

Chapter 3

Capacitive Top-Loading

3.0 Efficiency

The discussion in chapter 2 made it clear that the equivalent series resistance (i.e. R_L) 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 (X_i) because decreasing X_i reduces the size of the loading inductor and its associated R_L . In addition, often steps to reduce inductance can also increase R_r simultaneously.

Efficiency (η) in terms of R_r and R_L :

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

Clearly we want R_L small and R_r large! The reason for this rather obvious comment is that some top-loading schemes which reduce X_i also reduce R_r rather than increase it and at some point the efficiency may actually start to fall even though we continue to reduce X_i . 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 following 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 or improvement on the signal for some change.

For amateurs new to LF/MF 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 an example showing R_r , X_i and efficiency and then go on to explain why top-loading is so effective in reducing X_i and increasing R_r . 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 given.

At this point it will be 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

As in chapter 2, tuning inductor $Q_L=400$ at 475 kHz and 200 at 137 kHz is assumed. Keep in mind that efficiency determined from only R_L and R_r is an upper limit, i.e. the best we can do. Adding more losses only reduces efficiency. Once we've reduced R_L as much as possible we can deal with other losses. Reducing X_i 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 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 Smith's 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 some bookkeeping.

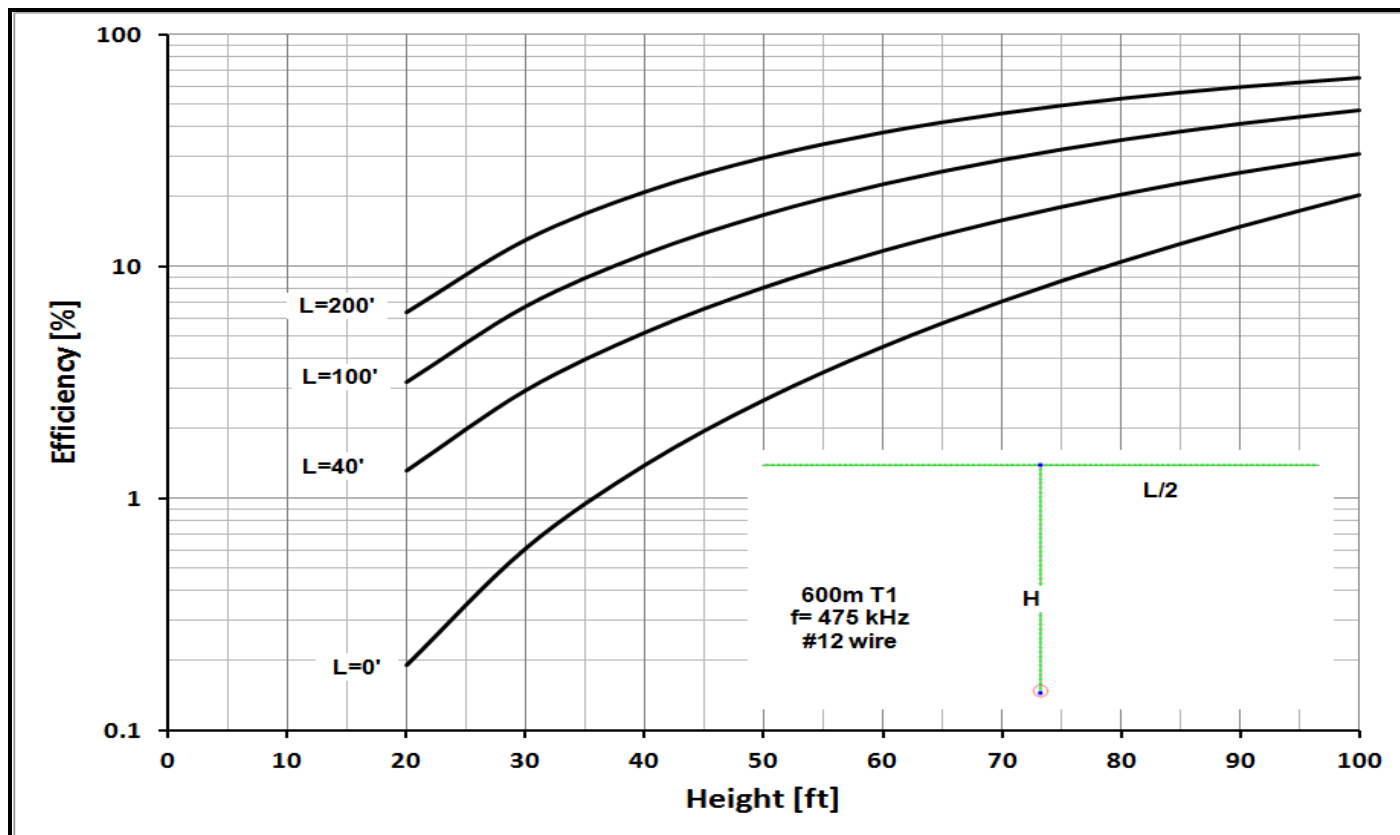


Figure 3.1 - Efficiency at 475 kHz with base tuning.

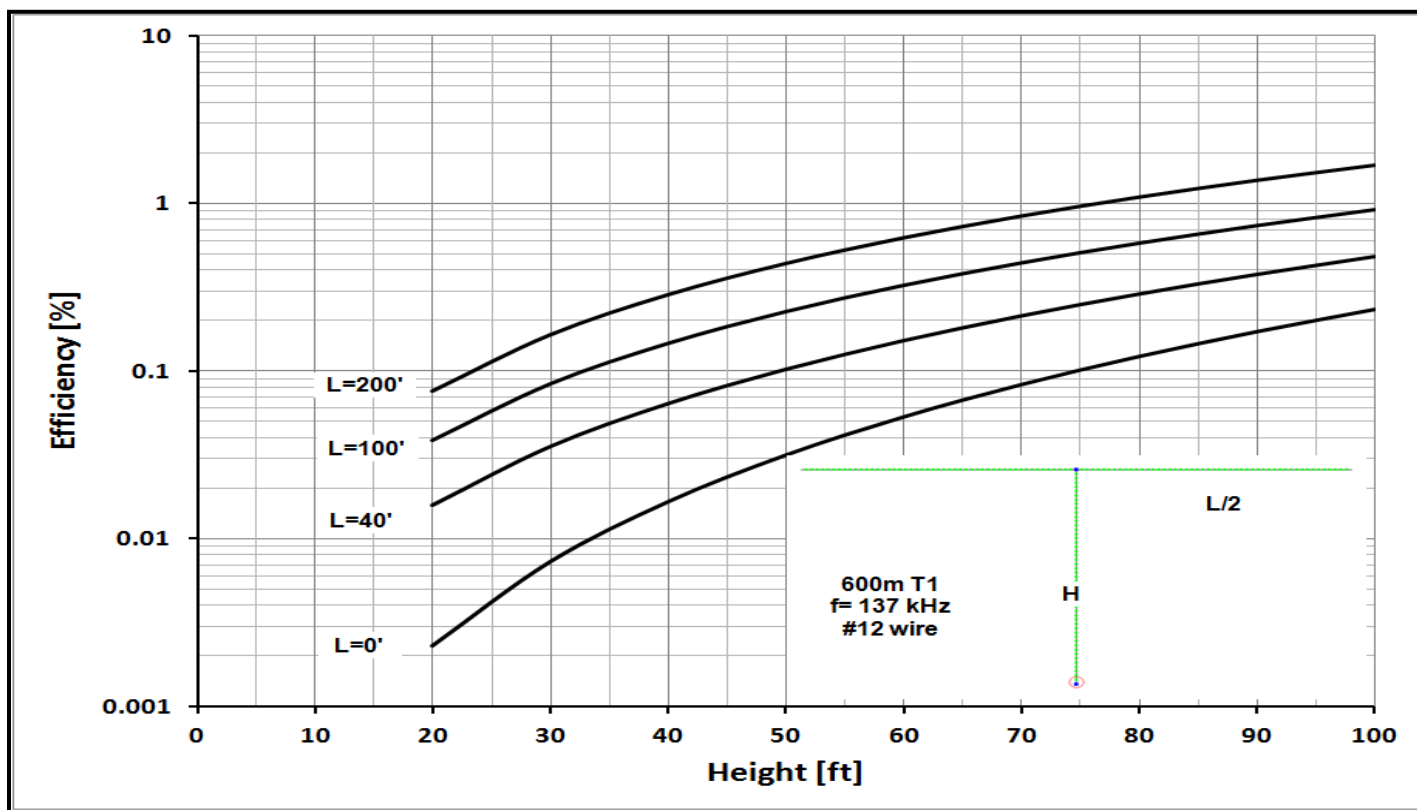


Figure 3.2 - Efficiency at 137 kHz with base tuning.

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 $H=20'$, $\eta=0.19\%$ at 475 kHz. Keeping $H=20'$ but adding a 40' top-wire, $\eta=1.3\%$, 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 X_i 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 R_r and decreasing X_i simultaneously. This section explains what's happening with X_i and the next section looks at R_r .

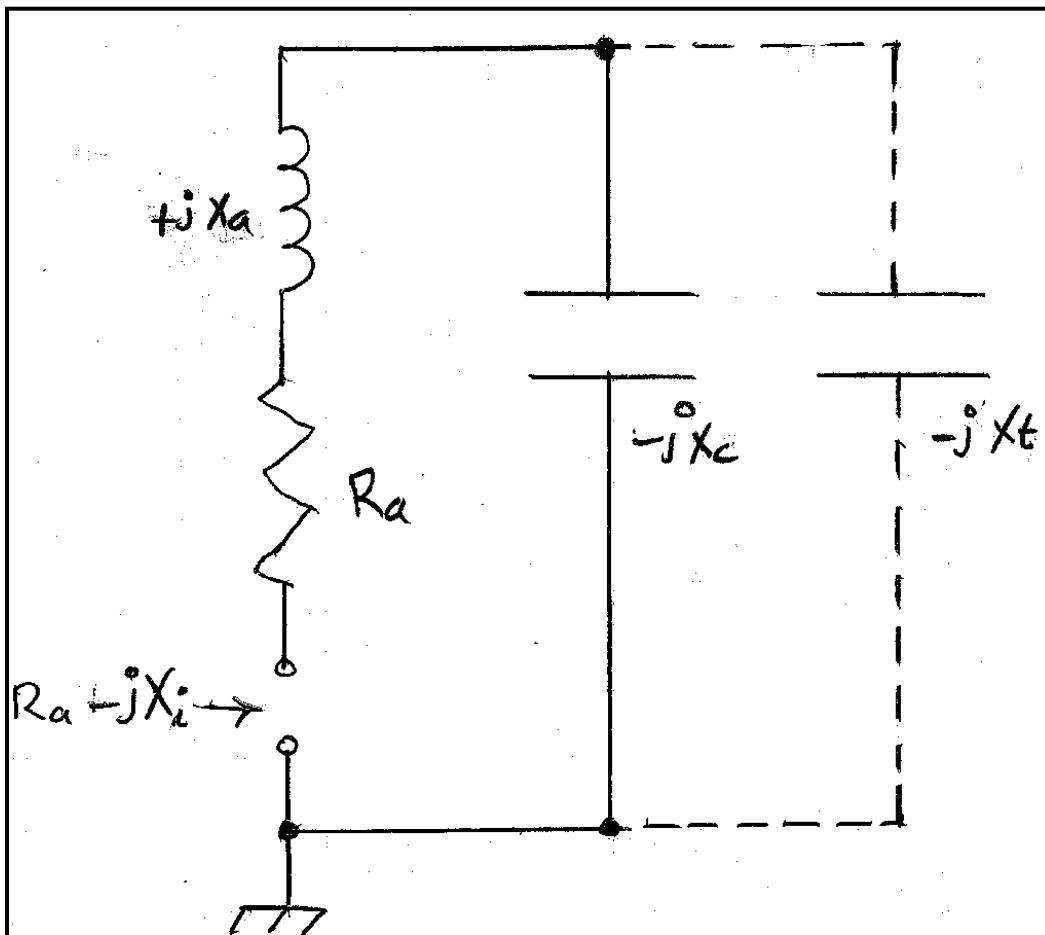


Figure 3.3 - Equivalent circuit for a vertical with capacitive top-loading.

Figure 3.3 shows an equivalent circuit for a vertical with capacitive top-loading. R_a , X_a and X_c represent the vertical, X_t represents the shunt capacitance introduced by the top-hat. X_i and X_t are:

$$X_i \approx \frac{X_c X_t}{X_c + X_t} \quad (3.2) \quad C_t = \frac{1}{(2\pi f) X_t} \quad (3.3)$$

Where C_t is the capacitance corresponding to X_t . X_t can be determined from modeling or in simple cases, calculated. X_t is in parallel with X_c reducing X_i . X_a 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 X_i associated with figures 3.1 and 3.2.

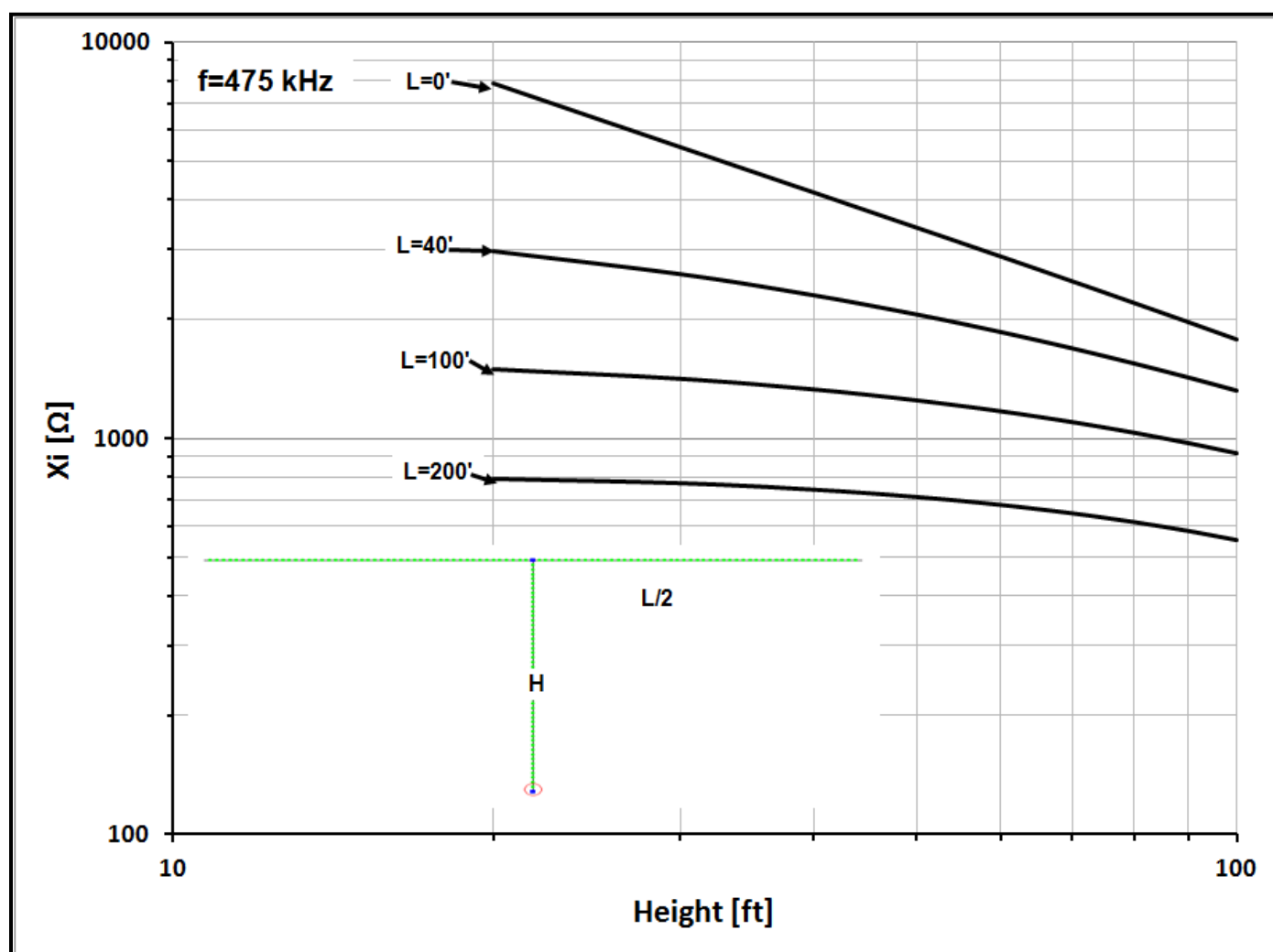


Figure 3.4 - X_i at 475 kHz.

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

$X_i \approx 3000\Omega$ which is a reduction of almost 3X. Increasing L to 100' reduces X_i by another factor of two, $X_i \approx 1500\Omega$. R_L will be reduced by the same factors which is part of the reason for the efficiency improvement.

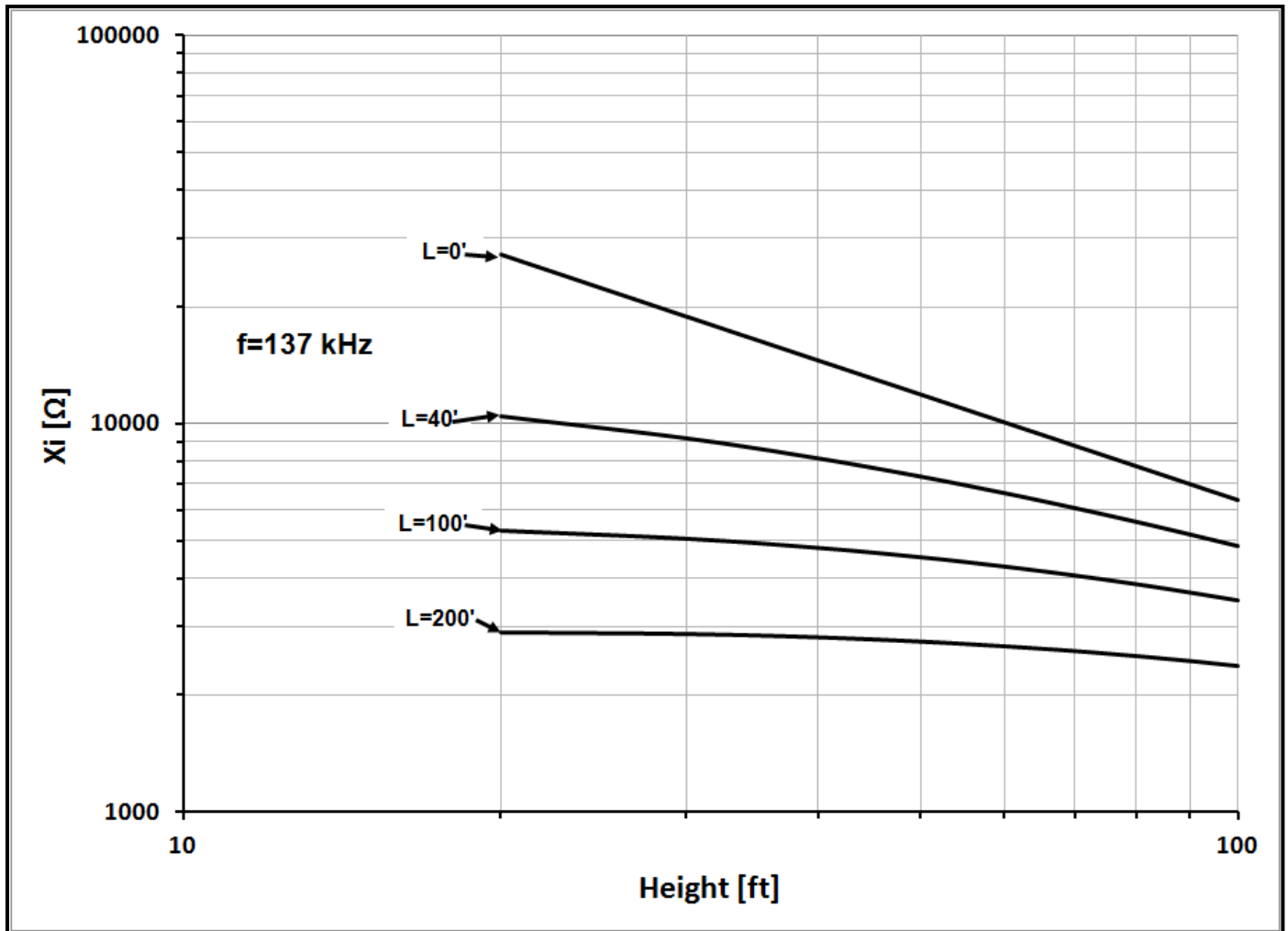


Figure 3.5 - X_i at 137 kHz.

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 a characteristic impedance of:

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

Where H is the height above ground of the wire and d is the wire diameter. We are free to choose 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 $Z_t=617\Omega$. With a value for Z_t in hand we can calculate X_t for each wire from the open circuit transmission line equation (chapter 2, equation (2.9)):

$$X_t = \left(\frac{1}{N}\right) \left(\frac{Z_t}{\tan(L')}\right) \quad (3.5)$$

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.

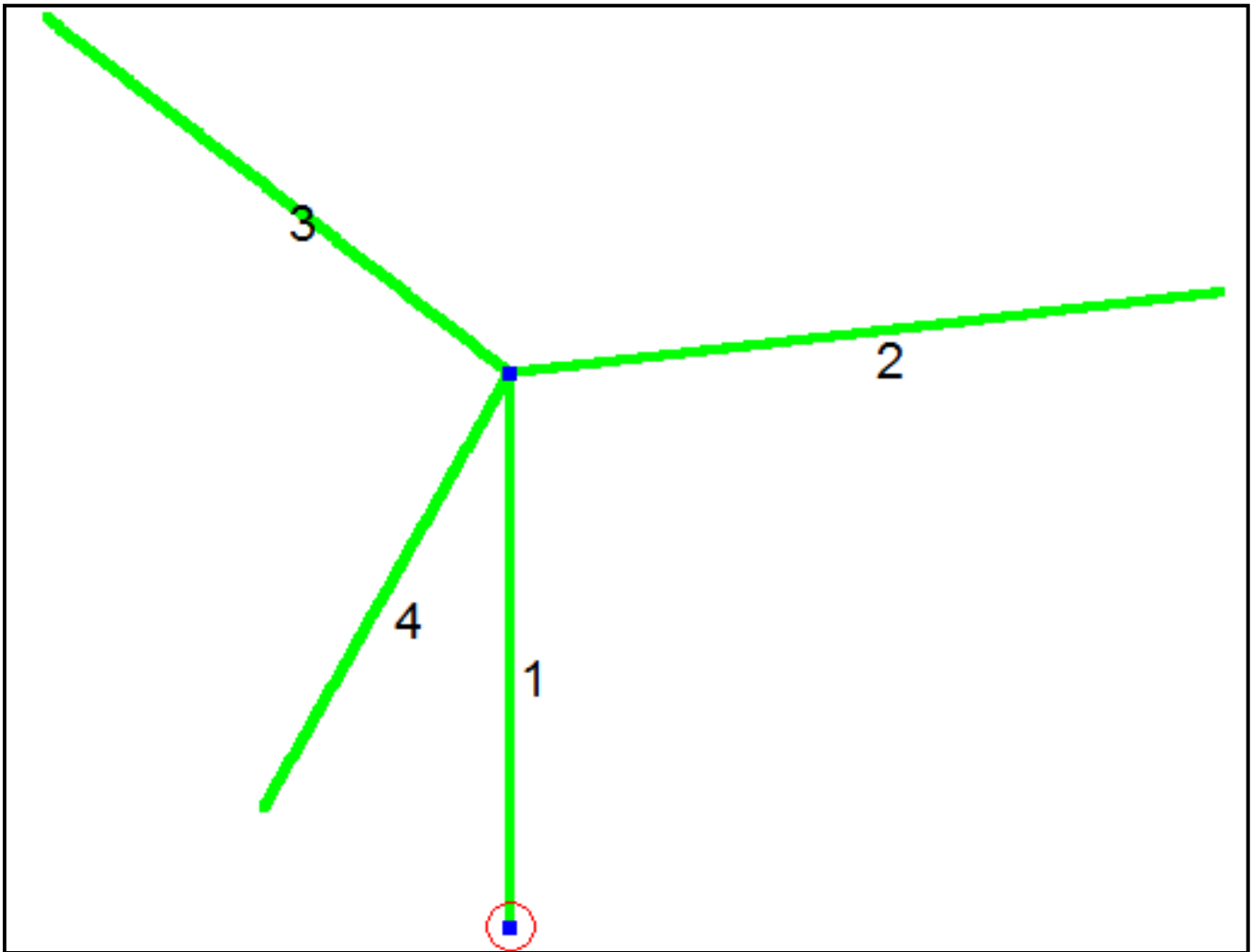


Figure 3.6 - Example for calculation.

We can use this approach to calculate X_t 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 $\lambda \approx 2072'$, will be:

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

From equation (3.4) $Z_0=617\Omega$ and from equation (3.5), for each wire:

$$X_{t'} = 4037\Omega \quad (3.7)$$

Using NEC we can determine X_i and X_t for each number of top-wires (N) and compare that to $X_{t'}/N$:

Table 1 - X_t comparison.

N	X_i	X_t NEC	X_t 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 ($X_L = X_i$). As N is increased the top-wires are closer together and the estimate of X_t is too low (i.e. the calculated value of C_t 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.

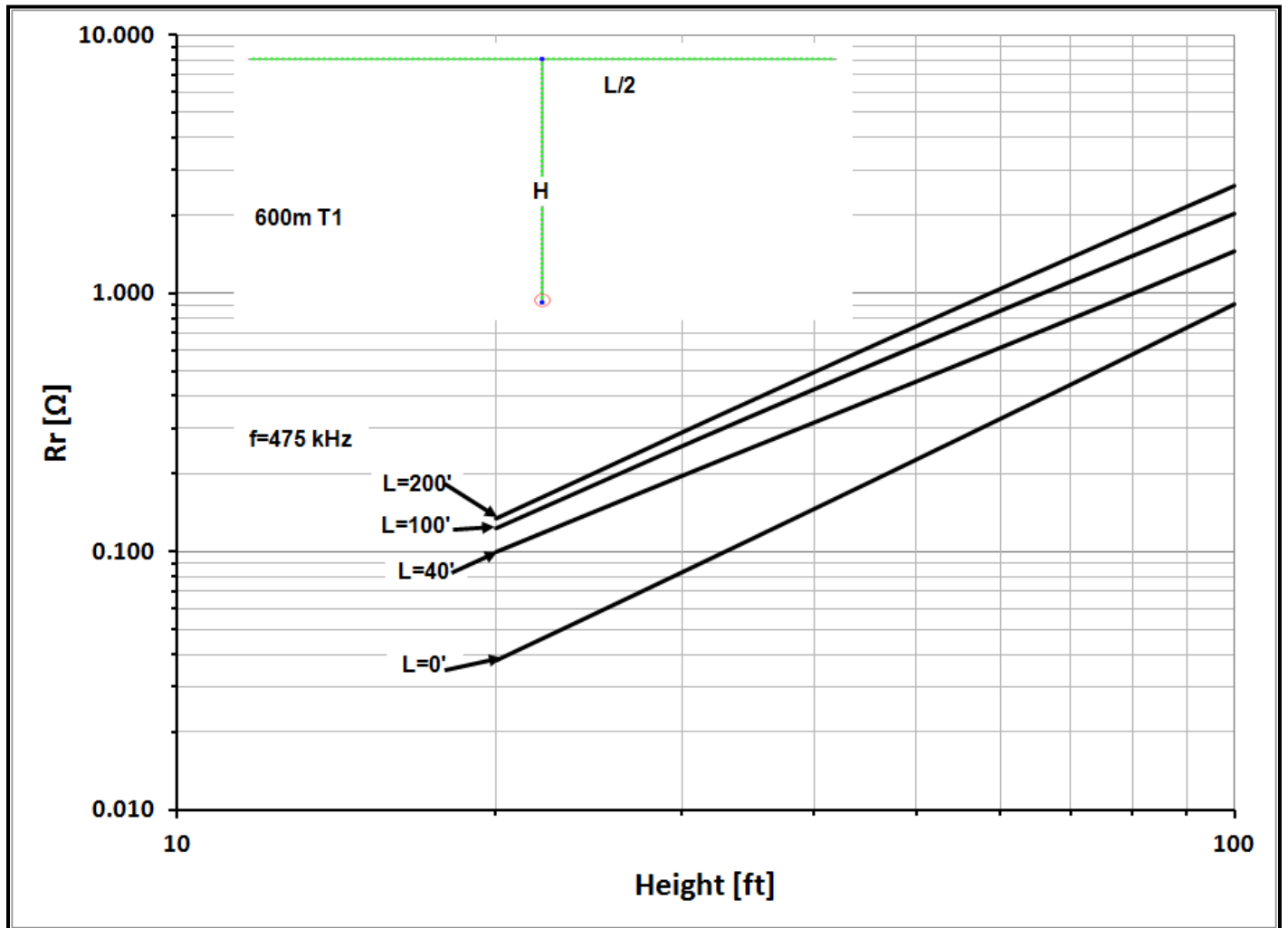


Figure 3.7 - R_r for a T antenna with a single top-wire at 475 kHz.

These R_r graphs are derived from NEC modeling. R_r 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 . I_0 is kept constant at 1A. With no top-loading the current at the top of the vertical (I_t) is close to zero but as the loading is increased I_t increases.

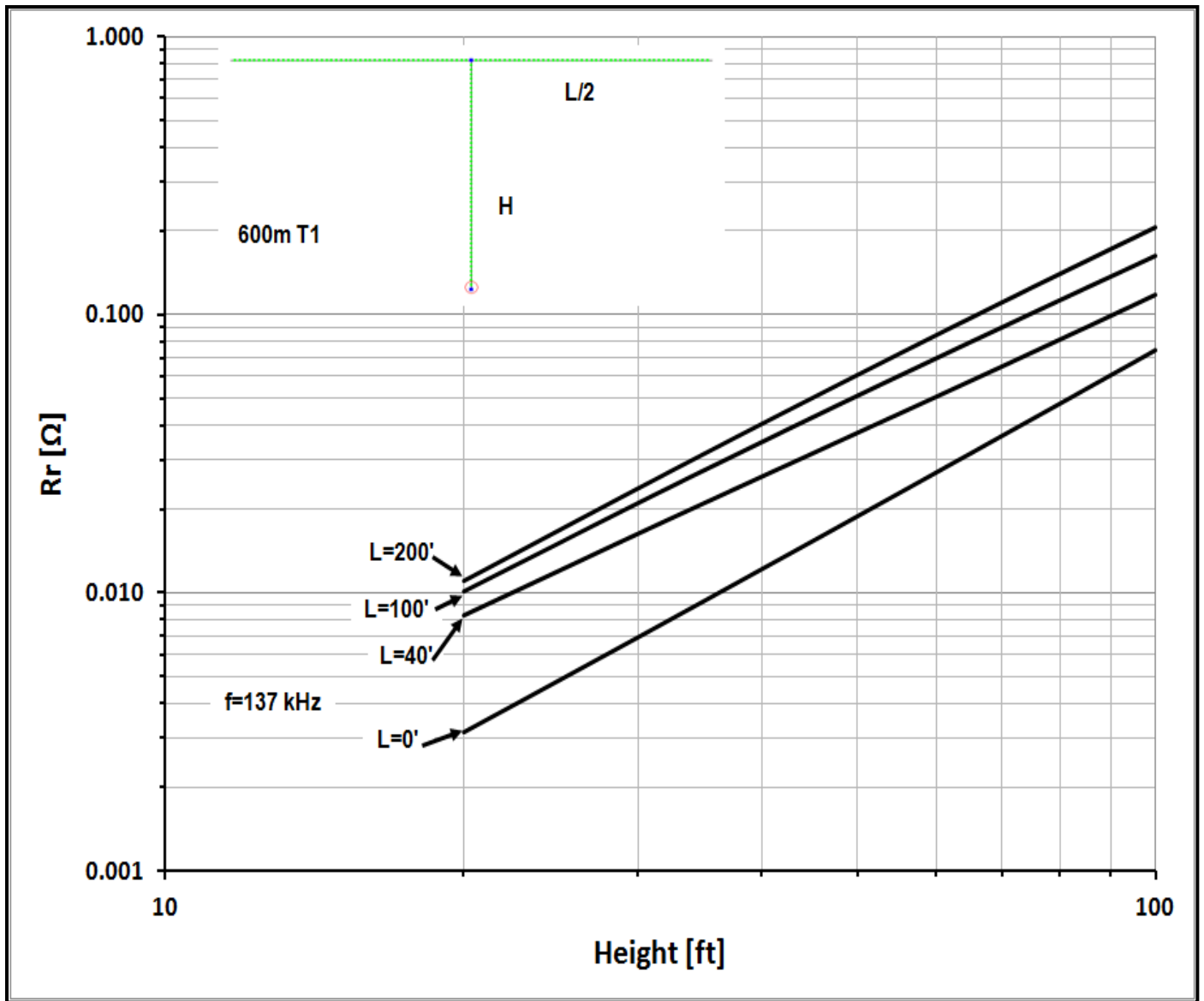


Figure 3.8 - R_r for a T antenna with a single top-wire at 137 kHz.

Equation (2.6) from chapter 2 is still valid:

$$R_r = 0.01215 A'^2 [\Omega] \quad (3.8)$$

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

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

G_v =electrical height in degrees.

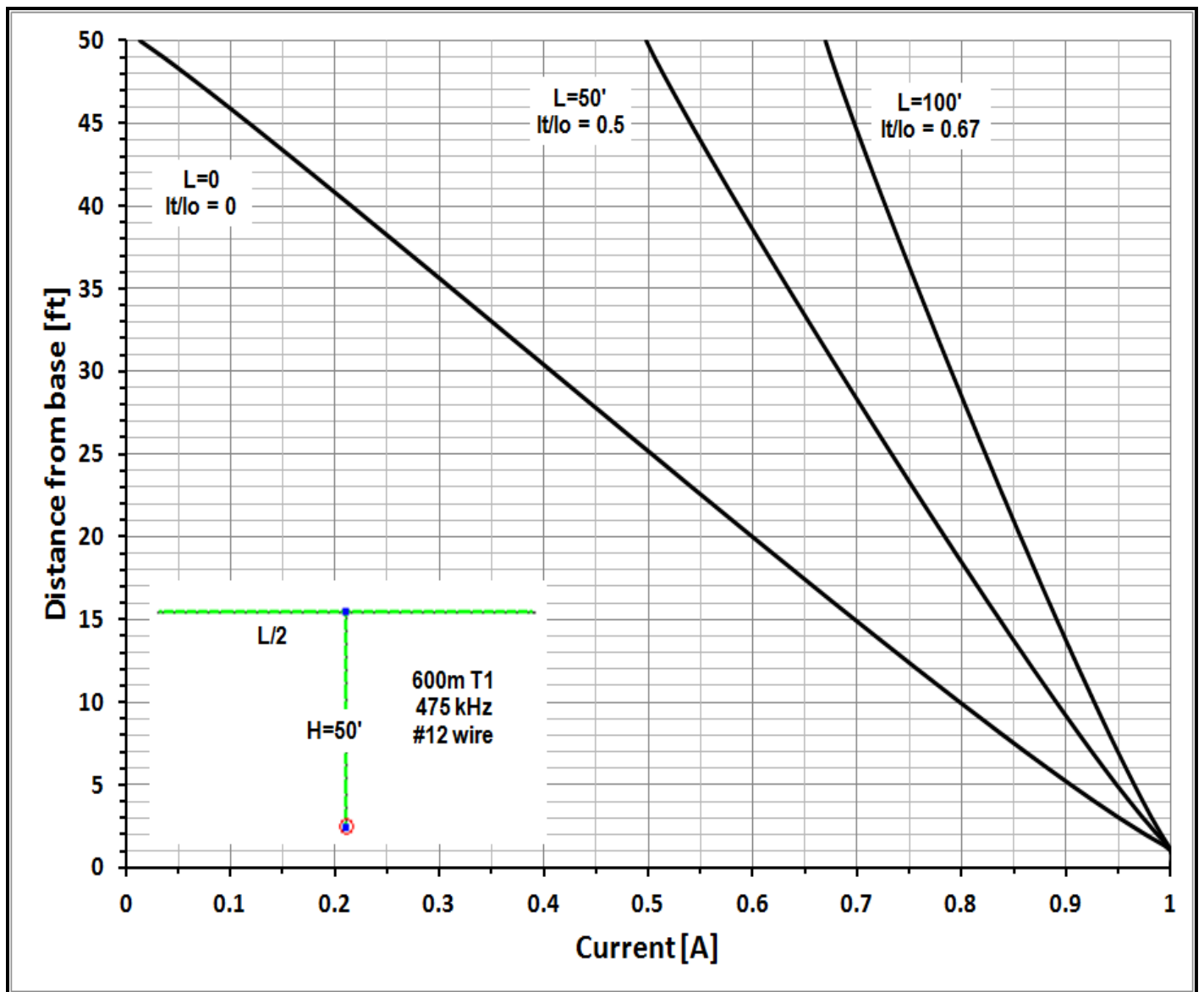


Figure 3.9 - Current distribution on the vertical part of a "T" antenna.

As shown in figure 3.10, inserting equation (3.9) into (3.8) we can create a universal graph for R_r as a function of antenna height in degrees (G_v) with the current ratio I_t/I_o as a parameter. The I_t/I_o 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. $I_t/I_o=1$). As I_t/I_o goes from zero to 1, R_r increases by a factor of 4X. Equations (3.8) and (3.9) are valid for $G_v < 45$ degrees.

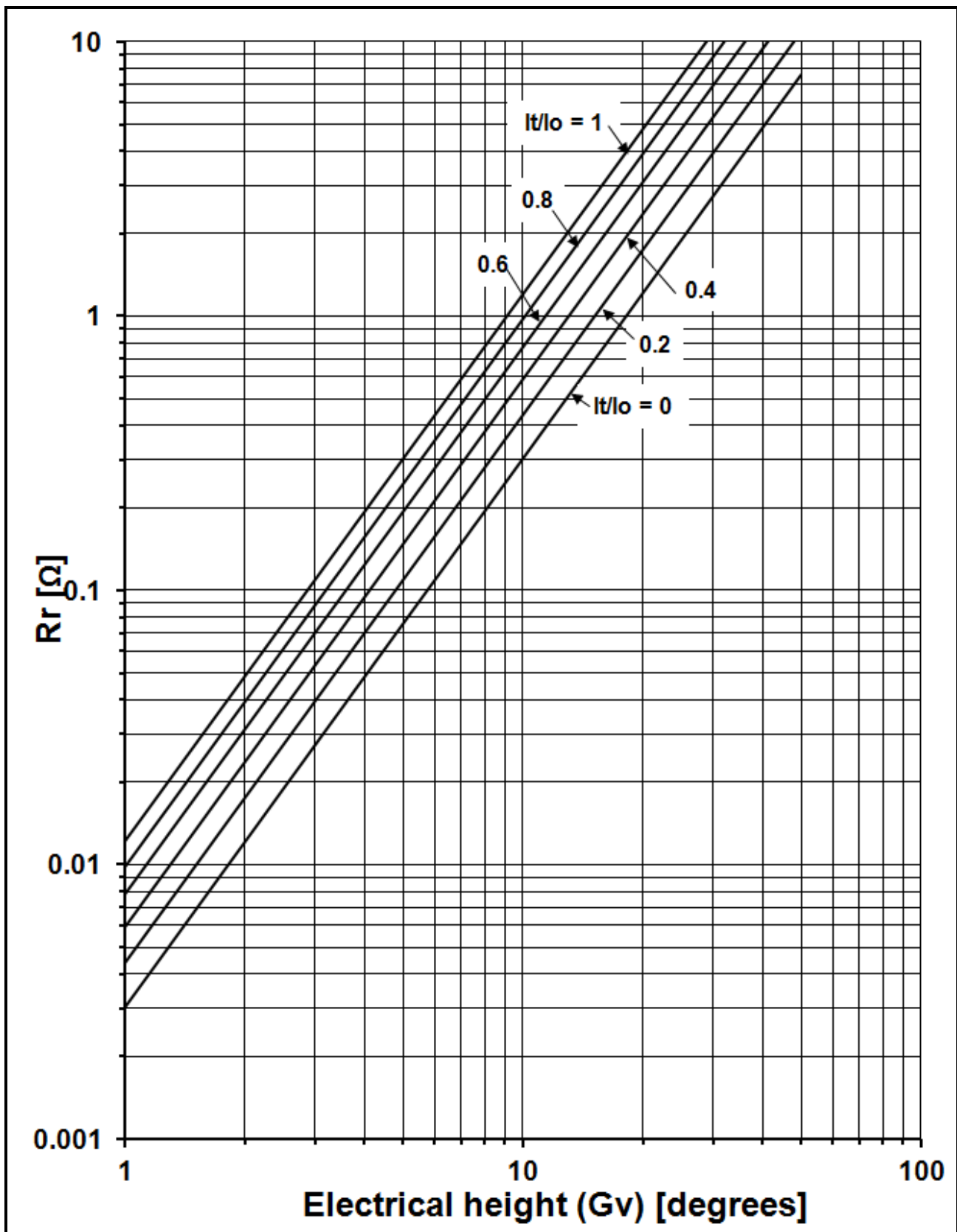


Figure 3.10 - R_r as a function of height in degrees.

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.

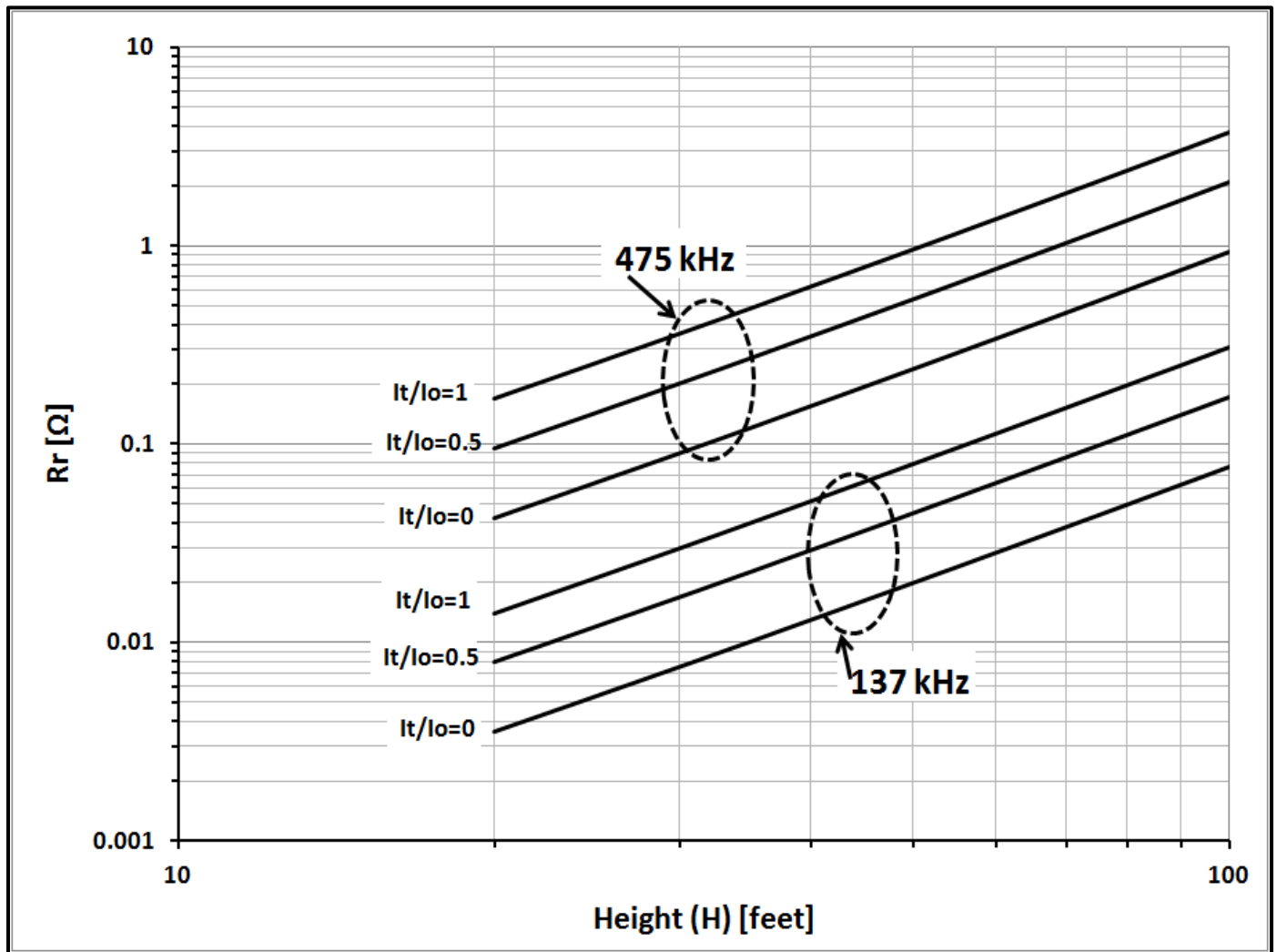


Figure 3.11 - R_r as a function of height in feet.

If we know I_t/I_o then we can simply read R_r off the graph. Finding I_t/I_o with modeling is easy but manually it's a bit tricky. I have never seen a discussion on calculating I_t/I_o 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 at 137 and 475 kHz. At each data point I recorded X_i . With no top-loading ($N=0$) $X_i=X_c$. Using that value for X_c and the value for X_i at each data point, I calculated X_t from:

$$X_t = \frac{X_i X_c}{X_c - X_i} \quad (3.10)$$

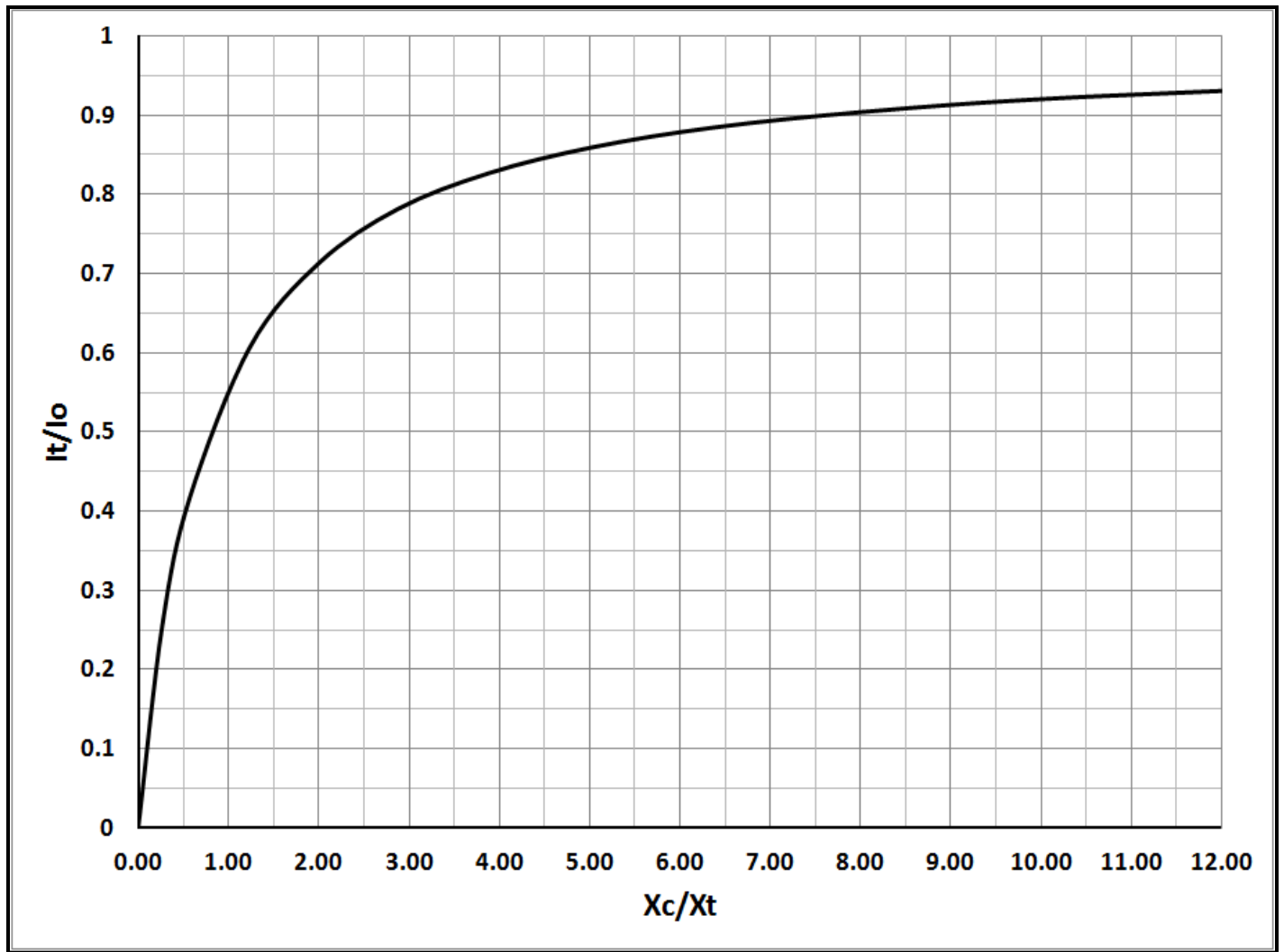


Figure 3.12 - X_c/X_t ratio.

I also recorded the value for I_t/I_o at each point and then graphed I_t/I_o versus X_c/X_t 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 X_c/X_t). The increase in R_r associated with a given value for X_c/X_t is shown in figure 3.13.

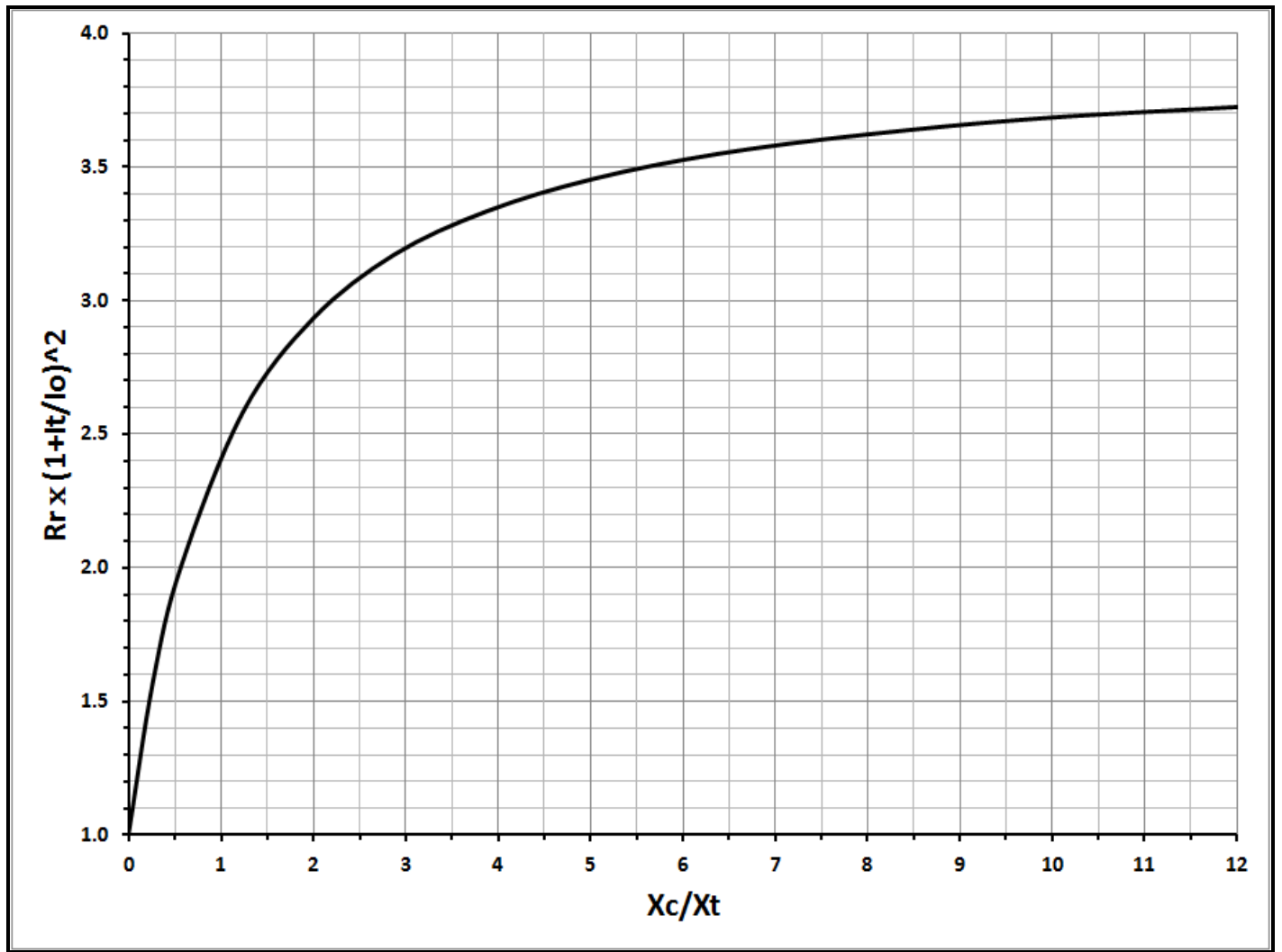


Figure 3.13 - Increase in R_r with top-loading (X_t).

We can calculate values for X_c and X_t using Equations (2.8), (2.9), (3.4) and (3.5), take the ratio and determine I_t/I_o from figure 3.12. With a value for I_t/I_o 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 R_r . One thing to notice in figures 3.12 and 3.13 is the flattening of the curves for $X_c/X_t > 2$. Adding more top-loading will initially increase R_r substantially but there is a point of vanishing returns. However, as we increase C_t further (i.e. make X_t smaller) we still get an almost linear reduction in X_i which reduces X_L and the associated inductor loss.

The small electrical size of our antennas allows us to simplify the expression for X_c/X_t . At 475 kHz 100' is $\approx 0.05\lambda$, which corresponds to 18° 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').

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

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

Note! The right side of equation (3.11), the ratio L/H, L and H can be in any units as long as both use the same units 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:

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

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

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

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.

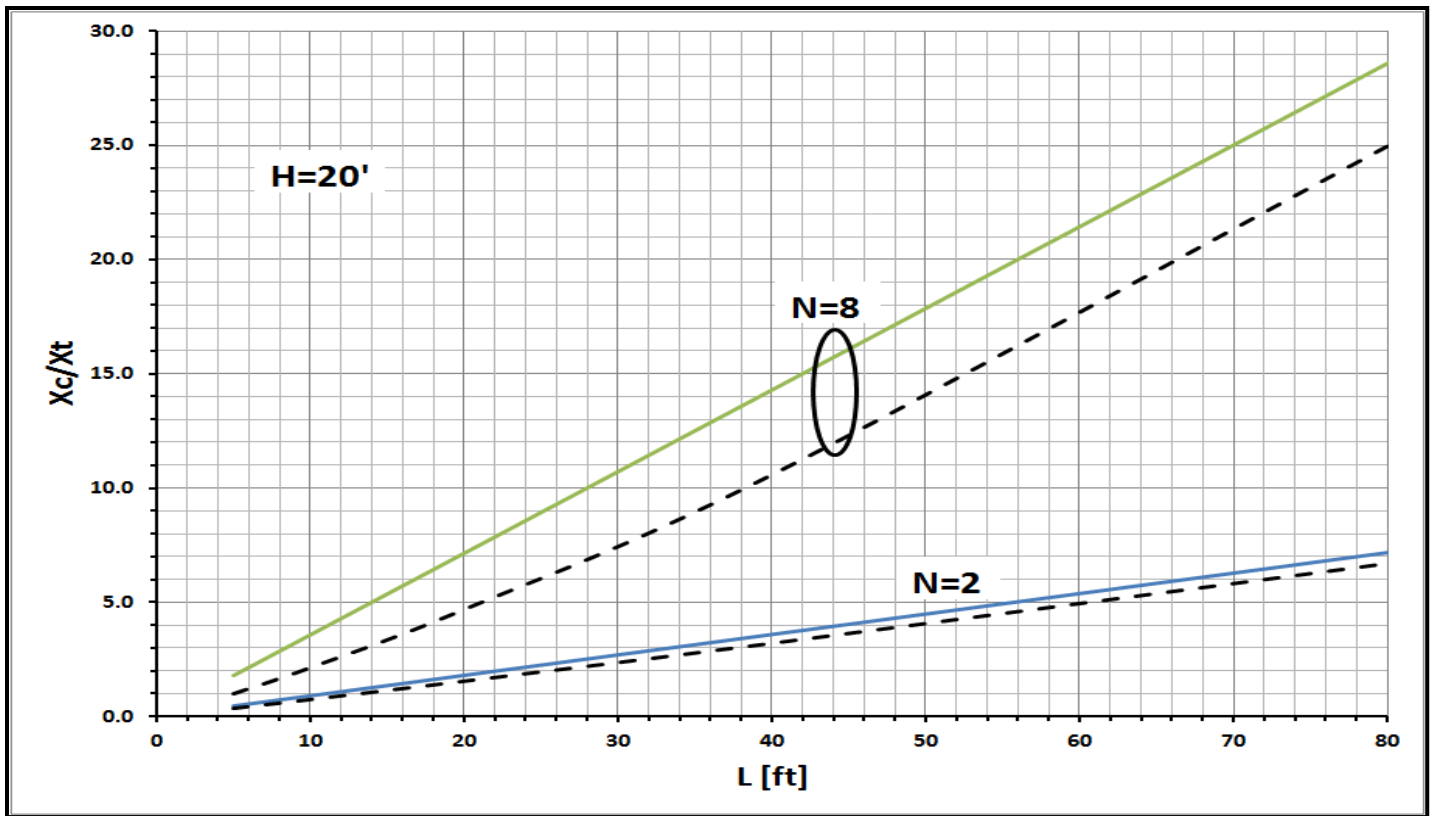


Figure 3.14 - Comparison of X_c/X_t derived from NEC and computation for $H=20'$.

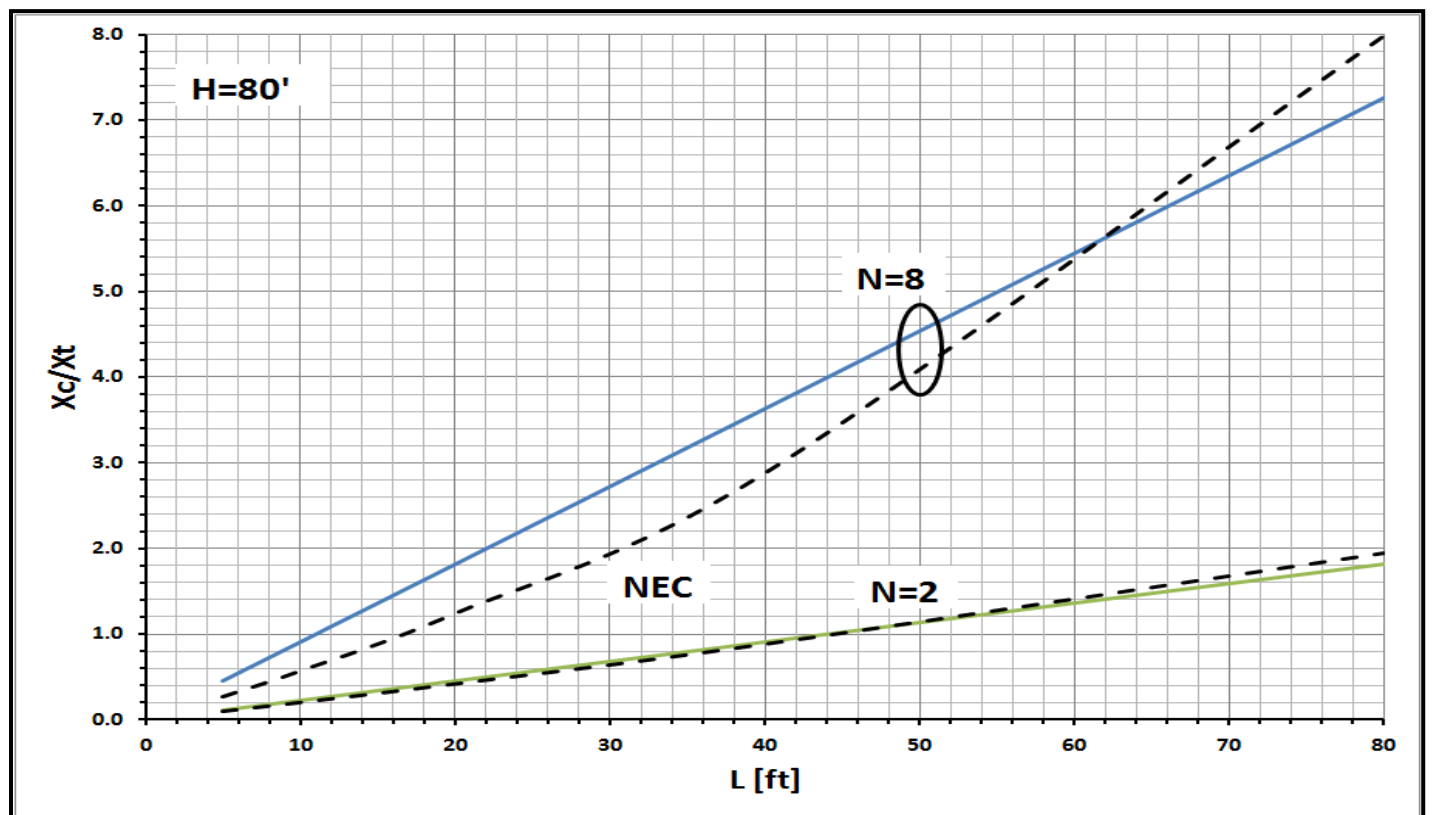


figure 3.15 - Comparison of X_c/X_t derived from NEC and computation for $H=80'$.

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 $\approx 1.5\%$. 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.

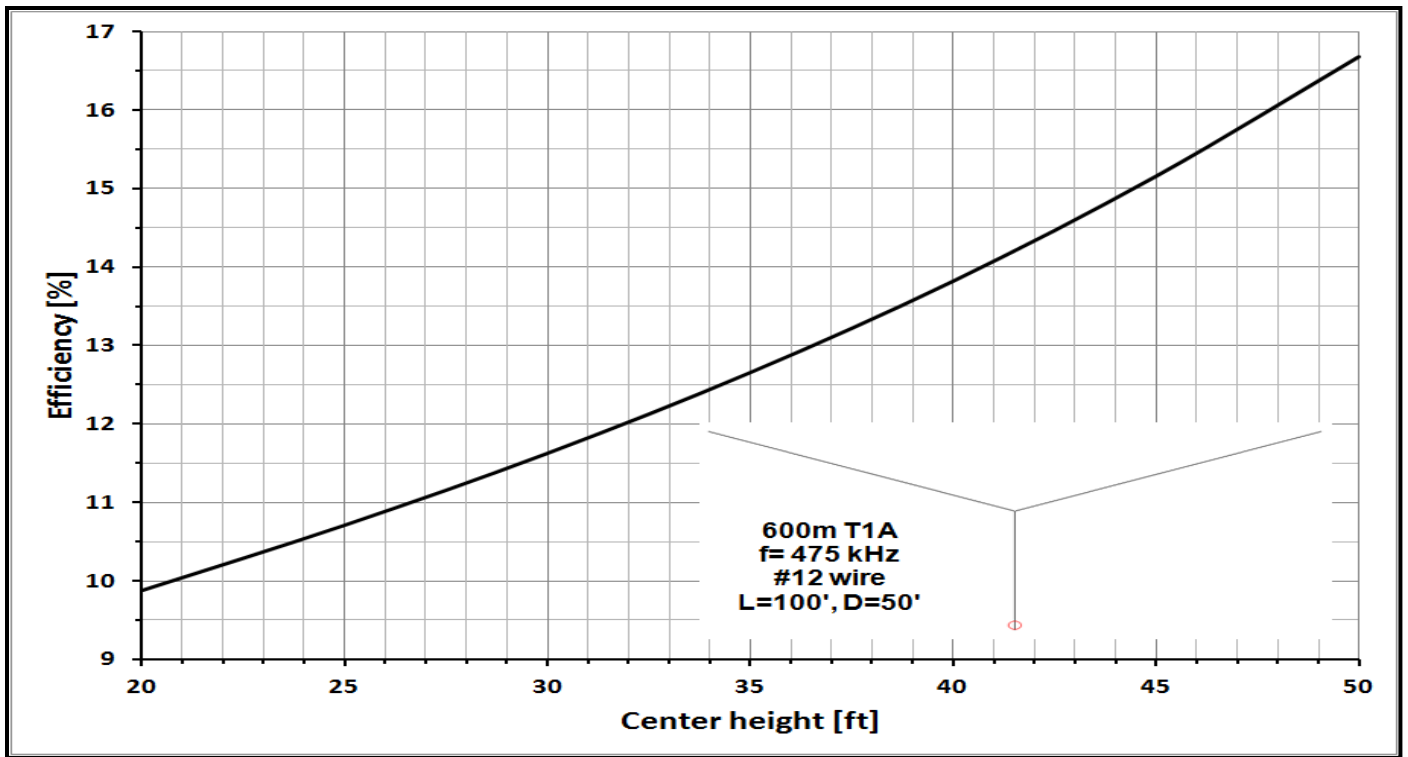


Figure 3.16 - Effect of sag on efficiency at 475 kHz.

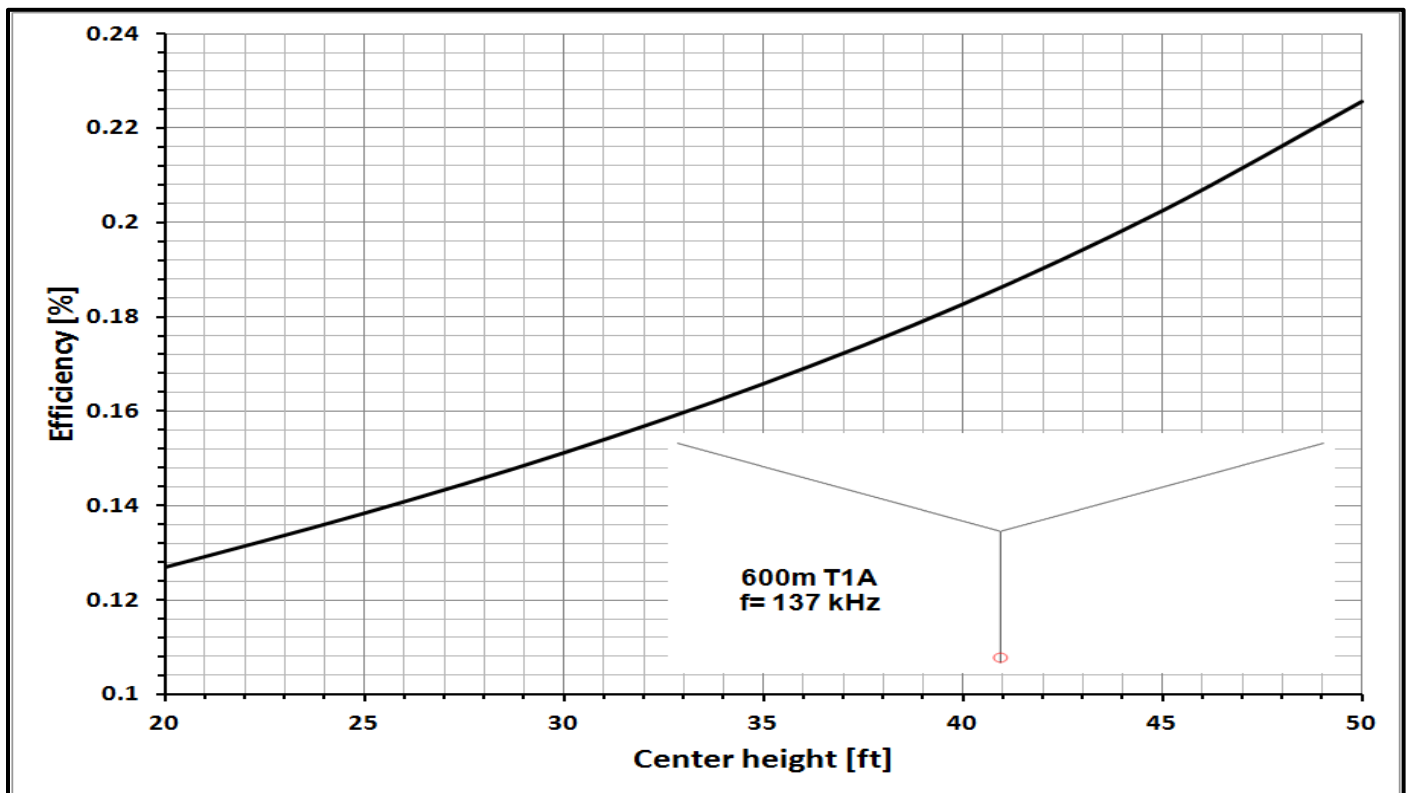


Figure 3.17 - Effect of sag on efficiency at 137 kHz.

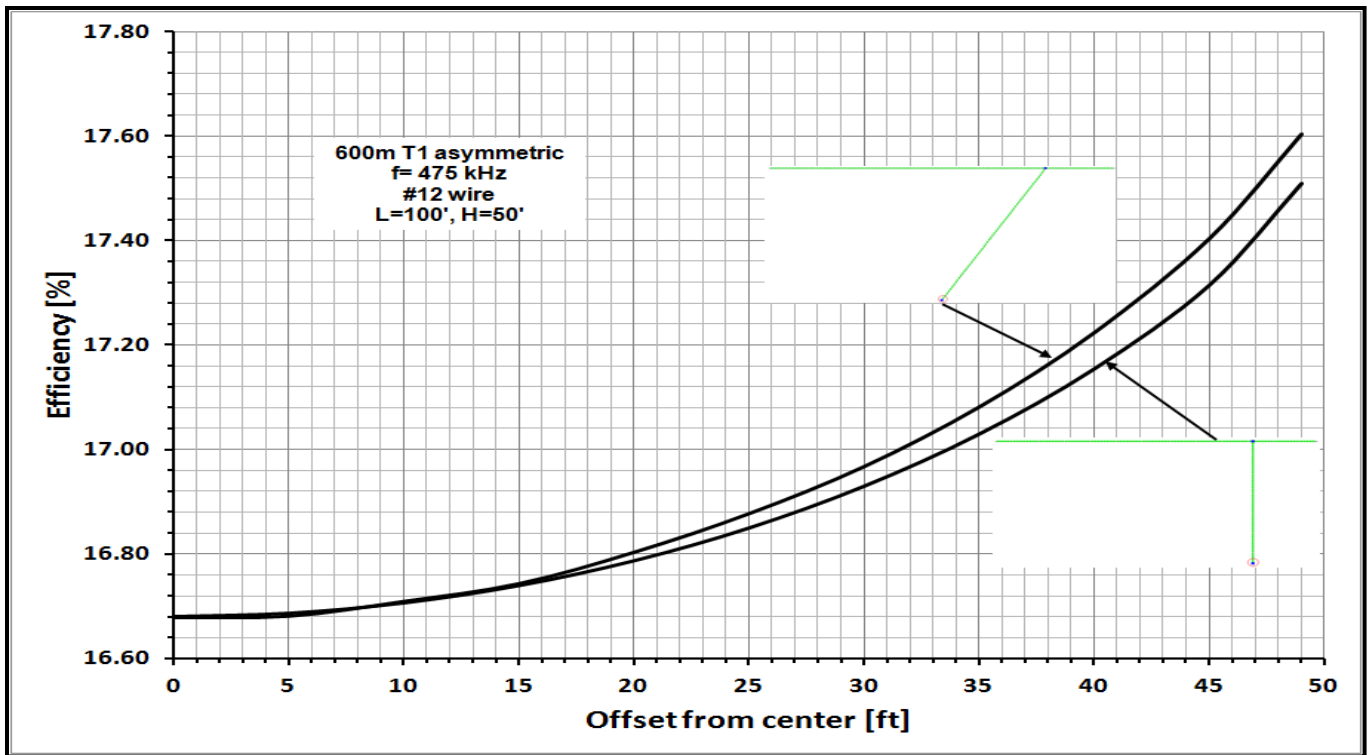


Figure 3.18- Effect of download attachment point, 475 kHz.

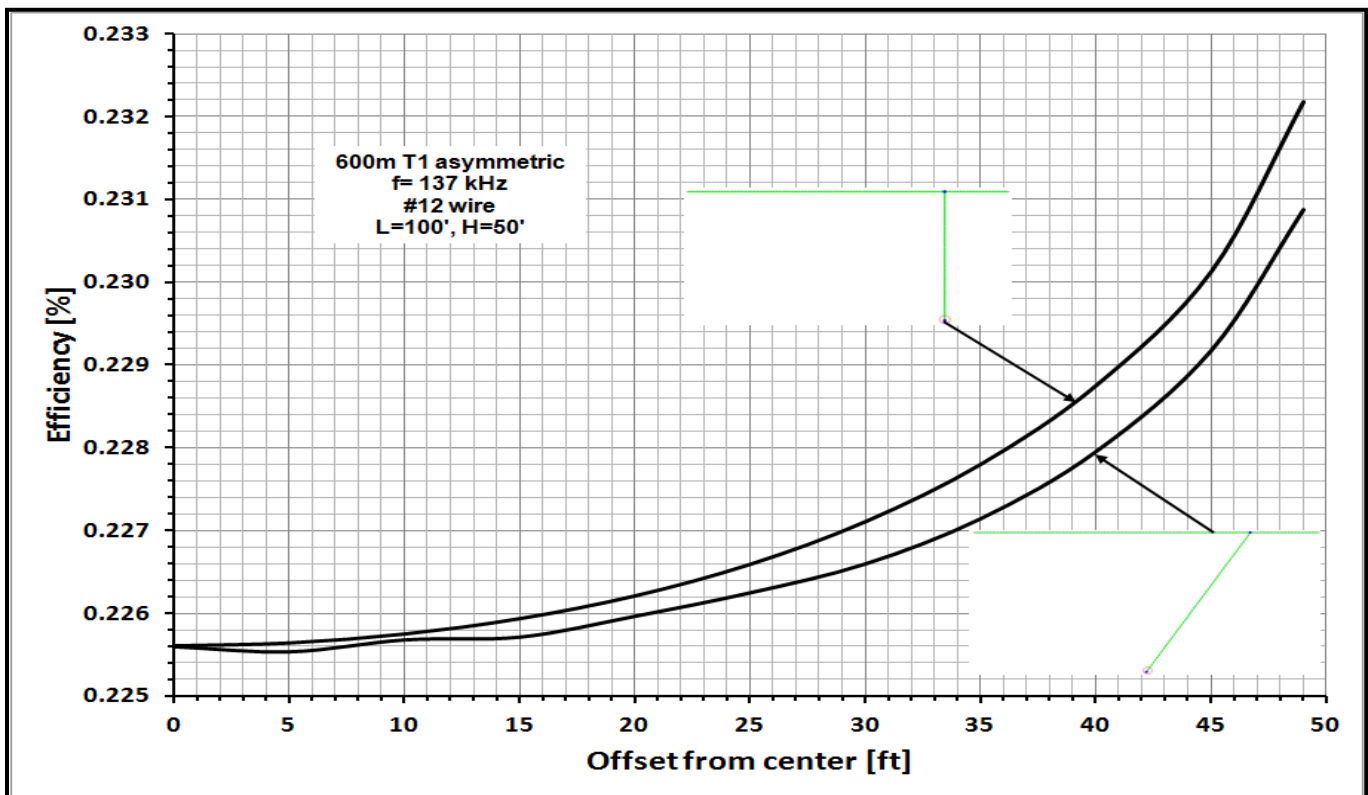


Figure 3.19 - Effect of download attachment point, 137 kHz.

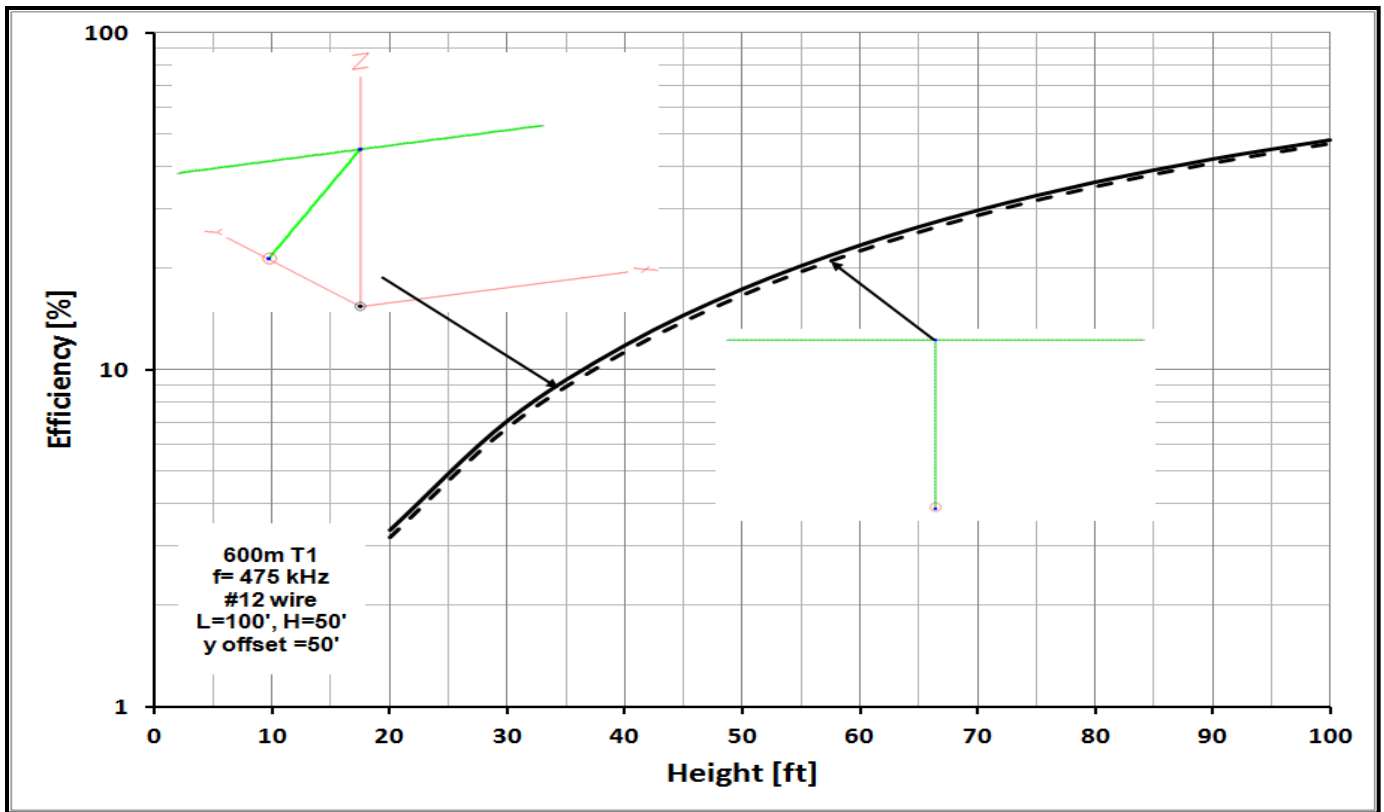


Figure 3.20 - Effect of downlead ground end offset, 475 kHz.

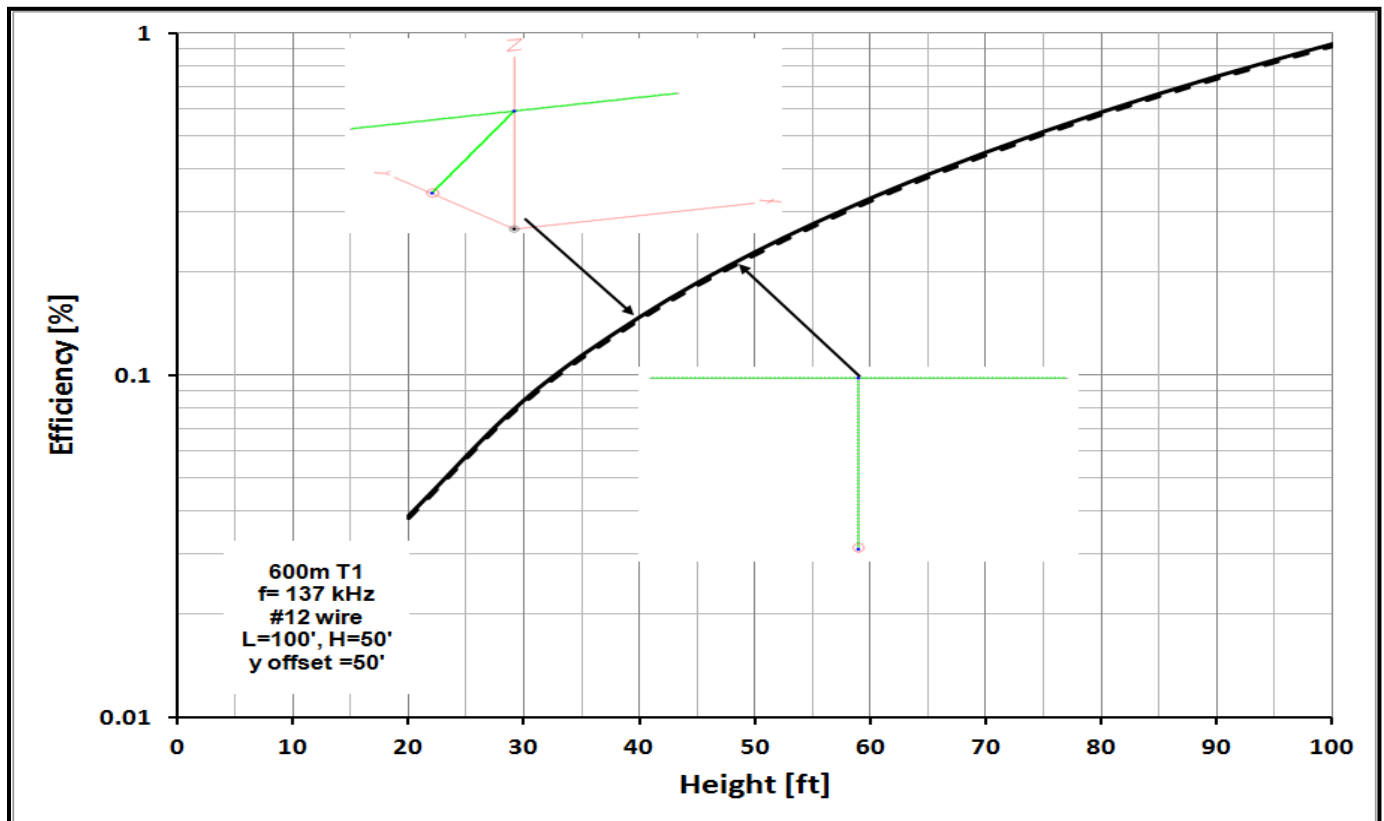


Figure 3.21 - Effect of downlead ground end offset, 137 kHz.

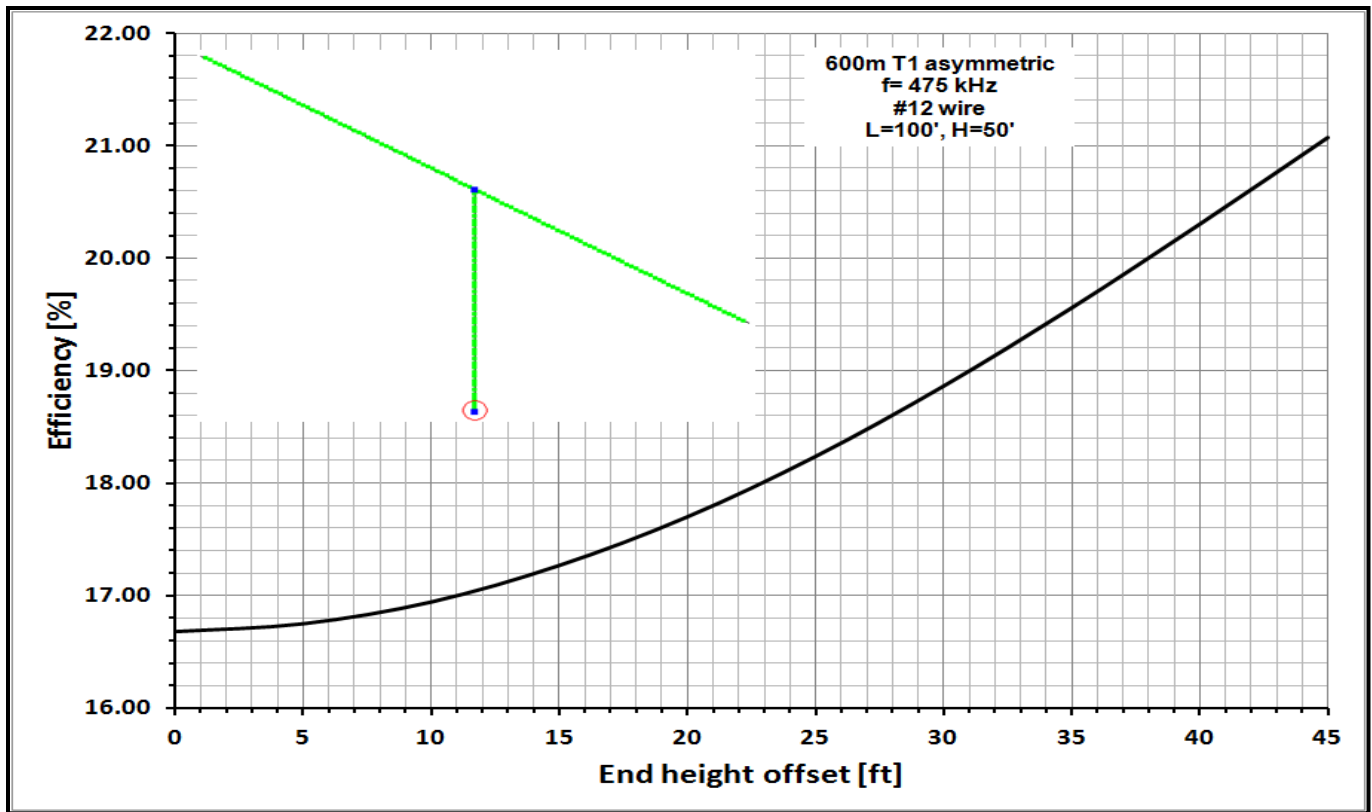


Figure 3.22 -Effect of slope in the top-wire, 475 kHz.

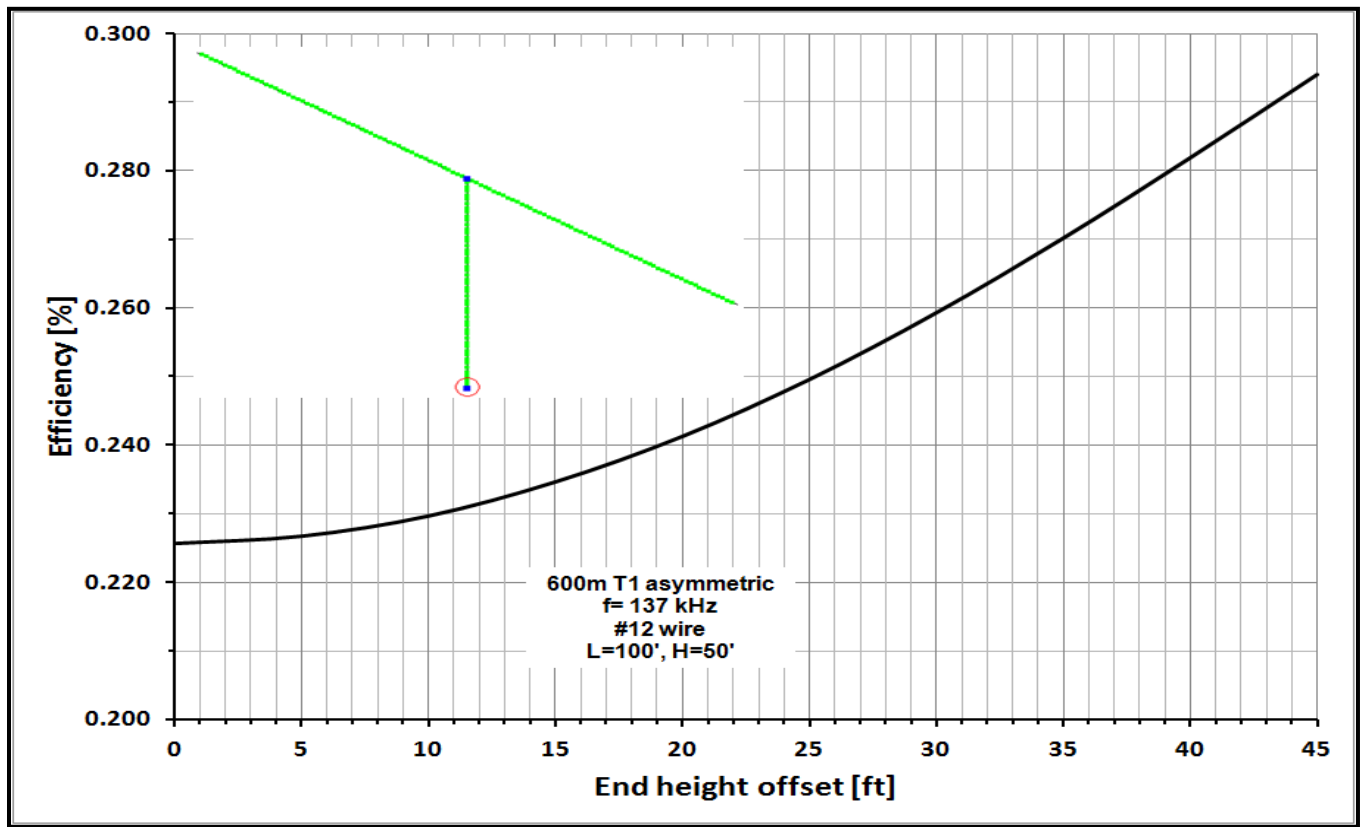


Figure 3.23 - Effect of slope in the top-wire, 137 kHz.

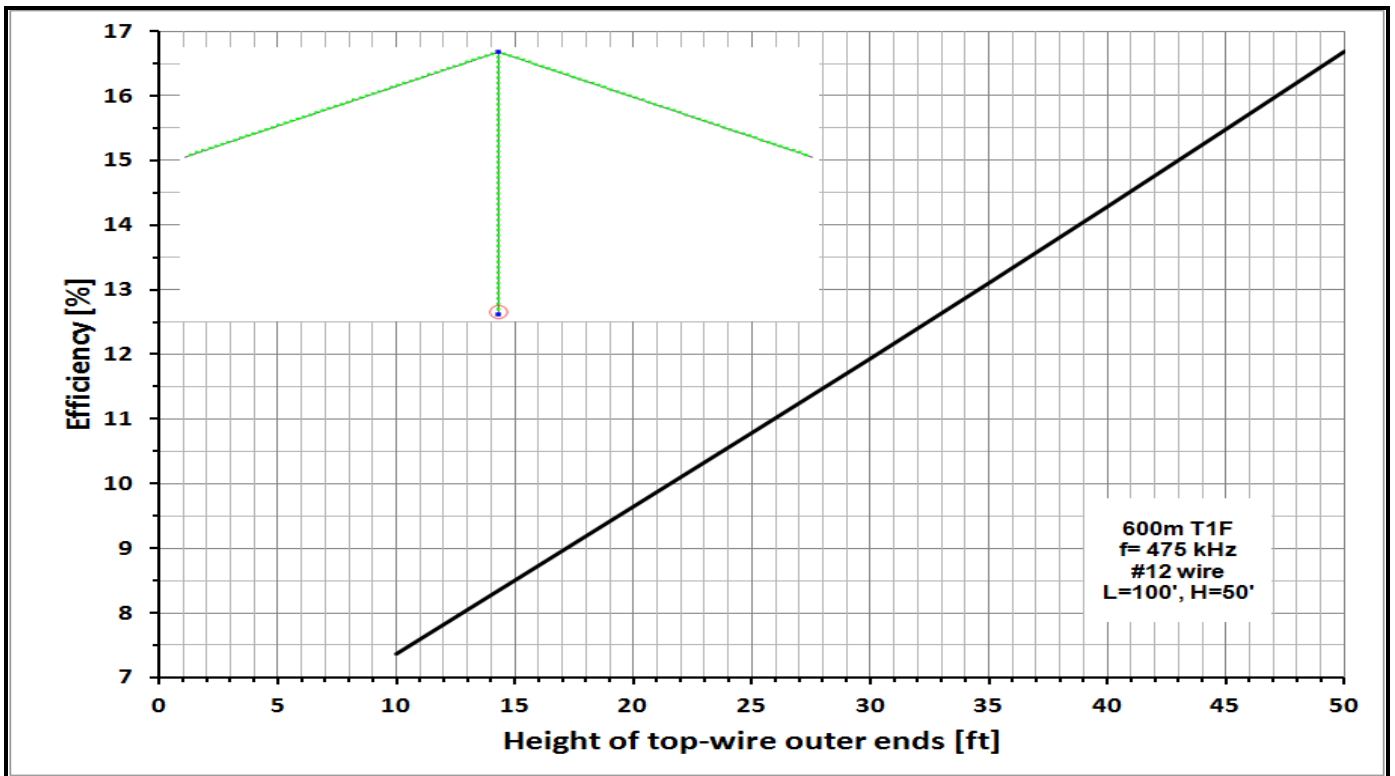


Figure 3.24 -Single support with sloping top-wires, 475 kHz.

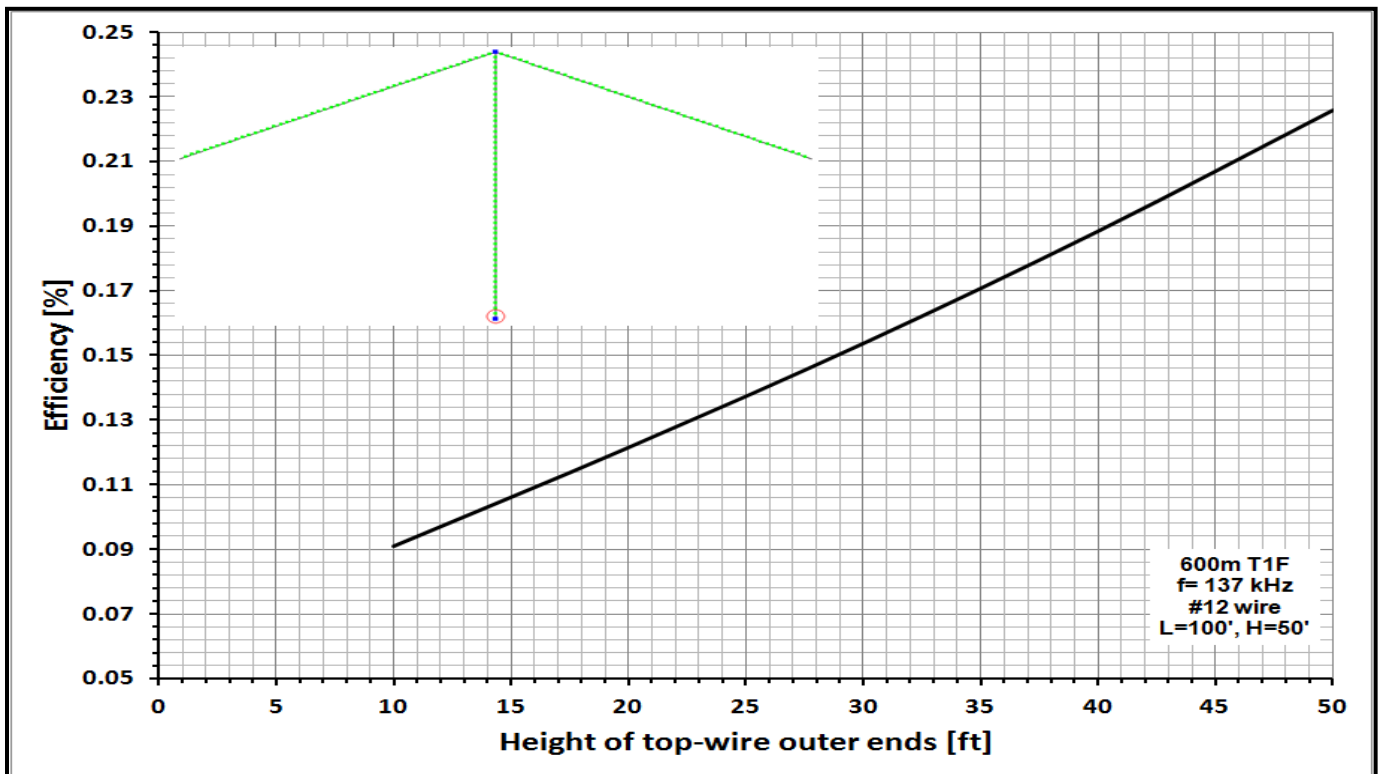


Figure 3.25 - Single support with sloping top-wires, 137 kHz.

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 R_r .

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 $\approx 180^\circ$ out of phase with the current in the vertical so there is some cancelation which reduces R_r while reducing R_L . Initially, as we make the drop wires longer R_r falls somewhat but X_c falls more rapidly until a peak in efficiency is reached. Note however, that the length of the end-loading wires is not very critical.

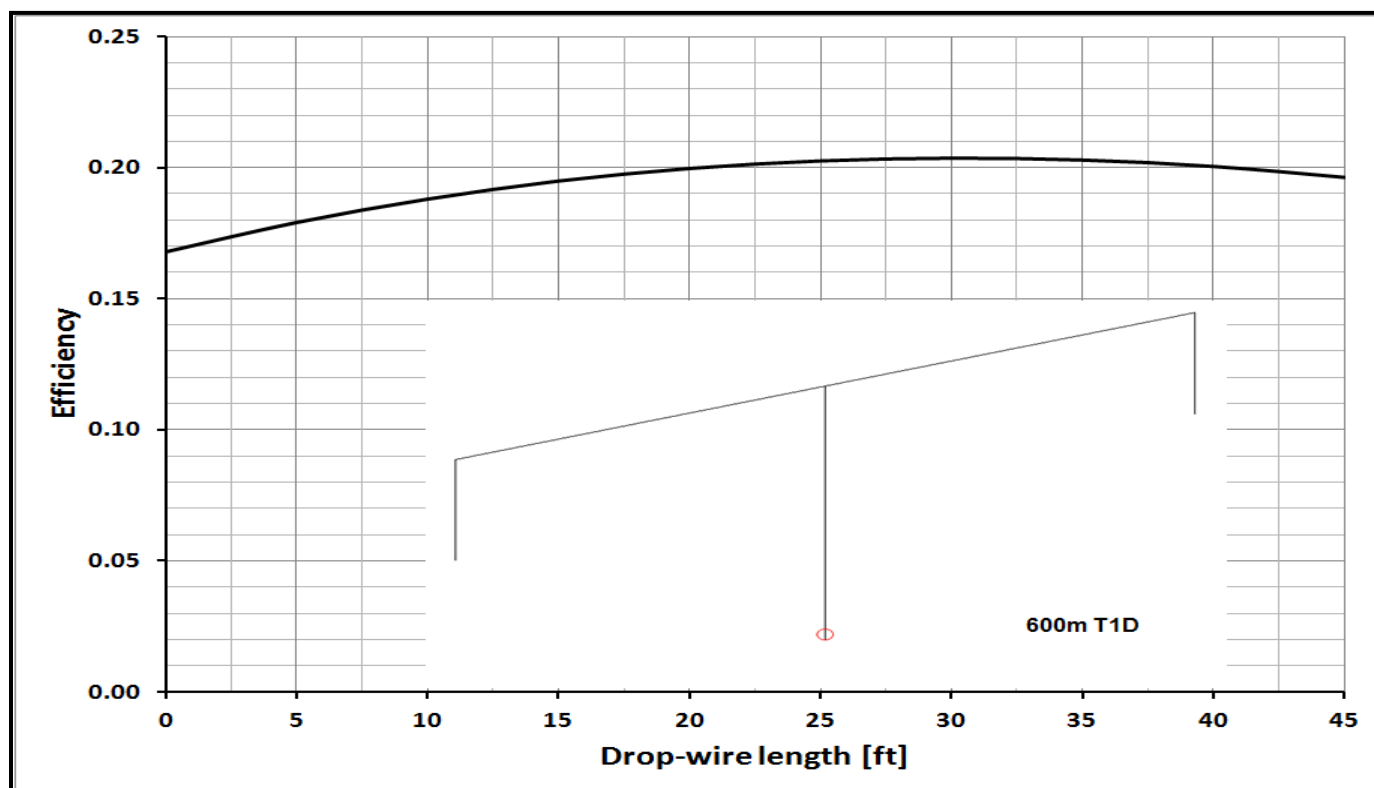


Figure 3.26 - T vertical with end-loading wires. $L=100'$, $H=50'$.

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 be made quite small ($<45^\circ$) before it matters very much.

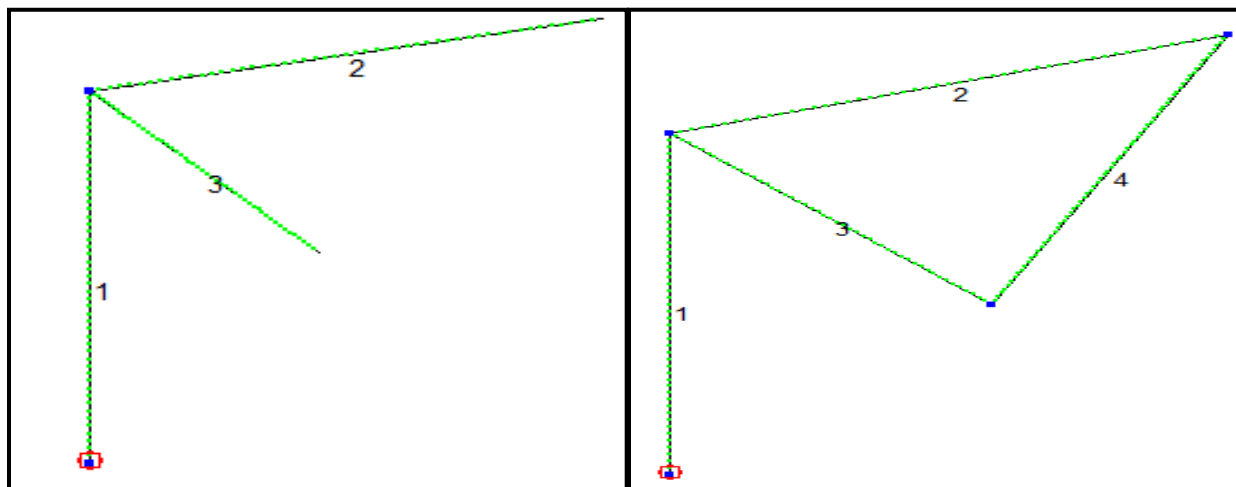


Figure 3.27 - 90° between top-loading wires. With and w/o skirt wire.

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 download could be connected at any 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. Exploit the opportunities at your QTH!

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 download? 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 download away from the tower as shown in figure 3.28 can also help. The effect on a specific installation is best explored with modeling.

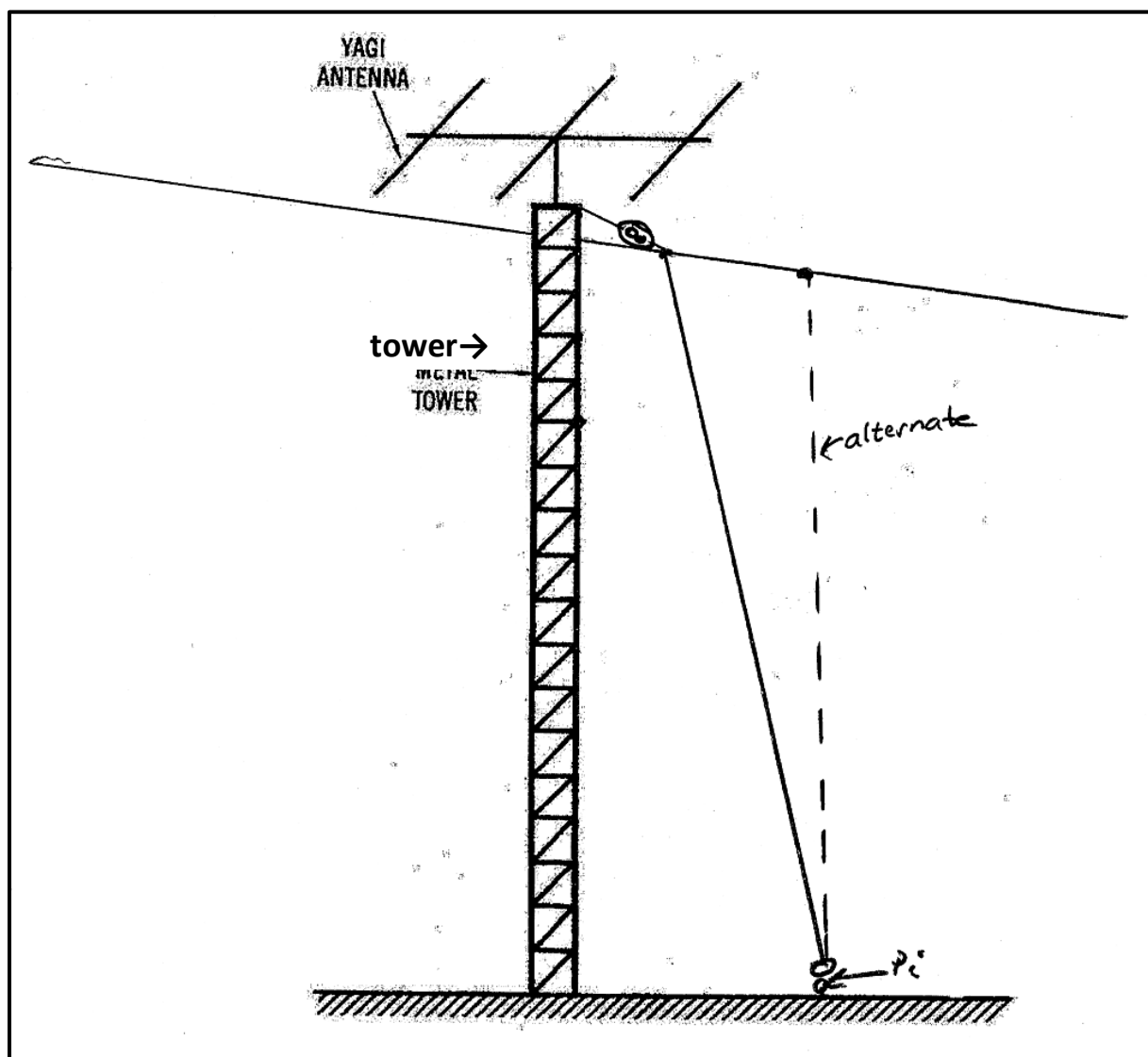


Figure 3.28 - Using a grounded tower as a center support.\

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 R_c . 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 $\approx 17\%$ but with two wires and 10' spreaders that jumps to $\approx 28\%$ and when we go to 30' spreaders the efficiency is $\approx 34\%$. 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 X_c and leads to higher efficiency but as can be seen in figure 3.30, for a given spreader length the rate 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 X_c 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 (C_t) of a top-hat with parallel wires depends on the separation between the wires. Unfortunately the calculations for X_t 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.

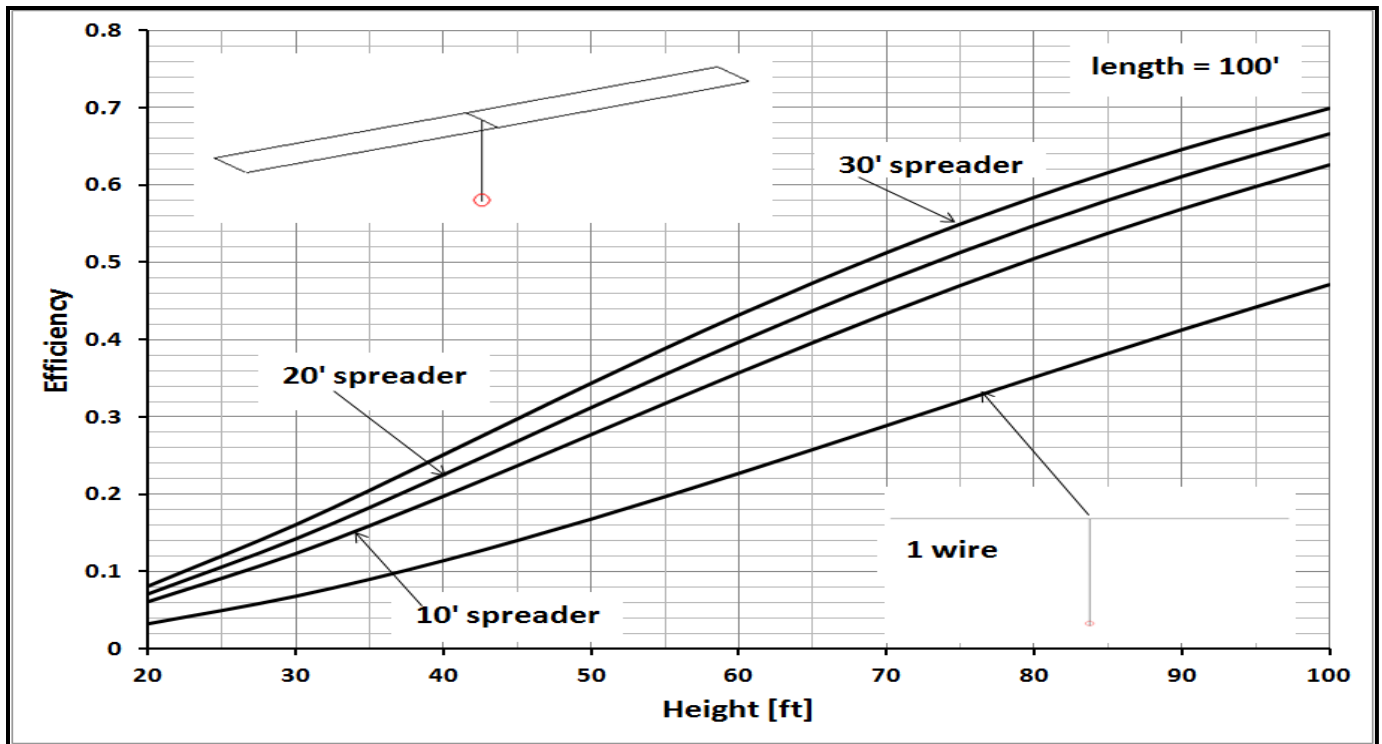


Figure 3.29 -Comparison of top-loaded verticals using a single wire or 2 horizontal wires with 10', 20' or 30' spreaders.

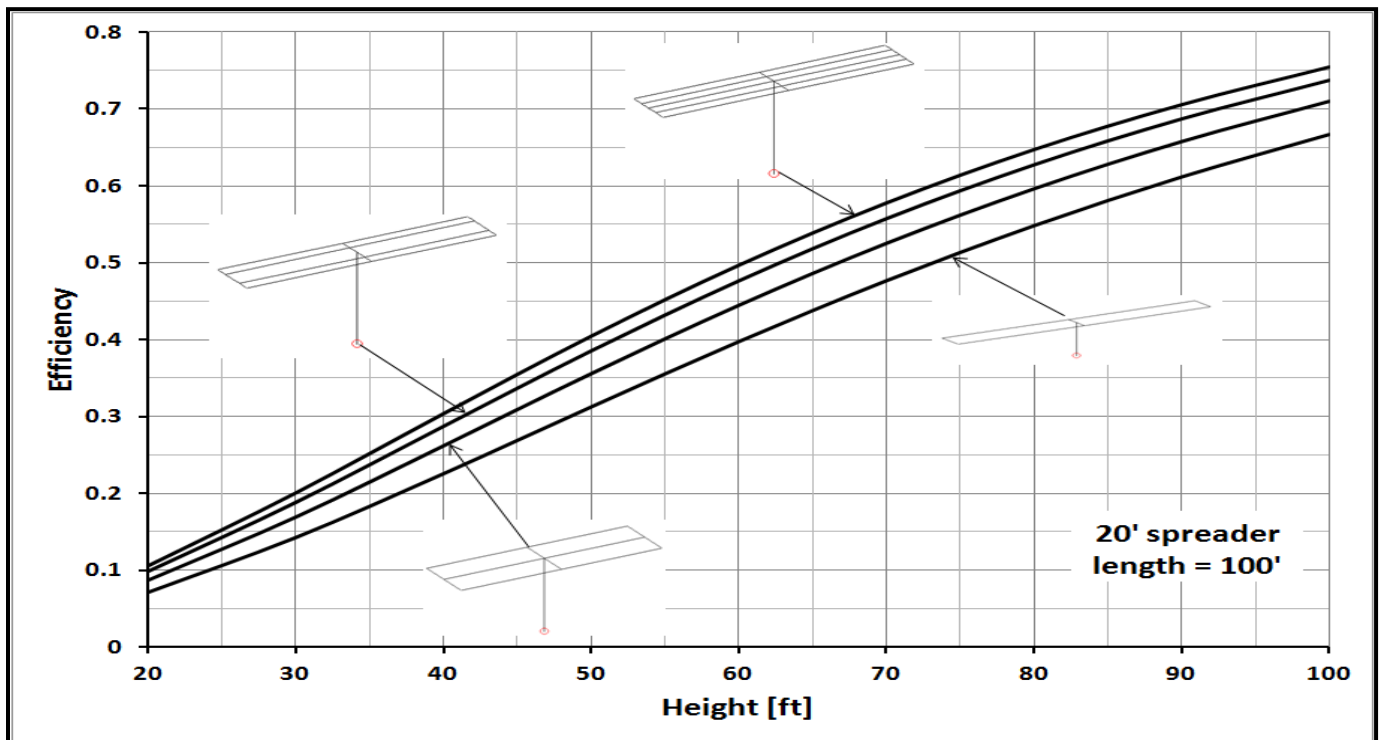


Figure 3.30 - Examples using more wires in the top-hat.

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 $\approx 2\%$ 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.

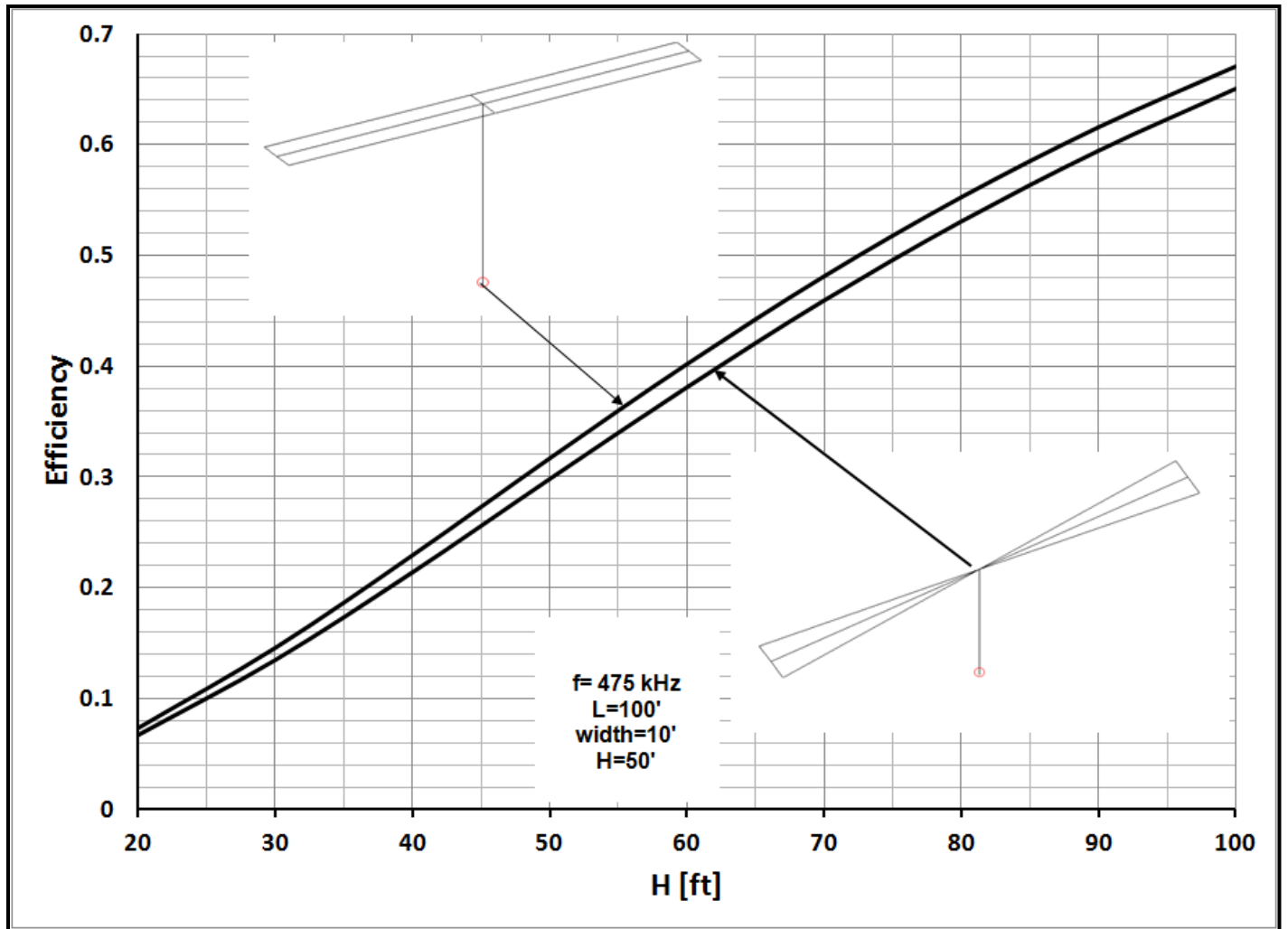


Figure 3.31 - 3-wire top-hat examples.

3.7 Umbrella top-loading

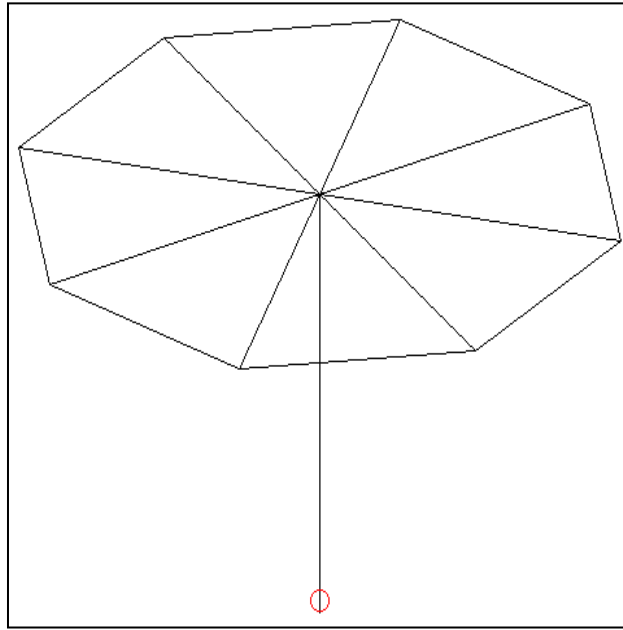


Figure 3.32 - Example of an "umbrella" for capacitive top-loading.

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.

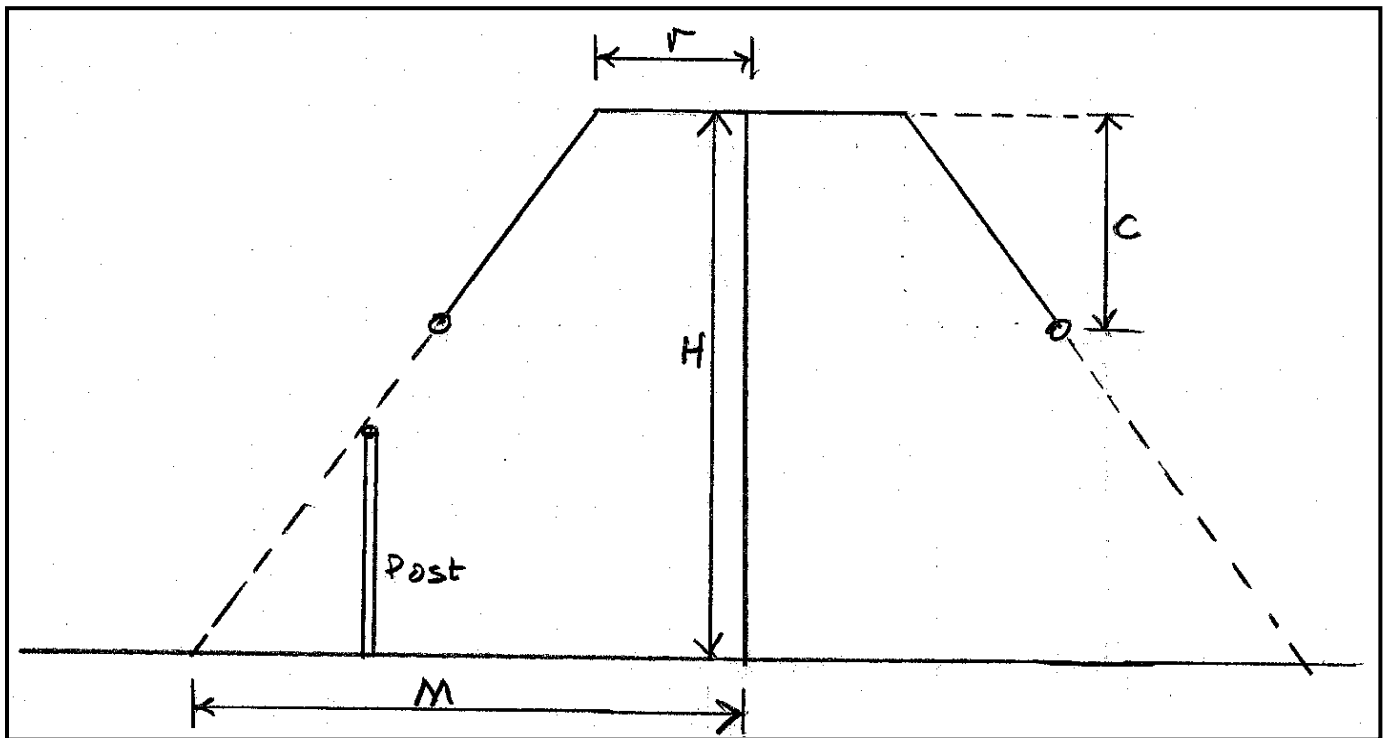


Figure 3.33- Definition of antenna dimensions.

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 R_r and X_c 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 R_r and X_c .

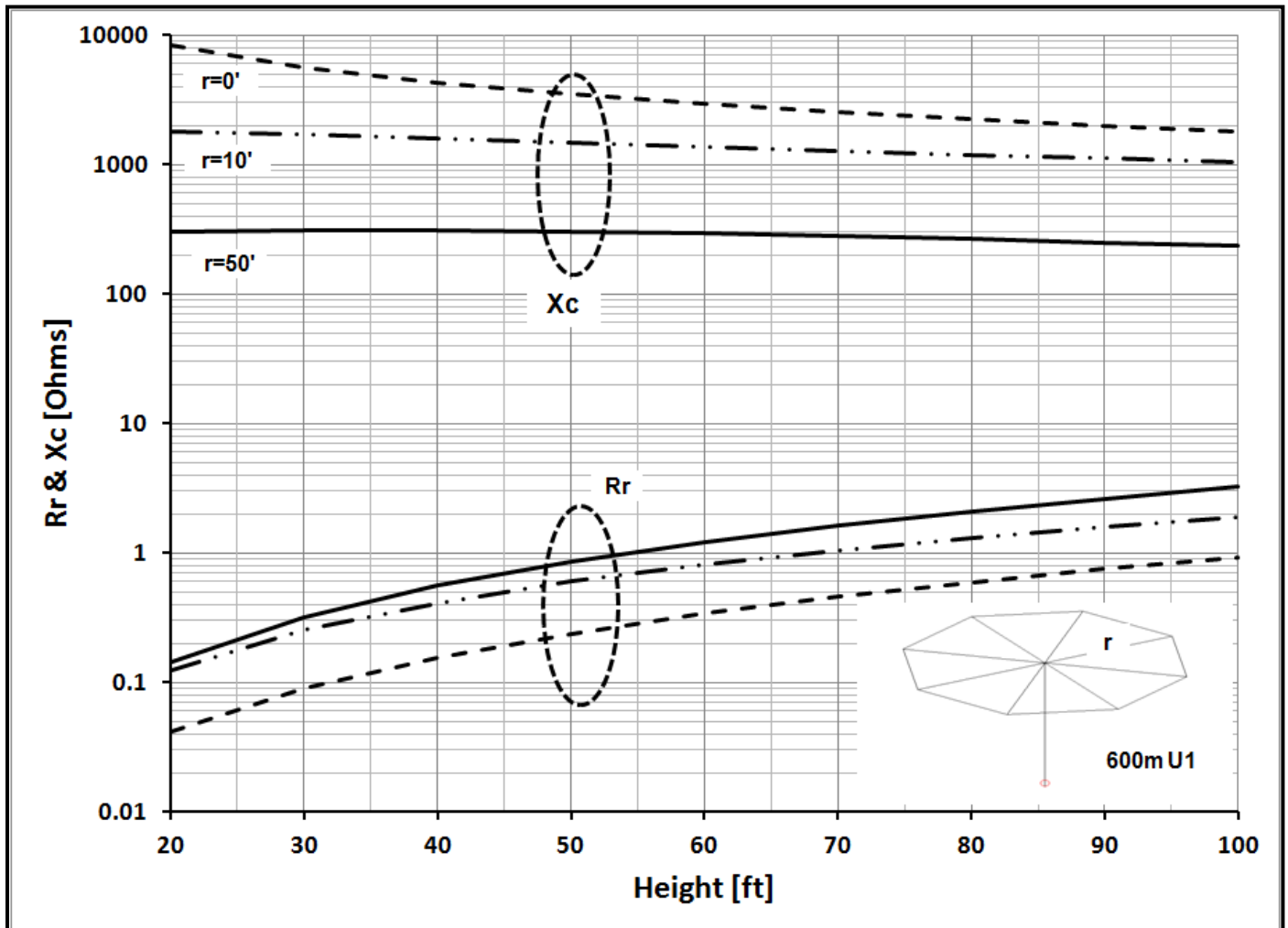


Figure 3.34 - R_r & X_c as a function of H and r .

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 3.36 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.

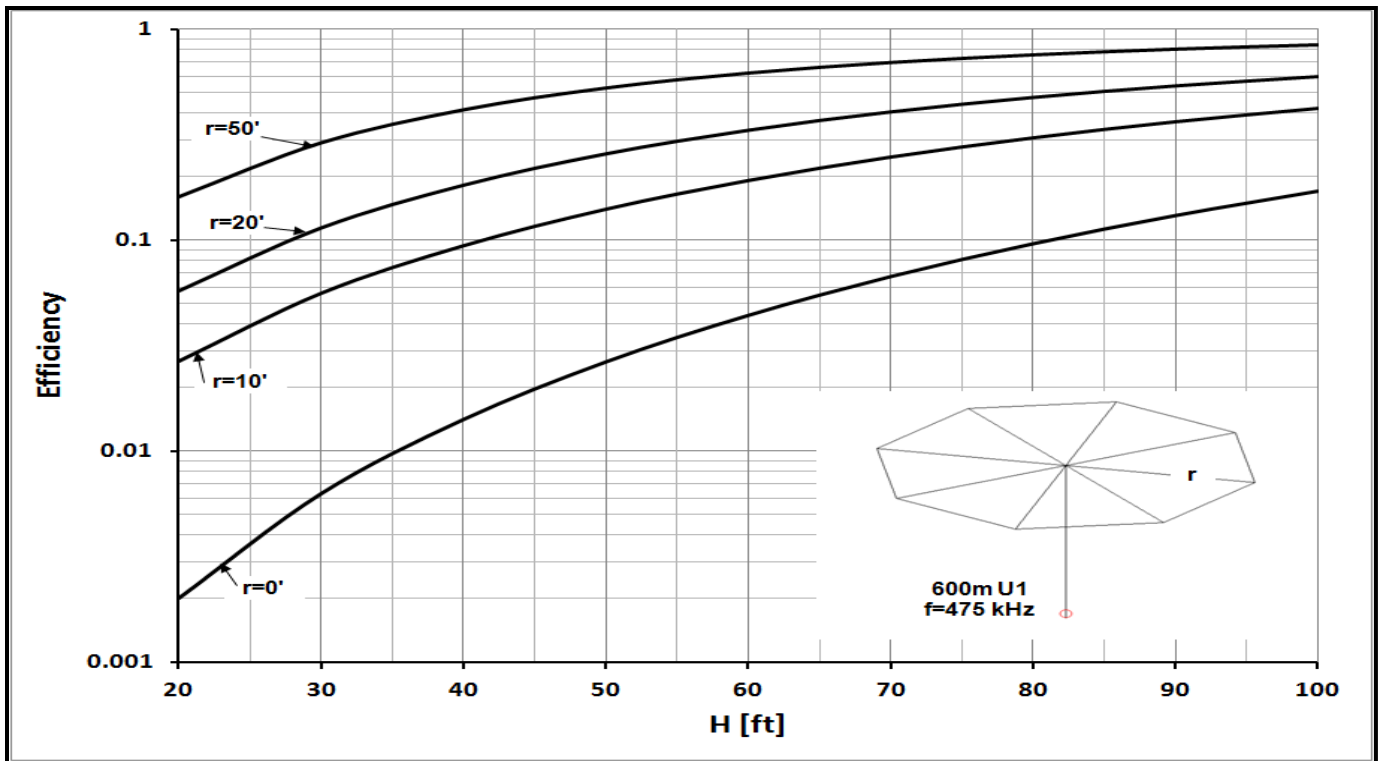


Figure 3.35 - Efficiency as a function of H and r.

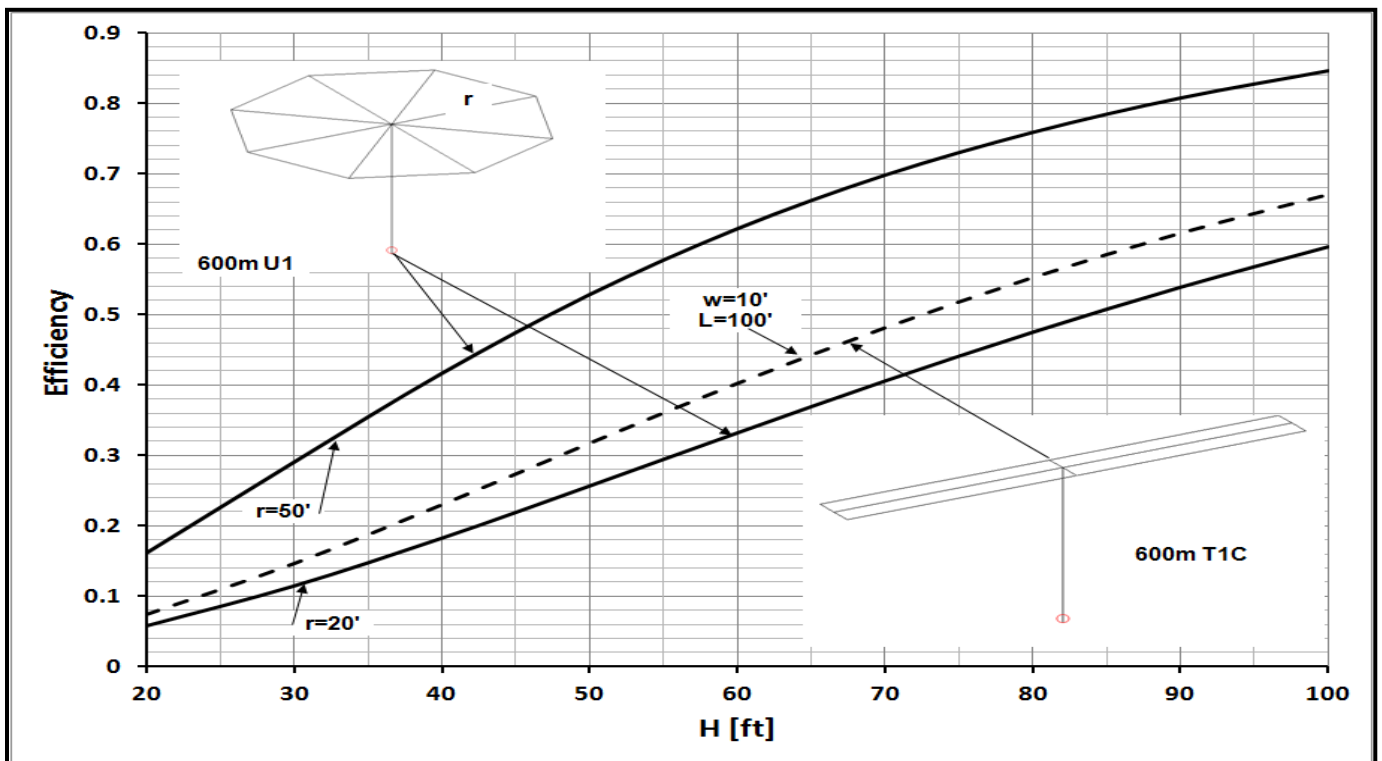


Figure 3.36 - Comparison between T and symmetric top-loading umbrellas.

3.9 Sloping wire umbrellas

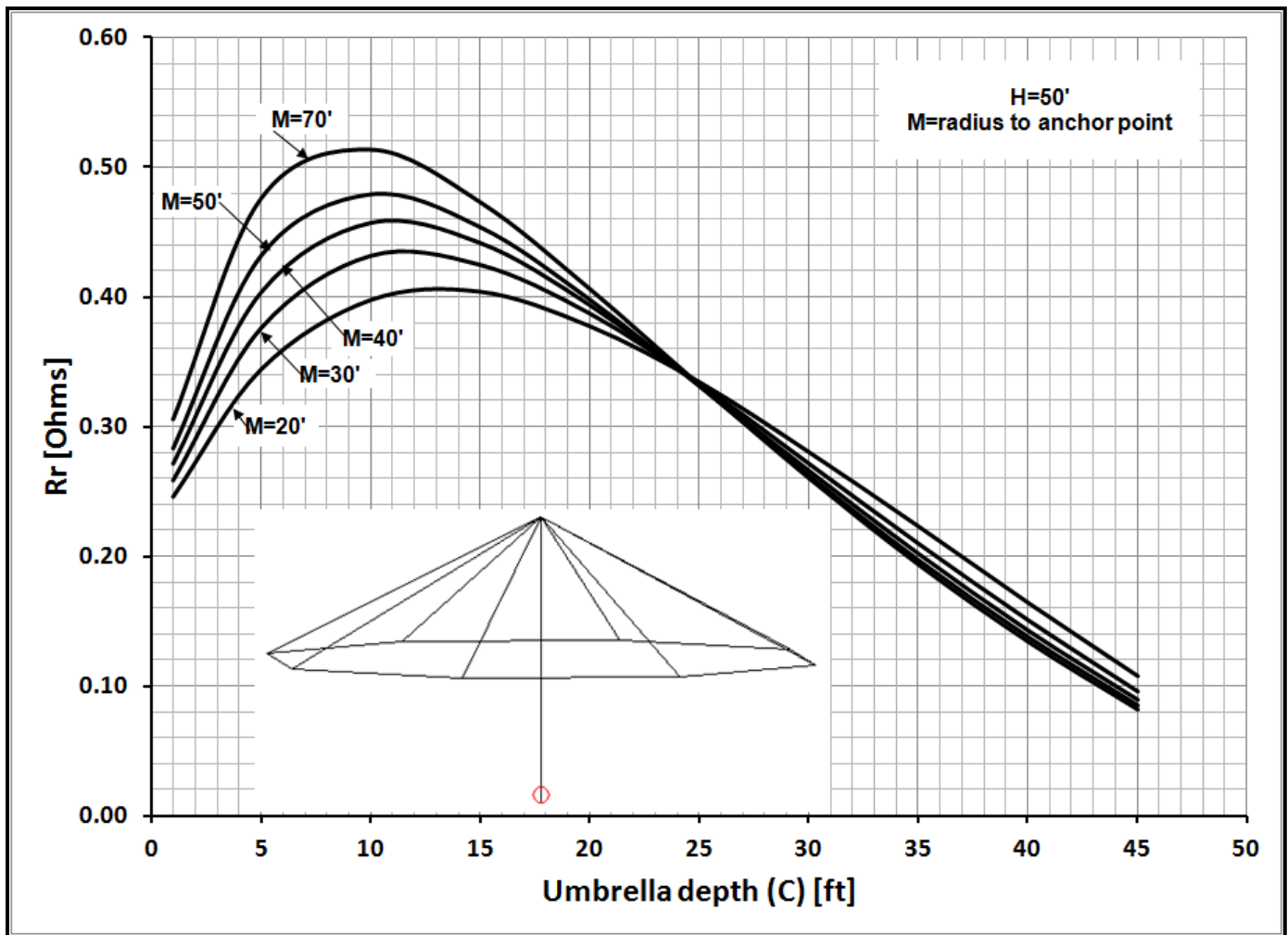


Figure 3.37 - An example of a sloping wire umbrella.

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 R_r 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: $\theta = \text{ATAN}(M/H)$. The larger we make M , the larger θ becomes. For a horizontal umbrella $\theta=90^\circ$. As shown in figure 3.34, with a flat umbrella R_r increases steadily as the radius is increased but in the case of a sloping umbrella as we increase either M or C , R_r goes down but R_r doesn't increase continuously. For a given M , as we increase C , R_r rises initially, reaches a maximum and then decreases. This decrease in R_r is due to the vertical component of umbrella current opposing the current in the vertical.

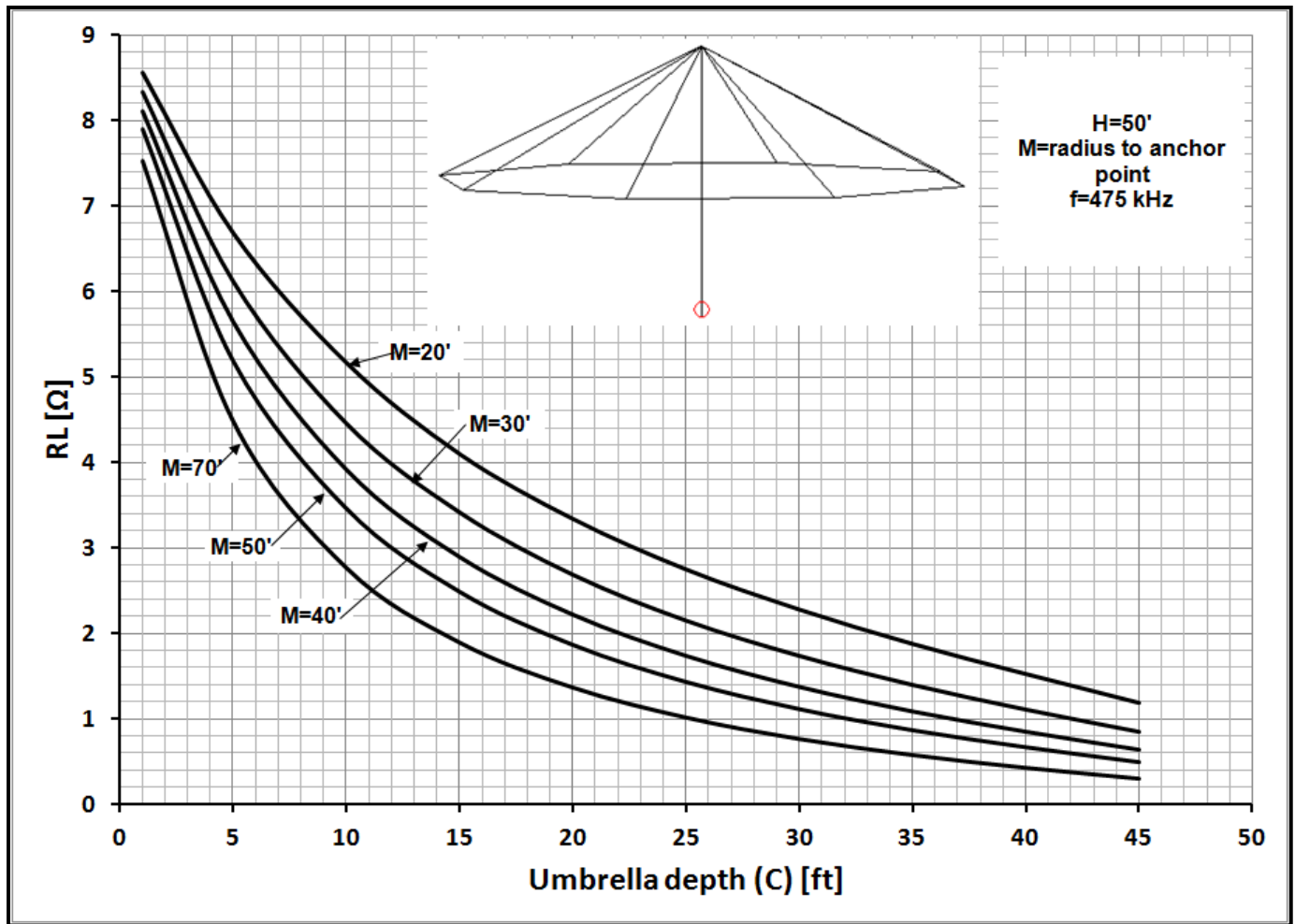


Figure 3.38- Variation of RL with A and C.

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/R_r as shown in figure 3.39. We can see the RL/R_r ratio continues to decrease well beyond the peak for R_r as we increase C but a point is reached ($C \approx 0.4-0.5 H$) where the ratio flattens out. Beyond $C \approx 0.4$ 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.

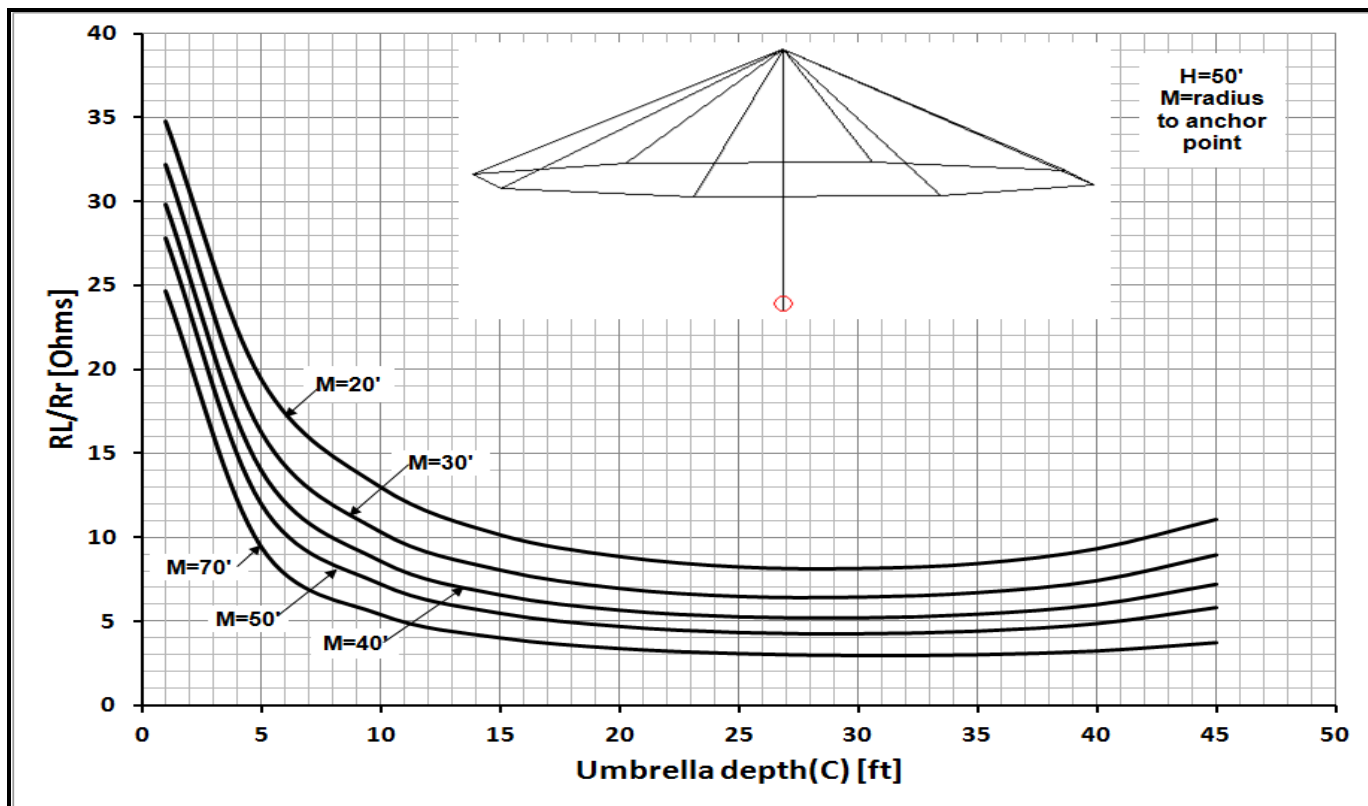


Figure 3.39 - Variation of RL/R_r with M and C .

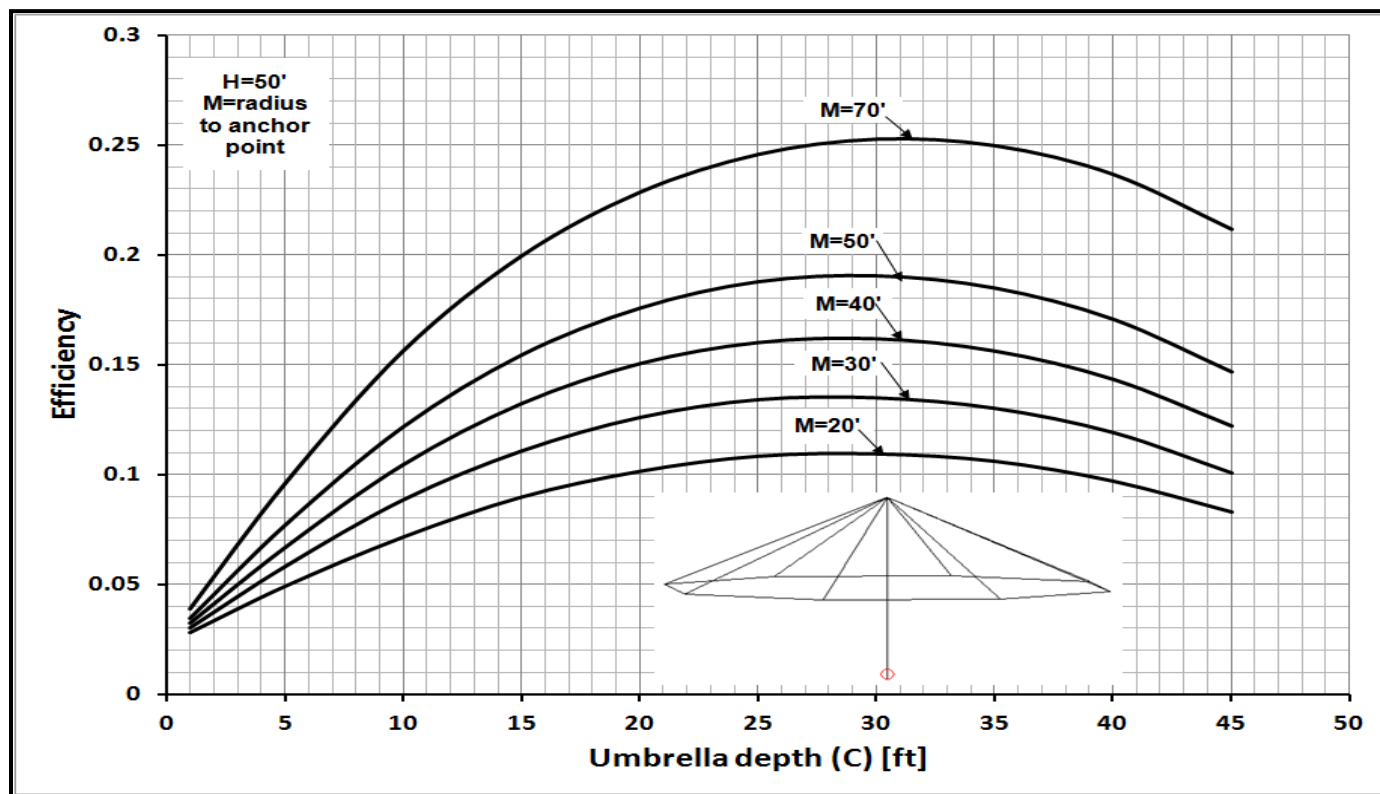


Figure 3.40- Efficiency as a function of M and C .

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 R_r decreases as the drop wire length (C) is made longer. However, R_L is also decreasing due to a falling X_c . The effect of C on efficiency is shown in figure 3.41.

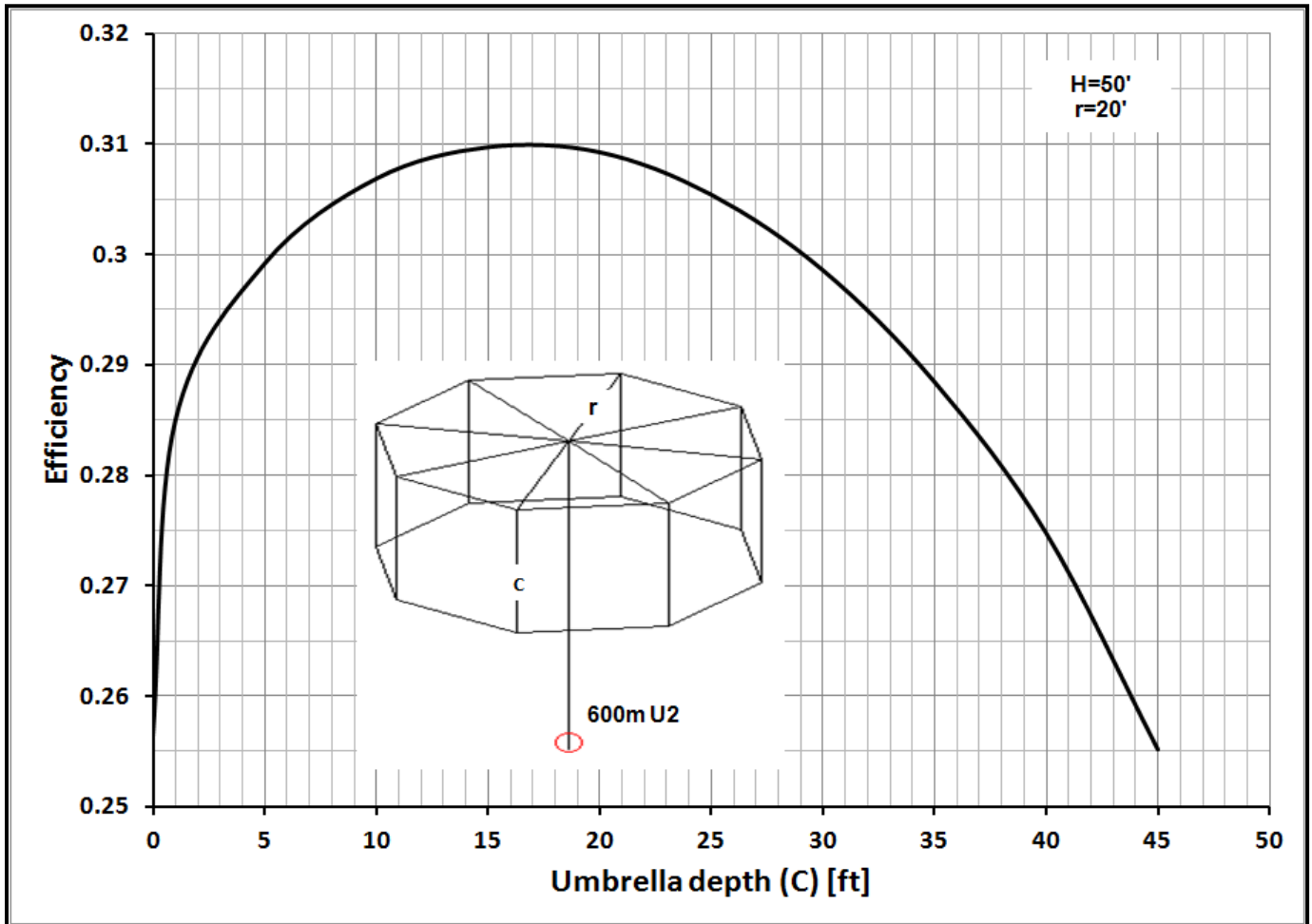


Figure 3.41 - Efficiency of a horizontal umbrella with vertical drop wires on the perimeter of the umbrella.

Adding drop wires allows an increase in efficiency of nearly 6% at $C \approx 0.35H$ 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.

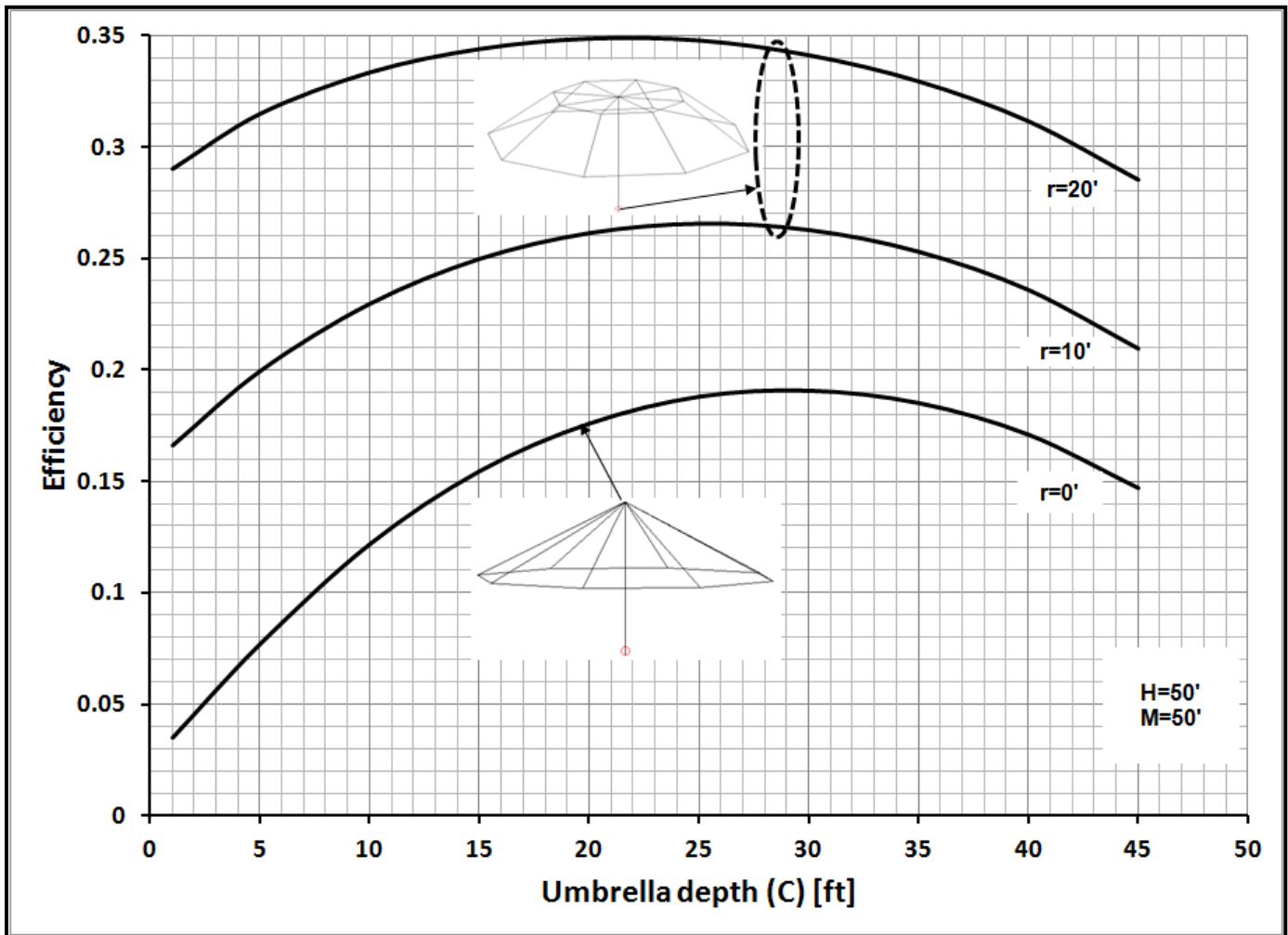


Figure 3.42 - Efficiency for a combined sloping and flat umbrella.

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 $r=0'$, $\eta \approx 19\%$ but when r is increased to $10'$, $\eta \approx 27\%$ and for $r=20'$, $\eta \approx 35\%$. 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 $\approx 4\%$.

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 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 (R_{dc}) is:

$$R_{dc} = \frac{l}{\sigma A_w} \quad [\Omega] \quad (3.12)$$

Where l is the length of the wire, A_w is the cross section area and σ is the conductivity in Siemens/meter [S/m]. For copper $\sigma=5.8 \times 10^7$ [S/m] and for aluminum $\sigma=3.81 \times 10^7$ [S/m]. R_{dc} for copper wire can be found in wire tables.

Unfortunately the AC resistance of the wire (R_{ac}) will be substantially different from R_{dc} due to two effects: skin effect and the effect of non-uniform current distribution.

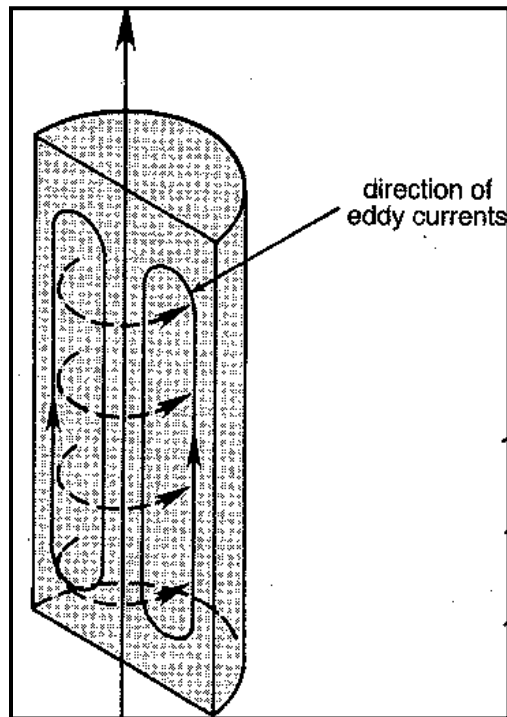


Figure 3.43 - Skin effect.

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 be 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:

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

Where:

σ is the conductivity in [S/m].

μ is the permeability of the material which for Cu and Al $= 4\pi \times 10^{-7}$ [H/m].

f is the frequency [Hz].

The skin depth in mils for copper is:

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

At 137 kHz $\delta=7.03$ mils (0.00703") and at 475 kHz $\delta=3.78$ mils.

The resistance of the wire, R_c , can be represented by the product of the DC resistance (**R_{dc}**) and a factor attributed to skin effect (**K_s**).

$$R_{ac} = R_{dc} \cdot K_s \quad (3.15)$$

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

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

which is graphed in figure 3.44. Note that K_s is only a function of the wire diameter d and the skin depth δ at the frequency of interest ($\delta \propto 1/\sqrt{f}$).

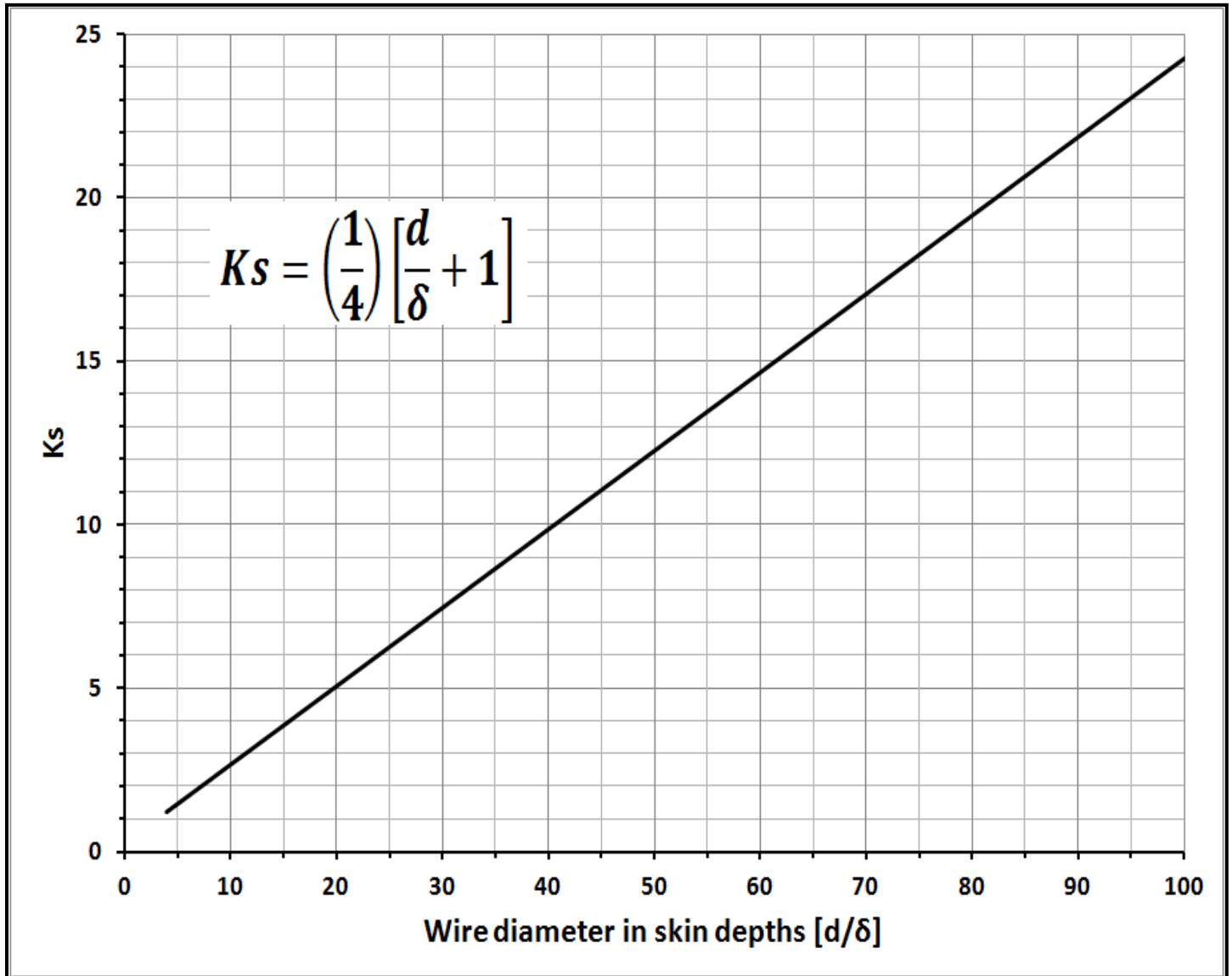


Figure 3.44 - Skin effect factor K_s versus wire diameter in skin depths (d/δ).

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

Table 3.2 - K_s for typical wire sizes.

	137 kHz	475 kHz
Wire #	K_s	K_s
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.

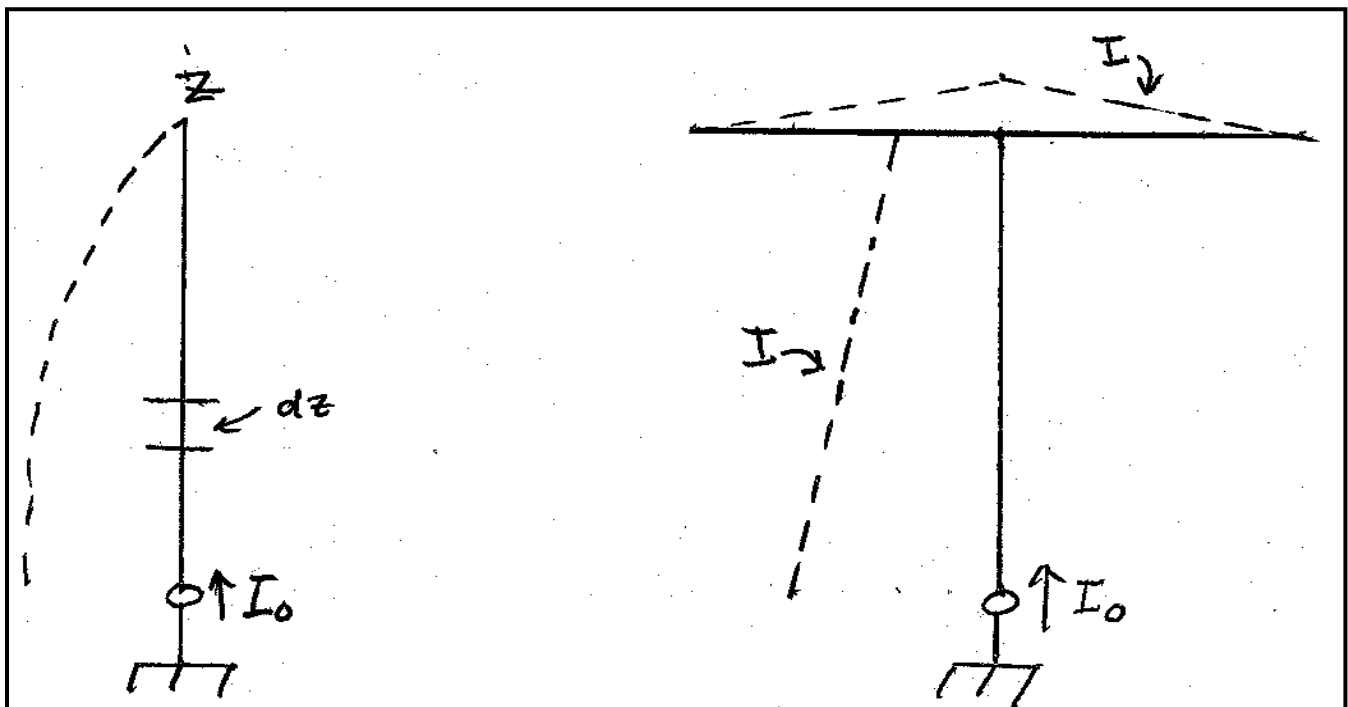


Figure 3.45 - Antenna current examples.

I_o = rms current at the high current end of the wire. R_e = effective resistance of the wire which results in the same power dissipation for a given I_o as the actual power dissipation on the wire. R_e/R_{ac} is the resistance ratio due to non-uniform current distribution.

A graph of R_e/R_{ac} for a linear current distribution is given in figure 3.46.

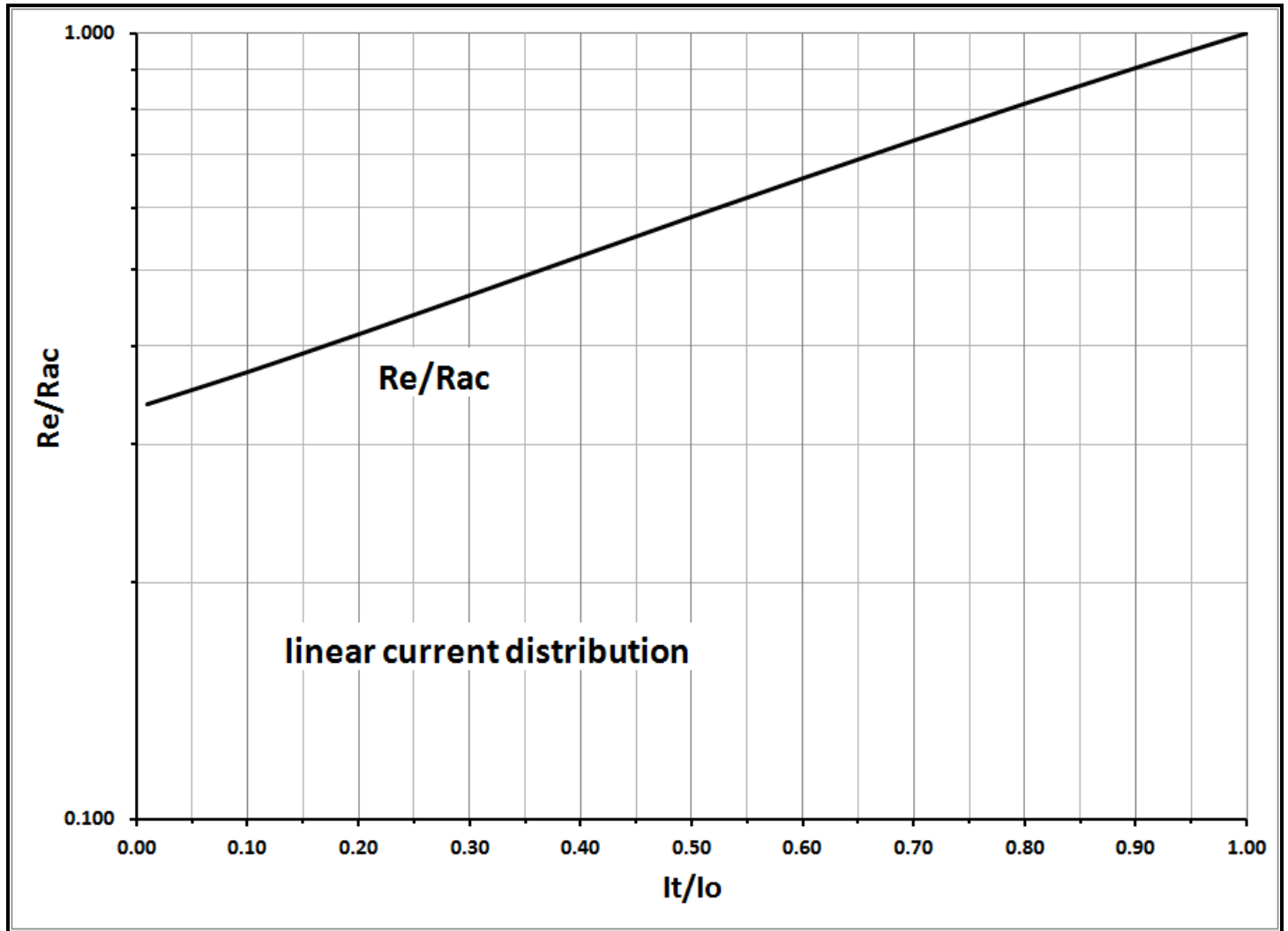


Figure 3.46 - R_e/R_{ac} versus I_t/I_o .

For a vertical with no top-loading, $I_t=0$ and $R_e/R_{ac}=1/3$. More detailed information on K_s can be found in chapter 6.

The cost of the conductors may be a concern. For copper $\sigma=5.8 \times 10^7$ [S/m]. Aluminum has somewhat lower conductivity, $\sigma=3.81 \times 10^7$ [S/m], but is much less expensive and a better strength to weight ratio.

Replacing copper with aluminum:

$$\frac{R_{cAl}}{R_{cCu}} = \sqrt{\frac{\sigma_{Al}}{\sigma_{Cu}}} = \sqrt{\frac{3.81}{5.8}} = \mathbf{0.81} \quad (3.17)$$

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

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

$$\eta = \frac{R_r}{R_r + R_L + R_g + R_c} \quad (3.18)$$

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 $R_r + R_L + R_g$. As the conductor size is 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 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 also 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%!

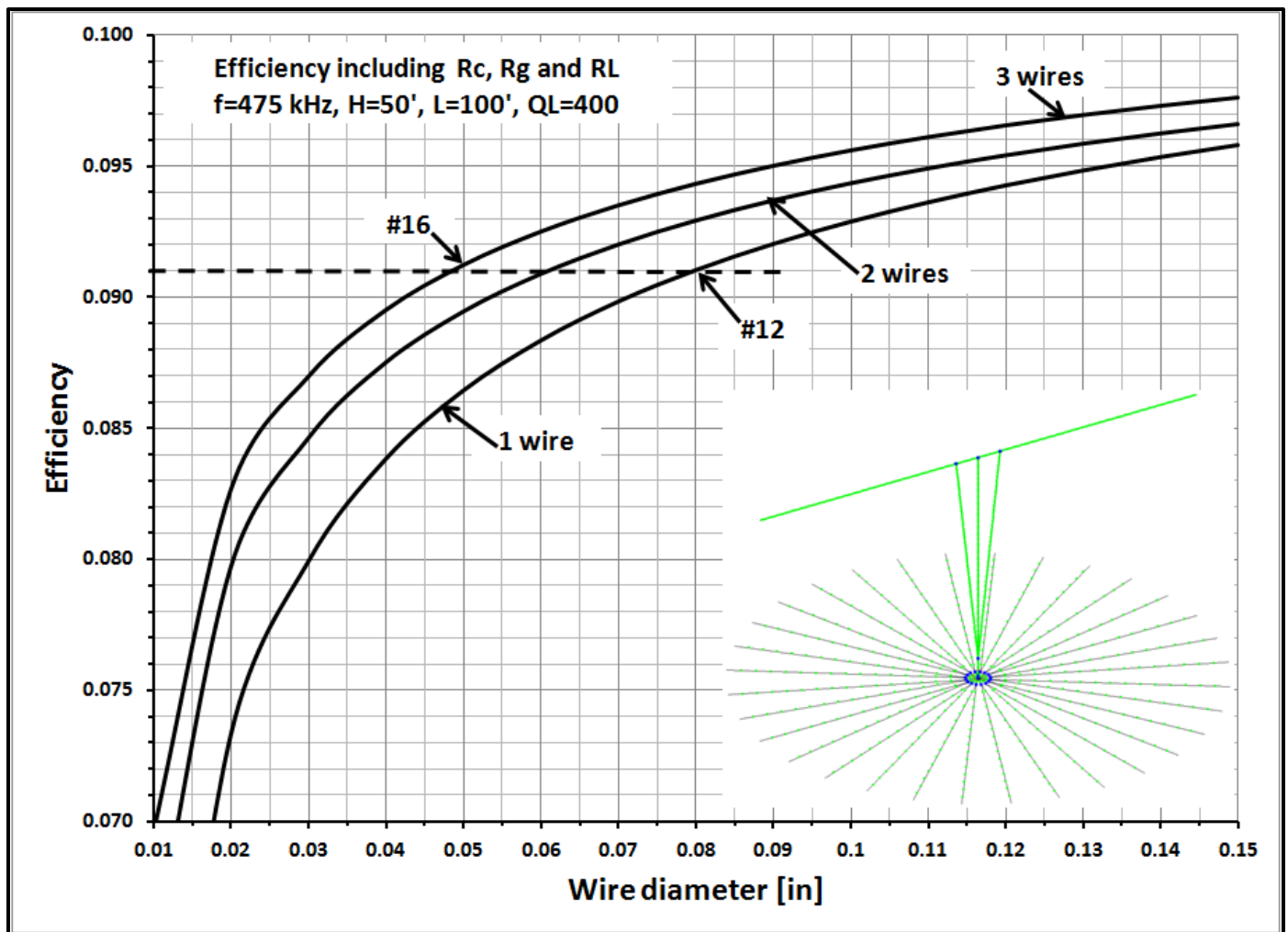


Figure 3.47 - Efficiency versus wire diameter for 1, 2 or 3 download wires.

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 download 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.

For this example we will assume the antenna in figure 3.47 with only one download.

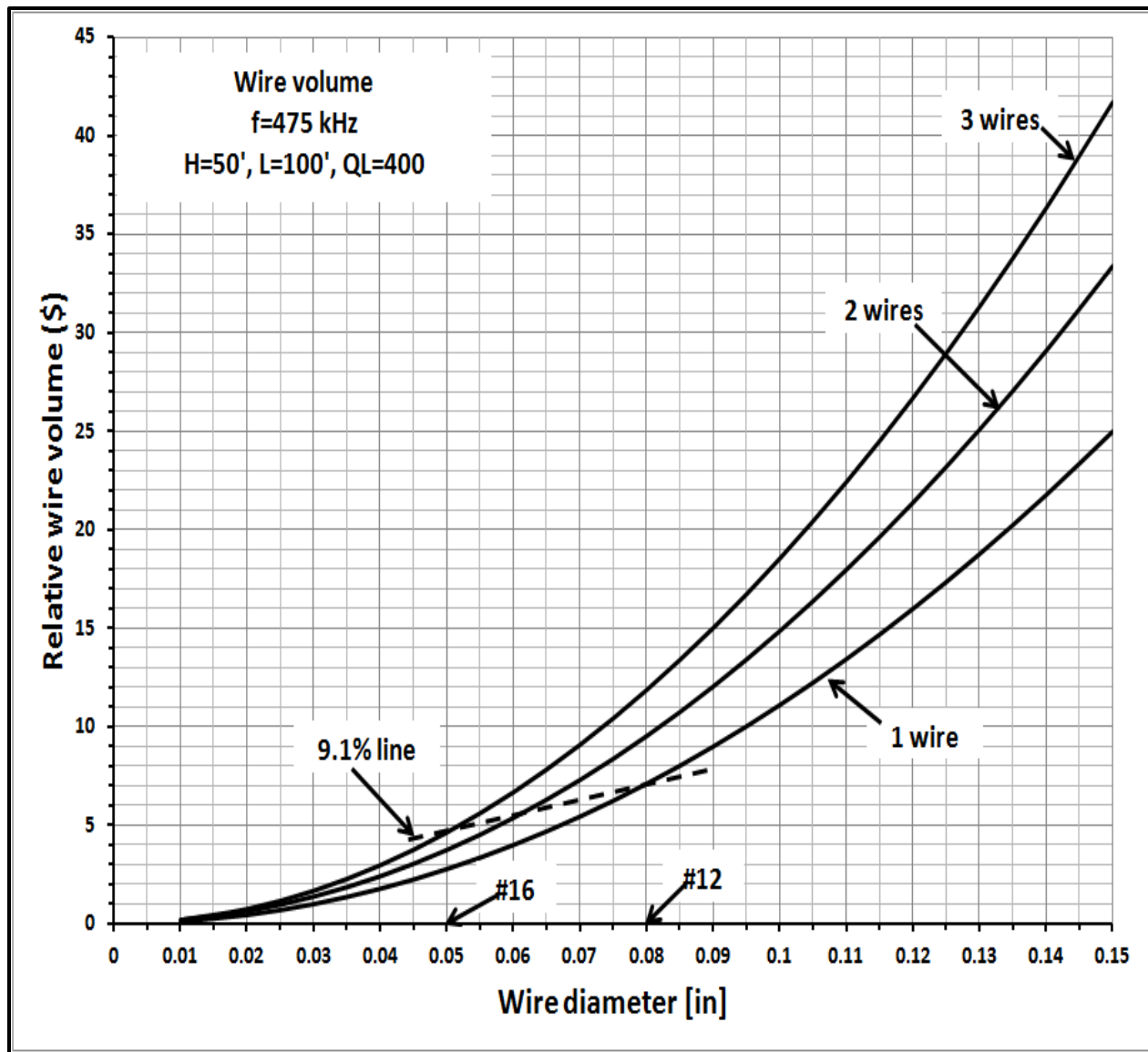


Figure 3.48 - Relative wire volume (\$) versus wire size and download number.

- 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 X_i slightly, from 1245Ω to 1209Ω . This means that X_L is slightly smaller reducing RL and increasing efficiency by $\approx 0.5\%$ 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.

3.12 Voltage, current and power dissipation

At the end of chapter 2 we looked at the voltages (V_o) and currents (I_o) at the feedpoint of a vertical without top-loading. The results were discouraging to say the least! Now it's time to see what happens to V_o and I_o when top-loading is present.

I_o is determined by the radiated power (P_r) and the radiation resistance (R_r):

$$I_o = \sqrt{\frac{P_r}{R_r}} \quad (3.19)$$

As explained in chapter 1, the maximum radiated power (P_r) is limited to 1.67W on 630m and 0.33W on 2200m. Combining the band specific values for P_r with R_r values derived earlier (figures 3.7 and 3.8) we can use equation (3.19) to create the graphs in figures 3.49 and 3.50. Note that L is the overall length of the top-wire in feet in all of the graphs in this section. $L=0$ represents the no top-loading condition.

V_o is the voltage at the feedpoint:

$$V_o = X_i I_o = X_i \sqrt{\frac{P_r}{R_r}} \quad (3.20)$$

We can use typical X_i values from figures 3.4 and 3.5 to generate values for V_o as shown in figures 3.51 and 3.52. Note that the y-axis is logarithmic, emphasizing the rapid change in V_o with top-loading.

These graphs illustrate one important point:

Even a small amount of top-loading significantly reduces I_o and greatly reduces V_o !

Despite the low radiated powers (P_r) V_o can easily approach 1kV on 630m and be even higher on 2200m. This must be kept in mind when selecting a base insulator. It's clear that substantial height (H) and top-loading are required on 2200m if V_o is to be kept below 10 kV. Given that we are trying to radiate only 330 mW that may come as a shock!

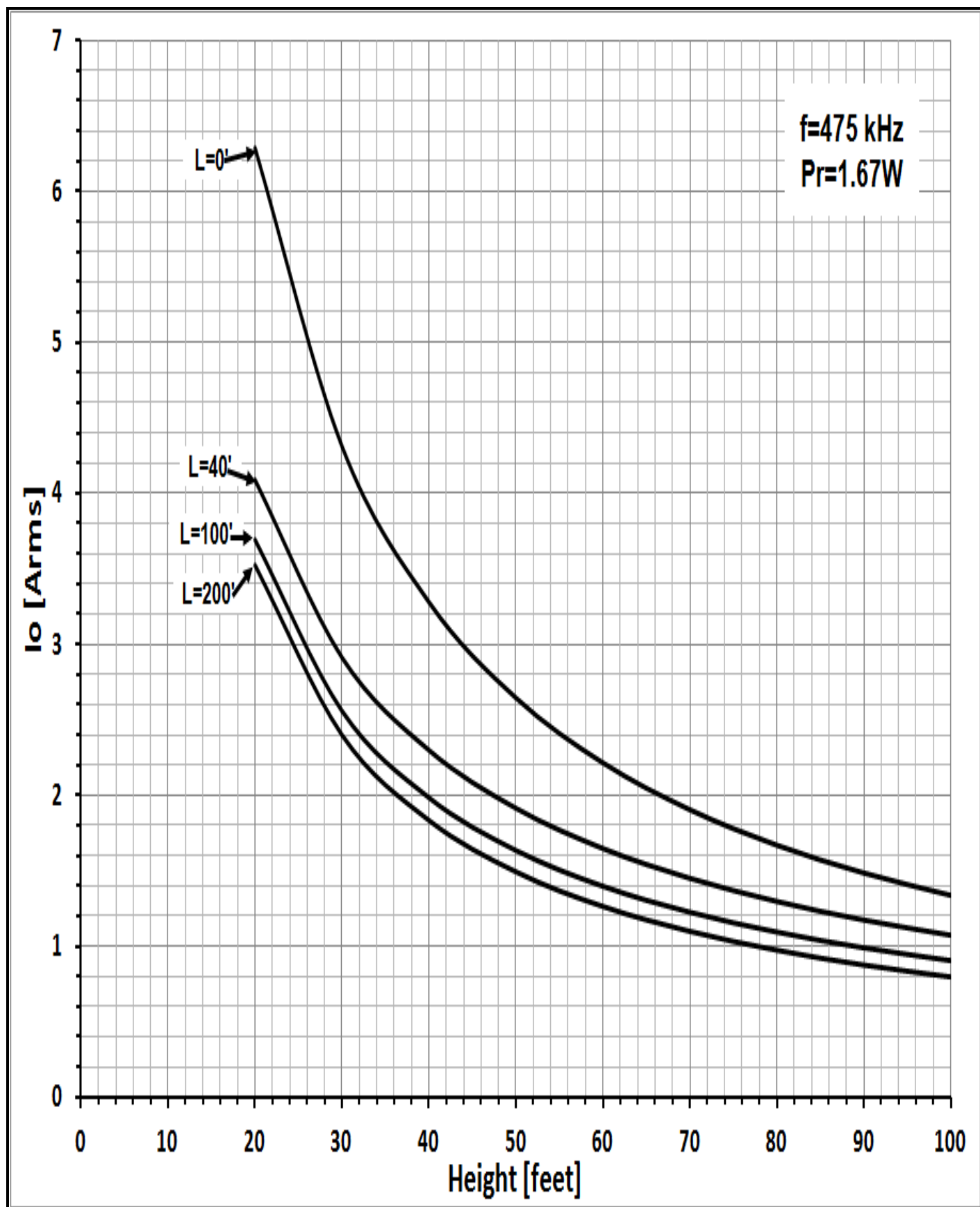


Figure 3.49 - I_o for $P_r=1.67$ W at 475 kHz.

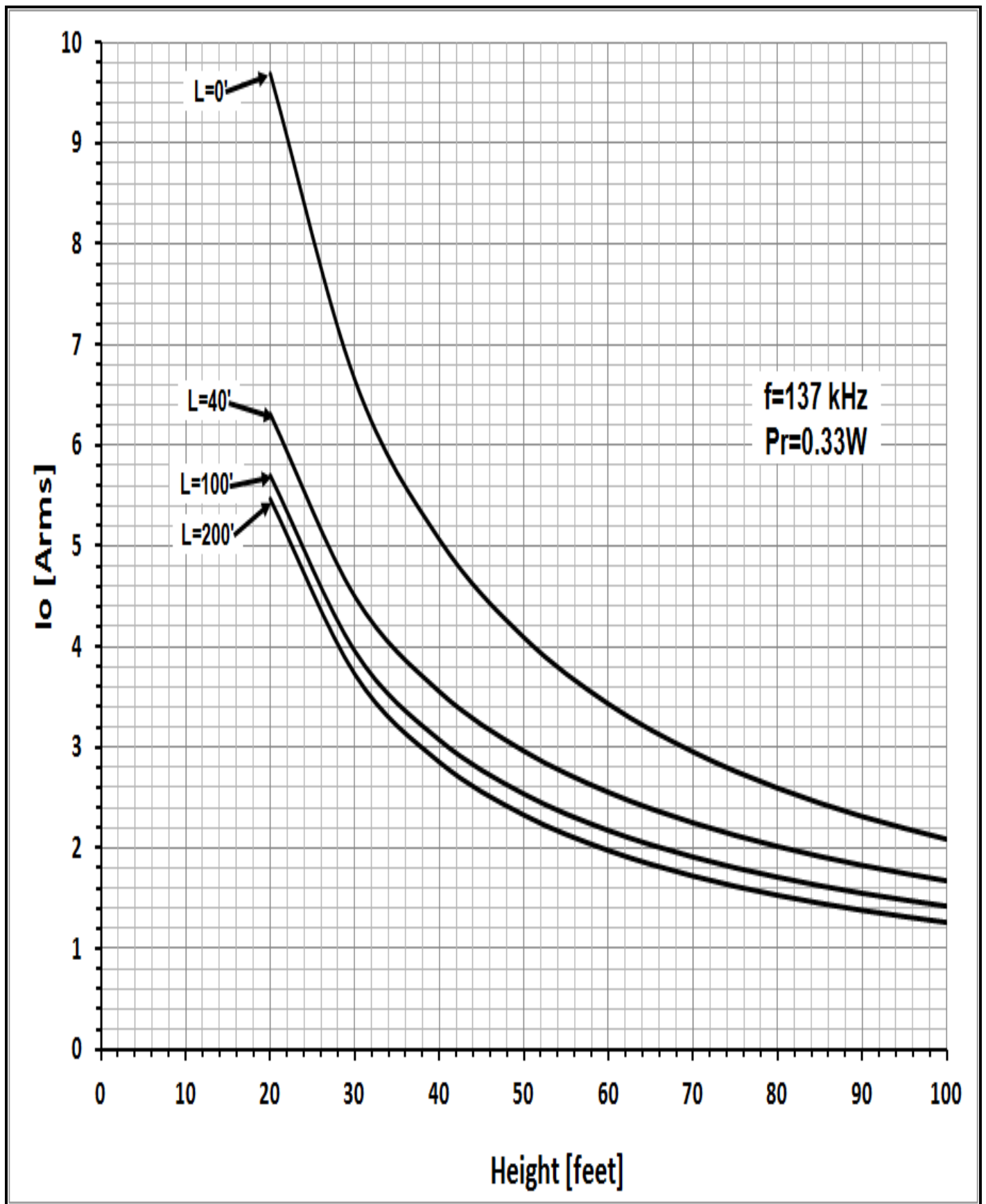


Figure 3.50 - I_o for $Pr=0.33W$ at 137 kHz.

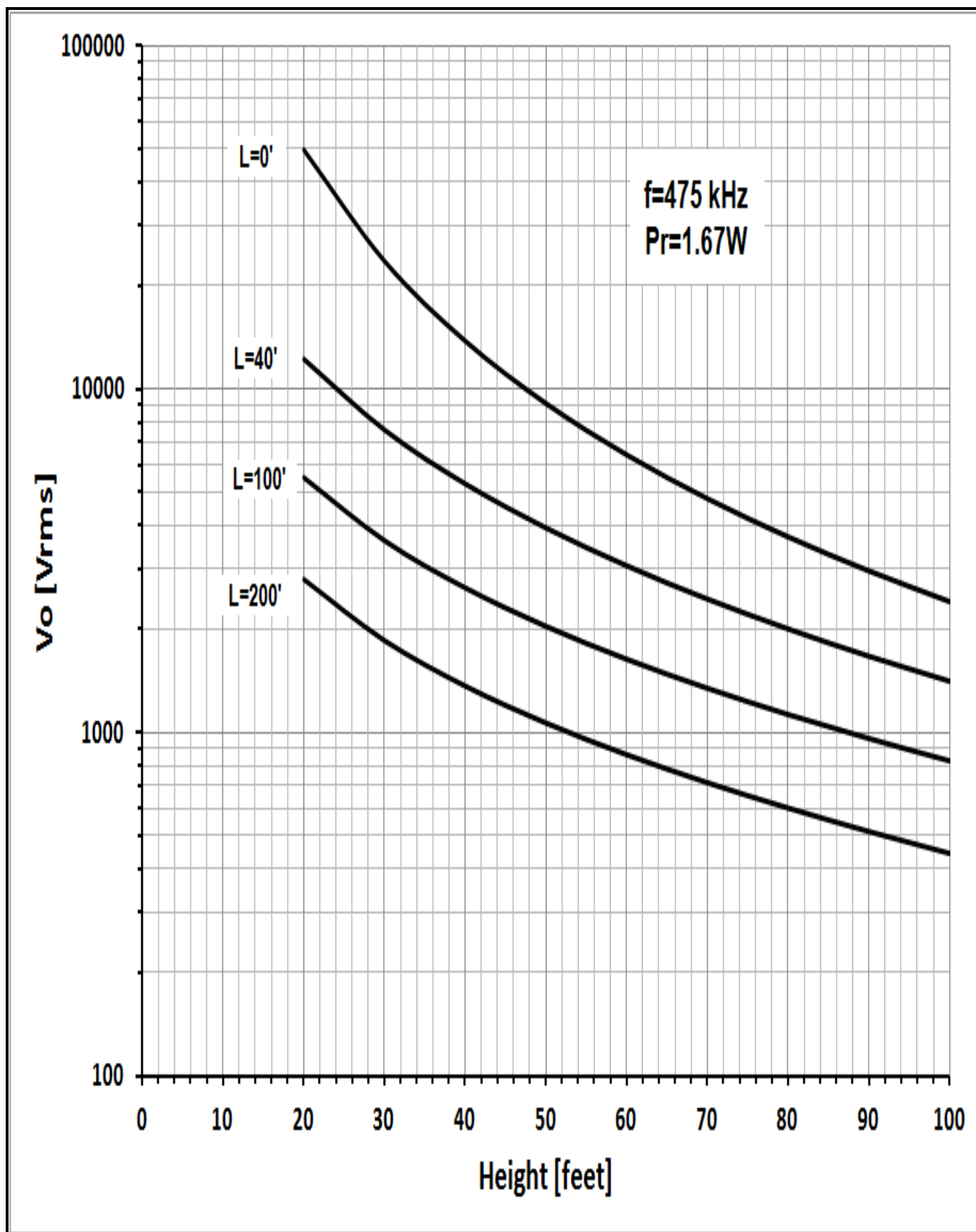


Figure 3.51 - V_o for $P_r=1.67W$ at 475 kHz.

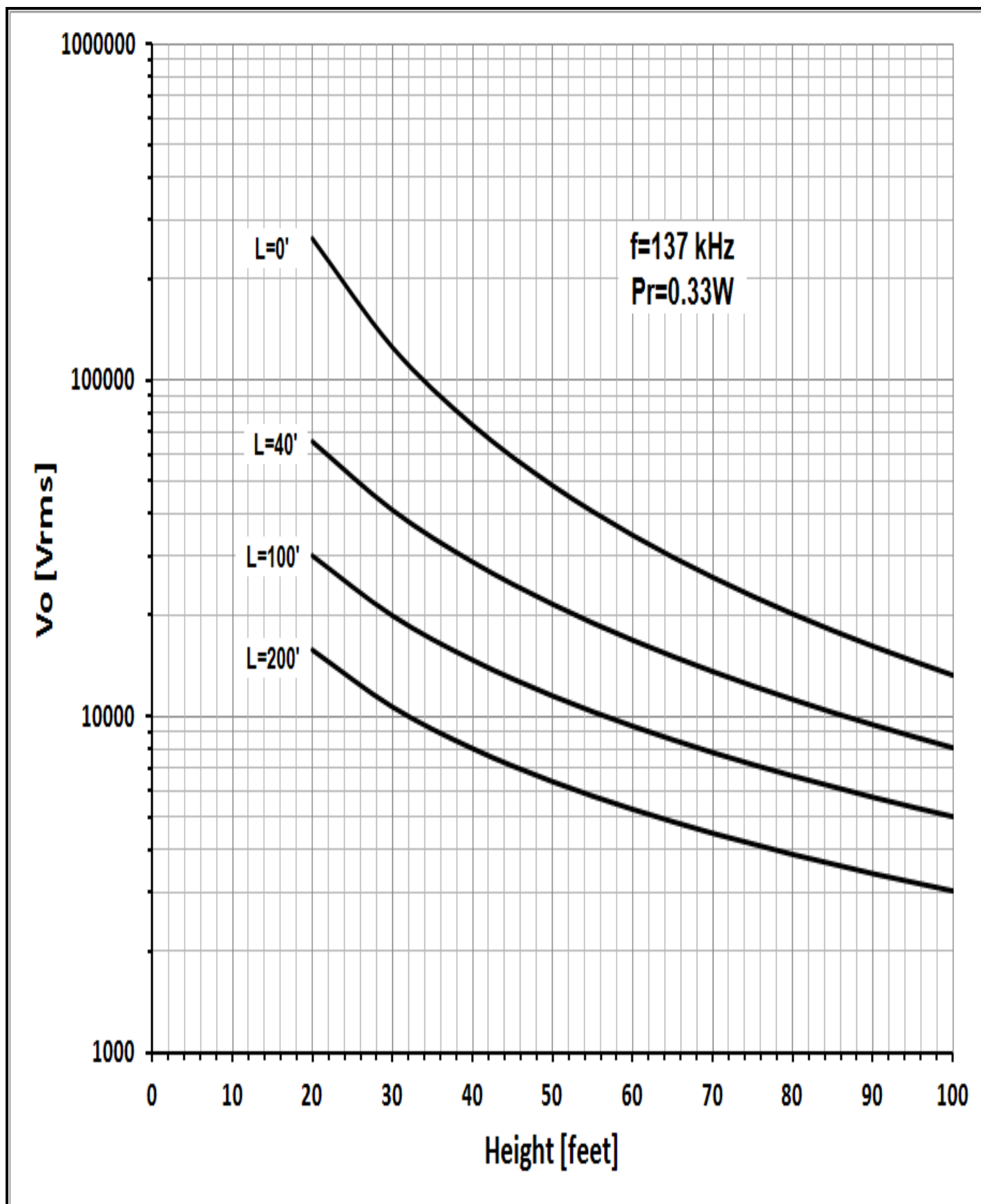


Figure 3.52 - V_o for $Pr=0.33W$ at 137 kHz.

The input power to the antenna will include P_r , the radiated power, P_L , the power dissipated in the loading inductor, P_g , the power lost the soil, plus conductor and leakage current losses. All of these losses are reduced substantially when I_o and V_o are reduced. P_c was discussed in section 3.11, P_g is addressed in chapter 5 and P_L is discussed in chapter 6. In general P_L and P_g are the dominant losses, usually very much greater than P_r .

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