Chapter 3

Capacitive Top-Loading

3.0 Efficiency

The discussion in chapter 2 made it clear that the equivalent series resistance (ESR, i.e. RL) of the tuning inductor can be a major loss contributor. A critical part of achieving higher efficiency is the reduction of capacitive reactance at the feedpoint (Xi) because decreasing Xi reduces the size of the loading inductor and its associated RL. In addition, much of what we do to reduce the needed inductance can also increase Rr simultaneously. Efficiency (**η**) in terms of Rr and RL:

$$\eta = \frac{R_r}{R_r + R_L} = \frac{1}{1 + \frac{R_L}{R_r}} \qquad (3.1)$$

Clearly we want RL small and Rr large! The reason for this rather obvious comment is that some top-loading schemes which reduce Xi also reduce Rr rather than increase it and at some point the efficiency may actually start to fall even though we continue to reduce Xi. This happens in top-loading schemes with sloping wires with currents opposing the current in the main vertical conductor. This is discussed in section 3.9. On most of the graphs efficiency is stated either in percent (%) or as a decimal, although in some cases efficiency is given in -dB to illustrate the effect of losses on signal strength or the signal improvement to be expected for some change.

For amateurs new to the LF-MF bands the first antenna needs to be as simple as possible to get on the air. In the first part of this chapter we're going to keep it simple and assume we have only one or two supports, a roll of wire and some insulators. We'll begin with a example showing Rr, Xi and efficiency and then go on to explain why top-loading is so effective in reducing Xi and increasing Rr. Subsequent sections give examples of more complex top-loading arrangements. The discussion relies heavily on NEC modeling but, as in chapter 2, simple expressions and graphs for pencil and paper calculations are provided.

From this point it is assumed that the height (H) has been made as tall as practical and we are now turning to capacitive top-loading to improve efficiency. Many different variables affect the capacitance introduced by the top-loading structure:

- The number and/or length of umbrella wires
- Whether or not there is a skirt tying the ends of the wires together
- The location of the tuning inductor along the vertical conductor
- conductor sizing
- Etc.

As in chapter 2, tuning inductor QL=400 at 475 kHz and 200 at 137 kHz is assumed. However, as will be shown in chapter 6, much higher QL is possible with some effort. Keep in mind that efficiency determined from only RL and Rr is an upper limit, i.e. the best we can do. Once we've reduced RL as much as possible we can deal with other losses. Reducing Xi has the further benefit of reducing the voltages and currents at the base. For the most part, if you make some change in your antenna which reduces the inductance required to resonate the antenna that change is likely to improve your efficiency. This is a useful guide when "fiddling"! One important point, most of the examples have symmetric wire arrangements because it's easier to model but symmetry is not required! Irregular wire lengths work fine. In general we need to be opportunistic, connect top-loading wires to whatever support is available, even when the supports are at very different heights. This goes right back to Woodrow Smiths advice[1]:

".... the general idea is to get as much wire as possible as high in the air as possible....."

3.1 Efficiency with top-loading

We can use the "T" antenna shown in figure 3.1 to illustrate how effective capacitive top-loading is. Efficiency in percent (%) as a function of the length of the top wire (L) at 475 and 137 kHz is shown in figures 3.1 and 3.2. Note that there is a small sketch of the antenna under discussion on many of the graphs. This serves as a reminder of which antenna we're talking about. The notation "600m T1" is the title for that model in the NEC model files. Just a bit of bookkeeping.

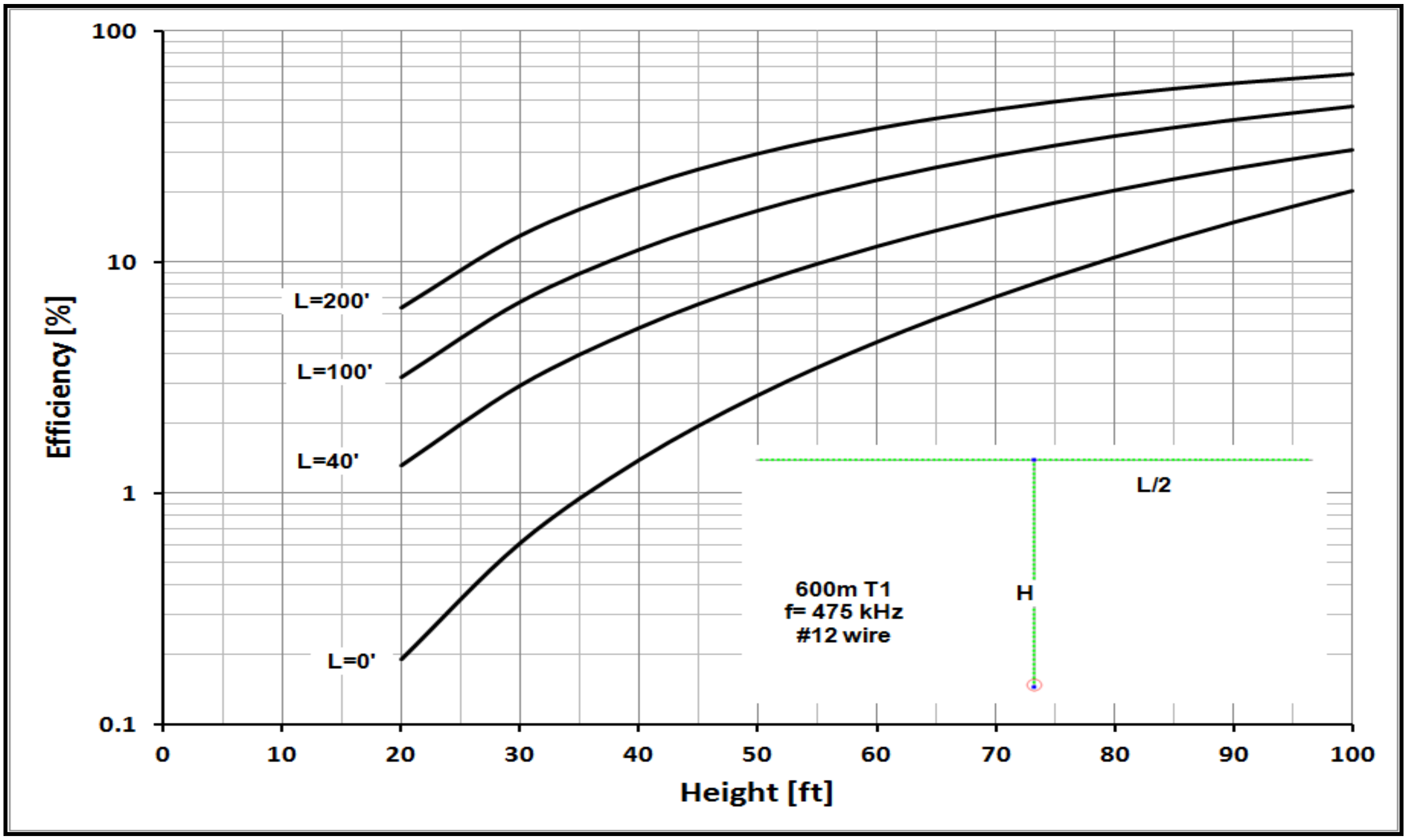

Figure 3.1 - Efficiency at 475 kHz with base tuning.

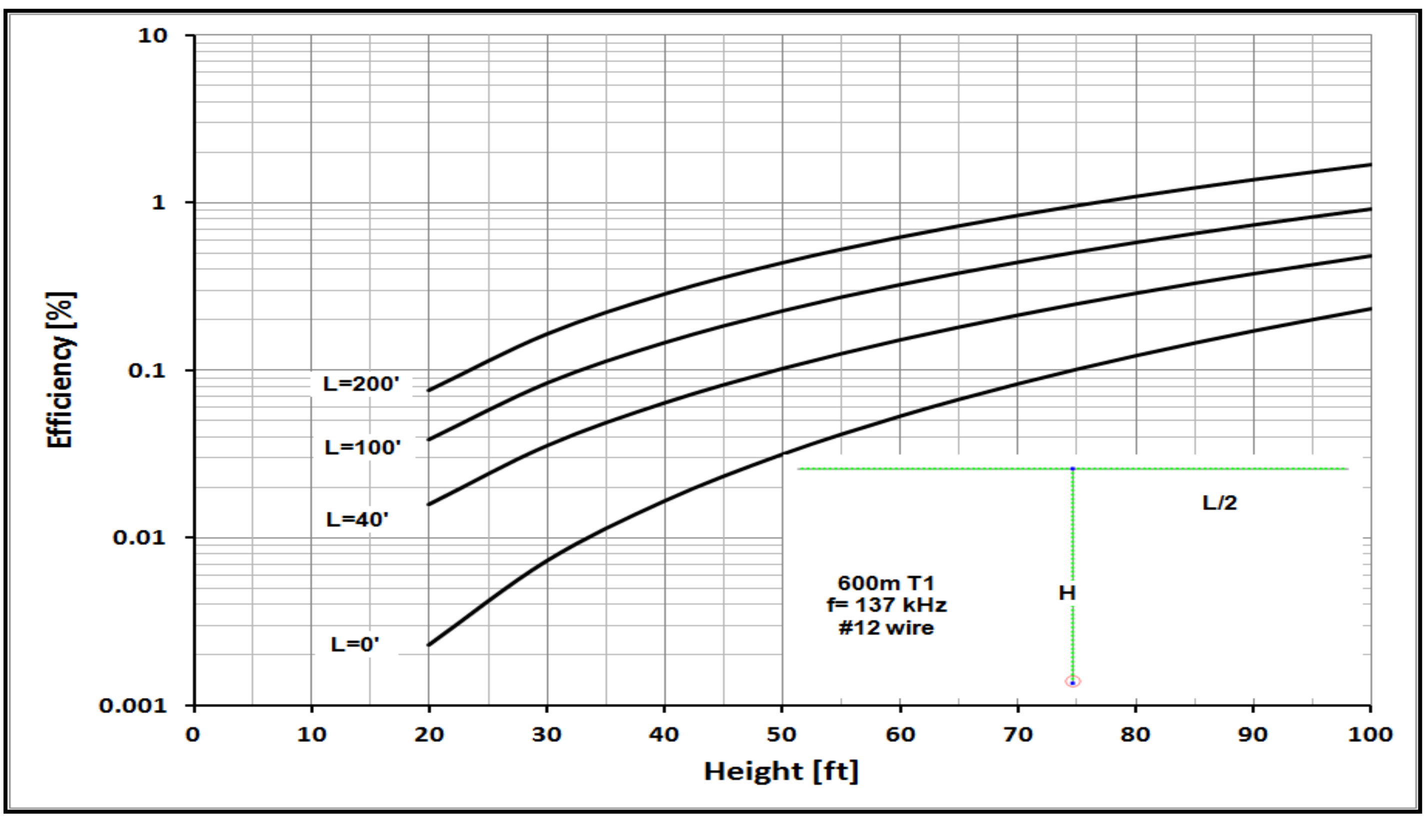

Figure 3.2 - Efficiency at 137 kHz with base tuning.

The L=0 line represents the case with no top-loading, just the bare vertical with a loading coil at the base. In these models the value of the tuning inductor was adjusted to maintain resonance as L and H were changed. #12 wire conductors are assumed. Even a small amount of top-loading increases efficiency. As an example, for L=0 and H=20', η=0.19% at 475 kHz. Keeping H=20' but adding a 40' top-wire, η=1.3%, a factor of 6.8X! Taking L to 100' increases the efficiency by 18X.!

Height and capacitive top-loading are keys to improving efficiency!

3.2 Xi with top-loading

To understand why the efficiency improves we need to look closer. For the T antenna the efficiency improvement is driven by increasing Rr and decreasing Xi simultaneously. This section explains what's happening with Xi and the next section looks at Rr.

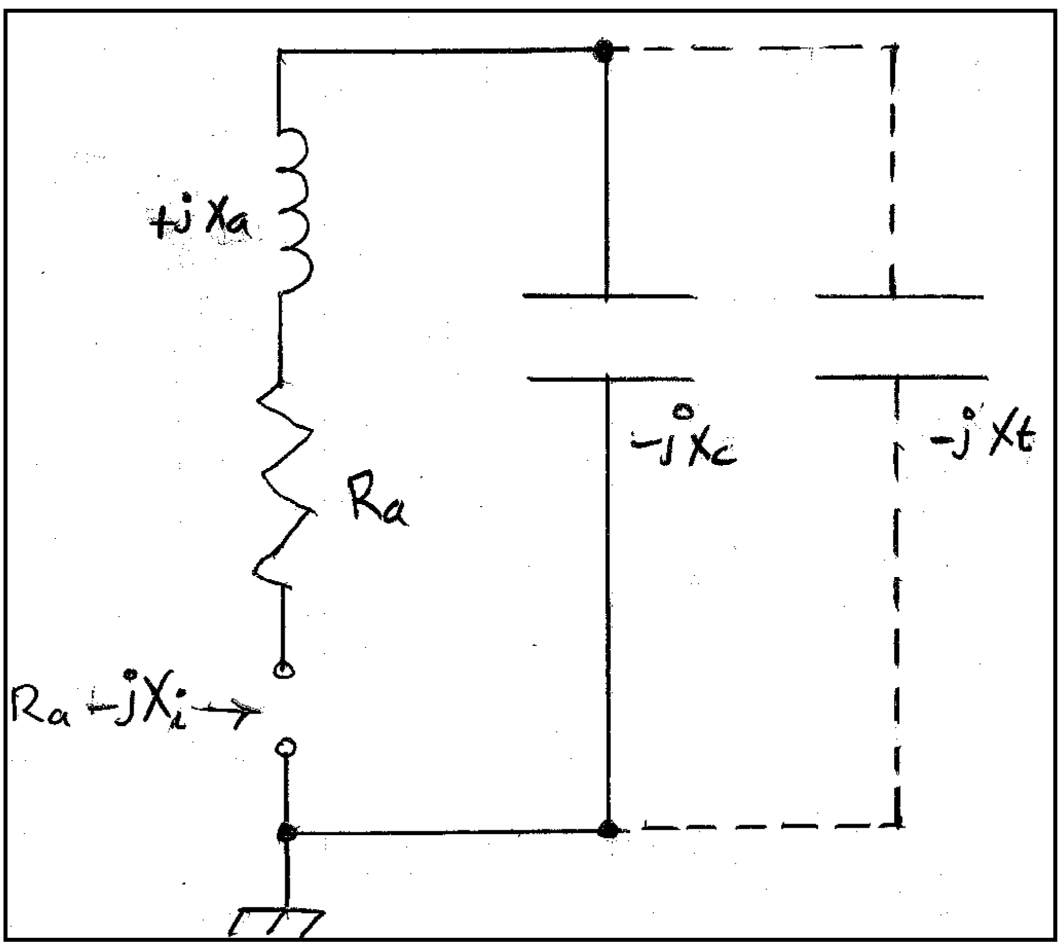

Figure 3.3 - Equivalent circuit for a vertical with capacitive top-loading.

Figure 3.3 shows an equivalent circuit for a vertical with capacitive top-loading. Ra, Xa and Xc represent the vertical. Xt represents the shunt capacitance introduced by the top-hat. Xi and Xt are:

$$\mathbf{Xi} \approx \frac{\mathbf{XcXt}}{\mathbf{Xc+Xt}} \quad (3.2) \qquad \mathbf{Ct} = \frac{\mathbf{1}}{(\mathbf{2\pi f})\mathbf{Xt}} \quad (3.3)$$

Where Ct is the capacitance corresponding to Xt. Xt can be determined from modeling or in simple cases, calculated. Xt is in parallel with Xc reducing Xi. Xa is usually small in the short verticals and can be ignored with only a small effect on the approximations. Figures 3.4 and 3.5 show values for Xi associated with figures 3.1 and 3.2.

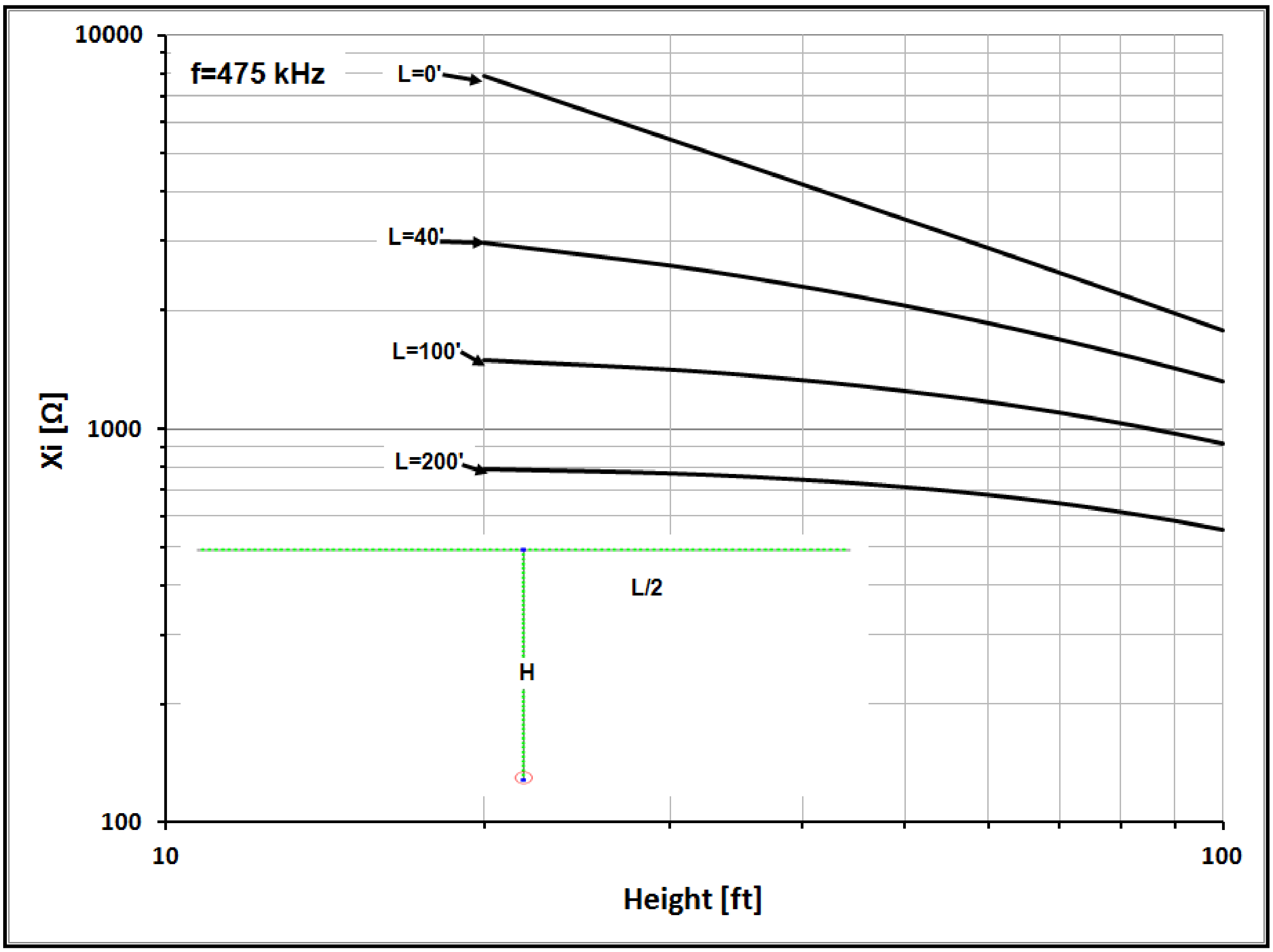

Figure 3.4 -Xi at 475 kHz.

The effect of even a small amount of top-loading on Xi is significant. For example in figure 3.4, at H=20', with no loading Xi≈7900Ω. However, when we add 40' of top-wire

Xi≈3000Ω which is a reduction of almost 3X. Increasing L to 100' reduces Xi by another factor of two, Xi≈1500Ω. RL will be reduced by the same factors which is part of the reason for the efficiency improvement.

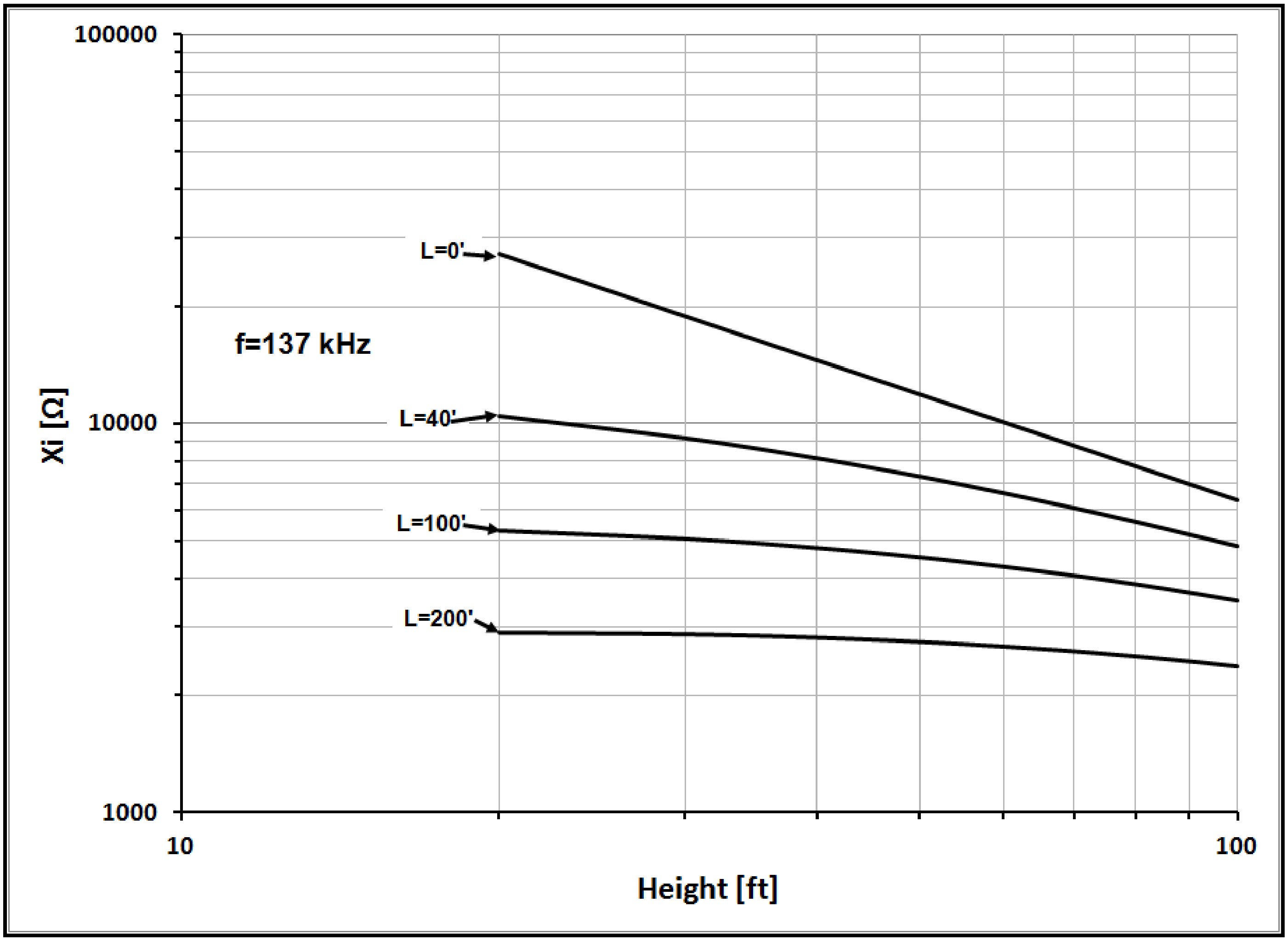

Figure 3.5 - Xi at 137 kHz.

The graphs in figures 3.4 and 3.5 were obtained from NEC modeling. We could also have derived this information with reasonable accuracy from calculations. We can consider each of the horizontal wires connected to the top of the vertical wire to be a single wire transmission line with an characteristic impedance of:

$$\mathbf{Zt = 138Log\left[\frac{4H}{d}\right] \quad [\Omega]} \quad (3.4)$$

Where H is the height above ground of the wire and d is the wire diameter. We are free to chose the units for H and d but both must use the same units.

As an example, a #12 wire (d=0.081" or 0.00675') at 50' will have Zt=617Ω. With a value for Zt in hand we can calculate Xt for each wire from the open circuit transmission line equation (chapter 2 equation (2.9)):

$$\mathbf{Xt} = \left(\frac{\mathbf{1}}{\mathbf{N}}\right)\left(\frac{\mathbf{Zt}}{\mathbf{tan(L')}}\right) \qquad (3.5)$$

When L is the physical length of the top-wire from the top of the vertical to the end, L' is the length in either degrees or radians at the operating frequency and N is the number of wires.

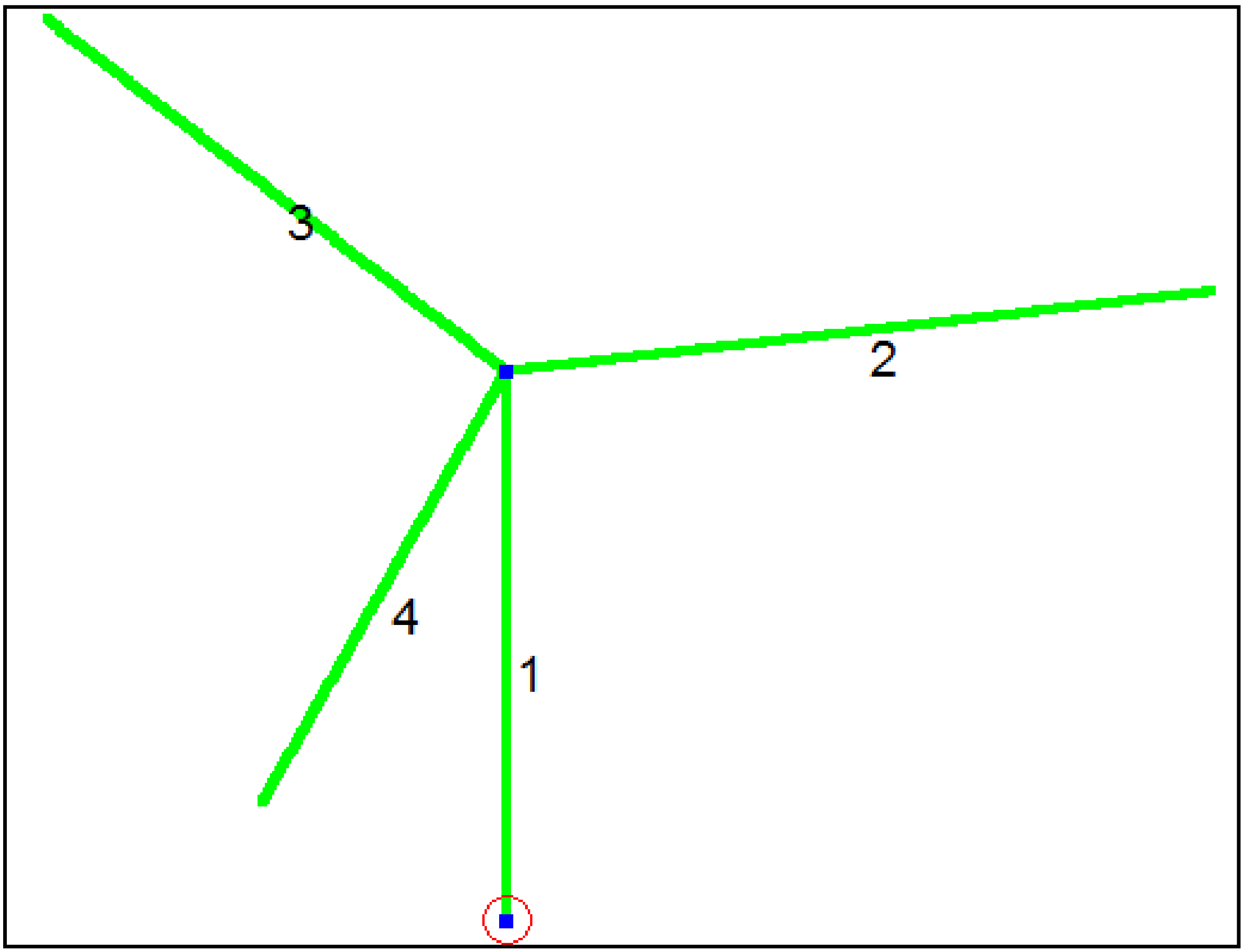

Figure 3.6 - Example for calculation.

We can use this approach to calculate Xt for N top-loading wires as shown in figure 3.6. In this figure N=3 but we will vary N from 0 to 8. If H=50' and L=50'. L' at 475 kHz, where λ≈2072', will be:

$$\mathbf{L'} = \frac{\mathbf{L \cdot 360^\circ}}{\boldsymbol{\lambda}} = \mathbf{8.69^\circ/0.152\ radians} \qquad (3.6)$$

From equation (3.4) Zo=617Ω and from equation (3.5), for <u>each wire</u>:

$$\mathbf{Xt' = 4037\Omega} \qquad (3.7)$$

Using NEC we can determine Xi and Xt for each number of top-wires (N) and compare that to Xt'/N:

Table 1 - Xt comparison.

N	Xi	Xt NEC	Xt calc	error
0	3360	0	0	0.00
1	1788	3822	4037	5.63
2	1239	1963	2019	2.84
3	961	1346	1346	0.02
4	795	1041	1009	3.09
5	685	860	807	6.16
6	607	741	673	9.18
7	549	656	577	12.12
8	504	593	505	14.89

For N<6 the error is <6% which gives a reasonable estimate for the tuning inductor value (XL=Xi). As N is increased the top-wires are closer together and the estimate of Xt is too low (i.e. the calculated value of Ct is larger than it should be). More complex top-hats should be modeled with NEC.

3.3 Rr with top-loading

Top-loading can also improve Rr as shown in figures 3.7 and 3.8. In these figures H is varied from 20' to 100' and L is between 0 and 200'. Rr increases substantially (up to 4X!) as we add more top wire.

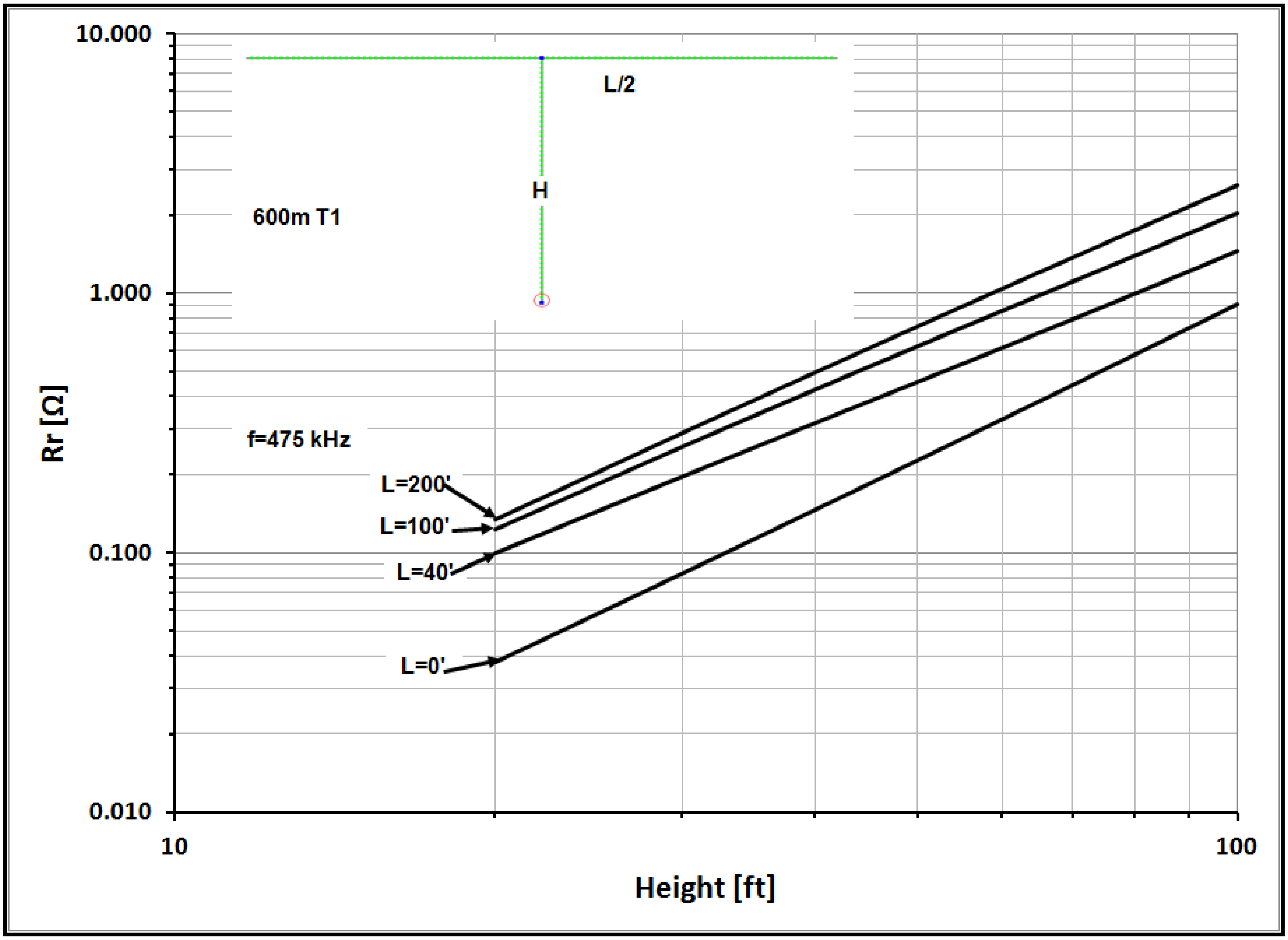

Figure 3.7 - Rr for a T antenna with a single top-wire at 475 kHz.

These Rr graphs are derived from NEC modeling. Rr can be calculated but it's a bit trickier than the unloaded vertical case discussed in chapter 2. The current along the vertical is not a simple triangle, it's trapezoidal and the dimensions of the trapezoid vary with top-loading. Figure 3.9 gives an example of the current distribution along the vertical for several values of L. Io is kept constant at 1A. With no top-loading the current at the top of the vertical (It) is close to zero but as the loading is increased, It increases.

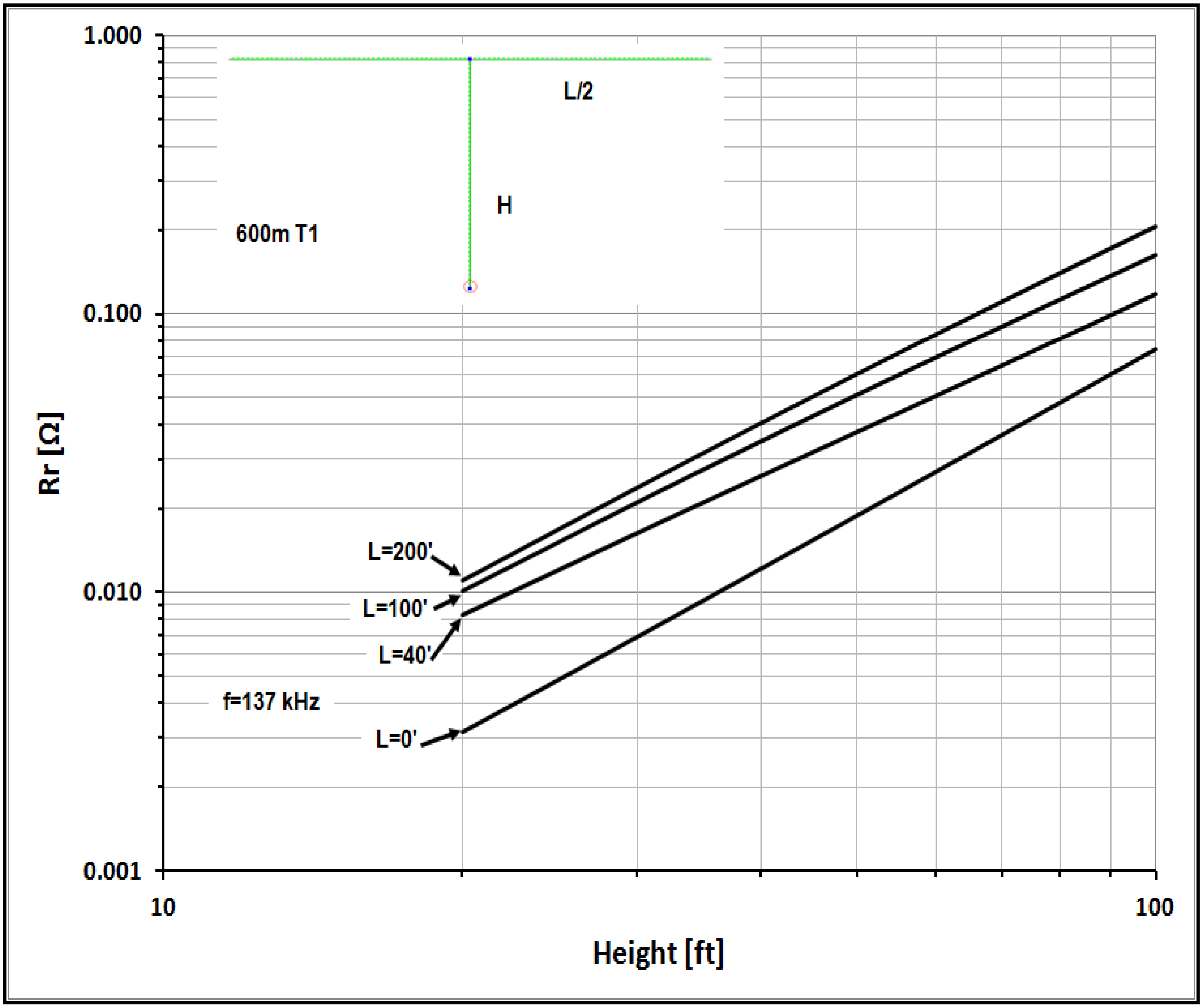

Figure 3.8 - Rr for a T antenna with a single top-wire at 137 kHz.

Equation (2.6) from chapter 2 is still valid:

$$Rr=0.01215A'^2\ [\Omega] \qquad (3.8)$$

But for trapezoidal current distributions equation (2.7) must be modified:

$$A' = \frac{G_v}{2}\left(\frac{It}{Io}+1\right) \quad \text{[Ampere-degrees] (3.9)}$$

Gv=electrical height in degrees.

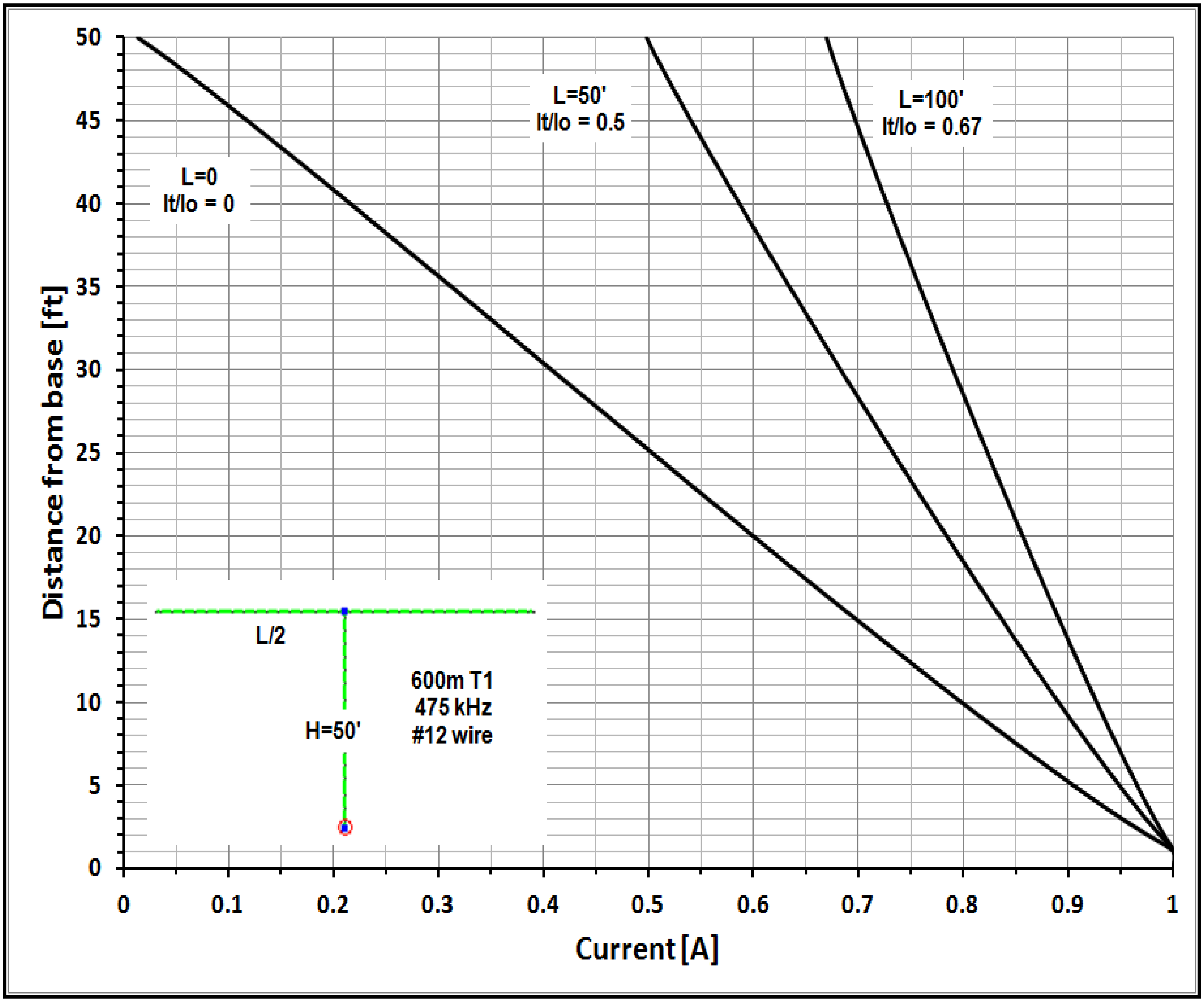

Figure 3.9 - Current distribution on the vertical part of a "T" antenna.

As shown in figure 3.10, inserting equation (3.9) into (3.8) we can create a universal graph for Rr as a function of antenna height in degrees (Gv) with the current ratio It/Io as a parameter. The It/Io ratio is varied from 0 (no top-loading) to 1, which corresponds to heavy top-loading and constant current on the vertical radiator (i.e. It/Io=1). As It/Io goes from zero to 1, Rr increases by a factor of 4X. Equations (3.8) and (3.9) are valid for Gv<45 degrees.

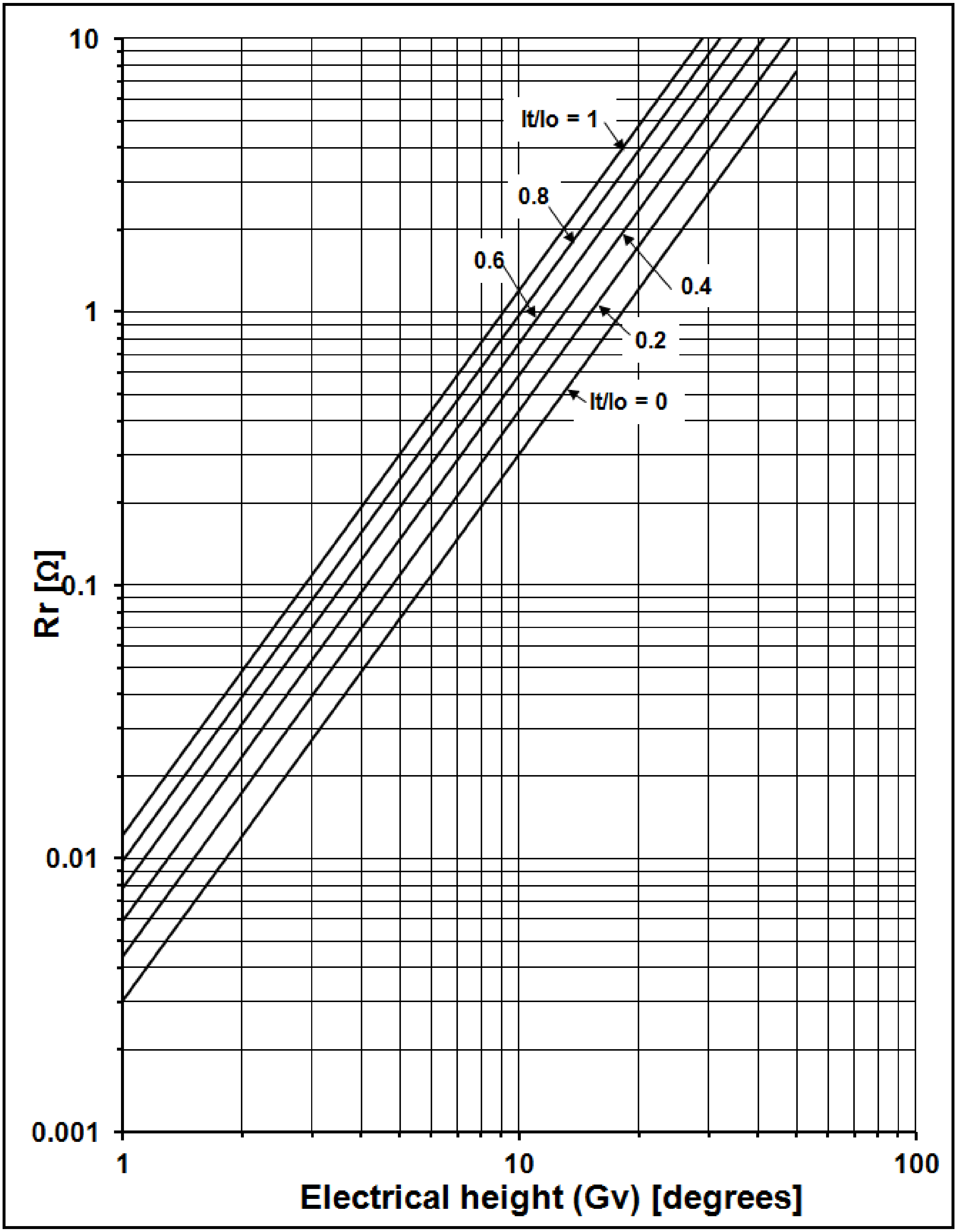

Figure 3.10 - Rr as a function of height in degrees.

For convenience we can convert the graphs in figure 3.10 to height in feet at 137 and 475 kHz as shown in figure 3.11.

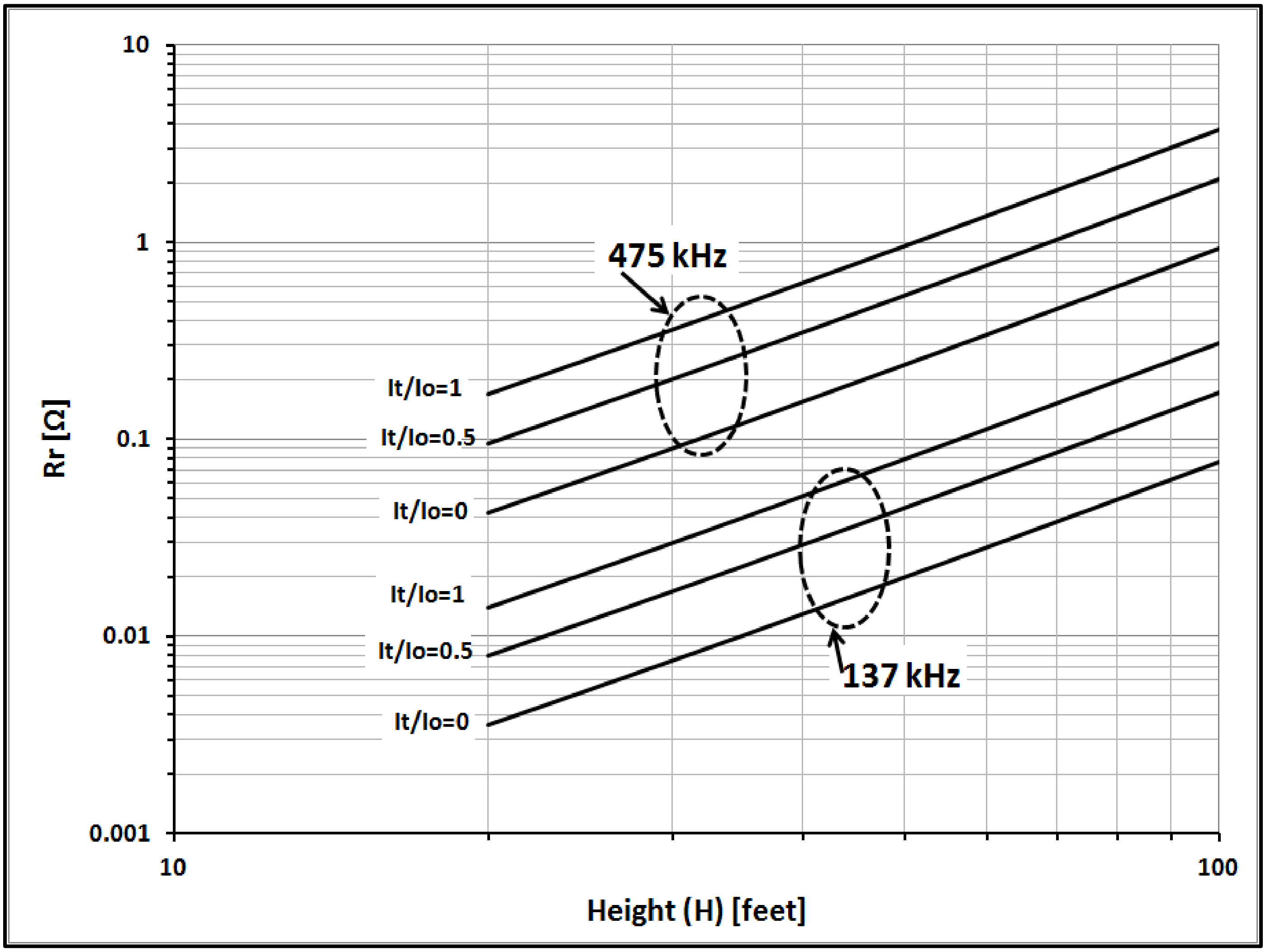

Figure 3.11 - Rr as a function of height in feet.

<u>If</u> we know It/Io then we can simply read Rr off the graph. Finding It/Io with modeling is easy but manually is a bit tricky. I have never seen a means for calculating It/Io so on a hunch I did an experiment with NEC using the antenna shown in figure 3.6 with N varying from 0 to 8, H varying from 20' to 100' and L varying from 0 to 80'. This was done a 137 and 475 kHz. At each data point I recorded Xi. With no top-loading (N=0) Xi=Xc. Using that value for Xc and the value for Xi at each data point, I calculated Xt from:

$$\mathbf{Xt = \frac{XiXc}{Xc - Xi}} \quad (3.10)$$

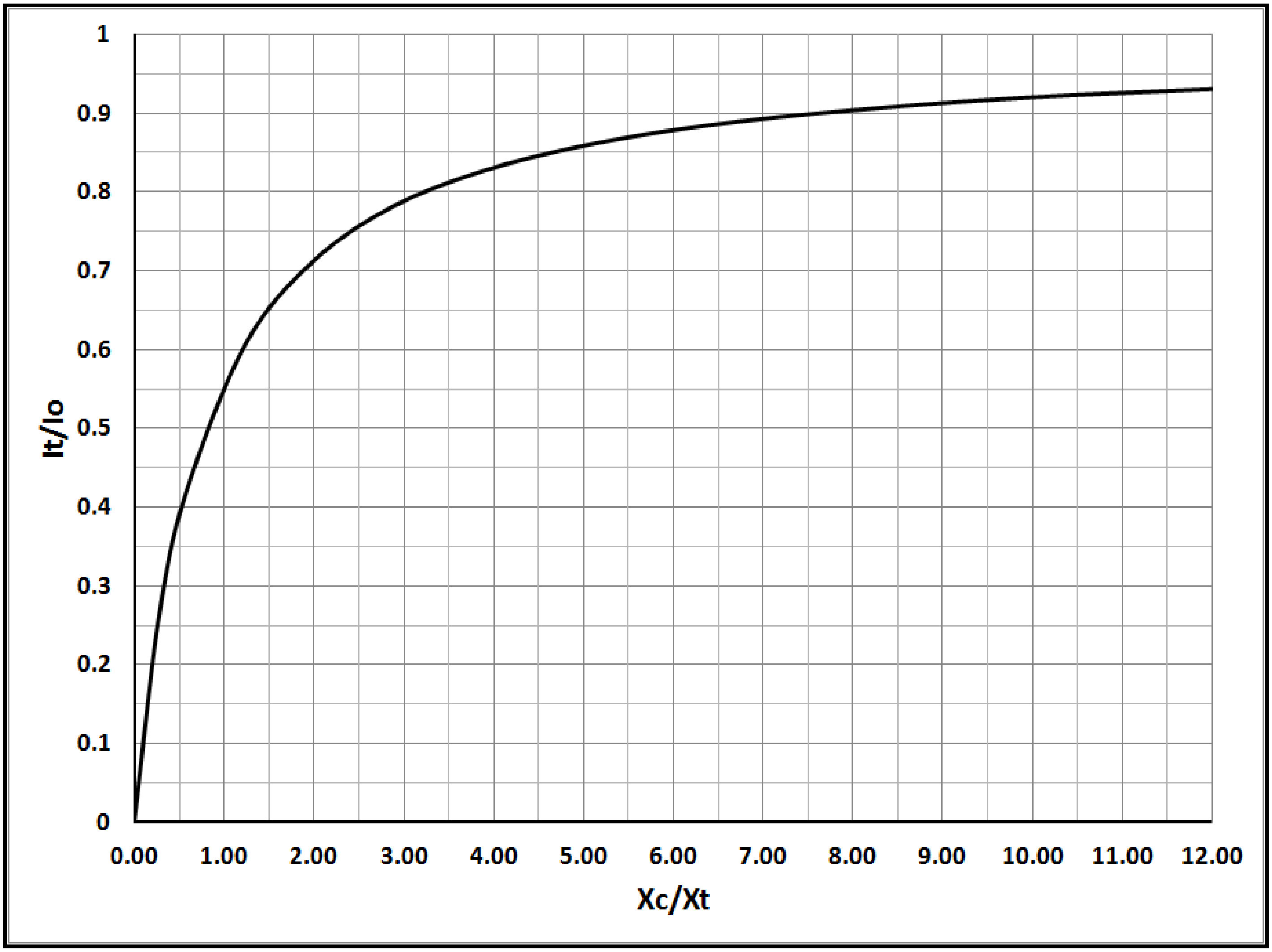

Figure 3.12 - Xc/Xt ratio.

I also recorded the value for It/Io at each point and then graphed **It/Io** versus **Xc/Xt** as shown in figure 3.12. The single line on the graph represents all values of H, L and frequency! This was a complete but very pleasant surprise! The curve is for the antenna with 8 radial top-wires but The individual values for N<8 lie along lower sections of the same curve (i.e. smaller Xc/Xt). The increase in Rr associated with a given value for Xc/Xt is shown in figure 3.13.

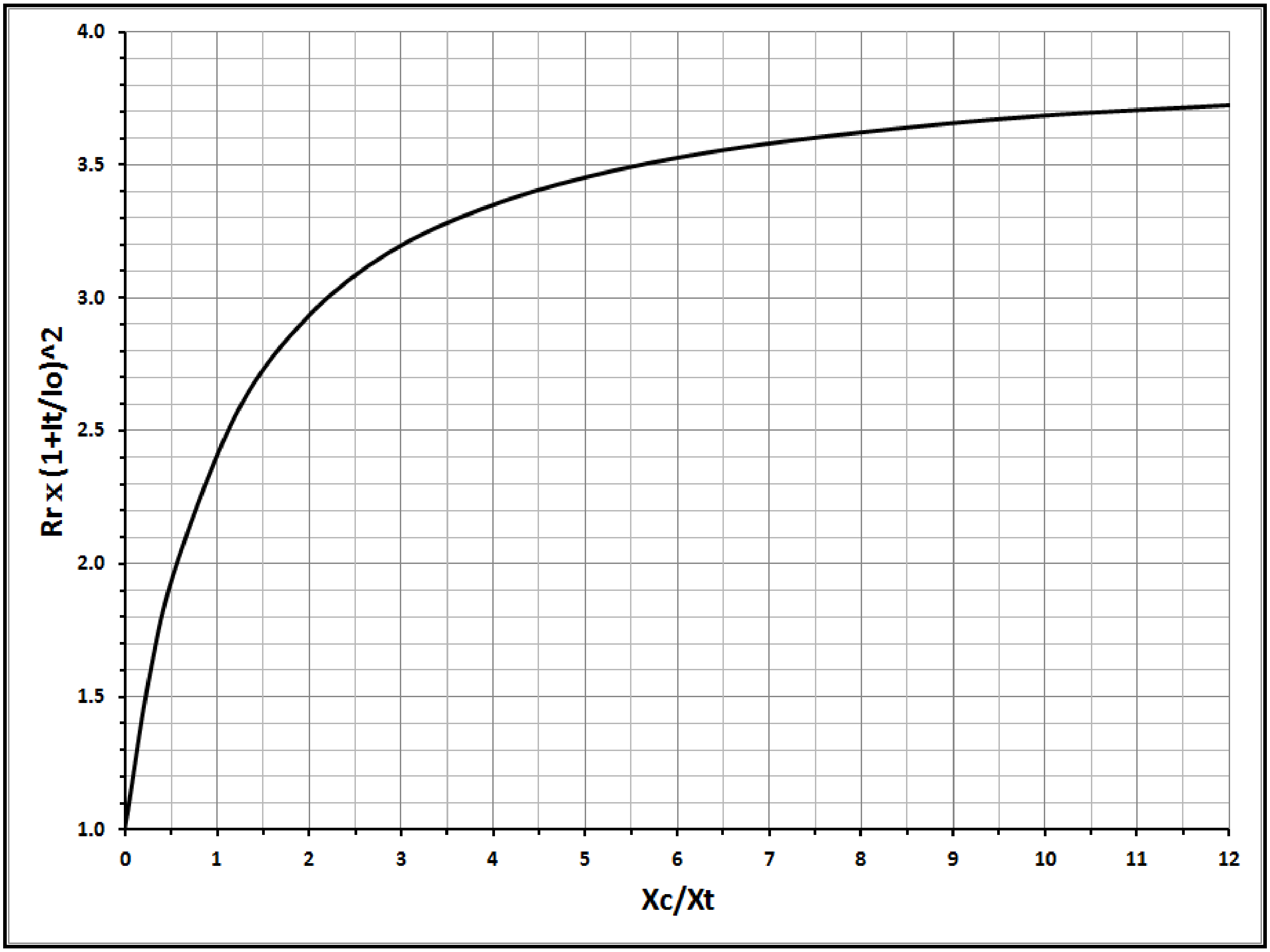

Figure 3.13 - Increase in Rr with top-loading (Xt).

We can calculate values for Xc and Xt using Equations (2.8), (2.9), (3.4) and (3.5), take the ratio and determine It/Io from figure 3.12. With a value for It/Io we can then go to figure 3.10 or 3.11 or use equations (3.8) and (3.9) to get a good approximation for Rr. One thing to notice in figures 3.12 and 3.13 is the flattening of the curves for Xc/Xt>2. Adding more top-loading will initially increase Rr substantially but there is a point of vanishing returns. However, as we increase Ct further (i.e. make Xt smaller) we still get an almost linear reduction in Xi which reduces XL and the associated inductor loss.

The small electrical size of our antennas allows us to simplify the expression for **Xc/Xt**. At 475 kHz 100' is ≈0.05λ, which corresponds to 18º or 0.314 radians. The Tan(0.314)=0.325, with is a difference of only 3%. This difference becomes even smaller for shorter lengths or lower frequencies. We can use this to replace Tan(H') with H in radians (H').

$$\mathbf{Xc} \approx \frac{\mathbf{Za}}{\mathbf{H'}} \quad \text{and} \quad \mathbf{Xt} \approx \left(\frac{\mathbf{1}}{\mathbf{N}}\right)\left(\frac{\mathbf{Zt}}{\mathbf{L'}}\right)$$

$$\frac{\mathbf{Xc}}{\mathbf{Xt}} = \left(\frac{\mathbf{Za}}{\mathbf{Zt}}\right)\left(\frac{\mathbf{L'}}{\mathbf{H'}}\right) = \left(\frac{\mathbf{Za}}{\mathbf{Zt}}\right)\left(\frac{\mathbf{L}}{\mathbf{H}}\right) \quad (3.11)$$

Note! The right side of equation (3.11), the ratio L/H, L and H can be in <u>any units</u> as long as both use the <u>same units</u> which is the same rule for Za and Zt. It is not necessary to convert H and L into radians (H' and L')!

For convenience we can restate:

$$\mathbf{Za} = \mathbf{60}\left[\mathbf{ln}\left(\frac{\mathbf{4H}}{\mathbf{d}}\right) - \mathbf{1}\right] \quad [\Omega] \quad (2.8)$$

$$\mathbf{Zt} = \mathbf{138Log}\left[\frac{\mathbf{4H}}{\mathbf{d}}\right] \quad [\Omega] \quad (3.4)$$

$$\frac{\mathbf{Xc}}{\mathbf{Xt}} = \left(\frac{\mathbf{Za}}{\mathbf{Zt}}\right)\left(\frac{\mathbf{1}}{\mathbf{N}}\right)\left(\frac{\mathbf{L}}{\mathbf{H}}\right) \quad (3.11)$$

Just remember to use the same units throughout!

Equations (2.8), (3.4) and (3.11) all include approximations so we need to check the effect of these on the computed value for Xc/Xt. We can do this by comparing the values derived from NEC modeling to those derived from the equations. figures 3.14 and 3.15 make that comparison using the figure 3.6 antenna with H=20' and 80' and the number of top wires (N) set to 2 and 8. In table 1 we saw that the error in Xt was small for N<7 and we see the same behavior in figures 3.14 and 3.15. For small values of N the agreement is quite good. For larger values of N Equation (3.11) over estimates Xc/Xt but for values of Xc/Xt>3 the It/Io curve flattens so the error in Rr prediction is not all that great. This illustrates the point that manual calculations work fine for simple top-loading arrangements but modeling is really best way for more complicated arrangements.

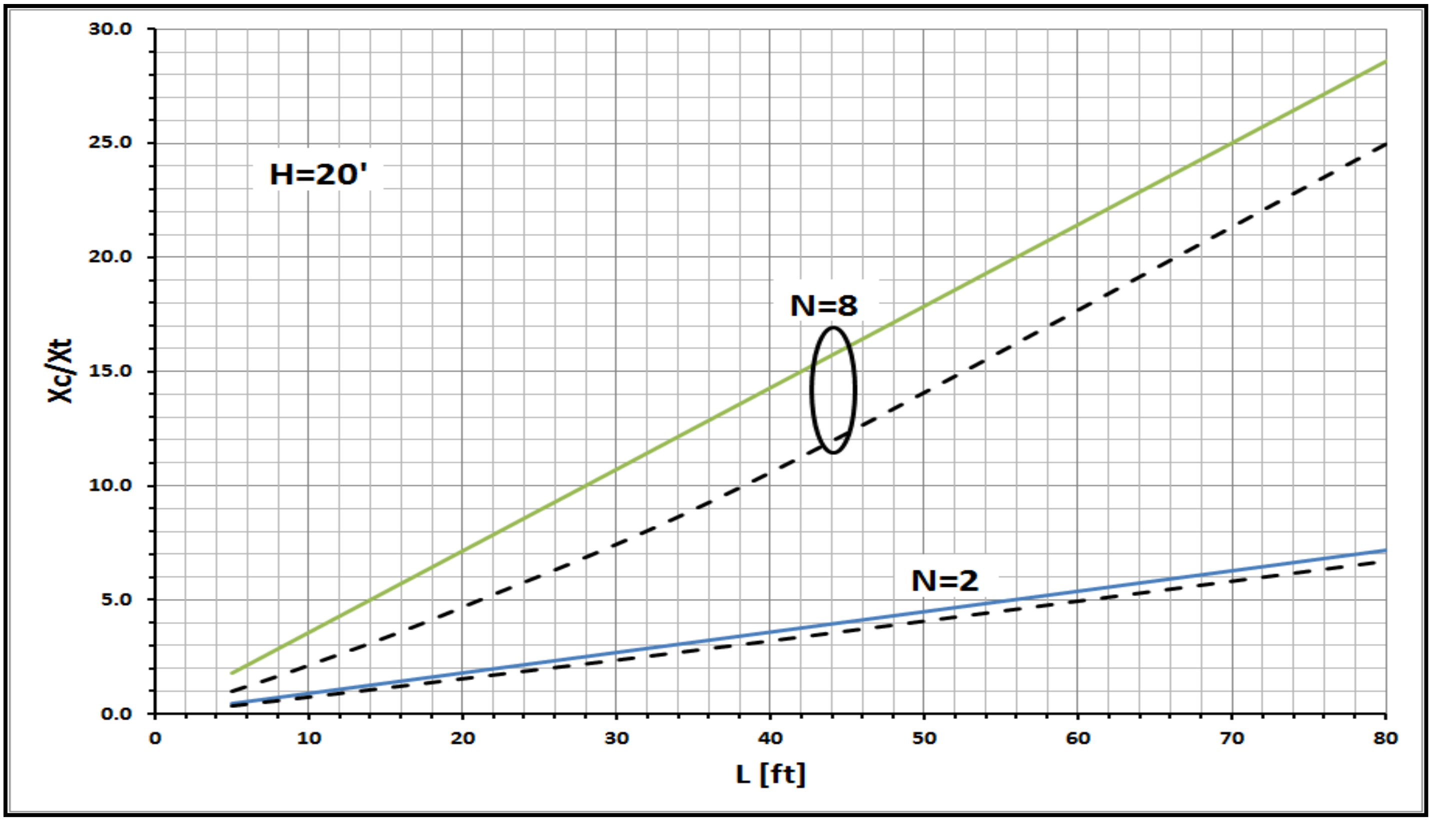

Figure 3.14 - Comparison of Xc/Xt derived from NEC and computation for H=20'.

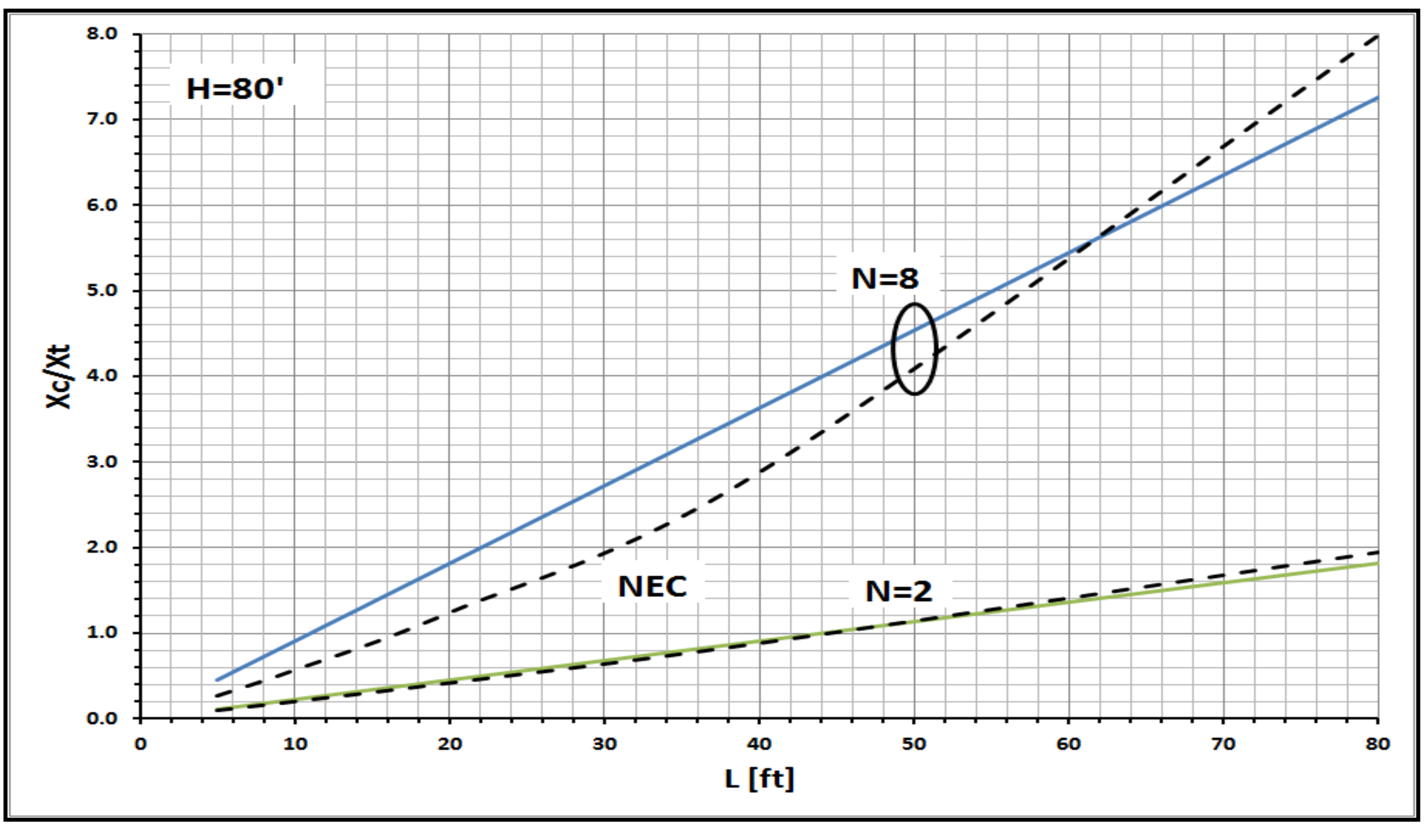

figure 3.15 - Comparison of Xc/Xt derived from NEC and computation for H=80'.

3.4 More realistic antennas

In the real world we won't have a perfectly symmetric T. The realities of a given QTH force us to fit within the available space and supports. This section explores the effect on efficiency of deviations from ideal.

Whenever you stretch a wire between two supports you must have at least some sag to limit wire tension in regions subject to ice loading! Another problem arises when a wire is suspended between trees. Trees move in the wind and two trees 50'-100' apart can be oscillating in opposite directions at the same moment. Both of these considerations can require significant sag in a top-wire. Figures 3.16 and 3.17 illustrate the effect of sag on efficiency. In this example the spacing of the support is 100' with the downlead attached at the center. The ends of the top-wire are fixed at 50' while the height of the center is varied from 25' to 50'. Certainly 25' of sag is excessive but 5' (H=45') is not. With 5' of sag in the 475 kHz antenna the efficiency drops by ≈1.5%. At 137 kHz the efficiency drops from 0.23% to 0.20%. Clearly we want to use as little sag as possible while still meeting the mechanical requirements.

In some installations it may be more convenient to attach the downlead at a point other than the center of the top-wire. As shown in figures 3.18 and 3.19, we can attach the downlead anywhere along the wire and we are also free to place the ground end of the downlead pretty much where we want with little effect on efficiency. Note that in these two figures the efficiency scale is expanded which tends to magnify the differences which are actually rather small.

In some cases the top-wire may not be directly over the point on the ground where we would like connect the downlead. As figures 3.20 and 3.21 show, we can move the downlead ground point many feet off the side with almost no effect on efficiency.

Using supports already on hand (trees, poles, structures), the two ends of the top-wire are likely to be at different heights. Figures 3.22 and 3.23 illustrate the effect top-wire ends at different heights. The horizontal axis on the graphs shows the end height offset from the center height, i.e. for example if one end is 10' higher than the center, the other end will be 10' lower than the center. This means the top-wire slopes downward from one end to the other. As can be seen in the graphs, for a given center height (50' in this example), when we raise one end the efficiency goes up even though we've lowered the other end.

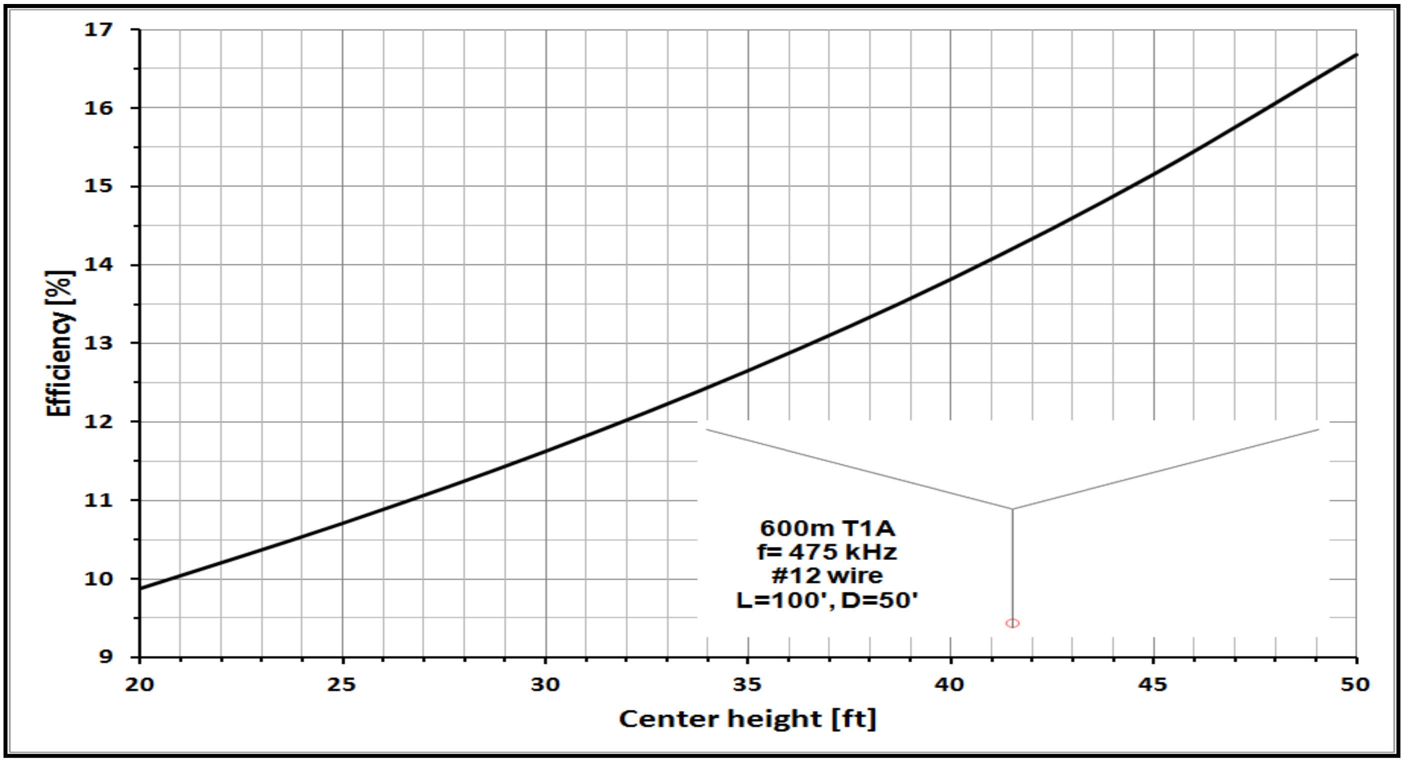

Figure 3.16 - Effect of sag on efficiency at 475 kHz.

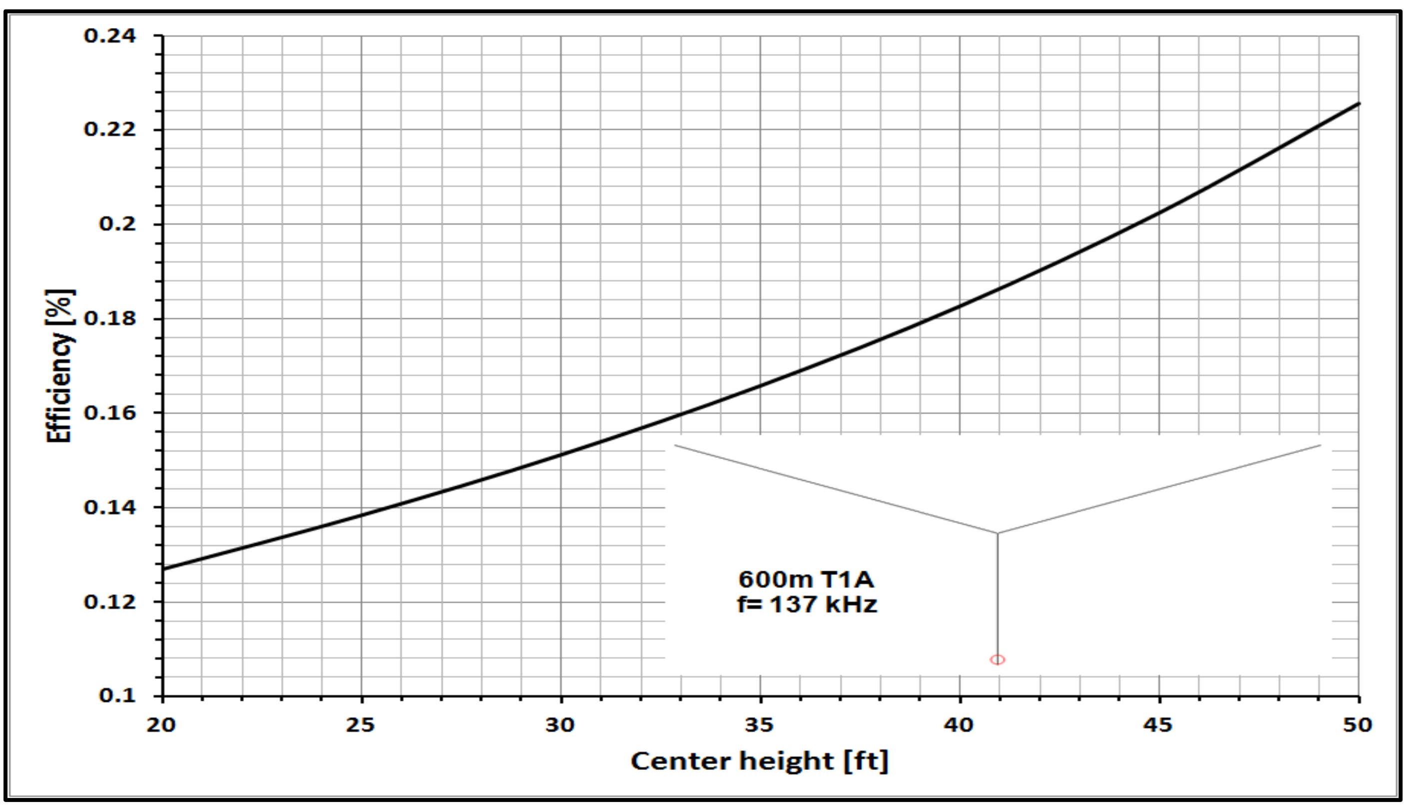

Figure 3.17 - Effect of sag on efficiency at 137 kHz.

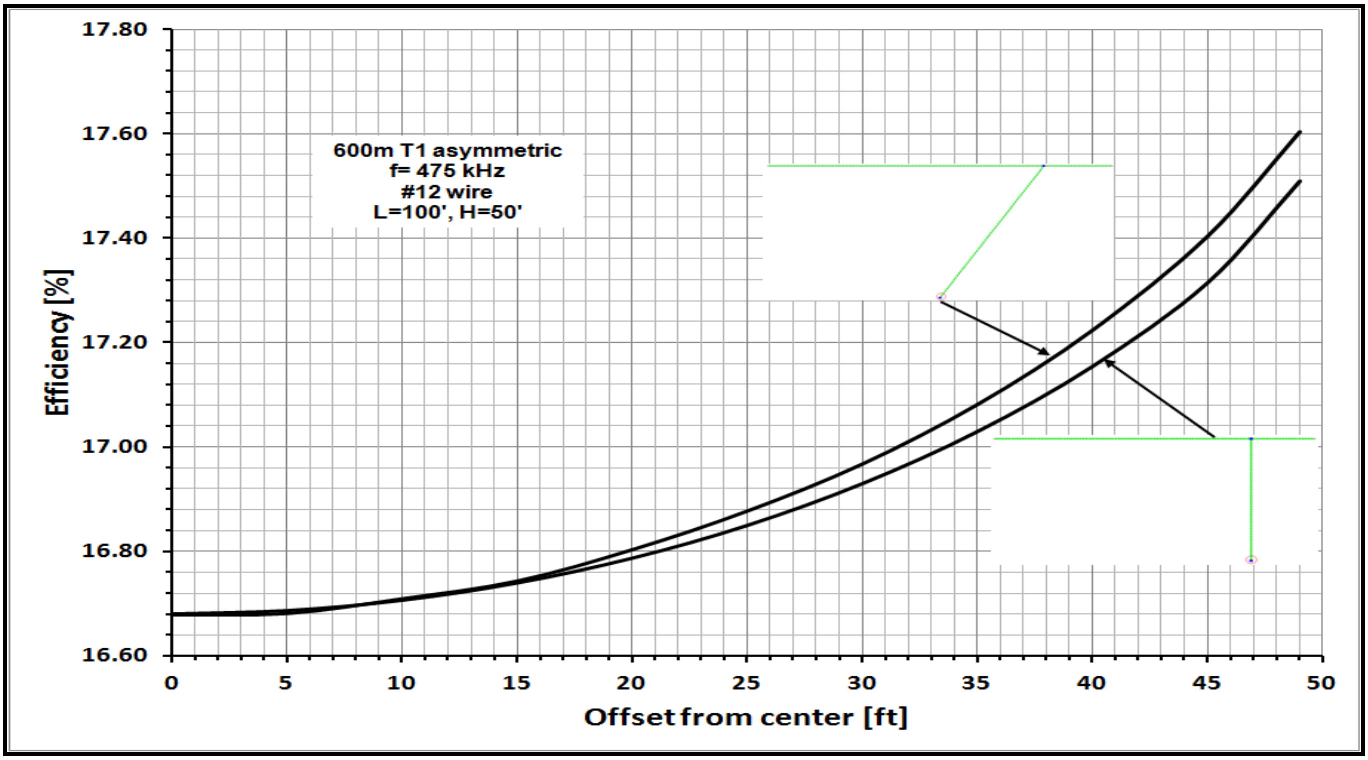

Figure 3.18- Effect of downlead attachment point, 475 kHz.

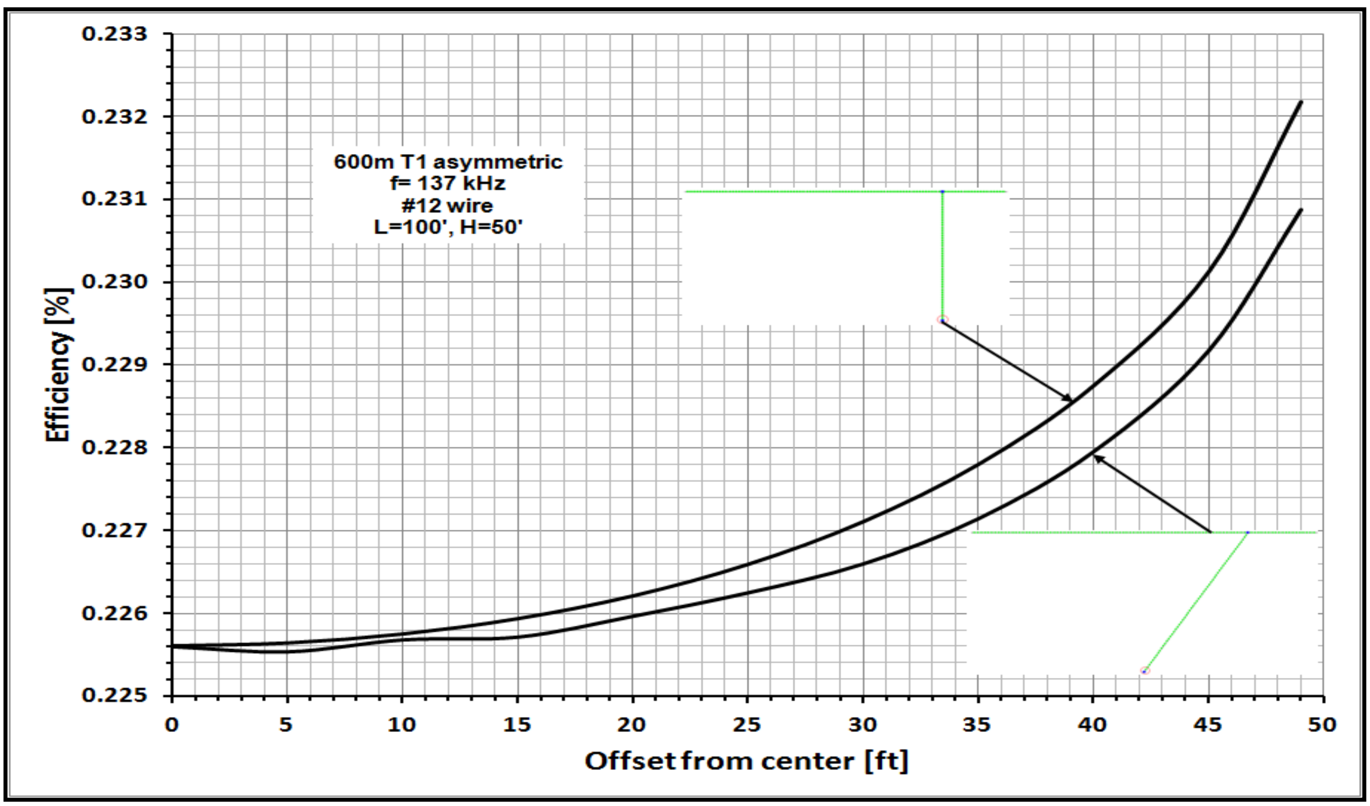

Figure 3.19 - Effect of download attachment point, 137 kHz.

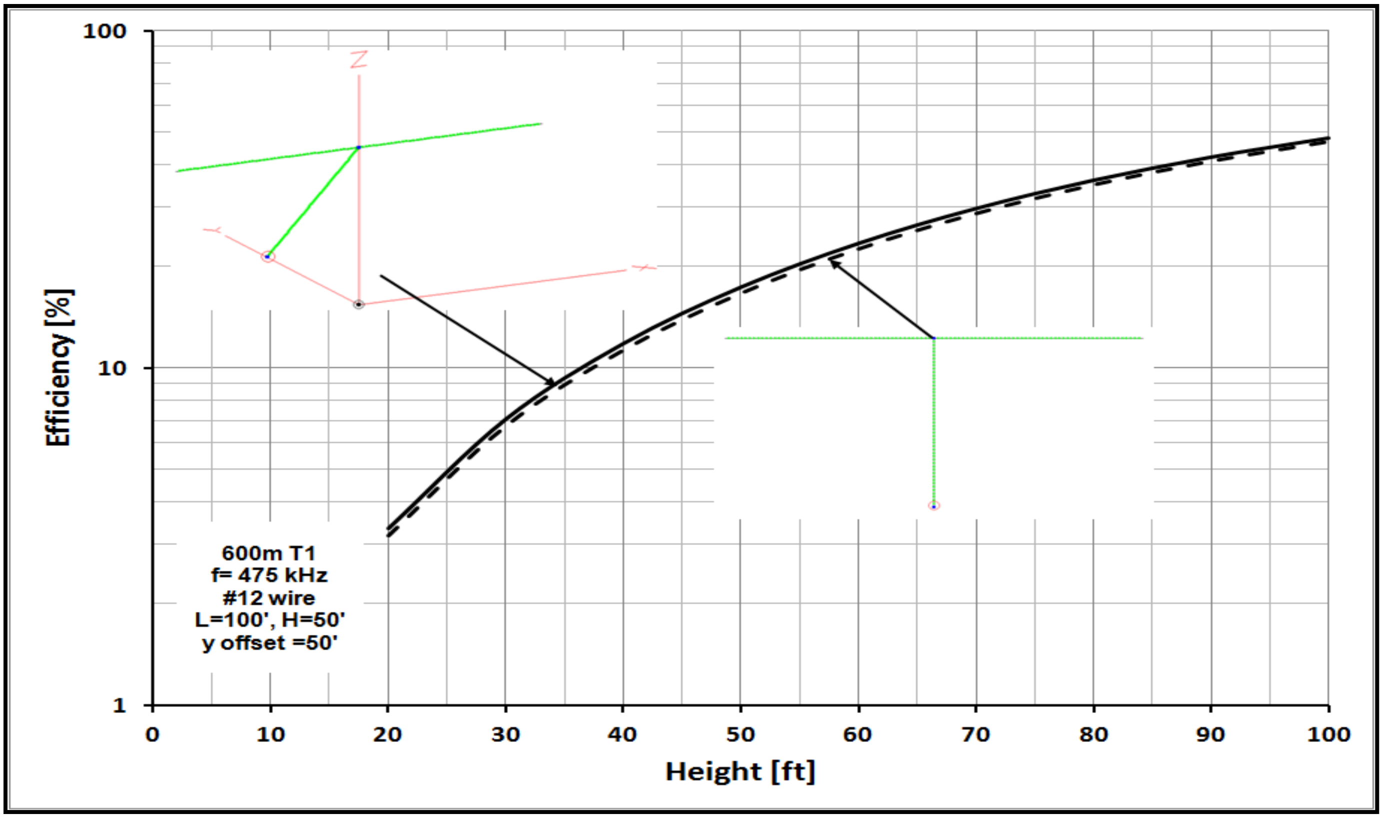

Figure 3.20 - Effect of downlead ground end offset, 475 kHz.

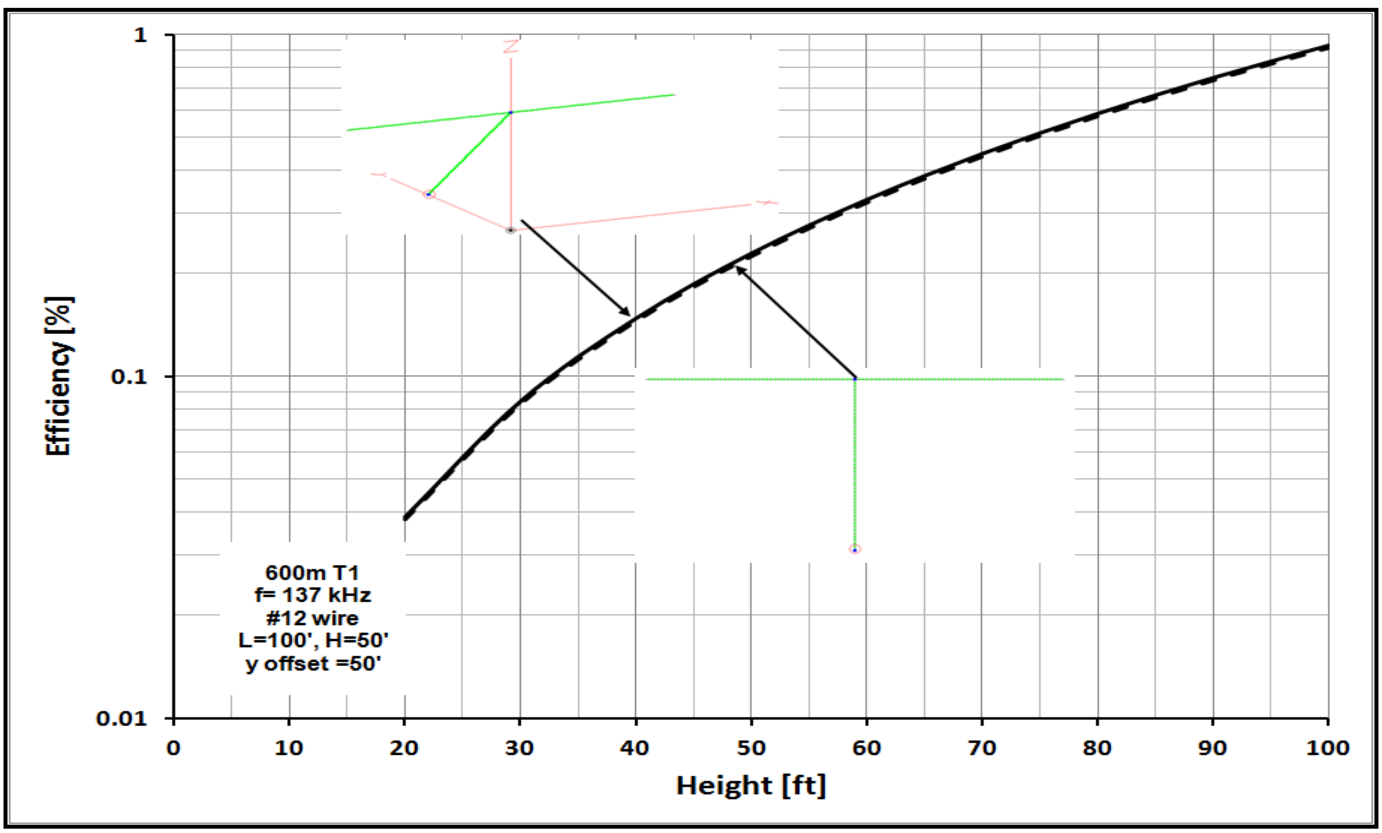

Figure 3.21 - Effect of downlead ground end offset, 137 kHz.

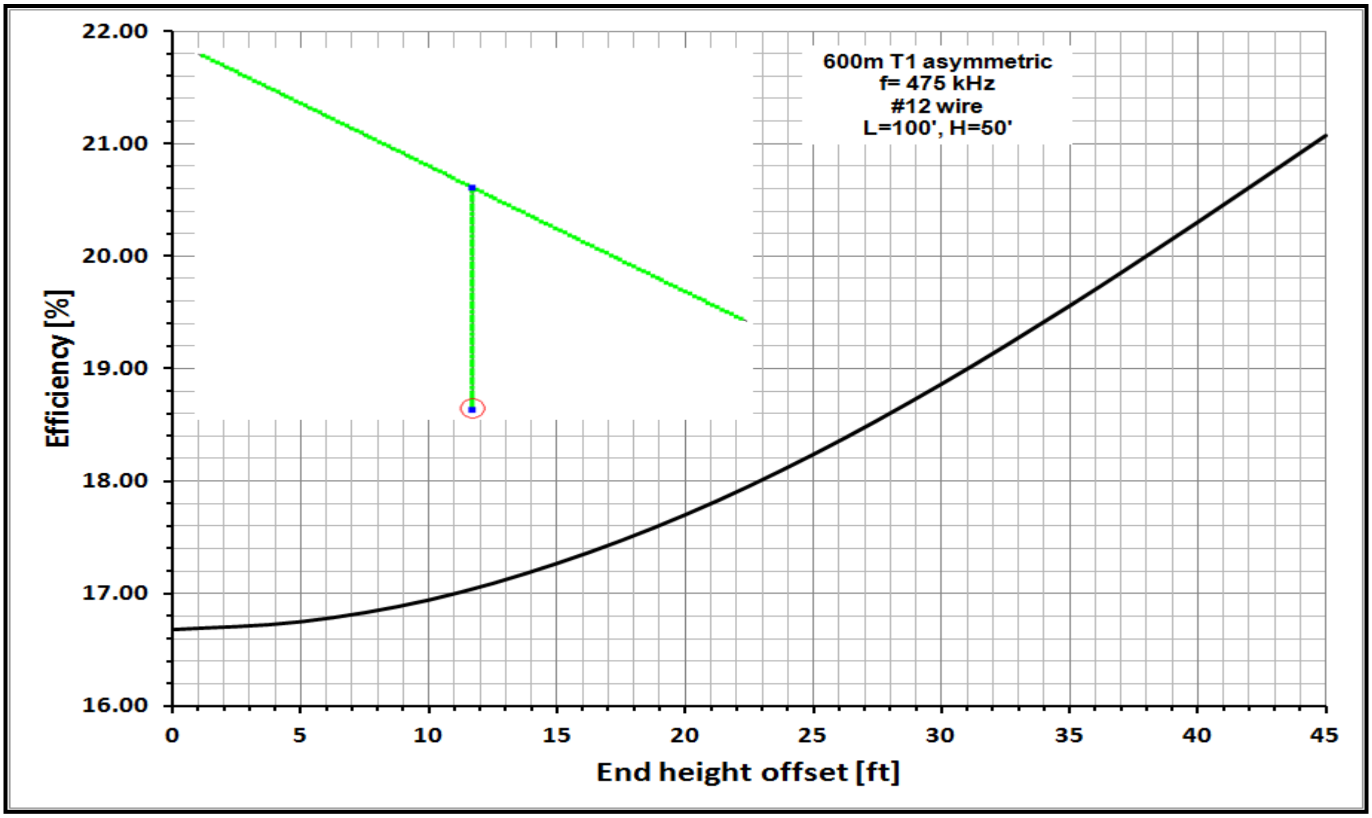

Figure 3.22 -Effect of slope in the top-wire, 475 kHz.

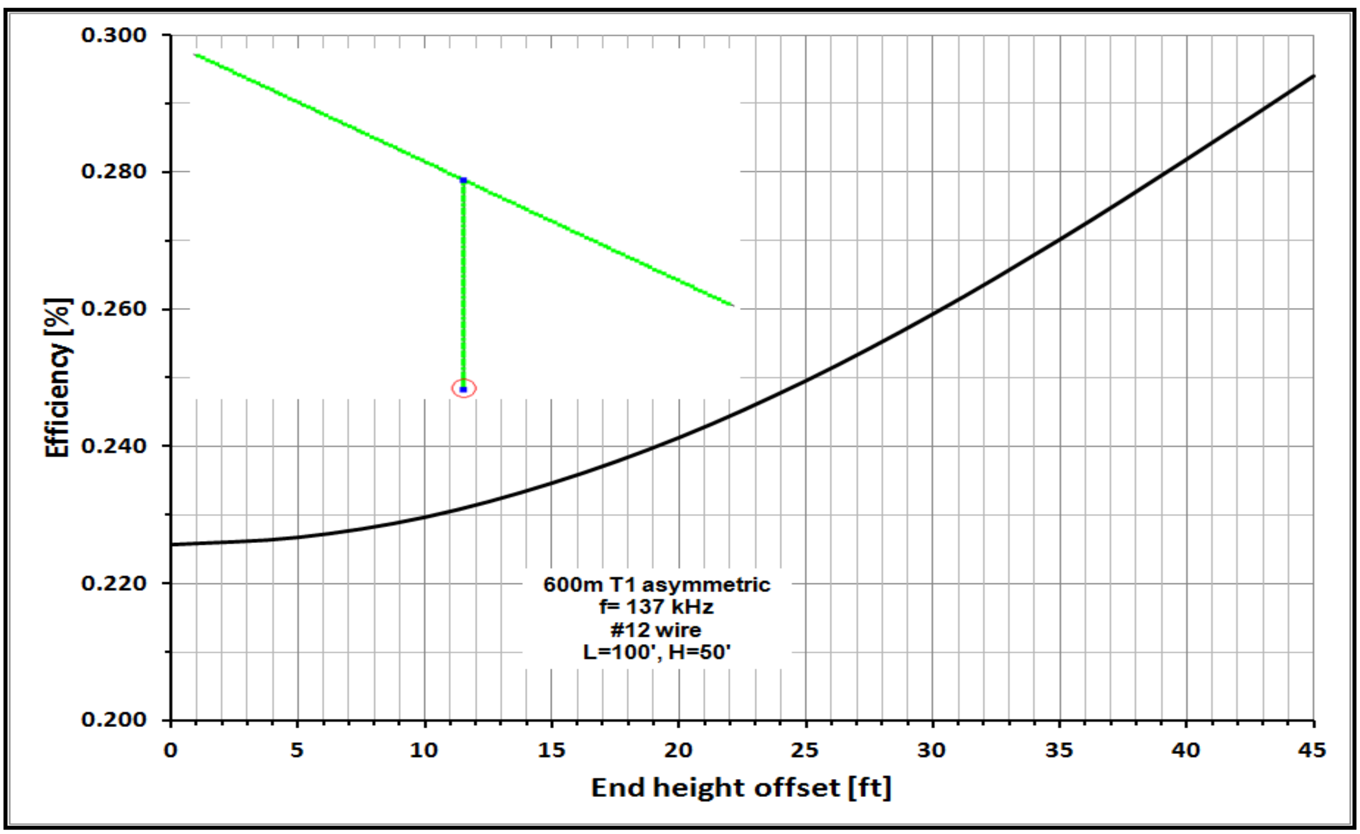

Figure 3.23 - Effect of slope in the top-wire, 137 kHz.

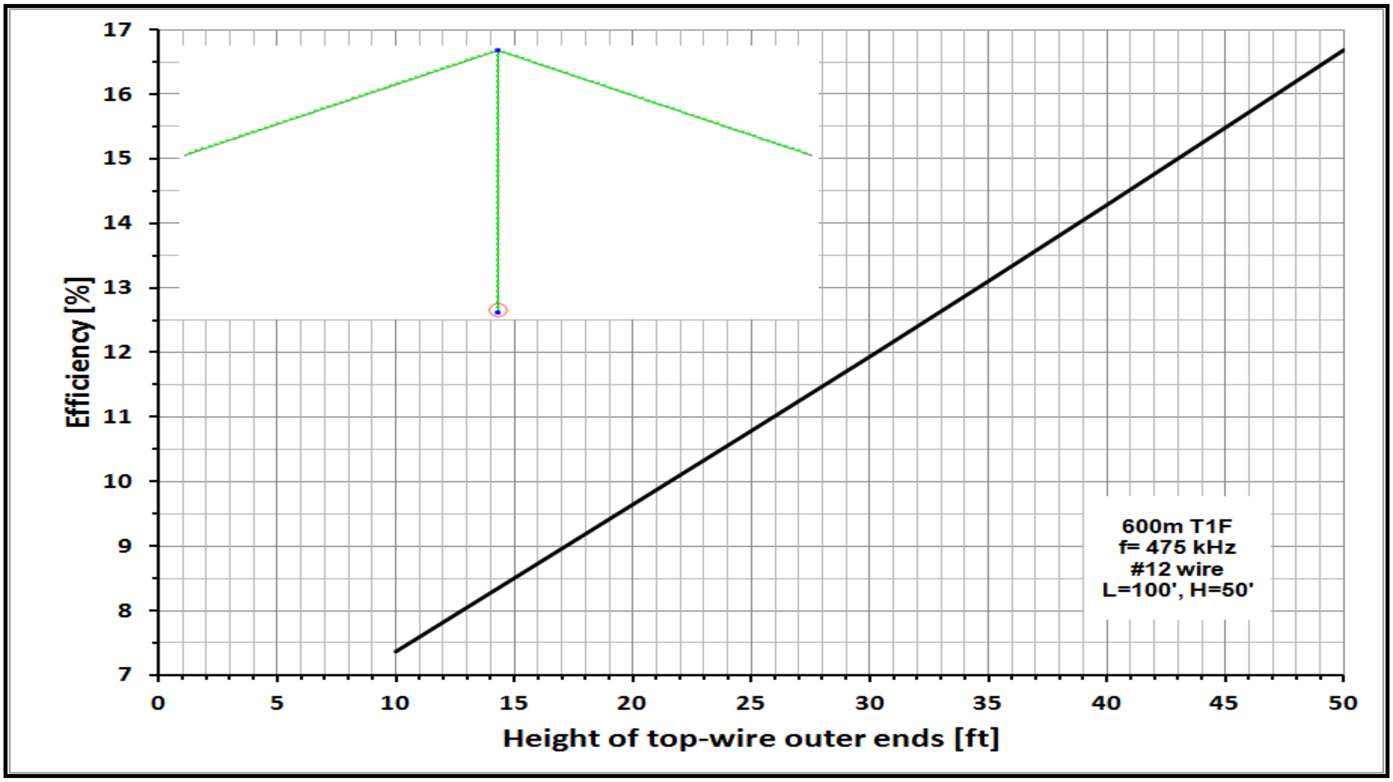

Figure 3.24 -Single support with sloping top-wires, 475 kHz.

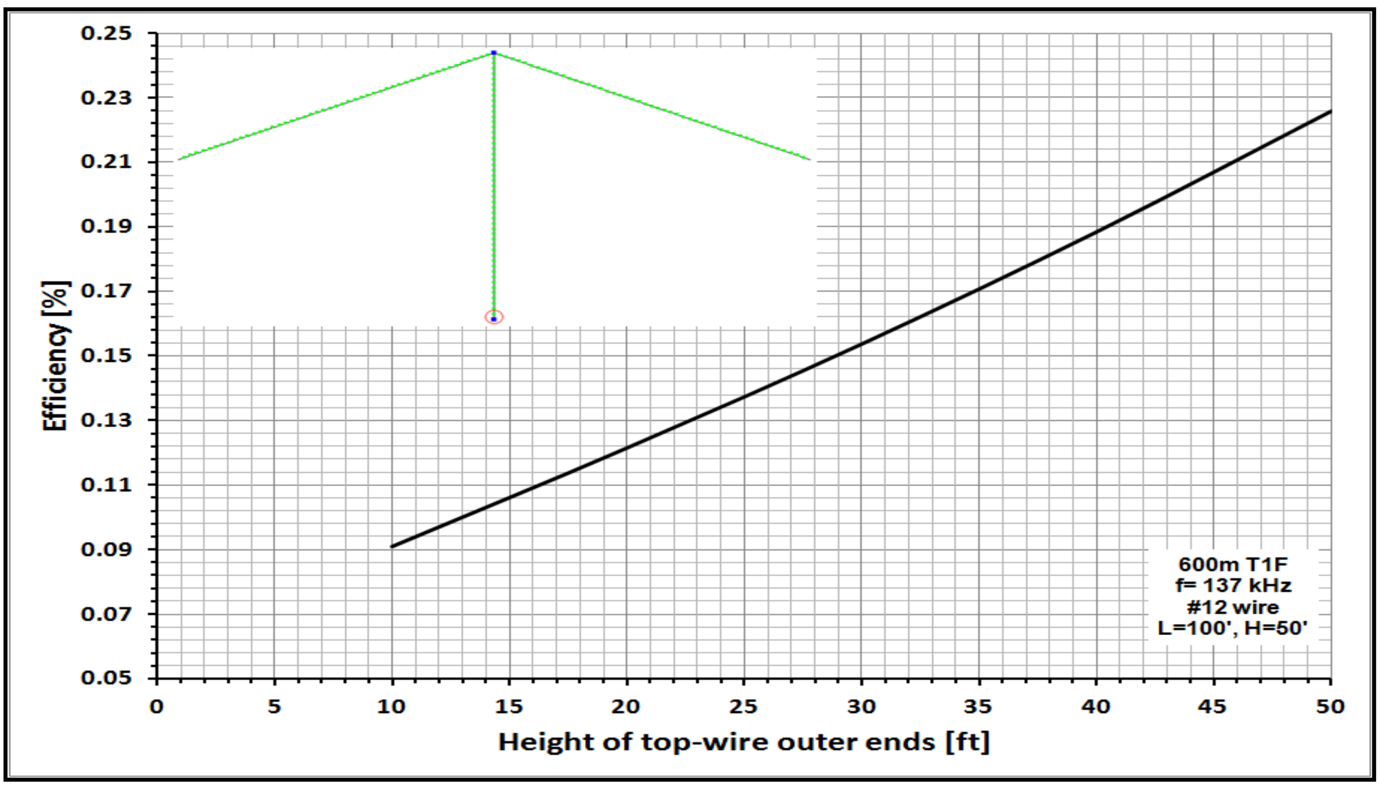

Figure 3.25 - Single support with sloping top-wires, 137 kHz.

Sometimes only one support will be available and the top-wires will have to slope downward from the center supports as indicated in figures 3.24 and 3.25. In this example the height of the vertical is assumed to be 50' and the two top-wires are 50' long. We see that the efficiency is a strong function of the height of the top-wire ends. The higher the better! This is a case where the current in the top-wires has a component that partially cancels the current in the vertical, reducing Rr.

In most cases the available spacing between the supports will be limited. For example, suppose L is limited to 100' and H=50', we can still improve things a bit by adding drop-wires to the ends of the top-wire as shown in figure 3.26 which also shows how the efficiency changes as we vary the drop-wire lengths. When there are no drop wires the efficiency is about 17% but when the drop-wires are 25-30' long (roughly H/2) the efficiency peaks about 3.6% higher. The current in the drop-wires is ≈180° out of phase with the current in the vertical so there is some cancelation which reduces Rr while reducing RL. Initially, as we make the drop wires longer Rr falls somewhat but Xc falls more rapidly until a peak in efficiency is reached. Note however, that the length of the end-loading wires is not very critical.

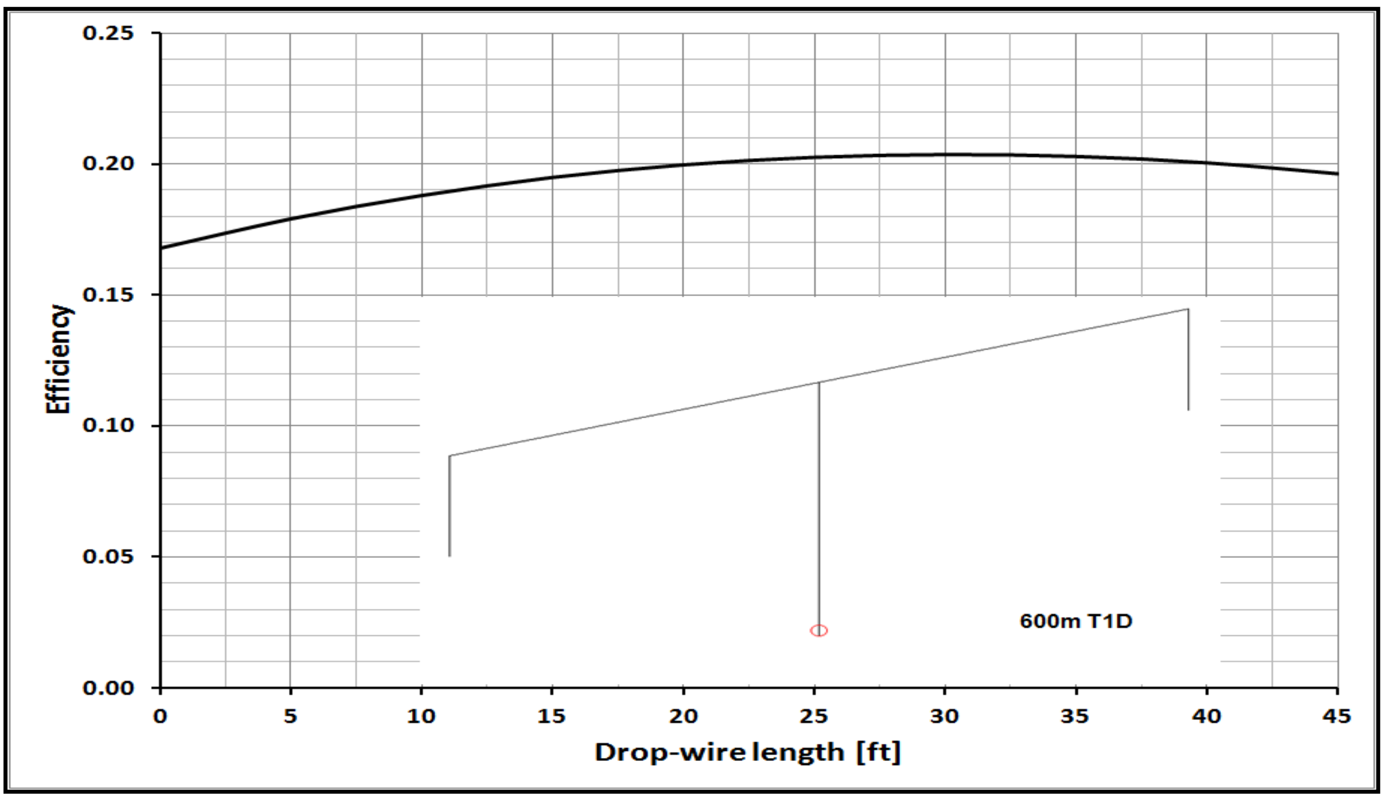

Figure 3.26 - T vertical with end-loading wires. L=100', H=50'.

We don't have to use a straight wire for top-loading, it may be bent as shown in figure 3.27. When the top-wire center angle is 180° the loading reactance for resonance is 1246Ω and the efficiency is about 16.7% (including only the inductor loss!). When the center angle is changed to 90°, the loading reactance increases only slightly to 1255Ω and the efficiency decreases to 16.6%, a very small change. It appears that the center angle for the top-wire is not at all critical and has to made quite small (<45°) before it matters very much.

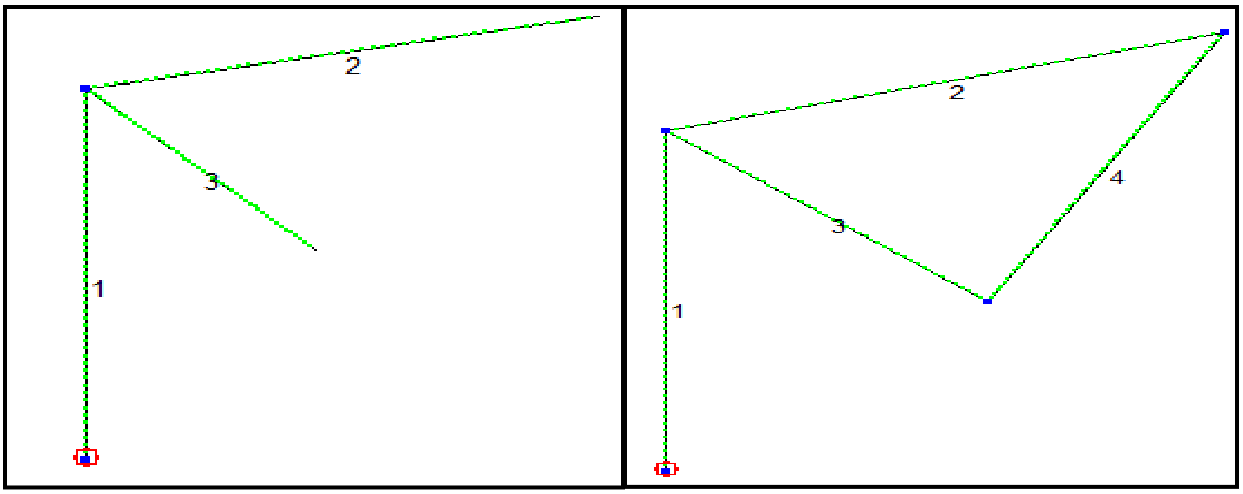

Figure 3.27 - 90° between top-loading wires. With and w/o skirt wire.

Note that when the top-wire is bent it may be possible to add a "skirt" wire as shown on the right (wire 4). For a 90° center angle adding the skirt wire reduces the loading reactance to 904Ω and the efficiency increases to 23.7%. Adding the extra wire is well worth doing! It should be pointed out that wire 1, the vertical, does not have to come straight down to ground. As shown earlier the wire can be slanted towards a more convenient point. In figure 3.27 wires 2, 3 and 4 constitute a loop "top-hat". The downlead could be connected at <u>any</u> point on the loop with only modest effect on efficiency! To generalize a bit further, if multiple support points, at different heights, are available a loop can be strung between these points to form a top-hat. An irregular top-hat works just fine. <u>Exploit the opportunities at your QTH!</u>

At HF we would expect the radiation pattern for the inverted-L to have significant asymmetry. However, the antennas in figures 3.15 through 3.27 are nowhere near self resonance without a loading inductor. The far-field patterns show very little difference between the antennas, i.e. circular to a fraction of a dB. The message is that these antennas are very tolerant of mechanical variations.

3.5 Using a Tower for support

A tower can be used as a support or as a radiator. Exciting the tower will be discussed in chapter 4. The immediate question is: what is the effect of coupling between a grounded tower and the vertical downlead? The simple answer is that it will reduce the efficiency somewhat but usually only a few percent because the tower, even with multiple Yagis for loading, is unlikely to be resonant anywhere near 475 kHz, not to mention 137 kHz. The coupling can be minimized by spacing the top anchor point as far out from the tower as possible, several feet would be helpful. Pulling the bottom and/or the top of the downlead away from the tower as shown in figure 3.28 can also help. The effect on a specific installation is best explored with modeling.

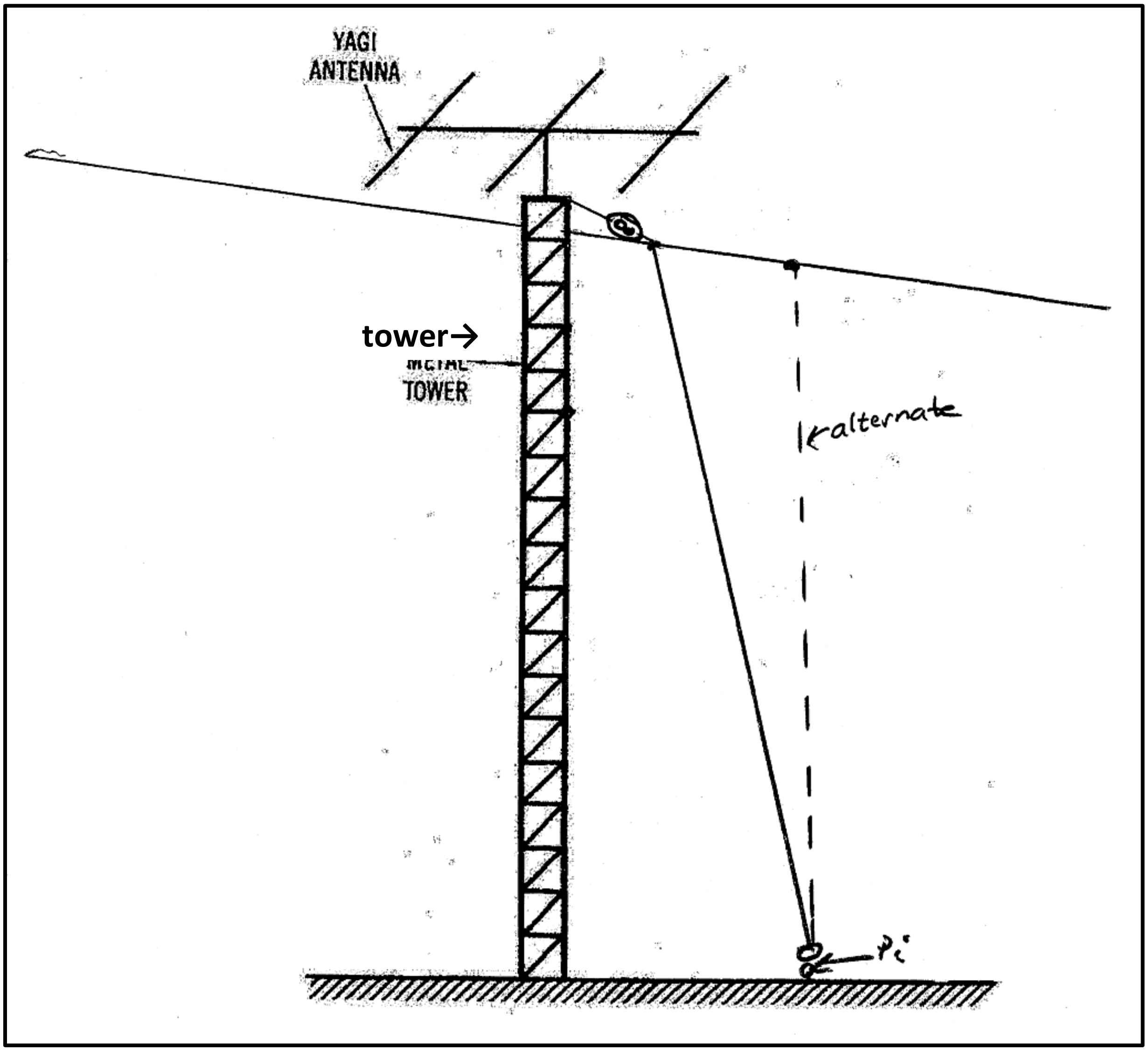

Figure 3.28 - Using a grounded tower as a center support.\

3.6 More complicated top-loading

While a vertical with a single top-wire is attractive, we're not limited to a single wire for top-loading. More complex top-loading can substantially improve efficiency. For example, we can add spreaders and use two or more wires as shown in figure 3.29. One note, the T and L models for this study show only a single conductor down-lead. When multiple top wires are used, the down-lead can also have multiple wires for at least part of its length which can make a small improvement in efficiency by reducing Rc. One of the problems with spreaders is that they tend to rotate and twist. Extra downleads can act as stabilizers. Light non-conducting lines can also be used to stabilize the spreaders.

Going from a single wire to two wires with 10' spreaders, makes a huge difference. For example, with 100' top-wires and H=50': for one wire the efficiency is ≈17% but with two wires and 10' spreaders that jumps to ≈28% and when we go to 30' spreaders the efficiency is ≈34%. However, there are practical limits to spreader length. 10' is easy, 20' takes some doing but spreaders longer than 20' are challenging. When the spreader length is increased to 20' the efficiency increases to 32%, significant but not nearly as great as the initial increase. For two wires 20' spacing is well into the region of vanishing returns and it's time to consider adding another wire or two. Figure 3.30 compares examples using 2, 3, 4 and 5 wires with a spreader length of 20' and an overall length of 100'. Clearly adding more wire to the hat reduces Xc and leads to higher efficiency but as can be seen in figure 3.30, for a given spreader length the <u>rate</u> of improvement falls pretty quickly and in this case using more than five wires gains very little. Adding more wire to the top-hat helps to reduce Xc but there's an important drawback to more wire up in the air: if you live in a area with ice storms, the antenna becomes much more vulnerable. From figures 3.29 and 3.30 it's clear that the effective capacitance (Ct) of a top-hat with parallel wires depends on the separation between the wires. Unfortunately the calculations for Xt shown in section 3.2 are not useful for closely spaced wires. An excellent and very complete paper on calculating the capacitances associated with LF-MF loaded verticals, written in 1926 by Fredrick Grover, is available on-line[2]. Excerpts from the Grover paper can be found in Terman[3]. In general it's much easier to use modeling for more complex top-loading structures.

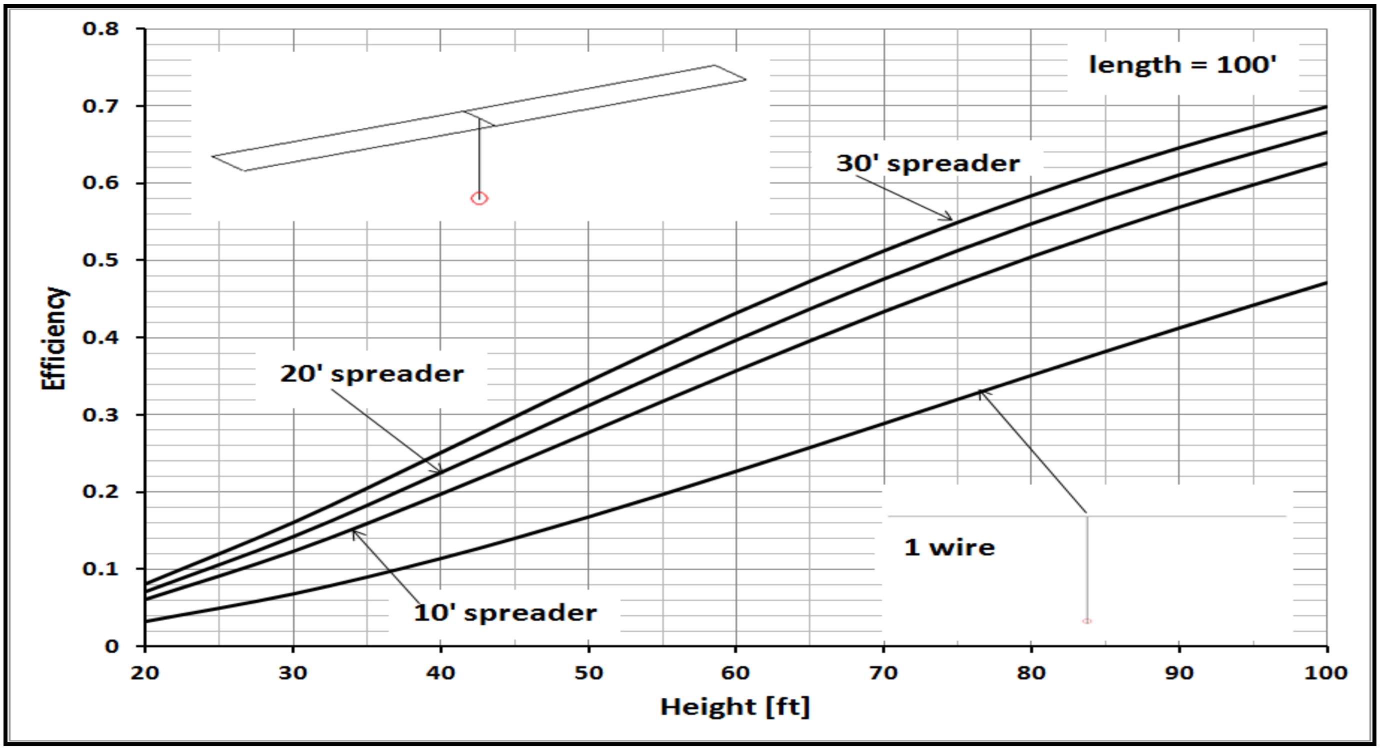

Figure 3.29 -Comparison of top-loaded verticals using a single wire or 2 horizontal wires with 10', 20' or 30' spreaders.

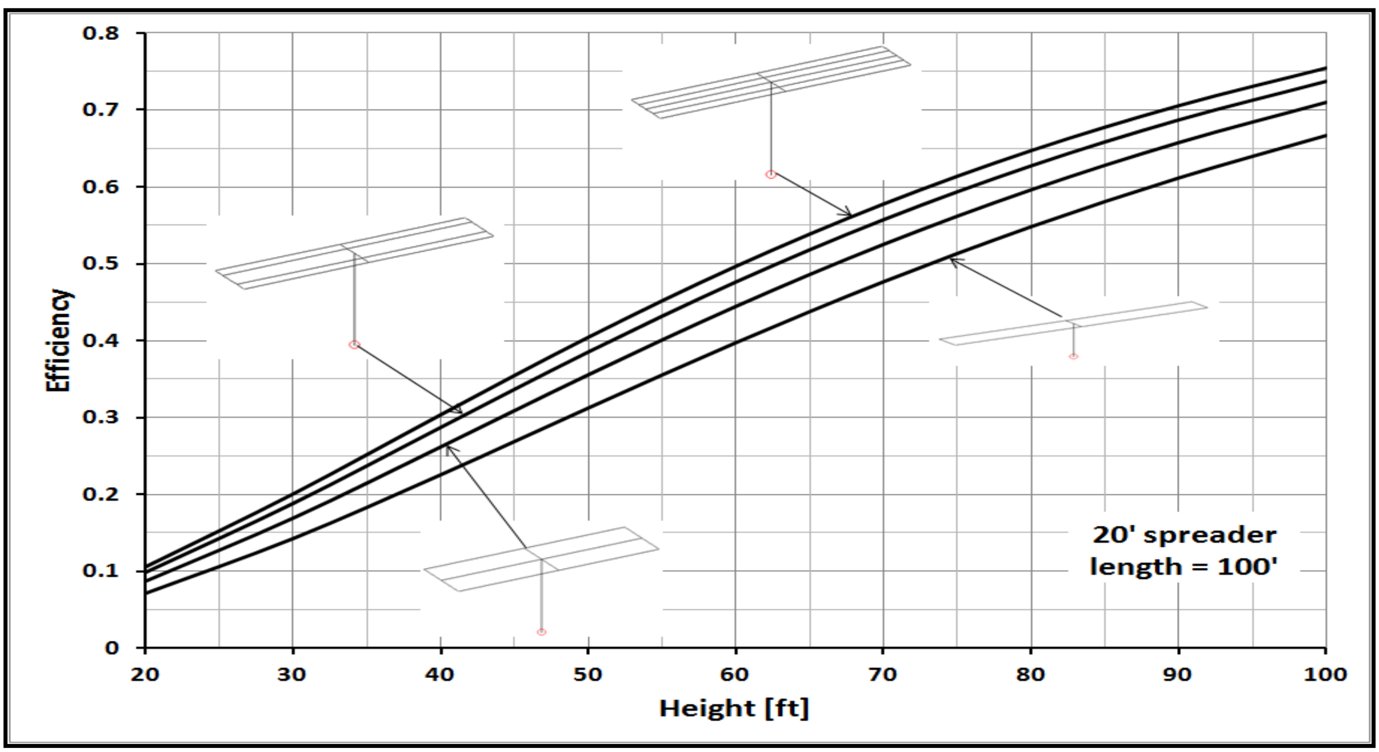

Figure 3.30 - Examples using more wires in the top-hat.

As shown in figure 3.31 in a multi-wire top-hat it may be possible to dispense with the center spreader, reducing the weight at the mid-point of the hat. The efficiency falls by ≈2% compared to the flat top but the reduction in sag due to the decrease in center-weight may compensate for that. One problem with the "bow-tie" arrangement, especially if the ends with the spreaders are supported only by a single line, is the tendency to twist in the wind. With a spreader at the midpoint and a fan for the downlead, twisting is much less of a problem. For the bow-tie configuration you will have to add some restraining lines at the ends of the spreaders.

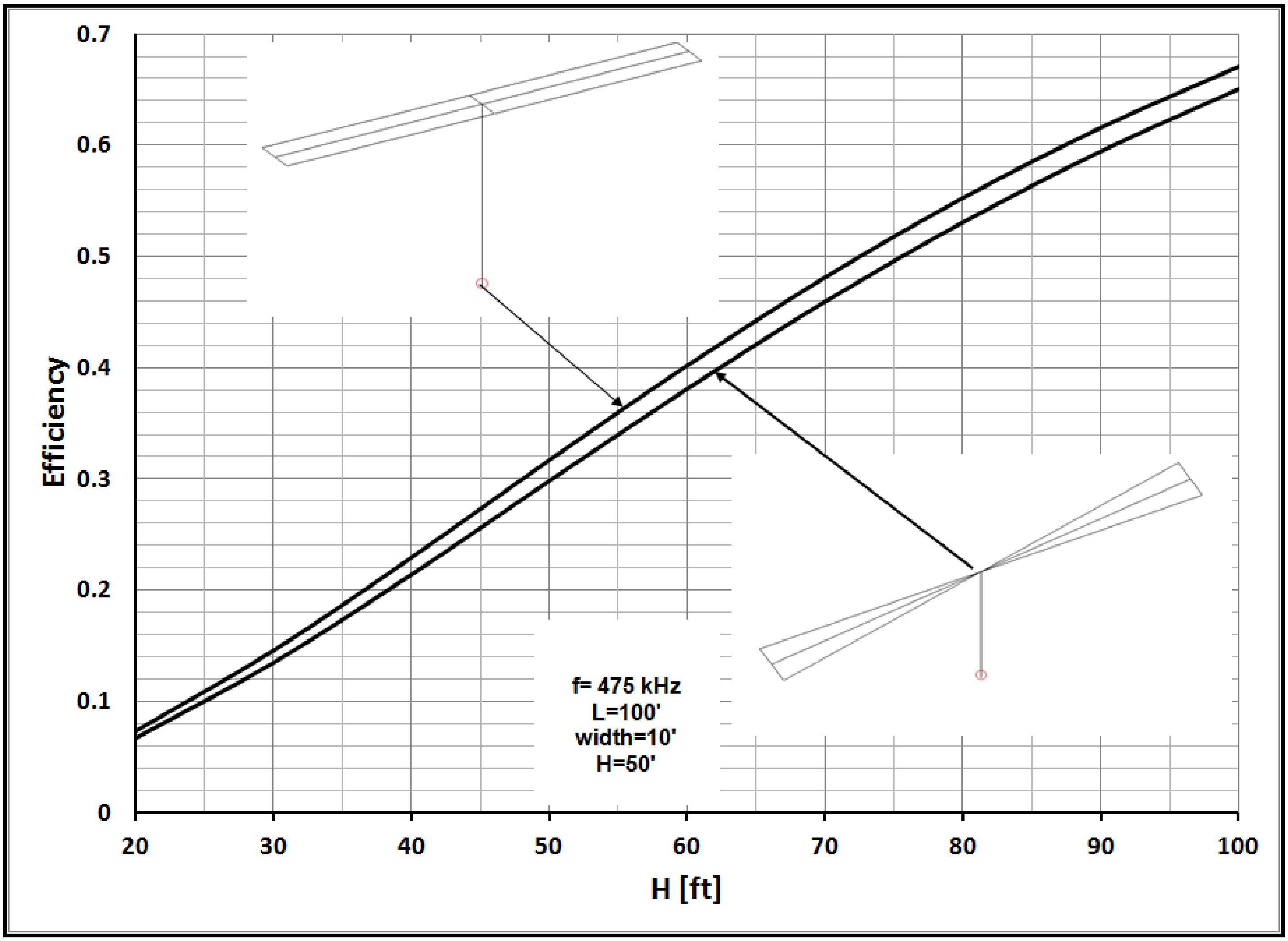

Figure 3.31 - 3-wire top-hat examples.

3.7 Umbrella top-loading

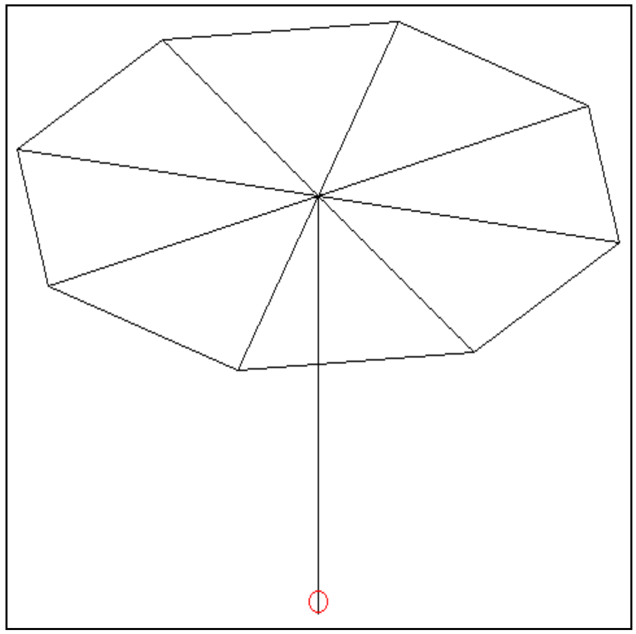

Figure 3.32 - Example of an "umbrella" for capacitive top-loading.

We've seen how helpful capacitive loading with various long top-wires can be. Now let's extend our investigation to symmetric top-hats which resemble umbrellas as shown in figure 3.32. Top-loading structures like this are often used when only one support (the vertical itself for example) is available.

There are many ways to construct an umbrella:

- Use several rigid radial supports like a wagon wheel. For example, the supports can be aluminum tubing or F/G poles supporting wires or some combination of the two. The practical limit for a self-supporting structure is probably a radius of 20' or so. Using the hub(s) and spreaders from an old HF quad can be a very simple way to fabricate an umbrella.
- Set up a circle of poles (3 to 8) at some distance from the base of the vertical to support the far ends of the umbrella wires. The radial dimension of the umbrella could be quite large but the length of the poles, which establishes the height of the outer rim of the umbrella, is a limiting factor.
- Attach a number of wires to the top of the vertical, sloping them downward at an angle towards anchor points located at some distance from the base of the vertical.
- You can add sloping wires to the outer rim of a horizontal umbrella to increase the loading.

- You do not have to connect the outer ends of the umbrella radial wires together with a "skirt" wire but a skirt-wire significantly increases the loading effect of an umbrella of a given radius.
- While most of this discussion shows symmetric umbrellas, symmetry is not required. Supports at different distances with different heights can also be used to good effect. Take advantage of what's on site!

For much of the modeling an 8-radial umbrella with a skirt wire is used. This represents a compromise. As few as three wires (with a skirt!) can make a useful umbrella but the performance improves substantially as you go from three to four and then eight wires. While the jump from four to eight wires gives a useful improvement the law of diminishing returns starts to set in and sixteen wires is about the useful limit. It's also possible to add more skirt wires inboard of the outer skirt wire. These are issues best explored with modeling.

Figure 3.33 is a generic sketch of the dimension designators used in the discussion.

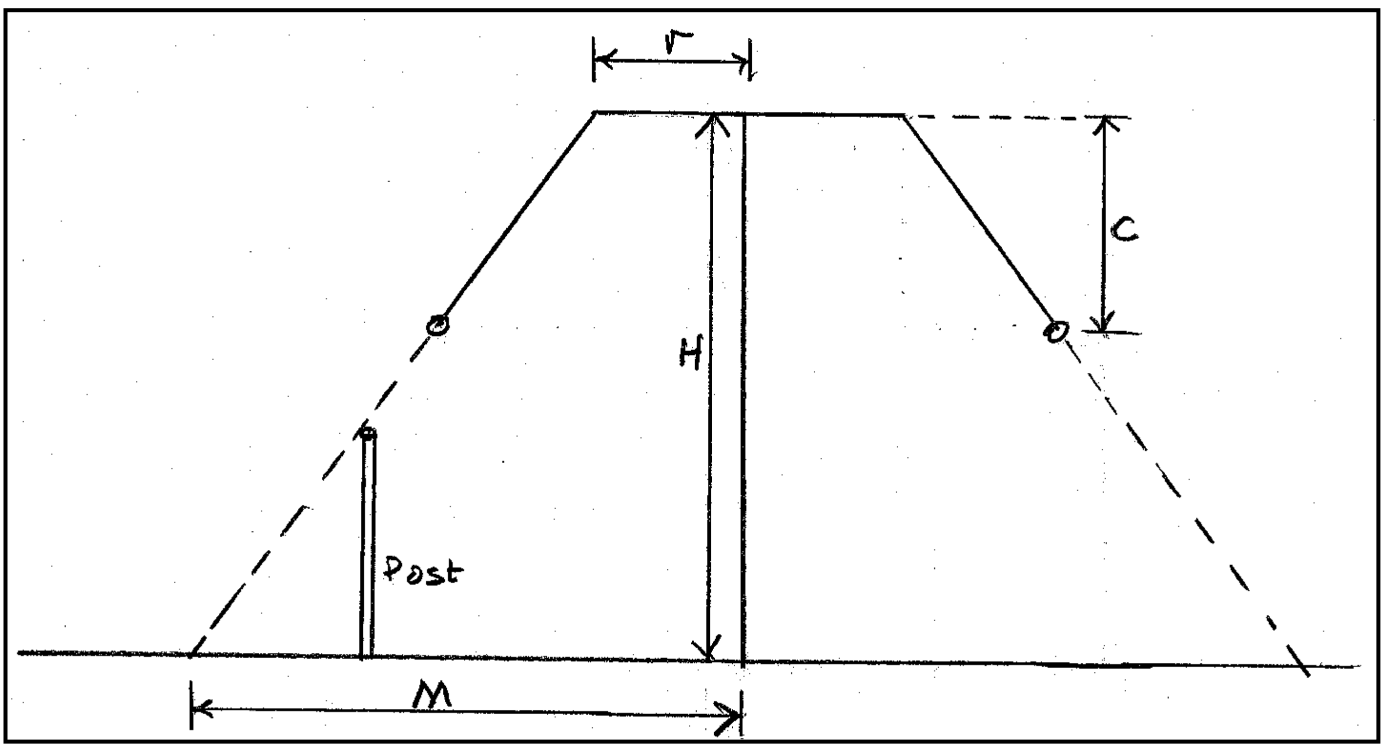

Figure 3.33- Definition of antenna dimensions.

Where: H=vertical height, r=radius of a flat umbrella, C=depth of a sloping umbrella, M=distance from the base to an anchor point,. When the available space restricts the radius to the anchors (M), as shown, a post can be used to increase the slope angle.

3.8 Horizontal or flat umbrellas

Figure 3.34 shows how Rr and Xc vary with H and r for a simple horizontal umbrella. r is varied from 0 (no umbrella) to 10' and then to 50'. We can see that even an umbrella radius as small as 10' makes a marked improvement in both Rr and Xc. Taking the data from figure 3.34 and assuming QL=400 we get the efficiencies shown in figure 3.35. The larger the umbrella, the better the efficiency!

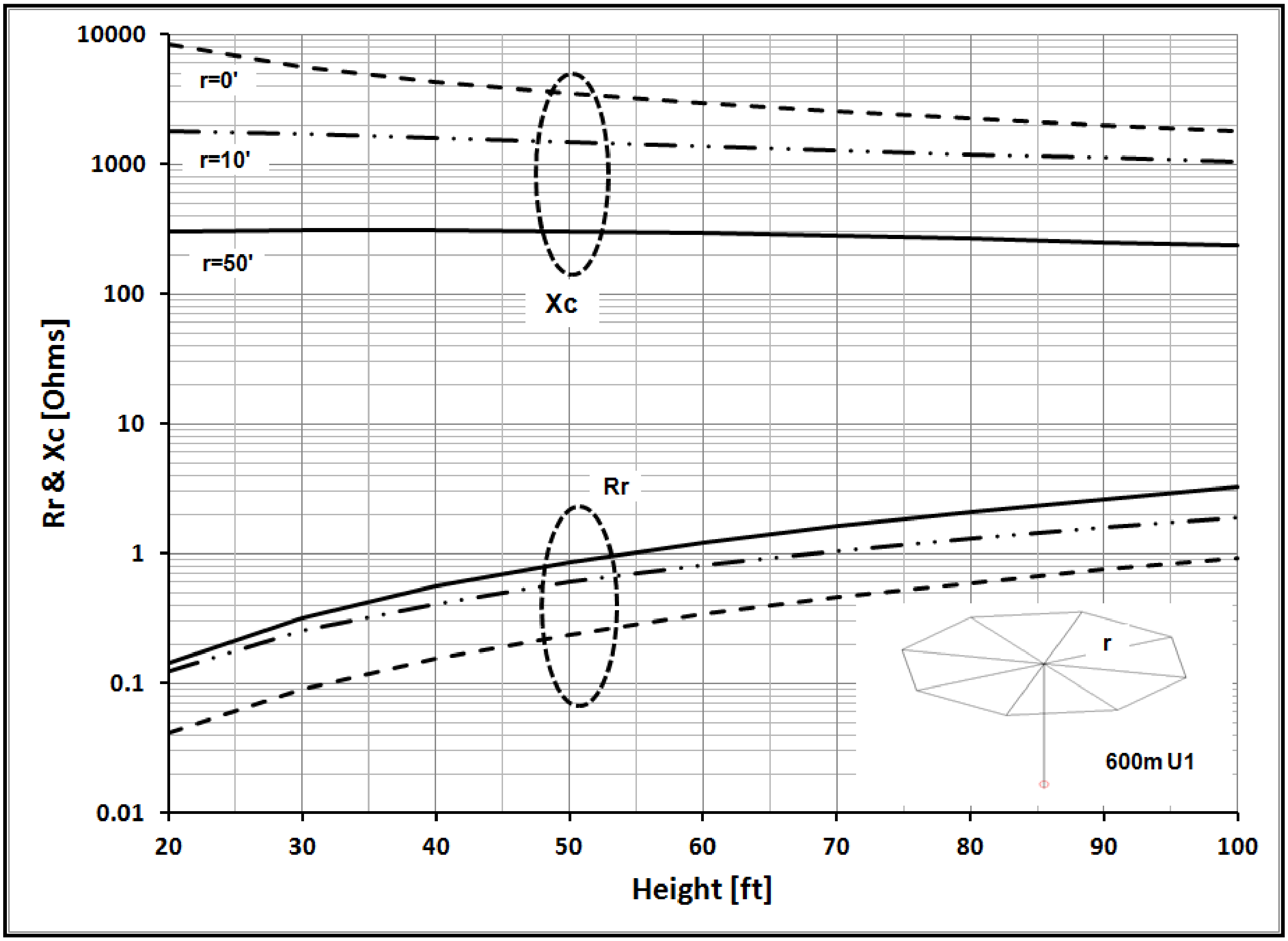

Figure 3.34 - Rr & Xc as a function of H and r.

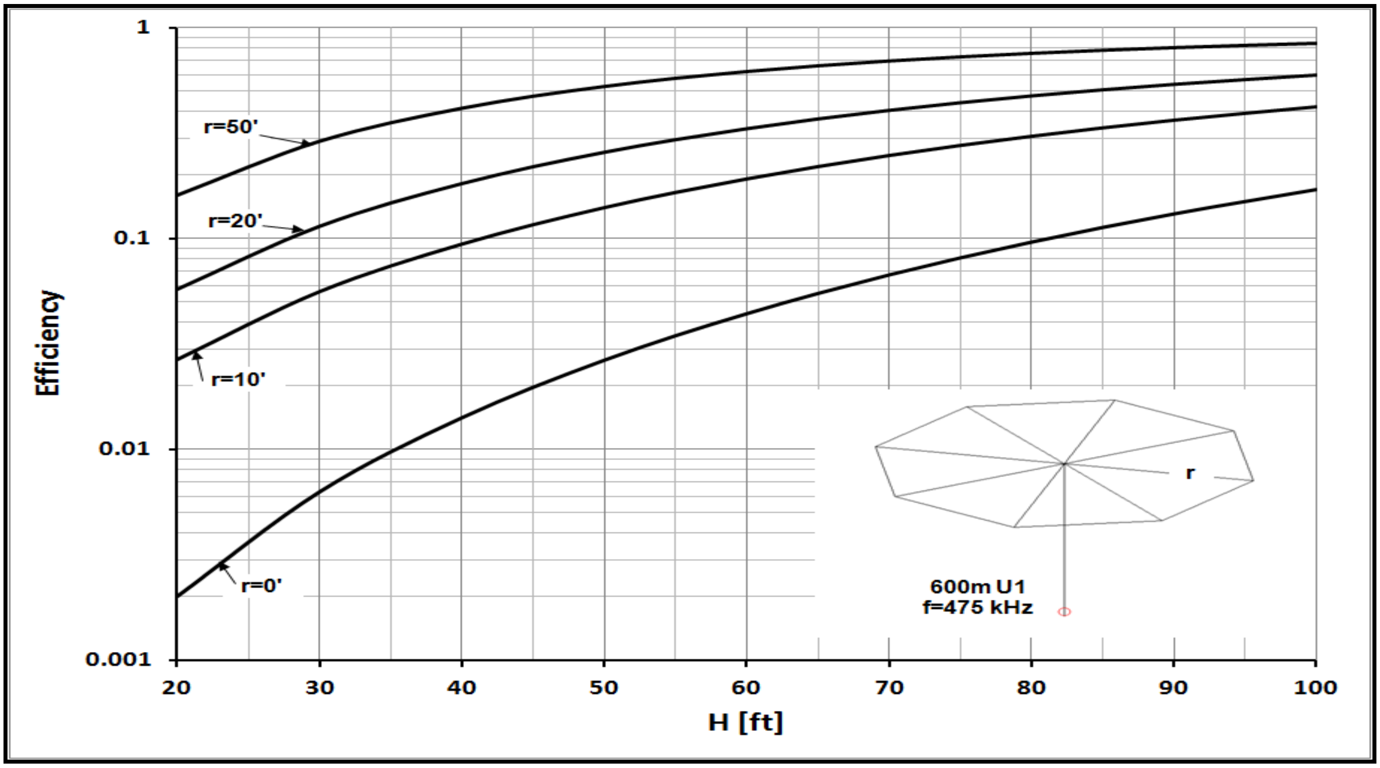

Figure 3.35 - Efficiency as a function of H and r.

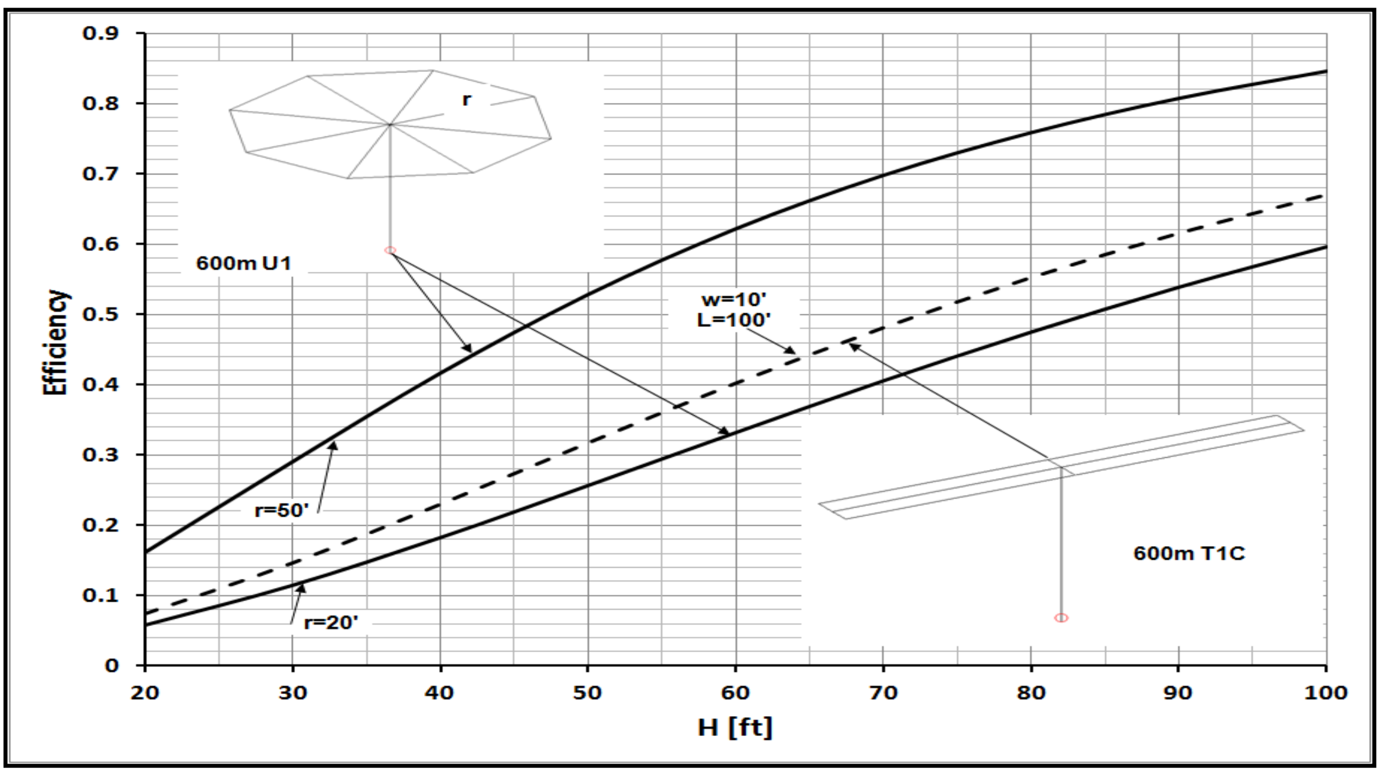

Figure 3.36 - Comparison between T and symmetric top-loading umbrellas.

Figure 3.36 compares T top-loading to umbrella loading. A circular umbrella with r=20' is almost the same as a 3-wire T with 10' spreaders and 100' wires.

3.9 Sloping wire umbrellas

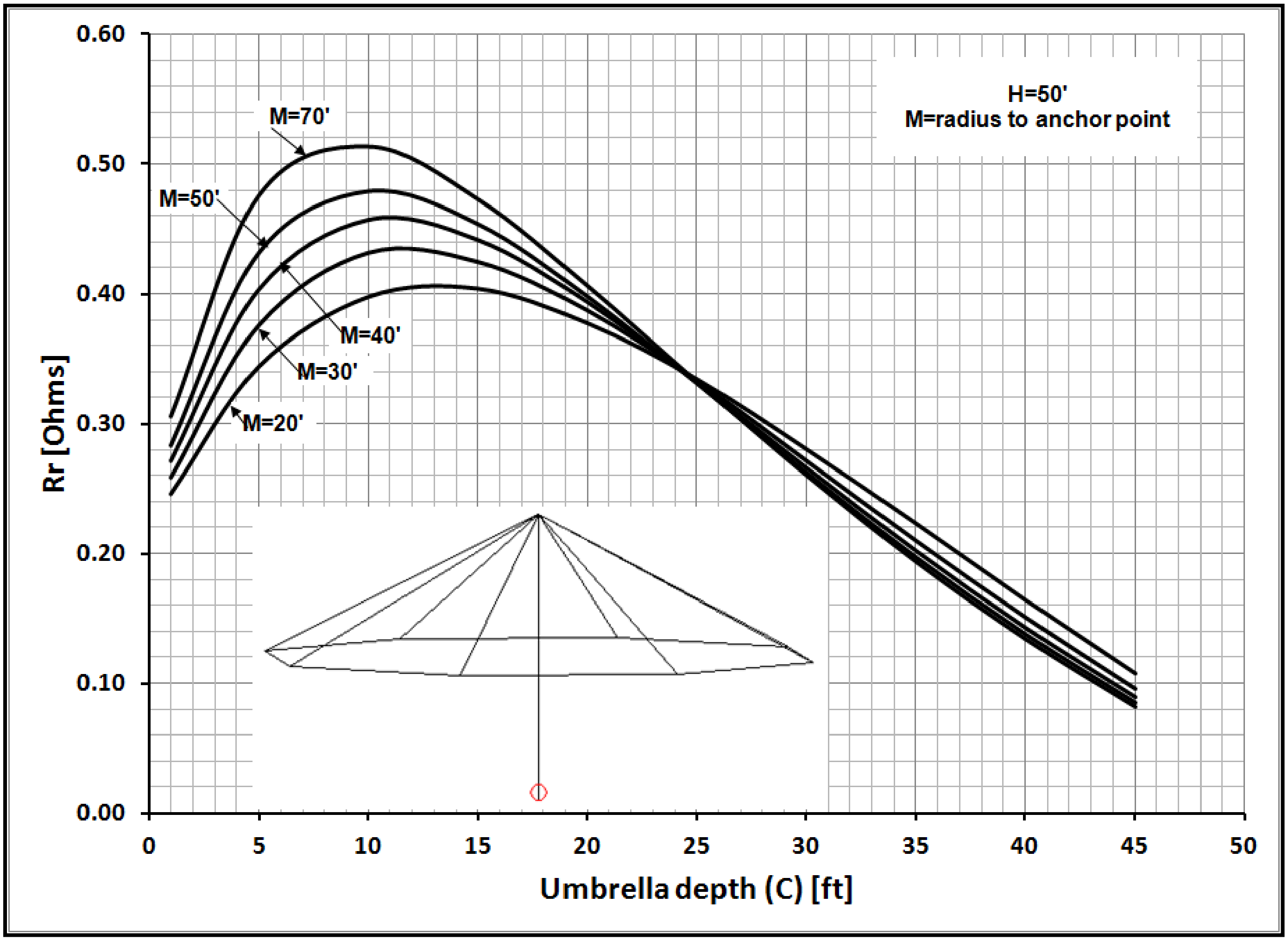

Figure 3.37 - An example of a sloping wire umbrella.

A large horizontal umbrella may not be practical. A alternative is to connect the umbrella wires to the top of the vertical and slope them downwards towards ground as shown in figure 3.37 which includes plots of Rr for H=50' over a range of anchor point distances (M) and umbrella depths (C). Other heights can of course be used and the results would be similar. The angle between the umbrella wires and the top of the vertical is: θ=ATAN(M/H). The larger we make M, the larger θ becomes. For a horizontal umbrella θ=90˚. As shown in figure 3.34, with a flat umbrella Rr increases steadily as the radius is increased but in the case of a sloping umbrella as we increase either M or C, Xi goes down but Rr doesn't increase continuously. For a given M, as we increase C, Rr rises initially, reaches a maximum and then decreases. This decrease in Rr is due to the vertical component of umbrella current opposing the current in the vertical.

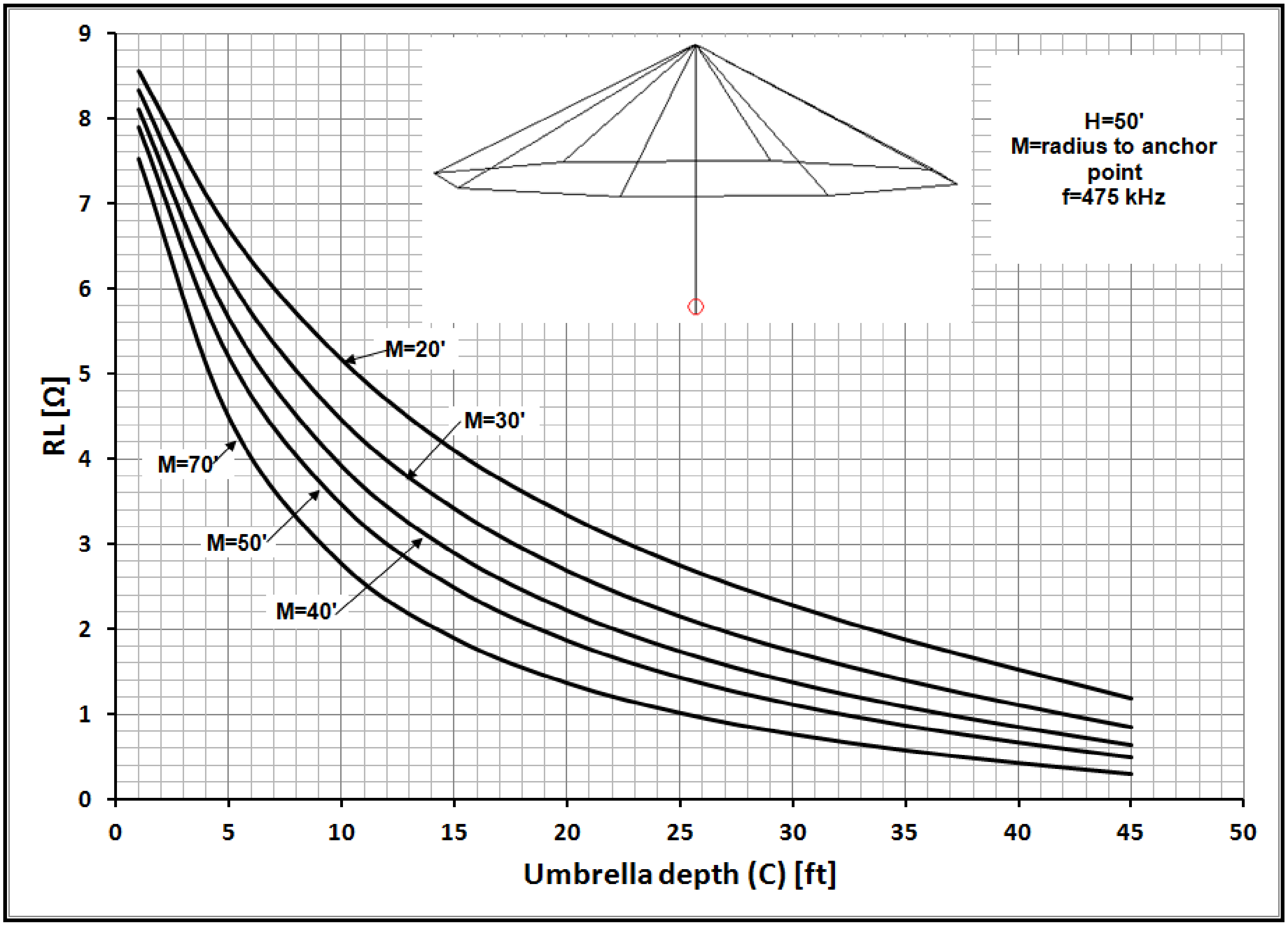

Figure 3.38- Variation of RL with A and C.

RL as a function of M and C is graphed in figure 3.38. We can take the information in figures 3.36 and 3.37 to create a graph of RL/Rr as shown in figure 3.39. We can see the RL/Rr ratio continues to decrease well beyond the peak for Rr as we increase C but a point is reached (C≈0.4-0.5 H) where the ratio flattens out. Beyond C≈0.4 there's no point on continuing to expand the umbrella.

We can take the numbers in figure 3.38 and use equation (3.1) to determine the efficiency as shown in figure 3.39 which indicates there is a optimum value for C with a given value of M. However, the optimum is very broad so the value for C is not critical. Figure 3.40 illustrates how increasing the distance to the anchor points increases efficiency.

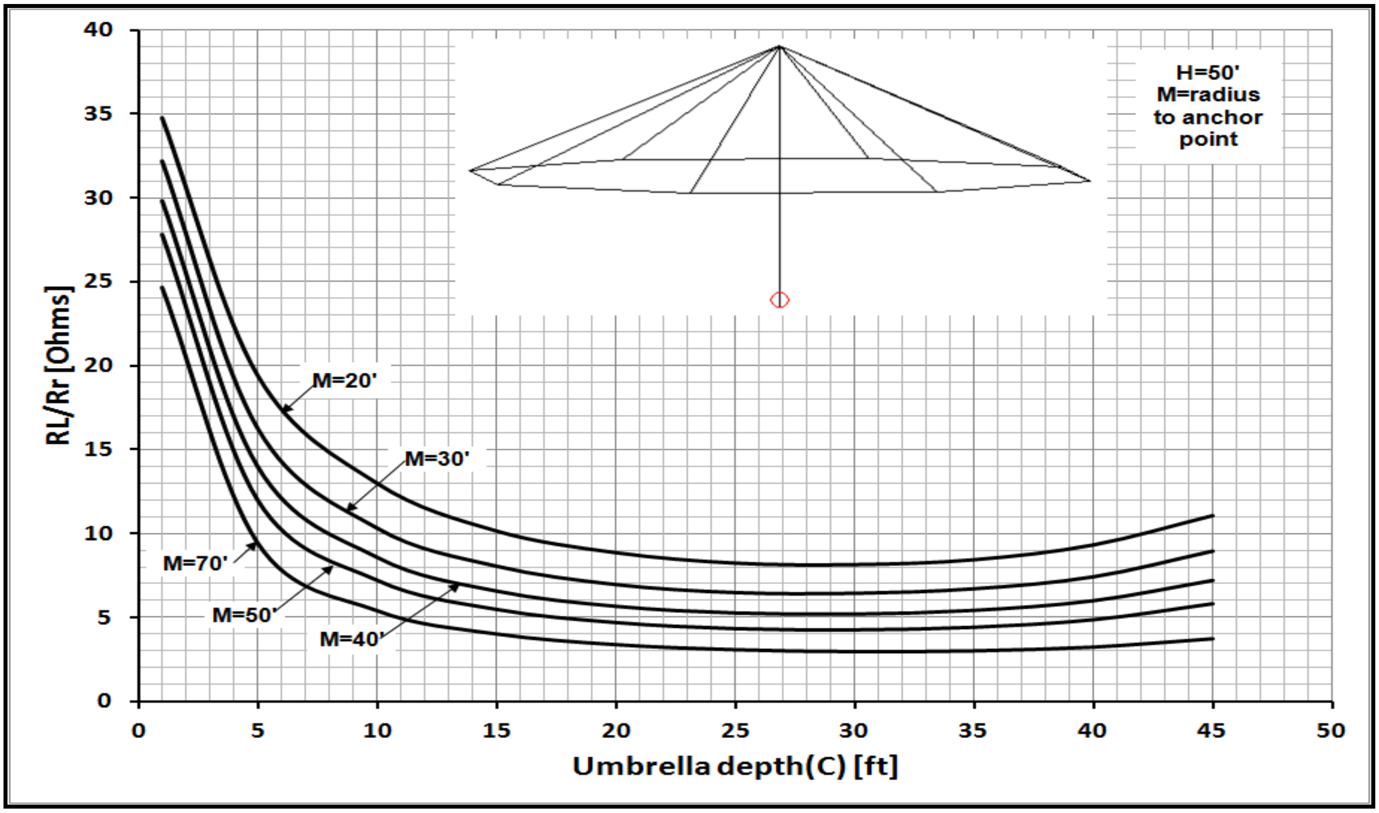

Figure 3.39 - Variation of RL/Rr with M and C.

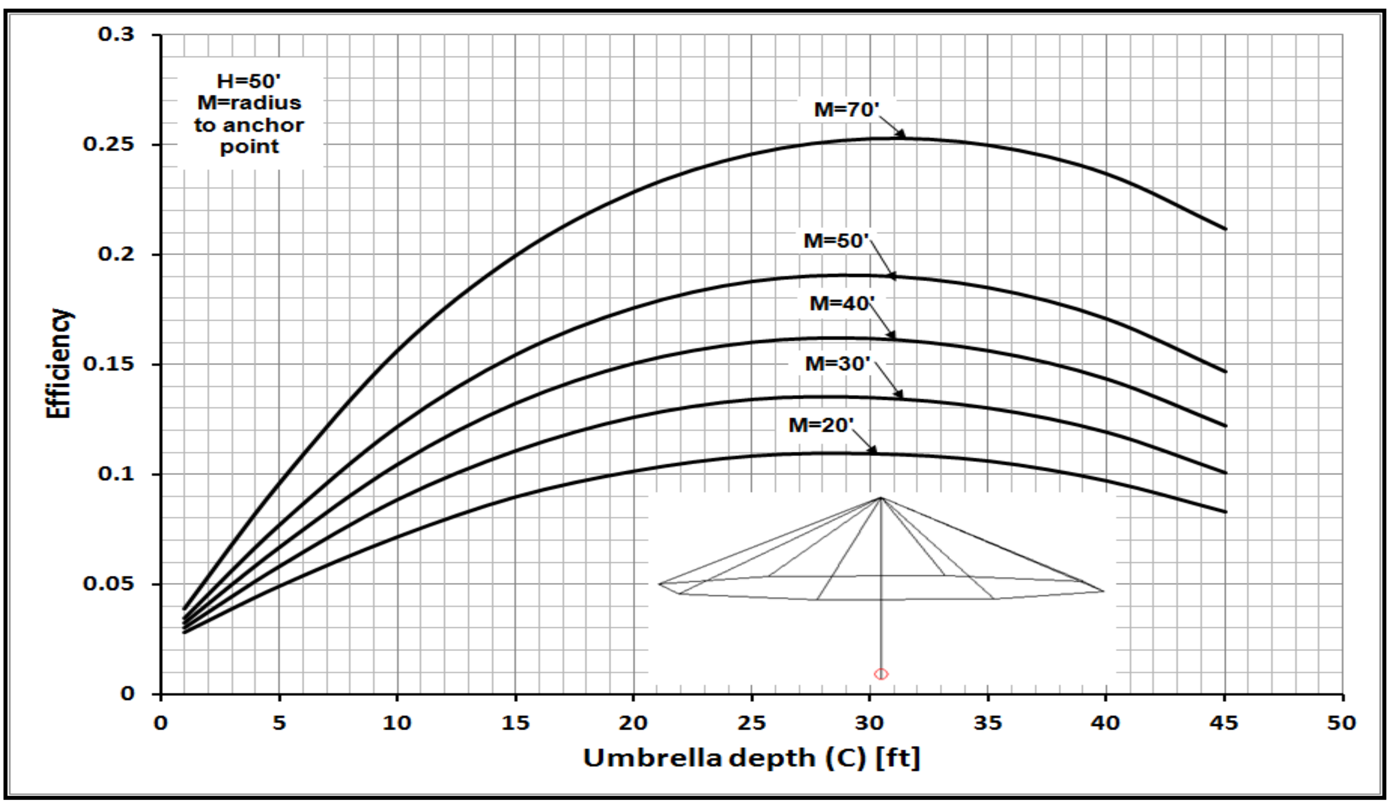

Figure 3.40- Efficiency as a function of M and C.

3.10 Combining sloping and flat umbrellas

There are practical size limits for a horizontal umbrella but we can improve the performance by adding sloping wires to the outer perimeter to form a composite umbrella. An example where the "sloping" wires actually hang straight down from the horizontal part of the umbrella is shown in figure 3.41. Due to the opposing currents in the drop wires Rr decreases as the drop wire length (C) is made longer. However, RL is also decreasing due to a falling Xc. The effect of C on efficiency is shown in figure 3.41.

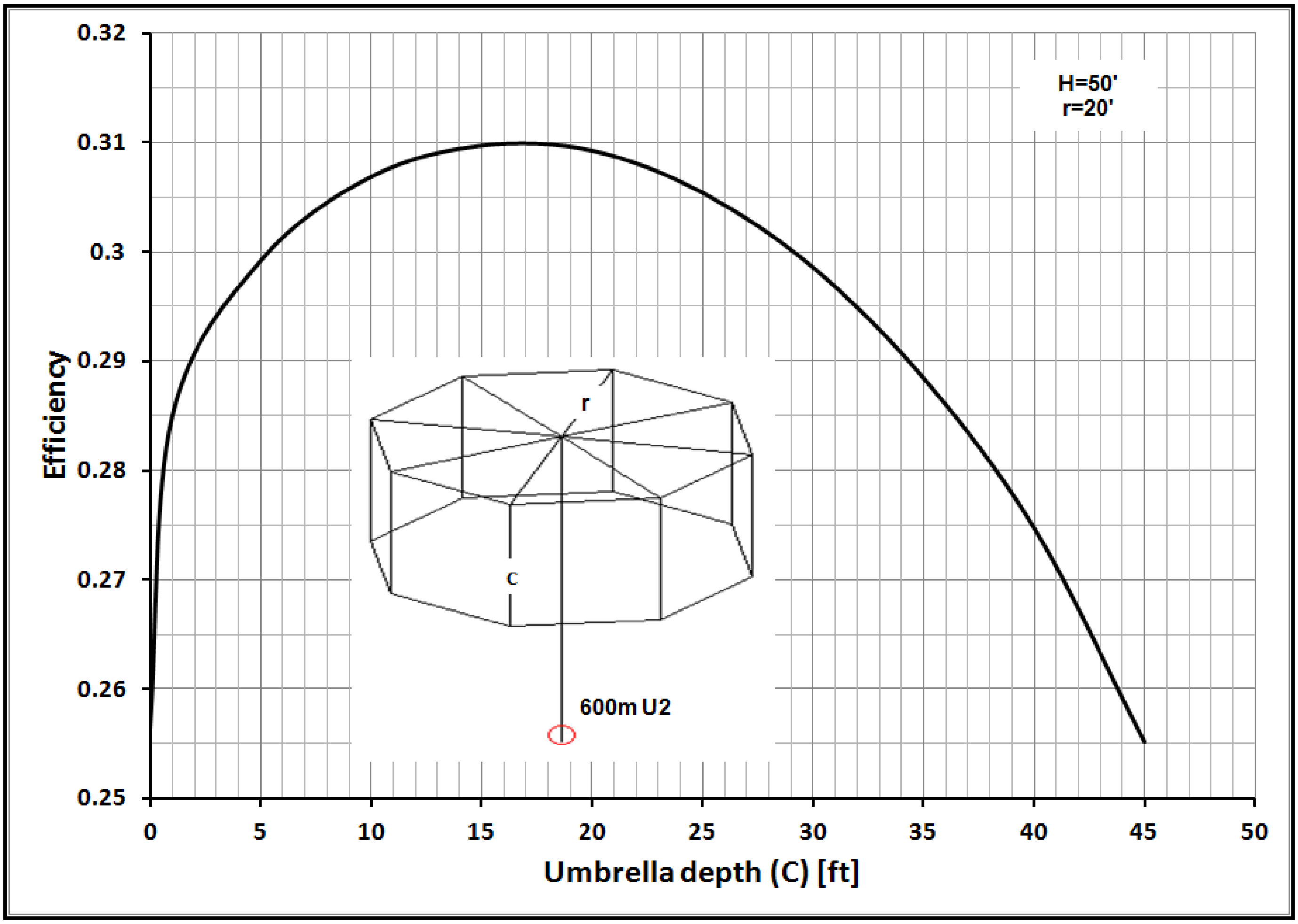

Figure 3.41 - Efficiency of a horizontal umbrella with vertical drop wires on the perimeter of the umbrella.

Adding drop wires allows an increase in efficiency of nearly 6% at C≈0.35H in this example. The peak is also quite broad so C is not critical. This type of umbrella might work very well in an urban backyard.

If there is space to move the anchor points for the drop wires further away then the drop wires can be sloping as shown in figure 3.42, where H=50' and M is kept constant at 50' as r is varied.

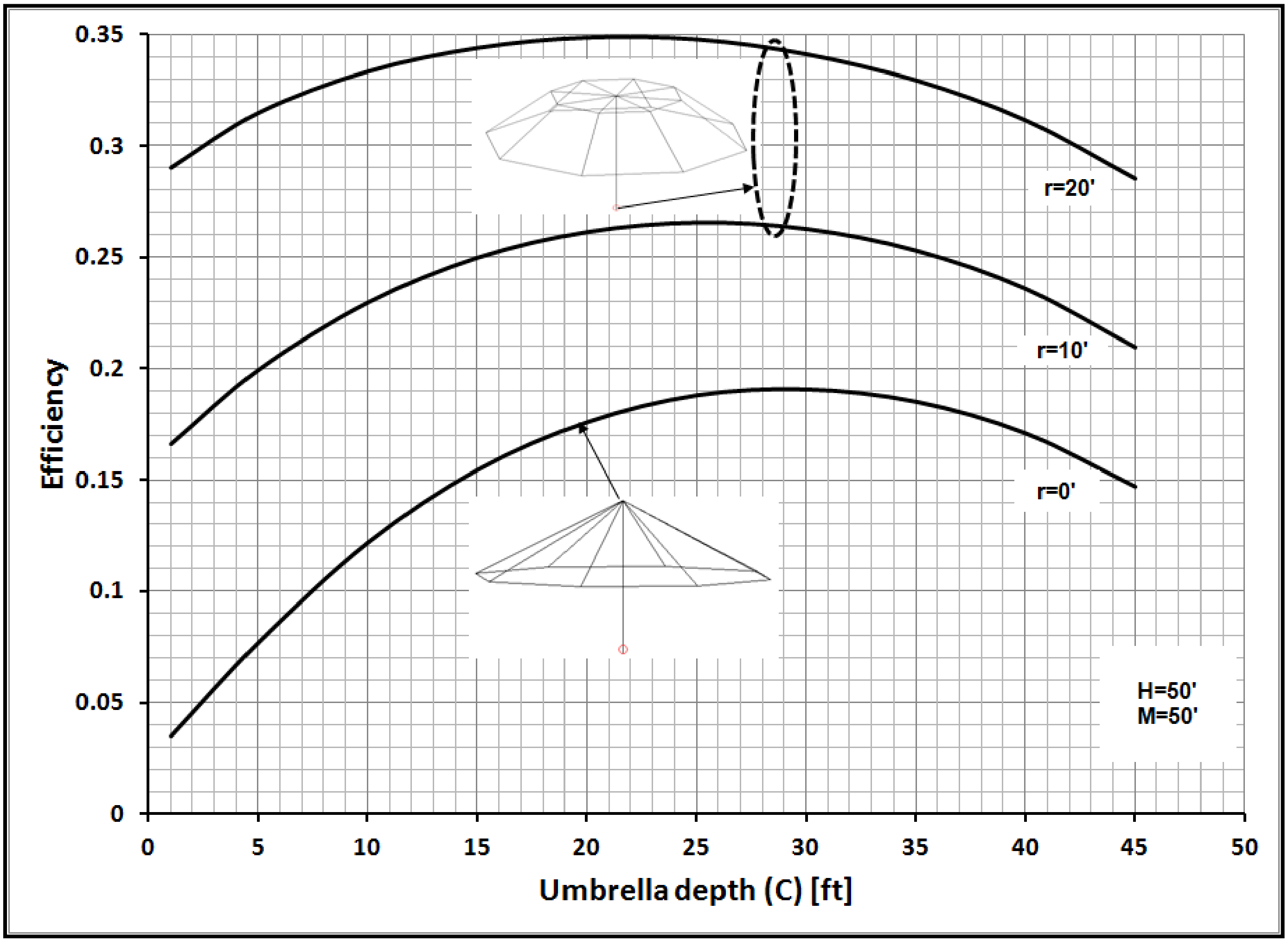

Figure 3.42 - Efficiency for a combined sloping and flat umbrella.

The r=0' trace represents the case of only sloping umbrella wires. The r=10' and 20' traces show the improvement gained by adding some horizontal component to the umbrella. For r=0', η≈19% but when r is increased to 10', η≈27% and for r=20', η≈35%. These are very worthwhile improvements which indicates that adding even a small horizontal section to the umbrella is worthwhile. Compared to figure 3.41 where the drop wires were vertical, sloping the drop wires away from the vertical shows an improvement in efficiency of ≈4%.

3.11 Rc and Conductors

Copper or aluminum wire and aluminum tubing are typical conductors. The wire may be bare or insulated. The choice of conductor is usually a matter of what's on hand and/or what's economical. Insulated wire intended for home wiring is of often the most economic choice for copper wire. Aluminum electric fence wire, available in #14 or #17 gauges, is a less expensive choice but aluminum has greater resistance than copper and because soldering aluminum is often not satisfactory, joints require special attention. We can work around the resistance issue by using multiple, well spaced, wires in parallel.

The resistance of a wire at DC (Rdc) is:

$$\boldsymbol{Rdc = \frac{l}{\sigma Aw}} \quad [\Omega] \quad (3.12)$$

Where l is the length of the wire, Aw is the cross section area and **σ** is the conductivity in Siemens/meter [S/m]. For copper $\sigma=5.8X10^7$ [S/m] and for aluminum $\sigma=3.81X10^7$ [S/m]. Rdc for copper wire can be found in wire tables.

Unfortunately the AC resistance of the wire (Rac) will be substantially different from Rdc due to two effects: skin effect and the effect of non-uniform current distribution.

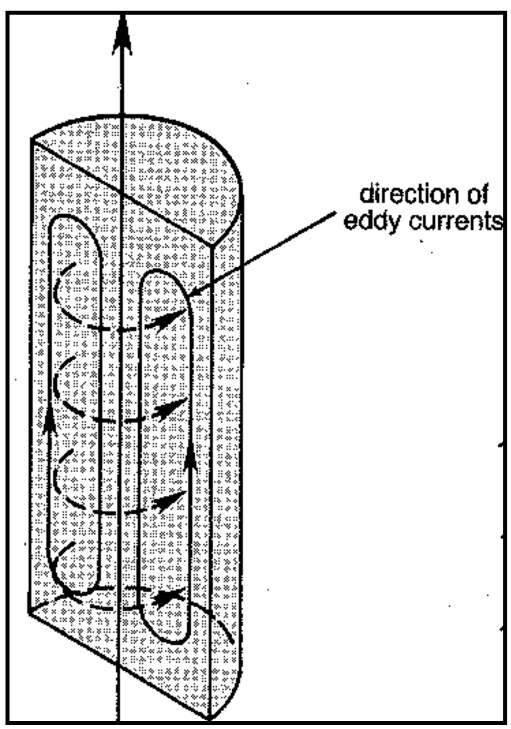

Figure 3.43 - Skin effect.

The cause of skin effect is the magnetic fields associated with the current flowing in the conductor as shown in figure 3.43. The dashed lines represent magnetic field lines resulting from the desired current flowing in the conductor. The solid lines represent currents induced in the conductor. At RF frequencies the current is concentrated in a very thin layer at the surface of the wire, hence the term "skin effect". Because the current is concentrated in a thin layer the resistance of a round conductor will proportional to the diameter (d), i.e. the wire circumference, rather than the cross sectional area. Changing from a solid conductor to a tubular one greatly reduces the amount of metal required. Typically solid wire up to #8 (d=0.13") is used. To lower losses further either two or more wires in parallel or thin wall aluminum tubing are used. Aluminum irrigation tubing, in sizes from d=2" to 6", is widely available, at least in rural areas. The larger sizes can be self supporting or need only limited guying. Making the vertical from tubing is very helpful when no other supports are available.

The "penetration" or "skin" depth δ is expressed by:

$$\boldsymbol{\delta = \frac{1}{\sqrt{\pi\sigma\mu f}}} \text{ [m]} \quad (3.13)$$

Where:

σ is the conductivity in [S/m].

μ is the permeability of the material which for Cu and Al $=4\pi x10^{-7}$ [H/m].

f is the frequency [Hz].

The skin depth in <u>mils</u> for copper is:

$$\boldsymbol{\delta = \frac{2.602}{\sqrt{f_{MHz}}}} \text{ [mils]} \quad (3.14)$$

At 137 kHz δ=7.03 mils (0.00703") and at 475 kHz δ=3.78 mils.

The resistance of the wire, Rc, can be represented by the product of the DC resistance (**Rdc**) and a factor attributed to skin effect (**Ks**).

$$\mathbf{Rac = Rdc \cdot Ks} \quad (3.15)$$

For the wire sizes typically used in tuning inductors, d/δ> 5, and Ks becomes a linear function of d/δ which can be closely approximated with a simple expression:

$$Ks = \left(\frac{1}{4}\right)\left[\frac{d}{\delta} + 1\right] \quad (3.16)$$

which is graphed in figure 3.44. <u>Note that Ks is only a function of the wire diameter d and the skin depth δ at the frequency of interest (δ∝1/√f).</u>

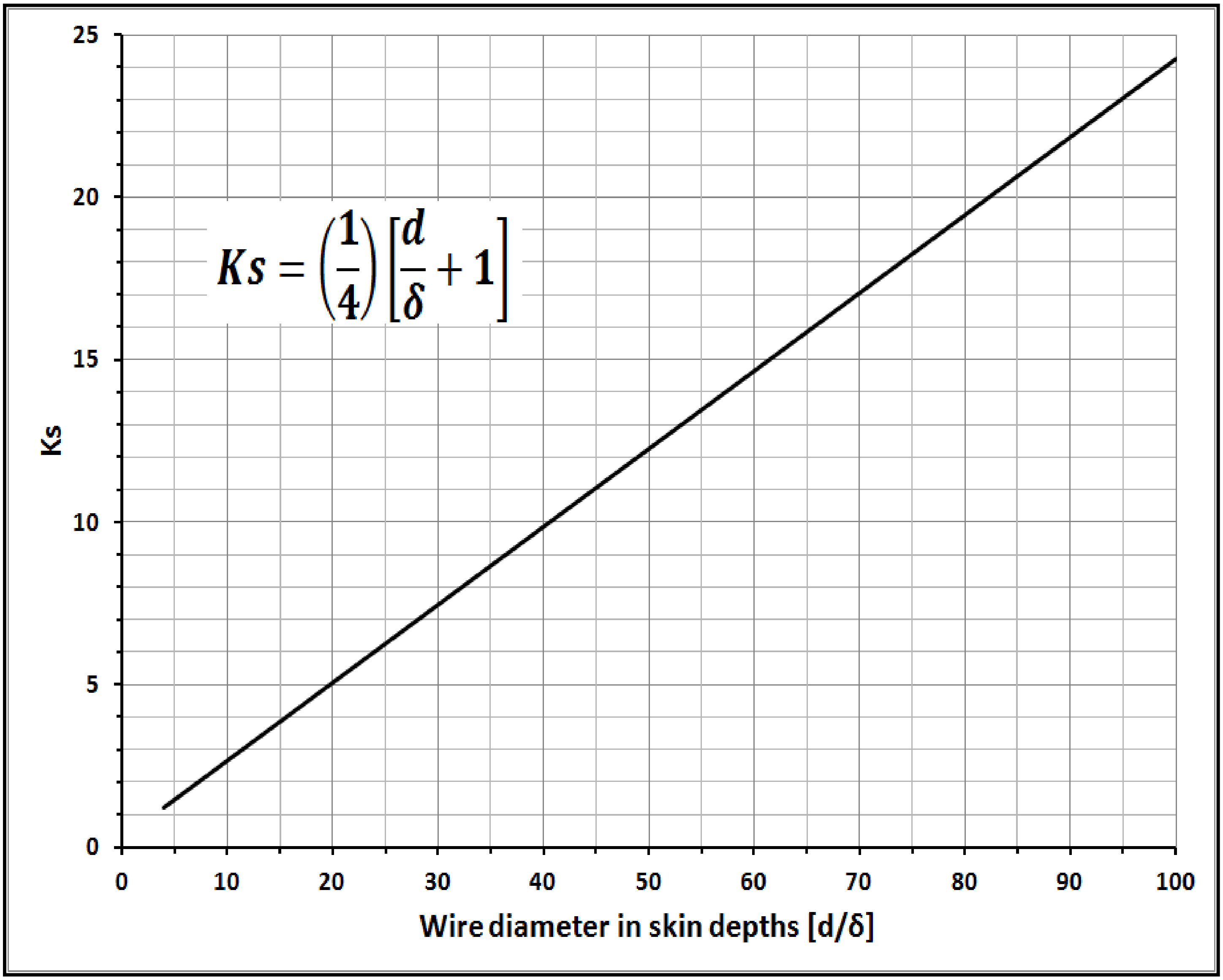

Figure 3.44 - Skin effect factor Ks versus wire diameter in skin depths (**d/δ).**

Table 3.2 gives Ks for typical wire sizes at 137 and 475 kHz.

Table 3.2 - Ks for typical wire sizes.

	137 kHz	475 kHz
Wire #	**Ks**	**Ks**
8	**4.82**	**8.76**
10	**3.87**	**7.00**
12	**3.10**	**5.55**
14	**2.53**	**4.49**
16	**2.06**	**3.61**
18	**1.15**	**1.93**

The current on antenna conductors will usually be non-uniform, i.e. the current amplitude will vary from one point to another. When the antenna is large enough to approach self-resonance the current distribution can be close to sinusoidal as shown in figure 3.45A. For small LF-MF antennas however, the current will be approximately linear as indicated in figure 3.45B.

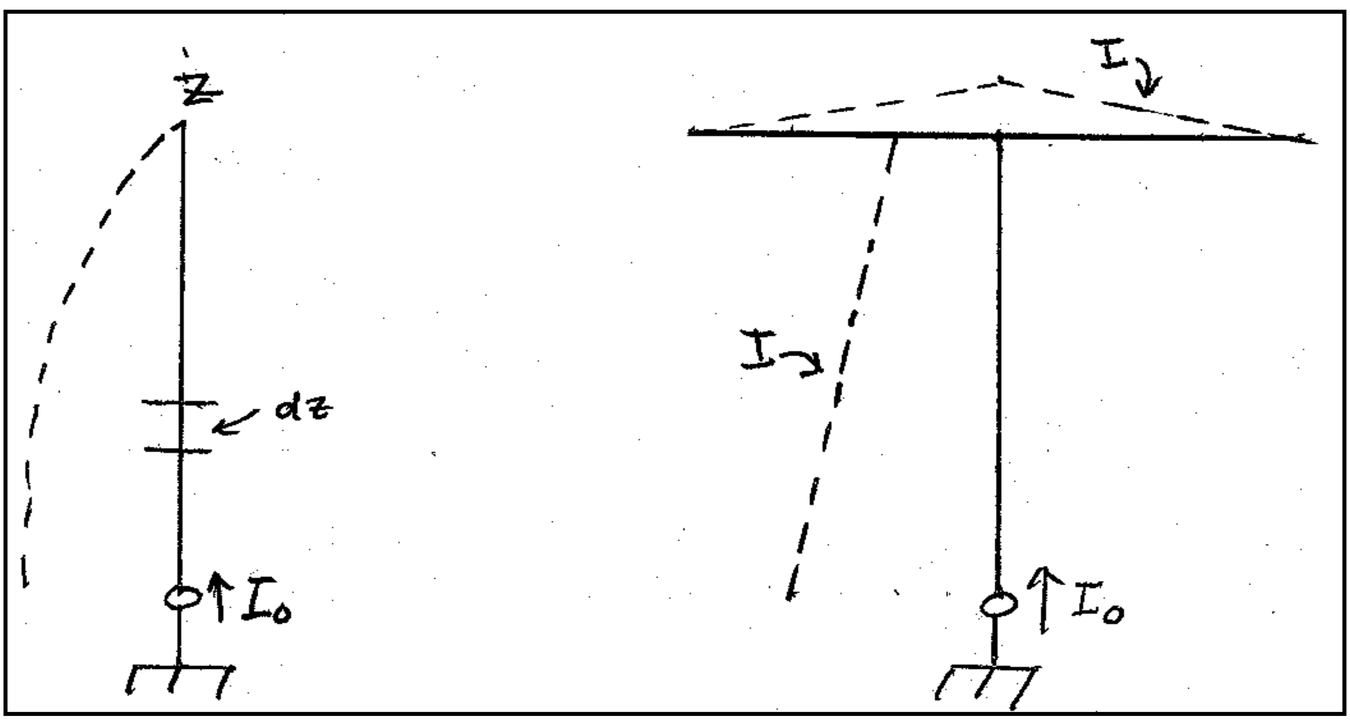

Figure 3.45 - Antenna current examples.

Io= rms current at the high current end of the wire. Re= effective resistance of the wire which results in the same power dissipation for a given Io as the actual power dissipation on the wire. Re/Rac is the resistance ratio due to non-uniform current distribution.

A graph of Re/Rac for a linear current distribution is given in figure 3.46.

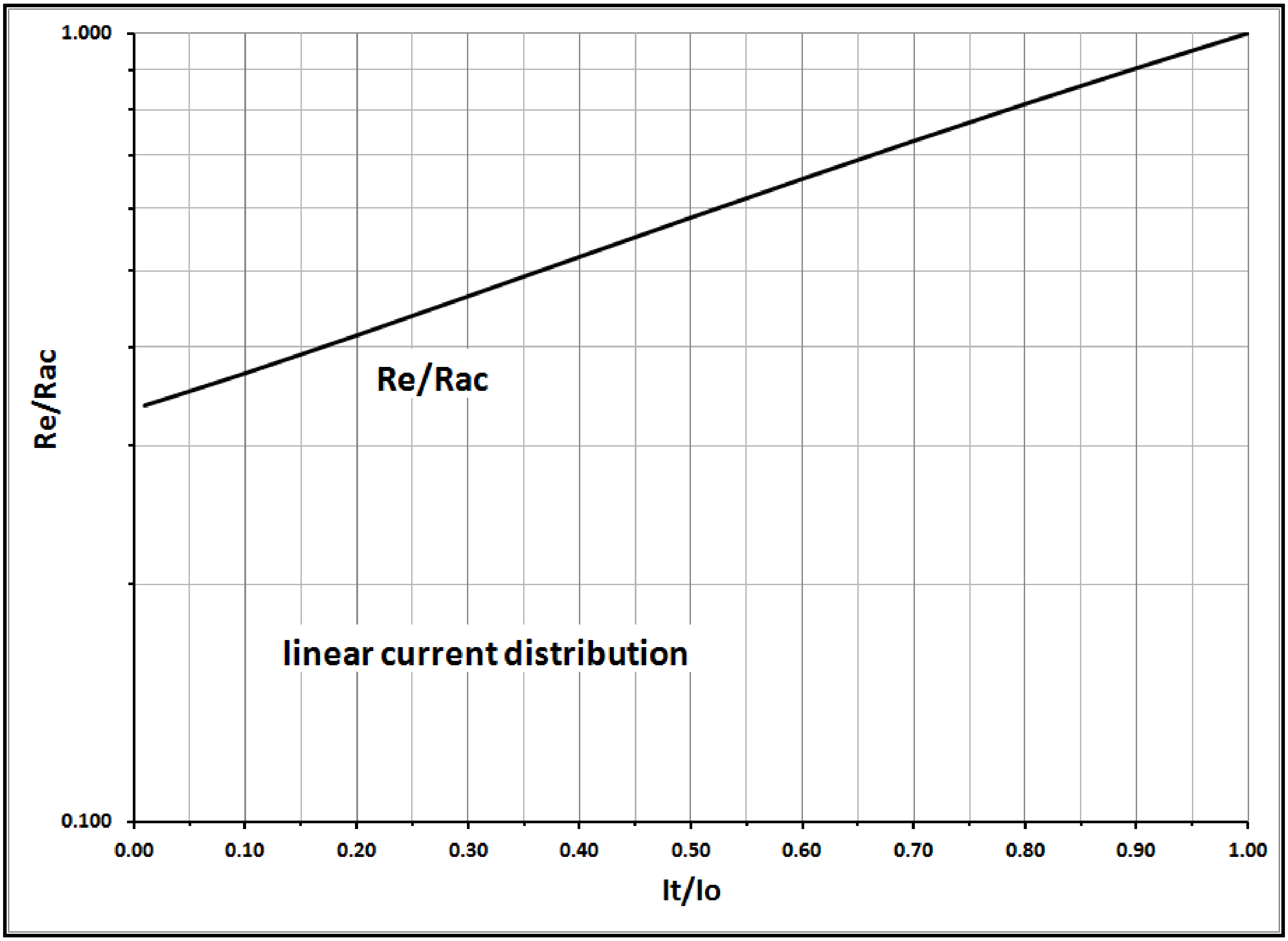

Figure 3.46 - Re/Rac versus It/Io.

For a vertical with no top-loading, It=0 and ***Rc/Rac=1/3***. More detailed information on Ks can be found in chapter 6 and appendix TBD.

The cost of the conductors may be a concern. For copper $\sigma=5.8\times10^{7}$ [S/m]. Aluminum has somewhat lower conductivity, $\sigma=3.81\times10^{7}$ [S/m], but is much less expensive.

Replacing copper with aluminum:

$$\frac{\mathbf{Rc_{Al}}}{\mathbf{Rc_{Cu}}} = \sqrt{\frac{\boldsymbol{\sigma}_{\mathbf{Al}}}{\boldsymbol{\sigma}_{\mathbf{Cu}}}} = \sqrt{\frac{\mathbf{3.81}}{\mathbf{5.8}}} = \mathbf{0.81} \quad (3.17)$$

The conductor loss (Pc) penalty of switching from copper to aluminum is ≈19%.

Up to this point we've not considered ground loss (Rg) or conductor loss (Rc). Including these losses the efficiency becomes:

$$\boldsymbol{\eta} = \frac{\boldsymbol{R_r}}{\boldsymbol{R_r + R_L + Rg + Rc}} \quad (3.18)$$

Rg will be discussed in chapter 5 but to properly evaluate the effect of conductor loss on efficiency we need to include it at this point. Figure 3.47 shows a "T" antenna with multiple downleads. The height is 50' over average ground. The top-wire is 100' and there are thirty two 50' buried radials. We want to know the effect of wire size on efficiency and the effect of using multiple downleads. A key question is "how much effect does the conductor loss have on efficiency?" From equation (3.18) we can see that the value for Rc matters but also its value in proportion to the sum of Rr+RL+Rg. As the conductor size in increased Rc will go down but at some point Rc becomes small compared to sum of the other terms so further reductions in Rc have limited effect.

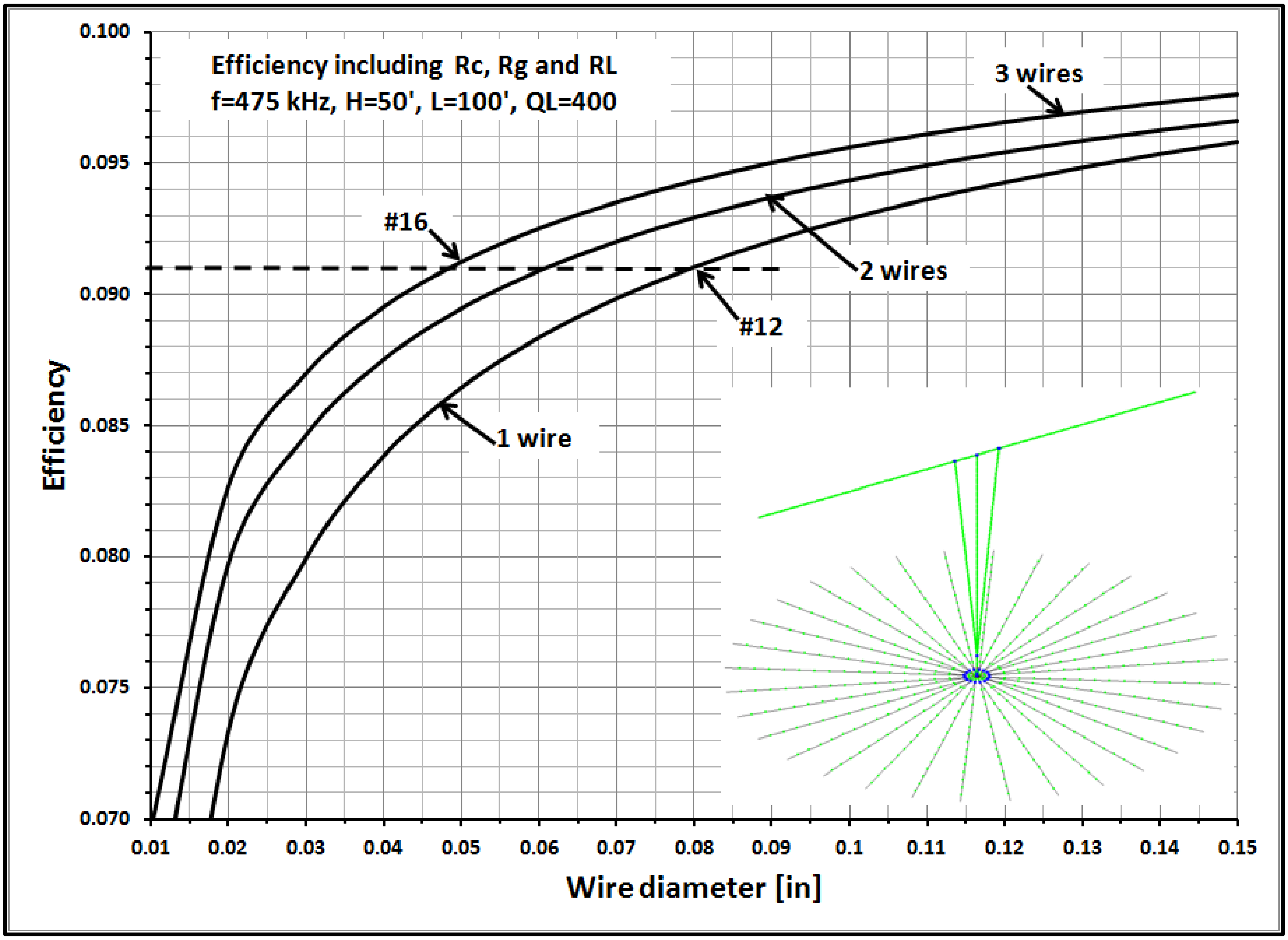

Figure 3.47 - Efficiency versus wire diameter for 1, 2 or 3 downlead wires.

Figure 3.47 shows the effect of wire diameter (d) on efficiency for different numbers of downleads. At any given point all the wires have the same diameter. d=0.01" corresponds to a #30 wire. d=0.150" corresponds to a #6 wire. From a practical point of view wire sizes ranging from #18 to #8 are the most likely, with #12 a very common choice.

Figure 3.47 shows that using more downleads improves efficiency, no real surprise there, but the graph also shows how the initial increase in wire size rapidly improves efficiency but the curve soon flattens out as the point of vanishing returns approaches. Note that for larger wire sizes the efficiency only changes by less than 1%!

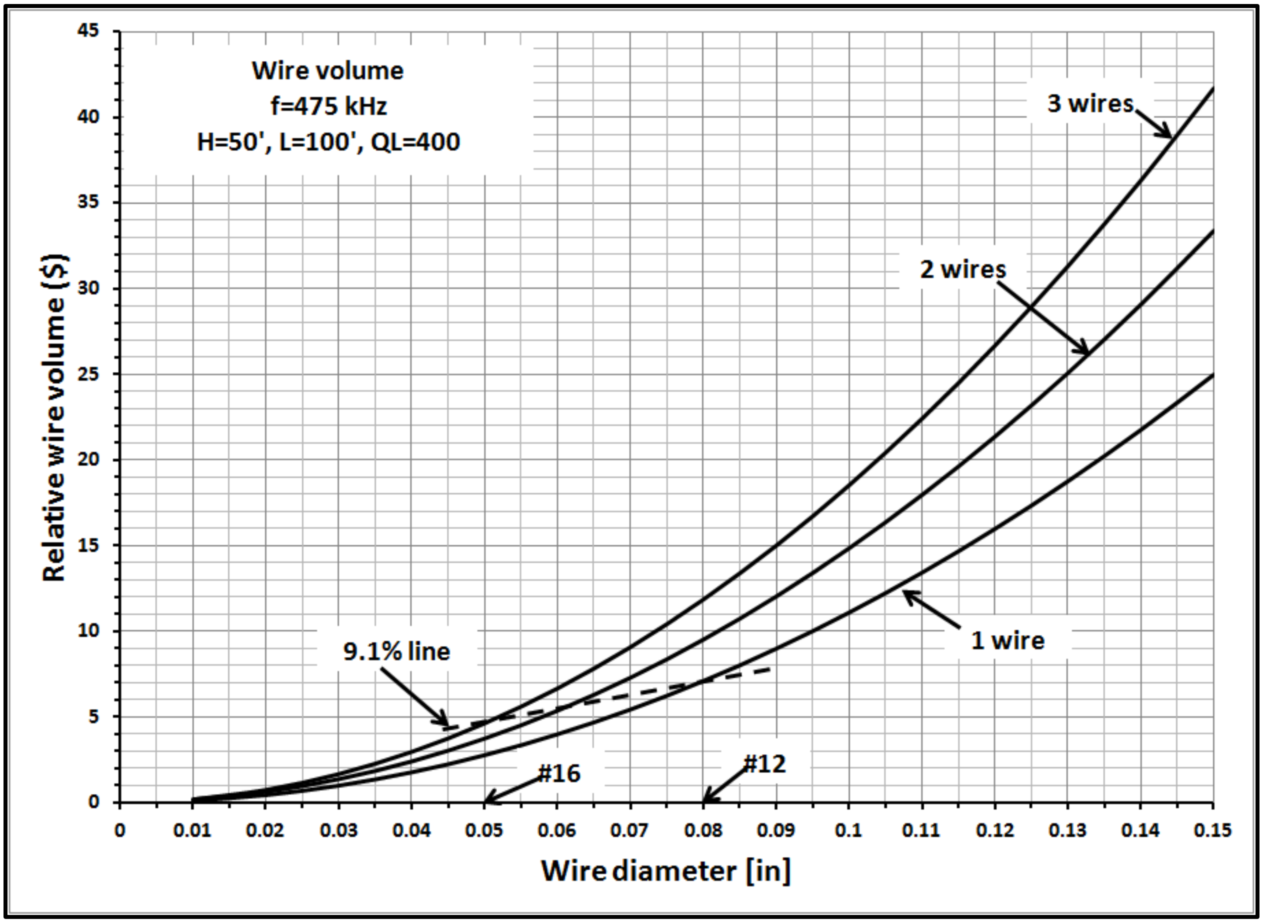

Figure 3.48 - Relative wire volume ($) versus wire size and downlead number.

Due to idiosyncrasies in wire pricing often there isn't an direct linear variation in wire cost with the amount of copper between different wire sizes but we can still graph the volume of wire as shown in figure 3.48 to give us an idea on the cost impact of different wire sizes and downlead numbers. What these graphs seem to be telling us is that the very common use of #12 wire is actually a very practical choice although we could save a bit by going down to #16 wire.

Insulated copper wire intended for home wiring is often used for antennas and ground systems, both elevated and buried. This wire is readily available at hardware and home improvement emporiums and often significantly less expensive than the equivalent wire without insulation (bare). Among amateurs there has been a recurring discussion whether it's necessary or even useful to strip the insulation. Stripping a few hundred feet isn't a serious chore but if you're laying out a radial field with thousands of feet of wire then stripping would be a chore. Appendix A2 has a broad discussion of the question but for our purposes we can summarize the effect of leaving the insulation on the wire for typical antennas. For this example we will assume the antenna in figure 3.47 with only one downlead.

1) The insulation introduces no additional loss even when the wire has been exposed to sun and weather for many years.

2) The insulation does introduce some dielectric loading which reduces Xi slightly, from 1245Ω to 1209Ω. This means that XL is slightly smaller reducing RL and increasing efficiency by ≈0.5% when QL=400.

3) The disadvantage of leaving the insulation on the wire is the increase in weight and diameter. The increase in diameter can lead to greater ice loading.

Summary

This chapter has shown many examples of top-loading arrangements, some simple, some more complex but all of them effective. The clear message throughout has been the great improvement in efficiency which capacitive top-loading can provide over a simple unloaded vertical. All the variations and discussion boil down to three practical points:

.... get as much wire as possible as high in the air as possible.....

...symmetry is not needed...

...even a small amount of top-loading is vastly better than none...

References

[1] Woodrow Smith, Antenna Manual, Editors & Engineers Ltd., 1948

[2] Grover, Fredrick, Methods, Formulas, and Tables for the Calculation of Antenna Capacity, NBS scientific paper 568, available on the NIST web site or use Google.

[3] Terman, Frederick E., Radio Engineers Handbook, McGraw-Hill Book Company, 1943