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Some Ideas for Short 160 Meter Verticals

Few amateurs have room for full sized vertical antennas on 160 meters. Shorter verticals are possible, but you have to be creative.

While it's desirable for a vertical to be a full ¼-wavelength high, on 160 meters that's ≈130 feet and many times that's not possible. For a variety of reasons we may be restricted to much shorter verticals. The late Jerry Sevick, W2FMI, showed us how to build efficient short verticals for 20 and 40 meters using a flat circular top-hat, which is very effective for capacitive loading and practical at 40 meters.[1, 2, 3] But a flat top becomes mechanically difficult on 160 meters, 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 shown in Figure 1. 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 has been done at MF.[4] Large antennas are difficult to work with so there hasn't been a lot of experimental optimization although Belrose, VE2CV, has written about his work with VHF models and at MF.[5, 12] 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.

[1]Notes appear on page 45.

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° = $\lambda/2\pi = 0.16\lambda_0$) where λ_0= free space wavelength. Sometimes "short" is defined as a vertical with a physical height $H<\lambda_0/8$ or 45°. At 1.83 MHz $\lambda_0/8 \approx 67$ feet. The focus of this article will be antennas with $H<0.125\lambda_0$.

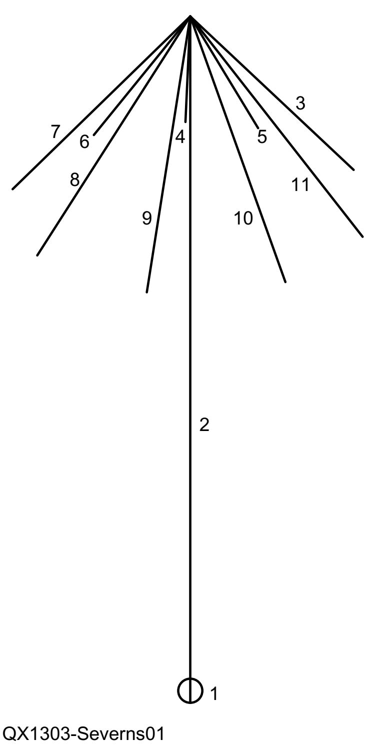

Figure 1 — Example of an umbrella vertical.

Is There a Problem?

Before starting a discussion on capacitive top-loading we need to ask if there is a problem with short verticals that 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. For a lossless antenna the radiation pattern of a very short vertical is almost the same as a $\lambda/4$ 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 and a major part of the design effort is directed towards minimizing losses.

The impedance at the feed point is $Z_{in} = R_a - jX_c$, where $R_a = R_r + R_L + R_g + R_c + R_i + R_{cor}$, and X_c is the capacitive reactance. R_r is the radiation resistance which represents the desired power "loss." Note that when modeling lossless examples, $R_a = R_r$.

Figure 2 shows a graph of Z_{in} for an ideal vertical (R_a=R_r) over a range of heights: $0.01\lambda_0 < H < 0.125\lambda_0$. Note how rapidly R_a falls ($\propto H^2$) and X_a rises ($\propto 1/H$).

In most of the following graphs and discussion H is given as a fraction of λ_0. The physical height in feet (H') at 1.83 MHz is given by:

λ_0 = 537.471 feet → H' = 537.471 × H

For example H = 0.05 λ_0 → H' = 26.9 feet and H = 0.125 λ_0 →67.2 feet

In Figure 2 $Q_a = X_c/R_a$. Because R_a falls rapidly as H is reduced and simultaneously X_c increases rapidly, Q_a becomes very large for small values of H. Q_a varies as $1/H^3$!

For H ≤ 0.125, the capacitive reactance dominates Z_{in} which implies that short antennas are basically just small capacitors in series with small resistances, with the equivalent circuit shown in Figure 3.

To tune out the capacitive reactance at the feed point we can add a series inductor as shown in Figure 4 where $X_L = X_c$ and R_L is the loss resistance associated with X_L ($R_L = X_L/Q_L$).

The efficiency (η) for the circuit in Figure 4 can be expressed by:

$$\eta = \frac{power\ radiated}{input\ power} = \frac{R_r}{R_a + R_L} \qquad \text{[Eq 1]}$$

Where $R_a = R_r + R_g + R_c + R_i + R_{cor}$. Ignoring for the moment $R_g + R_c + R_i + R_{cor}$, we can graph Equation 1 to show how the efficiency of a short vertical depends on Q_L and H as shown in Figure 5. A Q_L of 200 represents a pretty mediocre inductor. Q_L values 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. Table 1 shows the correlation between efficiency in percent and dB where η in dB = 10 Log(η(in %)/100).

Table 1
Relationship Between Efficiency in % and dB

Efficiency in %	*Efficiency in dB*
50%	–3 dB
10%	–10 dB
1%	–20 dB
0.1%	–30 dB

For small values of H, the efficiency is pretty depressing. What's even more depressing is that Figure 5 only shows the effect of R_L. When we include other losses the efficiency will be even lower.

Given the practical limitations on Q_L it's clear that short base-loaded verticals can be very inefficient. Mobile antenna work has shown that we can improve the efficiency by moving the inductor from the base up into the vertical itself. While this can help, we can do much better by adding capacitive top loading, which is practical for fixed installations.

Besides efficiency 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. For a given input power, short antennas can have much higher conductor currents and very high voltages at the feed point. For example, if we set H = 0.05 λ_0, $R_r \approx 1\ \Omega$ and $X_c \approx 1500\ \Omega$. If the base inductor Q_L = 400, then X_L = 3.75 Ω. $R_r + R_L$ = 4.75 Ω. For P_{in} = 1500 W the current into the base will be ≈ 18 A_{rms} and the voltage at the feed point (and across the inductor) will be ≈ 27 kV_{rms}! In addition, the inductor will be dissipating ≈1200 W. Clearly, base loaded short verticals have problems. Capacitive top-loading is the way out of this box.

Design Variables

There are many variables, all of which can 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

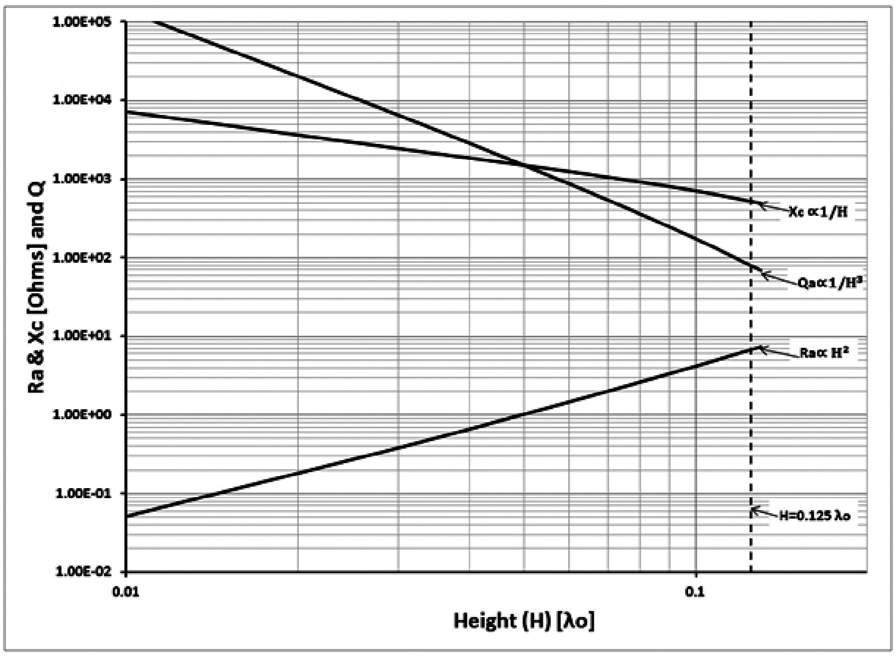

Figure 2 — Feed point impedance at the base of an ideal vertical.

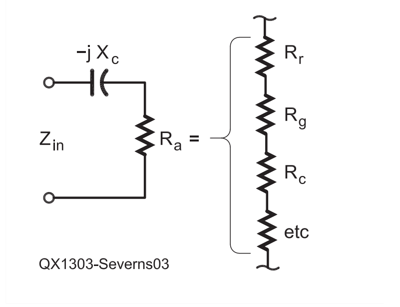

Figure 3 — Equivalent circuit for Z_{in}.

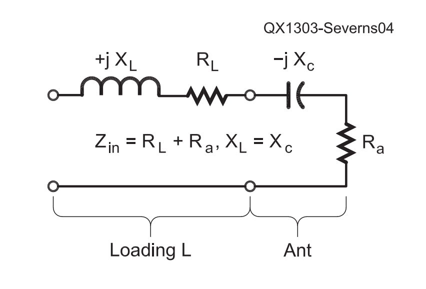

Figure 4 — Equivalent circuit for the input impedance with a series inductor.

• 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 many variables and we cannot work with all of them at once. What I've elected to do is deal with one or a few 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'll be including a real ground system, inductor and conductor losses, etc. I've chosen the 8-wire umbrella with a skirt for this discussion because it's relatively simple and it works well, but we should keep in mind that this is only one of many possibilities.[6] An example is shown in Figure 6. The apex angle (A) will be varied from 30˚ to 90˚. The modeling was done at 1.83 MHz. For the moment the ground is assumed perfect and there are no conductor losses.

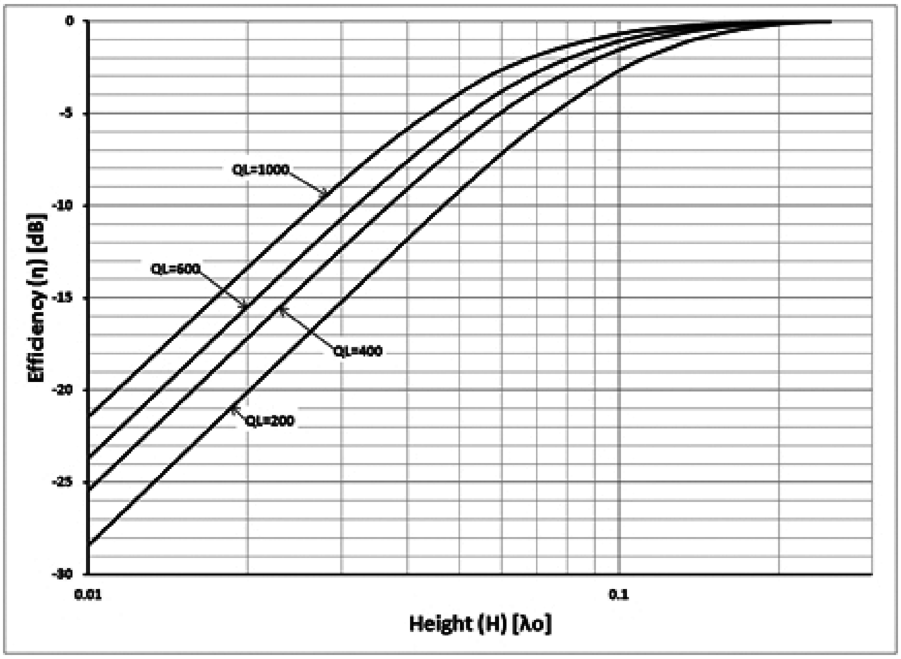

Figure 5 — Variation of efficiency in dB as a function H and Q_L.

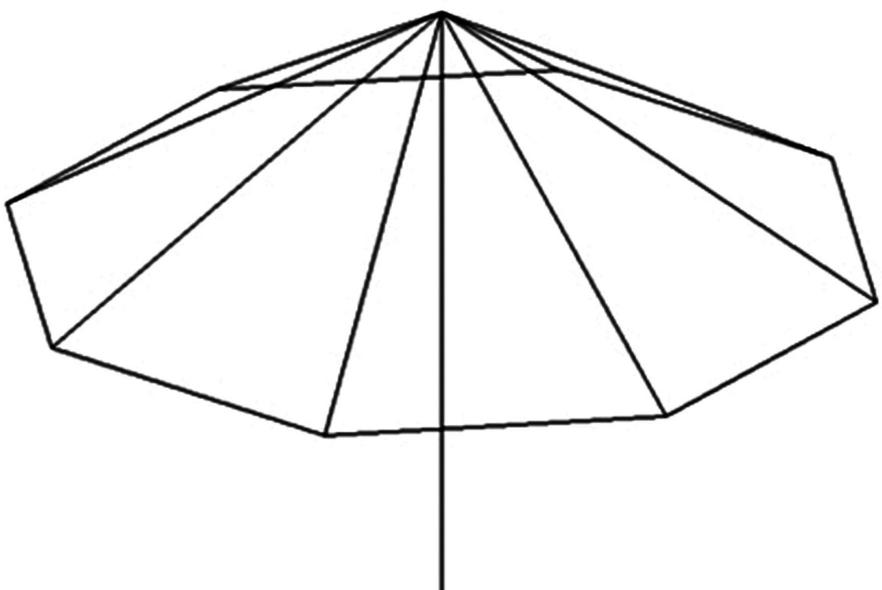

Figure 6 — *NEC* model.

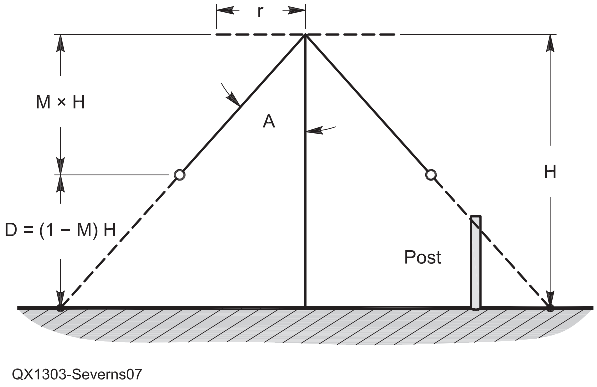

Figure 7 — Model dimensions.

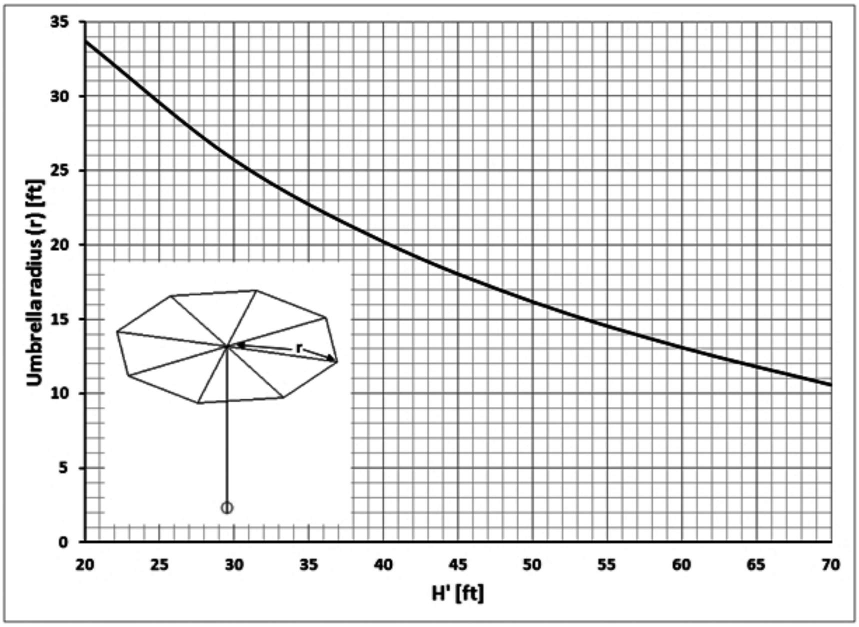

Figure 8 — Radius of the horizontal umbrella needed to resonate the vertical as a function of H'.

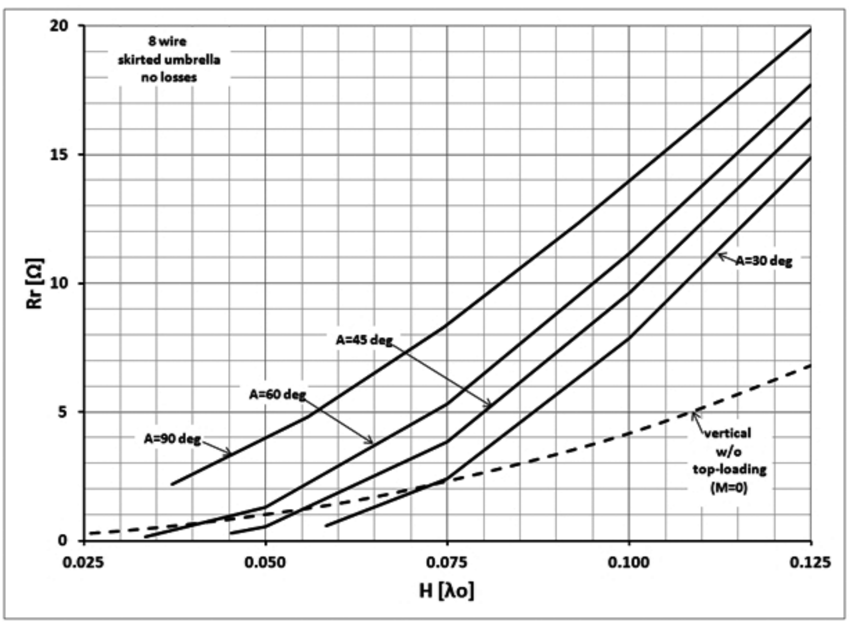

Figure 9 — R_r at resonance as a function of A and H compared to an unloaded vertical.

Figure 7 is a sketch of a top loaded vertical identifying the dimensions. The height of the vertical is H and the vertical dimension of the umbrella is M × H (from the top of the vertical to the bottom of the skirt wires). M is a fraction of H (0<M<1). As we increase M, the bottom of the umbrella 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 skirt. All these dimensions are in λ_0 except M which is a dimensionless ratio. The angle between the umbrella and the vertical at the top is A (in degrees). Initially all the conductors are #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 resonate the antenna *without a base inductor*, using only top-loading. This is possible for a wide range of H. We don't want to fool ourselves, however. Even without the need for a resonating inductor, we will very likely need a matching network with an inductor. Top-loading for resonance is not the only option. One widely held idea is that the top-loading should be adjusted to maximize R_r and then an inductor or capacitor should be used to resonate. It's also possible that some other combination may yield the best efficiency. We'll look at these possibilities after we've added a ground system to the model to introduce R_g into the efficiency calculation.

Horizontal Umbrellas

Jerry Sevick used flat or horizontal umbrellas (A=90°) for top loading on 40-meter verticals. This form of top-loading is very effective, but it may not be practical on 160 meters. Figure 8 shows how large the umbrella radius must be to resonate the vertical at 1.83 MHz for 20 feet ≤H'≤70 feet. To give a better feeling for the mechanical dimensions I've shown H and r in feet (H' and r').

For H' = 40 feet, resonance requires an umbrella with r' = 20 feet. An umbrella with r = 10 feet is pretty easy, but going to r = 20 feet or more becomes a mechanical challenge, at least if the umbrella is a free standing "wagon wheel." Mechanically, it's much simpler to just attach the umbrella wires to the top of the vertical and slope them towards ground. But there's a price to pay as shown in Figure 9. For most values of H and A, R_r is higher than its value without top-loading, but for sloping umbrellas R_r is substantially lower than for A = 90°. If it's possible to use a horizontal umbrella by all means do so, but for the rest of this article, we will assume we can't do that and we'll be considering umbrellas with sloping wires.

Umbrellas with Sloping Wires

Figure 9 makes the importance of A 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 farther 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 as indicated in Figure 7. In a given installation the value for A is likely to be limited by the available space.

Resonating the vertical using only capacitive loading helps a great deal by eliminating R_L, but we still have the problem of low R_r for small values of H as shown in Figure 9. The dashed line represents R_r for a bare vertical, without top-loading. 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.

Figure 10 shows the relationship between H and M *for resonance* for skirted umbrellas with 4 and 8 wires, for three apex angles (A).

Whether we can reach resonance depends

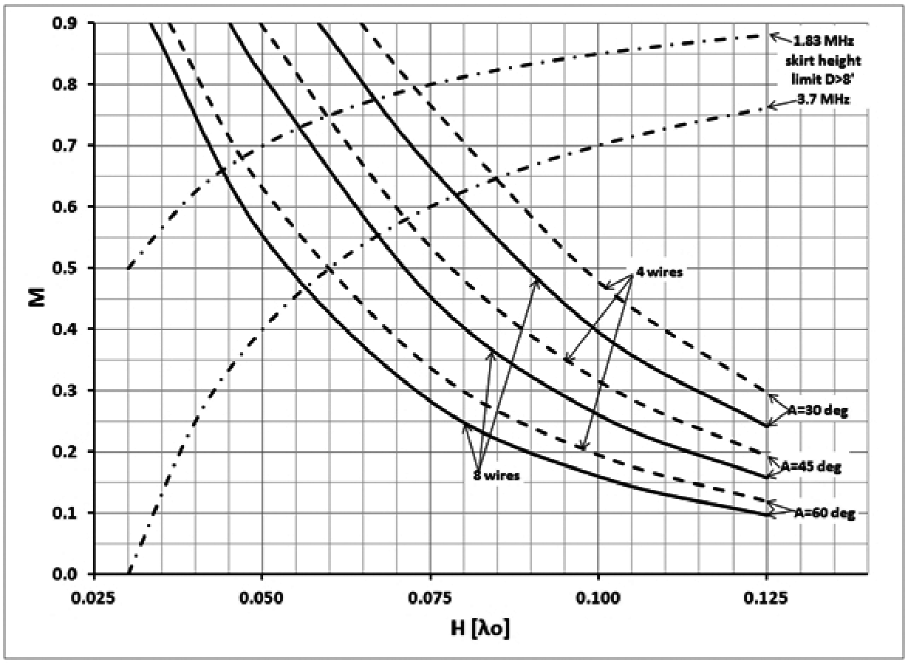

Figure 10 — Values of M for resonance when using 4 or 8 umbrella wires and a skirt.

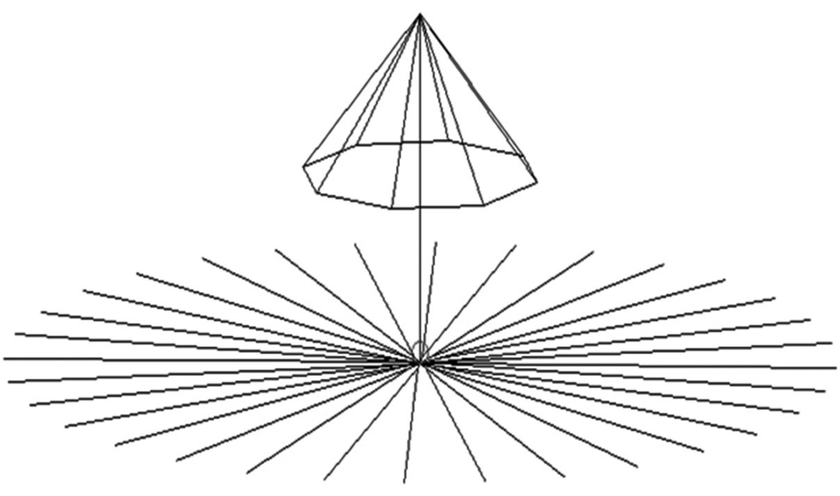

Figure 11 — *NEC* model for a top-loaded vertical with a ground system.

on H, A and the number of umbrella wires, but as Figure 10 shows we can do pretty well for antennas down to H ≈ 0.04λ_0 or a bit shorter on 160 meters if we use a large value for A and more wires in the umbrella. At 1.83 MHz, 0.04λ_0 = 21.5 feet, which is definitely a "short" vertical. Figure 10 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 16 wires would be 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 wire umbrellas is their vulnerability to ice loading. If you live in an area where ice storms are common you'll have to carefully think through your mechanical design.

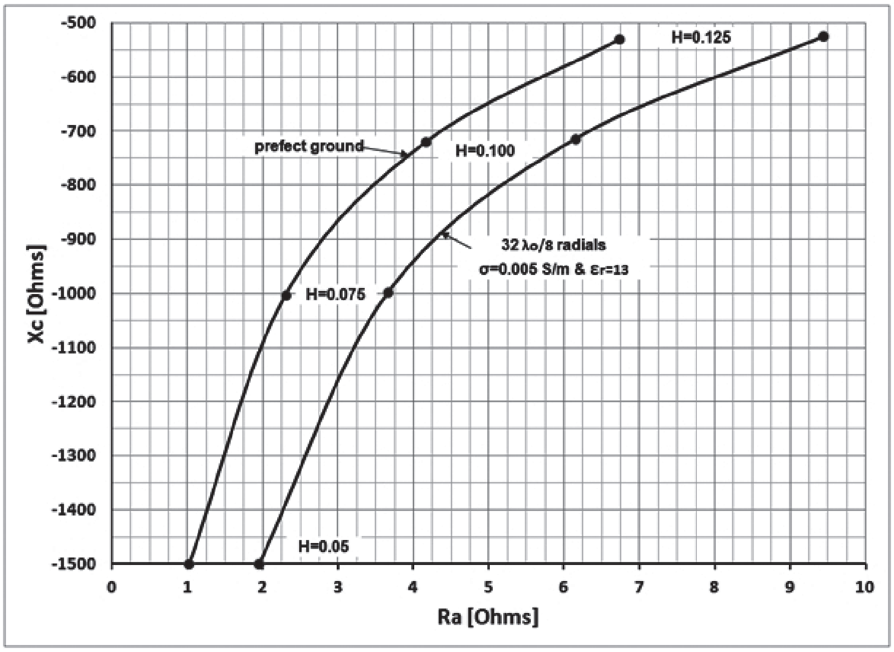

Figure 12 — R_a versus X_c as a function of H with no top-loading, with perfect and real ground systems.

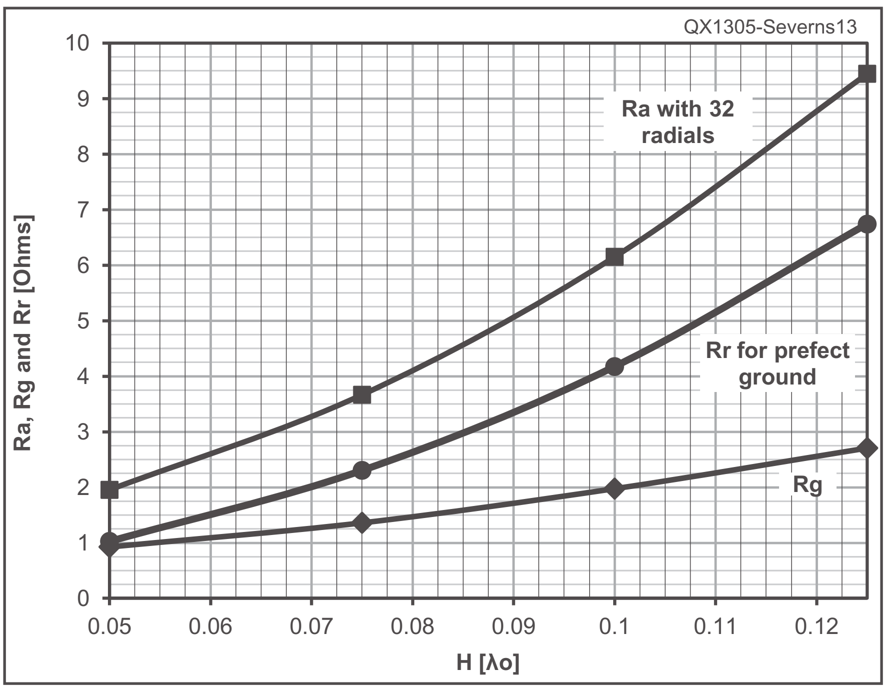

Figure 13 — R_r, R_a and R_g as a function of H *without top-loading*.

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 must *keep the skirt out of reach*, at least 8 feet above ground so you can't touch it. This limitation is indicated in Figure 10 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 boundary lines.

Non-Ideal Verticals

Now it's time to include losses in addition to R_L.

Affect of Ground System Losses

A model that includes a ground system is shown in Figure 11.

I've chosen to use 32 λ_0/8 radials (Lr ≈ 65 feet) buried 6 inches in average soil (σ = 0.005 S/m and ε_r = 13). This represents a compromise system; real systems may be larger or smaller depending on the limitations of a given installation. A = 45° 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've set A = 45° for many of the examples.

We need to keep our goal in mind. For a given set of limitations on H, the footprint area of the ground system and the distance to umbrella anchor points on the ground, etc, we want to achieve the maximum possible efficiency. For the moment we'll work with the major losses: R_g and R_L. In this part of the discussion we are *not* going to assume the umbrella loading alone is enough to resonate the antenna. We may use some X_L.

We can start by looking at the effect of real ground on R_a as shown in Figure 12 which compares R_a versus X_c between models with and without the ground system for four values of H. The dots correspond to the values for H at that point.

We can see that R_a increases substantially when a real ground system is used but we also see that X_c is not greatly affected. This indicates that using R_r for the perfect ground as the R_r value with a real ground is a reasonable approximation. This lets us calculate R_g from the model values for R_r and R_a:

$$R_g = R_a - R_r \quad \text{[Eq 2]}$$

Figure 13 is a graph using Equation 2 to calculate R_g with the ground system shown in Figure 11 but without top loading.

Even though we've 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 is how we account for the ground losses (P_g) associated with a given antenna for a given base current (I_o).

$$P_g = R_g I_o^2 \quad \text{[Eq 3]}$$

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_o and ground system, P_g will change and that means R_g will change.

Z_{in} with a Ground System

Figure 14 shows the feed-point impedance ($Z_{in} = R_a + jX_c$) as a function of H and M: where H = 0.05, 0.75, 0.100 and 0.125 and M is varied from 0 (no umbrella, just a bare vertical) to a limit imposed by the minimum allowed ground clearance (8 feet) 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 14, which correspond to points of maximum efficiency. We'll discuss these shortly.

Efficiency

In terms of R_r, R_g and R_L, the efficiency will be:

$$\eta = \frac{R_r}{R_r + R_g + R_L} \quad \text{[Eq 4]}$$

We know that $R_L = X_c / Q_L$ and we'll set $Q_L = 400$ which is a reasonable value. The *NEC* model gives us R_r from the ideal antenna and R_a from the antenna with the ground system.

Figures 15, 16 and 17 show how R_r and the loss resistances R_g and R_L vary as a function of M. In Figures 15 and 16 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 Figures 15 and 18 the circles mark the values of M corresponding to maximum R_r. In all these graphs M = 0 corresponds to no umbrella.

In Figure 15 as we enlarge the umbrella (increase M) R_r rises initially but there is a maximum point which depends on H. Increasing M further reduces R_r. This is not surprising given that the currents on the umbrella have a component ≈180° out of phase with the current on the vertical. This results in some cancellation, which increases as M increases. For H = 0.125 and 0.100, R_r maximum and resonance are fairly close

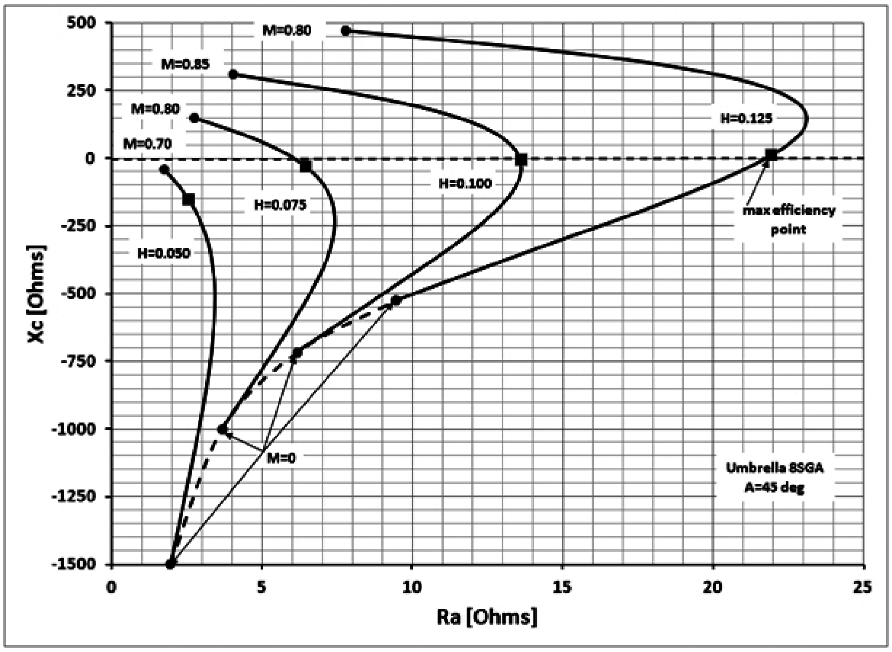

Figure 14 — Feed point impedance as M is increased for H = 0.05, 0.075, 0.1 and 0.125 and A = 45°.

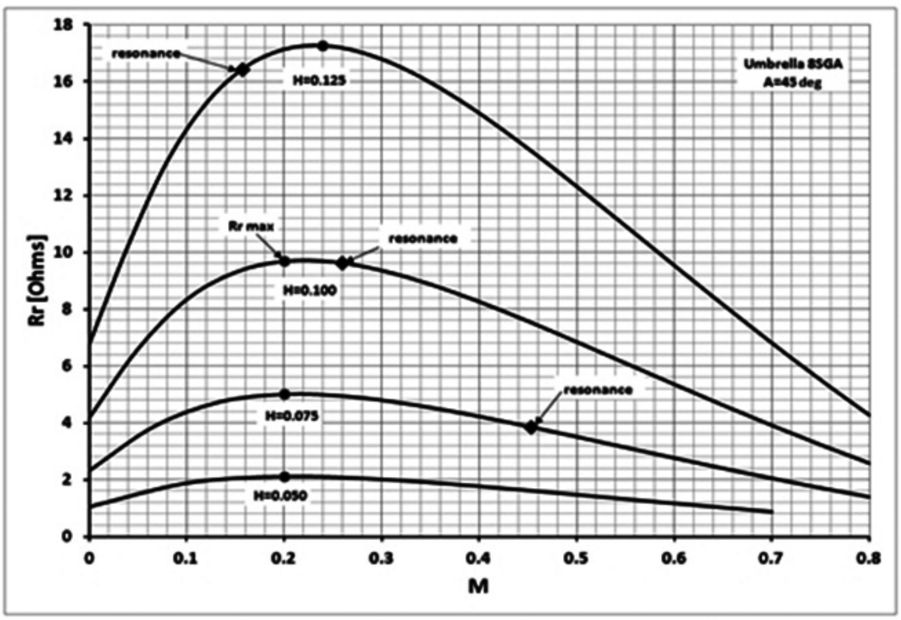

Figure 15 — R_r as a function of M with H as the parameter.

Table 2
L-Network Values and 2:1 SWR Bandwidths

H (λ_o)	*R_a* (Ω)	*X_a* (Ω)	*X_s* (Ω)	*R_s* (Ω)	*X_p* (Ω)	*2:1 Bandwidth*
0.050	2.56	–152.5	163.5	0.41	–12.56	15 kHz
0.075	6.46	–30.67	47.44	0.12	–19.26	33 kHz
0.100	13.60	–5.92	28.17	0.07	–30.56	56 kHz
0.125	21.94	11.42	13.39	0.03	–44.21	75 kHz

together, but for shorter antennas the two points are widely separated.

As shown in Figure 16, R_g behaves very much like R_r for smaller values of M; R_g rises but then reaches a peak and begins to fall as M is increased further.

Figure 17 shows R_L decreasing as M is increased and at some point resonance is reached ($X_c = 0$, except for H = 0.050). Above this point we no longer need X_L to resonate ($X_c>0$) so in Figure 17, $R_L = 0$ above resonance.

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 maximum efficiency occurs as shown in Figures 18 and 19.

Figure 18 shows the efficiency in dB where 100% efficiency would be 0 dB. Besides circles for maximum R_r and diamonds for resonance, there are squares to indicate values of M corresponding to maximum efficiency. 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's 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 could 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 E and H near-field values from *NEC2* and a spreadsheet to calculate R_g as shown in the *ARRL Antenna Book* (the equations are given in the *Excel* files on the associated CD).[8]

As shown in Figure 19, 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) becomes the umbrella. Note that for larger values of A the efficiency peaks are higher but narrower. Making A as large as practical is very helpful for shorter antennas.

Figures 18 and 19 indicate that it's possible to build very short verticals with efficiencies better than 50%. Figures 18 and 19 also bring out another important point. For the examples shown, with the exception of H = 0.125 in Figure 18, resonance occurs for values of M larger than those for maximum efficiency. This implies that it might be better to not load to resonance and use a small loading inductor. However, the differences in efficiency between the maximum and the values at resonance are small in most cases, at least for H> 0.050. From a practical point of view it's simpler top-load to resonance. That value for M can easily be obtained using *NEC2* and some field tuning adjustments. For really short verticals it may pay to do some *NEC4* modeling to see where the maximum efficiency occurs. You could also make field strength measurements with a given input power or use a VNA.[9]

Conductor Losses

It's time to consider conductor losses (R_c). Figure 20 gives examples of how the current at the feed point (I_o), for a given input power (1.5 kW in this example), can vary with H and M. A is fixed at 45° and the squares mark points of maximum efficiency. Figure 20 shows how rapidly I_o increases as H is reduced. Conductor loss varies as I_o^2 so the conductor losses grow rapidly as H reduced. It isn't only that I_o is larger but the current along the entire vertical that increases with more capacitive loading as illustrated in

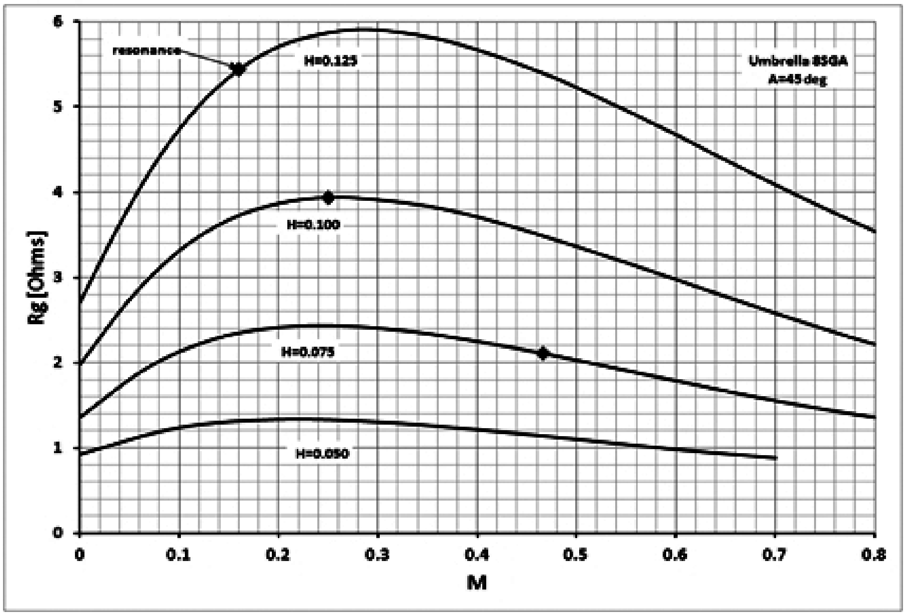

Figure 16 — R_g as a function of M with H as the parameter.

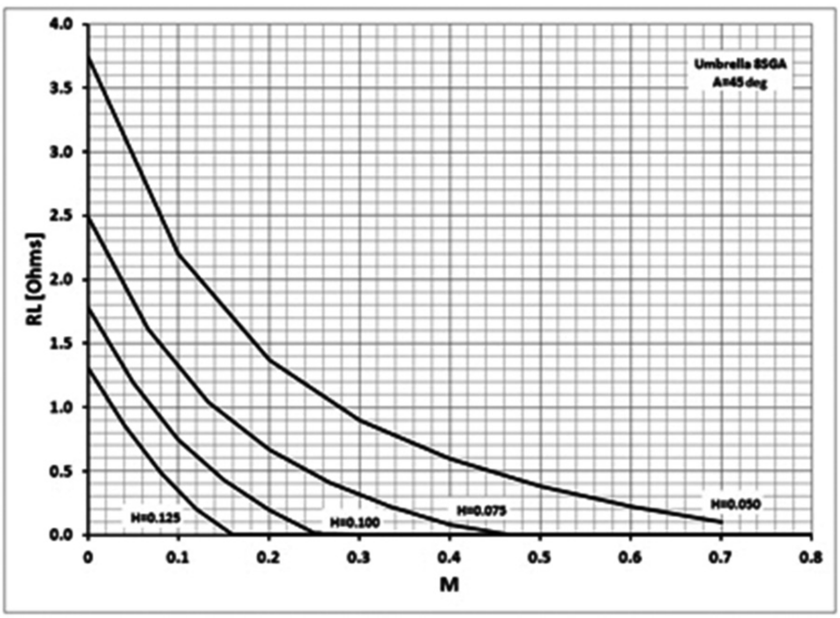

Figure 17 — R_L as a function of M with H as the parameter.

Figure 21, which shows examples of the current distributions on an H = 0.075 vertical. Note that these current distributions are for I_o = 1 A. As shown in Figure 20, for a given P_{in}, the value for the base current (I_o) will depend on R_a, where

$$I_0 = \sqrt{P_{in} / R_a}$$

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.

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 21, 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 if the top-loading is not great enough to be close to resonating the vertical. This may be the case when H < 0.05.

We can get a good measure of conductor loss by turning on the conductor loss option and then calculating the average gain (G_a) with only the conductor losses. Figure 22 illustrates conductor losses for two different conductor sizes for the vertical part of the antenna with 0.05 < H < 0.125. In each case shown the antenna is resonant with only top-loading.

The initial model had #12 wires for the vertical and four umbrella wires with a skirt. As can be seen, the conductor losses at H = 0.05 are very high, ≈–4.5 dB. Most of the loss is in the vertical conductor so increasing its diameter from 0.08 to 0.5 inch 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 λ_0 ≈ 27 feet, a 30 foot length of 4-inch 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 Feed Point

Not only is I_o large in short verticals but the voltage at the feed point can also be very high due to the high reactances below resonance (see Figures 12 and 14 for X_c). Figure 23 shows typical values for the feed point voltages for P_{in} = 1.5 kW as M is varied for several values of H.

Note that the vertical scale is in kV_{rms}! Fortunately, for H≤0.075 the highest efficiency point is close to resonance so the feed point voltages are relatively low. However, with H ≤0.05, you can't reach resonance, at least with A = 45° and 8 wires, and the feed point voltage is much higher. One way to improve both efficiency and reduce the feed point voltage would be to increase A to 60°. At 1.83 MHz, 0.050λ_0 ≈ 27 feet so it may be practical to increase A in shorter antennas.

If the power is reduced from 1500 W to 100 W we'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 feed point voltage by a factor of

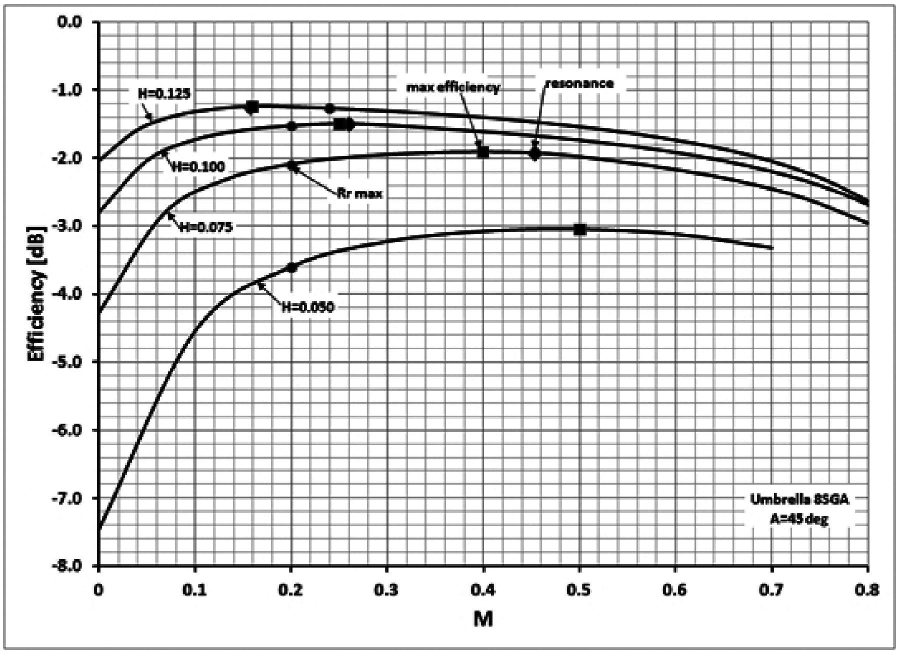

Figure 18 — Efficiency in dB as a function of M with H as the parameter and A = 45°.

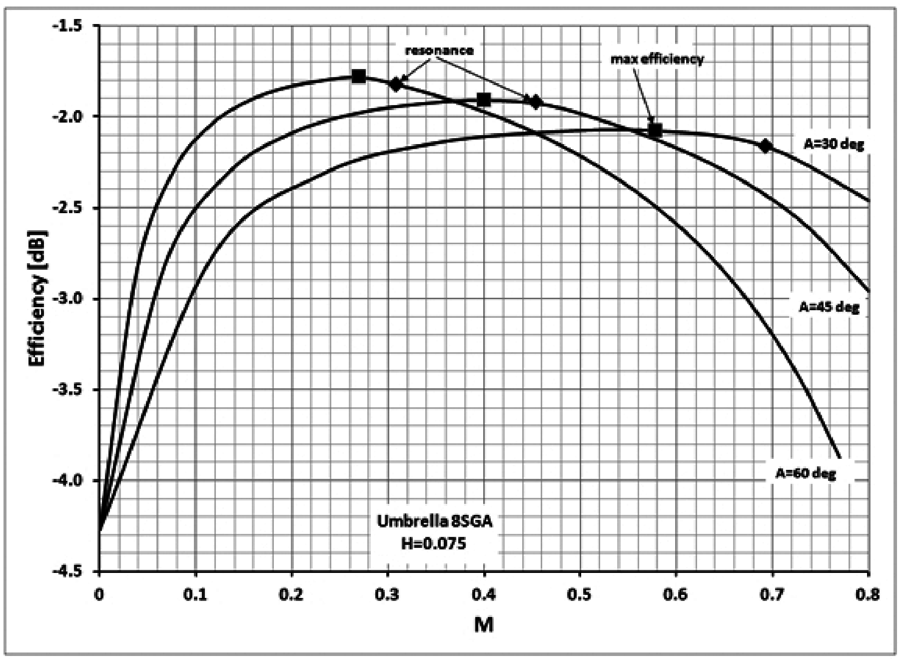

Figure 19 — Efficiency in dB as a function of M with A as the parameter and H = 0.075.

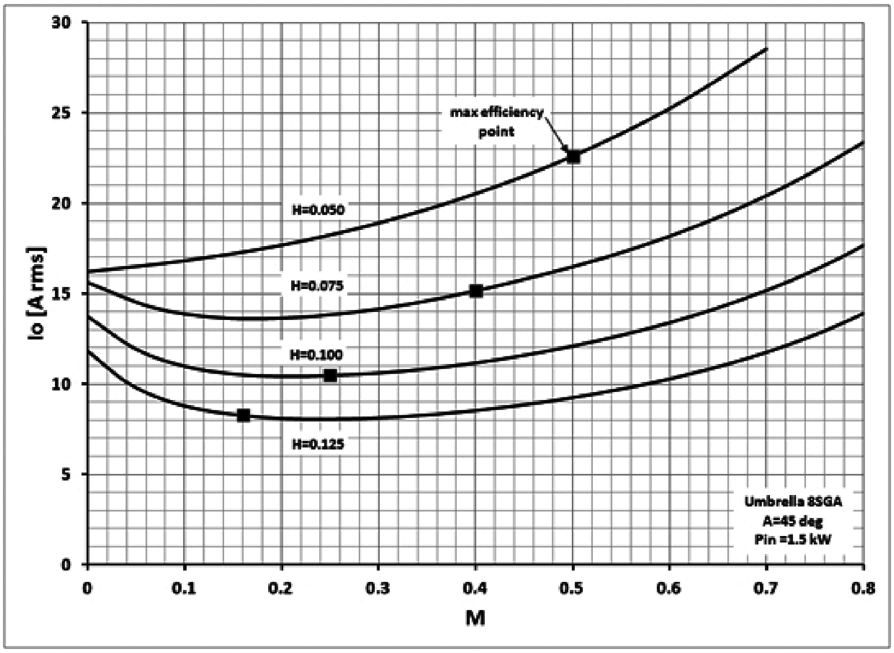

Figure 20 — I_o as a function of M with H as the parameter.

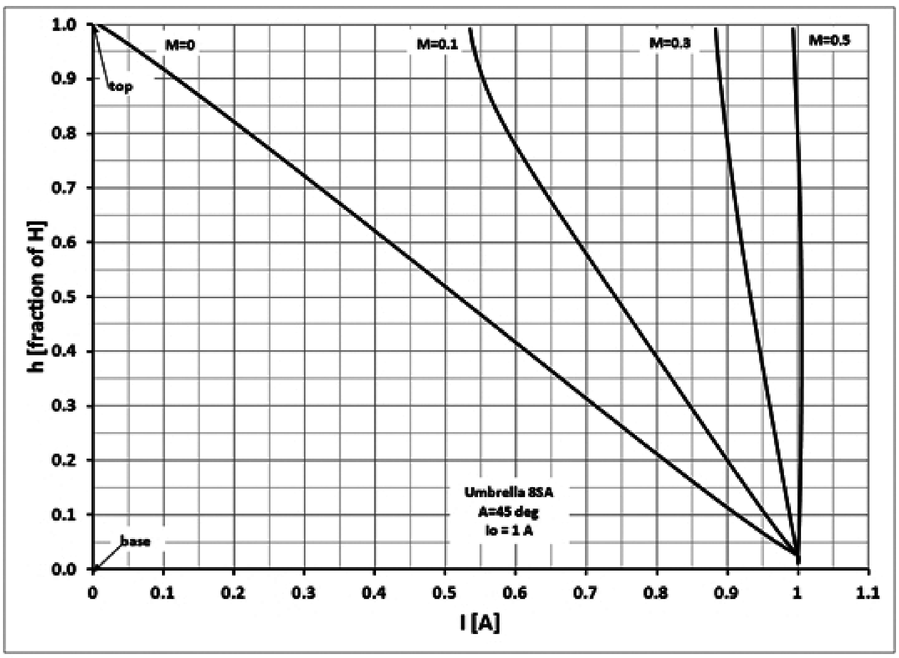

Figure 21 — Examples of the current distribution on a top loaded vertical.

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 achieve this. 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, Colorado. 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 feed point impedance to 50 Ω. This can be done in many ways but for this discussion I assume the use of a simple L-network matching the feed-point impedance at the highest efficiency point.[10] Assuming A = 45° and f = 1.83 MHz, Table 2 summarizes the L-network components and the 2:1 SWR bandwidth for each antenna. X_s is the series matching reactance, R_s is the loss resistance associated with X_s and X_p is the shunt reactance. In this example all the X_s are inductors with $Q_L = 400$ and the X_p are capacitors. The ground system in Figure 11 is included. Note that R_s (due to the loss in the matching inductor) has only a small effect on efficiency except for smaller values of H.

Table 2 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 a big bag of tricks along those lines that deserve discussion but this article is already too long.[11, 12, 13]

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 published an IRE paper on the "Performance of Short Antennas" which presented their experimental work at MF on a 300 foot tower with eight sloping umbrella wires and a loading inductor at the base. (See Note 4.) 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 feet to 450 feet. Figure 24 is a sketch of the tower and umbrella arrangements. The angle between the tower and the umbrella wires was ≈ 48°. H = 300 feet 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" vertical.

The ground system had five hundred 75-foot radials and 250 400-foot radials. The 400-foot radial wires extend a short distance past the outer edge of the umbrella when its wires are at maximum length. At 120 kHz, 75 feet = $0.009\lambda_0$ and 400 feet = $0.03\lambda_0$. At 350 kHz, 75 feet = $0.027\lambda_0$ and 400 feet =

$0.14\lambda_0$. Compared to standard broadcast 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 500 75-foot 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 Qs. An example of the results is given in Figure 25 for a loading coil $Q_L = 200$.

Changing frequency with a fixed H is equivalent to changing H at a fixed frequency. Figure 25 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 the 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 25 and the *NEC* results in Figure 18. 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 umbrella 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 λ_o) 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 as well as Belrose and Sevick. See the detailed reference information in the Notes.

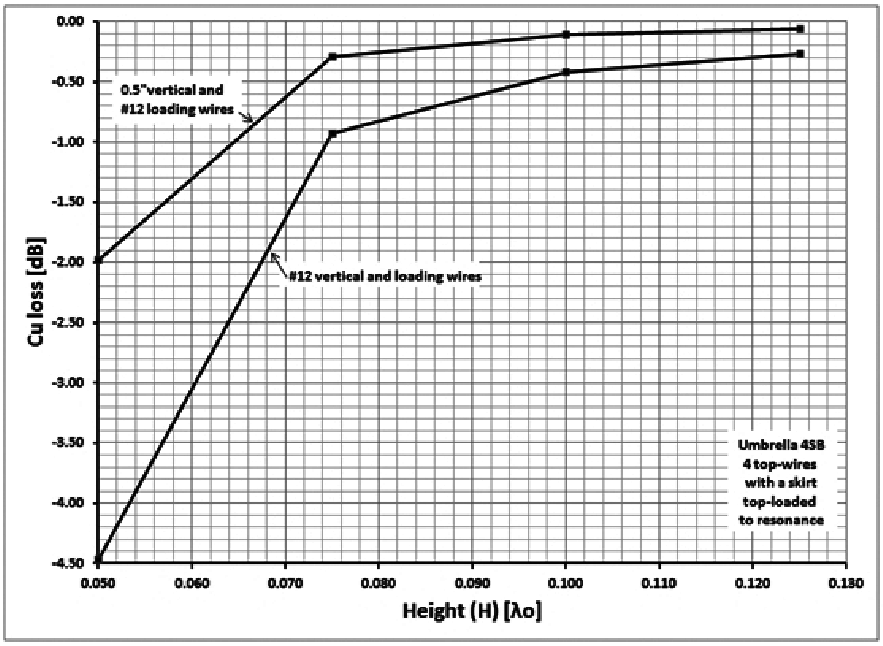

Figure 22 — Examples of conductor loss in short antennas.

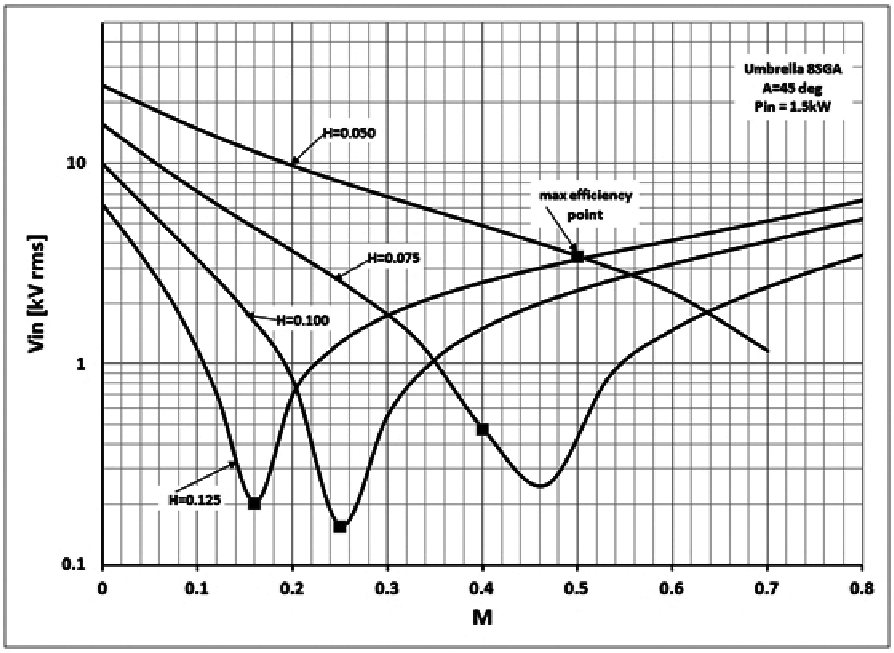

Figure 23 — Feed point voltage as a function of M with H = 0.050, 0.075, 0.100 and 0.125.

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 the apex angle (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.

Acknowledgements

The work in this paper was prompted by some questions on a short 160-meter 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. I want also to thank my reviewer Mark Perrin, N7MQ.

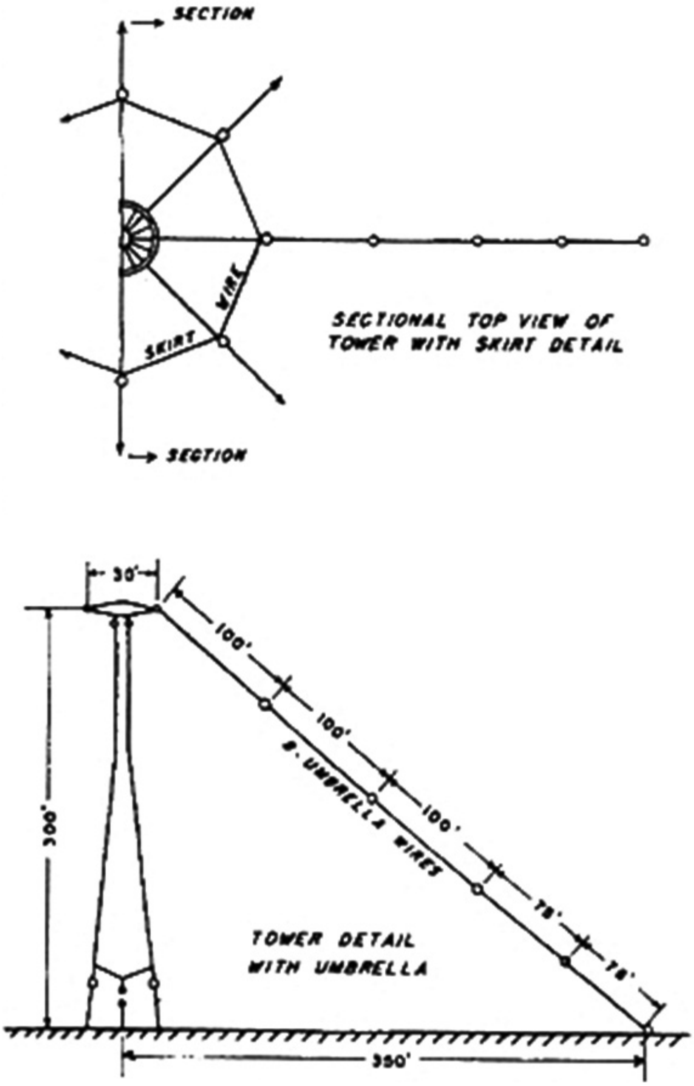

Figure 24 — Sketch of the experimental antenna from Smith and Johnson.[4]

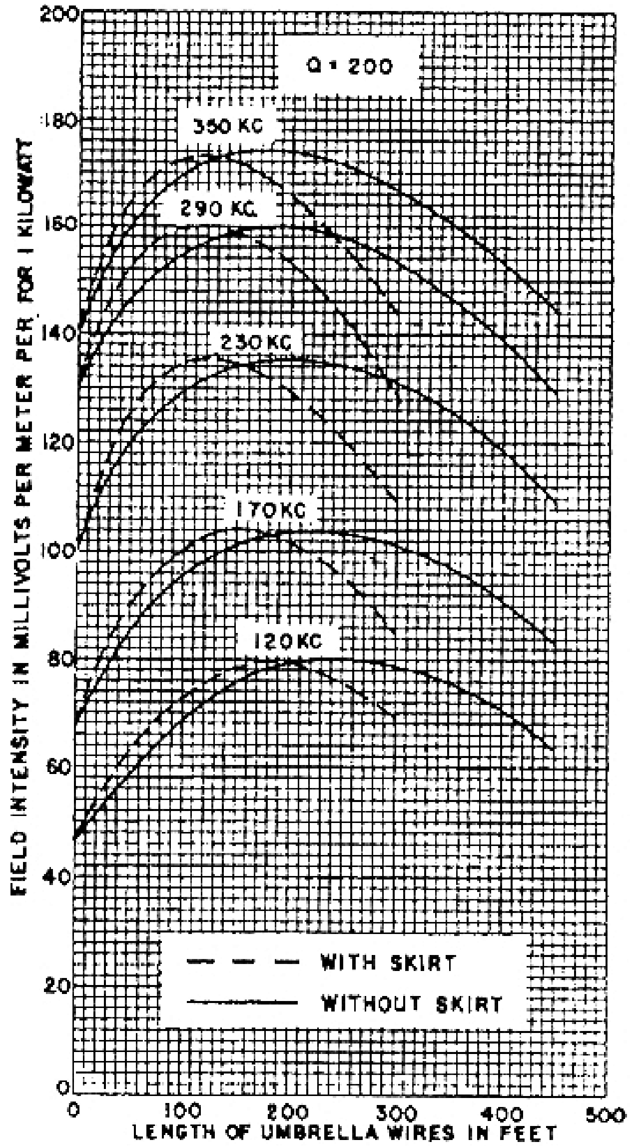

Figure 25 — An example from Smith and Johnson.[4]

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Notes

[1]Jerry Sevick, W2FMI, "The W2FMI Ground-Mounted Short Vertical," *QST*, March 1973, pp. 13-18 and 41.

[2]Jerry Sevick, W2FMI, "Short Ground-Radial Systems for Short Verticals," *QST*, April 1978, pp. 30-33.

[3]Jerry Sevick, W2FMI, "The Short Vertical Antenna and Ground Radial," *CQ Communications*, 2003.

[4]Smith and Johnson, "Performance of Short Antennas," proceedings of the I.R.E., October 1947, pp. 1026-1038.

[5]John Belrose, VE2CV, "Folded Umbrella Top Loaded Vertical Antenna," *Ham Radio Magazine*, September 1982, pp. 12-17.

[6]Belrose, Hatton, McKerrow and Thain, "The Engineering of Communication Systems for Low Radio Frequencies," IRE proceedings, May 1959, pp. 661-680.

[7]Howard Shepherd, W6US, "A High-Efficiency Top-Loaded Vertical," *Ham Radio Magazine*, October 1984, pp. 65-68.

[8]*The ARRL Antenna Book*, 22nd edition, 2011. See the discussion in Chapter 3 and the Chapter 3 material on the accompanying CD including the *Excel* graphs with the equations already loaded.

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

[10]*The ARRL Antenna Book*, 22nd edition, 2011. See page 24-2.

[11]Breakall, Jacobs, Resnick, Eastman, Machalek and King, "A Novel Short AM Monopole Antenna with Low-Loss Matching System." This paper can be found at **www.kintronic.com/resources/technicalPapers.asp**.

[12]Stuart and Best, "A Small Wideband Multimode Antenna," IEEE 2008.

[13]Grant Bingeman, KM5KG, "Short Omnidirectional Monopole Arrays," *ARRL Antenna Compendium Vol. 7*, 2002, pp. 172-175.

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