Chapter 1

LF-MF Overview

1.0 Introduction

100 years ago amateurs were restricted to wavelengths below 200m (f >1.5 MHz). This has recently changed, we now have allocations at 2200m (135.7-137.8 kHz, LF) and 630m (472-479 kHz, MF). However, amateurs have very little experience at these frequencies and it turns out that design and construction of antennas for the new bands is substantially different from HF. The primary purpose of these notes is practical advice on LF/MF transmitting antennas. There is a perception that substantial acreage is required for the antennas on these bands. That is not the case! Those with small properties can be successful but we have to know how!

There are differences between LF-MF and HF which impact antenna design:

1) Wavelengths are much longer so that any practical antenna will be electrically small.

2) Soil electrical characteristics change substantially going from HF down to LF/MF.

3) Power limitations are in terms of power radiated from the antenna rather than maximum transmitter output power although there are also limits on transmitter power.

1.1 Long wavelengths

At 1.9 MHz the wavelength (λ) ≈518' so a λ/4 vertical will be ≈130' high. If you divide 1.9 MHz by four you get 475 kHz, right in the middle of the new 630m band. A λ/4 on160m will be only ≈λ/16 at 475 kHz. 2200m is another factor of 3.5 lower in frequency so a λ/4 vertical on 160m is only ≈0.018λ on 137 kHz. At 475 kHz λ≈2071' so a λ/4 vertical would be ≈500' high. At 137 kHz λ/4 ≈1800'! In any case, the FCC has limited the maximum height to 197' (60m), which is still only 0.095λ. Most amateurs do not live on extensive acreage or have unlimited funds and in many cases their antennas have to fit in urban backyards so long wavelengths can be challenging but far from hopeless. The focus of this book is antennas with heights (H) practical for amateurs, i.e. H=20'→100' (H≈0.01→0.05λ at 475 kHz and H≈0.003→0.015λ at 137 kHz). In terms of electrical height these are certainly "short" antennas, with very low radiation resistance (Rr), narrow matched SWR bandwidth and low efficiency. A major part of the design effort for LF-MF antennas is directed towards obtaining adequate efficiency.

1.2 Soil characteristics

Because ground electrical characteristics have a profound affect, some basic information on soil electrical characteristics is needed for this discussion. Much more detailed information can be found in appendix TBD.

σ = soil conductivity in Siemens/meter [S/m], Siemen=Mho

ε_o = permittivity of a vacuum = 8.854×10^{-12} [Farads/m]

ε_r = relative permittivity or relative dielectric constant

$\varepsilon = \varepsilon_o \varepsilon_r$ = effective permittivity or dielectric constant [Farads/m]

μ_o = permeability of free space = $4\pi\ 10^{-7}$ H/m

$\omega = 2\pi f$

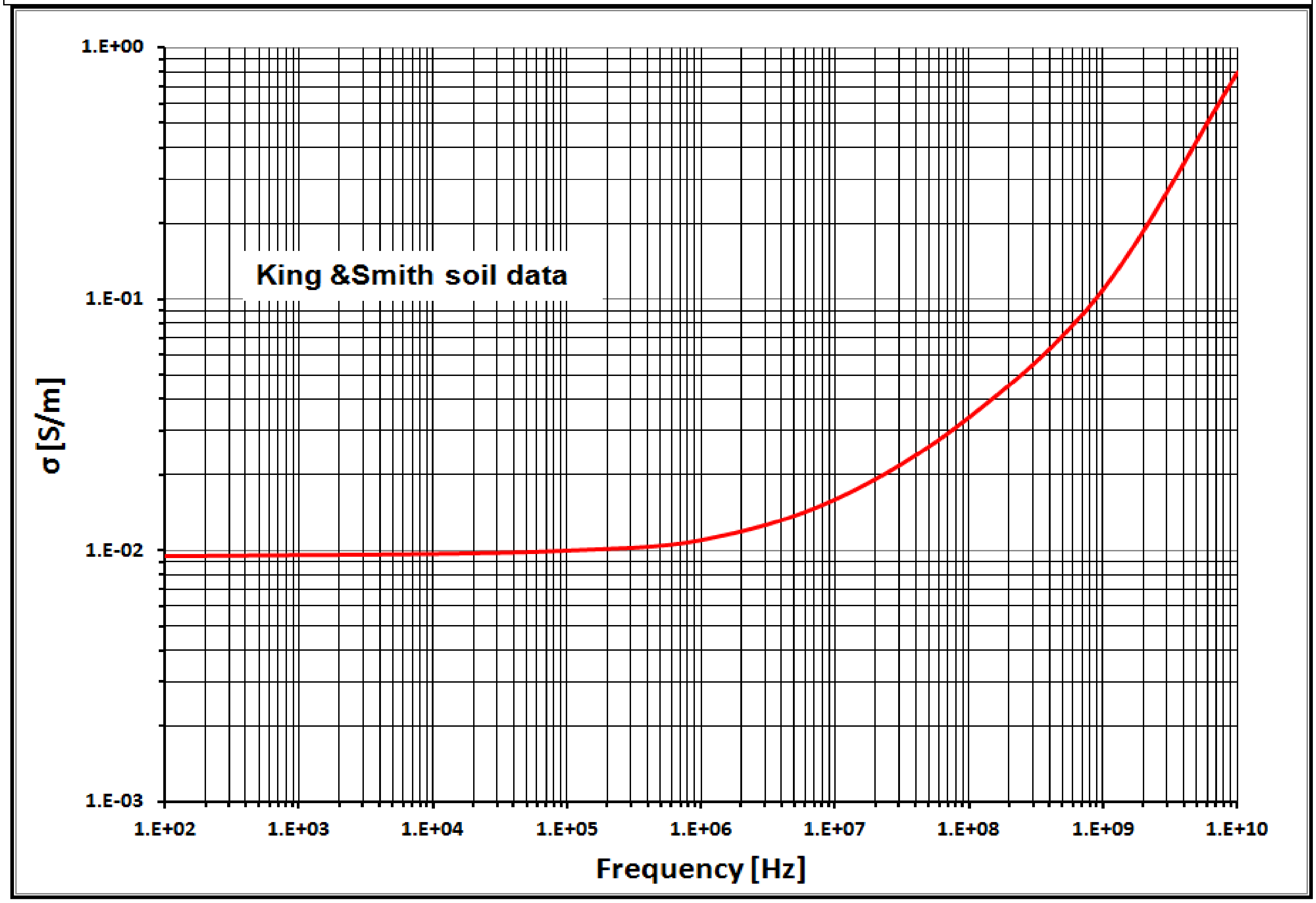

Figure 1.1 - Example of soil conductivity variation with frequency. Data from King and Smith[1].

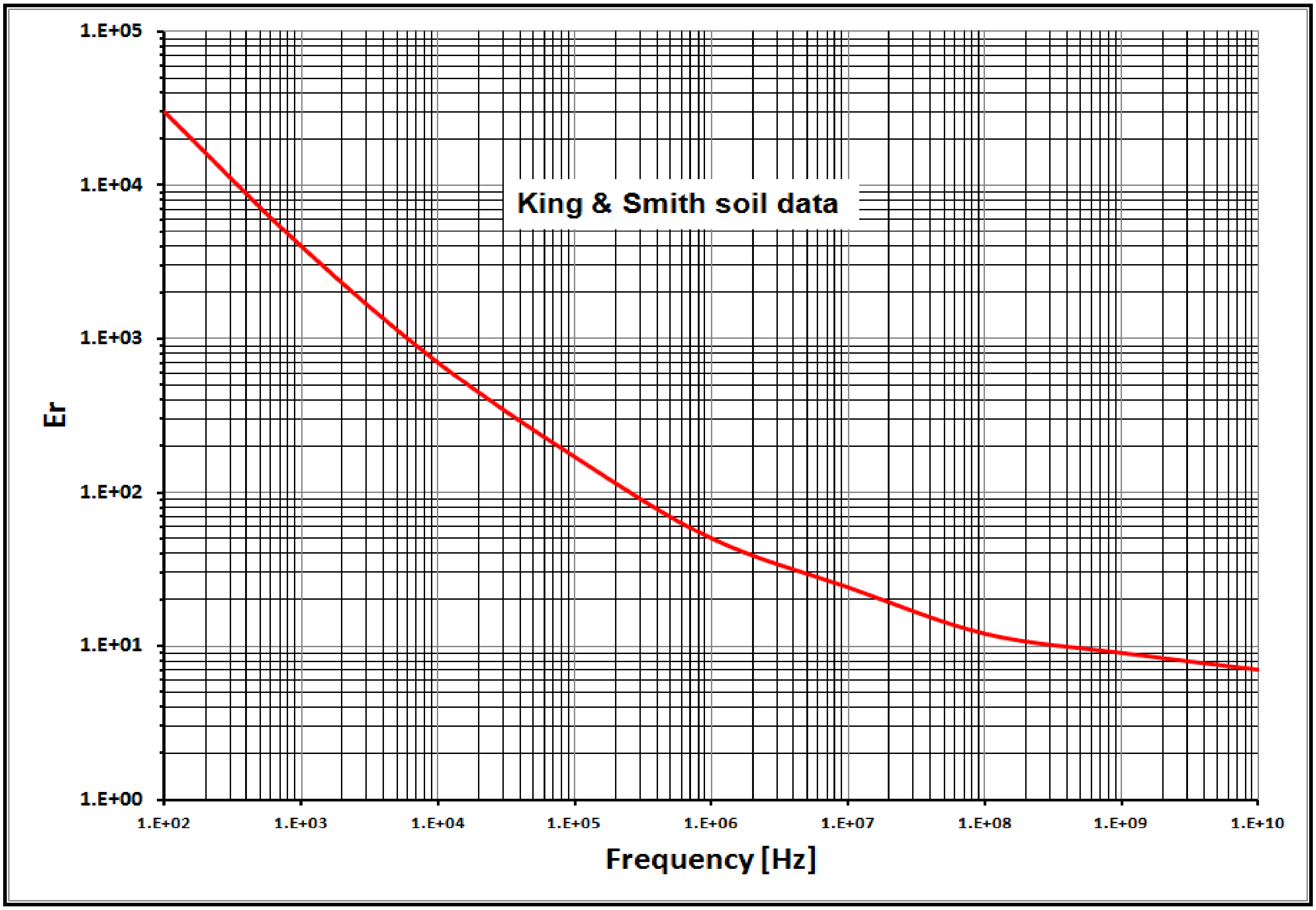

Figure 1.2 - Example of soil permittivity variation with frequency. Data from King and Smith[1].

Figures 1.1 and 1.2 show how much the electrical characteristics can vary with frequency. In this example at 100 Hz σ≈0.09 S/m and that value is relatively constant up to ≈1 MHz but beyond that point σ increases rapidly with frequency. εr behaves just the opposite, decreasing with frequency until ≈10 MHz and then leveling out. At a given QTH, with the same soil, the electrical characteristics will be very different between HF and LF-MF.

1.3 EIRP and radiated power

On the new LF-MF bands power limits are stated in terms of "effective isotropic radiated power" or EIRP. The "isotropic" in EIRP refers to an idealized antenna in free space which radiates power uniformly in all directions, i.e. if you measure the power density (S, in W/m^2) on the surface of a hypothetical sphere surrounding an isotropic radiator you'll find the power density is the same everywhere.

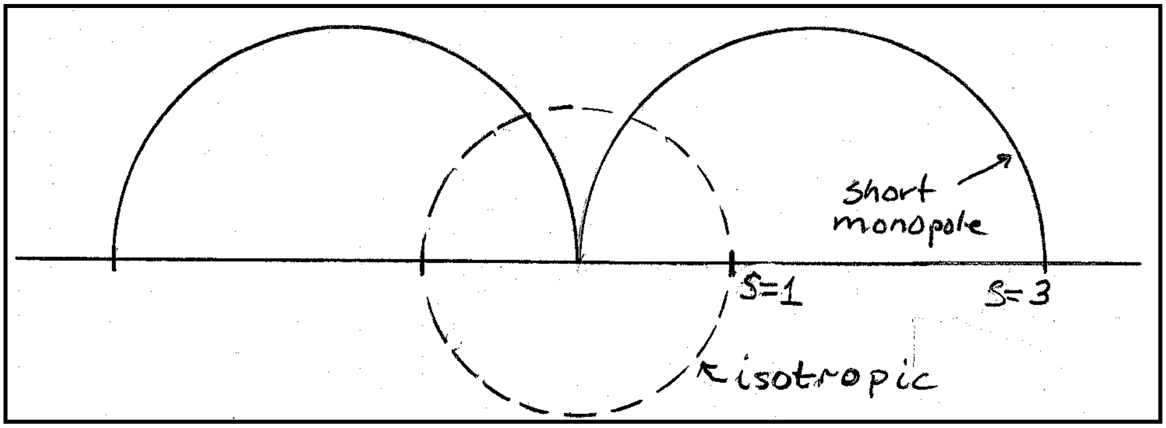

Figure 1.3 - Power density: isotropic radiator versus a short monopole.

Figure 1.3 compares the radiation patterns of an isotropic radiator in free space to a short vertical over ideal ground. The directivity of the isotropic radiator is 1 (0 dBi). When a short monopole is placed over a perfect ground-plane, for the same total radiated power (Pr) the power density, <u>at the same distance horizontally from the base</u>, will be greater by a factor of 3 (+4.77 dB). This increase comes from two sources, Pr is being radiated into a hemisphere rather than a sphere because of reflection from the ideal ground which doubles S and there is a further increase of 1.5X (+1.77 dB) due to the directivity of the short monopole. There is a direct relationship between the power density at a given distance and the magnitude of the electric field intensity (|E|) at that point:

$$|\mathbf{E}| = \sqrt{\mathbf{377S}} \quad (1.2)$$

Because of it's directivity we must reduce the Pr of the short monopole by a factor of three to maintain the same power density as an isotropic. On 630m 5W EIRP is allowed and on 2200m the allowed EIRP is 1W, which means Pr is about 1.7W on 630m and 0.33W on 2200m. The key word is "radiated" power.

At HF, antenna efficiencies are typically >90% and the focus is on antenna gain. On LF-MF our goal is to achieve sufficient efficiency that we can radiated the allowed power <u>with the available transmitter power</u>. This is a fundamentally different mindset from HF! We have the choice of a large efficient antenna with small input power (Pi) or a small inefficient antenna with a large input power. Most installations will be a balance between the two extremes. Running very high power is an option in theory but, as shown in chapter 6, section 6.10 and chapter 2, section 2.10, very high power into a small antenna results in very high voltages (tens of kV!) and currents. The high power approach is self limiting! A transmitter output power of 100W is generally pretty easy to obtain and 100W is frequently assumed in later chapters unless stated otherwise. In addition to the EIRP power limit, the FCC has also limited the input power to the antenna to 500W pep on 630m and 1.5 kW pep on 2200m, however, given limitations due to the high voltages associated with these power levels, from a practical point of view these limits are moot.

How can we determine the radiated power (Pr) for a particular antenna? The pros do it by measuring the electric field intensity at a given distance from which Pr can be calculated. For most amateurs that's not very practical. If we know the value for the antenna's radiation resistance (Rr) we can calculate Pr in a couple of ways. If we know Rr and can measure Io, the current at the base of the antenna, then:

$$\mathbf{Pr} = \mathbf{Io}^{\mathbf{2}}\mathbf{Rr} \qquad (1.3)$$

As an alternative, given Rr, we can measure the input power (Pi) and the resistive component of the feedpoint impedance (Ri):

$$\mathbf{Pr} = \mathbf{Pi}\left(\frac{\mathbf{Rr}}{\mathbf{Ri}}\right) \qquad (1.4)$$

Where do we get Rr from? As will be shown in chapters 2 and 3, Rr can be found using either modeling or manual calculations. Using the value for Rr from a model over perfect ground is in general <u>not</u> valid at HF where the dielectric properties of soil have a direct influence on Rr. However, at frequencies below ≈1 MHz the soil electrical characteristics are dominated by conductivity and Rr will be close to the perfect ground value. This makes our job much easier. Appendix TBD has a very extensive discussion of this issue.

1.4 Some fundamental advice

A very succinct summary of LF-MF antenna design was given by Woodrow Smith[2] 70 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."*

This sound advice can be organized in order of priority:

1) Make the vertical as tall as you can.

2) Use as much capacitive top-loading as practical (chapter 3).

3) Use carefully placed high Q loading coils (chapters 4 & 6).

4) Put substantial effort into the ground system, with the radial density high near the base of the vertical and under the top-loading hat (chapter 5).

5) Minimize conductor losses by using multiple wires and/or large diameter conductors (chapter 3).

6) Use high quality insulators, at the base and at wire ends.

This simple advice should be taken literally!

1.5 Modeling and calculations

Antennas for these bands have to be customized for each installation to take advantage of available resources, space and/or supports. There are several ways to approach the design: use a combination of algebraic approximations and graphs or use antenna modeling CAD software or some combination of the two.

Much of the material in this book was derived using CAD modeling, EZNEC Pro4 v6[3] (with the NEC4.2 engine) and AutoEZ[4] an EXCEL spreadsheet which automates many modeling functions were used. These are very good tools but except for buried ground systems most design questions can be adequately addressed with NEC2 based software like 4NEC2[5] which is an excellent free program.

Computer modeling is not the only way. One of the consequences of the small electrical size of LF-MF antennas is that the currents on the conductors tend have only small phase differences and relatively linear amplitude variation. As will be shown in chapters 2 and 3, it's possible to use simple algebraic expressions to estimate radiation resistance (Rr), effective capacitance of top-loading structures (Ct) and other quantities.

1.6 Loading inductors

A major part of the design effort for LF/MF antennas is directed at obtaining adequate efficiency. Given practical height limitations, most LF-MF antennas will require loading inductors for resonance and matching. In many cases the losses in this inductor will determine the efficiency of the antenna. Much of the design effort is directed towards first minimizing the required inductance (L) (chapter 3) and then maximizing inductor "Q" (QL) (chapter 6).

1.7 Examples of early LF/MF antennas

Small antennas are not new. At the beginning of radio very long wavelengths were used so all antennas were "small" even those hundreds of feet high. A lot of effort was directed towards improving these antennas, work that continued into the 1960's for VLF applications[6]. The low efficiency and narrow bandwidth associated with small antennas arises from fundamental physics and the underlying physical processes have been carefully studied[7,8]. Like the perpetual motion machine, 100% efficiency in small antenna is not in the cards but it's not hopeless either. Interestingly, short antennas are still a hot topic today among professionals where the interest is in very small antennas[9] for wireless mobile devices, RFID, etc. Despite 120 years of work there's still a lot to learn! A rich source of ideas for LF-MF antennas are old radio books. Often these books are seen at ham flea markets or used book stores for a few dollars. The 1920'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. Much of what was done then is still useful today.

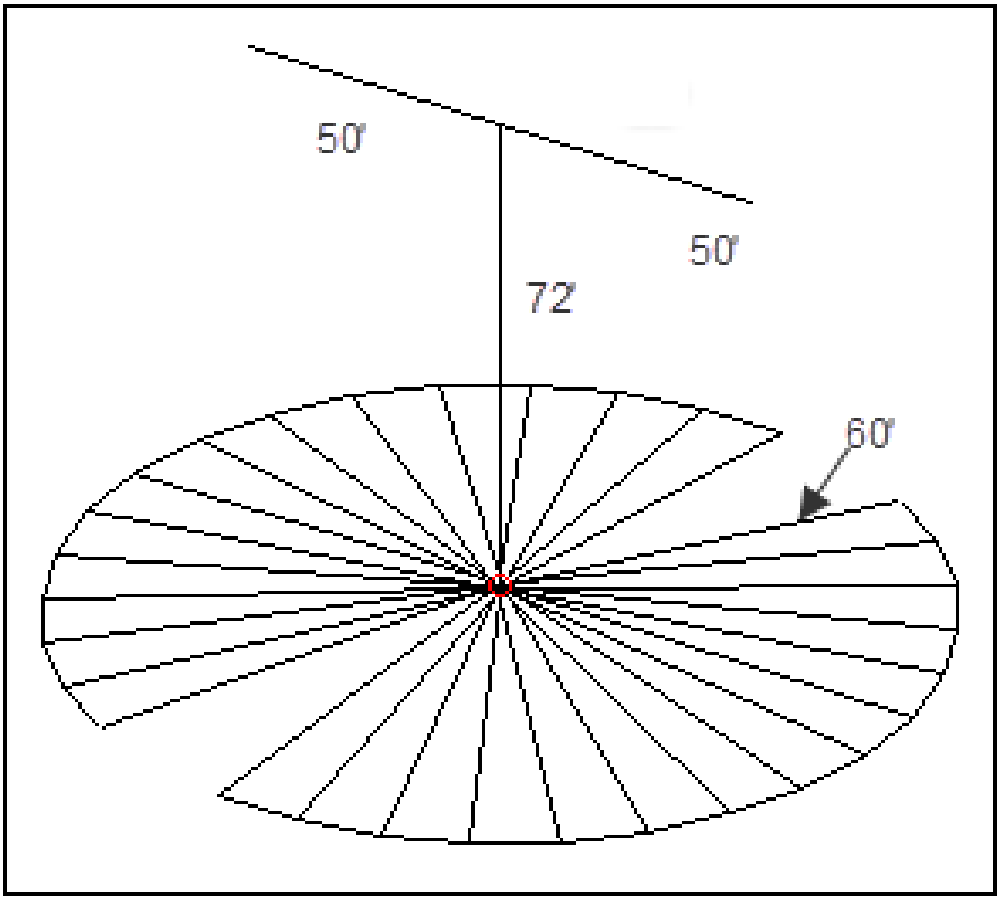

Figure 1.4 - EZNEC model of the 1BCG antenna.

Figure 1.4 is a sketch of the antenna used for the initial transatlantic tests by amateurs (1BCG) in 1921-22[10, 11]. The operating frequency was ≈1.3 MHz (λ≈230m). At 1.3 MHz λ/4 = 189' so the 60' radius of the counterpoise corresponds to ≈0.08λ. Figure 1.5 (taken from the Moyer & Wostrel[12]) shows a variety of possibilities, including inverted L's, T's, fans and umbrellas. Some of the simplest top-loaded antennas are the "inverted-L" and the "T" which can be just a single wire suspended between two supports with a wire (the "down lead" or "lead-in") down to the shack as shown in figure 1.6 or it can use a multi-wire top-hat and down-lead as shown in figure 1.7. Figure 1.7 also shows a very large elevated ground system or counterpoise. Very effective but probably few amateurs would build something on that scale!

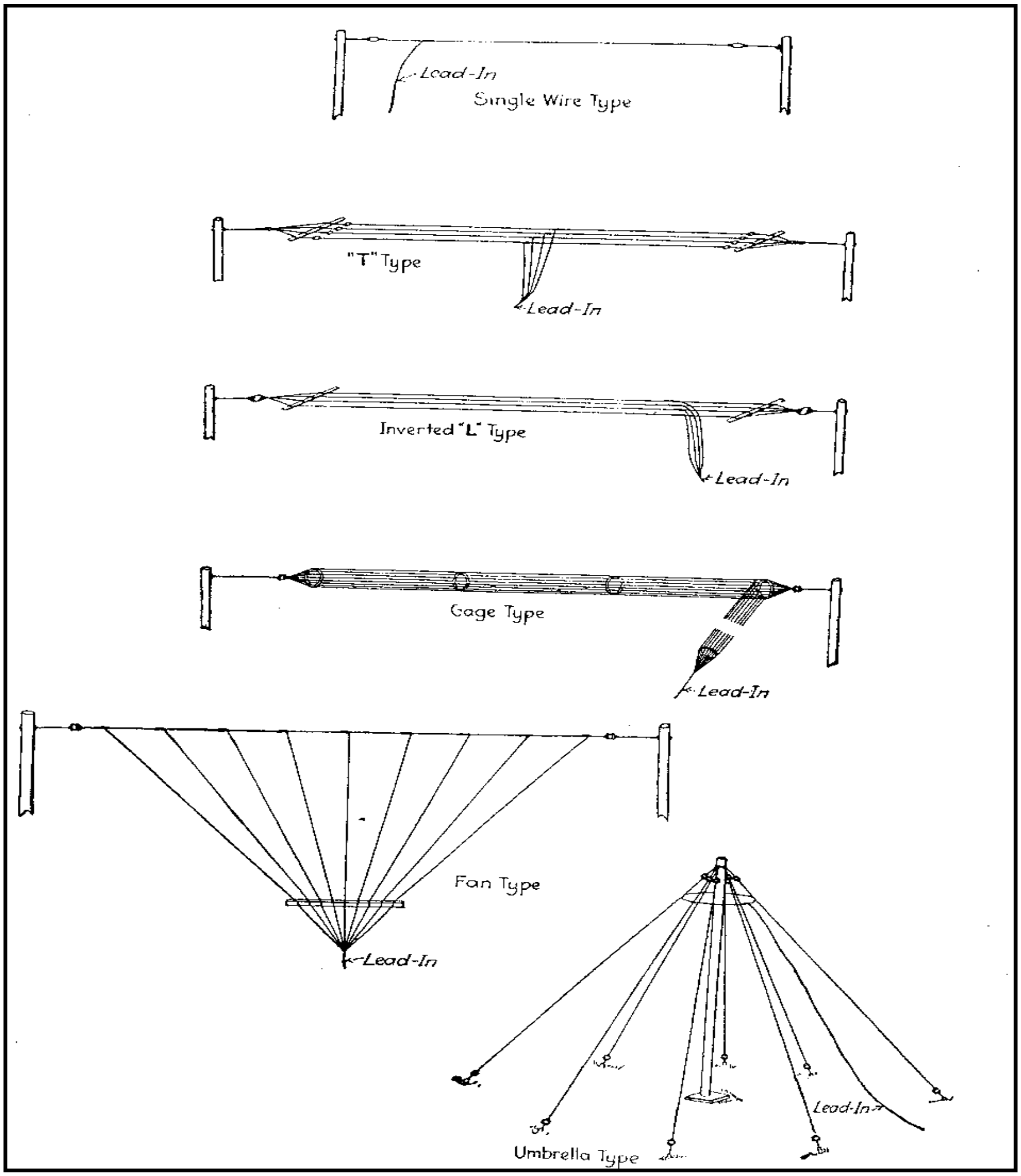

Figure 1.5 - Examples of early antennas [12].

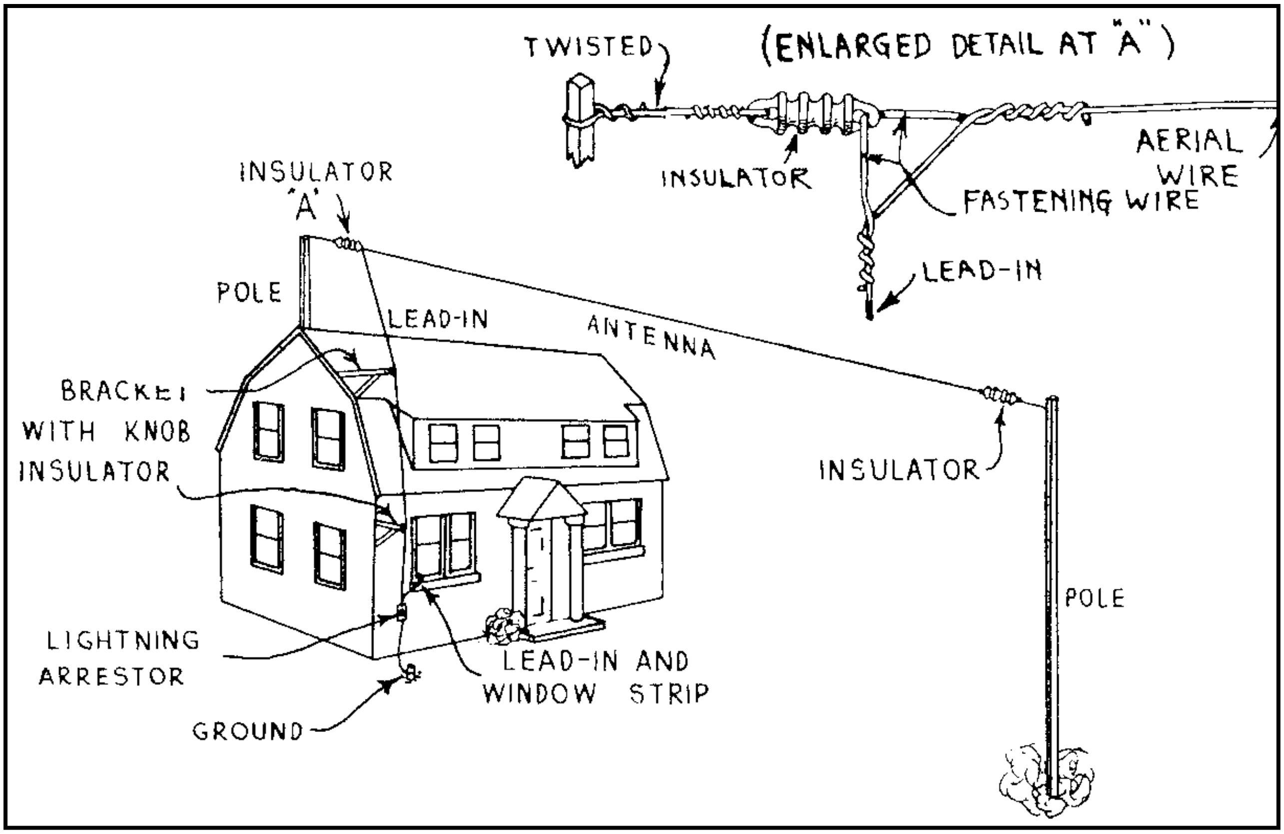

figure 1.6 - Example of an inverted L antenna. From Ghirardi[13].

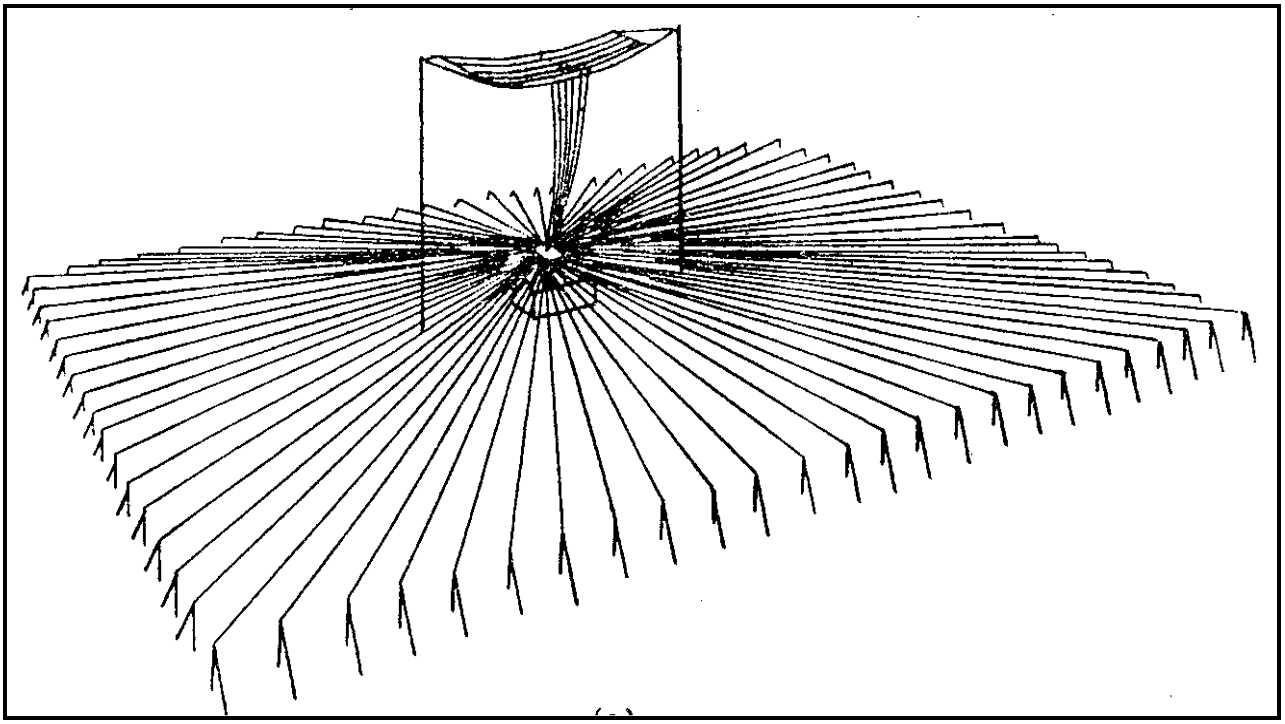

Figure 1.7 - A very large LF elevated ground system. From the Admiralty Handbook of Wireless Telegraphy, 1932 [14].

References

[1] King and Smith, Antennas in Matter, MIT press 1981, page 399, section 6.8

[2] Woodrow Smith, Antenna Manual, 1948

[3] Lewallen, Roy, W7EL, EZNEC Pro/4 v6, www.w7el.com

[4] Maguire, Dan, AC6LA, AutoEZ, http://ac6la.com/autoez.html

[5] 4NEC2, http://home.ict.nl/~arivoors/

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

[7] Wheeler, Harold A., Fundamental Limitations of Small Antennas, Proceedings of the I.R.E., vol. 35, December 1947, PP. 1479-1484

[8] Chu, Lan J., Physical Limitations of Omni-Directional Antennas, Journal of Applied Physics, vol. 19, December 1948, pp. 1163-1175

[9] Yaghjian and Best, Impedance, Bandwidth and Q of Antennas, IEEE transactions on Antennas and Propagation , Vol. 53, No. 4, April 2005, pp. 1298-1324

[10] Burghard, George, "Station 1BCG", QST, February 1922, pp. 29-33

[11] Kelley and Hudson, "Hams Span the Atlantic on Shortwave!", QST, December 1996, pp. 28-30

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

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

[14] Admiralty Handbook of Wireless Telegraphy, His Majesty's Stationary Office, 1932, pg. 799, Figure 452