance to 50 Ω by making the vertical taller and the radial fan radius smaller has actually been around for many years: R_{in} at resonance can be increased by sloping the radials downwards from the base. In effect you are making the vertical taller and reducing the radial fan radius, which is what we did in the above example.

Figure 9 (in Part 1) showed how L_r varied for different values of N and H. For H = 69 feet, L_r decreased rapidly as more radials were added. We can play this game to find designs where $Z_{in} = 50\ \Omega$ at resonance. Figure 35 is a graph where L is varied from 15 feet to 100 feet for two values of H (72 feet and 77.6 feet). Note that H in the range of 72 feet <=> 77.6 feet represents the limit that allows $R_{in} = 50\ \Omega$. Longer or shorter values for H do not have a point where $R_{in} = 50\ \Omega$ for L = 15 feet <=> 100 feet. The combination of H = 72 feet, L = 25 feet, N = 16 and J = 8 feet over average ground will give us $Z_{in} = 50\ \Omega$ at 3.65 MHz. Figure 36 shows the comparison for SWR between two combinations where N = 4 and N =16. This illustrates one of the advantages of using more radials.

For H = 72 feet and N = 16, L is only 25 feet that represents a drastic reduction in the radius of the radial fan. In exchange for an increase in height on the order of 6 feet, we have a good match over a wide portion of the band and a small diameter radial fan. Instead of increasing the height we could have just added a couple of short top-loading wires. This is very nice but it's not entirely for free. When compared to the normal four radial system (H = 67 feet, L = 67.7 feet), G_a for the H = 72 feet, L = 25 feet combination is lower by about 0.25 dB. You sacrifice a small amount of gain. Whether that is acceptable for the improvement in matching is an individual decision.

In a private communication with Dick Weber, K5IU, he made a suggestion that overcomes the reduction in gain associated with small radial length: use longer radials. This will result in $X_{in} \neq 0$ but you can tune out the reactance with a series impedance. He has also pointed out that if X_{in} is inductive (+) then you can tune out the reactance with a series capacitor at the feed point. Looking back at Figure 35, we see that this trick will work for H > 72 feet. (That is for this particular case, where N = 16, J = 8 feet over average ground!). If we chose H = 75 feet, L = 70 feet, N = 16 and adjust the series capacitor at the feed point as we move across the band, we get the result shown in Table 1. Note that X_{in} is given in the Table, but C_s (the added series capacitor) tunes it out.

What we see is a vertical that can have a very low SWR across the entire 75/80 m band. It isn't necessary that C_s be adjusted at every point. Three or four values of C_s switched with relays would probably still provide acceptable SWR over the entire band. For the case where H = 72 feet, L = 25 feet and N = 16, $G_a = -5.52$ dB. When we change to H = 75 feet, L = 70 feet and N = 16, $G_a = -5.03$ dB. That's an improvement of +0.5 dB in signal strength.

There is another option to make $Z_{in} = 50 + j0\ \Omega$ at resonance. Instead of making the antenna taller (or top-loading it) and the radials shorter, you can simply shift the feed point up into the vertical to a point where $R_{in} = 50\ \Omega$. This is just a matter of moving the base insulator up into the antenna. You won't get quite as much match bandwidth as with the taller vertical but it will be close and you can use longer radials that give a better G_a. Whether this trick is mechanically feasible depends on the particular implementation.

All the examples to this point have assumed that the excitation at the base of the

Table 1

Z_{in} and SWR from 3.5 to 4.0 MHz for H = 75 Feet, L= 70 Feet and n = 16

Frequency (MHz)	R_{in} (Ω)	X_{in} (Ω)	C_s (pF)	*SWR*
3.50	43.7	69.6	654	1.14
3.65	49.4	113.7	384	1.01
3.80	56.0	159.4	263	1.12
4.0	66.6	223.6	178	1.33

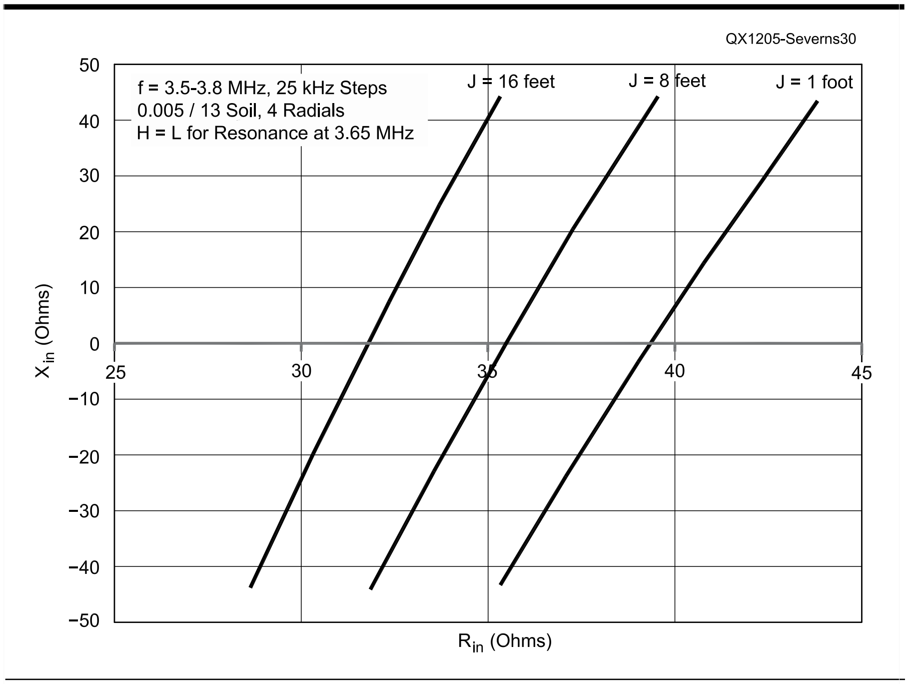

Figure 30 — The effect of height above ground on Z_{in}.

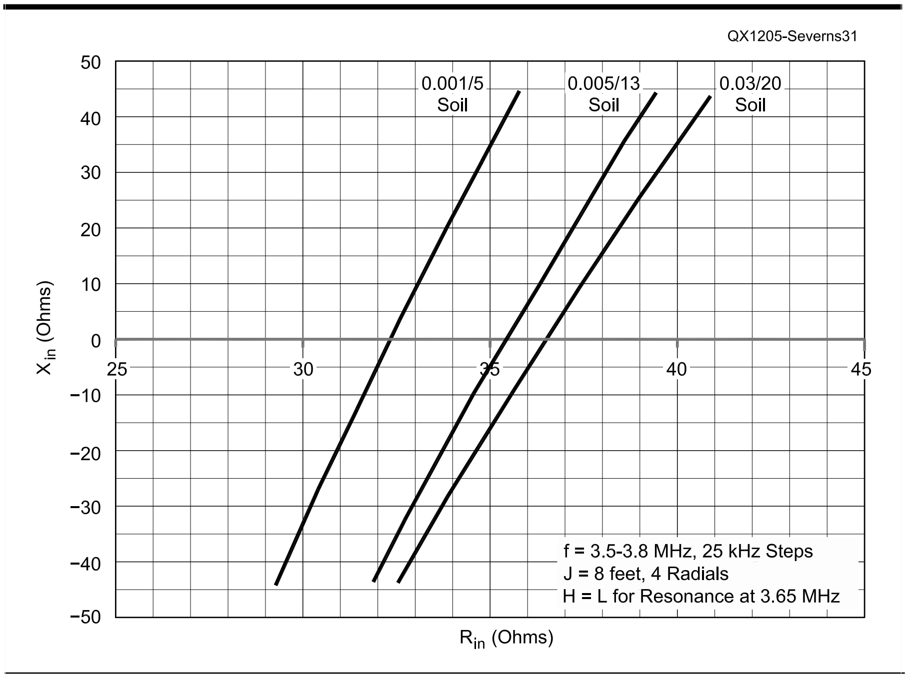

Figure 31 — The effect of different soil characteristics on Z_{in}.

vertical was isolated from ground: a choke (balun) was used in series with the feed line. If a choke is not used and the coaxial feed line is simply connected to the antenna and run down to ground, usually with the shield connected to the radials and the center conductor to the vertical, there will be additional ground currents that increase loss. In a 4-radial elevated system, G_a typically falls -0.25 to –0.5 dB or even more for lossy soils if a choke is not used. If 12 to 16 radials are used, the increased loss is much smaller, usually only a few tenths of a dB. You might argue that when N is large a choke is not needed but I think it is better to be cautious and use a choke even in that case.

Earlier we saw how the radial length (L) affected the efficiency (G_a) of the antenna. We also saw that the effect was reduced when more radials were used. It is useful to look at Z_{in} as both N and L are varied, especially around values of L near $\lambda_0/4$. Figure 37 shows the effect of varying L on X_{in}.

Figure 37 is particularly interesting in that it shows how sensitive the X_{in} component of Z_{in} is to radial length when only a few radials are used. The R_{in} component is not nearly as sensitive. This becomes important when we look at current asymmetries in the radials. Adding more radials reduces the sensitivity of Z_{in} to radial length and also the susceptibility to radial current asymmetry. Dick Weber, K5IU (see Note 43) generated a graph very similar to Figure 37 by assuming the radials were open circuit transmission lines and plotting the impedance at the feed point as more radials were added in parallel. I have more on radials as transmission lines in the next section.

Effect of Asymmetries in the Radial Fan

Is there significant current division asymmetry among the radials of typical installations and, if there is, do we need to be concerned about it? To answer the first part of this question, Dick Weber, K5IU, made a series of measurements on representative 80 m and 160 m verticals with two and four elevated radials. Dick's work was published in "Optimum Elevated Radial Vertical Antennas," in the Spring 1997 edition of *Communication Quarterly*. (See Note 9 in Part 1 of this article.) I have summarized some of his data in Table 2 but I strongly recommend reading his complete article.

Data tables are helpful but sometimes a graph of the data has more impact. Figure 38 compares the radial current division for Weber's 80 m vertical with four radials. Figure 38 shows two things: the radial current division between the radials is far from equal and the division ratios change as we move across the band. Unfortunately, this is typical of elevated ground systems with only a few radials, as shown in Table 2.

Weber explains this behavior by pointing out that a horizontal radial above ground is actually a section of single wire transmission line open-circuited at the far end so that in the region where L ≈ $\lambda_0/4$ it acts like a series resonant circuit. Figure 39 shows an equivalent circuit.

Individually the radials may have differ-

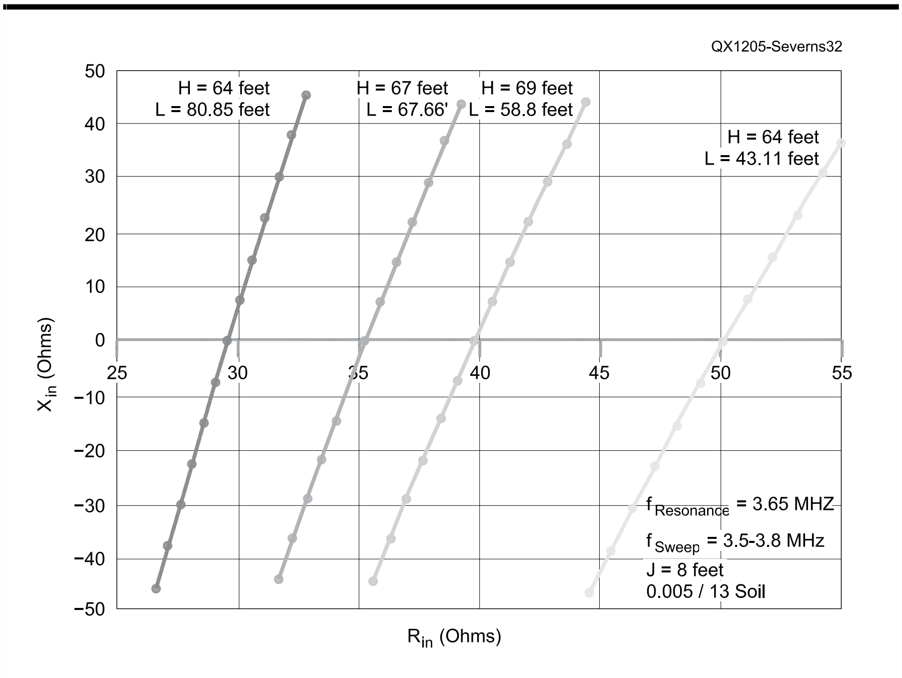

Figure 32 — Z_{in} variation for different combinations of H and L that are resonant at 3.65 MHz.

Table 2
Radial Current Comparisons from K5IU Measurements
(See Note 9 in Part 1 of this article for a reference to the source of this data.)

Antenna #	*Station ID*	*Frequency (MHz)*	*Relative Current Radial 1*	*Relative Current Radial 2*	*Relative Current Radial 3*	*Relative Current Radial 4*
1	K5IU	3.528	1.00	0.52	0.27	0.27
1	K5IU	3.816	0.96	1.00	0.51	0.51
1	WX0B	1.805	1.00	0.01	-----	-----
1	WX0B	1.885	1.00	0.05	-----	-----
2	WX0B	1.805	1.00	0.80	-----	-----
2	WX0B	1.885	1.00	0.10	-----	-----
1, 0.125 λ radials, w/inductor	WX0B	1.805	1.00	0.83	-----	-----
1, 0.125 λ radials, w/inductor	WX0B	1.885	1.00	0.76	-----	-----
1	W7XU	1.805	1.00	0.00	0.00	0.00
1st trim	W7XU	1.805	0.03	1.00	0.10	0.07
Last trim	W7XU	1.805	1.00	0.00	0.00	0.00
Last trim	W7XU	1.900	0.03	1	0.10	0.07

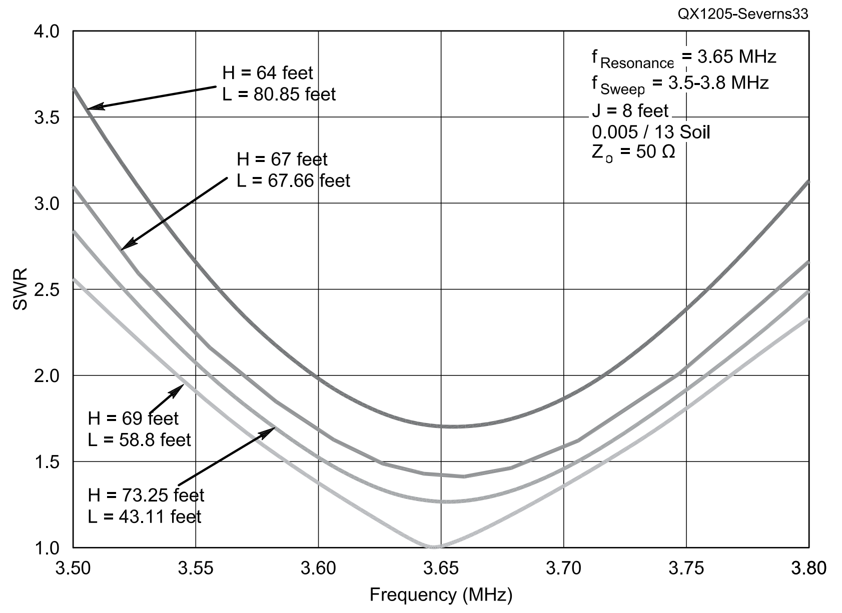

Figure 33 — SWR for various combinations of resonant H and L. Z_0 = 50 Ω for all curves.

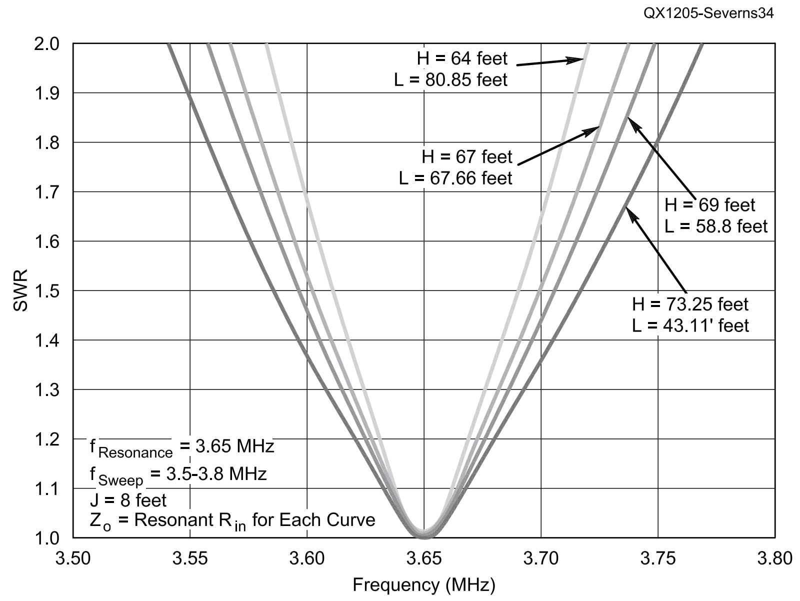

Figure 34 — SWR with Z_0 equal to R_{in} at resonance for the particular combination of H and L.

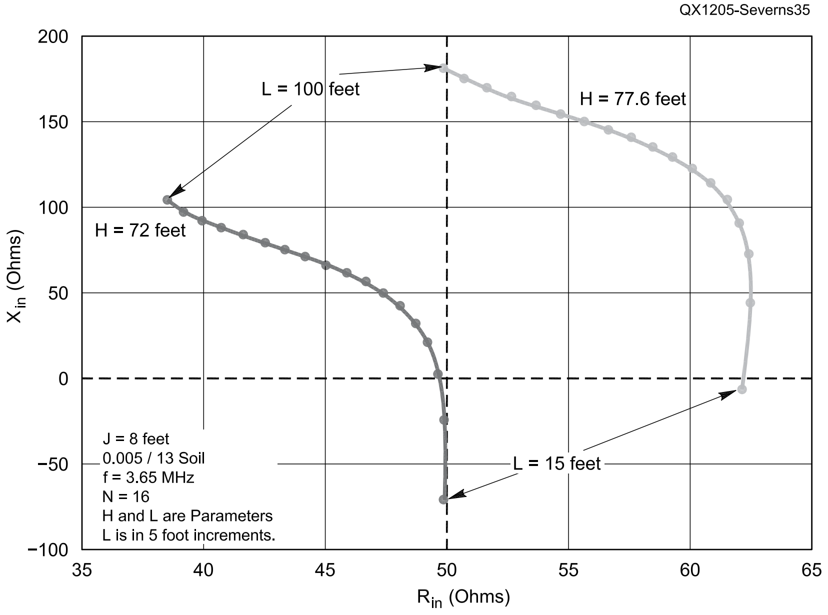

Figure 35 — Z_{in} as a function of radial length (L) for H = 72 feet and 77.6 feet with N = 16.

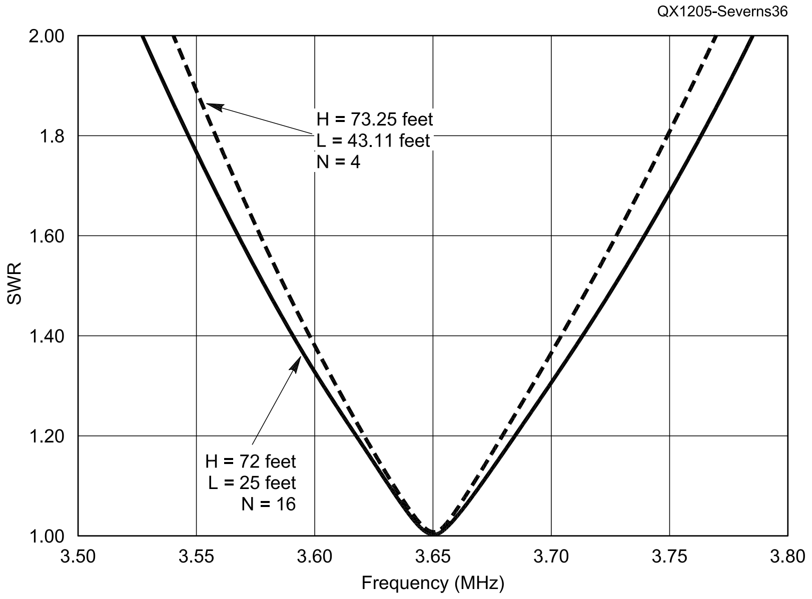

Figure 36 — SWR over 3.5 to 3.8 MHz for two different combinations of H and L.

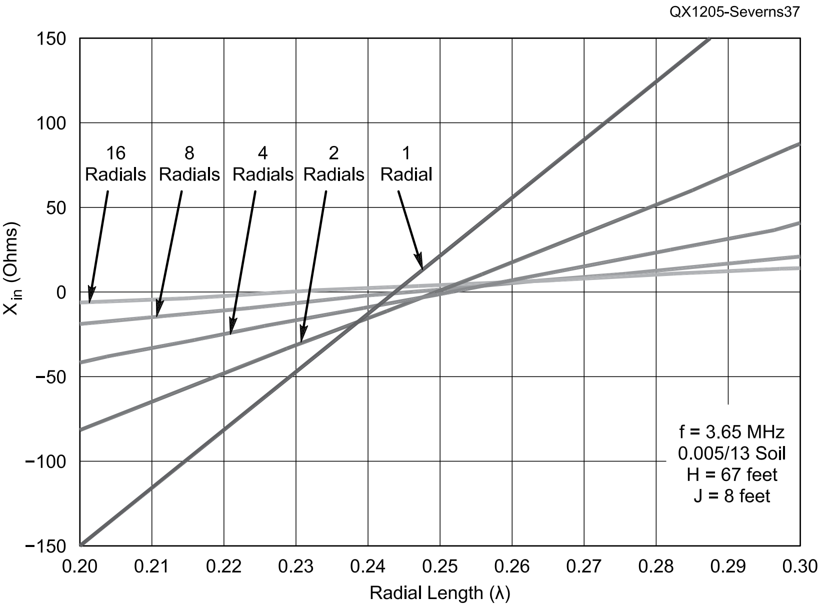

Figure 37 — Effect of changing L in the neighborhood of λ/4 as a function of radial number.

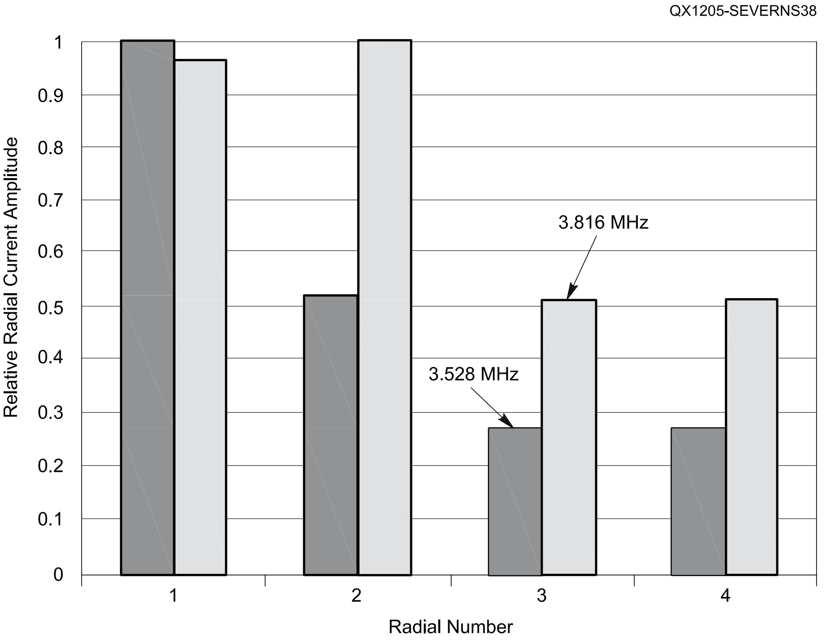

Figure 38 — Current division between the four radials at 3.528 and 3.816 MHz for the 80 m vertical at K5IU.

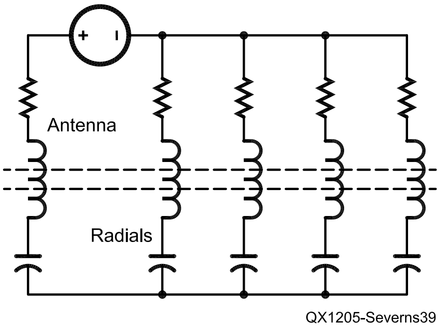

Figure 39 — Equivalent circuit for a vertical with elevated radials.

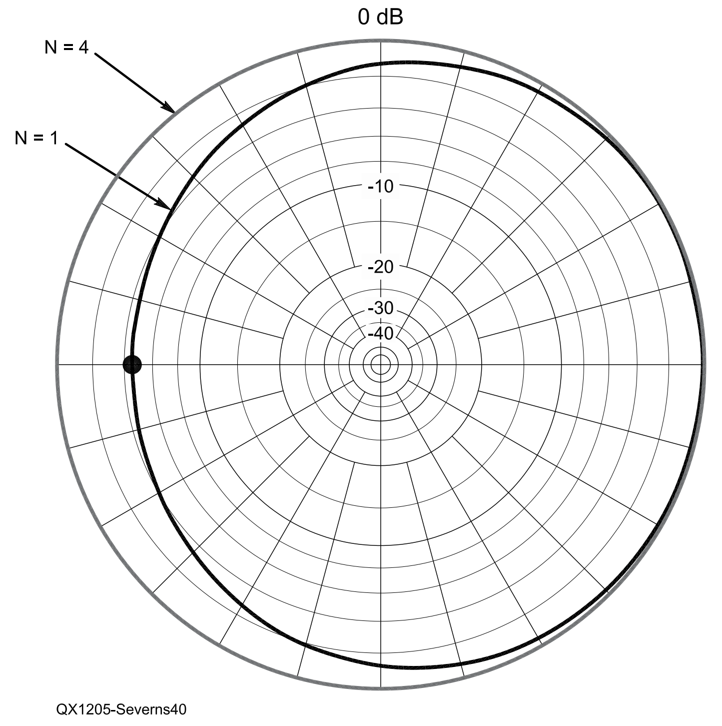

Figure 40 — Azimuth radiation pattern comparison between one and four elevated radials. J = 8 feet, f = 7.2 MHz over average ground. The elevation angle for these plots is 22°.

ing resonant frequencies due to length variations, varying ground characteristics under a particular radial, nearby conductors, and other factors. (See Note 12 in Part 1, Doty, Frey and Mills, "Efficient Ground Systems for Vertical Antennas," *QST*, Feb 1983, p 20.) At a given frequency, a particular radial may be close to series resonance, which means it has a low input impedance and may therefore take the majority of the current. This is a reasonable idea but the basic model in Figure 39 doesn't take into account the coupling between the individual radials or between the radials and the vertical. It would be more correct to add mutual coupling between all the inductive elements of Figure 39 as shown by the dashed lines. In the case of four radials, the radials are at right angles to each other and to the vertical so that the mutual coupling is small (but not zero). When you go to eight radials, for example, the angle between the radials goes from 90° to 45°. That greatly increases coupling between the radials.

All this is very interesting but so what? Does current-division asymmetry in the radials cause any problems we should worry about? One way to look into this is to model a system with only one radial, which might be a worst case. Several of the examples in Table 2 show almost all the radial current to be in one radial. Figure 40 shows a comparison in the azimuth radiation patterns between one and four radials with J = 8 feet and f = 7.2 MHz, at an elevation angle of 22°. Note that I have changed from 80 m to 40 m for the following examples simply because this work was already on hand. With four radials, the pattern is symmetric within 0.1 dB but with only one radial the pattern is distorted with a F/B ratio of 4.6 dB. In addition, the average gain for one radial is about 0.5 dB lower than G_a with four radials. There is substantial signal reduction (almost 5 dB!) in the direction away from the single radial. Over poor soil, G_a is even lower and the F/B can be 6 dB or more.

Does having all the current in one radial actually represent the worst case or can we have even more pattern distortion and/or lower G_a in some other cases? NEC modeling can be used to investigate this question. We'll start with a 40 m $\lambda/4$ vertical with four radials (see Figure 4 in Part 1). Radials 1 and 2 form an opposing pair with a length = L. Radials 3 and 4 are a second opposing pair with length = M. First we'll model the antenna with all the radials the same length (L = M) and then with radials that differ in length ($L \neq M$).

The feed point impedances for three different radial length configurations are compared in Figure 41 as the frequency is varied from 7.0 to 7.3 MHz. The plot on the left is for the case where all the radials are identical (L = M = 34.1 feet). The looping plot on the right is for the case where L = 35.6 feet and M = 33.1 feet. This represents a length error of ± 2.9%. The middle plot is for L = 34.6 feet and M = 33.6 feet. That is a length error of ± 1.4%. Clearly even modest radial length asymmetry can have a dramatic effect on the feed point impedance and resonant frequency. The resonant frequency is the point at which $X_{in} = 0$.

Feed point impedance is not the only problem associated with asymmetric radial lengths. Figure 42 compares radiation patterns between symmetric and asymmetric systems at 7.25 MHz. The amount of pattern distortion varies across the band from a fraction of a dB at 7.0 MHz to 3 dB at 7.25 MHz. Besides the distortion, the gain in all directions is smaller for the asymmetric case. Computing the average gains for the symmetric and asymmetric cases, there is about a 1.6 dB difference. What this tells us is that asymmetric radials can lead to significantly higher ground losses!

Pattern distortion and increased ground loss with asymmetric radials occurs because the radial currents with asymmetric radial lengths are very different from the symmetric case. An example is given in Figure 43.

The graph bars represent the current amplitudes at the base of the vertical and each of the radials immediately adjacent to the base of the vertical. The grey bars are for symmetric radial lengths (L = M = 34.1 feet) and the black bars are for asymmetric radials (L = 35.1 feet and M = 33.1 feet). In the symmetric case, each of the radials has a current of 0.25 A, which sums to 1 A, the excitation current at the base of the vertical. The radial currents are also in phase with the base current.

With asymmetric radials the picture is very different: the current amplitudes are different between radial pair 1 and 2 and pair 3 and 4, and the sum of the current amplitudes is *not* 1 A (the base current amplitude), it is much larger! This would seem to violate Kirchhoff's current law that requires the sum of the currents at a node to be zero. In this

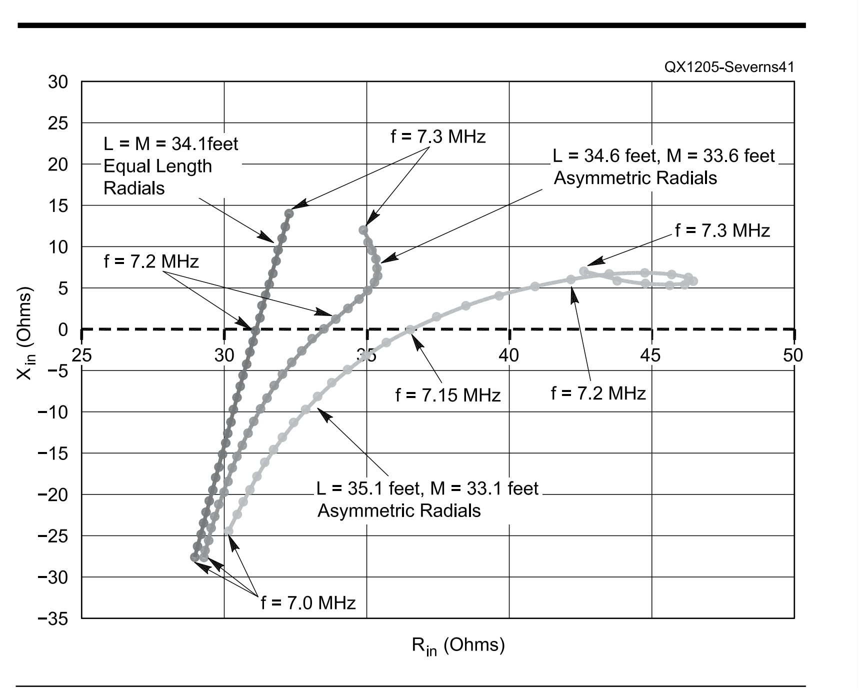

Figure 41 — A comparison of the input impedances ($Z_{in} = R_{in} + j X_{in}$) from 7.0 to 7.3 MHz at the feed point of the vertical, for symmetric and asymmetric radial lengths. The frequency is stepped in 10 kHz increments.

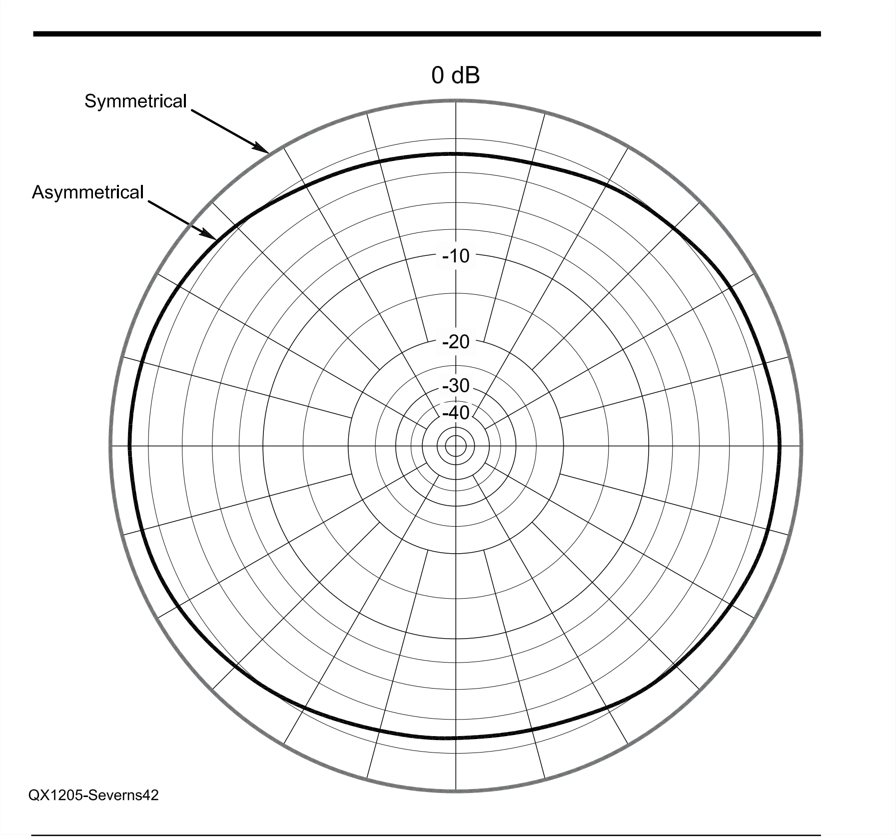

Figure 42 — Radiation pattern comparison between symmetric (L = M = 34.1 feet) and asymmetric (L = 35.1 feet and M = 33.1 feet) radials at 7.25 MHz.

case the radial currents in the two pairs of radials are not in phase with each other or the vertical base current. The current in radials 1 and 2 is shifted by –62° from the base current and the current in radials 3 and 4 is shifted by +89°. The base and radial currents sum *vectorially* to 0 however. That satisfies Kirchhoff's law! These large asymmetric currents go a long way towards explaining the increased ground loss and pattern distortion. Note that the current asymmetry shown in Figure 43 is for f = 7.25 MHz. As the frequency is changed the pattern for the asymmetric currents in Figure 43 will change in a way similar to Weber's data shown in Figure 38.

If we take the example of L = 35.6 feet and M = 33.1 feet and add a wire from the junction of the radials to a ground stake, the G_a drops *another* –0.5 dB and the radial current asymmetry increases.

These examples represent only two particular cases. Obviously there are an infinite variety of radial fan distortions including radial lengths, azimuthal asymmetry, droop of the radials, and on and on. As we increase the number of radials what we see is a rapid decrease in the sensitivity to asymmetric radial lengths. A primary effect of additional elevated radials (>4) is to reduce the sensitivity to radial asymmetry, nearby conductors, variations in ground conductivity or objects under the radial fan, and, as shown in Figure 27, more numerous radials reduce the potentials on the radials.

How can we tell if there is a problem in an existing radial fan? One way is to measure the current amplitudes in the individual radials close to the base of the vertical. (See Part 1 of my series, "Experimental Determination of Ground System Performance on HF Verticals; Test Setup and Instrumentation," in the Jan/Feb 2011 issue of *QEX*.) If the current amplitudes are significantly different between the radials and/or if the sum of the current amplitudes in the radials is greater than the base current, then you have a problem. Current amplitude measurements can be made with an RF ammeter. More accurate measurements that also show the phase can be made using current transformers and an oscilloscope or a vector network analyzer.

Final Comments

This discussion has shown that a vertical with an elevated ground system has many subtleties and many potentially useful variations, but it has also shown that you cannot simply throw up a vertical with a few radials dangling in various directions and expect it to work properly. You have to take some care. Are there a few simple rules that will keep us out of trouble?

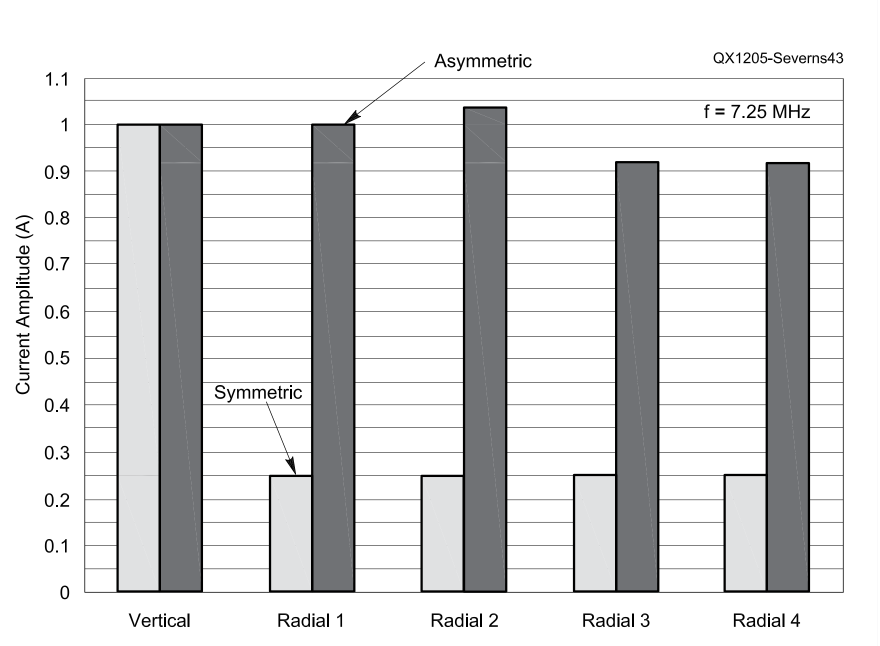

Figure 43 — Comparison of currents between symmetric and asymmetric radials.

Here's my advice:

1) Use at least 10 to 12 radials.

2) Make an effort to have the radial system as symmetric as possible.

3) Keep the radial system as far as possible from other conductive objects.

4) While it is certainly possible to use almost any height for the vertical, I suggest you start with H = $\lambda_0/4$ and trim the radials for resonance. This makes H a little tall, but it shortens your radials (especially if you're using 10 to 12) and raises the feed point impedance a bit.

5) Use a balun or common mode choke on the feed line at the base of the vertical. To be effective, the balun should have a shunt impedance of >2 kΩ.

6) If you have a special problem situation by all means model some trial solutions first. That will save you a lot of time over cut-and-try in the field. If you can't afford NEC4 software, the free NEC2 software will still be very helpful. (See **www.4nec2.com**.)

This article has covered a lot of ground looking in detail at the behavior of verticals with elevated ground systems. Despite the length of this article, it really just scratches the surface of the subject. There are many other topics that deserve attention. For example: a more detailed look at counterpoises, or, in an array, the interaction between the radial systems associated with the individual verticals, the effect of non-level terrain, and so on. I particularly recommend the articles by Al Christman, K3LC, that address many of these issues. (See Notes 18 through 33 in Part 1.) While I hope the work reported here is helpful, there's still lots more to be done before we can claim to really understand this class of antennas.

Acknowledgement

Much of the modeling data for the graphs was derived using *MultiNEC*, an *Excel* program developed by Dan Maguire, AC6LA, that interfaces with NEC modeling programs allowing multiple runs for parameter studies. This is truly a wonderful program. Unfortunately it is currently being revised and not available as of this writing. I also want to thank my reviewers Al Christman, K3LC, George Cutsogeorge, W2VJN, Mark Perrin, N7MQ, Ward Silver, NØAX, Dean Straw, N6BV, and Dick Weber, K5IU. They gave freely of their time going through my drafts, making many important suggestions and corrections.

Rudy Severns, N6LF, is a retired electrical engineer (UCLA '66). He holds an Amateur Extra class license and was first licensed in 1954 as WN7WAG. He is a life fellow of the IEEE and a life member of the ARRL. His current Amateur Radio interests are antennas, particularly HF vertical arrays and interactions between towers and arrays. He also enjoys 600 m operation as part of the group under the WD2XSH experimental license. Some of his publications about antennas are posted on his website at ***www.antennasbyn6lf.com****.*