Some Thoughts on 630m Verticals

Part 1, the problem with simple verticals

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July 2012

Introduction

There will be a 630m (472-479 kHz) amateur band sometime next year. Except for a few experimental licenses over the past 10 years amateurs haven't been allowed on these frequencies for over 100 years. This lack of experience means there will be a great need for practical information on many subjects including antennas. As pointed out by Mark Perrin, N7MQ, efficient and practical antennas for 630m will be a challenge:

> "Operating 630 meters under the new rules will for many, be much like those who operate 160 meters while mobile. The antenna, almost always a vertical, will be very short and at least comparatively, very inefficient. But, just like the 160m mobile aficionado and others who operate on the low bands with short verticals, the 630 meter operator will be successful and enjoy the band."

I think Mark's comparison to 160m is important. Recruits for the new band are very likely to come from the top-band crowd who are accustomed to building their own antennas and dealing with longer wavelengths. If you divide 1.9 MHz by four you get 475 kHz which is right in the middle of the new band. A 160m 1/4-wave vertical will be a 1/16-wave (0.0625 λ_o) vertical on 630m.

Most amateurs do not live on extensive acreage and/or have unlimited funds and in many cases their antennas will have to fit in urban backyards. This multi-part series of articles on 630m antennas discusses limitations inherent in small antennas, makes suggestions for optimizing short antennas and gives practical examples which have been field tested. The free space wavelength (λ_o) at 475 kHz is ≈2071' so a $\lambda_o/4$ vertical would be ≈500' high! It's unlikely many amateurs will put up anything near that height. This series looks at verticals with physical heights (H) between 20' (≈0.01λ_o) and 100' (≈0.05λ_o), with emphasis on the shorter end of the scale (H=40'-60'). By any definition these are "small" or "short" antennas, which will have very low radiation resistance (R_r), narrow bandwidth and high losses even with the best design and construction.

There's nothing new about short antennas. Given the very long wavelengths used initially in radio all the antennas were "small" even those hundreds of feet high. A lot of work was done to improve these antennas, work that continued into the 1960's for VLF applications[1]. The low efficiency and narrow bandwidth associated with short antennas derive from fundamental physics and the underlying physical processes have been studied very carefully[2,3]. Like the perpetual motion machine, a 100% efficient small antenna is not in the cards but much can be done. Interestingly, short antennas are still a hot topic today among professionals where the interest is in very small VHF and UHF antennas[4]. Despite 120 years of work there's still a lot to learn! One rich source of ideas for MF antennas can be found in old radio books from the 20's and 30's[5-18]. Often these books are seen at ham flea markets for a few dollars. The 20's and 30's were a time when most amateurs did not have a lot of money and improvisation was the order of the day. A lot of what was done then is still useful today. A very succinct summary of low frequency antenna design was made by Woodrow Smith[21] some 65 years ago:

> "the main object in the design of low frequency transmitting antenna systems can be summarized briefly by saying that the general idea is to get as much wire as possible as high in the air as possible and to use excellent insulation and an extensive ground system."

I've organized this advice into a list <u>in order of priority</u>:

1) Make the vertical as tall as you can.

2) Use as much capacitive top-loading as practical.

3) Use loading coils with as high a Q as you can.

4) Put a lot of effort into the ground system, making the radial density high near the base of the vertical.

5) Try to minimize conductor losses by using multiple wires and/or large diameter conductors (tubing!)

This series provides a lot of justification for this advice and the order of priorities but in the end boils down to Smith's simple characterization.

About this series

I'm planning to write quite a bit of material on 630m antennas but that will take time. So I've divided the work into multiple parts some of which will be available initially with more to follow as I have time to work on them. None of the parts of the series is intended to be the final word. All will be subject to additions, revisions, criticism and corrections over time.

Part 1 begins with the introduction you've just read and then takes a critical look at simple straight verticals to illustrate problems intrinsic to small antennas, in particular the fundamental limitations on efficiency imposed by loading inductor losses. Most of the terms I use are common in antenna discussions but if you haven't read the ARRL Antenna Book[19] for a while do so, it's a good review which will make it much easier to follow the discussion in later parts. In particular read carefully the discussion on ground systems in chapter 3 (22nd edition) and the basic concepts in chapter 1.

Part 2 is aimed at those with some experience on 80 or 160m and discusses improving the performance of short verticals using a variety of techniques. Part 2 looks closely at the effect of loading inductor losses and how to reduce them by reducing the required loading inductance (XL). To keep in touch with reality, ground and conductor losses are introduced at several points but a more detailed review of ground systems is deferred to part 5. The intent of part 2 is to give you ideas and illustrate tradeoffs to help you design an antenna that fits your particular situation.

Part 3 gives examples of actual antennas which have been built and tested. The descriptions have sufficient detail to enable you to reproduce these antennas if they fit in your QTH.

Part 4 looks at transmitting loop antennas. One wrinkle in this section is a discussion of wire ground systems for vertical loop antennas. This is unusual because I have never seen a discussion of such ground systems in either the amateur or professional literature although I can't imagine someone hasn't thought about it before. Most people seem to think that a transmitting loop does not need a ground system. I'll show how far from the truth that idea is!

Part 5 goes into much more detail on ground systems.

Part 6 treats the subject of matching networks and bandwidth. There is also information on inductor design and other practical details.

Additional parts will be added as they become available.

Characteristics of simple verticals

This section looks at a short vertical with a single straight conductor (a wire or some tubing, etc) with some height (H). The purpose of this discussion is to expose the problems and limitations inherent in these antennas to illustrate why we need to go to the trouble of building the more complex designs described in later parts and to identify which problems need to be addressed first. Later parts of this series are devoted to minimizing these problems to realize practical and reasonably efficient antennas. What do I mean by "reasonably efficient"? I mean efficiencies in the range of 10% to 30%. For 5W of radiated power 10% efficiency would require 50W to be delivered to the antenna feedpoint.

A NEC model for a vertical with a small ground system is shown on the graph in figure 1. The vertical is fed at the base.

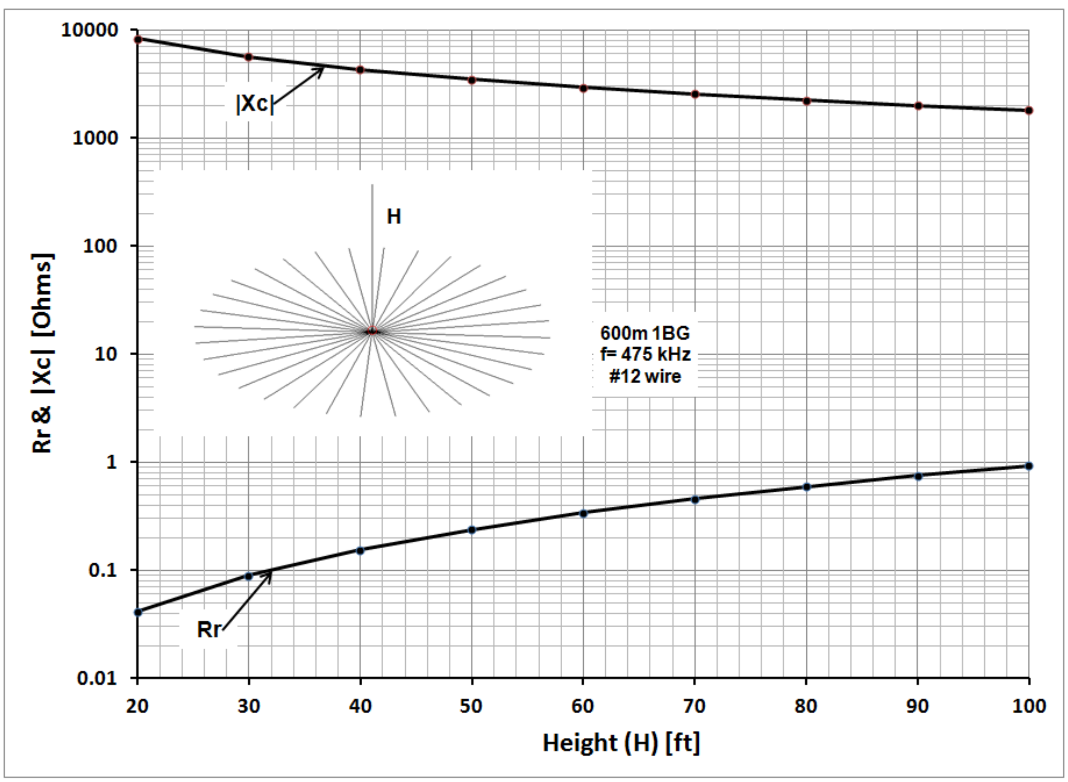

Figure 1 - Example of the feedpoint impedance (Zin = Rr + j Xc) without losses.

Figure 1 graphs two components of the feedpoint impedance: the radiation resistance (Rr) and the magnitude of the capacitive reactance (Xc) measured at the base of a lossless #12 (d=0.08") wire vertical at 475 kHz as H is varied from 20' to 100'. These very low values for Rr are typical for short antennas as are the high values for Xc. Remember that:

$$C = \frac{1}{2\pi f Xc} \; and \; L = \frac{XL}{2\pi f} \quad (1)$$

At 475 kHz 2πf=2.98x10^6 ≈3x10^6. At 475 kHz equation (1) can be simplified to:

$$C \approx \frac{1}{3Xc} \; \mu F \; and \; L \approx \frac{XL}{3} \; \mu H \quad (2)$$

Very short antennas represent a small capacitance (large Xc) in series with a very small resistor. Figure 1 shows only Rr but we know that real antennas will have losses so the resistive part of Zin will be Ra=Rr+ loss resistances. An equivalent electrical circuit for Zin is shown in figure 2.

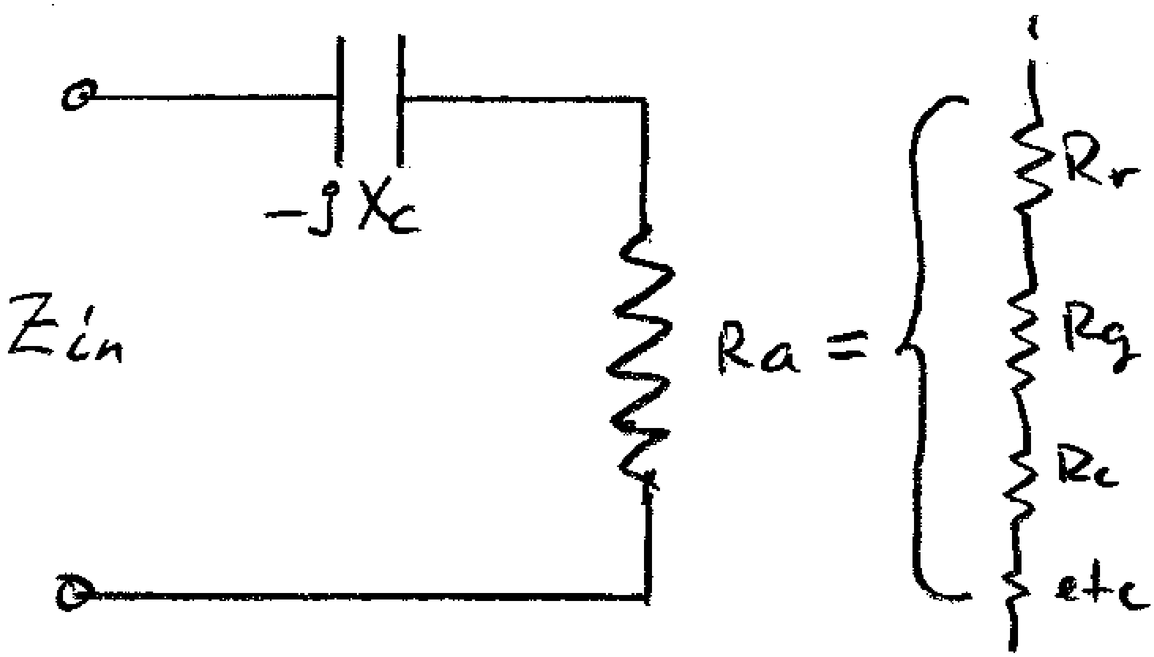

Figure 2 - Equivalent circuit for Zin.

In short antennas the loss resistances are not small and frequently Ra is much larger than Rr, which is the same as saying the efficiency is low (efficiency = Rr/Ra). There are several sources of loss:

- Loading coil resistance - RL
- Equivalent ground loss resistance - Rg
- Conductor resistance - Rc
- Loss due to leakage across insulators (at the base and at wire ends) - Ri

- Corona loss at wire ends - Rcor
- Matching network losses - Rn

In general RL and Rg are the dominate losses but in short antennas conductor currents and the potentials across insulators will be much higher (for the same input power) than in taller verticals. The shorter the antenna the greater the losses from all causes and a major part of the design effort is directed towards minimizing all losses.

We can use NEC to estimate many of these losses. Modeling over perfect ground can give good estimates for Rr, Rc and RL (derived from the value for Xc) but for Rg we need to add the ground system which requires NEC4. The ground system shown in figure 1 has thirty two 100' radial wires buried 6" in average soil (σ = 0.005 S/m and ε_r = 13). By amateur standards this is a pretty large ground system but the radial lengths are only $0.05\lambda_o$ which is quite short electrically. By commercial standards this is a very modest ground system. We'll use this ground system for much of the following discussion but in part 5 we'll look at other ground systems.

Given the impedances shown in figure 1, it's pretty clear that the 50 Ohm SWR at the feedpoint will be very high >1000:1! The logical first step is to tune out the capacitive reactance (-jXc) by adding a series inductor at the feedpoint as shown in figure 3. For resonance XL = Xc and RL is the loss resistance associated with the inductor (RL = XL/QL). QL is the Q of the loading inductor which will normally be in the range of 100 to 600. QL=100 represents a pretty mediocre inductor but QL's in the range of 400-600 are practical with some care in construction. However QL's much larger than this are difficult so for much of the discussion in this series a compromise QL=400 will be used unless stated otherwise.

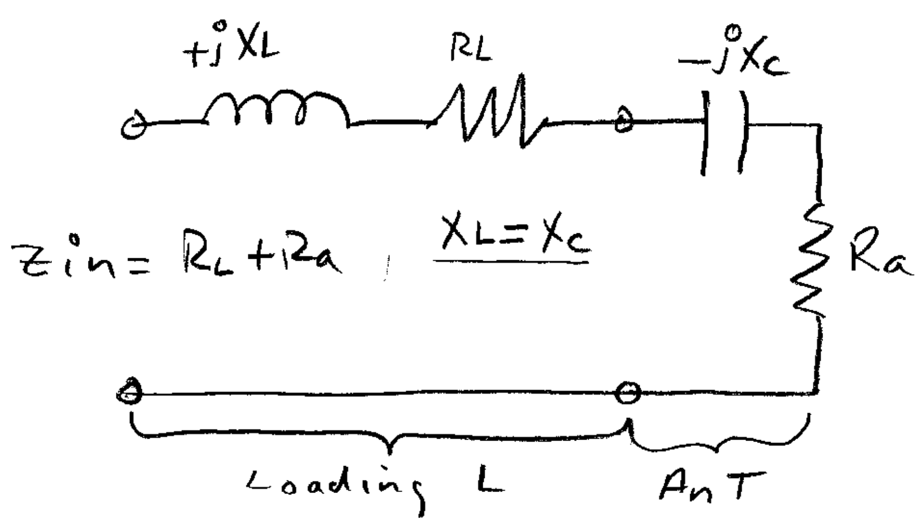

Figure 3, equivalent circuit of a short vertical with a resonating inductor.

From NEC we can derive values for Rr, RL, Rg and Rc as shown in figure 4 where RL=Xc/400.

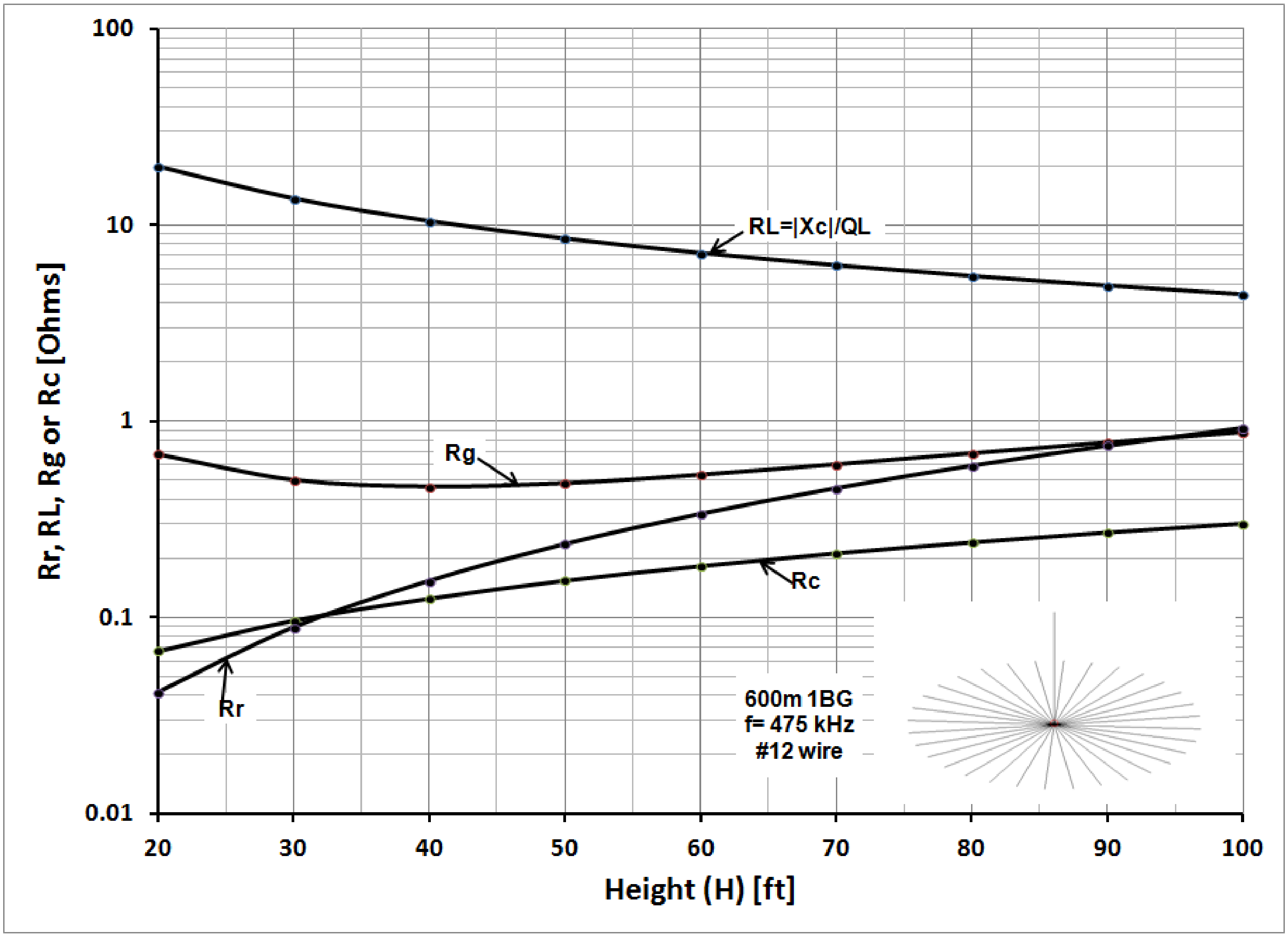

Figure 4 - Values for Rr, RL, Rg and Rc for the antenna shown figure 1.

Notice how much larger RL is than the other resistances! We can calculate the antenna efficiency (η) using the following expression (for now I've left out the corona, leakage and matching network losses):

$$\boldsymbol{\eta} = \frac{\textbf{\textit{power radiated}}}{\textbf{\textit{input power}}} = \frac{R_r}{R_r+R_L+Rg+Rc} = \frac{1}{1+\frac{R_L+Rg+Rc}{R_r}} \quad (3)$$

Using equation (3) and the values in figure 4, we can graph the efficiency as a function of H as shown in figure 5. The efficiency is given in decimal form, i.e. 0.1 =10%.

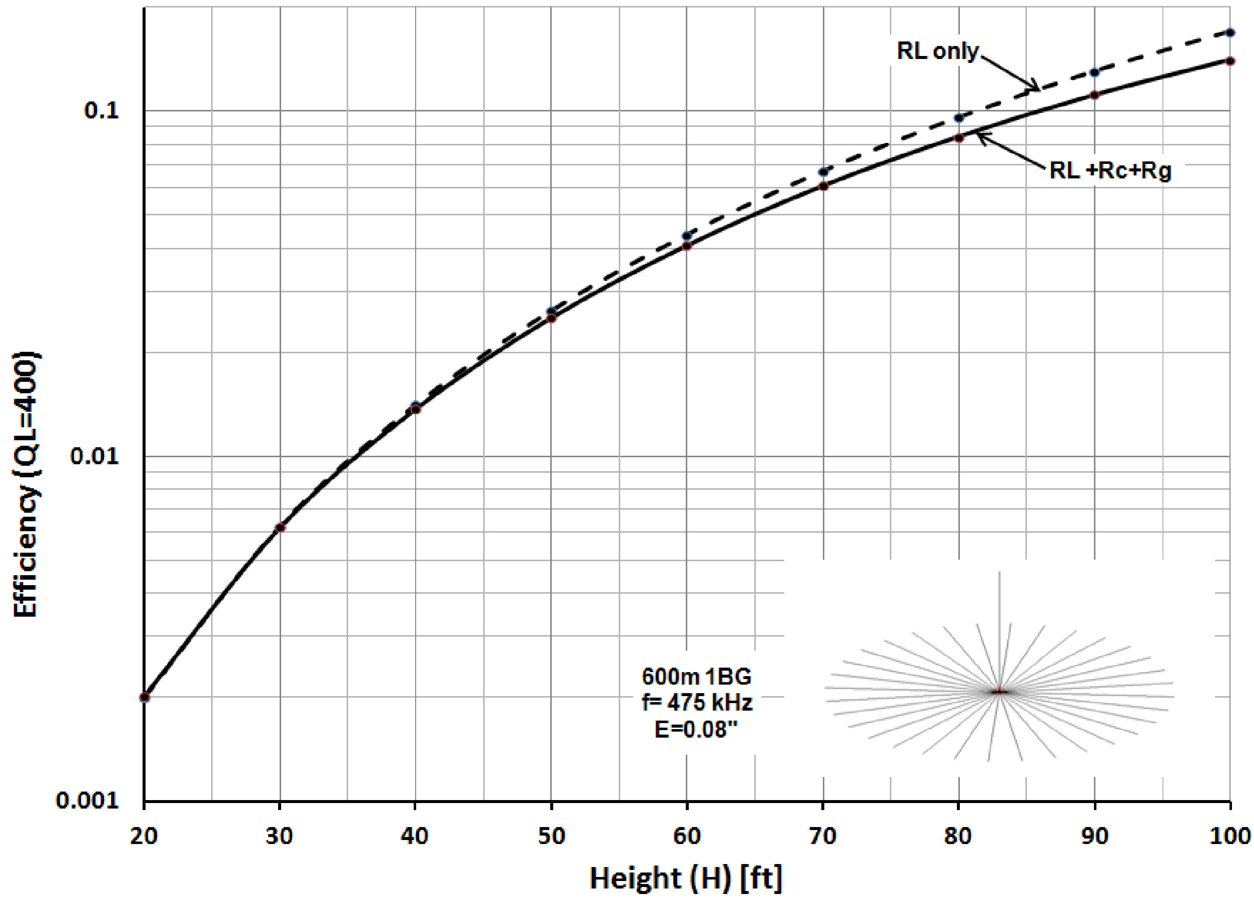

Figure 5 - Efficiency of a simple vertical.

The dashed line in figure 5 represents the case where only Rr and RL are considered which illustrates that RL is the dominant loss throughout this range of H. This observation is important because it tells us what our design priorities must be. The value of RL is tied directly to the value of XL (XL= Xc) through QL. This sends a very clear message:

To reduce RL we must reduce Xc!

As equation (3) shows, in addition to reducing Xc increasing Rr will also help. At higher frequencies it is often possible to use enough capacitive loading that XL can be eliminated[20] but at 475 kHz that's usually not practical and we have to settle for minimizing XL. Practical ways to minimize XL and increase Rr are the subject of part 2.

References

[1] Watt, Arthur D., VLF Radio Engineering, Pergamon Press, 1967.

This is an engineering text for LF and VLF antenna design and it has a lot of math but even for the mathematically challenged there is still a lot of useful non-mathematical information.

[2] Hansen, R.C., Electrically Small Superdirective and Superconducting Antennas, Wiley 2006.

One of the great parts of this book is the discussion on "pathological" antennas. A lot of nonsense has been written on small antennas and Hansen does a nice job of reviewing these. The is also a chapter on antennas which are ok but really don't provide any new benefits.

[3] Wheeler, Harold, Fundamental Limitations of Small Antennas, Proceeding of the IRE, vol. 35, December 1947, pp. 1479-1384.

This paper, by an eminent 20th century physicist, shows the fundamental limits on small antennas. There are a lot of equations but they're mostly simple algebraic expressions. This paper has stood the test of time and is well worth the effort to read. As Marshall Cross (W1HK) pointed out in quoting Hansen, a primary application of the Wheeler paper to identify “nut-house” antennas and impossible performance claims.

[4] Miron, Douglas B., Small Antenna Design, Elsevier Inc., 2006.

Available in paperback and used on Amazon. This book has a good discussion on NEC modeling which I found very helpful.

[5] Ghirardi, Alfred A., Radio Physics Course, Radio & Technical Publishing, 1933

[6] Moyer and Wostrel, The Radio Handbook, McGraw-Hill, 1931

[7] Morecroft, Pinto and Curry, Principles of Radio Communication, Wiley 1934

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[9] The Principles Underlying Radio Communication, U.S. Army signal Corps, Radio Communication Pamphlet No. 40. May 1921

[10] Bucher, Elmer E., Practical Wireless Telegraphy, Wireless Press

[11] Radio Fundamentals, United States Naval Institute, 1940

[12] Admiralty Handbook of Wireless Telegraphy, 1931

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[17] Henney, Keith, Radio Engineering Handbook, many editions over the years, latest 1959

[18] Doane, Francis H., Radio Devices and Communication, International Textbook Company, 1925

[19] ARRL Antenna Book, 22nd edition, 2011

[20] Severns, Rudy, N6LF, Some Ideas For Short 160m Verticals, QEX tbd

[21] Smith, Woodrow, Antenna Manual, 1948

Bibliography

There are many other books and articles with useful information for short verticals. Here are a few of them.

[1] Laport, Edmund, Radio Antenna Engineering, McGraw-Hill, 1952.

Chapter 1 on low frequency antennas is particularly useful. This book is available on-line for free.

[2] Fujimoto, K., et al, Small Antennas, Research Studies Press, 1987 (Wiley is the US Distributor).

[3] Smith and Johnson, Performance of Short Antennas, Proceeding of the IRE, October 1947, pp. 1026-1038.

This paper is a wonderful summary of experimental work done at MF (100-400 kHz) for a short vertical top-loaded with an “umbrella” of down-sloping wires. There is a summary and discussion of their experimental results at the end of part 2.

[4] Smeby, Lynne, Short Antenna Characteristics, Proceedings of the IRE, October 1949, pp. 1185-1194. This paper has a discussion of umbrella top-loading with and without a skirt wire.

[5] Harrison, Charles Jr., Monopole with Inductive Loading, IEEE transactions on Antennas and Propagation, July 1963, pp. 394-400.

This paper discusses inductive loading as the inductor is moved up into the antenna. It is a excerpt from an earlier study done by the author: Monopole With Inductive loading, Sandia Corporation Monograph, SCR-590, November 1962.

[6] Czerwinski, W. P., On Optimizing Efficiency and Bandwidth of Inductively Loaded Antennas, IEEE transactions on Antennas and Propagation, September 1965, pp. 811-812. This is a follow up note to the Harrison paper.

[7] Gangi, Sensiper and Dunn, The Characteristics of Electrically Short, Umbrella Top-Loaded Antennas, IEEE transactions on Antennas and Propagation, Vol. Ap-13, No. 6, November 1965, pp. 864-871.

This is another report on experimental work that pretty much confirms the theoretical analysis in earlier papers.

[8] Jansen, Gerd, Kurze Antennen (Short Antennas), Franckh'sche Verlagshandlung, Stuttgart, 1986.

If you can decipher a German text this book is full of useful details on short antennas.

[9] Sevick, Jerry, W2FMI, The Ground-Image Vertical Antenna, QST, July 1971, pp16-19, 22

[10] Sevick, Jerry, W2FMI, The W2FMI Ground-Mounted Short Vertical, QST, March 1973, pp 13-18, 41

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[12] Sevick, Jerry, W2FMI, Short Ground-Radial Systems for short Vertical, QST, April 1978, pp 30-33

[13] Sevick, Jerry, W2FMI, The Short Vertical Antenna and Ground Radial, CQ Communications, Inc., 2003.

This small book is a collection of Jerry's earlier QST articles on short verticals. It also contains a previously unpublished article on loading coil design which is very good.

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[15] Gibilisco, Stan, W1GV/4, Efficiency of Short Antennas, Ham Radio, September 1982, pp 18-21

[16] Shepherd, Howard F., W6US, A high-Efficiency Top-Loaded Vertical, Ham Radio, October 1984, pp. 65-68

[17] Brown, Bruce F., Optimum Design of Short Coil-Loaded High-Frequency Mobile Antennas, ARRL Antenna Compendium Vol. 1, 1985, pp. 108-115.

This is a really good discussion on where to place a loading coil on a short vertical. Much of the material in the original article has been incorporated into recent editions of the ARRL Antenna Book. See for example, the 21st edition pp 16-5 through 16-13.

[18] Belrose, John S., VE3BLW (now VE2CV), Short Antennas for Mobile Operation : Loading the Whip for Low Frequencies, QST September 1953, pp 30-35 + 108

[19] Jasik, Henry, Antenna Engineering Handbook, McGraw-Hill 1961, Chapter 19 by Martin and Carter, Low-Frequency Antennas. See also chapter 20, by Howard Head, Medium-Frequency Broadcast Antennas.

[20] Jasik, Henry, Antenna Engineering Handbook, McGraw-Hill, 3rd edition, 1993, Chapter 24, Low-Frequency Antennas, by Hagaman.

[21] Howard Shepherd, W6US, A High-Efficiency Top-Loaded Vertical, Ham Radio magazine, October 1984, pp. 65-68

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

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

This is another paper with experimental results for umbrella verticals which agree very nicely with NEC modeling predictions.