Chapter 19

LOW-FREQUENCY ANTENNAS*

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19.1. GENERAL DISCUSSION

Although radio development in the last thirty years has occurred mainly at medium and higher frequencies, the propagation characteristics of low-frequency (LF) waves still tend to recommend that region for certain special services. At low frequencies, ground waves are subject to less attenuation and sky waves are less affected by ionospheric conditions and disturbances. These characteristics make the region especially favorable for communications and for navigational aids to widely dispersed ships and aircraft. Another characteristic, applying especially to *very* low frequencies (VLF), is the ability of the waves to penetrate into salt water, making communications with submerged submarines possible.

The advantage of low frequencies would increase continually with decreasing frequency except for the tendency of the prevailing atmospheric noise (static) level to increase at the same time. The result is the existence of an optimum frequency with respect to signal-to-noise ratio at the receiving location for a given transmitting antenna. For example, the optimum frequency for the New York–London low-frequency circuit has been found to be about 40 kilocycles per second (kc).[1]

Low frequencies are of special utility in polar regions. This is because ionospheric disturbances are extra severe and atmospheric noise levels are relatively low in these areas.

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* 15 to 500 kilocycles per second.

The main disadvantages of low frequencies are the high cost and practical difficulties associated with the construction of radiators having dimensions appreciable with respect to the wavelength. For this reason it is generally not feasible to obtain directive gain by the use of either a high antenna or an array. In a few cases having especially severe performance requirements, antennas with effective lengths near a quarter wavelength are used. Usually, however, cost and practical considerations result in the radiators being electrically in the "small" category. (A definition for a small antenna which is adopted here is stated in chap. 10 of Ref. 2 as follows: " . . . *an antenna is said to be small if its largest dimension, measured from its input terminals, does not exceed one-eighth of the wavelength.*") Small antennas have special problems in connection with efficiency, power capacity, and bandwidth. The requirements in regard to these characteristics are so varied and the economic factor is so important that little standardization has been obtained in low-frequency transmitting-antenna systems. Existing radiators are in the form of vertical radiators, umbrella-loaded vertical radiators, and flat-tops (of a large variety of sizes and shapes) fed by downleads.

Receiving-antenna problems are generally less severe than those of transmitting antennas at low frequencies. Since atmospheric noise rather than receiver noise is the controlling factor in regard to signal-to-noise ratio, the efficiency of the receiving antenna is of very minor importance. For the same reason, directive gain[38] is of great importance, and therefore loops and wave antennas have found favor for this application.[1,3,4,6]

19.2. LOW-FREQUENCY-ANTENNA CHARACTERISTICS

The antenna input resistance R_a may be considered as being composed of two main parts: R_{ar} associated with radiated power and $R_{a\ell}$ associated with power lost in heat. Loss of power occurs in the ground, in conductors and insulators, and in some cases in corona discharge. Figures 19-1 and 19-2 show plots of theoretical radiation resistance R_{ar} for the two assumed current distributions depicted in the figures. Figure 19-1, which pertains to a sine-wave current distribution, is more generally applicable to the largest antennas under consideration here. Figure 19-2, which ranges down to very low values of radiation resistance, is more useful in connection with the smallest. In practice, the antenna is energized by a transmitter through an electrical network which may consist of either a tuning element alone or, effectively, a tuning element and an L, T, or π network. In the present discussion the antenna circuit is considered to be composed of the antenna, a tuning element of resistance R_t, and a zero-loss generator. The antenna efficiency is defined by the equation

$$\text{Eff} = \frac{R_{ar}}{R} \tag{19-1}$$

where $R = R_a + R_t = R_{ar} + R_{a\ell} + R_t$.

A few unusually large low-frequency antennas have equivalent lengths somewhat greater than a quarter wavelength and therefore inductive input reactances; however, most are in the small category and have high capacitive reactance. In any case, the input reactance X_a can be represented with good accuracy throughout the frequency range under consideration by the equation

$$X_a = -Z_0 \cot \frac{2\pi\ell}{\lambda} \qquad \text{ohms} \tag{19-2}$$

where Z_0 is the characteristic impedance, ℓ is the length of an *equivalent uniform* transmission line, and λ is the wavelength, ℓ and λ being expressed in the same units. For the special case of a vertical cylindrical radiator of height h and radius a ($a \ll h$), Eq. (19-2) is commonly evaluated by letting $\ell = h$ and

$$Z_0 = 60 \left[\ln \left(\frac{2h}{a} \right) - 1 \right] \qquad \text{ohms} \tag{19-3}$$

where h and a are expressed in the same units. Equation (19-3) is the *average* value of the characteristic impedance of the cylinder as derived in Chap. 13 of Ref. 2.

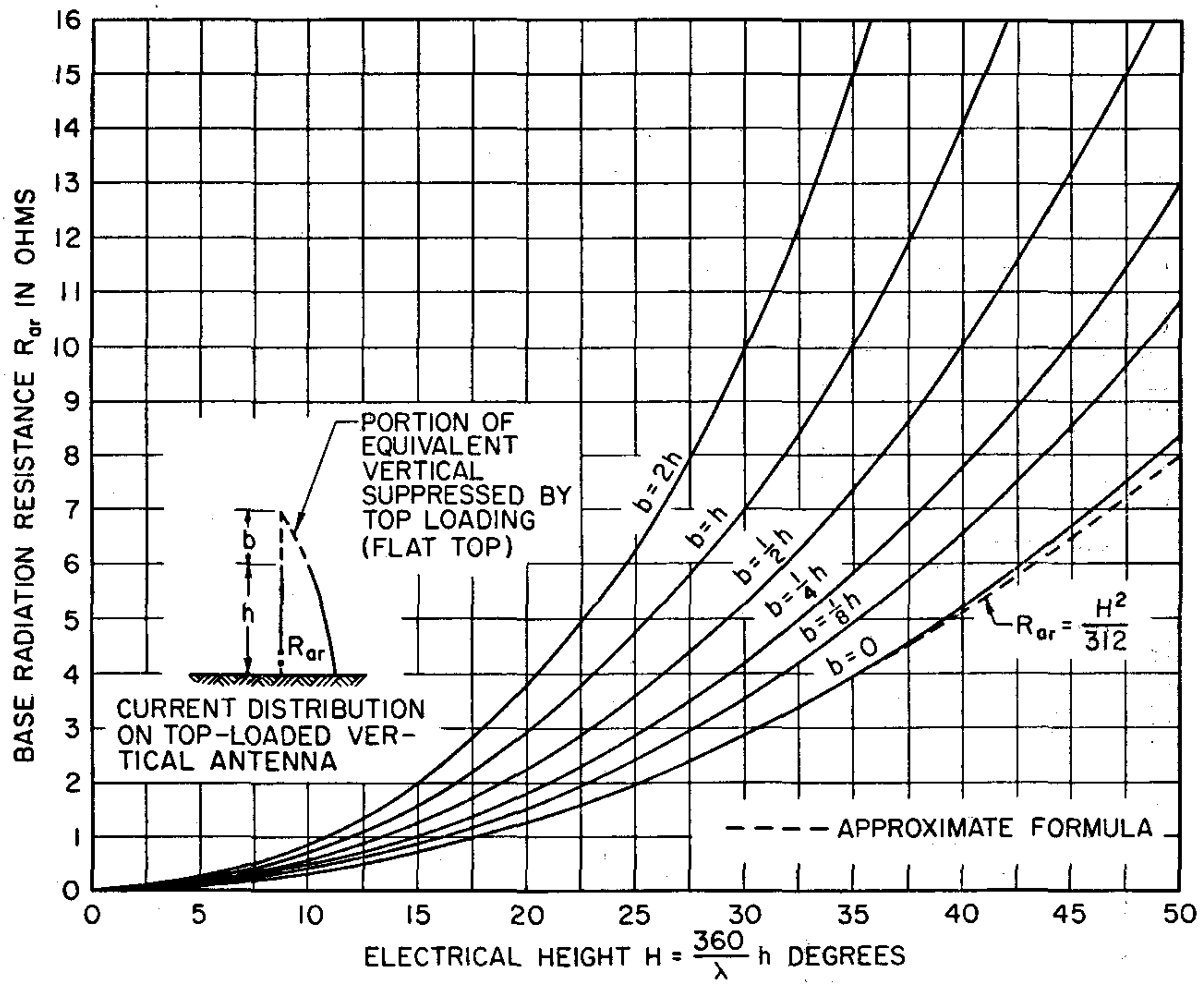

FIG. 19-1. Theoretical radiation resistance of vertical antenna for assumed sine-wave current distribution. (*Reference 5.*)

Another expression for Z_0, which fits experimentally measured values for short vertical radiators more closely than does Eq. (19-3),[8] is

$$Z_0 = 60 \left[\ln \left(\frac{h}{a} \right) - 1 \right] \qquad \text{ohms} \tag{19-4}$$

The Q of the antenna circuit with zero-loss generator is conventionally given by the equation

$$Q = \frac{f_0 \left(\frac{dX}{df} \right)_{f_0}}{2R} = \frac{|X_a| + f_0 \left(\frac{dX_a}{df} \right)_{f_0}}{2R} \tag{19-5}$$

where X is the total circuit reactance ($X = X_a + X_t$) and $|X_a|$ is the magnitude of the antenna reactance at the operating frequency f_0. Equation (19-5) holds for the total range of antenna sizes under consideration, from very small to somewhat larger than a quarter wavelength. The bandwidth of the circuit is determined by the equation

$$\text{BW} = \frac{f_0}{Q} \tag{19-6}$$

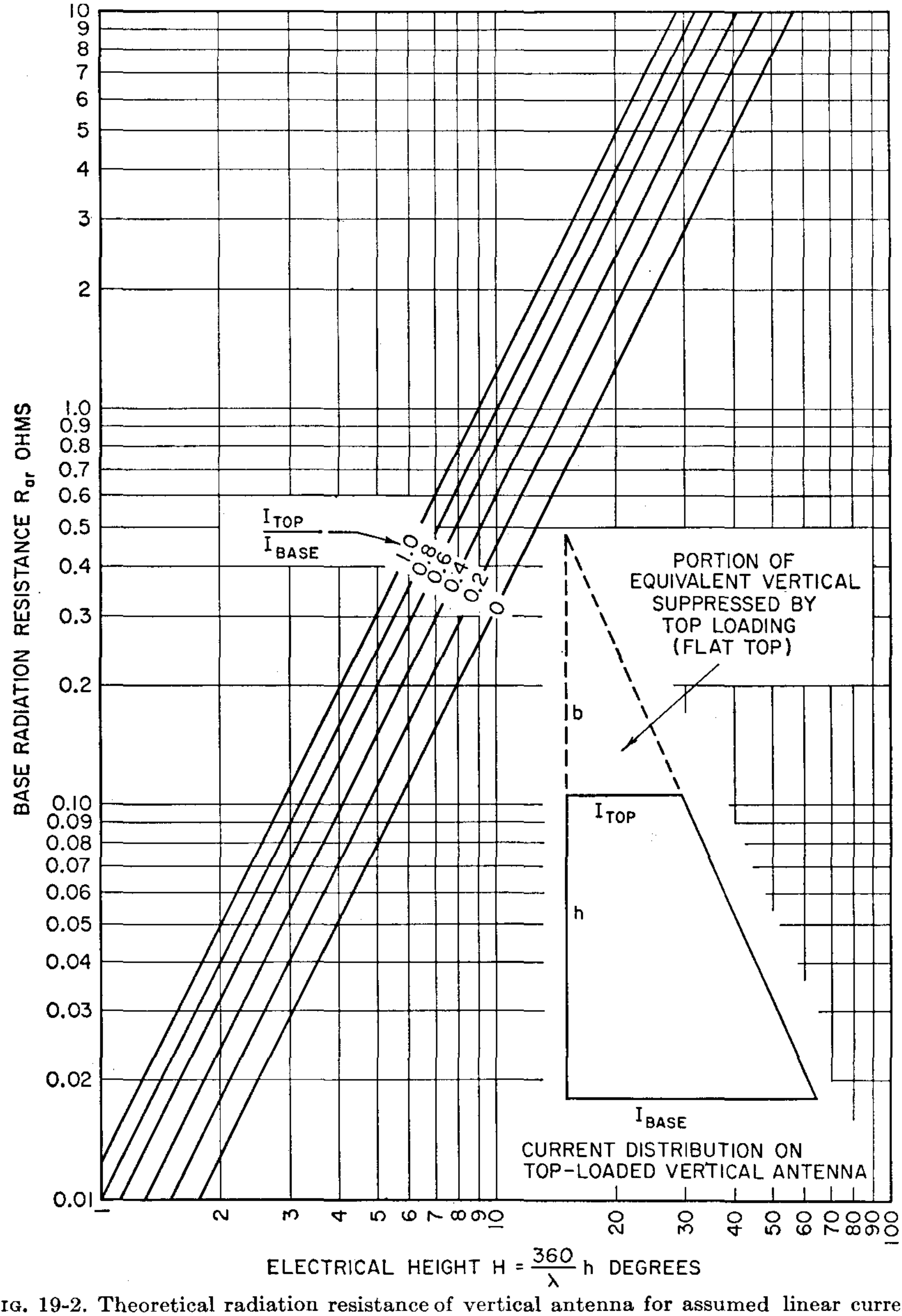

FIG. 19-2. Theoretical radiation resistance of vertical antenna for assumed linear current distribution. (*Reference 6.*)

Since no prescribed method of determining the Q factor or bandwidth of an antenna has become standard, these quantities are not always defined in the literature as they are defined here. Sometimes the transmitter internal impedance is assumed to double the bandwidth of the antenna alone, and sometimes the effect of the tuning element is neglected. Actually, the effect of the transmitter impedance is not zero, as Eqs. (19-5) and (19-6) imply, but it is not possible to specify the effect in general. In many cases the exact matching of the transmitter impedance by the antenna load would seriously overload the transmitter. References 9, 10, 11, and 24 contain interesting information in regard to the over-all bandwidth question, including the effect of coupling networks between the transmitter and antenna.

The main consideration in low-frequency-antenna design is often the amount of power to be radiated in order to obtain a required range of communication. In other cases the determining factor is that of obtaining a low value of antenna Q, in order to satisfy a bandwidth requirement in regard to the transmission of a short-pulse, high-speed radiotelegraphy or high-fidelity radiotelephone. In many ways these two performance requirements are similar; for example, the size of the antenna needed increases as either requirement becomes more severe. The quality of a small antenna, in regard to efficiency, power capacity, and bandwidth, increases with antenna height. However, at low frequencies the height needed in a simple vertical radiator is often greater than is practical to construct. It is then necessary to use some form of top loading in order to obtain the required performance.

The characteristics of short vertical radiators may be improved by adding a top-loading umbrella. As the length of the umbrella wires increases, the antenna effective height increases to a maximum, because of the increase in height of the center of charge, after which it decreases, because of the umbrella's shielding effect on the vertical radiator. The umbrella also tends to increase the bandwidth to a certain extent by decreasing both the reactance and the slope of the reactance vs. frequency curve of the antenna [Eqs. (19-5) and (19-6)]. A further effect of the umbrella, which is important in some cases, is to decrease the voltage, and hence the power loss, associated with the base insulator. On the disadvantage side, the umbrella cables place an additional mechanical load on the tower, tending to increase its cost. For the last reason, the simple vertical radiator is preferred to the umbrella in some low-frequency applications. Examples of umbrella-loaded vertical radiators are described in Refs. 5 and 14.

At VLF, practical towers are electrically so short that a large amount of top loading is generally required. Although the top loading is beneficial to a certain extent in increasing the effective height, the required amount of top loading is usually determined by the maximum antenna voltage that can be tolerated—up to about 250,000 volts at the present stage of insulation development. For a given effective height the power radiated determines the antenna current. Since the antenna voltage is equal to the product of the current and the capacitive reactance, the maximum allowable voltage specifies the minimum antenna capacitance, and thereby the size flat-top required. Tower-base insulators are not satisfactory at high voltages, and it is necessary to support the flat-top from masts or towers by long tubular insulators and to feed the flat-top by downleads similarly insulated at the ground. As a result of these considerations a typical VLF antenna consists of an extremely large flat-top supported by towers and fed by one or more cage downleads.

In the design stage, the characteristics of radiation resistance and reactance occurring in Eqs. (19-1) and (19-5) are generally determined under the assumptions that the antenna is lossless and its ground plane is infinite. Because of the effect of towers and guys, edge and end effects of flat-tops, and the general complexity of low-frequency antennas, these characteristics cannot be rigorously calculated and it is necessary to determine them by either approximate calculations or by experiment.

In some situations, mainly those in which the antenna is electrically quite large, the characteristics can be determined by impedance measurements, using a small-scale model mounted on a large ground plane.[6,7,12,13] Such measurements yield useful information in regard to those antenna characteristics which are not greatly affected by losses. When a large-scale factor is used, it is usually necessary to idealize various sections of antenna, such as lattice towers by cylinders, the configurations of the wires in the flat-top by a metal sheet, and cages by wires. In this case, some judgment or theoretical calculation is necessary to correct the measured results to apply to the actual conditions.

In one instance reported in the literature,[14] several design problems connected with an 820-ft umbrella-loaded vertical antenna were investigated, using an existing 240-ft broadcast tower as a support for the experimental umbrella. According to the theory of models,[13] the model measurements at 610 kc correctly represented the full-scale antenna as if it were located on a site having a value of ground conductivity equal to that of the experimental site divided by the scale factor, or approximately by 3. However, much experience with broadcast antennas has shown that, for the electrical height involved and for the ground systems of both the model and the proposed antenna, the effect of substantially perfect ground is obtained regardless of the ground conductivity (for example, see Ref. 6, sec. 2.1.2). The experiment was successful in predicting with good accuracy the final performance of the full-scale antenna with respect to both impedance and field-strength characteristics.

When the proposed antenna is in the small category, many problems associated with the design can be attacked from an electrostatic rather than an electromagnetic viewpoint. The reactance of a small antenna can be represented by the combination of a lumped capacitance C_a and a lumped inductance L_a in series (Ref. 2, sec. 10.2). The capacitance is of chief importance since it determines the antenna voltage [given by $I/(\omega C_a)$] and the Q factor [given by $1/(R\omega C_a)$]. Usually, in connection with antennas of this class, it is necessary to consider the antenna inductance only in so far as it affects the value of tuning inductance required. For example, the static capacitance assignable to each downlead of the antenna shown in Fig. 19-8 is about 1,000 ohms, whereas the corresponding antenna inductive reactance is only 18 ohms.

For any grounded antenna, there exists a length of vertical wire which, if caused to carry a uniformly distributed current equal to the input current of the antenna, would produce a distance field strength on the horizon equal to that of the antenna, assuming infinite ground conductivity in both cases. The length of the hypothetical wire is commonly called the "effective height" (h_e) of the antenna. A quarter-wave grounded vertical wire has an effective height equal to $2/\pi$ times the actual height. In the case of a small antenna, a definition which is equivalent to that just stated but which is of more general utility is: *the effective height is the height of the center of charge in the antenna, its supports, and other nearby elevated structures, assuming the antenna to be raised to a d-c potential above ground.* It should be noted that the charges induced in the supports and other nearby objects oppose the charges in the antenna, thereby reducing the effective height. The effective height of a short vertical radiator, unloaded and standing alone, is approximately equal to one-half the actual height. This is equivalent to assuming a linear distribution of current in the first definition and, equivalently, a uniform distribution of charge in the second definition. That curve of Fig. 19-2 which is labeled $I_{\text{top}}/I_{\text{base}} = 0$ pertains to this particular condition. In general, the radiation resistance of any small grounded antenna is related to the effective height h_e by the equation

$$R_{ar} = 160\pi^2 \left(\frac{h_e}{\lambda}\right)^2 \qquad \text{ohms} \tag{19-7}$$

where h_e and λ are expressed in the same units. Equation (19-7) applies to that curve of Fig. 19-2 which is labeled $I_{\text{top}}/I_{\text{base}} = 1.0$ with $h = h_e$.

Figure 19-3 shows a typical low-frequency antenna. A large capacitance C_1 between the flat-top and ground, besides establishing the effective height near that of the flat-top, is beneficial in reducing the voltage and the Q factor of the antenna. The downlead and the towers increase the antenna capacitance; on the other hand, however, they detract from the effective height established by the flat-top—a very considerable amount in typical VLF antennas. Consequently, mainly the flat-top is depended upon to obtain the desired minimum capacitance. The downlead capacitance C_2 is made as small as possible (consistent with the voltage-gradient limitation on the downlead), and the coupling between the flat-top and the tower, represented in Fig. 19-3 by C_3, is made as small as is practical.

The electrostatic nature of the design problems of small antennas justifies a unique experimental procedure called the "tank method."* The antenna (including supports) is modeled on a copper sheet, and the whole is placed in tap water contained in a tank which is constructed of insulating material. The model is sectionalized into n sections, each section being isolated electrically and furnished with an insulated lead running out of the tank. Provision is made to measure the current in each section, with the sections composing the antenna being maintained at the same potential and the tower sections at ground (copper-sheet) potential. Alternating current is used in order to avoid polarization. The lines of current flow in the tank correspond exactly to electrostatic flux in the air, and the current values in the antenna sections correspond to electrostatic charges in the full-scale antenna. The antenna effective height is determined from the equation

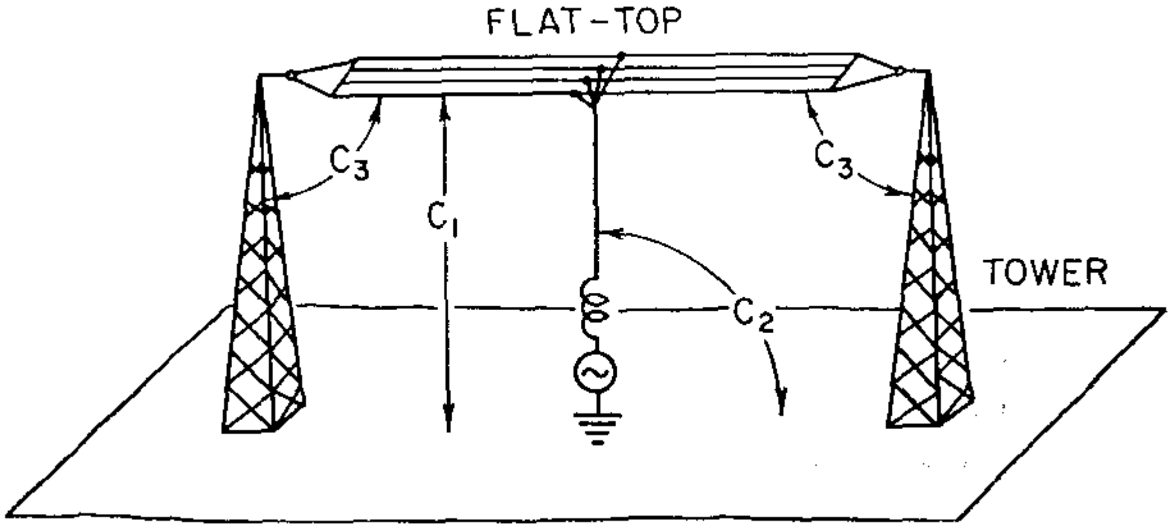

FIG. 19-3. Typical low-frequency antenna.

$$h_e = \frac{\sum_{i=1}^{n} I_i h_i}{I} \times \text{scale of model} \tag{19-8}$$

where I_i = current in ith section taken positive for antenna sections and negative for tower sections
h_i = average height of ith section
I = total current in antenna

The antenna capacitance C_a is obtained from the measured resistance values of the antenna model R_m and that of a standard R_s, immersed in the same tank. The standard is of such a form that its capacitance in air may be readily calculated, such as a horizontal disk provided with a guard ring. Then

$$C_a = \frac{R_s C_s}{R_m} \times \text{scale of model} \tag{19-9}$$

An alternative means of determining h_e may be provided in the tank experiments. For this purpose a probe is placed at a position remote from the model on a wall of the tank. Two experimental set-ups are used: (1) the flat-top only in place and (2) the entire model, including supports in place. The probe potentials V_1 and V_2 are measured with the model at the same potential for the two conditions. The ratio

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* Early literature contains numerous references to the tank method of measuring antenna capacitance. The material contained here was obtained from a 1920 unpublished General Electric Company report concerned with tank experiments to solve various design problems connected with the Rocky Point antenna of Fig. 19-8.

V_2/V_1 is called the "shielding factor" (SF). The values of capacitance C_1 and C_2 ($= C_a$) are also measured for the two conditions. Then

$$h_e = \frac{C_1}{C_2}\,(\text{SF})(\text{average height of flat-top}) \tag{19-10}$$

As examples of the application of the tank experimental methods, the following design problems in connection with the Rocky Point antenna (Fig. 19-8) were investigated.

1. The effect of the steel tower bridge on the antenna wire capacitance and the determination of the optimum distance between the wire and the bridge
2. The effect of the steel tower on the antenna wire capacitance and the determination of the optimum distance between the tower and the wire nearest to it
3. The effect of the tower on the downlead and the optimum location of this lead
4. The effective height of the antenna
5. The capacitance of the antenna

For application to the design of *very* small antennas (including virtually all VLF antennas), the tank-model method has two definite advantages over the model-in-air method mentioned above. First, the radiation resistance, because it is extremely small, is difficult to measure directly as in the model-in-air method. Second, the data provided by the sectional currents in the model-in-tank method allow the evaluation of effects of the individual sections, as in the Rocky Point antenna experiment. The same difficulties in accurately modeling the various components of the antenna when very large scale factors are used are encountered in both experimental procedures.

Other experimental methods for determining the characteristics of small antennas have been used in the investigation of low-frequency antennas on aircraft.[15]

An approximate method of calculating antenna capacitance which is sufficiently accurate for many low-frequency antenna applications was suggested by G. W. O. Howe in 1914. The method is discussed in detail in Refs. 16 and 17 and in Ref. 2, chap. 10. The antenna and its supports are considered to be divided into parts, and the charge carried by each part is determined by means of mutual (and self-) potential coefficients. The approximate values of the potential coefficients are calculated by averaging over each part the potential due to an assumed uniformly distributed unit charge on each of the other parts (and itself). The method can be readily extended to obtain the effective height as well as the capacitance of the antenna. If a uniformly distributed charge is assumed for a downlead which is top-loaded by a nonradiating flat-top having nonradiating supports, the radiation is given precisely by the curves of Fig. 19-2. It is interesting to note that Howe's method obtains for the capacitance to ground of an *unloaded* vertical radiator the equation

$$C_a = \frac{2\pi\epsilon_v h}{[\ln(h/a) - 1]} \quad \text{farads} \tag{19-11}$$

where ϵ_v = absolute dielectric constant of free space $\simeq (1/36\pi)\,10^{-9}$ farad/meter
h = height, meters
a = radius, meters

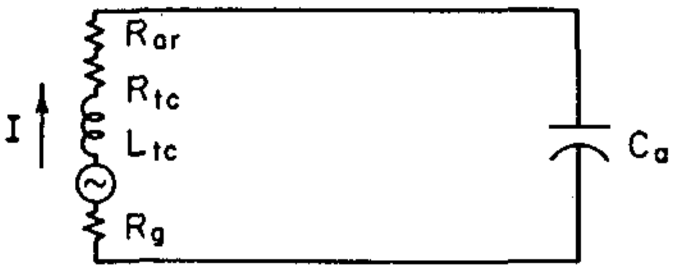
which is consistent with Eq. (19-4), an experimentally verified equation for the characteristic impedance of a short vertical radiator.

19.3. MULTIPLE-TUNED ANTENNA

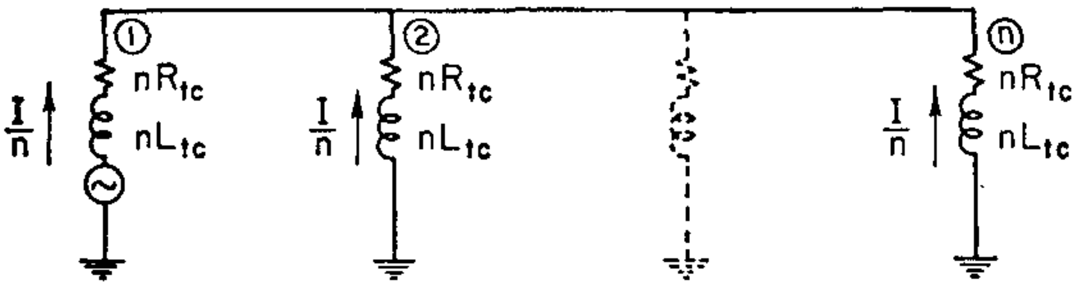
Multiple tuning was originally devised by E. F. W. Alexanderson for the purpose of reducing the ground loss of VLF antennas of the long inverted-L type.[18] Essentially, a multiple-tuned antenna consists of a number of antennas having closely coupled radiation characteristics but with substantially independent ground systems.

Consider first (Fig. 19-4*a*) a long narrow flat-top of capacitance C_a fed by a single downlead of negligible capacitance and tuned by a coil of inductance $L_{tc} = 1/\omega^2 C_a$. Neglecting the antenna inductance and all losses except those in the tuning coil and ground, the equivalent circuit is as shown in Fig. 19-4*b*. For a given antenna current *I*, the power radiated is I^2R_{ar} and the powers lost in the tuning coil and ground are I^2R_{tc} and I^2R_g, respectively. For the usual condition that the feed resistance $R_{ar} + R_{a\ell} + R_g$ is small compared with the capacitive reactance $1/\omega C_a$, the antenna voltage is very nearly $I/\omega C_a$.

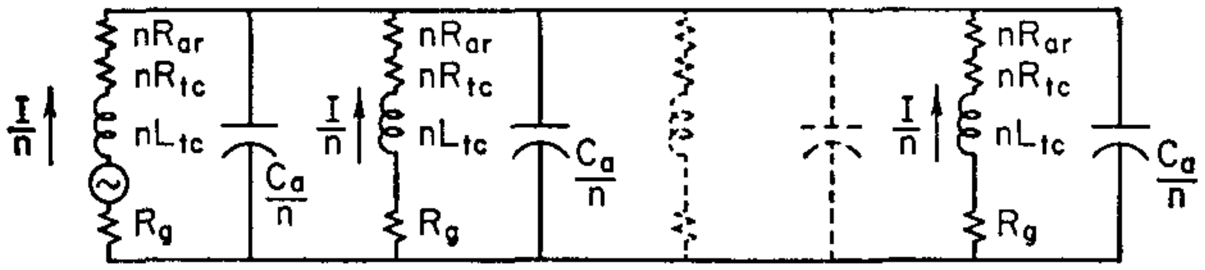
a. SINGLE-TUNED ANTENNA



b. SINGLE-TUNED EQUIVALENT CIRCUIT



c. MULTIPLE-TUNED ANTENNA



d. MULTIPLE-TUNED EQUIVALENT CIRCUIT

FIG. 19-4. Single-tuned and multiple-tuned flat-top antenna.

Next consider the same flat-top fed by a number (n) of spaced downleads (Fig. 19-4*c* and *d*) with the same *total* antenna current (the sum of the downlead currents). With a tuning inductance of nL_{tc} in each downlead, the circuit is again resonant and the current in each downlead is equal to I/n. If the individual antenna sections are small, all currents are substantially in phase. Assuming equal values of coil Q in both single- and multiple-tuned cases, the resistance of each coil is nR_{tc}. The total radiated power for a given total current I is the same as for the previous case; therefore, the radiation resistance assignable to each downlead is nR_{ar}. The total power lost in the tuning coils is the same as before, being equal to $(I/n)^2(nR_{tc})n$, or I^2R_{tc}, but that in the ground, under the assumption of an equal value of ground resistance for each downlead in both single- and multiple-feed cases, is reduced to $(I/n)^2R_gn$, or

$I^2(R_g/n)$. The total power into the antenna is therefore equal to

$$I^2\left(R_{ar} + R_{tc} + \frac{R_g}{n}\right)$$

If the individual ground resistance R_g is much larger than $R_{ar} + R_{tc}$, this input power is much less than for the single-tuned case, $I^2(R_{ar} + R_{tc} + R_g)$. Since the current supplied by the generator is I/n, the input resistance of the antenna is equal to $n^2(R_{ar} + R_{tc} + R_g/n)$. The antenna voltage is the same as for the single-tuned condition.

In application to multiple-tuned antennas, in general, the ratio of total current to the generator current is defined as the "feed ratio" (n in the case of the example). The antenna input resistance is called the "feed resistance." The total antenna power for unit *total* current is defined as the "multiple" resistance and is equal to the feed resistance divided by the square of the feed ratio.

Four factors tend to limit the extent to which multiple tuning should be carried for a given flat-top. First, the several downleads subtract somewhat from the effective height established by the flat-top. Second, as the number of downleads increases, their ground currents tend to overlap to a greater degree, resulting in the multiple tuning being less effective in improving the efficiency. Third, each additional downlead represents added costs in respect to itself, its tuning coils, and the mechanical loads it places on the towers, halyards, and insulators. Fourth, the antenna adjustments, when a substantial change in operating frequency is made, become more difficult as the number of tuning coils increases.

For the case of a vertical radiator having a relatively small amount of top loading, it is not feasible to supply independent and uncoupled ground systems for several downleads. Then the full advantage with regard to reduction of ground loss is not realized by multiple tuning. However, the general principle may be employed in order to simulate a vertical radiator of large radius and to increase the input resistance of the antenna. In this case the input resistance is equal to the single-tuned input resistance multiplied by the square of the feed ratio. Some such applications of multiple tuning are discussed in Ref. 6.

19.4. LOW-FREQUENCY GROUND SYSTEMS

A large variety of ground-system types have been used with low-frequency antennas. In contrast with the situation at broadcast frequencies where the radial-wire ground system has been generally adopted, no one type has become universally standard for low-frequency application. There are little quantitative data available by which the performance of the various types can be compared directly. This situation requires that the subject be presented mainly on the bases of history and practice.

Most low-frequency installations of recent years have included a radial-wire ground system. This type consists of a large number of generally radial wires, laid on or buried in the ground, extending out from the points of feed. Copper mesh is commonly included near the feed points to shield the ground from the high field existing there and to serve as a convenient termination for the inner ends of the radials. The outer ends are ordinarily terminated on ground stakes. As pertains to the design of all other parts of a low-frequency antenna, cost balanced against performance is the major consideration in determining the amount of labor and material to put into the ground system. The ground loss decreases as both the number and the length of the radials are increased. Up to 360 wires and lengths up to one-half wavelength have been used, although ordinarily that length is impractical at low frequencies. A design method applying to this type of ground system is given in Ref. 19. Installations of radial-wire ground systems are described in Refs. 10, 14, 20, and 22 to 25.

"Multiple-star" ground systems have been used in several VLF installations. In this type a number of relatively small radial-wire systems are scattered over that ground area in which all significant ground currents occur. The ground current collected by each star is returned to the downlead by way of an overhead bus. For design purposes, the resistance R_s of each star is calculated from a d-c equation such as[39]

$$R_s = \frac{\rho}{n\pi\ell}\left[\ln\left(\frac{2\ell}{an}\right) + 1.23n - 2.23\right] \quad \text{ohms} \quad \text{for } n > 6 \qquad (19\text{-}12)$$

where ρ = ground resistivity, ohms/meter cube
n = number of wires in star
ℓ = length of each wire, meters
a = radius of wire, meters

The ground current collected by each star I_s is determined according to the portion of the antenna flux assignable to the star. The total ground loss, $\Sigma I_s{}^2 R_s$ watts, is then calculated. By dividing this loss value by the square of the antenna current, the equivalent ground resistance R_g is calculated.

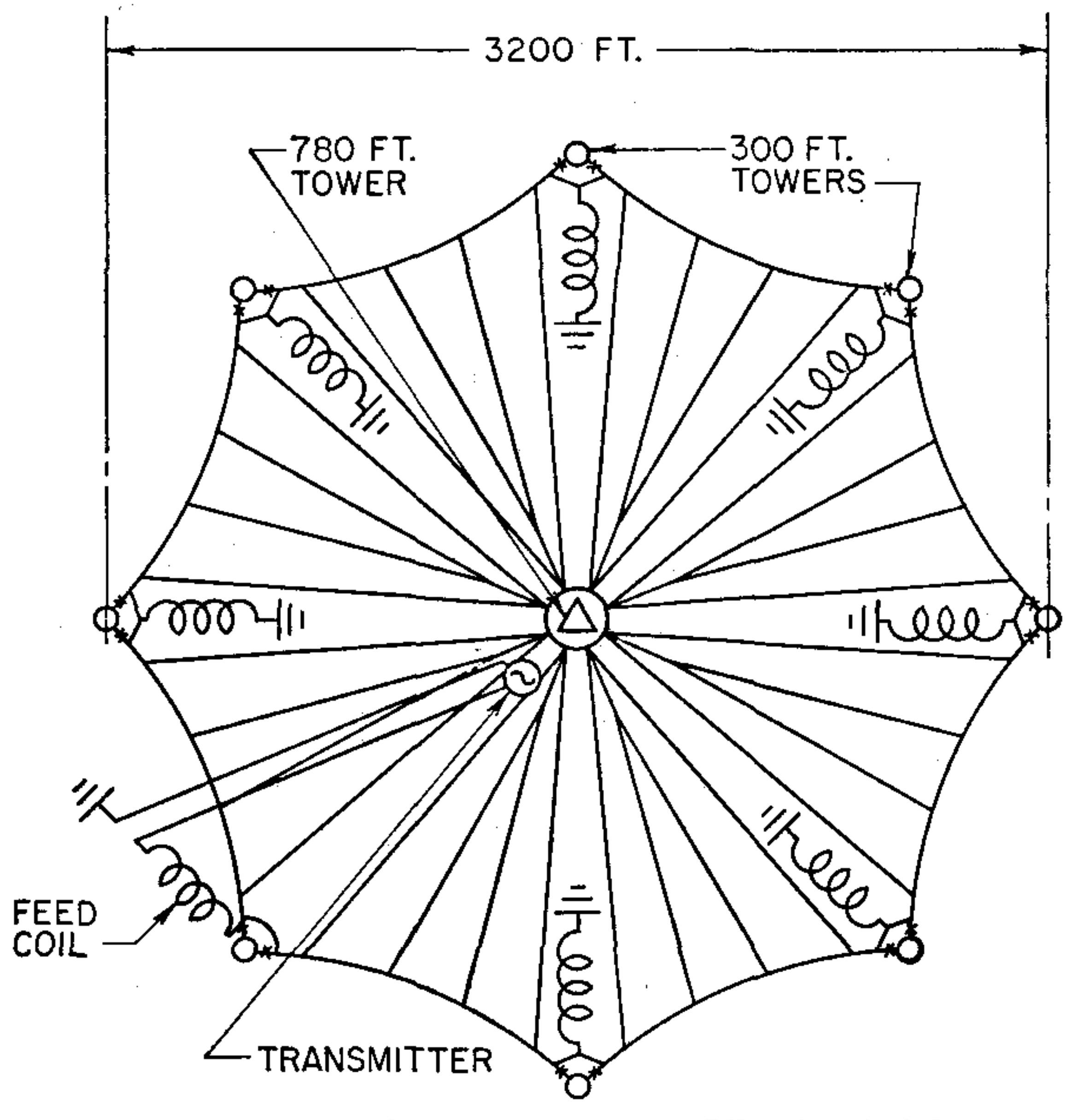


Fig. 19-5. Tuckerton, N.J., VLF umbrella antenna. Effective height, 315 ft; capacitance, 0.050 μf; allowable voltage, 160 kv; efficiency at 18.000 kc, 22 per cent. (*Courtesy of RCA Communications, Inc.*)

An example of a multiple-star system is that, shown in Fig. 19-6, of the multiple-tuned Tuckerton umbrella antenna (Fig. 19-5). The "equalizer" coil 1, shown in the figure at the center star of the system for each downlead, is of such inductance that the same current is drawn from the subsoil star to which it is connected as from other stars of the division. A bridge circuit is effectively formed by coil 2 combined with the capacitance from antenna to mast and the effective inductance of the star distribution system combined with the capacitance from antenna to ground. The inductance of coil 2 is adjusted so that no current flows in the direct ground connection at the base of the mast. Coils 2 and 3 combined perform a similar function in regard to the current induced in the copper tuning house. The antenna efficiency of 22 per cent reported for Tuckerton is high considering the small amount of wire employed by the multiple-star ground system; however, the ground problem there is relatively easy because the site is a salt marsh of extremely high conductivity.

Multiple tuning was first employed in 1917 with the very-low-frequency New Brunswick antenna then under the control of the U.S. Navy. That antenna was originally installed by the American Marconi Company as an inverted-L type (in accordance with Fig. 19-7 but without the unfed downleads). It had a ground system consisting of a number of plates buried in a 300-ft-radius circle with center at the feed point, plus 16 buried wires, spaced over the width and extending over the length of the flat-top. At 35 kc the input resistance of the inverted-L was 3.8 ohms and the radiation resistance was estimated to be 0.07 ohm. During the changeover to multiple tuning, experiments were made which confirmed that the field strength at a distant receiving position was dependent only on the total antenna current. The multiple

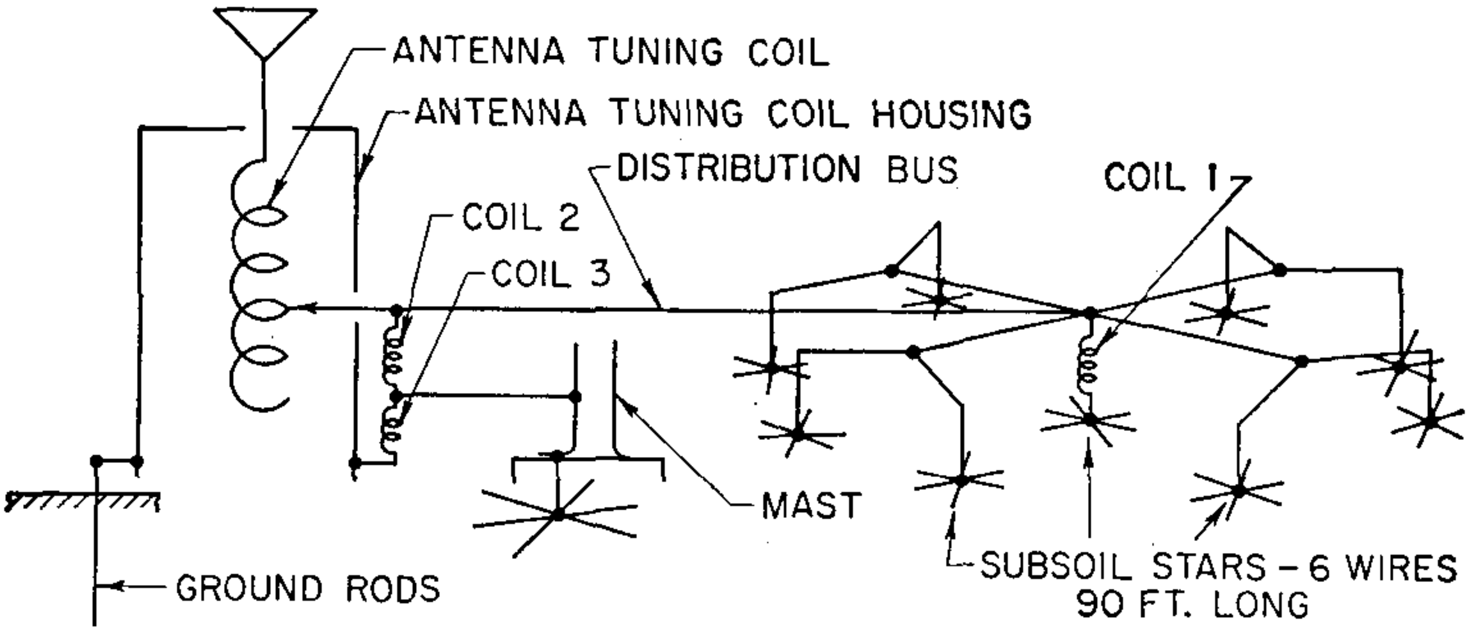


Fig. 19-6. Multiple-star ground system of Tuckerton antenna (Fig. 19-5). Typical for each tuning coil. (*Courtesy of RCA Communications, Inc.*)

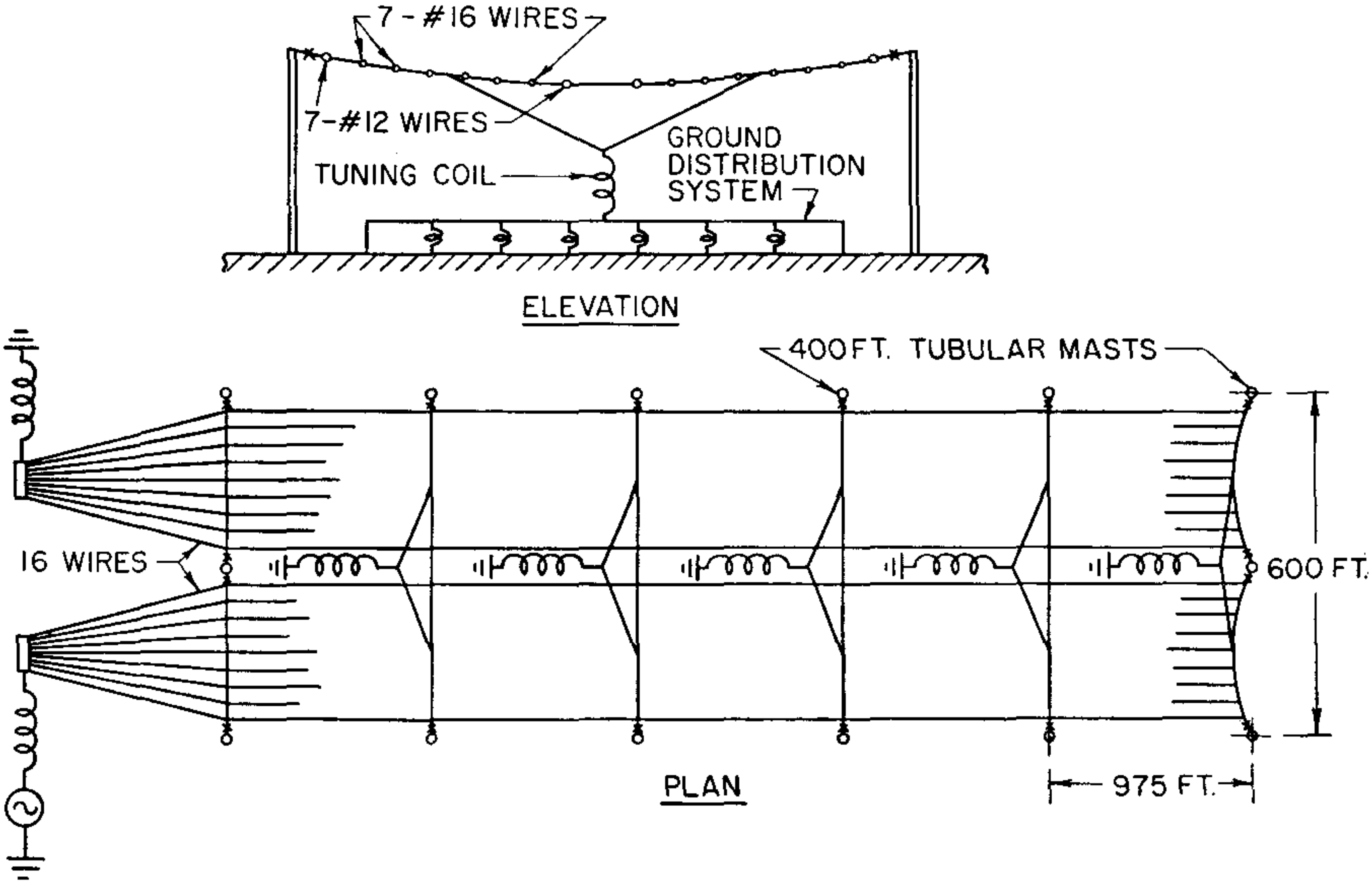


Fig. 19-7. New Brunswick, N.J., VLF antenna and ground-distribution system. Effective height, 223 ft; capacitance, 0.068 μf; allowable voltage, 125 kv; efficiency at 22.140 kc, 11 per cent. (*Courtesy of RCA Communications, Inc.*)

resistance obtained, with the tuning coil of each unfed downlead directly connected to all the buried ground wires by means of a transverse tie wire, was 0.9 ohm. With this arrangement, however, it was discovered that the most central buried wires carried almost all the ground current. To correct this condition "equalizing" coils were inserted between the tuning coil and the individual ground wires, as shown in Fig. 19-7. These were adjusted to force an equal distribution of the current among the ground wires. The equalizing coils further reduced the multiple resistance from 0.9 to 0.7 ohm.

An overhead ground system called a "capacitance" ground has been used in conjunction with a buried system in some VLF installations. The function of the overhead system was to reduce the ground currents directly beneath the antenna, where otherwise they tend to be highly concentrated. Such a system was used for a time with the New Brunswick antenna of Fig. 19-7 after the changeover to multiple tuning, described above. In that case the capacitance ground consisted of a grid of wires about 10 ft above ground and covering most of the area directly under the antenna. The connections of the buried system and the capacitance ground to the tuning coils were such that the latter operated at a potential opposite to that of the antenna with respect to ground. The relative potentials were so adjusted that the ground current divided equally between the two systems. This capacitance ground was effective in reducing the multiple resistance from 0.7 to 0.5 ohm. On the other hand, it required much maintenance because of damage by ice storms, and it hindered maintenance aloft to such an extent that it was finally discarded. At the time of removal, the buried-wire ground system was overhauled and improved so that a still lower value of multiple resistance (0.35 ohm at 22 kc) was obtained.

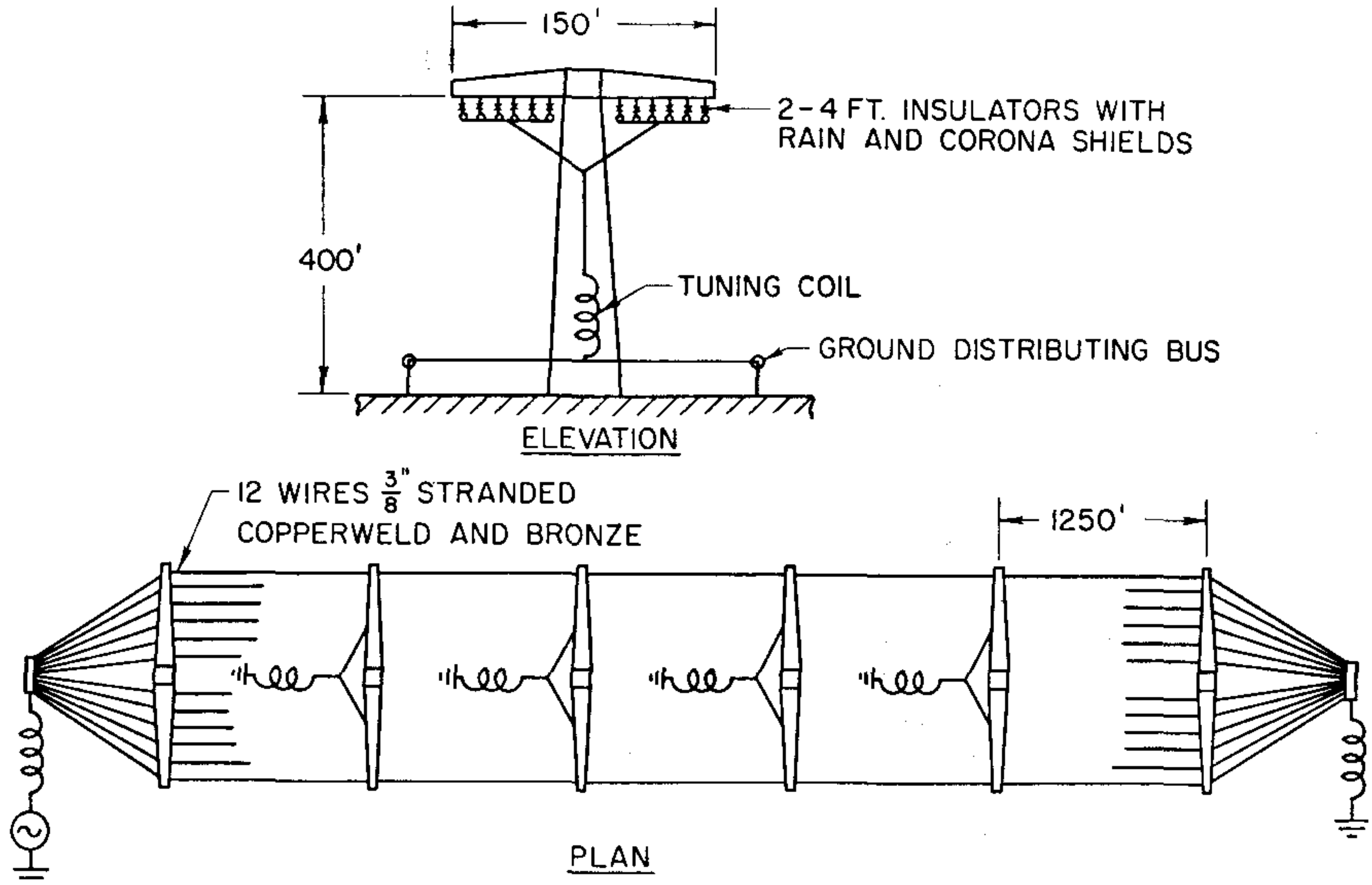


FIG. 19-8. Rocky Point, N.Y., VLF antenna. Effective height, 272 ft; capacitance 0.050 μf; allowable voltage, 150 kv; efficiency at 18.220 kc, 10 per cent. (*Courtesy of RCA Communications, Inc.*)

Another example of a ground system for a multiple-tuned antenna is that of the Rocky Point antenna (Fig. 19-8). Sixty buried "stars," half on each side of the antenna, are located with their centers spaced 250 ft on lines 150 ft from the line of towers. Each star consists of 40 wires, each 125 ft long. From the stars, buried wires spaced 10 ft extend out alternately to distances of 500 and 1,000 ft from the line of towers. Figure 19-9 shows the ground distribution and equalizing system for each tower and downlead. The ground connections shown in the figure are to the buried stars. The distribution buses run the entire length of the antenna and are supported on telephone poles. The equalizing coils are wound on those poles and are adjusted to give equal current at each grounding point. The tower coil, which is connected between the distribution bus and a lead sloping up to the tower's 60-ft level, is adjusted to divert the tower current from its normal path through the earth into the overhead distribution system.

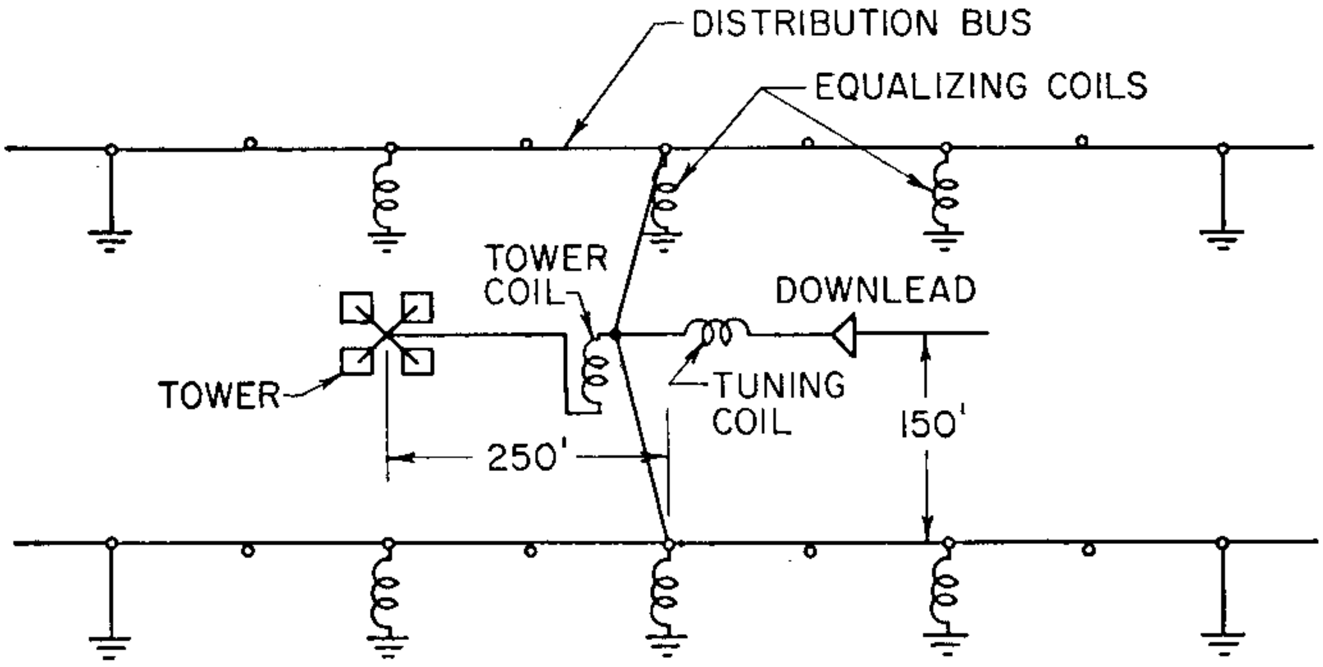


Fig. 19-9. Ground-distribution and equalizing system for Rocky Point antenna (Fig. 19-8). Typical for each downlead. (*Courtesy of RCA Communications, Inc.*)

An example of a recently designed ground system for a VLF multiple-tuned antenna is that of the Air Force antenna at Marion, Mass.* This antenna, which is practically the same as the New Brunswick antenna of Fig. 19-7, was used in the past by RCA Communications, Inc., with a ground system similar to that described above for New Brunswick, excepting that, at Marion, a number of stars covered an additional area nominally 250 ft beyond the periphery of the antenna. An overhead distribution system, with equalizing coils to distribute the ground current both longitudinally and laterally from each downlead position, was employed. Under more recent operation by the U.S. Air Force at a frequency about 26 kc, an average value of multiple resistance of 0.32 ohm, with variations up to 0.615 ohm when the ground was very dry, was obtained. The multiple resistance was estimated to be made up of radiation resistance 0.050 ohm, resistance of tuning coils and antenna wires 0.140 ohm, and the remainder ground-loss resistance. Thus the estimated average ground-loss resistance was 0.130 ohm, and the average efficiency was 0.05/0.32, or 15.6 per cent.

Besides being very inefficient under prolonged dry-weather conditions, the ground system at Marion developed several minor faults in its overhead portion, causing interference to local broadcast and television reception and also starting several field fires. Consequently, the Air Force sponsored a rehabilitation under which the overhead ground distribution was removed and a buried radial-wire system, sketched in Fig. 19-10, was installed over the original buried portion. The only overhead members included in the revised installation were two cages running from a copper square between the two end downleads to the transmitter and to tuning coil 1*B*, respectively. The value of multiple resistance obtained after the rehabilitation was 0.219 ohm, which figure represents an estimated ground-loss resistance of 0.029 ohm (22 per cent of the previous average value) and an efficiency of 23 per cent.

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* Descriptive details and performance characteristics of both original and rehabilitated ground systems were furnished by J. L. Finch of RCA Communications, Inc., with permission of the U.S. Air Force.

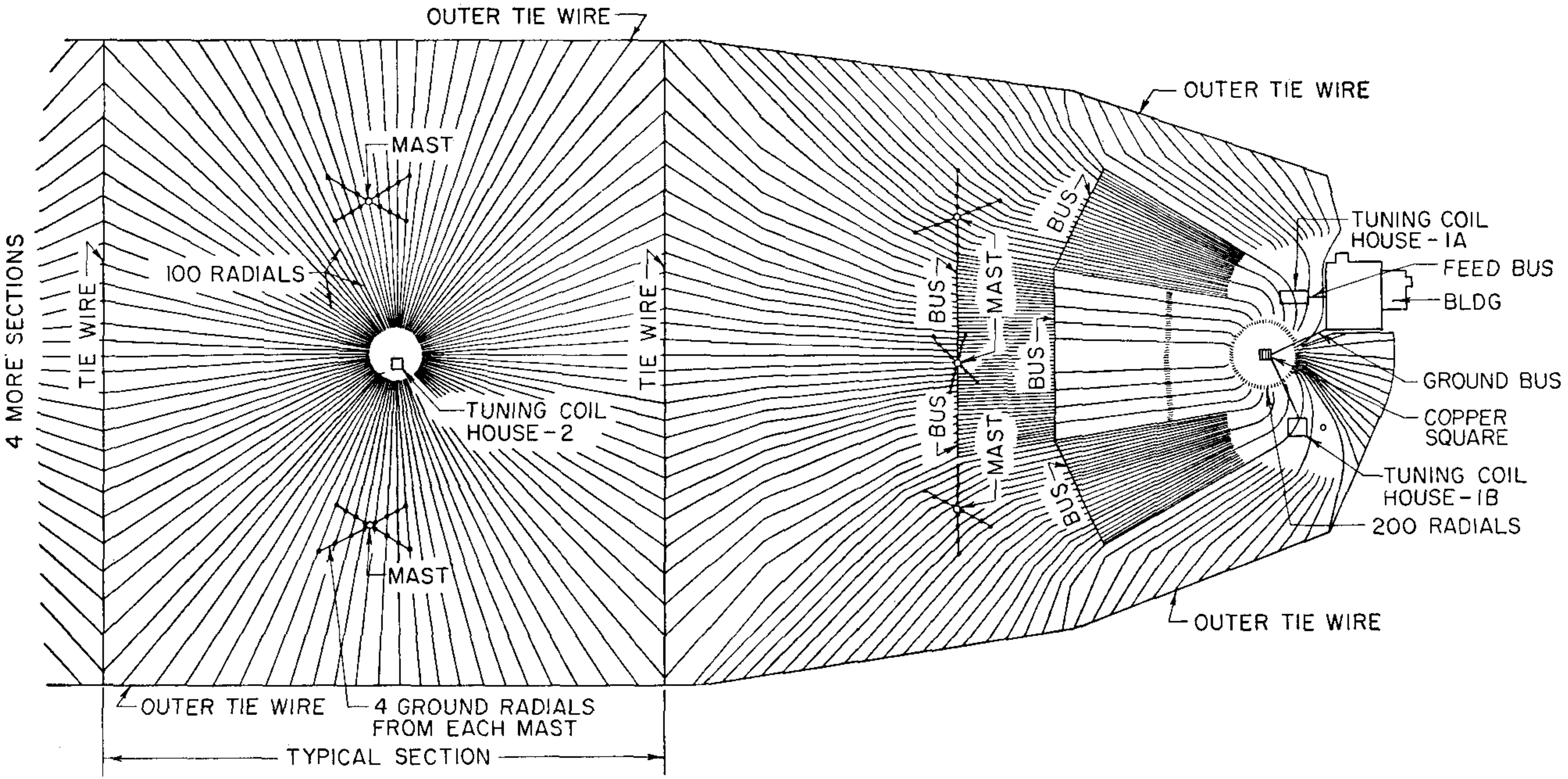

Fig. 19-10. Rehabilitated ground system of Air Force VLF antenna at Marion, Mass. The antenna is practically the same as the New Brunswick antenna (Fig. 19-7). (*Courtesy of U.S. Air Force and RCA Communications, Inc.*).

The extensive usage at VLF of the multiple star and other special types has tended to complicate the standardization of low-frequency ground-system design. It has been argued that the special types and the overhead distribution and equalizing systems, although not necessary at higher frequencies, are required at VLF because of the extra difficulties of the grounding there. The question has remained open because of the general lack of quantitative experimental VLF data available by which the performance of the various types could be compared under equal circumstances. The recent Air Force results at Marion are especially important in that they tend to oppose the arguments favoring the special types of systems. With the same antenna, site, and expanse of ground system and at the same very low frequency, a generally radial ground system resulted in considerably less ground loss than had previously been obtained with a combination of multiple stars, parallel-wire grid, and a complex overhead distribution and equalizing system.

Even though, on the basis of evidence now available, the radial-wire system were to be accepted as preferable to any of the special types, the design of low-frequency ground systems would necessarily remain relatively unstandardized, as compared with ground systems for broadcast radiators. This is because of the extra importance and variety of the economic factor, the requirement of lower values of ground loss due to the electrically small size of the antennas, and the variety of antenna types used at low frequencies.

19.5. MISCELLANEOUS PROBLEMS OF LOW-FREQUENCY ANTENNAS

The large physical size and the electrical smallness of low-frequency antennas cause several miscellaneous problems. These are especially evident in VLF antennas but may also be present in the larger or higher-power LF antennas.

A low-frequency installation involves a considerable amount of structual design. The wires in the antenna are subject to loads because of their own weight, the weight of ice (in most locations), and windage. Ice loading and windage are especially severe in the far north, and windage is high in hurricane belts. Stresses in the antenna wires and halyards are dependent on allowable antenna sag and shift, which may be limited by electrical considerations. In order to limit stresses in the antenna and loads on the towers, halyards are sometimes provided with counterweight assemblies or friction drums. Provisions are often made to melt sleet on the flat-top by means of 60-cycle power. Protective devices may be added to release the flat-top when failure of the 60-cycle power supply causes the ice formation to be especially heavy. These subjects are treated in more detail in Refs. 26 to 28. The structural design of low-frequency antennas is a specialized field, the details of which are usually accomplished by the companies furnishing the towers or the antenna wire. However, because of practical and economical considerations and the interrelation of design problems, the antenna design is generally the result of a considerable amount of mutual effort by structural and radio engineers. Interesting antenna structural information is contained in Refs. 6, 10, 11, 20 to 23, and 29 to 34.

VLF antenna insulators are generally of tubular porcelain. To withstand the large mechanical loads provided by large flat-tops, tubes up to 6 in. in diameter and rated at working loads of about 12,000 lb are used; often two, three, and four of these are connected in parallel by means of load-equalizing yokes. Insulators up to 6 ft in length and rated as high as 150 kv are employed. In a few cases two are connected in tandem to withstand still higher antenna voltage. Individual porcelain insulators have very small losses, but a typical VLF antenna may use enough of them so that they dissipate an appreciable amount of power. Losses in such insulators are discussed in Refs. 29 and 35. Another type of insulator having higher mechanical load ratings than the conventional porcelain type has been incorporated in several LF antennas in recent years. This type consists of an oil-filled porcelain tube containing a "safety core" (a phenolic-resin impregnated link between end caps).[6,7]

The question of whether or not to insulate the guys and masts supporting flat-tops is mainly an economic one. These insulators tend to reduce the charges induced in the guys and masts and thereby to increase the antenna's effective height. If the insulators are used, it is extremely important, because of the high voltages to which they are subjected, that the insulation material be of high quality. Base insulators are employed to advantage in the masts of the Rugby antenna.[30] On the other hand, in the case of the Tuckerton umbrella of Fig. 19-5, a considerable increase in antenna efficiency was obtained by replacing weathered insulators in the central mast with metal blocks. The insulation of guys and masts is discussed in more detail in Refs. 5, 14, 29, 30, and 37.

Corona is an important design consideration of VLF antennas because of the extremely high voltages to which they are subjected. As the power into the antenna is increased above the point at which corona discharge starts, the antenna input resistance increases rapidly, representing a corresponding decrease in efficiency. Ordinarily, precautions are taken in the antenna design to prevent the occurrence of corona. Consideration is given to voltage gradients in the selection of wire size (hollow and jute core conductors have been used on this account), and attention is given the elimination of sharp corners on antenna fittings and to maintaining large separations between high-potential components and grounded objects. These represent electrostatic problems the solution of which can be facilitated by calculations according to Howe's method or by use of the water-tank experimental method.

The losses in the tuning coil and variometer of a VLF antenna are usually appreciable. These losses occur in the coil conductors, in the coil frame, and in the surroundings. The loss in the conductors can be made small by using Litzendraht wire having thousands of insulated strands, each 0.005 to 0.010 in. in diameter, and by making the coil physically large. The loss in the frame is made low by the use of low-loss insulating material, such as porcelain, and the absolute minimum of metal fittings. In order to make the loss in the surroundings as low as possible, the room containing the tuning coil is often lined with copper sheet. References 20, 22, 29, 30, and 36 contain interesting information in regard to existing tuning coils and variometers for VLF antennas.

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