

# Some Suggestions For Short Verticals On 160m

Rudy Severns N6LF

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## Introduction

While it's considered desirable for a vertical to be a full  $\lambda_o/4$  height (H), on 160m  $\lambda_o/4 \approx 130'$  and many times that height is not possible. For a variety of reasons we may be restricted to much shorter verticals. Jerry Sevick, W2FMI (SK), showed us how to build efficient short verticals for 20 and 40m<sup>[1,2,3]</sup> using a flat circular top-hat which is very effective for capacitive loading and practical at 40m. But a flat top becomes mechanically difficult on 160m, at least for really short verticals where a large diameter is needed. However, capacitive top-loading is still the key to maximizing efficiency in short verticals. This drives us to consider other forms of top-loading. One traditional approach has been the "umbrella" vertical, like that shown in figure 1.

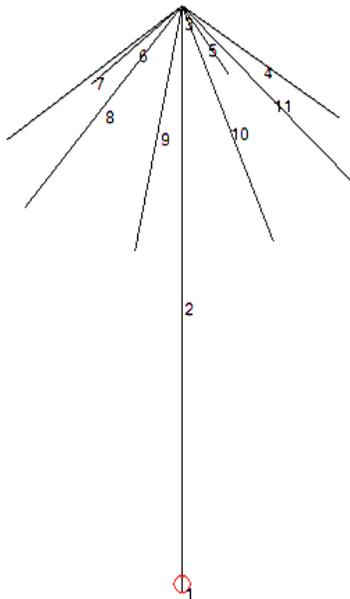


Figure 1 - Example of an umbrella vertical.

It's called an umbrella vertical because of its resemblance to a partially open umbrella. The attraction of this approach is its simplicity: just hook some wires to the top and pull them out at an angle.

Umbrella verticals aren't new, they've been around since the early days of radio and some really excellent experimental work<sup>[4]</sup> has been done at MF but because of the difficulty working with large antennas, optimization has not been explored experimentally in detail although Belrose, VE2CV, has reported work with VHF models<sup>[5]</sup>. The advent of NEC modeling software has made it much easier to explore antenna optimization and this article is mostly a NEC modeling study. While NEC can be very informative, it's my policy to compare my NEC modeling to reliable experimental data whenever possible and I do so near the end of this article.

## What's a "short" antenna?

What's meant by a "short" vertical. In professional literature the definition is usually a vertical shorter than one radian (1 radian =  $57.3^\circ = \lambda/2\pi = 0.16\lambda_0$ , where  $\lambda_0$  is the free-space wavelength). Sometimes "short" is defined as a vertical with a physical height  $H < \lambda_0/8$  or  $45^\circ$ . At 1.83 MHz  $\lambda_0/8 \approx 67'$ . The focus of this article will be antennas with  $H < 0.125\lambda_0$ . Throughout the article H is given in fractions of  $\lambda_0$  and the  $\lambda_0$  dimension is omitted.

## Is there a problem?

Before starting a discussion on capacitive top-loading we need to ask "is there a problem with short verticals which justifies the added complexity of a top-hat"? After all, we could put up a simple vertical and load it with an inductor as is done for mobile antennas. There is certainly lots of information on optimizing mobile verticals. We know that for a lossless antenna the radiation pattern of a very short vertical is almost the same as a  $\lambda_0/4$  vertical. The differences between short and tall verticals show up when losses are taken into account. We also know that as H is reduced Q rises rapidly and the match bandwidth narrows.

Real antennas have several sources of loss:

- Loading coil resistance -  $R_L$
- Equivalent ground loss resistance -  $R_g$
- Conductor resistance -  $R_c$
- Loss due to leakage across insulators (at the base and at wire ends) -  $R_i$
- Corona loss at wire ends -  $R_{cor}$
- Matching network losses -  $R_n$

In general  $R_L$  and  $R_g$  are the major losses but in short antennas conductor currents and the potentials across insulators can be much higher than in taller verticals. In fact the shorter the antenna the greater the losses from all causes. In short verticals a major part of the design effort is directed towards minimizing losses.

The impedance at the feedpoint is  $Z_{in} = R_a + j(X_b - X_a)$ , where  $R_a = R_r + R_L + R_g + R_c + R_i + R_{cor}$ , and  $X_a$  is the capacitive reactance and  $X_b$  is the inductive reactance.  $R_r$  is the radiation resistance which represents the desired power "loss". Note that in this discussion when modeling lossless examples  $R_a = R_r$  and I may use either symbol when the model is ideal. Figure 2 shows a typical graph of  $Z_{in}$  for an ideal vertical over a range of heights:  $0.01 < H < 0.25$ . Note how rapidly  $R_a$  falls ( $\propto H^2$ ) and  $X_a$  rises ( $\propto 1/H$ ).

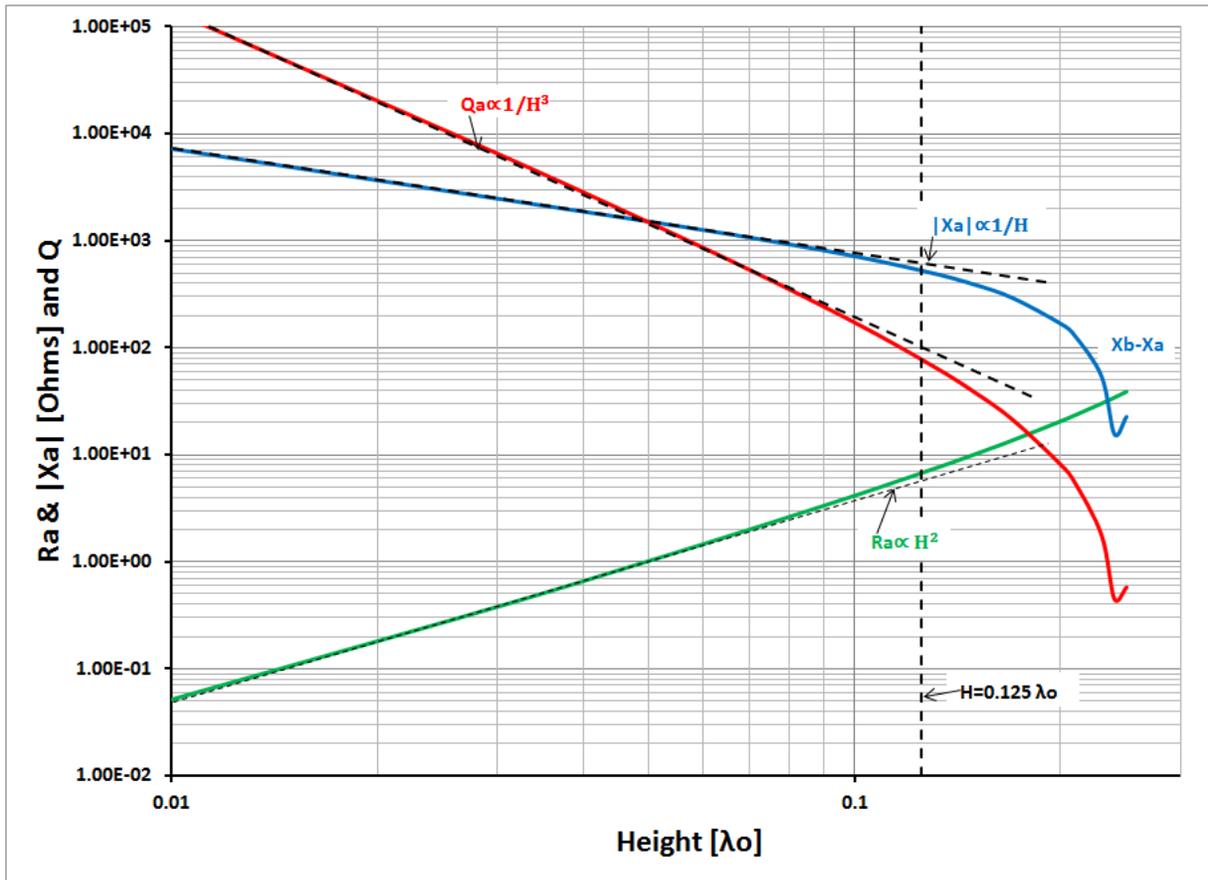


Figure 2 - Example of the feedpoint impedance of an ideal vertical.

Figure 3A shows an equivalent electrical circuit for  $Z_{in}$  at a frequency near the lowest series resonance ( $H \approx 0.24 \lambda_0$ ).

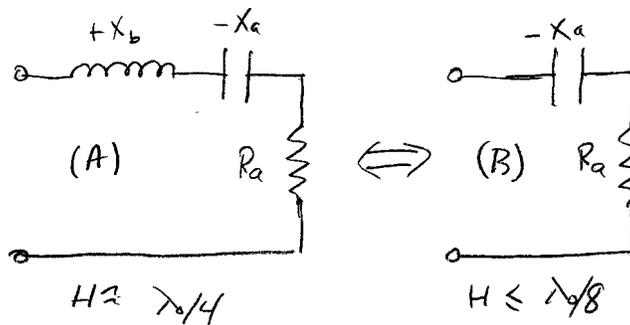


Figure 3 - Equivalent circuits for  $Z_{in}$ .

Referring to figure 2, we can see for  $H \leq 0.125$ ,  $X_b$  (the inductive component) becomes very small and  $X_a$  dominates. This is indicated by the dashed straight line approximation on the log-log scale which is what you expect for a pure capacitance. This implies that short antennas are basically just capacitors and we can use the equivalent circuit in figure 3B as a good approximation which simplifies the math.

In figure 2 I have defined  $Q_a = |X_a|/R_a$  which is associated with circuit in figure 3B.  $R_a$  falls rapidly as  $H$  is reduced and simultaneously  $|X_a|$  increases rapidly. The result is very large values of  $Q_a$  for small values of  $H$ .  $Q_a$  varies as  $1/H^3$ !

To tune out the capacitive reactance ( $-X_a$ ) we can add a series inductor at the feedpoint as shown in figure 4 where  $X_L = |X_a|$  and  $R_L$  is the loss resistance associated with  $X_L$  ( $R_L = X_L/Q_L$ ).

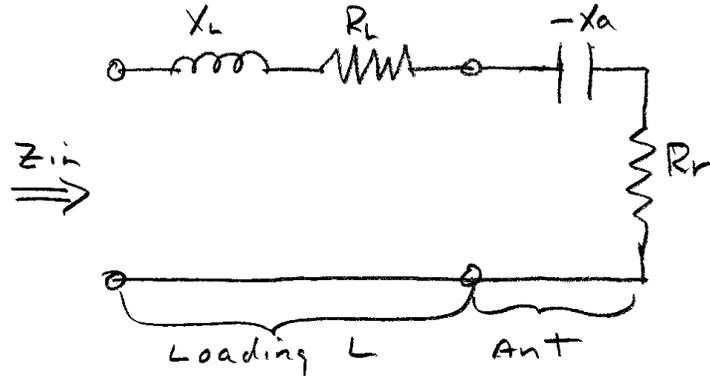


Figure 4, equivalent circuit for the input impedance of a short vertical.

We can calculate the efficiency ( $\eta$ ) for the circuit in figure 4:

$$\eta = \frac{\text{power radiated}}{\text{input power}} = \frac{R_a}{R_a + R_L} = \frac{1}{1 + \frac{R_L}{R_a}} \quad (1)$$

We know that  $R_a = |X_a|/Q_a$  and  $R_L = X_L/Q_L = |X_a|/Q_L$ . If we substitute these relationships into equation (1) we get:

$$\eta = \frac{1}{1 + \frac{Q_a}{Q_L}} \quad (2)$$

We can graph equation (2) to show how the efficiency of a short vertical (for a given  $Q_L$ ) varies with  $H$  as shown in figure 5. A  $Q_L$  of 200 represents a pretty mediocre inductor.  $Q_L$ 's of 400 to 600 are practical with a little care. A  $Q_L=1000$  is possible but not easy. The efficiencies in figure 5 are expressed in dB of signal lost due to power absorbed in the inductor. For small values of  $H$ ,  $\eta$  is pretty depressing. What's even more depressing is that figure 5 only shows the effect of  $R_L$ . When we include the other losses, especially  $R_g$ ,  $\eta$  can be substantially worse.

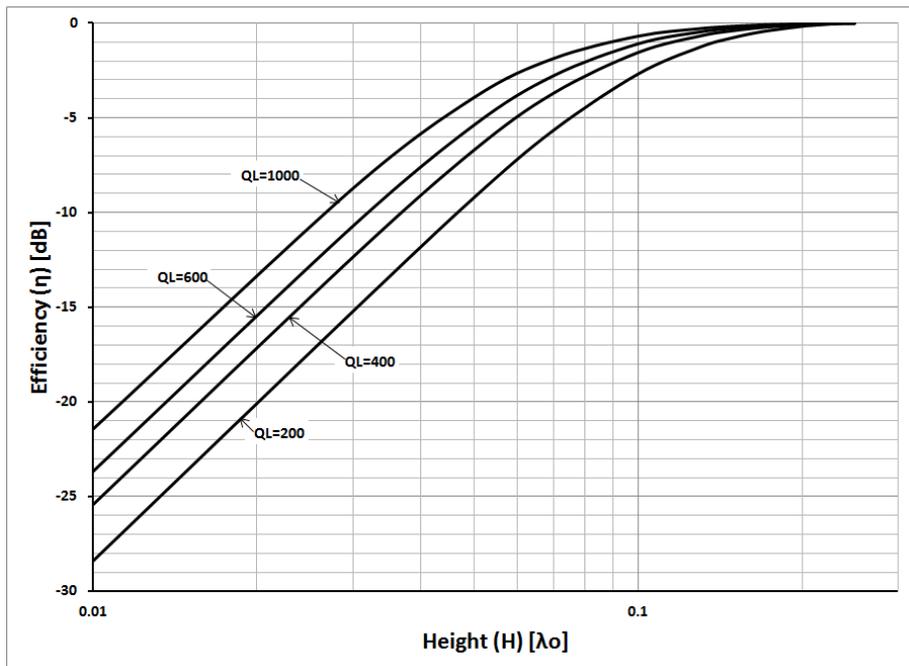


Figure 5 - Variation of efficiency in dB as a function H with  $Q_L$  as a parameter.

Given the practical limitations on  $Q_L$  it is clear that short base loaded antennas can be very inefficient because of high values for  $Q_a$  which increase rapidly for small values of H. Mobile antenna work has shown that we can reduce  $Q_a$  by moving the inductor from the base up into the vertical itself. While this can help it's usually not enough when  $H < 0.1 \lambda_0$ . For mobile verticals adding significant top-loading is usually impractical but for fixed installations substantial capacitive loading is viable.

There are other problems. The match bandwidth will be proportional to  $1/Q_a$ , becoming very narrow as the vertical is shortened. Of course higher losses provide damping which increases the bandwidth somewhat but that's not the direction we want to go in! For a given input power level, short antennas can have much higher conductor currents and very high voltages at the feedpoint. For example, if we set  $H=0.05 \lambda_0$ ,  $R_f \approx 1 \Omega$  and  $|X_a| \approx 1500 \Omega$ . If the base inductor  $Q_L=400$ , then  $X_L=3.75 \Omega$ .  $R_a + R_L = 4.75 \Omega$ . For  $P_{in}=1500 \text{ W}$  the current into the base will be  $\approx 18 \text{ A rms}$  and the voltage at the feedpoint will be  $\approx 27 \text{ kV rms}$ ! In addition the inductor will be dissipating  $\approx 1,200 \text{ W}$ . Base loaded short verticals have a problem! The way out of the box is to use capacitive top-loading.

### Design variables

There are many variables all of which affect performance:

- The height (H)
- The number of umbrella wires (N)
- The length of the umbrella wires (L)
- Whether or not there is a skirt tying the ends of the umbrella wires together
- The apex angle (A) between the top of the vertical and the umbrella wires
- Whether or not a loading coil is used

- The location of the loading coil if one is used
- $Q_L$  of the loading coil
- conductor sizing and losses in conductors
- Insulator losses
- Matching network design and losses
- Possible corona losses
- Currents and potentials on the antenna
- The characteristics of the ground system and surrounding soil.

There are a lot of variables and we cannot possibly work with all of them at once. What I have elected to do is deal with only a few variables at a time, adding loss elements as a better understanding of the antenna develops. The initial models are very idealized but in the end we will be including a real ground system, inductor and conductor losses, etc. I have chosen the 8-wire umbrella with a skirt for this discussion because it is relatively simple and it works well but we should keep in mind that this is only one of many possibilities<sup>[6]</sup>. An example is shown in figure 6. The apex angle (A) will be varied from 30° to 60°. The modeling is done at 1.83 MHz. For the moment the ground is perfect and there are no conductor losses.

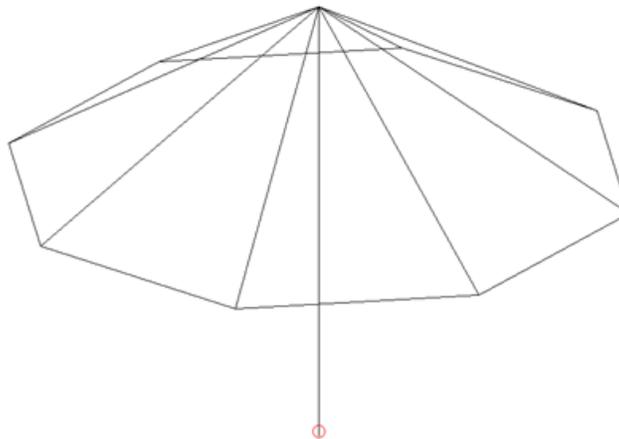


Figure 6 - NEC model.

The height of the vertical is  $H$  and the vertical dimension of the top-hat is  $M \cdot H$  (from the top of the vertical to the bottom of the skirt wires).  $M$  is expressed as a fraction of  $H$  ( $0 < M < 1$ ). As we increase  $M$  the bottom of the hat moves closer to ground. The distance from the bottom of the umbrella to the ground is  $D = H(1-M)$ . Another dimension we may use is the radius ( $r$ ) from the vertical to the outside of the umbrella lower edge. All these dimensions will be in  $\lambda_0$ . The angle between the umbrella and the vertical at the top will be  $A$  (in degrees). The relationship between  $r$  and  $M$  is:  $r = MH \tan(A)$ . Initially all the conductors will be #12 perfect conductors.

### Idealized top-loaded verticals

There are many possible combinations of top and inductor loading we could use but given the losses associated with loading coils, our first instinct might be to use enough top loading to resonate the

antenna without any base inductor. This is possible for a wide range of H. We don't want to fool ourselves however, even without the need for an inductor for resonance, we will very likely need a matching network with an inductor but we'll look at that loss later. Loading for resonance is not the only option. One widely held idea is that the loading should be adjusted to maximize  $R_r$  and then an inductor or capacitor used to resonate. It's also possible that some other combination may yield the best efficiency. We'll look at all of these possibilities after we have added a ground system to the model so that we're including  $R_g$  in the efficiency calculation.

Figure 7 shows the relationship between H and M for resonance for three apex angles, for skirted umbrellas with 4 and 8 wires.

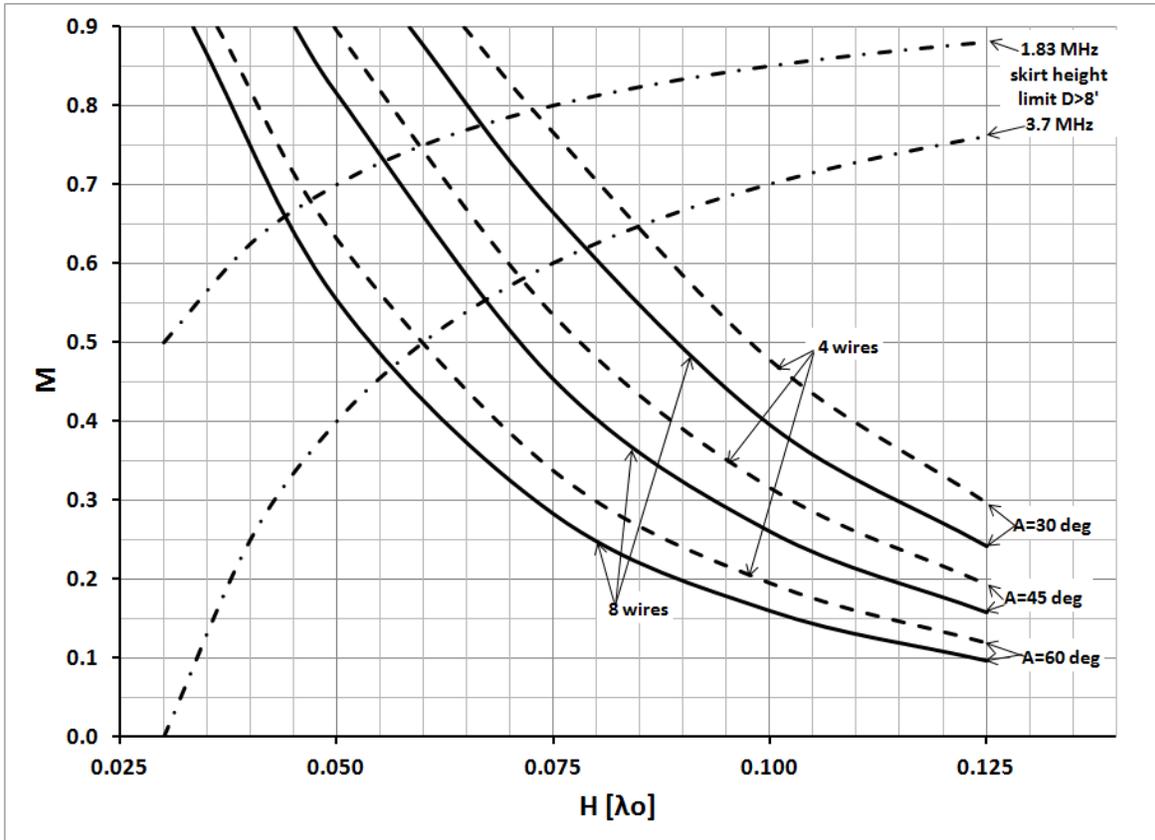


Figure 7 - Values of M for resonance when using 4 or 8 umbrella wires and a skirt.

Whether we can reach resonance depends on H, A and the number of umbrella wires but as figure 7 shows we can do pretty well for antennas down to  $H \approx 0.04 \lambda_0$  or a bit shorter on 160m if we use a large value for A and more wires in the umbrella. At 1.83 MHz,  $0.04 \lambda_0 = 21.5'$ . This is definitely a "short" vertical! Figure 7 shows that increasing the number of wires in the hat increases its effectiveness but the point of vanishing returns sets in quickly. The improvement gained by doubling the eight wires to sixteen wires is relatively small. The number of umbrella wires becomes a judgment call: is it worth the cost and increased vulnerability to ice loading? The major drawback to this class of antennas is their vulnerability to ice loading. If you live in an area where ice storms are common you will have to carefully think through your mechanical design.

There is an important limitation on M, especially for small values of H: the distance above ground of the lower edge of the umbrella. Because there can be very high potentials on the skirt you will want to keep the skirt out of reach, at least 8' above ground so you can't run into it. This limitation is indicated in figure 7 by the dash-dot lines. There is one set of limits for 1.83 MHz and a second for 3.7 MHz. You are limited to values of M below these boundaries.

The importance of A is clear. For a given M and H, the larger we make A the larger r will be and the greater the top-loading capacitance. This allows us to reach resonance with smaller values of M. However, larger values of A require the umbrella wire anchor points to be further from the base of the vertical, increasing the ground footprint. One way to reduce the footprint would be to place the umbrella wire anchor points on posts above ground. In any given installation the value for A may be limited by the available space. The best results are achieved with  $A=90^\circ$  but the thesis of this discussion is that may not be practical so we're focusing on values for  $A < 90^\circ$ .

Resonating the vertical using only capacitive loading helps by eliminating  $R_L$  but we still have the problem of low  $R_a$  as we reduce H. Figure 8 is a graph of  $R_r$  at resonance as a function of A and H. The dashed line represents  $R_r$  for a bare vertical, without top-loading ( $M=0$ ).

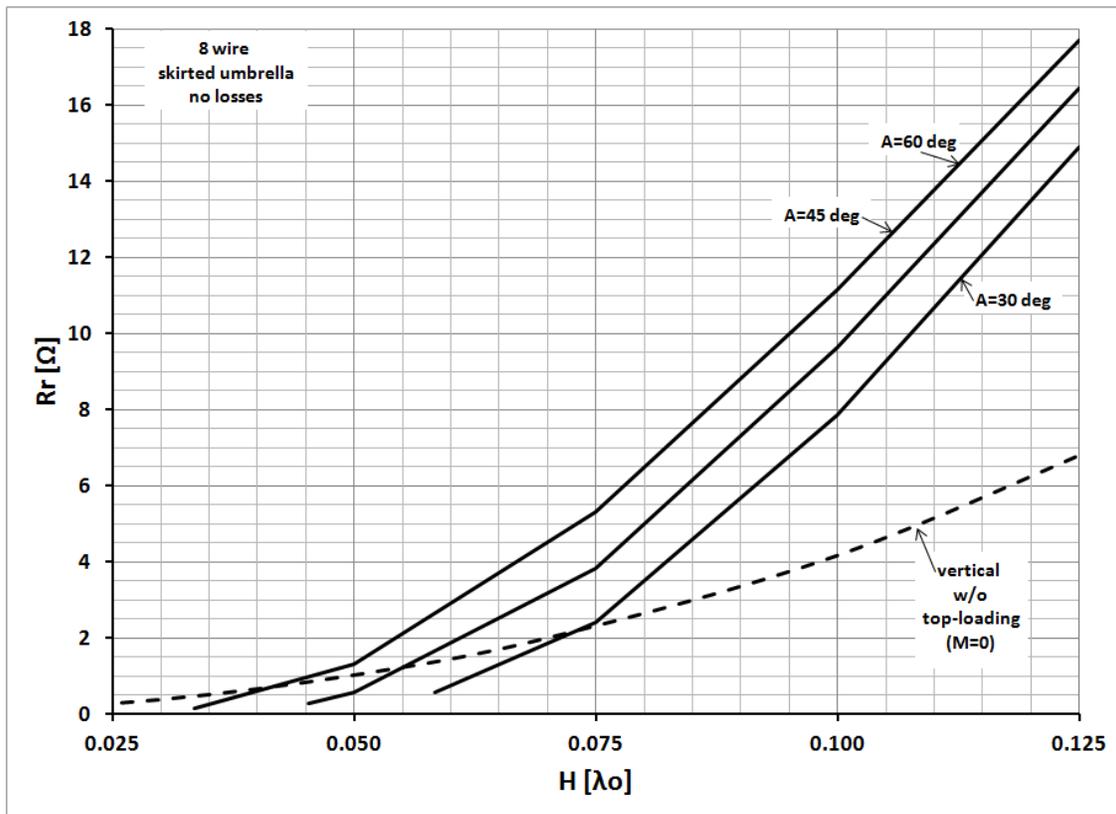


Figure 8 -  $R_r$  at resonance as a function of A and H compared to an unloaded vertical.

Over much (but not all!) of the graph we see that top-loading not only resonates the antenna but also increases  $R_r$ . That's great but for really short antennas  $R_r$  with capacitive loading can be little better or even lower than the simple vertical.

## Adding a ground system and $R_g$

Modeling of a lossless antenna has given us some information but in real antennas the losses due to  $R_g$  and  $R_L$  greatly affect performance and optimization. It's the time to add a ground system and real soil to the model as shown in figure 9.

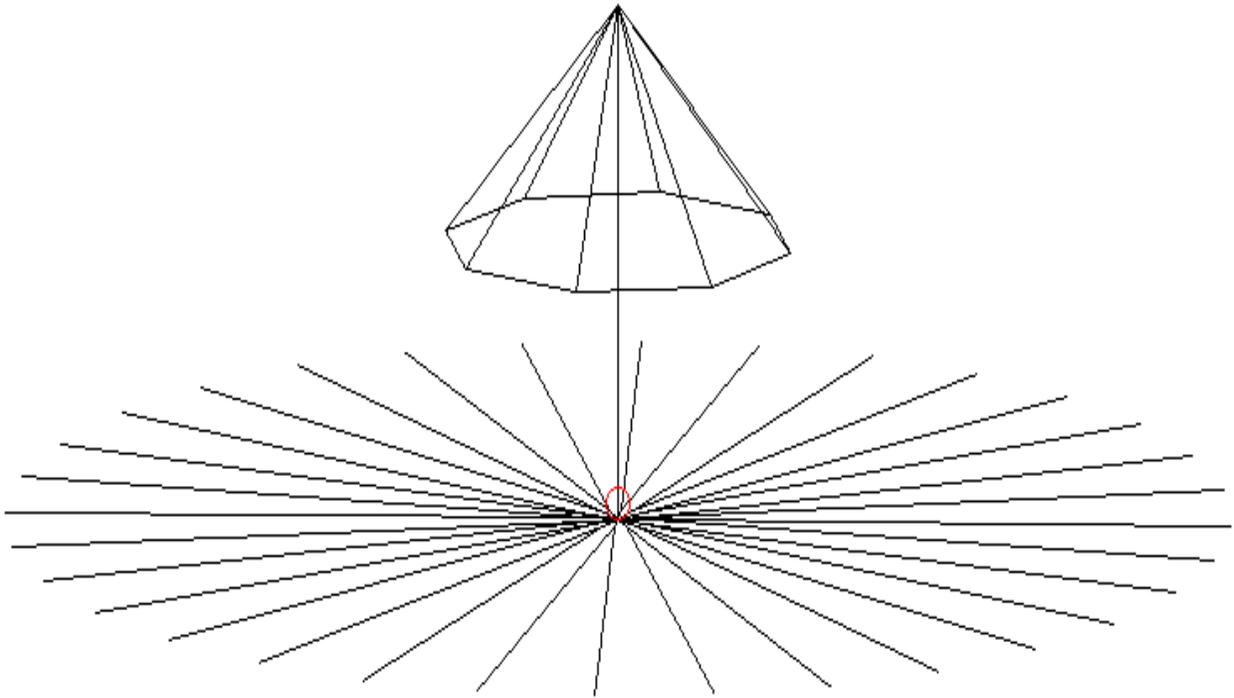


Figure 9, NEC model for a top-loaded vertical with a ground system.

I've chosen use thirty two  $\lambda_o/8$  radials ( $L \approx 65'$  @ 1.83 MHz) buried 6" in average soil ( $\sigma = 0.005$  S/m and  $\epsilon_r = 13$ ). This represents a compromise system, real systems may be larger or smaller depending on the limitations of a given situation.

We need to keep in mind what our goal is: for given limitations on H and the footprint area of the ground system and the umbrella wire anchor points, we want to achieve the maximum possible efficiency. For the moment we'll work with the major losses:  $R_g$  and  $R_L$  which dominate efficiency and optimization.

In the following modeling:  $H = 0.050, 0.075, 0.100$  or  $0.125$ ,  $A = 30^\circ, 45^\circ$  or  $60^\circ$  and the frequency is 1.83 MHz. The umbrella uses eight wires and a skirt unless stated otherwise. The ground system has thirty two 65' radials in  $\sigma=0.005$  S/m and  $\epsilon_r = 13$  soil.  $A=45^\circ$  is a common apex angle where the radius of the umbrella wire anchor points is about the same as H. To keep the number of graphs in bounds I set  $A=45^\circ$  for most of the examples.

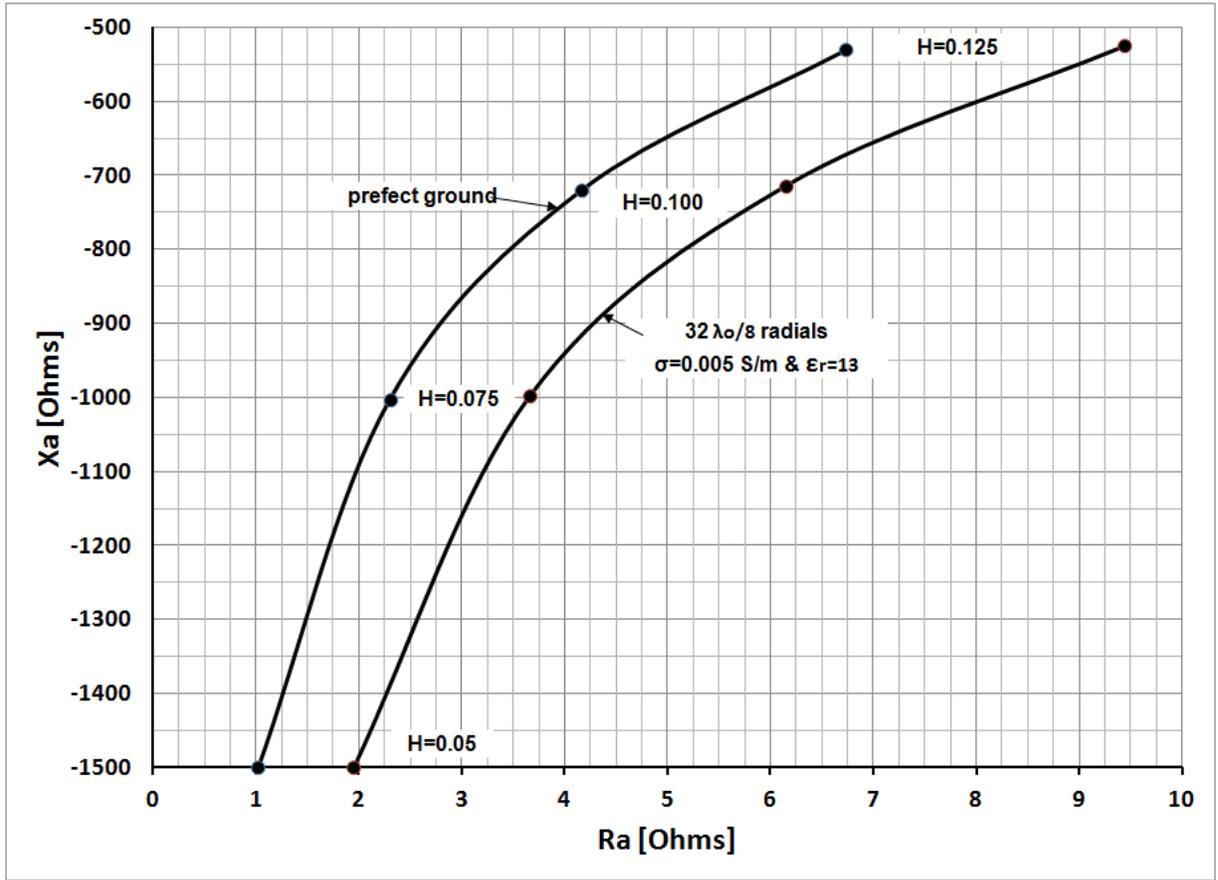


Figure 10 -  $R_a + jX_a$  as a function of  $H$  with  $M=r=0$ , with perfect and real ground systems.

In figure 10 we can see that  $R_a$  increases substantially when a real ground system is used but note also that  $X_a$  is not greatly affected. This indicates that using  $R_r$  for the perfect ground as the  $R_r$  value with a real ground is probably a good approximation.

### Efficiency

In terms of  $R_r$ ,  $R_g$  and  $R_L$ ,  $\eta$  will be:

$$\eta = \frac{R_r}{R_r + R_g + R_L} = \frac{1}{1 + \frac{R_L + R_g}{R_r}} \quad (3)$$

For a given ground system and soil,  $R_r$ ,  $R_g$  and  $R_L$  will vary as we change the umbrella design. We know that  $R_L = |X_a|/Q_L$  and we'll set  $Q_L = 400$  which is a reasonable value. The model gives us  $R_a$  with the ground system. If we assume that  $R_r$  from the perfect ground case does not change substantially when the ground system is added we can determine  $R_g$  from:

$$R_g = R_a - R_r \quad (4)$$

In figure 11 we use equation (4) to calculate  $R_g$ .

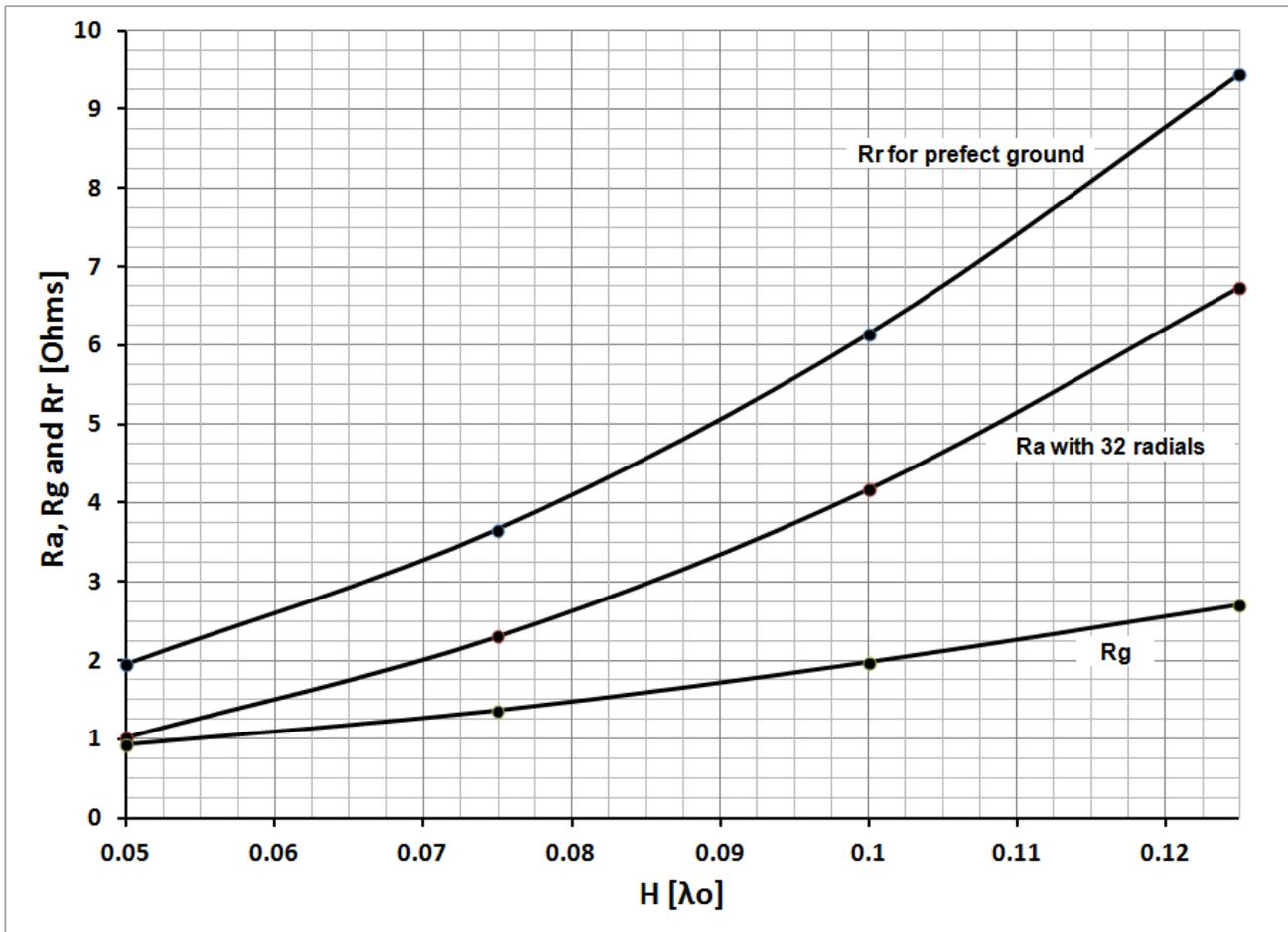


Figure 11 -  $R_g$  as a function of H with  $M=r=0$ .

Note that even though we have kept the ground system and soil characteristics constant as we varied H,  $R_g$  is not constant. There is a common misconception that at a given frequency, with a given ground system design and soil characteristics, that  $R_g$  is some fixed number without regard to the details of the vertical. This is not the case!  $R_g$  is not something you measure with an ohmmeter. It's how we account for the ground losses ( $P_g$ ) associated with a given antenna for a given base current ( $I_0$ ).

$$P_g = R_g I_0^2 \quad (5)$$

$P_g$  is created by E and H-fields which in turn are a function of both the base current and the details of the antenna. As we change the antenna, for a given  $I_0$  and ground system,  $P_g$  will change and that means  $R_g$  will change. This point is important because as we increase M the lower part of the umbrella will be closer to ground. For small values of M the fields at the ground surface won't change much but when M gets large,  $P_g$  increases and becomes a limiting factor on how large a hat we can use. The problem is that as we change H and M to minimize losses,  $R_r$ ,  $R_g$  and  $R_L$  all change!

## Zin with the ground system

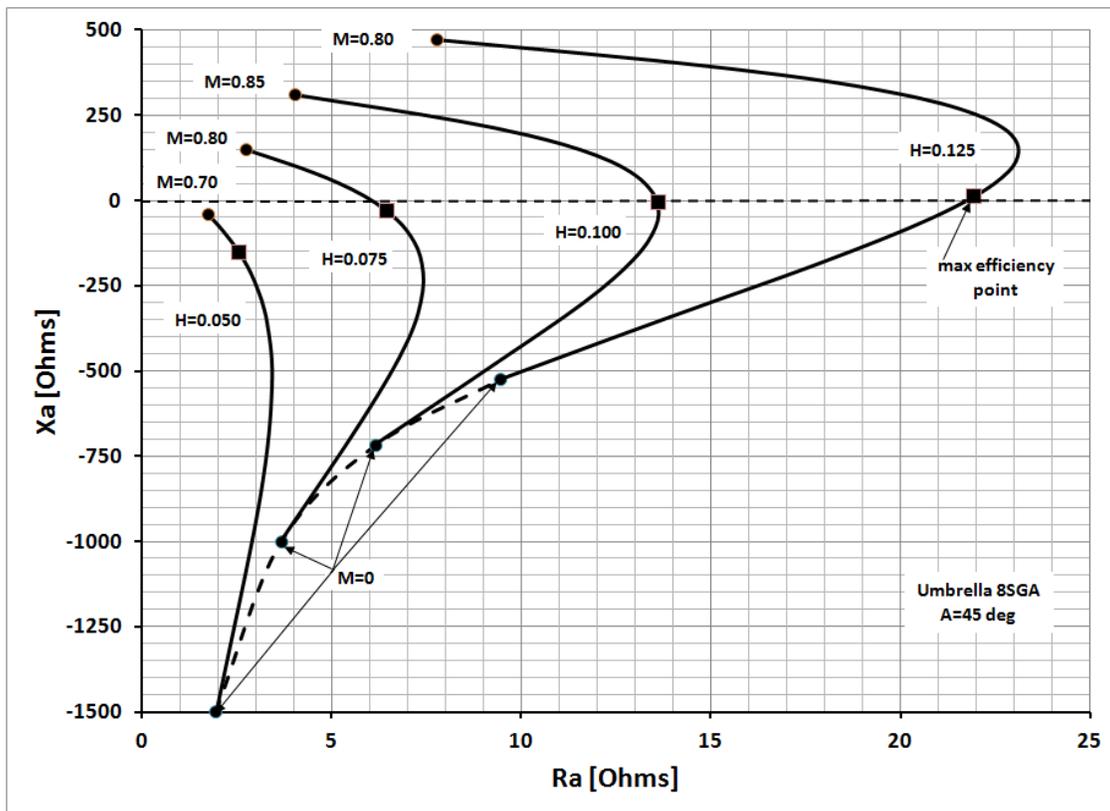


Figure 12 - feedpoint impedance.

Figure 12 graphs the feedpoint impedance ( $Z_{in} = R_a + jX_a$ ) using an Argand diagram where  $X_a$  is plotted as a function of  $R_a$ . There are two parameters:  $H$  and  $M$ .  $H = 0.05, 0.75, 0.100$  and  $0.125$ .  $M$  is varied from 0 (no umbrella, just a bare vertical) to a limit imposed by the minimum allowed ground clearance (8') for the umbrella skirt. The dashed line represents  $Z_{in}$  for a bare vertical as  $H$  is varied. We can see that the addition of an umbrella drastically changes  $Z_{in}$  and  $Z_{in}$  is a strong function of both  $H$  and  $M$ . There are some square markers in figure 12 which correspond to points of maximum efficiency. We'll discuss these shortly.

Figures 13, 14 and 15 show how the loss resistances ( $R_r$ ,  $R_g$  and  $R_L$ ) vary as a function of  $M$ . In figures 13 and 14 there are markers (the diamonds) for the values of  $M$  which correspond to resonance. Note that for  $H=0.050$  resonance is not reached with the maximum value of  $M$  so there is no diamond marker. In figure 13 the circles mark the values of  $M$  corresponding to maximum  $R_r$ . In figure 15,  $R_L = |X_a|/400$ . As shown in figure 12, as  $M$  is increased from zero at some point resonance is reached ( $X_a=0$ ). Above this point we no longer need  $X_L$  to resonate ( $X_a>0$ ) so in figure 15,  $R_L=0$  above resonance. In all these graphs,  $M=0$  corresponds to no umbrella.

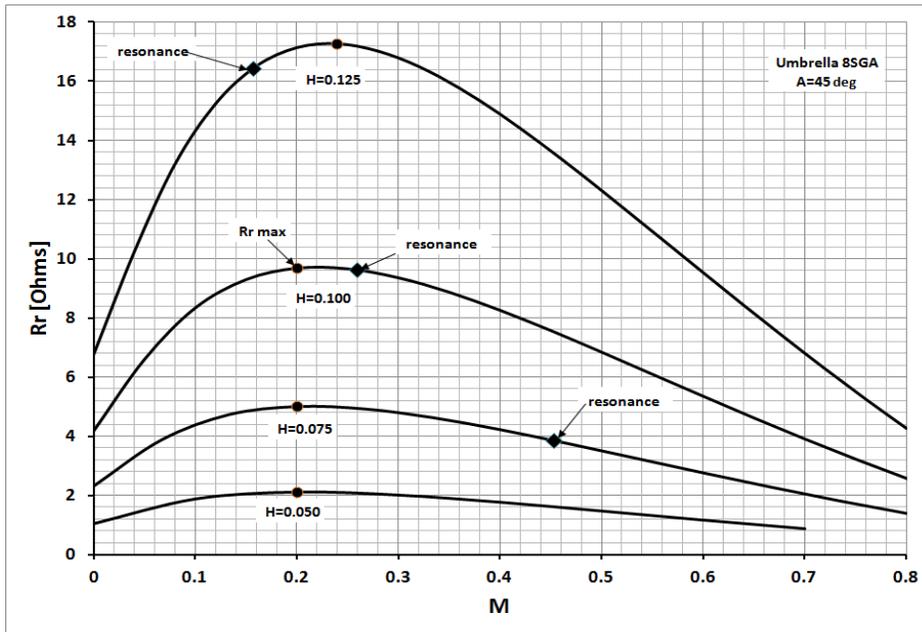


Figure 13 -  $R_r$  as a function of  $M$  with  $H$  as the parameter.

In figure 13 as we enlarge the umbrella (increase  $M$ )  $R_r$  rises but there is a maximum point which depends on  $H$  and  $A$ . Increasing  $M$  further reduces  $R_r$ . This is not surprising when we realize that the currents on the umbrella have a component  $180^\circ$  out of phase with the current on the vertical. This results in some cancellation which increases as  $M$  increases. However, in the region near  $R_r$  maximum the curves change slowly. For  $H=0.125$  and  $0.100$   $R_r$  maximum and resonance are fairly close together but for shorter antennas the two points are widely separated.

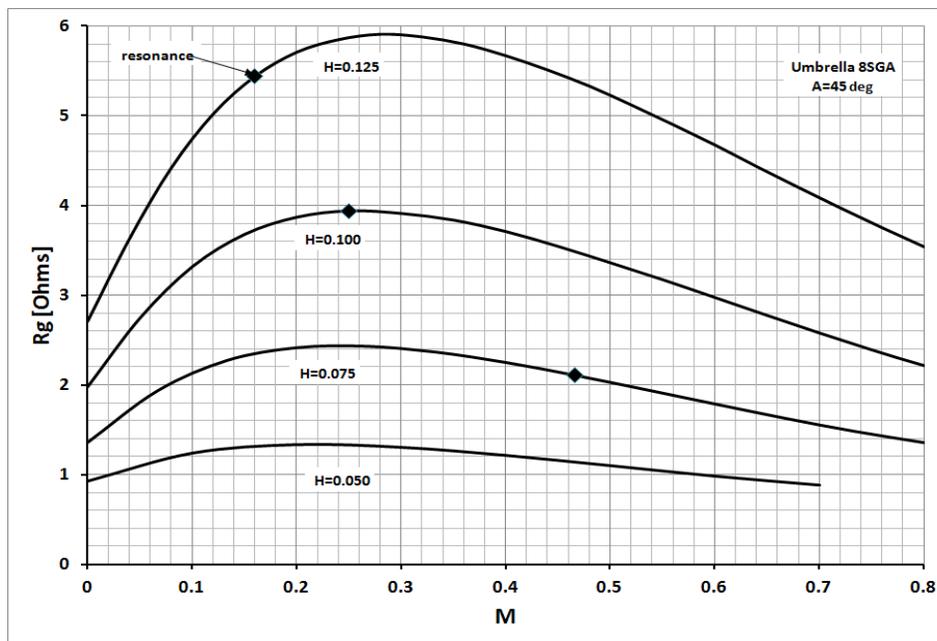


Figure 14 -  $R_g$  as a function of  $M$  with  $H$  as the parameter.

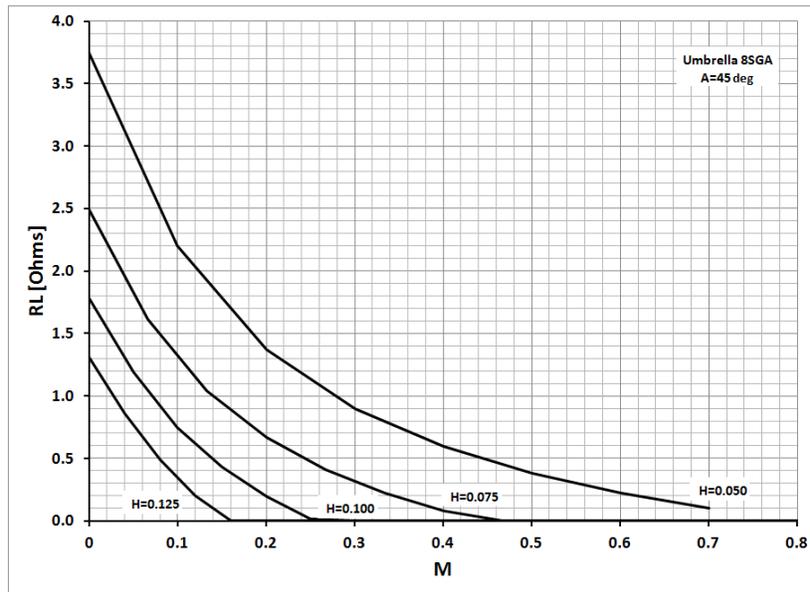


Figure 15 -  $R_L$  as a function of  $M$  with  $H$  as the parameter.

The values for  $R_g$  shown in figure 14 are substantially lower than the values for  $R_r$ . In figure 13  $R_g$  also has a maximum and then declines for larger values of  $M$ . This decline in  $R_g$  does not mean that the ground losses are going down! This is the same point I made with regard to  $R_g$  in figure 11.  $R_g$  may be falling but  $I_o$  for a given  $P_{in}$  is rising so that the net ground loss is higher. Putting aside for the moment the loss in  $R_L$ , we can graph the ratio  $R_r/R_g$  as shown in figure 16 to illustrate that a falling  $R_g$  does not imply higher  $\eta$ . Note also in figure 16 that the ratio gets smaller for shorter values of  $H$ . What this tells us is that lower efficiency is directly associated with shorter verticals over a given ground system even without taking into account conductor loss ( $R_c$ ) or  $R_L$ . This represents a fundamental limitation!

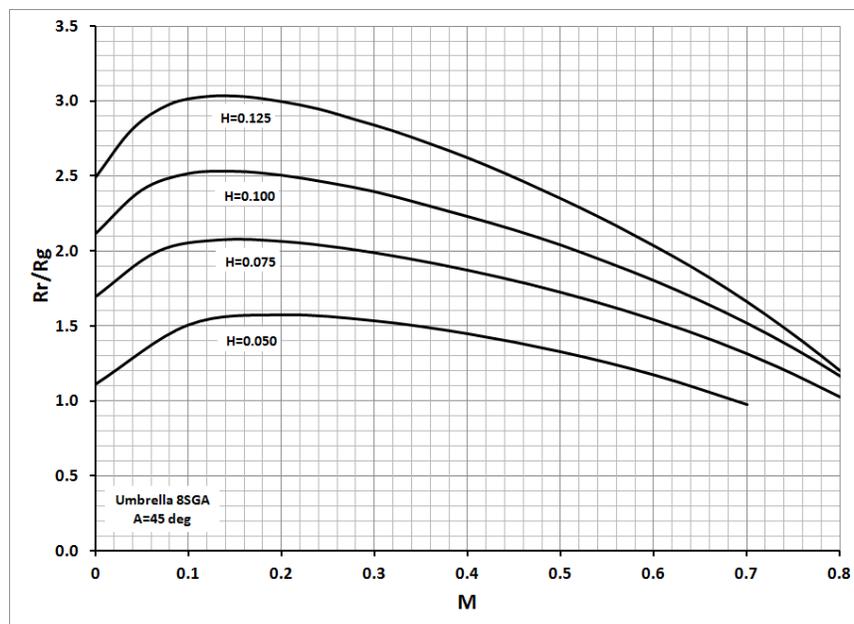


Figure 16 -  $R_r/R_g$  a function of  $M$  with  $H$  as the parameter.

Despite the hint given in figure 16, all three loss resistances vary with  $M$  so it's hard to see simply by inspection where the minimum loss or highest efficiency point is. Better to plug in values for  $R_r$ ,  $R_g$  and  $R_L$  into equation (3) and see where the maximums are as shown in figures 17 and 18.

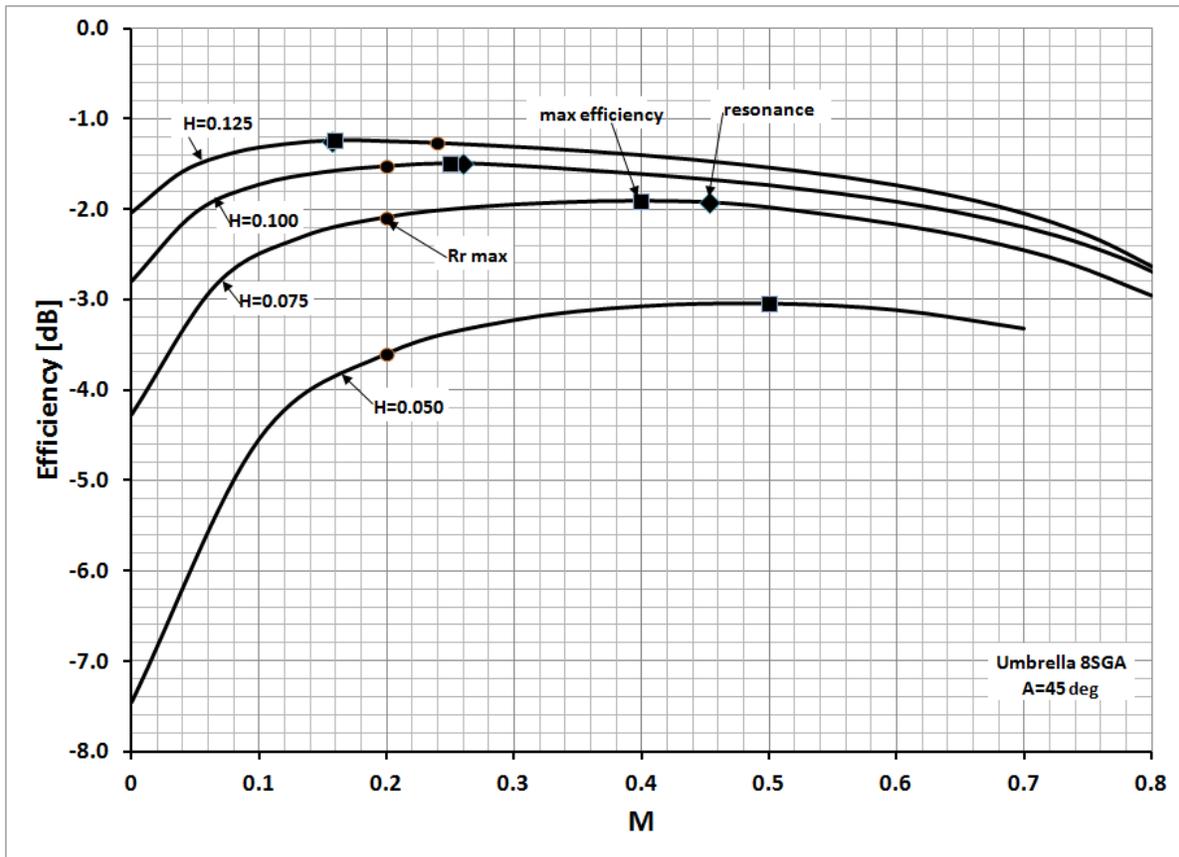


Figure 17 - Efficiency in dB as a function of  $M$  with  $H$  as the parameter.

Figure 17 shows the efficiency in dB where 100% efficiency would be 0 dB. Besides circles for maximum  $R_r$  and diamonds for resonance, in figure 17 there are squares to indicate values of  $M$  corresponding to maximum efficiency (the squares in figure 12 have the same meaning). One important point to notice is that while there are distinct points of maximum efficiency these maximums are very broad. For  $H=0.125$ , resonance and maximum efficiency coincide and for  $H=0.100$  and  $0.075$  they're also nearly coincident. The choice for  $M$  is not critical but in general the shorter the vertical the larger the optimum value for  $M$ .

It is also interesting to note that the points of maximum  $R_r$  don't coincide with either resonance or maximum efficiency. This brings into question the common assumption that designing for maximum  $R_r$  will result in maximum efficiency. That's actually a shame because if maximum  $R_r$  is our goal then NEC2 modeling can easily be used to determine the value. Unfortunately we need NEC4 which is often not available to determine  $R_g$  as it varies with the design of the vertical. However, it is possible to use  $\mathbf{E}$  and  $\mathbf{H}$  near-field values from NEC2 and a spreadsheet to calculate  $R_g$  as shown in the ARRL Antenna Book<sup>[7]</sup> (the equations are given in the Excel files on the associated CD).

As shown in figure 18, the apex angle of the umbrella (A) has an effect on the value for M at the maximum efficiency point. The larger A the lower the losses and the smaller (in terms of M) the umbrella. Note that for larger values of A the efficiency peaks are narrower.

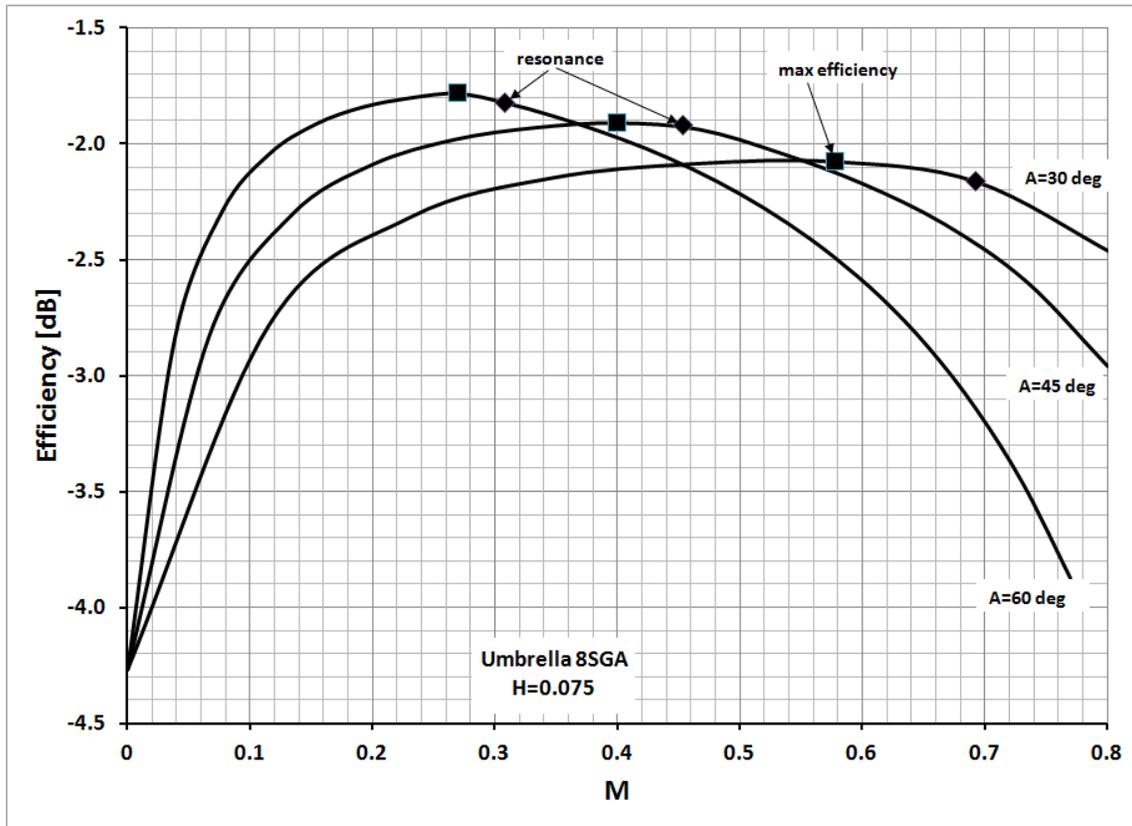


Figure 18 - Efficiency in dB as a function of M with A as the parameter.

Making A as large as practical is very helpful for shorter antennas.

### Conductor losses

It's time to look at conductor losses. Figure 19 gives examples of how the current at the feedpoint ( $I_o$ ), for a given input power (1.5 kW in this example), can vary with H and M. A is fixed at 45°. Figure 19 shows how rapidly  $I_o$  increases as H is reduced. Conductor loss varies as  $I_o^2$  so that in addition the increased losses shown earlier, conductor losses grow rapidly as H reduced. It isn't only that  $I_o$  is larger but the current along the entire vertical increases with more capacitive loading as illustrated in figure 20, which is an example of typical current distributions on an H=0.075 vertical. Note that these current distributions are for  $I_o = 1$  A. As shown in figure 19, for a given  $P_{in}$ , the value for the base current ( $I_o$ ) will depend on  $R_a$ , where  $I_o = \text{SQRT}(P_{in}/R_a)$ . As we vary the power level  $I_o$  will vary but the ratio  $I_{top}/I_o$ , where  $I_{top}$  is the current at the top of the vertical, will remain the same as shown.

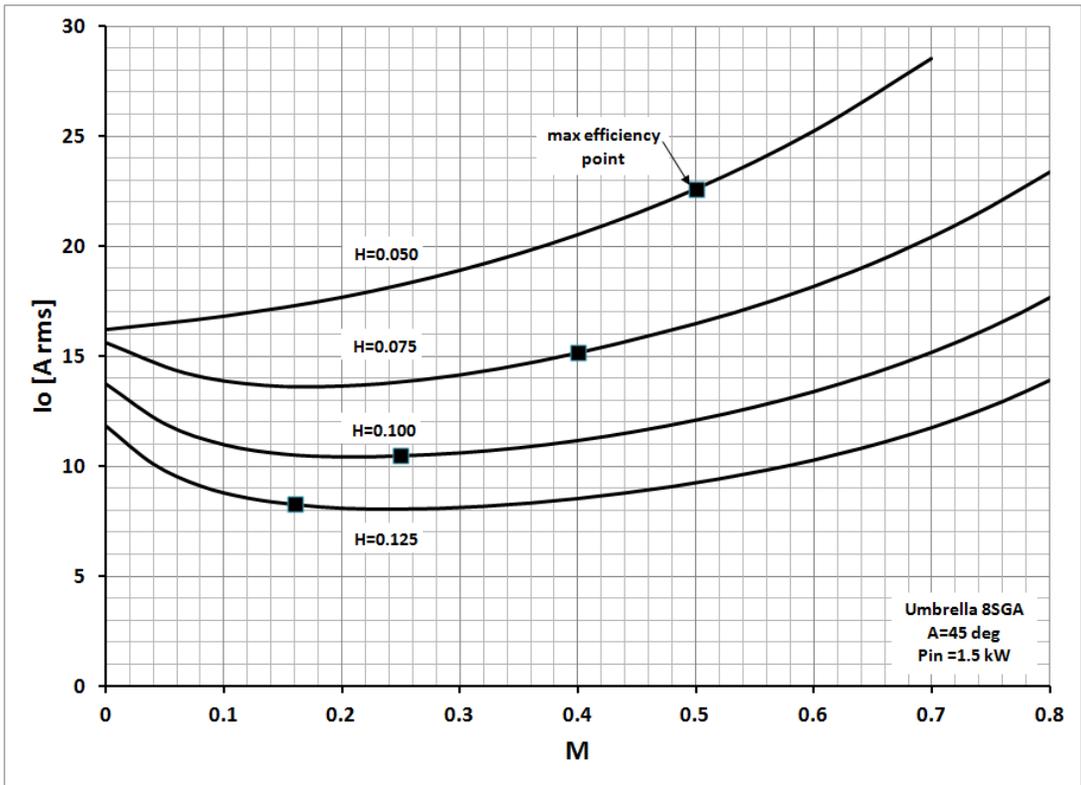


Figure 19 -  $I_o$  as a function of  $M$  with  $H$  as the parameter.

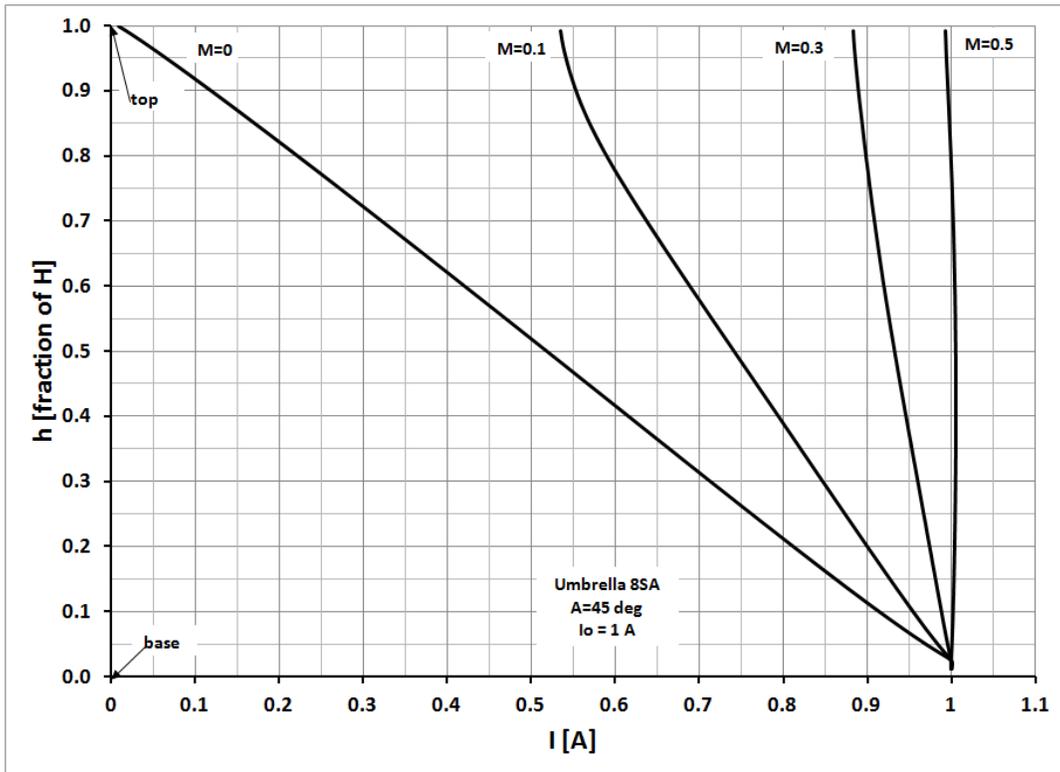


figure 20 - Example of the current distribution on a top loaded vertical.

In this example, for resonance,  $M = 0.45$ . The current distribution for  $M = 0.50$  has  $I_{top}/I_o = 0.99$ , in other words the current is almost constant along the vertical part of the antenna.  $I_{top}/I_o$  ratios greater than 0.9 are typical for short antennas top-loaded to near resonance. As shown in figure 20, the current without top-loading ( $M = 0$ ) falls almost linearly to zero (or close to it) at the top. In the case of mobile antennas the current distribution can be significantly improved by moving the loading inductor up into the vertical which raises the question if that idea is also useful when heavy top-loading is used. It turns out that when the current distribution is nearly constant the loading coil position has limited effect on the current distribution. From a practical point of view moving the inductor up into the vertical is a nuisance but in some cases you may be able to gain some improvement by relocating the inductor particularly if the top-loading is not large. This may be the case when  $H < 0.05$ .

We can get a good measure of conductor loss by turning on the copper loss option and then calculating the average gain ( $G_a$ ) with only the conductor losses. Figure 21 illustrates conductor losses for two different conductor sizes for vertical part of the antenna with  $0.05 < H < 0.125$ . In each case shown the antenna is resonant with only top-loading.

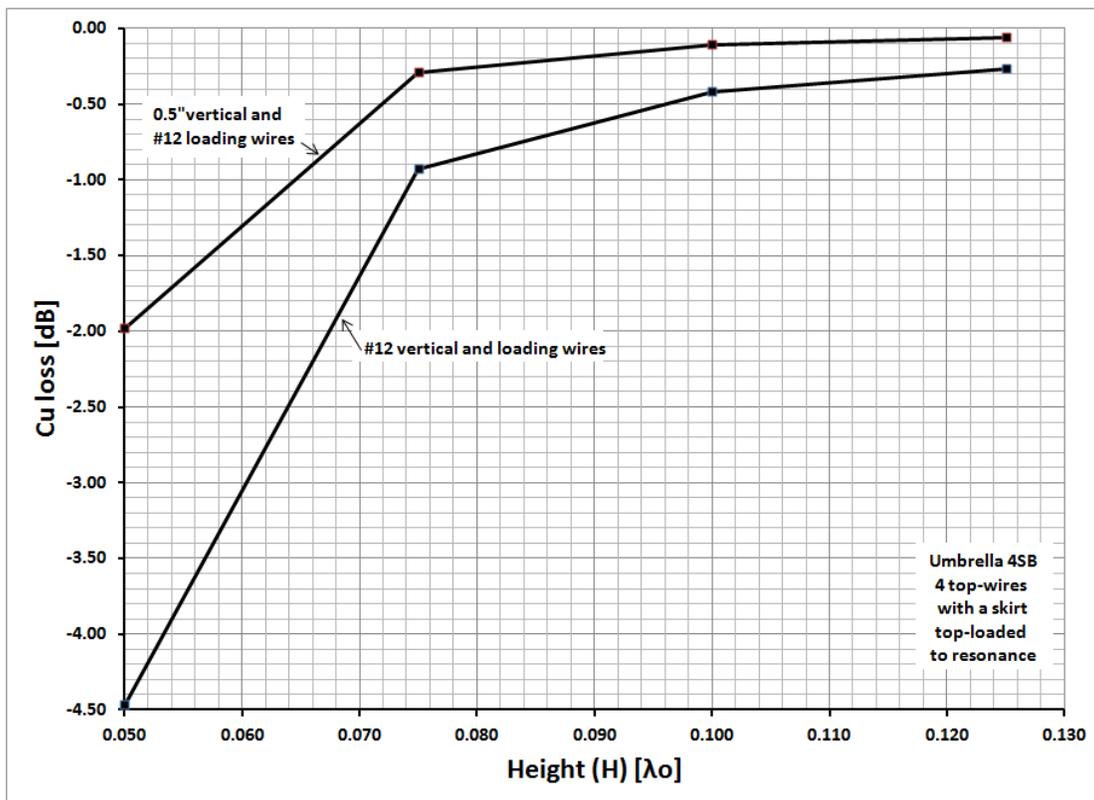


Figure 21- Examples of conductor loss in short antennas.

The initial model had #12 wires for the vertical and the four umbrella wires. As can be seen, the conductor losses at  $H = 0.05$  are very high,  $\approx -4.5$  dB. Most of the loss is in the vertical conductor so increasing its diameter from 0.08" to 0.5" cuts the loss almost in half. An even larger diameter conductor along with eight umbrella wires would reduce the conductor loss to less than 1 dB. For example, at 1.83 MHz,  $0.05 \lambda_0 \approx 27'$ , a 30' length of 4" aluminum irrigation tubing along with a skirted 8-wire top-hat could have low conductor losses.

*The message here is to be very aggressive in conductor sizing. If we are, we can keep conductor losses low even in very short antennas!*

### Voltage at the feedpoint

Not only is  $I_o$  large in short verticals but the voltage at the feedpoint can also be very high due to the high reactances below resonance (see figure 12 for  $X_a$ ). Figure 22 shows typical values for the feedpoint voltages for  $P_{in} = 1.5$  kW.

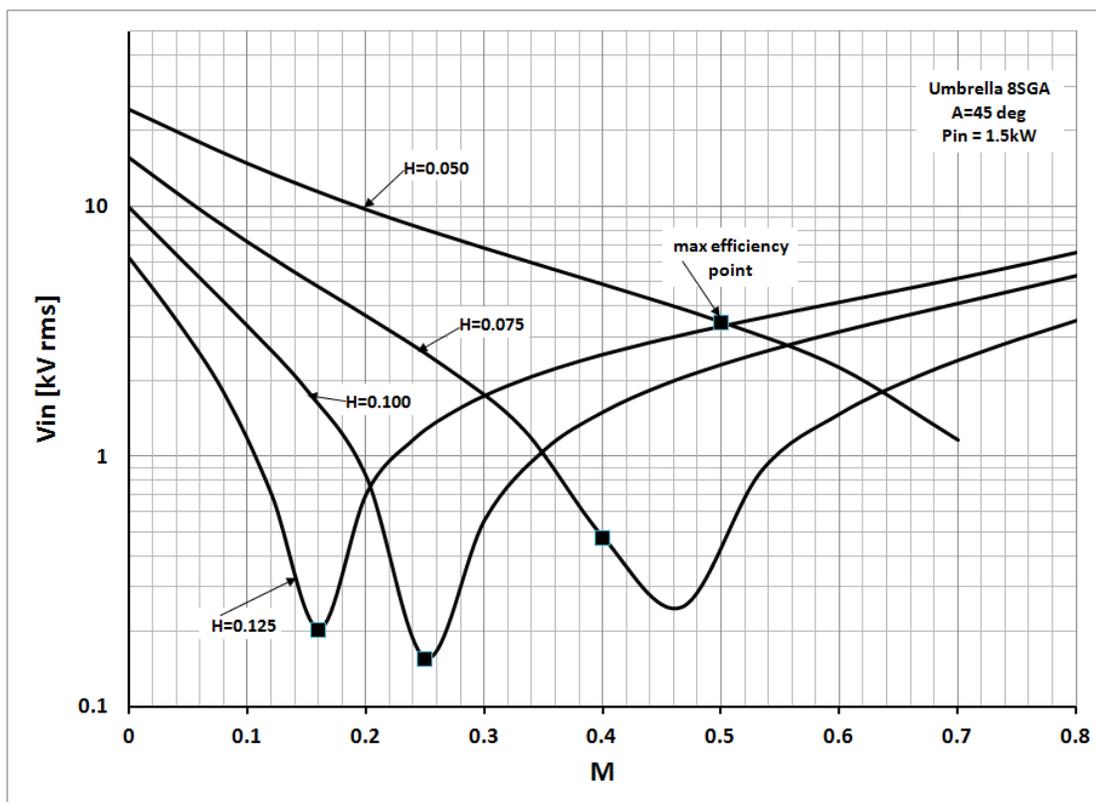


Figure 22 -

Note, the vertical scale is in kV rms! Fortunately for  $H \geq 0.075$  the highest efficiency point is close to resonance so the feedpoint voltages are relatively small. However, with  $H \leq 0.05$ , you can't reach resonance, at least with  $A = 45^\circ$ , and the feedpoint voltage is much higher. One way to improve both efficiency and reduce the feedpoint voltage would be to increase  $A$  to  $60^\circ$ . At 1.83 MHz,  $0.050\lambda_o \approx 27'$  so it may be practical to increase  $A$  in shorter antennas.

If the power is reduced from 1500 W to 100 W you're still not out of the woods because the voltage varies as the square root of  $P_{in}$ . Going from 1500 W down to 100 W reduces the feedpoint voltages by a factor of 1/3.9 not 1/15! Even at low power levels the voltages can be dangerous. These voltage levels at RF frequencies can introduce significant loss associated with leakage across the base insulator. A plastic bottle base insulator doesn't cut it! Keeping the insulator surface clean and dry is also important. Some form of plastic shield can help to keep the insulator clean and dry. The use of equipotential rings can also help.

Besides the base insulator these voltages will appear across the base loading inductor if one is present and/or the output of the matching network. There is also the problem of dealing with the power dissipation in the loading inductor. In addition there will be very high potentials on the lower part of the umbrella. These potentials are lower with skirted umbrellas and such umbrellas are usually further above ground but you still have to consider corona losses. Any sharp points where the umbrella and skirt wires are joined or where insulators are connected can result in substantial losses due to corona, especially if you live at higher altitudes such as Denver, CO or up in the mountains. You should use high grade insulators on the support lines spreading the umbrella even if they are non-conducting.

### SWR bandwidth

The final step is to match the feedpoint impedance to 50  $\Omega$ . This can be done in many ways but for this discussion I assume the use of a simple L-network<sup>[8]</sup> matching the feedpoint impedance at the highest efficiency point. Assuming  $A=45^\circ$  and  $f=1.83$  MHz, table I summarizes the L-network components and the 2:1 SWR bandwidth for each antenna.  $X_s$  is the series matching reactance and  $X_p$  is the shunt reactance. In this example all the  $X_s$  are inductors and the  $X_p$  are capacitors.

Table I, L-network values and 2:1 SWR bandwidths.

H [ $\lambda_o$ ]	$R_a$ [ $\Omega$ ]	$X_a$ [ $\Omega$ ]	$X_s$ [ $\Omega$ ]	$X_p$ [ $\Omega$ ]	2:1 Bandwidth
0.050	2.56	-152.5	163.5	-12.56	15 kHz
0.075	6.46	-30.67	47.44	-19.26	33 kHz
0.100	13.60	-5.92	28.17	-30.56	56 kHz
0.125	21.94	11.42	13.39	-44.21	75 kHz

Table I illustrates the sharp reduction in match bandwidth associated with shorter verticals. For a given H, one way to improve bandwidth without reducing efficiency is to make A larger. Making the diameter of the vertical conductor larger will also help especially if you can go to a wire cage several feet in diameter! There's big bag of tricks<sup>[9,10, 11]</sup> along those lines which deserve discussion but this article is already too long.

### **Experimental verification**

As mentioned in the introduction, NEC modeling is a powerful tool but it's not perfect. Whenever possible I like to compare my results with high quality experimental work. Fortunately such work is available for this discussion. In October 1947 Smith and Johnson<sup>[4]</sup> published an IRE paper on the "Performance of Short Antennas" which presented their experimental work at MF on a 300' tower with eight sloping "umbrella" wires and a loading inductor at the base. This paper is a beautiful example of first class experimental work. Measurements were made at several frequencies from 120 to 350

kHz with the umbrella wire lengths varied in steps from 100' to 450'. Figure 23 is a sketch of the tower and umbrella arrangements. The angle between the tower and the umbrella wires was  $\approx 48^\circ$ .  $H=300'$  represents  $0.037\lambda_0$  at 120 kHz and  $0.107\lambda_0$  at 350 kHz so despite the large physical size, this is still a "short" antenna. These heights are also within the range of  $H$  we have been modeling.

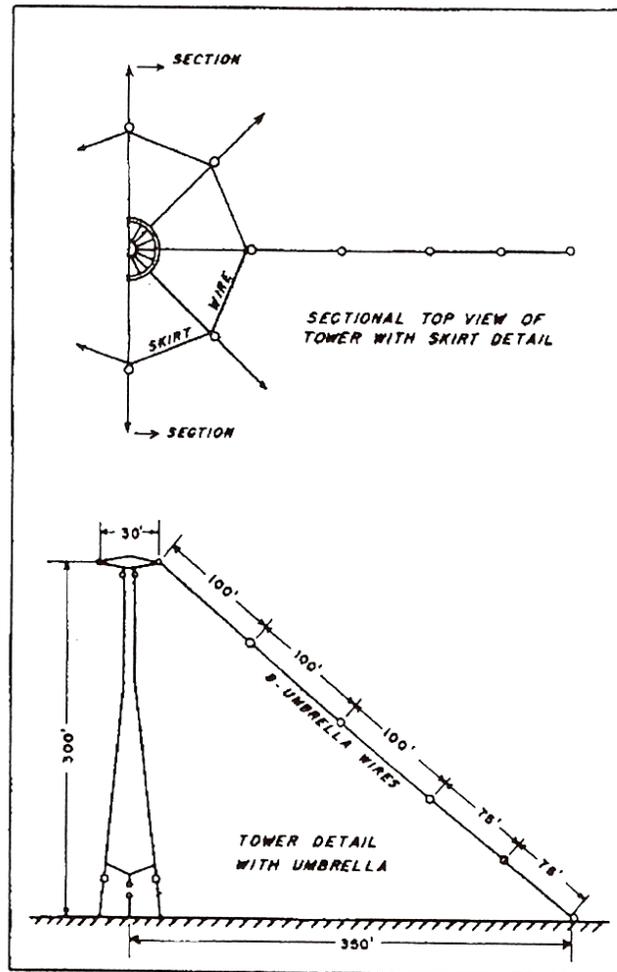


Figure 23 - Sketch of the experimental antenna from Smith and Johnson<sup>[4]</sup>.

The ground system had five hundred 75' radials and two hundred and fifty 400' radials. Note that the 400' radial wires extend a short distance past the outer edge of the umbrella when it's wires are at maximum length. At 120 kHz  $75'=0.009\lambda_0$  and  $400'=0.03\lambda_0$ . At 350 kHz,  $75'=0.027\lambda_0$  and  $400'=0.14\lambda_0$ . Compared to standard BC practice ( $0.4\lambda_0$  radials) this is a very abbreviated ground system. A small ground system is just what we might expect with a short amateur vertical! The five hundred 75' radials are in effect a ground screen close to the base of the vertical where the **E**-fields can be very intense.

Part of the experiment was a measurement of field strength at one mile with 1 kW of excitation. This was done at several frequencies with a range of umbrella wire lengths and loading coil Q's. An example of the results is given in figure 24 for a loading coil  $Q=200$ .

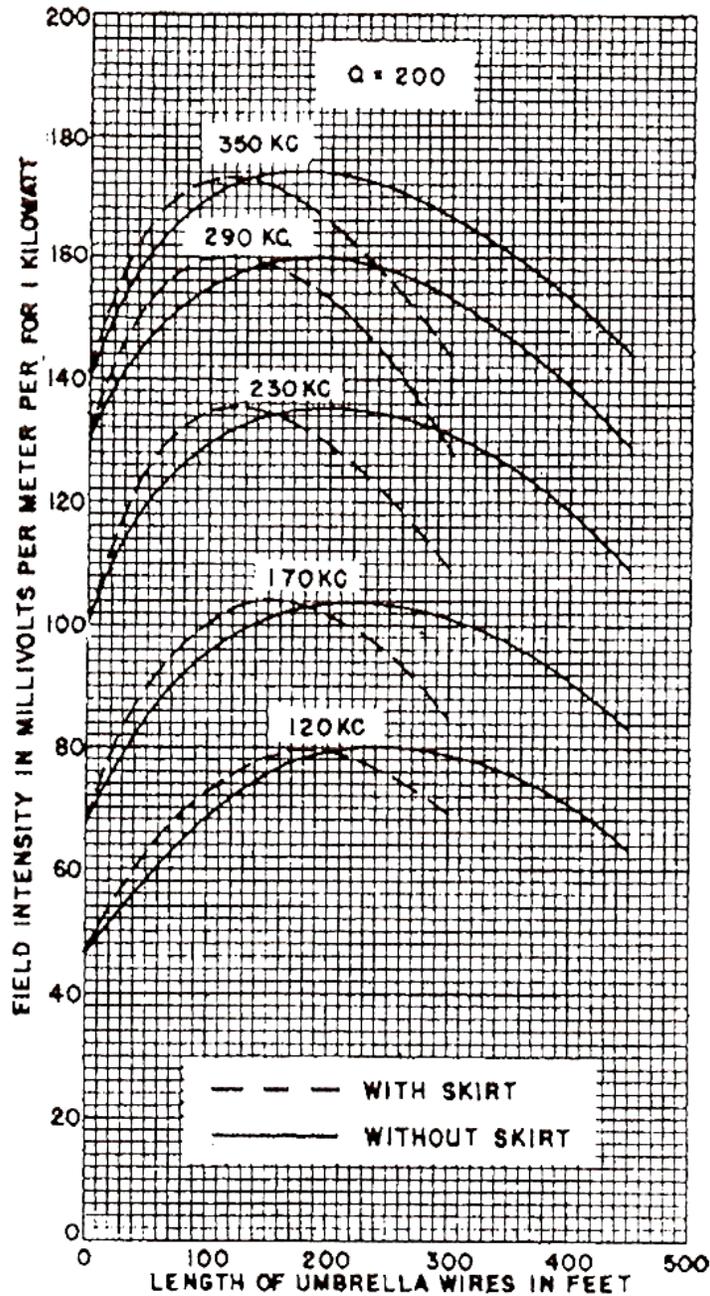


Figure 24 - An example from Smith and Johnson<sup>[4]</sup>.

Changing frequency with a fixed H is equivalent to changing H at a fixed frequency. Figure 24 sends a clear message: the taller the better! H is a dominate factor in achievable efficiency. There are two sets of data on the graph: the first is the solid line for the case of no skirt wire around the outer perimeter of the umbrella and the second (the dashed line) is for case where a skirt wire connects the outer ends of the umbrella wires. The point of maximum signal can be viewed as the optimum length for the umbrella wires. The relative field intensity can be used as a surrogate for efficiency. The higher the field intensity, at a given distance, for a given input power, the higher the efficiency.

*Note the correspondence between the experimental work in figure 24 and the NEC results in figure 17: both figures tell the same story!*

Using a skirt provides more capacitive loading for a given length of umbrella so we see the peak move to the left, toward shorter wires. But notice that the peak value doesn't change much, it just moves towards shorter wires. In both cases the peak is quite broad especially for the un-skirted umbrella.

It is also interesting how the peak field point moves towards longer umbrella wires at lower frequencies (corresponding to smaller  $H$  in  $\lambda_0$ ) and the peak field also declines indicating lower efficiency. No surprise really, the antenna is electrically smaller at the lower frequencies and less efficient. The shift of the peak towards longer umbrella wires is a reflection of increased loss (lower efficiency). Again, this agrees well with the NEC modeling.

I strongly recommend reading the Smith and Johnson paper<sup>[4]</sup> as well as Belrose<sup>[5]</sup> and Sevick<sup>[1,2,3]</sup>.

## **Summary**

From both modeling and experimental work we can draw some general conclusions:

1. Make the vertical a tall as possible.
2. Make the ground system as large and dense as practical.
3. Make  $A$  as large as practical.
4. Use at least eight wires and a skirt in the umbrella.
5. Be very aggressive in conductor sizing especially for the center conductor.
6. Use high-Q inductors for loading/matching networks.
7. Use high quality insulators both at the base and for the umbrella.

If you do these things then it is possible to have reasonable efficiencies even in very short antennas.

Despite the length of this discussion there's far more that could be said and many more ideas for improving short antennas are out there. This discussion has just covered a narrow slice of the possibilities but it has looked at one practical option which I hope will be helpful.

## **Acknowledgement**

The work in this paper prompted by some questions on a short 160m antenna from Paul Kisiak, N2PK. Because I hadn't dug deeply into this subject I couldn't help him much beyond some general comments on ground systems. so I got to work! I want also to thank my reviewers tbd.

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