Radial System Design
And
Efficiency In HF Verticals

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The efficiency of an HF vertical depends on its associated ground system and the soil over which the antenna is erected. The most direct way to determine the efficiency of an antenna is to determine the fraction of the input power which is actually radiated. However, there is a small complication, what do we mean by "radiated power" and how might we determine it? It turns out that there are a couple of ways to define radiated power depending on what we're using the antenna for. One practical way to address this question is to use NEC modeling which can provide the actual radiated power and that's where the information in this note was derived from. Modeling results are discussed below but details of the modeling itself are given in reference [2].

A related efficiency question is the long standing "conventional wisdom" that shorter radials work better with shorter verticals. It can be argued that because shorter verticals have significantly higher field intensities close to the base of the antenna (for a given input power), which leads to higher ground losses, that it makes sense that more attention be given to the radial system close in. While this sounds reasonable I couldn't find any quantitative justification. So I extended the modeling study to include shorter antennas to see if the conventional wisdom had any quantitative basis.

Efficiency

Power (**Pi**) is delivered to the feedpoint from the source, some of this power will be radiated (**Pr**), some will be dissipated in the soil (**Pg**) and some will be dissipated in the conductors and any loading elements that may be present. For the purposes of this discussion we will ignore the losses due to conductors and loading elements.

Efficiency (**η**) can be expressed in several ways but the most obvious is as the ratio of radiated power to input power:

$$\eta = \frac{\mathrm{Pr}}{Pi} \qquad (1)$$

We usually state efficiency in percent (%). However, in a vertical what we are concerned with is the change in signal strength for a given change in the ground system and many times it can more useful to express efficiency in terms of dB:

$$\eta = 10\log\left(\frac{\mathrm{Pr}}{Pi}\right) \qquad (2)$$

For example, if the antenna has an efficiency of 90% that represents a signal loss of about -0.46 dB compared to a lossless antenna. On the other hand if the efficiency is only 60% then the signal loss is -2.22 dB. In most of the following discussion this is the form I will use, although for some graphs it's more convenient to use the conventional % representation.

Radiated power (Pr)

Our definition of efficiency is a direct function of **Pi** and **Pr**. The meaning of "input power" is obvious but what do we mean by "radiated power" and how do we determine it? One way of finding **Pr** is to compute the total power passing through a virtual surface completely enclosing the antenna. For antennas over ground this surface is typically a constant radius hemisphere some distance (**r**) from the antenna. In the absence of ground losses (i.e. perfect ground) **Pr** = **Pi** everywhere in space and the choice of **r** doesn't matter. However, if lossy ground is present then the value for r does matter. As we go further from the base of the antenna (larger **r**) ground loss increases and **Pr** will decrease.

If your only interest is skywave propagation for DX then you will be interested only in the power radiated into space. Ground loss in the near field, energy that propagates as a ground wave and reflection losses in the far field are all losses that reduce the "radiated" or skywave signal. NEC will compute **Pr** directly for the case where the radius of the hemisphere is infinite. This is the average gain (**Ga**). **Ga** represents the fraction of the input power which is radiated at an infinite distance, i.e. the "skywave radiation".

$$\mathrm{Pr} = GaPi \qquad (3)$$

Dividing through by **Pi** we get:

$$\eta = Ga = \frac{\mathrm{Pr}}{Pi} \qquad (4)$$

EZNEC gives **Ga** in two forms, a decimal value and in dB. The decimal value multiplied by 100 is the efficiency in percent. Over perfect ground no power is lost and **Ga** = 1, or equivalently, 0 dB. Over real ground **Ga** still represents the radiated power but **Ga** will have some -dB value which takes into account the power dissipated in the ground surface out to infinity. The curvature of the earth is not taken into account in the NEC **Ga** calculation but that has only a very small effect.

While stating efficiency in terms of sky-wave radiation makes a good deal of sense, it's more common to think of efficiency in terms of only the near-field losses within 1/2 to 1 wavelength of the base of the antenna. This is the region within which it may be practical to install a ground system to reduce **Pg** and thereby increase **Pr** for a given **Pi**. For that reason when calculating **Pr** the radius of the hemisphere is typically made 1/2 to 1 wavelength and integration of the radiated power density over that surface gives us **Pr**. We then can go on to determine **η**.

The problem with this approach is that NEC does not automatically do this for you. You have to first use NEC to compute the complex values of the **E** and **H** fields over the surface of the hemisphere and then take the vector cross product to get the power density on that surface. Finally you need to integrate over the surface to get **Pr**. This is complicated and you have to have some mathematical skill. Taking this approach you will get values for **η** which reflect what is going on in the immediate region of the antenna.

This information may be interesting but if your only interest is in determining the improvement in your DX signal a given radial system improvement will provide, then you can just use the average gain calculation. No math skills required! The incremental change in signal will be very similar for both methods but the absolute values for **η** will be different.

7.2 MHz Modeling results

Figures 1 and 2 show the efficiency for **r** = 1 wavelength for two different soils.

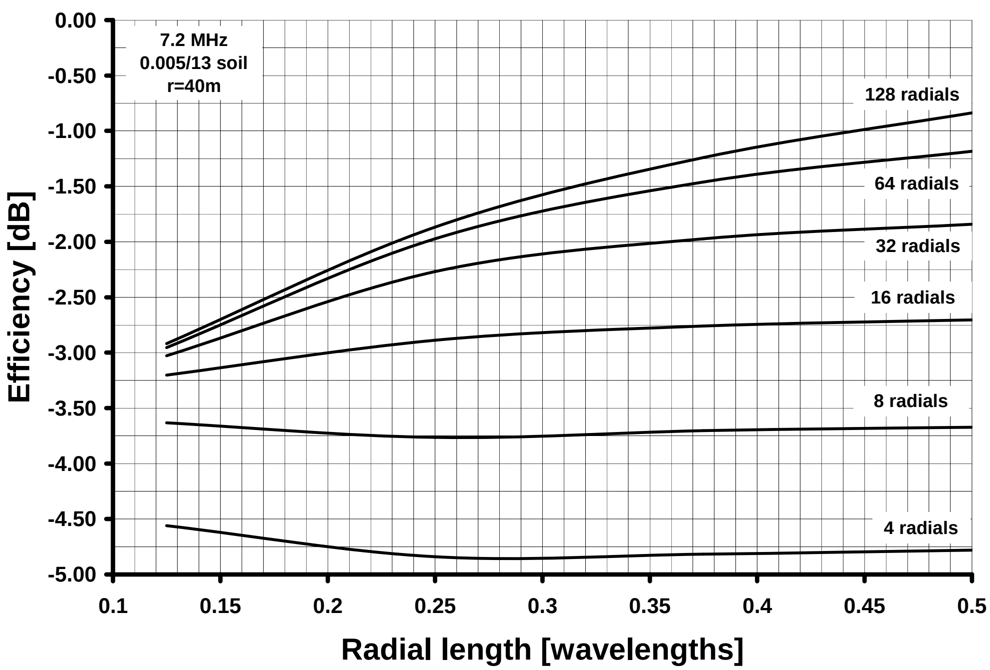

Figure 1, efficiency in dB as a function of radial number and length in average soil. **r**=40 m.

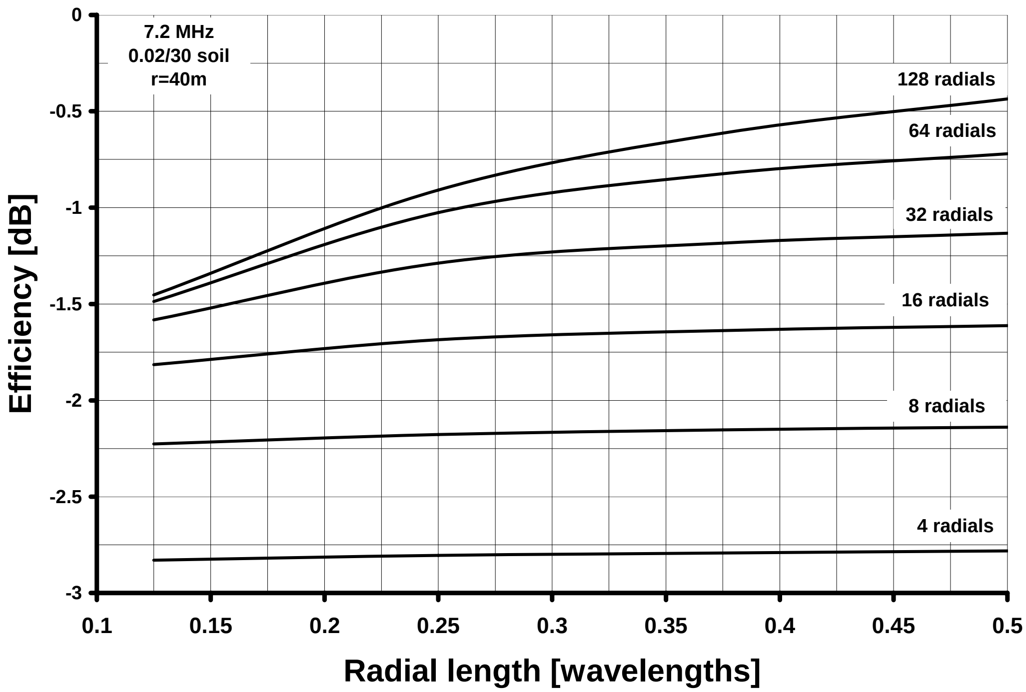

Figure 2, efficiency in dB as a function of radial number and length in very good soil. **r**=40 m.

These two figures very clearly illustrate what is to be "gained" by using more and longer radials. However, looking at figure 1 (average ground) we see something funny. When using only four radials, as we increase the length from 1/8-wave the efficiency goes down, not up. The same thing happens for eight radials only not quite as much. More copper means more loss not less!

We do not see this effect in figure 2 which is for the same antenna over very good ground. In this case when there are only a few radials, increasing the radial length does no harm but also does little good. A few long radials in good soils are a waste of copper. The loss effect seen in figure 1 stems from a radial resonance which can increase ground loss. This effect is described in reference [1].

Alternately we can graph efficiency in terms of Ga as shown in figures 3 and 4. Unfortunately this also shows how inefficient verticals are even over very good ground. Very depressing! For example, with very good soil (0.02/30) and 128 1/2-wave radials, the efficiency of a 1/4-wave vertical is still only -2.76 dB (53%)!

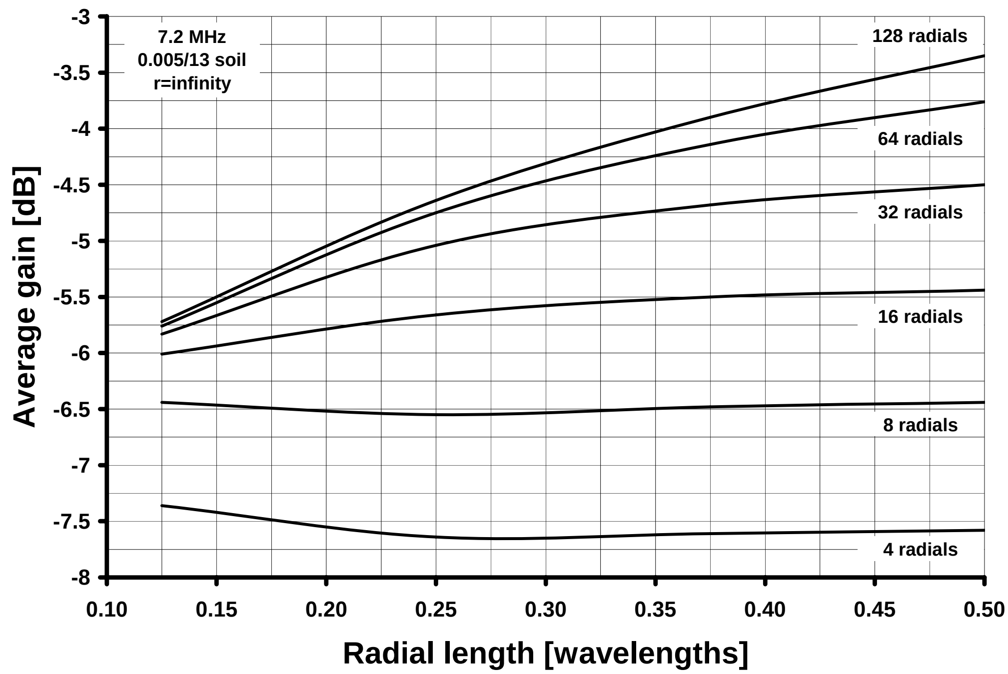

Figure 3, Efficiency in terms of **Ga** for average soil.

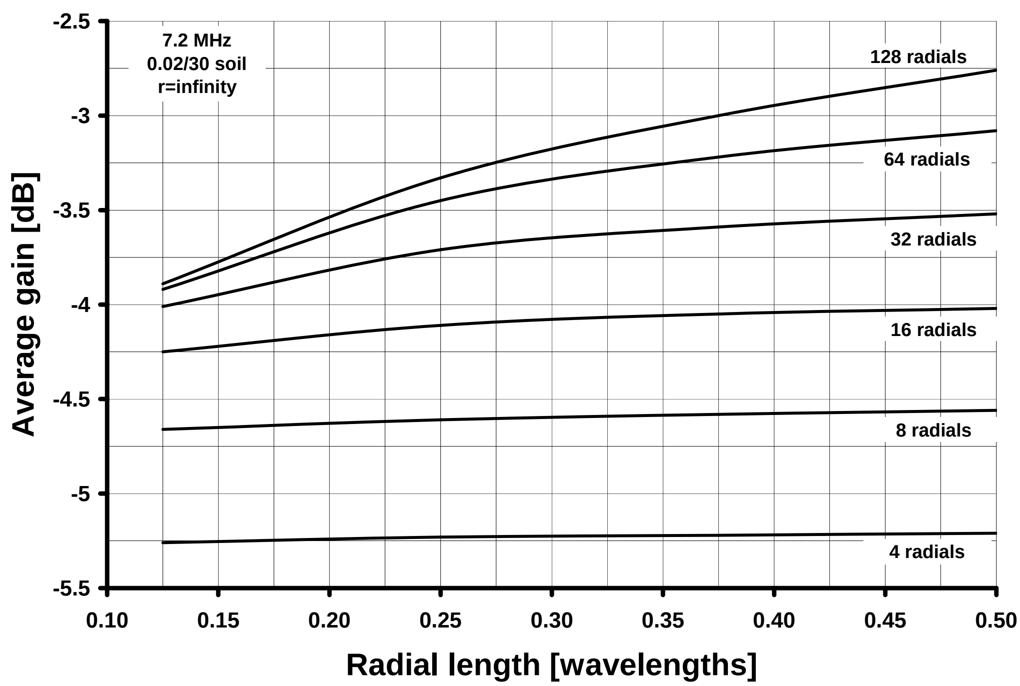

Figure 4, Efficiency in terms of **Ga** for very good soil.

This observation does not imply we should abandon verticals! In many cases, particularly on the low bands where support height is usually limited, verticals can often provide a stronger signal at the desired low angles for DXing than a practical horizontal antenna. Incorporated into arrays verticals provide a practical way to have gain arrays with steerable patterns on the low bands.

If we redid the average gain graphs for verticals over seawater we would see the efficiency become very nearly 0 dB and essentially independent of radial number. That's why verticals can work so well for some DXpeditions.

1.8 MHZ modeling

Besides the modeling at 7.2 MHz with a 1/4-wave vertical I also ran models of 1/4-wave and 1/8-wave verticals at 1.8 MHz over average soil to check out the relationship between height and radial length. The results are shown in figures 5 and 6. Note that the y-axis has been changed from efficiency in dB to "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. I did this because it nicely illustrates what you "gain" by adding more copper to the radial field.

How you add the copper matters. As we can see from graph when only a few radials are used, making them longer is waste. You gain little or nothing. In fact as shown earlier you can actually lose. The dashed lines on figures 5 and 6 represent ground systems with constant total wire lengths in the radial system: 1, 2, 4, 8 and 16 wavelengths total. 16 wavelengths at 1.8 MHz is almost 9,000' of wire, as substantial ground system.

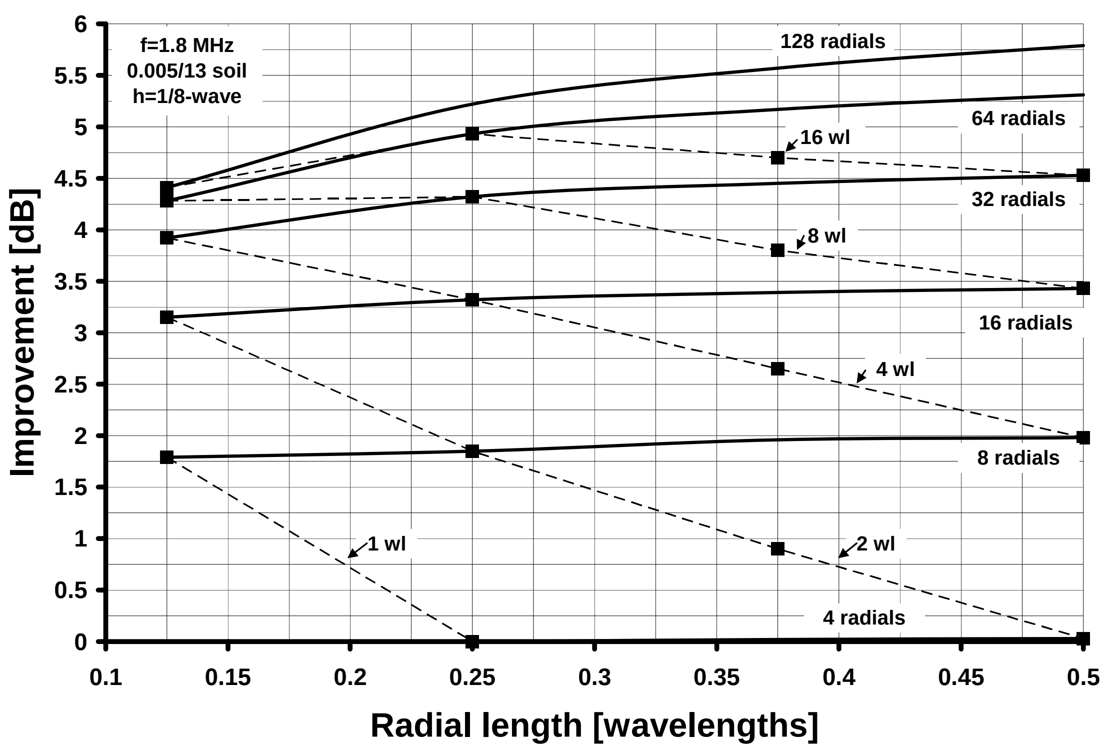

Figure 5, improvement in dB for various radial combinations for a 1/8-wave vertical.

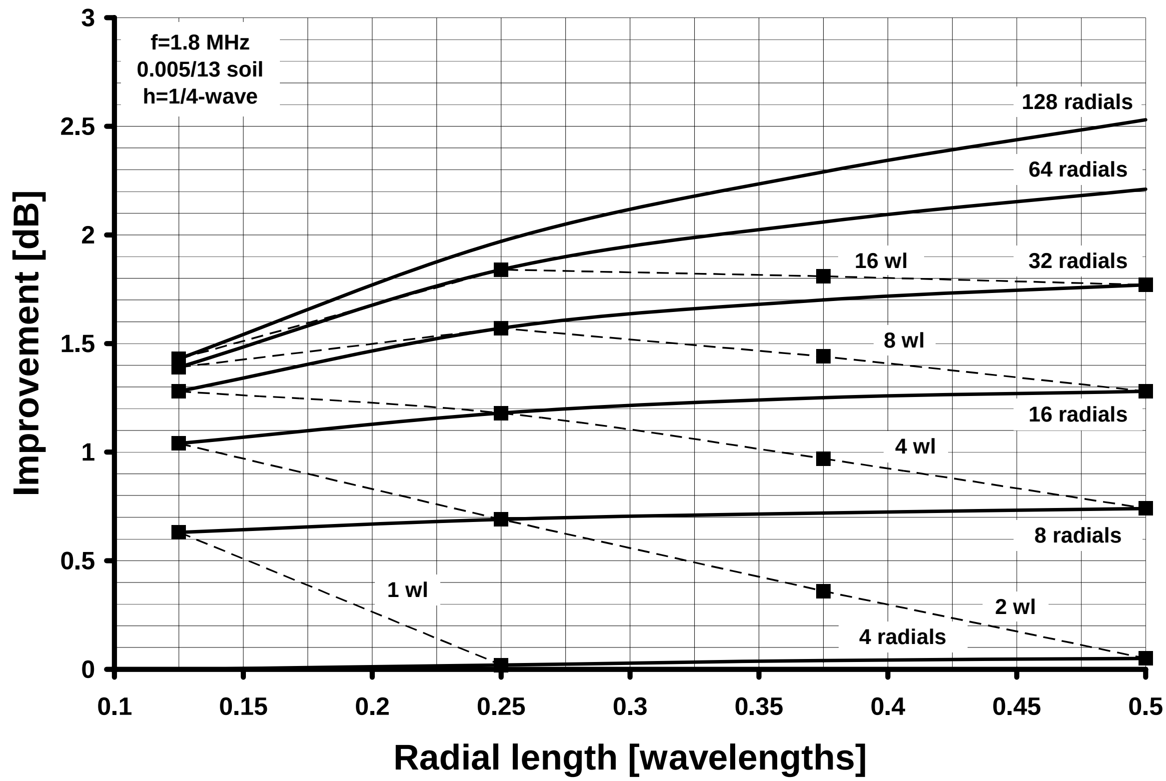

Figure 6, improvement in dB for various radial combinations for a 1/4-wave vertical.

Referring to figure 5, which is for an 1/8-wave vertical. If your wire length is limited to four wavelengths, you are much better off to use thirty two 1/8-wave radials than 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 work best.

When we look at the gain improvement shown in figure 6, which is for a 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 also works best when 16 wavelengths of wire are available. If we go up to 32 wavelengths of wire 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 element". In the case of the 1/8-wave vertical (figure 5) this seems to be true up to at least 8 wavelengths of total wire. Beyond this, longer radials are more effective. In the case of the 1/4-wave vertical (figure 6), 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 physics of this seem fairly clear, once you have taken care of the losses near the base of the antenna, adding more close in copper doesn't buy much. At that point it's time to put the copper further out and reduce those losses, which may be smaller but are still significant.

In both cases it would appear that the rule of thumb has some validity at least until we go to 16 or more wavelengths of wire.

Summary

The choice of what constitutes useful radiation has a direct impact on what we call "the efficiency". In the typical case where we are interested in the power radiated into space for DX communications, efficiencies are typically quite low, except perhaps over seawater. Even over very good soils, with no loss in the antenna, the efficiency is barely 50% (-3 dB). This is intrinsic to vertical polarization due to the ground loss associated with the near fields and propagation in the far-field. This does not to imply that horizontally polarized antennas are always superior to verticals! There are many applications where a vertical can still provide a better signal for DX or ground wave work than a horizontal antenna. This becomes more true as we do down in frequency towards 160m.

References

[1] Severns, Rudy, N6LF, Antenna Ground System Experiments 2, 3 and 4, May 2008, a copy of this can be found at: www.antennasbyn6lf.Com .

[2] Severns, Rudy, N6LF, Radiation Resistance Variation With Radial System Design, September 2008, a copy of this can be found at: www.antennasbyn6lf.Com