Chapter 5

LF-MF Ground Systems

5.0 Why do we need a ground system?

The discussion of efficiency in earlier chapters has focused on loss introduced by the tuning inductor which is reasonable given that RL often represents a major loss in short antennas. While much can done to reduce Xi and increase Rr, there are practical limits and at some point we have to start thinking about reducing other losses. A substantial portion of the power supplied to the antenna may be absorbed in the soil near the base. To reduce this loss we install a ground system. This chapter is mostly practical examples and simple advice with little justification. However, there is a great deal more that could be said justifying that advice. That information has been placed appendices TBD-TBD, which have an extensive discussion of soil characteristics, ground loss, skin depth and wavelength in soil and a discussion of radial and mesh ground systems design.

This chapter begins with some basic definitions and then moves on to examples and practical questions like:

- what type of ground system?
- how many radials?
- radial lengths?
- what performance can we expect?
- optimum use of a fixed amount of wire?

A range of examples have been chosen to provide general guidance but none should be taken as exact numerical descriptions for all cases. You will have to do some measurements, modeling and/or calculations to arrive at the best solution for your unique situation.

5.1 Choices for ground systems

Ground systems can take several forms:

1. A radial wire fan lying on the ground surface or buried a few inches.
2. A rectangular grid of wires
3. Ground rod(s).
4. Elevated wires in the form of a counterpoise or "capacitive" ground.

5. Various combinations of the above.

The choice of ground system will be dictated by the operating wavelength, available space, soil mechanical characteristics (i.e. sandy loam or tree stumps and boulders), available resources, etc. Because of the much longer wavelengths at LF-MF and significant differences in soil electrical characteristics between LF-MF and HF (shown in chapter 1), the ground systems will be significantly different from what we are accustomed to at HF.

Most of information given here is derived from NEC modeling simply because it's far easier to generate that way but in the end we have to have experimental verification. References [1] through [15] provide this and in general the correlation is excellent. As a practical matter the accuracy of NEC modeling is limited by how well the actual soil electrical characteristics are known. References [9, 15] show how to measure these characteristics but we must keep in mind that soil characteristics vary widely with moisture content with changes of season. We usually have to assume the worst case when modeling. At HF this seasonal variation is usually not noticeable especially if there is an extensive ground system. But with the short, heavily top-loaded verticals and limited ground systems typical on 2200m and 630m, the seasonal change in soil conductivity can significantly detune the antenna. This is mostly a capacitive loading effect as the soil conductivity increases or decreases.

Since the mid 1930's the generally accepted "ideal" for a ground system has been the broadcast (BC) system using 120 0.4λ radials, typically #8 Copperweld buried 12-18". This system originated with the work of Brown, Lewis and Epstein[16] and other work by Brown[17-21] published in the 1930's. The value of this work was immediately recognized and a standard design was adopted by the BC industry and sanctified with FCC regulations. While this was certainly seminal work of great value, it's adoption as a standard had the effect of making ground system design appear to be a "perfected art" and attention shifted to other problems!

5.2 Ground system dimensions

At 475 kHz λ≈2072' and at 137 kHz λ≈7,182'. Most amateurs will not be using 0.4λ radials! For this discussion I have limited ground system radii to ≤150' but even that will be larger than most, so many examples have smaller ground systems.

5.3 Feedpoint equivalent circuit

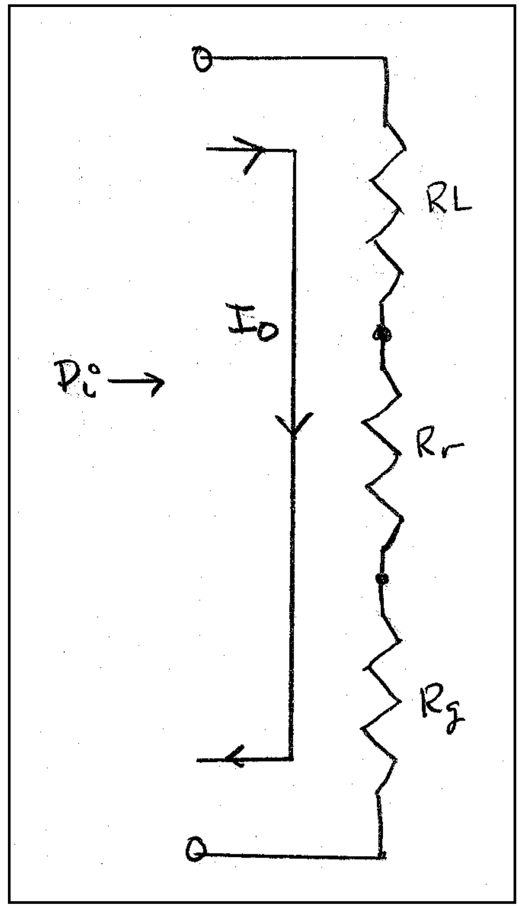

Figure 5.1 - Equivalent circuit for the resistive part of the feedpoint impedance. →

Figure 5.1 is an equivalent circuit often used to represent the resistive part of an antenna's feedpoint impedance (Ri). Rr is the radiation resistance representing the radiated power (Pr) and Io is the current at the feedpoint. Rg accounts for the power dissipated in the soil (Pg) and RL represents the tuning inductor loss. RL is a physical resistor arising from the series resistance (RL=XL/QL) of the inductor, but Rr and Rg are not lumped physical resistors.

In earlier chapters we've seen how dependent Rr is on specific details of the antenna: i.e. dimensions and loading. Earlier examples determined Rr with perfect ground but Rr can also be a function of soil electrical characteristics and ground system design. This effect is prominent at HF though significantly less at LF/MF[22] as is discussed in appendix TBD.

Rg depends on frequency, soil electrical characteristics, details of the ground system and the antenna associated with the ground system. If we modify the antenna, even without changing the ground system or soil, Rg will change. The reason for the change in Rg is that the soil loss depends on the EM field intensities close to the antenna. The field intensity changes when the antenna is altered which in turn changes soil loss and Rg. For example, the field intensities are directly proportional to Io, when we add top-loading Rr increases which means we must reduce Io to stay within the Pr limits. Reduced Io results in less power dissipation in the soil and an altered value for Rg.

5.4 Definitions for Pr, Pg, Rr and Rg

Figure 5.2 illustrates "Pr" and "Pg". The dashed line represents a hypothetical cylindrical surface, with radius r, enclosing the antenna. Pg is defined as the power radiated through the bottom of the cylinder, which is the ground surface, and dissipated in the soil. r=λ/2 is usually chosen because it is approximately the outer boundary of the reactive near-field for verticals with a height of λ/8-λ/4 (see appendix TBD). For shorter antennas r is somewhat smaller[22]. Pr is defined as the total power radiated through the other surfaces of the cylinder (top and sides).

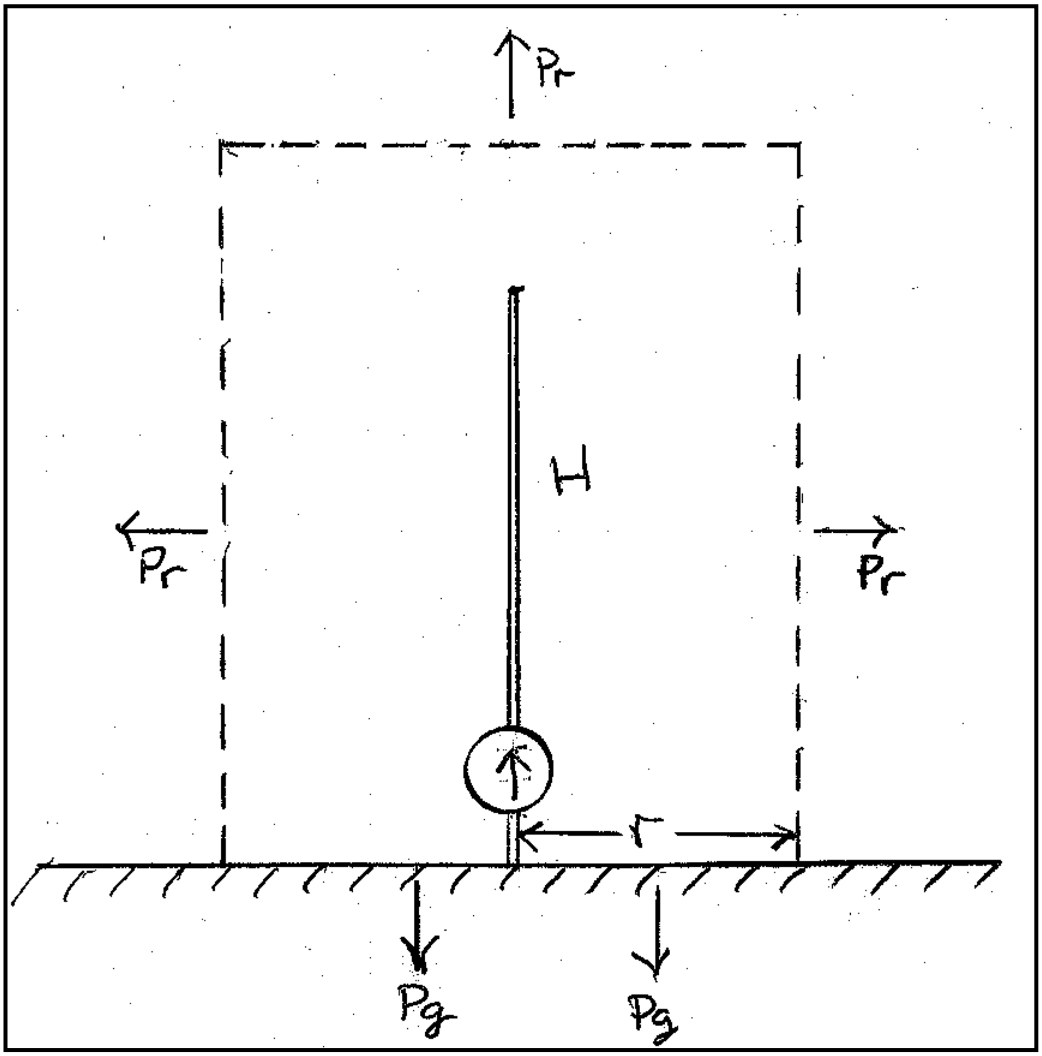

Figure 5.2 - Pr and Pg.

Rr and Rg are defined in terms of Pr and Pg:

$$\mathbf{Rr} \equiv \frac{\mathbf{P_r}}{\mathbf{I_o^2}}\ \boldsymbol{\Omega} \quad (5.1) \qquad \mathbf{Rg} \equiv \frac{\mathbf{P_g}}{\mathbf{I_o^2}}\ \boldsymbol{\Omega} \quad (5.2)$$

5.5 Efficiency with ground losses

In the following discussion Ri at the feedpoint is assumed to be the sum of Rr + Rg + RL. Conductor and other losses will be omitted, not because these are unimportant, but the interest here is in RL/Rr and Rg/Rr. We can state efficiency η In terms of Rr, RL and Rg:

$$\eta = \frac{1}{1+\frac{R_L}{R_r}+\frac{R_g}{R_r}} \qquad (5.3)$$

5.6 Simple advice

The instructions for an adequate ground system can be boiled down to:

1) Use at least 50 radials. Note, we are not talking about 0.25λ radials! Most backyards will only have room for 30-40' radials. Where possible the radials should be somewhat longer than the height of the vertical

2) In the case of a very large top-hat, the radials should extend out to 1.25X the top-hat radius if possible.

3) When a large number of radials are used the size is not important. The wire needs to be strong enough to be installed and survive in its environment.

4) Almost any metal can be used for the radials but the usual choice is insulated copper house wiring because it is usually cheaper than the same wire bare. For an elevated system #17 aluminum electric fence wire can be used. However, lying on the surface or buried, aluminum wire may degrade quickly

5) If the radials are lying on the surface, use lots of staples to keep them close to the ground so mowing or other traffic will not damage them.

6) Use at least one ground stake at the base for safety.

5.7 Ground system for an unloaded vertical

Figure 5.3 shows a typical buried radial wire ground system.

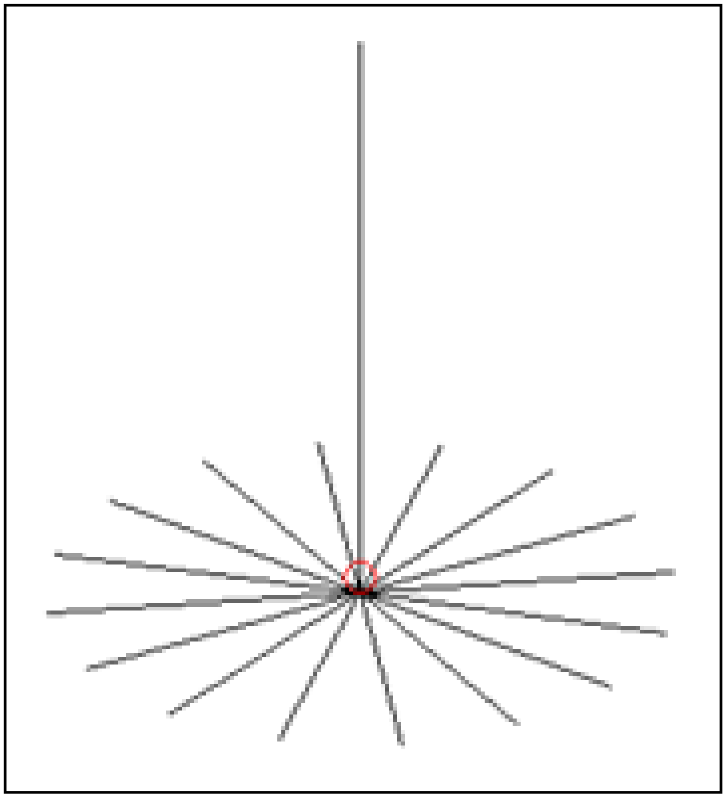

Figure 5.3 -Vertical with a buried wire radial ground system

Typical urban lots have a width of 50-60' and a depth of roughly 100-120'. Usually most of the lot will be occupied by the house and front yard setbacks so in the end at most a 50'X50' area is available for the ground system. For those lucky enough to have more property longer radials can be used so for the following discussion radial lengths from 25' to 150' will be used. Unless noted otherwise average soil (0.005/13) is assumed along with bare #12 radial wire buried 12". Insulation on the wires and larger or smaller wire sizes generally have only small effects. Radial wires can also be lying on the ground surface with similar effectiveness.

Figure 5.4 is an example of how efficiency varies as a function of radial length for a given number of radials (32 in this case). For H=20' the maximum usable radial length is about 30'. Making the radials longer has very little effect. The reason is that in a vertical this short Xi is very large which means a large loading inductor (XL=Xi) and consequently large RL. For this short a vertical RL is large compared to Rr and it's also becomes large compared to Rg as radial length approaches 30', i.e. Rg falls as the radial lengths are increased so that it becomes small compared to RL.

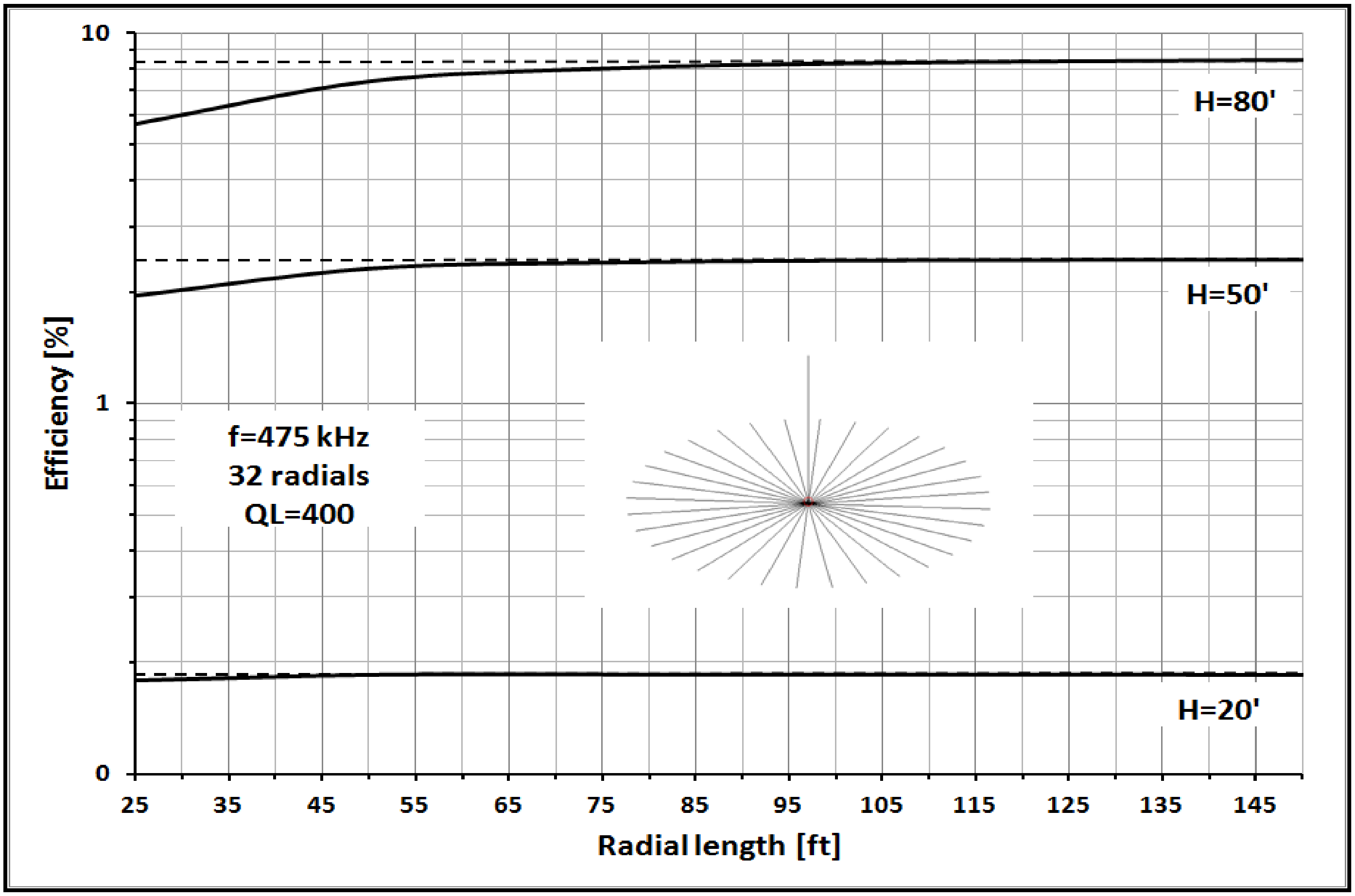

Figure 5.4 - Efficiency as a function of H and radial length.

As we increase H the efficiency rises quickly because RL is reduced and the maximum usable radial length expands to 50' or more. There is a further increase in efficiency and usable radial length when we let H=80' but even with that height the efficiency is not very good. As shown in chapter 3 even a small amount of capacitive top-loading can greatly reduce Xi and improve efficiency. In addition, because the loading inductance will be much larger on 2200m, the dominance of the RL will be even more pronounced. For those reasons the use of at least some top-loading will be assumed in the following discussion.

5.8 Ground systems for urban lots

In this and following sections T antennas with H=20', 50' or 80' and a top-wire length =100' will be used to illustrate the interplay between efficiency, radial length, radial number, QL and H. It should be kept in mind that although the following examples use a single top-wire for loading, any loading structure which gives similar value for Xt will produce the same result. As emphasized in chapter 3, it's the amount of loading (Xt) not the shape that matters. This means the conclusions we'll draw from the following graphs can apply to different antennas with similar heights.

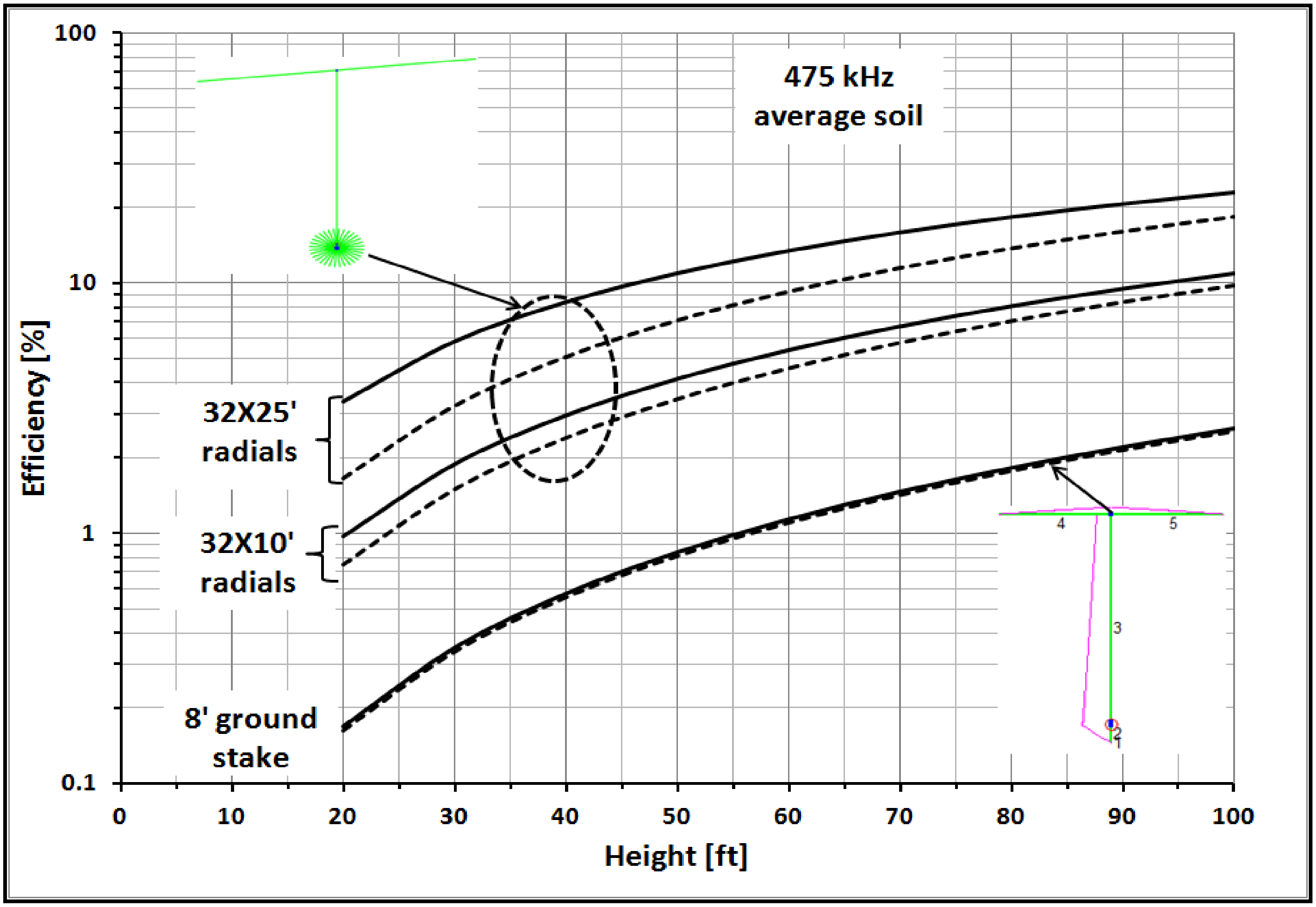

Figure 5.5 - Small ground system comparison.

The simplest ground system would be a single ground stake. From there we can add various numbers of radials of lengths up to 25'. It is also possible to have a radial system with ground stakes at the far ends of the radials.

Figure 5.5 gives comparisons between three ground systems: a single 8'X5/8" ground rod or stake, thirty two 10' radials and thirty two 25' radials. The solid lines represent the efficiency without the tuning inductor loss and the dashed lines represent the efficiency when QL=400. With a the single ground rod the ground loss (Rg) is so large that RL doesn't matter very much. As soon as we add even the small radial system (32X10') the efficiency increases by almost an order of magnitude and expanding the radial lengths to 25' yields another factor of ≈3X in efficiency. This is due to reductions in Rg with longer radials.

As shown in figure 5.6, increasing the radial number to 64 improves the efficiency but not by a lot. The efficiency tapers off because the Rg/Rr term becomes small compared to the RL/Rr term. Another option when radial lengths are restricted by available space is to add ground stakes at the ends as indicated in figure 5.24. This yields more improvement in efficiency than doubling the radial number but represents significant cost and labor for which only 1% or so is gained!

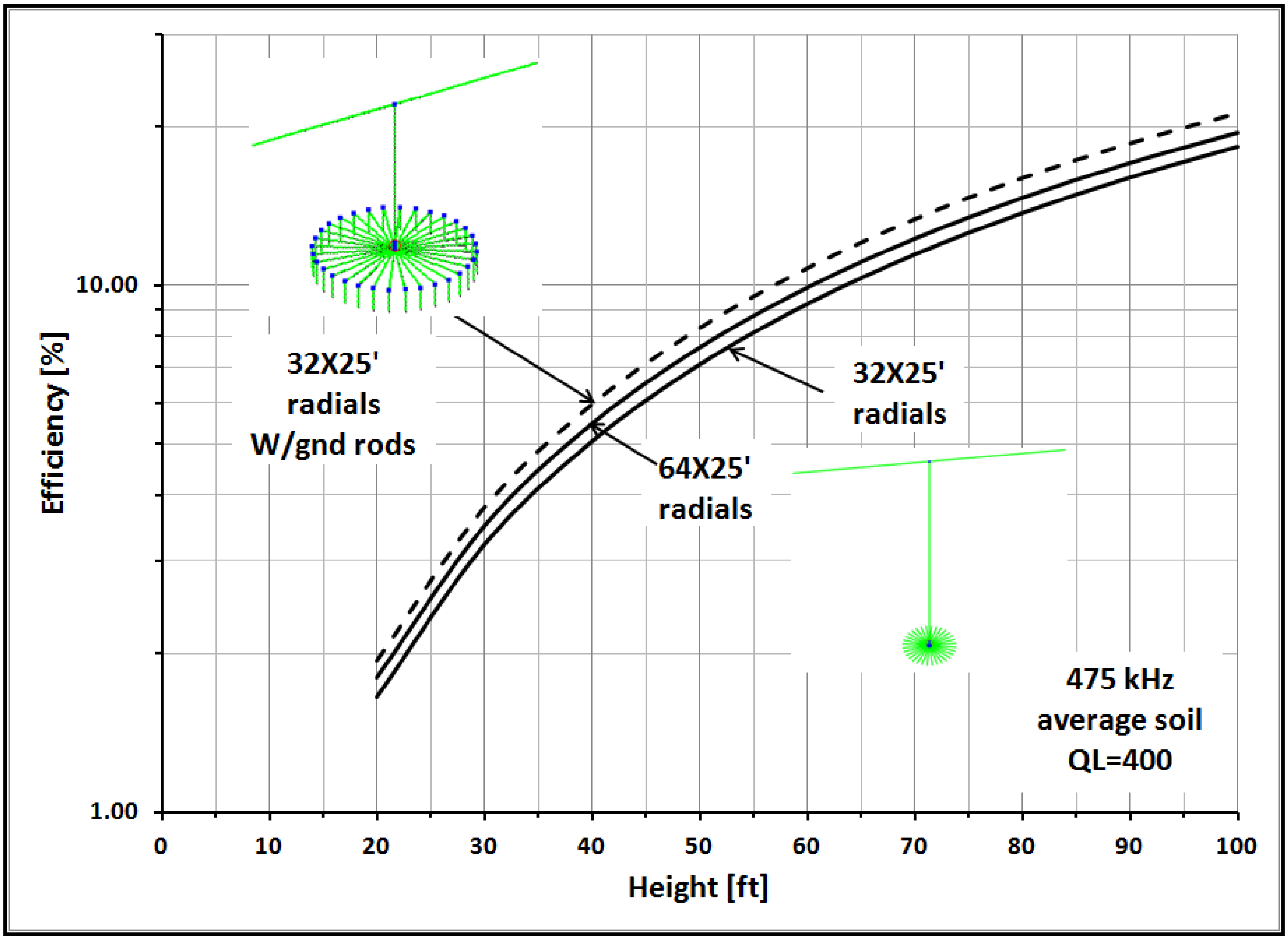

Figure 5.6 - Increasing radial number and adding ground stakes.

5.9 Larger ground systems

Figure 5.7 shows efficiency as a function of radial length with the radial number as a parameter. The dashed lines are straight-line approximations for the curves which allow us to identify the point of vanishing returns, i.e. the point at which increasing the radial length begins to provide less improvement. On some of the graphs this point is labeled the "knee". Many of the graphs to follow will have these dashed lines. Two points to notice, first increasing the radial number is very helpful, in fact we could have gone to 128 radials and still have had some useful improvement. Of course every time you double the number of radials you double the amount of wire used! Second, the efficiency improves rapidly up to lengths of 60-70' before leveling out. By 150' there isn't much point in making the radials longer. Independent of radial number (for this example!) the "knee" corresponds to a radial length of ≈65'-70' which is a bit more than H (50'). This the reason for comment 1 in section 5.6. Note that 64 radials are only marginally better than 32.

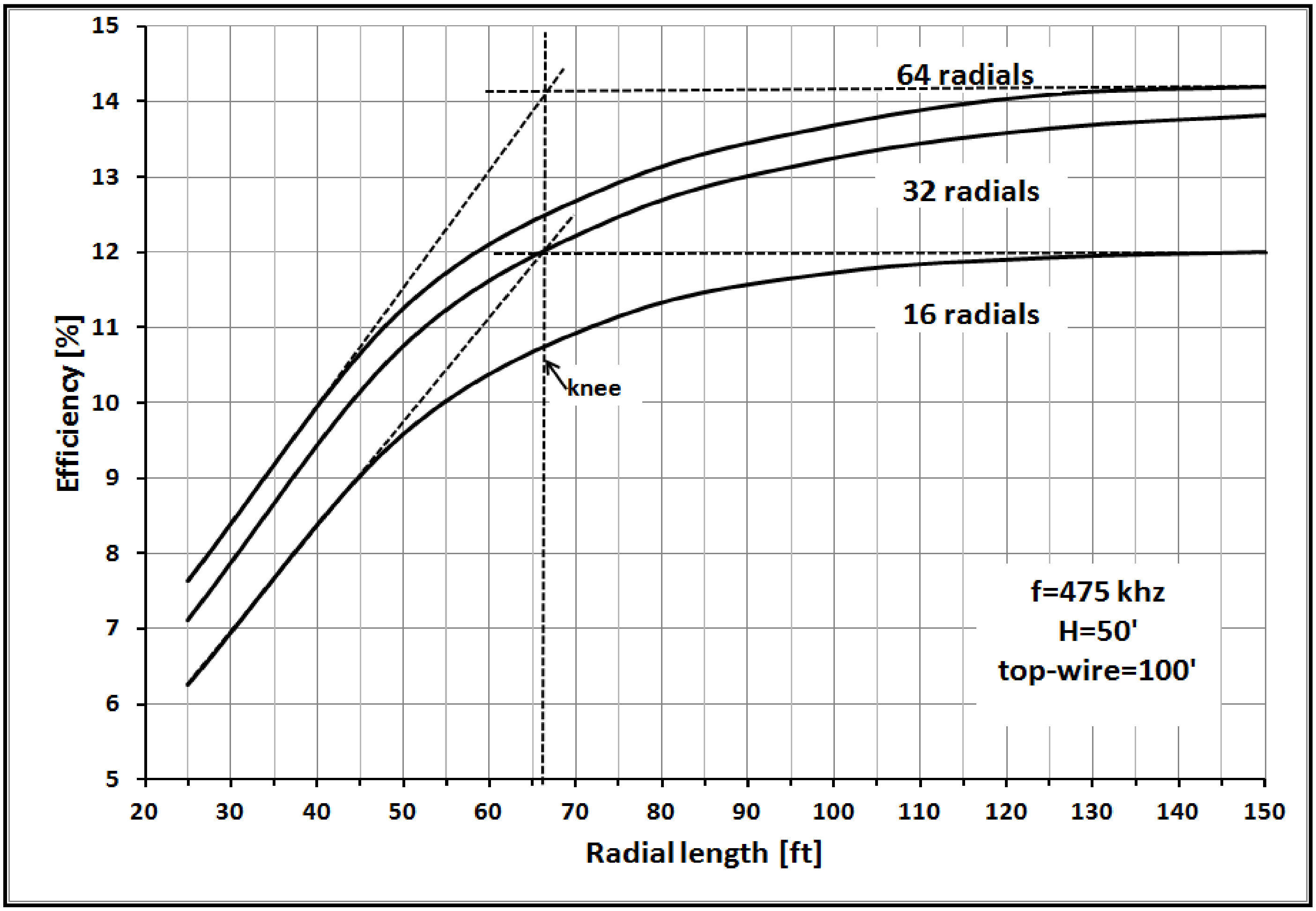

Figure 5.7 - Efficiency versus radial length.

Figure 5.8 graphs the same data in a different way, efficiency as a function of radial number for different radial lengths. Independent of radial length, the knee is about 30 radials. Above the knee it's better to use longer radials rather than more numerous radials! This behavior is quite different from what is normally seen in HF verticals. At HF the radial lengths are typically 0.125λ or longer but at 475 kHz 50' is only 0.024λ and the E and H fields are quite different as shown in appendix TBD. Ground system optimization is somewhat different at LF-MF.

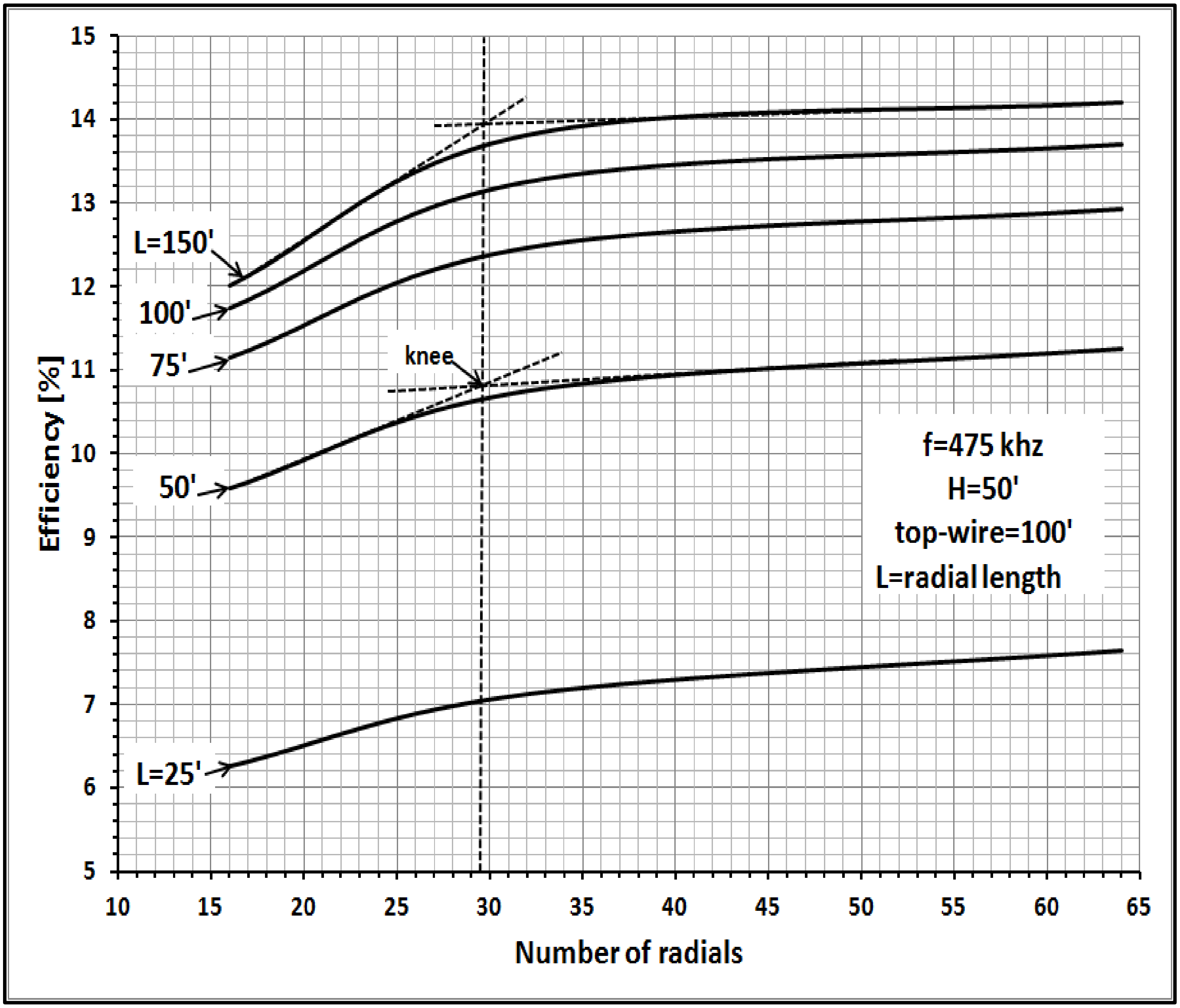

Figure 5.8 -efficiency versus radial number for different radial lengths.

One frequently asked question is, "If I have a limited amount of wire available for radials how should I divide it up?" In other words, "should I use a few long radials or many short radials?" We can re-plot the data in figure 5.8 to answer that question as shown in figure 5.9. Here we see that for H=20', 32X50' radials would be the best use of the wire. At H=50' or 80' either 16X100' or 32X50' radials would work pretty much the same. Given that 50' radials take up 1/4 the area of the 100' radials, 32X50' radials would seem to be a good choice in those cases also. It is interesting to note 32 radials is close to the knee value for the radials in figure 5.8, although this should not come as a great surprise since all three of these graphs are using the same data graphed in different ways.

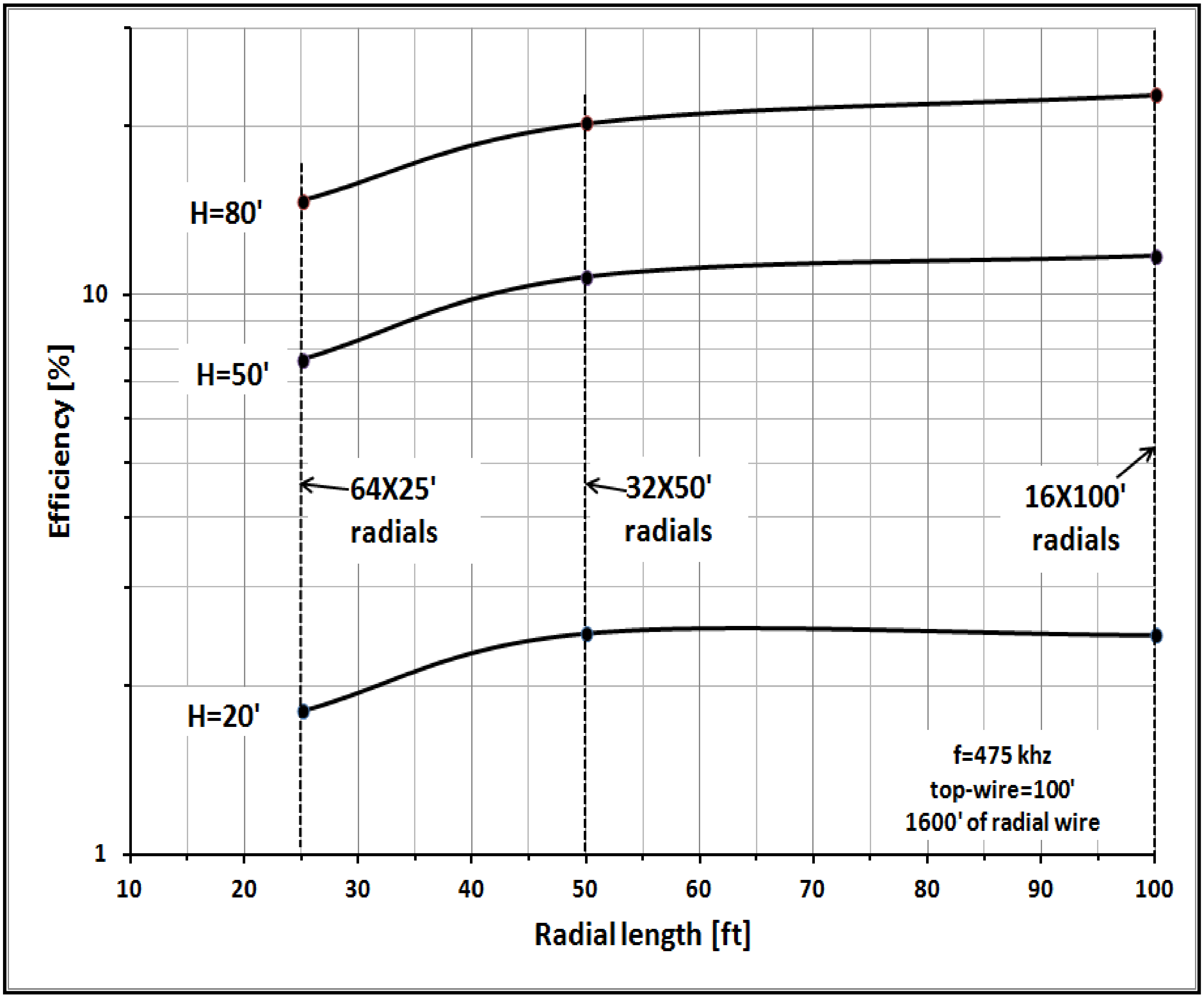

Figure 5.9 - Efficiency versus radial length for various heights.

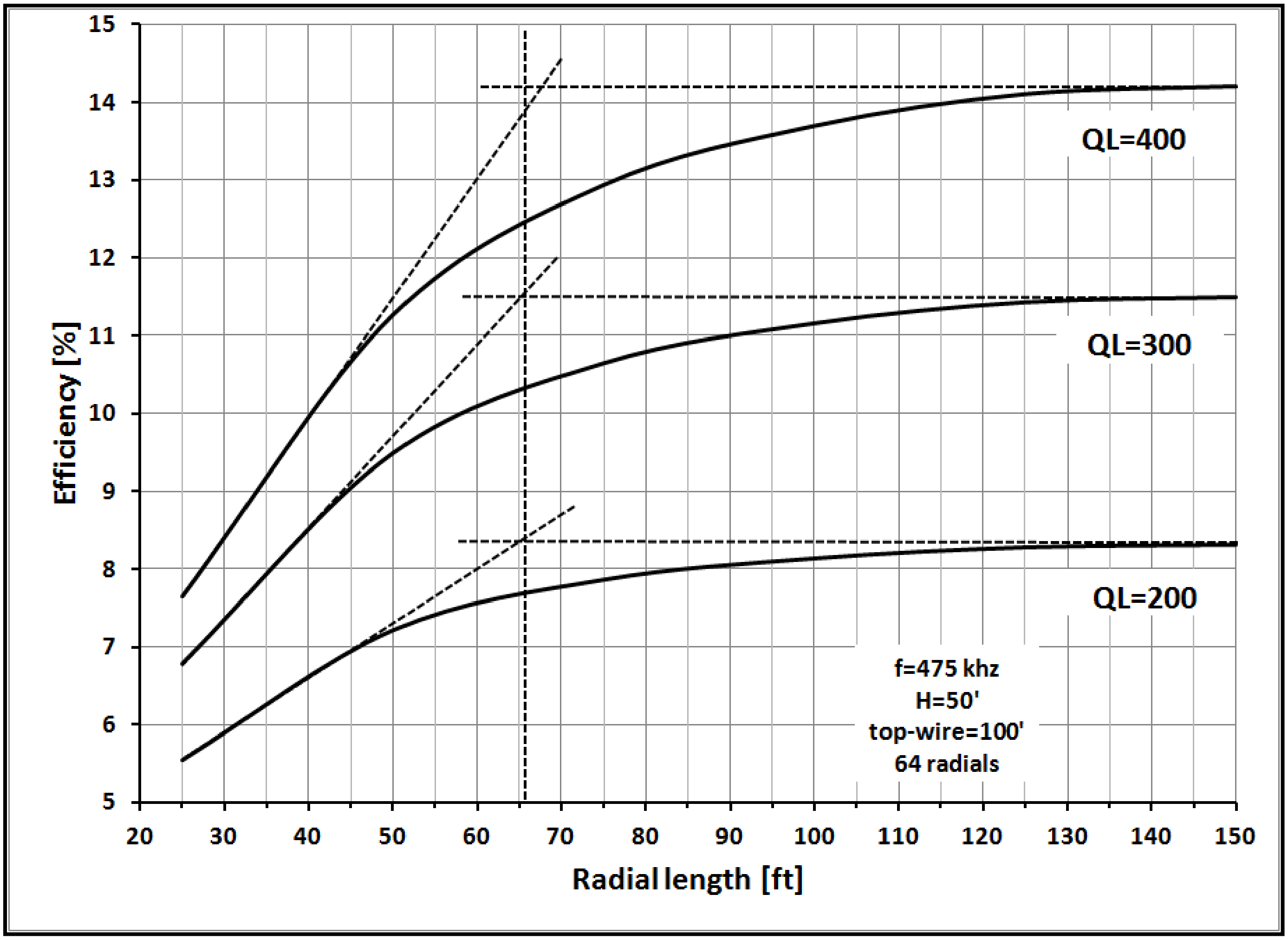

Figure 5.10 -Efficiency versus radial length versus QL.

Up to this point QL has been assumed to be 400. At 475 kHz that's practical with some modest effort. However, as shown in chapter 6, much higher QL is possible but requires careful inductor design and construction. Figure 5.10 illustrates what happens to the efficiency when QL is lower, as it easily could be. This graph shows how critical QL is for efficiency. For radial lengths < 70' both QL and radial length play a role but as we make the radials longer the accompanying reduction in Rg/Rr gets smaller and RL dominates. This again reminds us that if we really want higher efficiency we need to increase height and/or Xt. With more top-loading, RL is smaller and longer radials can be used to advantage.

Figures 5.11 through 5.13 are another way to show the relationship between H, radial length and radial number.

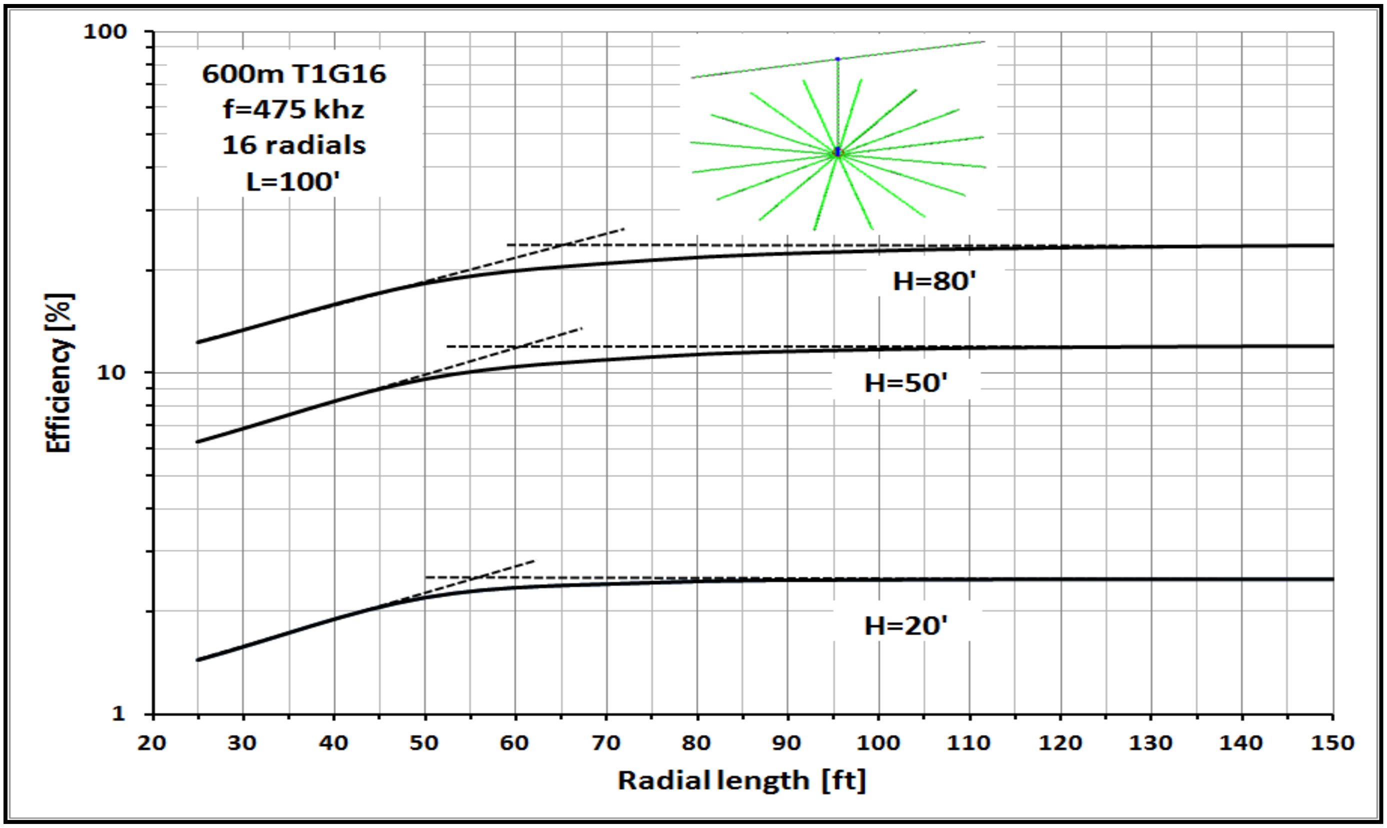

Figure 5.11-Efficiency versus radial length, 16 radials.

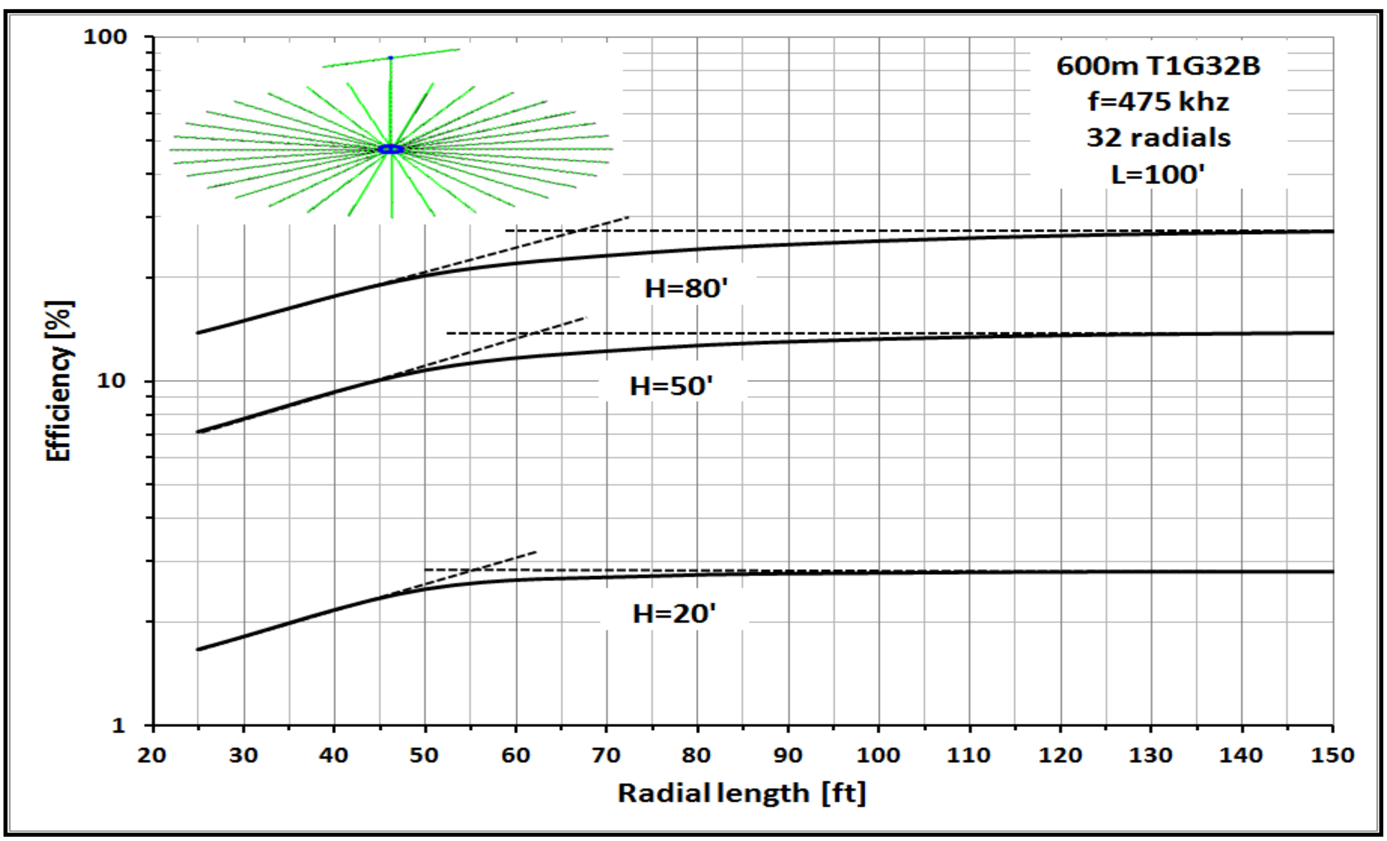

Figure 5.12 - Efficiency versus radial length, 32 radials.

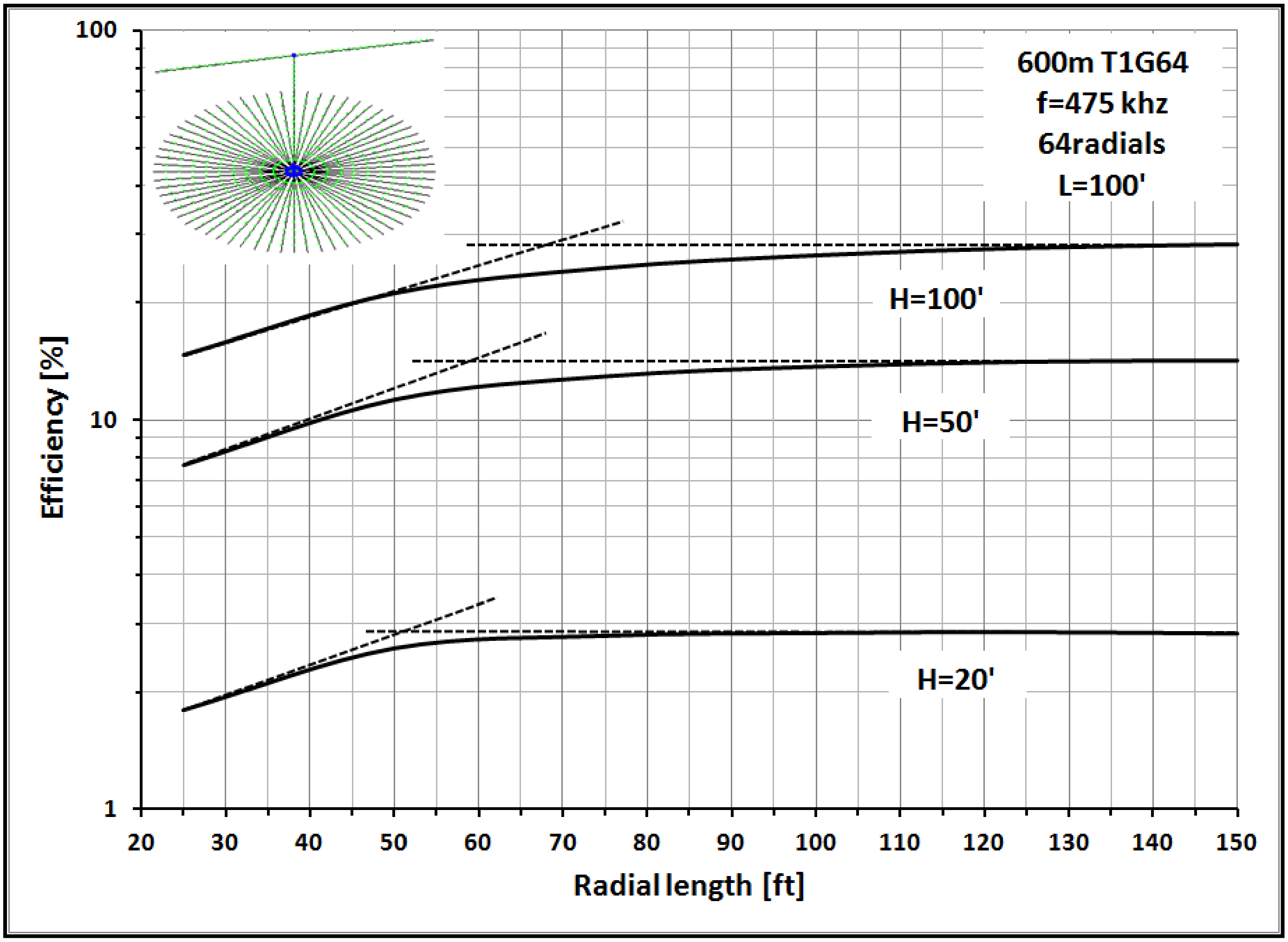

Figure 5.13 - Efficiency versus radial length, 64 radials.

The earlier suggestion that radial length is related to height has long been part of amateur antenna lore. The idea is that with a 1/4-wave antenna you use 1/-4wave radials and with an 1/8-wave vertical 1/8-wave radials, etc. To explore this idea I modeled 1/4-wave and 1/8-wave verticals at 1.8 MHz over average soil (0.005 S/m, Er=13). The radial lengths were stepped in the sequence 1/8, 1/4, 3/8, 1/2-wavelength. The number of radials was stepped in the sequence 4, 8, 16, 32, 64 and 128. At each point I recorded the average gain (Ga) and used this as a measure of relative efficiency between different radial configurations. The radials were buried 3" below the ground surface.

The results are shown in figures 5.14 and 5.15. Note that the vertical axis is "improvement" in dB when going from four 1/8-wave radials to more and/or longer radials. The gain for four 1/8-wave radials was used as the reference and set to 0 dB. This nicely illustrates what you might "gain" by adding more wire, in different ways, to the radial fan.

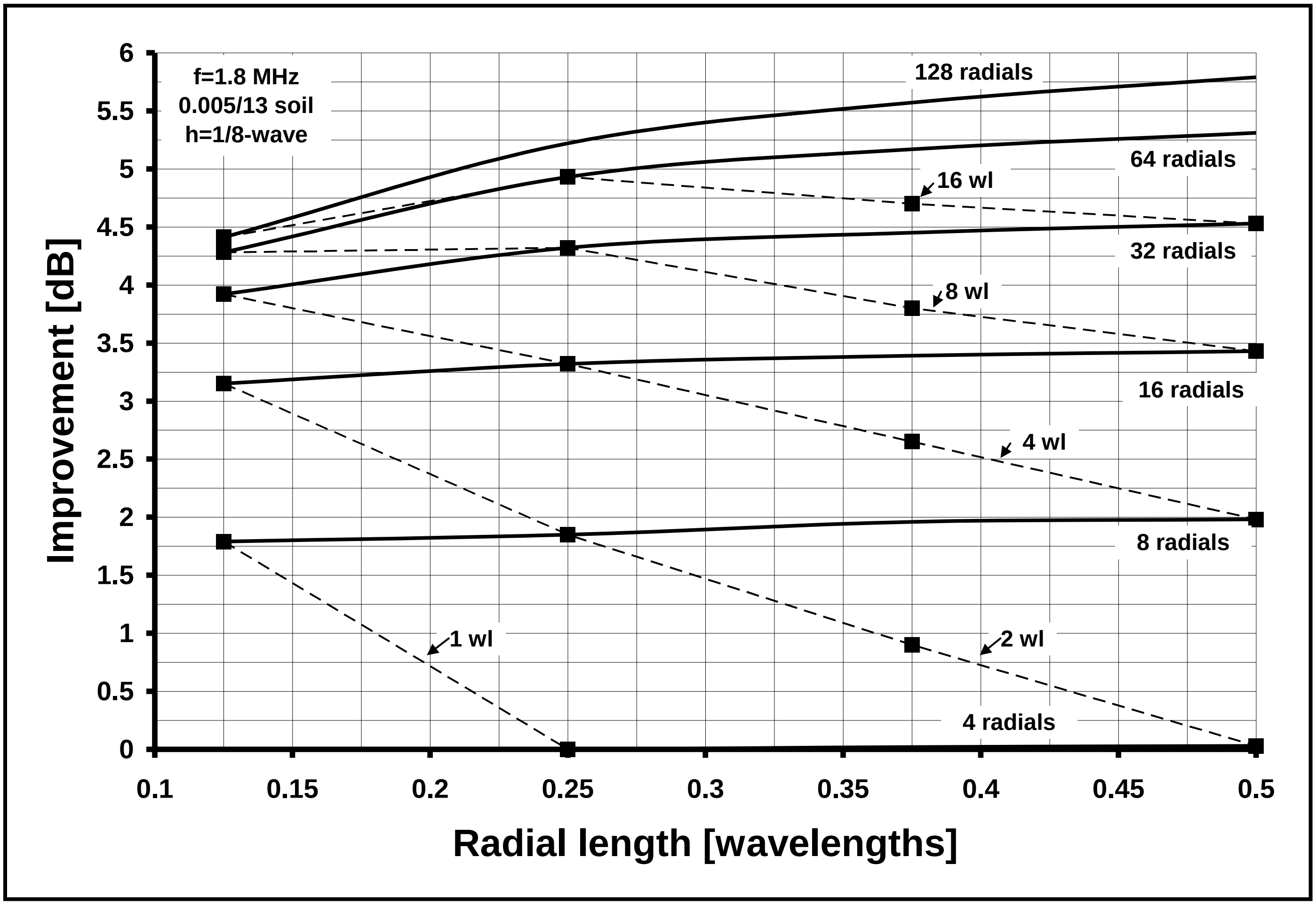

Figure 5.14, Signal improvement for various radial configurations: 1/8-wave vertical.

Note that the solid lines represent constant radial numbers of different lengths. The dashed lines connect points of common total radial wire length: 1, 2, 4, 8 and 16 wavelengths. For example, 4 radials 1/2-wave long represent a wire total of 2-wavelengths. Eight 1/4-wave and sixteen 1/8-wave radials also total 2-wavelengths, etc. 16 wavelengths at 1.8 MHz is almost 9,000' of wire, which is a substantial ground system (64 1/4-wave radials).

These graphs show that <u>how</u> you add wire to the radial system matters as well as <u>how much</u> wire you add. As we can see from the graphs when only a few radials are used (4 to 8 radials), making them longer is waste. In fact[2] you can actually lose in the case of ground surface radials. This is by no means a first look into optimum radial lengths, Stanley[23], Sommer[24] and Christman[25] have all written on this subject.

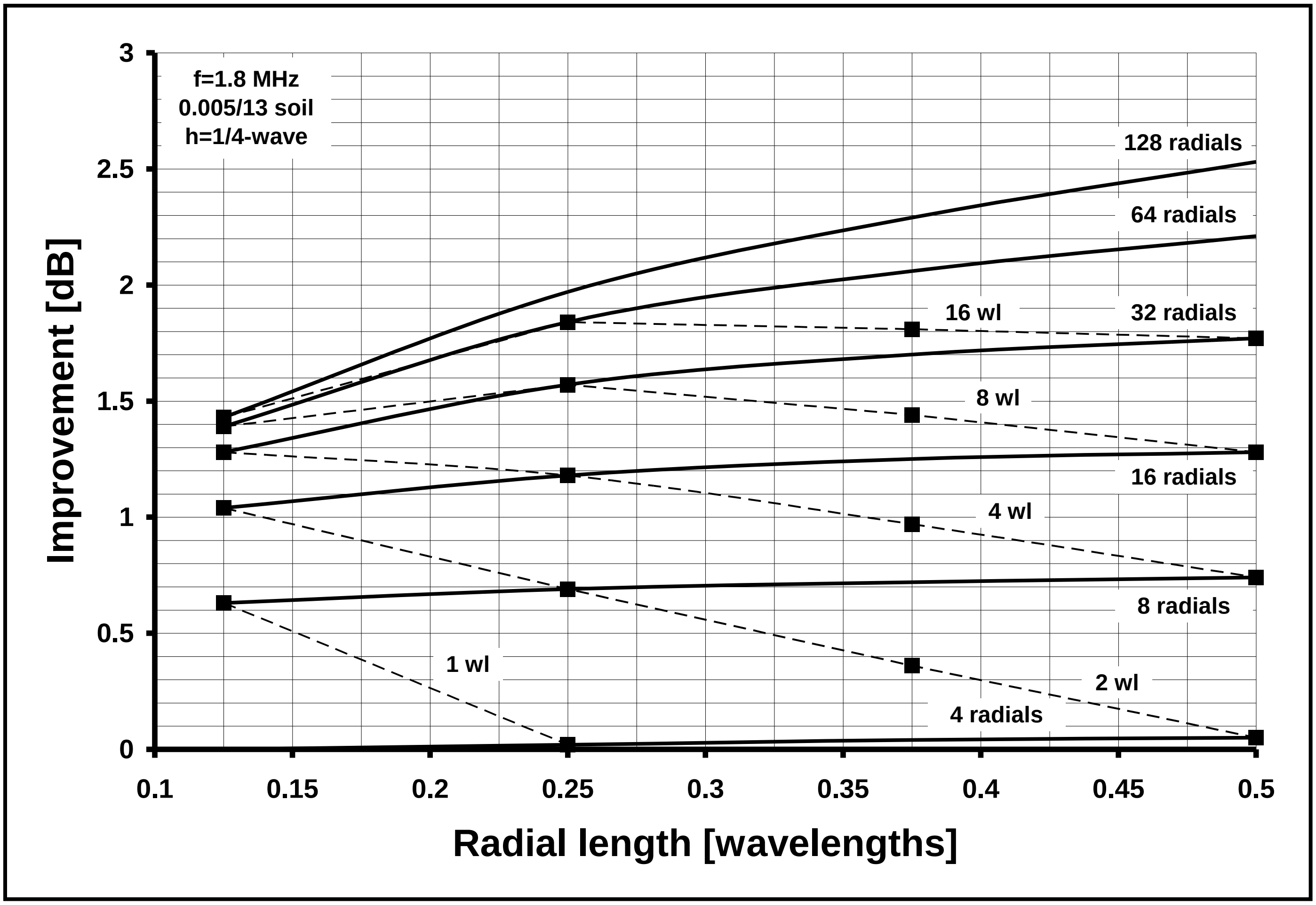

Figure 15, signal improvement for various radial combinations: 1/4-wave vertical.

Referring to figure 5.14 (the 1/8-wave vertical), if your total wire length is limited to four wavelengths, the gain improvement goes from 2 dB with 8 radials to 3.3 dB with 16 radials and 3.9 dB with 32 radials. Obviously you're much better off to using thirty two 1/8-wave radials as apposed to a smaller number of longer radials. When you increase the wire length to 8 wavelengths then it's a wash whether you use either thirty two 1/4-wave or sixty four 1/8-wave radials. The choice becomes one of convenience in laying out the radial field. If you don't have room for the 1/4-wave radials then the larger number of 1/8-wave radials will work just as well. When you go up to 16 wavelengths of wire then sixty four 1/4-wave radials will give you about 0.6 dB improvement over 128 1/8-wave radials.

When we look at the gain improvement in figure 5.15 (the 1/4-wave vertical), we see similar behavior except that when we are using 8 wavelengths of wire there is a clear advantage to go from 1/8-wave to 1/4-wave radial lengths. 1/4-wave radials also work best when 16 wavelengths of wire are available. If we go up to 32 wavelengths of wire (about 18,000'!) then radial lengths of 3/8-wavelength are best.

These graphs shed some light on a long standing rule of thumb: "the radials should be the same length as the height of the vertical". In the case of the 1/8-wave vertical this seems to be true up to at least 8 wavelengths of total radial wire. Beyond this, longer radials become a more effective use of the wire. In the case of the 1/4-wave vertical, for small amounts of wire, 1/8-wave radials are best but as we make more wire available the 1/4-wave radials are superior. The break point in radial number where you shift from 1/8-wave to 1/4-wave lengths is lower for the 1/4-wave vertical than the 1/8-wave vertical.

The physics of this seem fairly clear. Once you have greatly reduced the losses near the base of the antenna, adding more close in copper doesn't buy much. At some point it's time to put the copper further out and reduce more distant losses, which may be smaller but still significant. The difference in break point (in terms of radial number) between the two antennas stems from differences in the field intensities around the two antennas. For the same power, the fields near the base of the 1/8-wave vertical will be much higher than those for the 1/4-wave vertical (see appendix TBD) so we need to put more effort into reducing the close-in power losses.

The forgoing optimization was for relatively tall antennas. Figure 5.16 shows an a short top-loaded vertical for 630m.

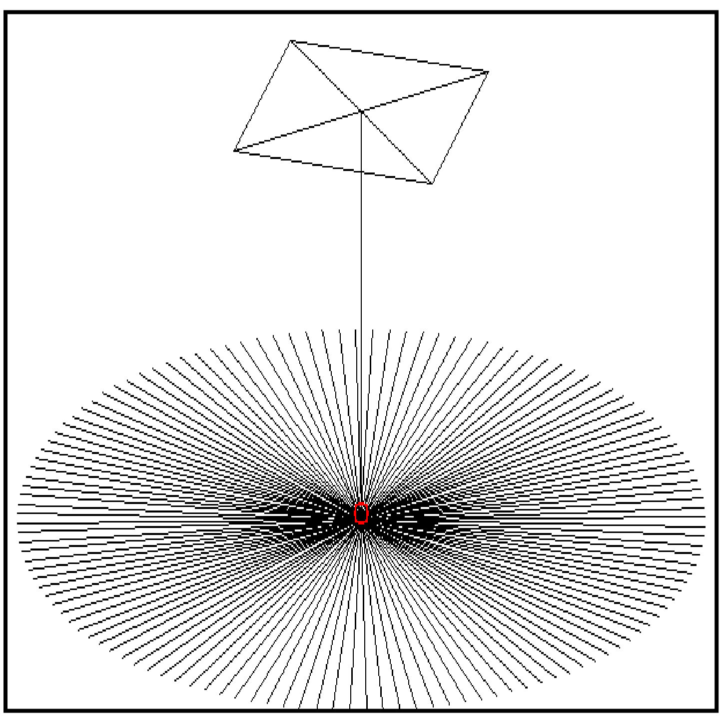

Figure 5.16 - typical 630m antenna.

The vertical is 15.24m high (50', 0.024λ) with 7.62m (25', 0.012λ) radial arms in the hat. The usual practice for very short verticals is to have a dense ground system which extends some distance beyond the edge of the top-hat and/or a bit longer than the height of the vertical.

5.10 Elevated ground systems

In many cases the ground under and near the antenna may not be suitable for a buried radial system. Systems with elevated wires are well known at HF, i.e. ground-plane verticals, but these systems typically use radials with lengths close to λ/4. For most amateur installations this will not be possible but all is not lost. In the early days of radio ground systems it was recognized that an elevated system called a "counterpoise" or "capacitive ground", with dimensions significantly smaller than λ/4, could be very effective. Figure 5.17 shows an example of a counterpoise.

Here is an interesting quotation from Laport[26] regarding counterpoises:

> ***"From the earliest days of radio the merits of the counterpoise as a low-loss ground system have been recognized because of the way in that the current densities in the ground are more or less uniformly distributed over the area of the counterpoise. It is inconvenient structurally to use very extensive counterpoise systems, and this is the principle reason that has limited their application. The size of the counterpoise depends upon the frequency. It should have sufficient capacitance to have a relatively low reactance at the working frequency so as to minimize the counterpoise potentials with respect to ground. The potential existing on the counterpoise may be a physical hazard that may also be objectionable."***

Rectangular counterpoises, some with a coarse rectangular mesh, were common. A rather grand radial-wire counterpoise is shown in Figure 5.18. Amateurs also used counterpoises. Figure 5.19 is a sketch of the antenna used for the initial transatlantic tests by amateurs (1BCG) in 1921-22[27,28]. The operating frequency for the tests was about 1.3 MHz (230m). At 1.3 MHz λ/4 = 189' so the 60' radius of the counterpoise corresponds to ≈0.08λ.

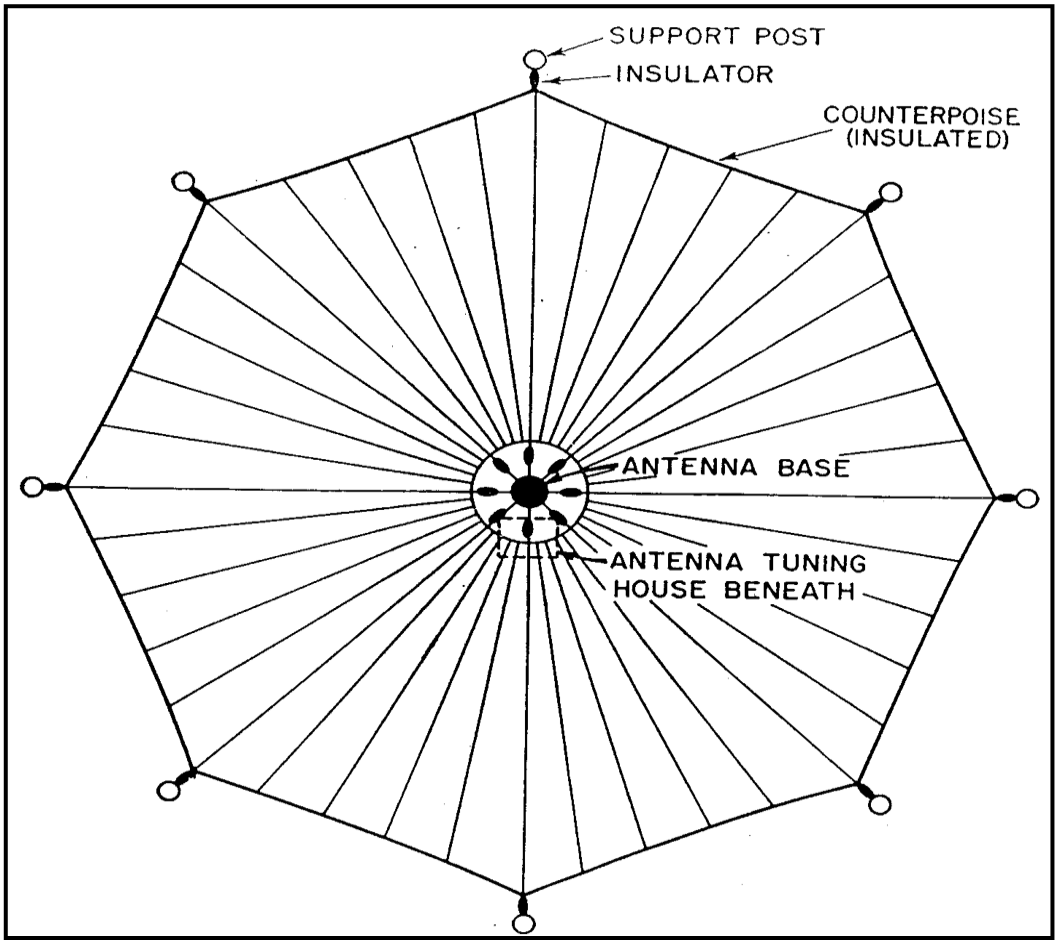

Figure 5.17 - A typical counterpoise ground system. Figure from Laport[26].

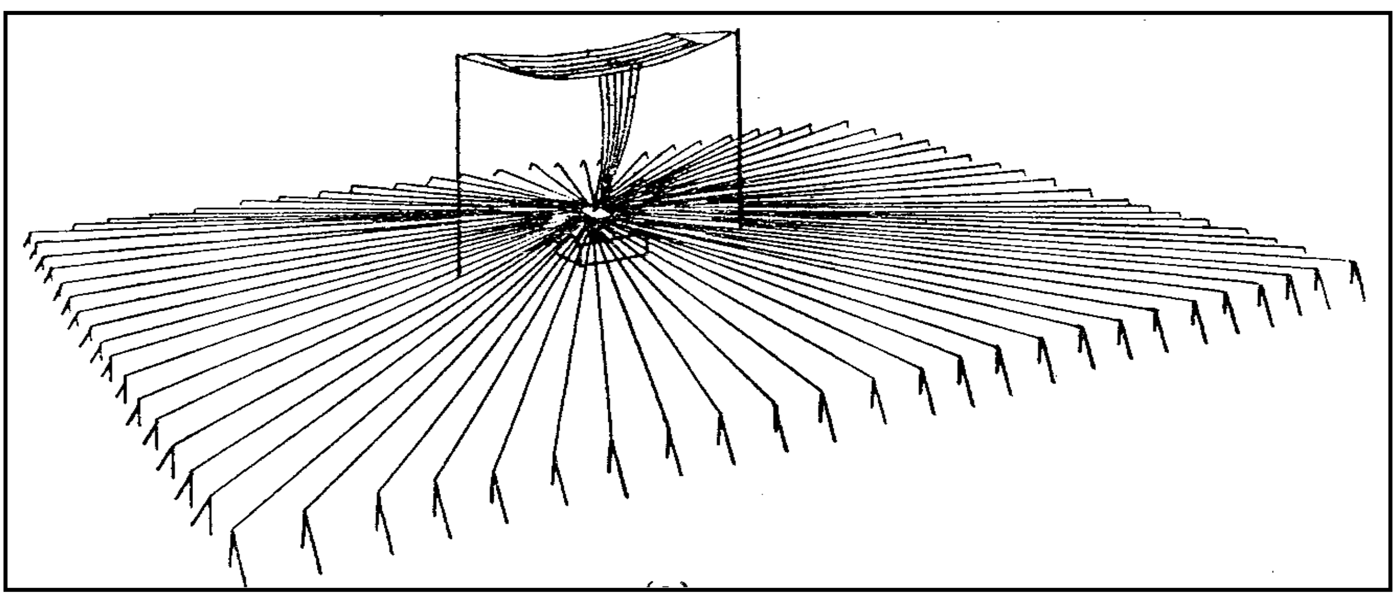

Figure 5.18- A very large LF elevated ground system. From [29].

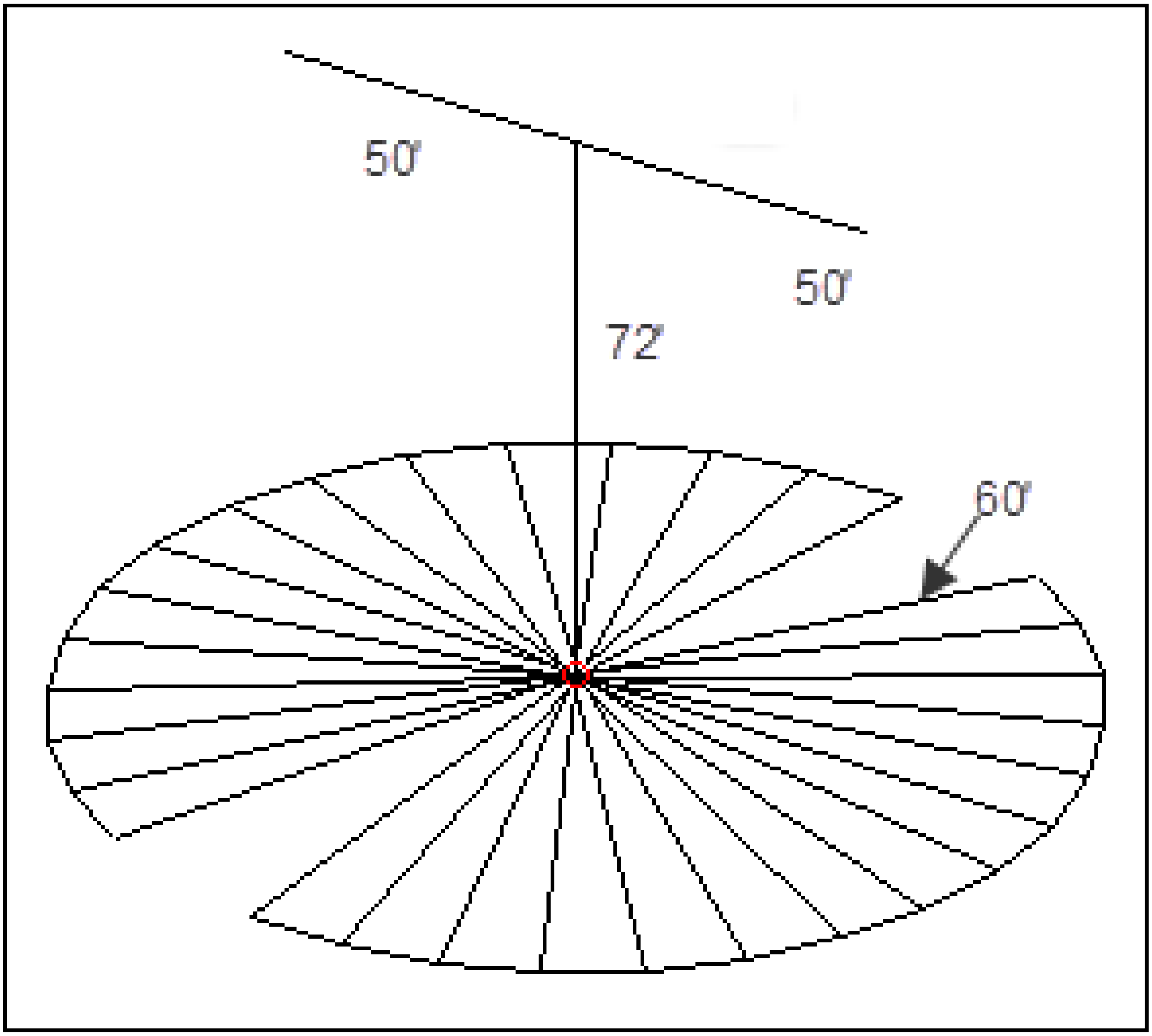

Figure 5.19 - EZNEC model of the 1BCG antenna.

Note that in all these examples a large number of radials were used.

We could replace the buried radial systems shown earlier with a counterpoise. For safety reasons the counterpoise will have to be at least 8' off the ground so that there is no danger of casual contact with the high potentials on the counterpoise while transmitting. For the moment we'll keep the height of the top of the vertical at 50' and assume a 16-wire, 25' radius umbrella with a skirt. This means that the total length of the vertical will be reduced from 50' to 42'. Figure 5.20 shows a comparison between 64 radial buried radial systems and 16 radial counterpoises (with skirt wires) as the radius of the ground system is varied from 10' to 50'. Note, in figures 5.20-5.24 the solid lines are for the counterpoise and the dashed lines are for the buried wire system.

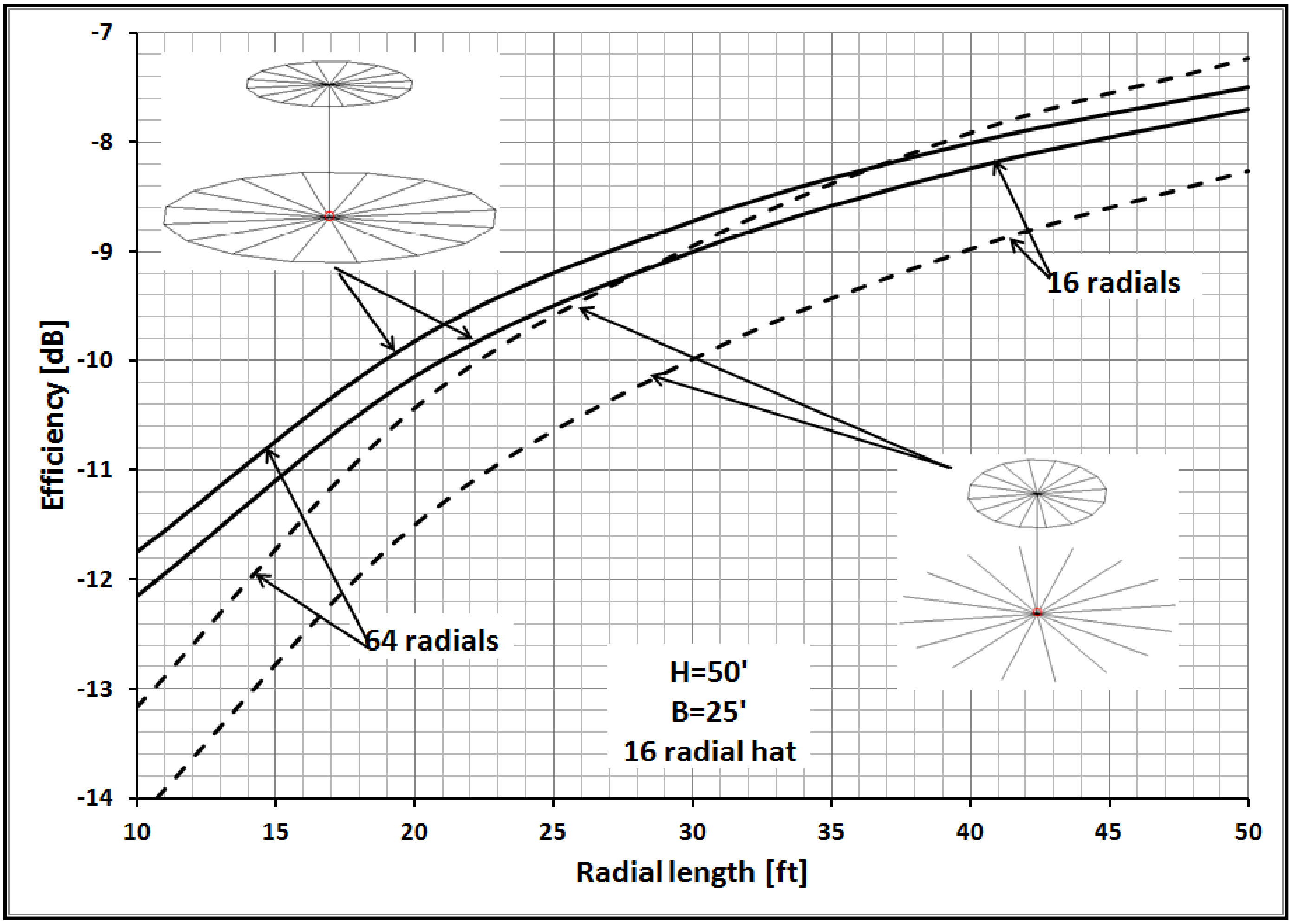

Figure 5.20 - A comparison between buried ground systems and counterpoises.

With 16 radials the counterpoise is superior for radii less than 100'. With 64 wires the counterpoise is better out to about 35' after which the buried system is better. That's great but we have to remember that the counterpoise is a large and very visible elevated structure while the buried or ground surface system is out of sight. In addition the counterpoise will require posts to support the ends, insulators at the outer periphery, a larger value for the loading inductor and an isolation choke for the feedline.

This is just for one example. To generalize to other configurations it's useful to look in more detail at what's happening to Rr and the loss components RL and Rg as we vary the ground system radius. Figures 5.21 through 5.23 show comparisons between a buried system and a counterpoise of Rr, RL and Rg as a function of radial length. Note, the top is constant at 50', for the counterpoise H=42' but for the buried system H=50'.

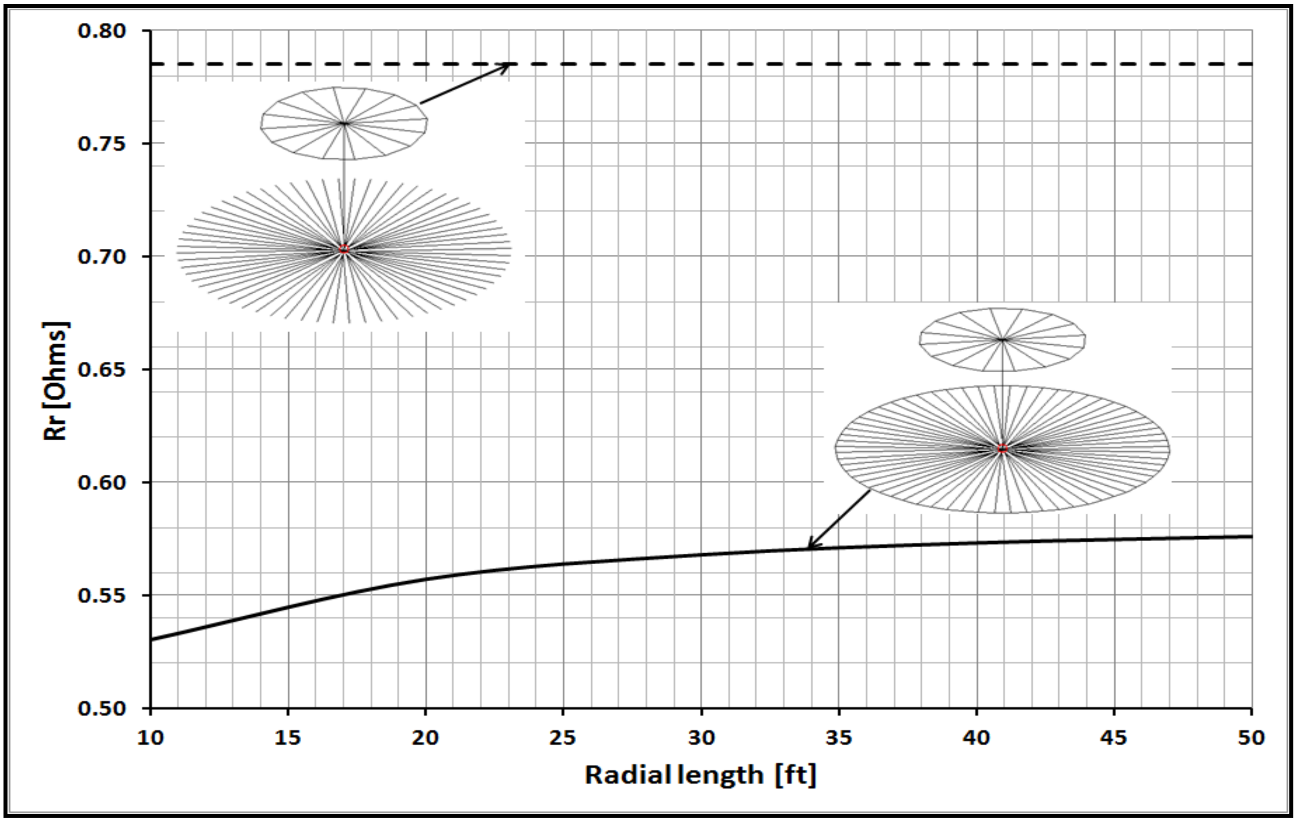

Figure 5.21 - Comparison for Rr between buried and counterpoise ground systems.

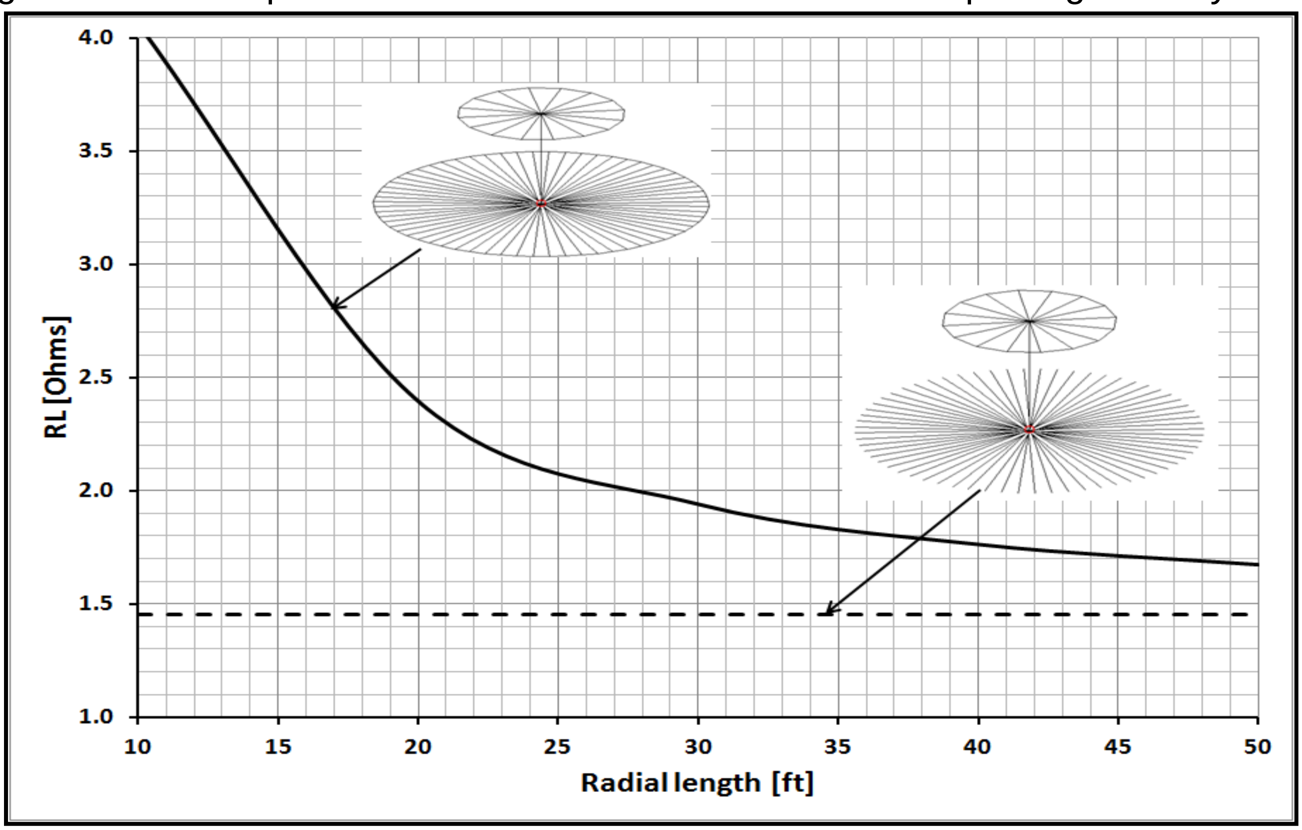

Figure 5.22 - Comparison for RL between buried and counterpoise ground systems.

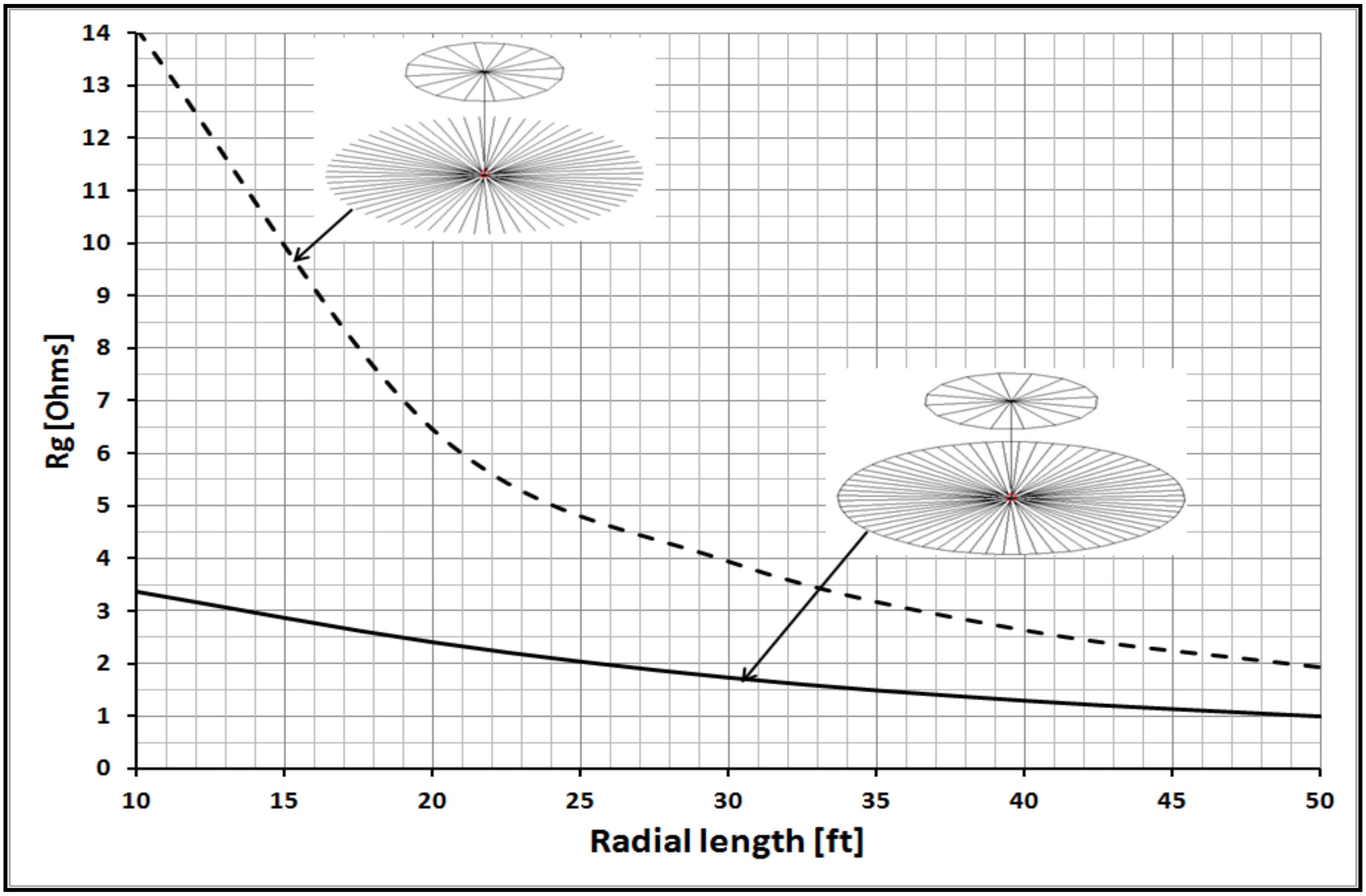

Figure 5.23 - Comparison for Rg between buried and counterpoise ground systems.

As the figures show, there are significant differences between the values and behavior of Rr, RL and Rg. As shown in figure 5.21, Rr for the vertical with a counterpoise is significantly lower than the ground based system. The reason for this is that the length of the vertical is shorter with the counterpoise (42'). For short verticals, Rr varies as the square of the length. For example comparing Rr' at 42' to Rr at 50', where Rr=0.79 Ω:

$$Rr' = \left(\frac{42}{50}\right)^2 0.79 = 0.56\,\Omega$$

Which agrees with what we see in figure 5.21. If we have a vertical taller than 50' the reduction in Rr from shortening it's length by 8' will be reduced but if the vertical is shorter than 50' the reduction in Rr will be greater.

Figure 5.22 shows how much larger RL becomes when the counterpoise is employed. This comes from two sources: first, Xc is larger due to the shorter length and second, the counterpoise itself introduces a reactance (Xcp) in series with Xc. For resonance, XL=Xc+Xcp, the loading inductor will be larger which increases RL. Increasing the radius of the counterpoise and the number of radial wires reduces Xcp.

The trends in figures 5.21 and 5.22 would seem to favor the buried ground system but figure 5.23 gives the opposite message. Figure 5.23 shows the counterpoise is indeed a very efficient ground system which has much lower ground losses as seen in the lower values for Rg. When you combine the values in figures 5.21-5.23 with equation (2) you get the result shown in figure 5.24 where the counterpoise has better efficiency for the smaller radii (<40').

In some ways however, the comparison just made between a ground base system and a counterpoise is a bit misleading because I assumed that the overall height of the vertical was limited to a fixed value (50'). If we keep H=50' and simply elevate the entire vertical 8' so that the top is now at 58' then the results are different as shown in figure 5.24 where the dashed lines are for buried wire ground systems and the solid lines are for a counterpoise with the same number of radials and radius.

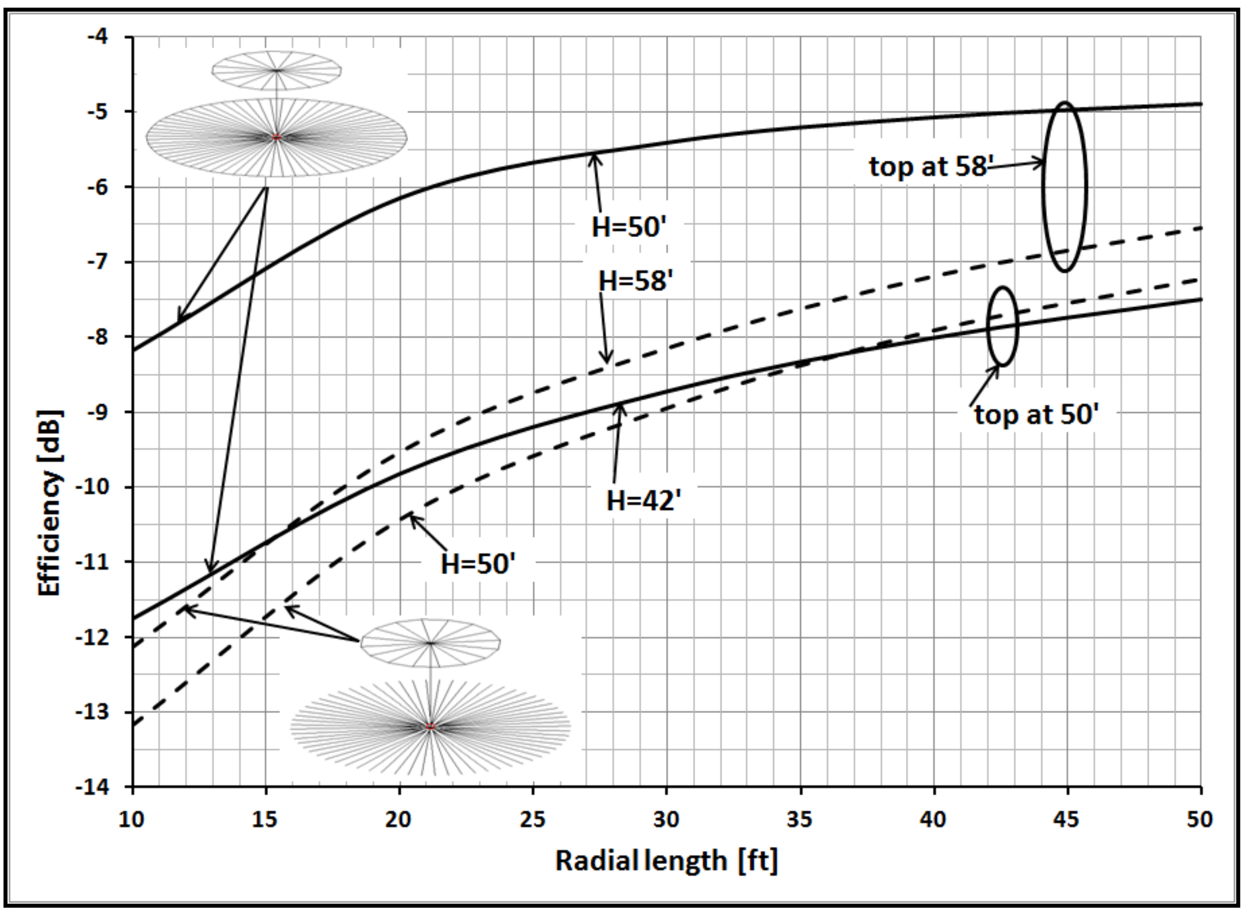

Figure 5.24 - Efficiency comparisons between counterpoise and buried wire ground systems for top heights of 50' and 58'.

What we see in the upper two traces in figure 2.24 is that simply raising the entire antenna up 8' and substituting the counterpoise for the buried wire system, there is a large improvement in efficiency and the counterpoise is superior at all radii up to 50' or more. You could argue that if we can raise the entire antenna 8' we could just as well have simply increased H to 58' and retained the buried ground system but as we can see in figure 5.24, the counterpoise is still better at least out to radii of 50'.

The point being made here is that if you have reasonable heights for the vertical and lots of capacitive top-loading but very restricted room for the ground system, then a counterpoise may be the best option. But we have to be careful in drawing general conclusions from the limited examples given here. There are many variables: ground characteristics, height of the top of the vertical, height of the bottom of the vertical, the amount of top-loading, the number of wires in the counterpoise, the radius, etc. The choice between buried wire and counterpoise ground systems is not obvious! The considerable mechanical complexity, vulnerability to ice damage and visual impact of a counterpoise may also militate against it. This choice has to be made on a case-by-case basis and will probably require modeling with NEC4 software.

5.11 Summary

This discussion has shown many examples for ground systems from which we can draw the following conclusions:

...the ground system can be elevated, on the surface or buried. Properly designed any of these will work...

...a significant number of radials must be used, 16 or more for elevated systems and 50 or more for ground based systems...

...the radial length should be somewhat greater than the height of the vertical and extend beyond the outer edge of the top-loading...

References

[1] Severns, Rudy, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 1, Test Setup and Instrumentation", QEX, January/February 2009, pg. 21

[2] Severns, Rudy, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 2, Excessive Loss in Sparse Radial Screens", QEX, January/February 2009, pg. 48

[3] Severns, Rudy, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 3, Comparisons Between Ground Surface and Elevated Radials", QEX, March/April 2009, pg. 29

[4] Severns, Rudy, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 4, How Many Radials Does My Vertical Really Need?", QEX, January/February 2009, pg. 38

[4] Severns, Rudy, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 5, Ground Systems For Multi-band Verticals", QEX, January/February 2009, pg. 19

[6] Severns, Rudy, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 6, 160m Vertical Ground System", QEX, January/February 2009, pg. 15

[7] Severns, Rudy, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 7, Ground Systems With Missing Sectors", QEX, January/February 2010, pg. 18

[8] Severns, Rudy, N6LF, "An Experimental Look at Ground Systems for HF Verticals", QST, Mar 2010, pg. 30

[9] R. Severns, N6LF, MEASUREMENT OF SOIL ELECTRICAL PARAMETERS AT HF, ARRL, QEX magazine, Nov/Dec 2006, pp. 3-9

[10] R. Severns, N6LF, "Verticals, Ground Systems and Some History," *QST*, Jul 2000, pp 38-44

[11] Abbott, Frank, Design of Optimum Buried-Conductor RF Ground System, IRE proceedings, July 1952, pp. 846-852

[12] Rudy Severns, N6LF, Radial System Design and Efficiency in HF Verticals, 2008, available at www.antennasbyn6lf.com

[13] Rudy Severns, N6LF, The Case of Declining Beverage-on-Ground Antenna Performance, QST June 2016, pp. 38-41

[14] Rudy Severns, N6LF, The Case of Declining Beverage-on-Ground Antenna Performance, QEX Jul/Aug 2016, pp. 7-18

[15] Rudy Severns, N6LF, Determination of Soil Electrical Characteristics Using a Low Dipole, QEX Nov/Dec 2016, pp. 5-8

[16] Brown, Lewis and Epstein, “Ground Systems as a Factor in Antenna Efficiency,” *Proc. IRE* , Jun 1937, pp. 753-787

[17] George H. Brown, A Theoretical and Experimental Investigation of the Resistance of Radio Transmitting Antennas, University of Wisconsin, Madison, Ph.D. thesis, June 1933.

[18] George H. Brown and Ronold King, High-Frequency Models in Antenna Investigations, IRE proceedings, Volume 22, Number 4, April 1934, pp. 457-480

[19] George H. Brown, The Phase and Magnitude of Earth Currents Near Radio Transmitting Antennas, IRE proceedings, Volume 23, Number 2, February 1935, pp. 168-182

[20] H.E. Gihring and G.H. Brown, General Considerations of Tower Antennas for Broadcast Use, IRE proceedings, Volume 23, Number 4, April 1935, pp. 311-356

[21] G. H. Brown, A critical Study of the Characteristics of Broadcast Antennas as Affected by Antenna Current Distribution, IRE proceedings, Volume 24, Number 1, January 1936

[22] Rudy Severns, N6LF, Radiation Resistance Variation with Radial System Design, QEX Jul/Aug and Sept/Oct 2015.

[23] J. Stanley, “Optimum Ground Systems for Vertical Antennas,” *QST*, Dec 1976

[24] R. Sommer, N4UU, "Optimum Radial Ground Systems", QST August 2003, pp. 39-43

[25] Al Christman, K3LC, "Maximum-Gain Radial Ground Systems For Vertical Antennas", NCJ magazine, March/April 2004, pp. 5-10

[26] Laport, Edmund, Radio Antenna Engineering, McGraw-Hill, 1952. You can find this one free on-line by Googling Edmund Laport.

[27] Burghard, George, "Station 1BCG", QST, February 1922, pp. 29-33

[28] Kelley and Hudson, "Hams Span the Atlantic on Shortwave!", QST, December 1996, pp. 28-30

[29] Admiralty Handbook of Wireless Telegraphy, His Majesty's Stationary Office, 1932, pg. 799, Figure 452